

CUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS

**Search for New Physics with Razor Kinematic Variables at
 $\sqrt{s}=13$ TeV Using Ultra Legacy Samples**

Ufuk Güney TOK

Physics Department

September, 2024

CUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

PhD THESIS APPROVAL

**Search for New Physics with Razor Kinematic Variables at
 $\sqrt{s}=13$ TeV Using Ultra Legacy Samples**

Ufuk Güney TOK

Physics Department

This Doctorate Thesis was evaluated by the following Jury Members on 18/09/2024 and was approved by unanimity / majority of votes.

Jury : Prof. Dr. Aysel KAYIŞ TOPAKSU (Advisor)

: Prof. Dr. İsa DUMANOĞLU

: Prof. Dr. Kenan SÖĞÜT

: Asst. Prof. Dr. Emine GÜRPINAR GÜLER

: Prof. Dr. Kadri ÖZDEMİR

**This Thesis was written in the Department of Physics Institute of Natural and Applied Sciences.
Thesis Number:**

Prof. Dr. Sadık DİNÇER
Director
Institute of Natural and Applied Sciences

¹This study was supported by Çukurova University Scientific Research Fund.
Project No: FDK-2019-11226

Note: The usage of the presented specific declarations, tables, figures, and photographs either in this thesis or in any other reference without citation is subject to "The law of Arts and Intellectual Products" number of 5846 of Turkish Republic

Sevgili eřim Aslı'ya ve Leo ile Mati'ye...

CONTENTS

ABSTRACT	I
ÖZ	II
GENİŞLETİLMİŞ ÖZET	III
ACKNOWLEDGEMENTS	V
LIST OF TABLES	VI
LIST OF FIGURES	VIII
ABBREVIATIONS	XVI
1. INTRODUCTION	1
2. THEORY OF SUPERSYMMETRY (SUSY)	3
2.1. Standard Model of Particles	3
2.2. SUSY	11
2.3. MSSM	15
2.4. Simplified SUSY Models	16
2.5. Razor Kinematic Variables	18
2.6. SUSY Searches on LHC, Run-II	22
3. THE LHC and CMS EXPERIMENT	27
3.1. The Large Hadron Collider (LHC)	27
3.2. CMS Experiment	27
3.2.1. Sub-Systems of CMS	29
3.2.2. Phase-2 Upgrades	31
4. SPS H2 BEAMLINE SIMULATION	33
4.1. Introduction	33
4.2. Particle Production	34
4.3. The HGCALE Test Beams	35
4.4. Beamline Simulation with G4beamline	35
4.5. Energy Loss and Material Affect	36
4.5.1. Synchrotron Radiation	36
4.5.2. Materials on the Beamline	37
4.6. Test Beam Data and MC	38
4.7. Results	38
5. INCLUSIVE RAZOR BOOST ANALYSIS FOR NEW PHYSICS	41

5.1. Inclusive Search for SUSY with M_R and R^2 variables for 2016 CMS Data	41
5.2. Analysis Strategy	43
5.3. Dataset and Monte-Carlo	44
5.3.1. Datasets	44
5.3.2. Monte-Carlo Samples	45
5.4. Trigger	45
5.4.1. Baseline Event Selection	47
5.5. Event Selections	47
5.5.1. Jets	48
5.5.2. b-tagged Jets	48
5.5.3. Leptons	49
5.5.4. Photons	50
5.5.5. Boosted Hadronic and Leptonic Objects	51
5.5.6. Search Regions	52
5.6. Background Estimation Strategy and CFs	56
5.6.1. BG Estimation Strategy	57
5.6.2. BG Estimation for $Z \rightarrow \nu\nu$ Process	57
5.6.3. Validation Regions to Check Background Estimation	68
5.6.4. Validation of $Z \rightarrow \nu\nu$ Background Estimation with $W \rightarrow l\nu$	78
5.6.5. Other Background Estimations: Dilepton and QWT	79
5.7. Systematic Uncertainties	81
5.8. Results and Limit Calculations on Simplified Models	86
6. CONCLUSION	107
REFERENCES	109
CURRICULUM VITAE	121
APPENDIX	123
Appendix A Datasets for Each Data Taken Periods for Run 2	125
Appendix B Monte-Carlo Samples for Background and Signal	130
Appendix C Systematic Uncertainties	145
Appendix D Validation Results	148

**Search for New Physics with Razor Kinematic Variables at
 $\sqrt{s}=13$ TeV Using Ultra Legacy Samples**

Ufuk Güney TOK

Advisor: Prof. Dr. Aysel KAYIŞ TOPAKSU

Department of Physics

ABSTRACT

In this thesis, a detailed analysis of Supersymmetry (SUSY) using the razor kinematic variables with the Run-2 Ultra-Legacy (UL) dataset is presented. By exploiting the distinctive kinematic features of SUSY events, the razor analysis allows for the discrimination between signal and background processes. The UL dataset provides a comprehensive collection of data from proton-proton collisions at $\sqrt{s} = 13$ TeV, recorded by the CMS detector with an integrated luminosity of 137 fb^{-1} . The sensitivity achieved with the UL dataset provides valuable insights into the potential existence of new physics beyond the Standard Model. The analysis strategy involves event selection based on specific razor variables, M_R and R^2 . Additionally, dedicated background estimation techniques and systematic uncertainty studies are performed to ensure accurate predictions of the Standard Model backgrounds. The results are interpreted in the context of simplified SUSY models, focusing on producing gluinos and squarks decaying to various final states for both RPV and RPC cases.

Keywords: SUSY, Razor, CMS, Ultra Legacy, HGCAL

**$\sqrt{s}=13$ TeV’ de Razor Kinematik Değişkenleri ve Ultra
Legacy Verisi ile Yeni Fizik Araştırmaları**

Ufuk Güney TOK

Danışman: Prof. Dr. Aysel KAYIŞ TOPAKSU

Fizik Anabilim Dalı

ÖZ

Bu tezde, Run-2 Ultra-Legacy (UL) veri seti kullanılarak Süper-Simetri (SUSİ) araştırmaları için detaylı bir analizi sunulmaktadır. Razor kinematik değişkenleri SUSİ olaylarının karakteristik kinematik özelliklerini kullanarak sinyal ve arka plan süreçleri arasındaki ayrımı sağlar. UL veri seti, CMS detektörü tarafından kaydedilen ve $\sqrt{s} = 13$ TeV’de proton-proton çarpışmalarından elde edilen 137fb^{-1} toplam ışıklılık değeri ile kapsamlı bir veri koleksiyonunu sunar. UL veri seti ile elde edilen hassasiyet, Stan-dart Model ötesinde yeni fiziksel fenomenlerin potansiyel varlığına dair değerli bilgiler sunar. Analiz stratejisi, belirli razor kinematik (M_R ve R^2) değişkenlerine dayalı olay seçimini içerir. Ayrıca, Standart Model arka planlarının doğru tahminlerini sağlamak için özel arka plan tahmini teknikleri ve sistematik belirsizlik çalışmaları gerçekleştirilmiştir. Sonuçlar, basitleştirilmiş SUSİ modelleri bağlamında hem RPV (R-parite korunmayan) hem de RPC (R-parite korunumlu) durumlara bozunan gluino, LSP ve squarkların kütle üst limit değerleri hesaplanarak yapılmıştır.

Anahtar Kelimeler: SUSİ, Razor, CMS, Ultra Legacy, HGCAL

GENİŞLETİLMİŞ ÖZET

İnsanlığın Antik Çağlardan bu yana sorduğu sorular halen temel varoluşsal, felsefi bir öneme sahiptir, bunlardan en önemlileri evrenin yapısı ile ilgili olanlardır. Parçacık fiziğinin tarihi, evrenin yapısıyla ilgili aynı temel belirsizliği aydınlatmaya çalışan birçok parlak bilim insanının bitmek bilmeyen çabalarıyla elde edilen şaşırtıcı keşiflerle doludur. SUSİ, fiziğin cevaplanmamış gizemini yanıtlamaya yönelik en üretken yaklaşımlardan biridir. SUSİ, temel parçacıkların davranışları hakkında pek çok şeyi açıklayan ve Standart Model (SM) olarak adlandırılan çok başarılı bir teori üzerine inşa edilmiştir. SM, Higgs bozonu, kuarklar, mezonlar vb. gibi teori tarafından öngörülen birçok keşifle desteklenen köklü bir teoridir. SM ve SUSİ teorisi Bölüm 2’de ele alınacaktır.

SUSİ, karanlık madde (DM), elektrozayıf sektör ince ayarı ve $g - 2$ anomalisi ile ilgili çözülmemiş soruları ele alan SM teorisinin açıklamakta zorlandığı birçok soruya yanıt getirmesi beklenen potansiyel bir genişleme önermektedir. SUSİ, yeni bir fermiyon-bozon simetrisi önererek ve bununla birlikte SM parçacık içeriğini genişleterek büyük birleşik teoriye en yakın teori olarak dikkat çekmektedir. Bu tez, CMS deneyi tarafından Run-2 veri toplama sürecinde toplanan, 13 TeV enerjili ve $137fb^{-1}$ toplam ışıklılık değerine sahip Ultra-Legacy veri setlerini kullanarak razor kinematik değişkenleri ile yeni fizik araştırmalarına odaklanmaktadır. CMS deneyine ve veri toplama sürecine kısa bir genel bakış Bölüm 3’te verilecektir. Daha sonra, CMS detektörünün bakımı ve geliştirilmesi çalışmalarına yapılan katkılar Bölüm 4’te verilecektir.

ATLAS ve CMS deneyleri tarafından yürütülen kapsamlı araştırmalar süpersimetrik parçacıklar için doğrudan bir kanıt ortaya koyamamıştır. Sonuç olarak, bu kanıt noksanlığı SUSİ aday parçacıklarının kütlelerini ve tesir kesitlerini sınırlandırmamız gerektiği fikri ortaya çıkmıştır. Mevcut sınırlamalar, daha yüksek parçacık kütlelerine ve daha düşük tesir kesitlerine sahip senaryoların daha fazla araştırılması gerektiğini göstermekte ve böylece bu araştırmaların devamlılığını motive etmektedir.

Bu tezde açıklanan çalışmada, ağır parçacıklar ve parçacık kütlelerinde önemli farklılıklar içeren süpersimetri teorisi kapsamlı bir şekilde incelenmektedir. Bu tür kütle farklılıklarına sahip konfigürasyonlar, ağır parçacıkların yüksek Lorentz artışlarına (boost) sahip daha hafif parçacıklara bozunmasına neden olur. Bu nedenle, bu araştırma çeşitli güçlendirilmiş (boosted) SM veya SUSİ parçacıklarını içeren son durumları kapsar (W,Z veya Higgs bozonu, ya da leptonik son durumlar).

Önemli kütle farklılıkları ve güçlendirilmiş bozunma ürünleri sergileyen son durumlar, özellikle TeV ölçeği mertebesinde gluinoları ve 3. nesil skuarkları öngören , naturel SUSİ tarafından motive edilenler olmak üzere çok çeşitli SUSİ senaryolarında ortaya çıkabilir. Ağır gluino, top skuark ve elektrozayıf gaugino üretimini ve ardından R-paritesini koruyan (RPC) modeller içinde çok daha hafif, kararlı en hafif SUSİ parçacığına (LSP) bozunmayı içeren basitleştirilmiş modeller incelenmektedir.

Doğrudan veya zincirleme olarak gerçekleşen bu bozunmalar, güçlendirilmiş ağır SM W , Z , Higgs bozonları veya topkuarklar üretir. Son durum ayrıca daha hafif SM leptonları ve kuarkları ve kararlı en hafif nötralinodan kaynaklanan önemli miktarda kayıp dik enerji içerir. Bir diğer önemli senaryo, LSP'nin kararlı olmadığı ve SM parçacıklarına bozunduğu R-parite ihlalini (RPV) içerir. Bu durumda, güçlendirilmiş nesne, SM bozunma ürünlerinden önemli ölçüde daha ağır olan yüksek momentumlu bir RPV LSP olacaktır. Her iki durumda da, RPV senaryosu kapsamında, LSP bir veya daha fazla kuarka ve bir leptona bozunur.

Bölüm 5'te, razor kinematik değişkenleri ile yapılan kapsamlı SUSİ araştırmasında kullanılan yöntemler ve veri setleri detaylı olarak verilmiştir. SUSİ araştırmalarında hayati öneme sahip SM arka planı tahmini ve sistematik belirsizliklerin belirlenmesi konuları üzerinde ağırlıklı olarak durulmuş olup, bu hesaplamalardan elde edilen sonuçlar detektörden elde edilen çarpışma verileri ve Monte-Carlo simulasyonu verileri kullanılarak analiz araştırma bölgelerine (kontrol, sinyal ve validasyon bölgeleri) uygulanmıştır. Sonuç olarak, analizin kapsamlı yapısına uygun olarak belirlenen basitleştirilmiş SUSİ modelleri üzerinden olası SUSİ parçacıklarının kütle değerlerinde bir üst limit belirlenmesi amaçlanmıştır.

ACKNOWLEDGEMENTS

All the people I got in touch with during my long Ph.D. period improved my personality. It is hard to list all the people that I appreciated their contribution to this thesis with their wisdom, love, and fellowship.

First of all, I am glad to be part of the high-energy physics community and CMS Collaboration since the beginning of my Ph.D. While being a scientist is a privilege in itself, contributing the particle physics is another level of pride and fulfillment for me.

My family got bigger during this challenging period. I married a beautiful, intelligent woman, Asli Izoglu-Tok, whose constant encouragement has sustained me even during the darkest moments of my journey. So her and our cats' (Leo and Mati) emotional support was priceless.

My colleagues were excellent, brilliant scientists. I learned a lot from them. I appreciate the mentorship of Sezen Sekmen, Aysel Kayış Topaksu, and Nikolaos Charitonids and never forget their contribution to my pilgrimage.

Moreover, I would like to acknowledge the tireless support of Fatma Boran, Changgi Hu, Janos Karancsi, and Ali Eren Simsek, who have been my steadfast companions in tackling every challenge encountered along the way.

It would be tough to overcome my bad times without my dear friends; İ. Soner Zorbakir, Ebru Uslan Zorbakir, Sinem Simsek, Boran Simsek, Candan Dozen, Ezgi Taştekin, Sibel Yukler and especially M. Ferman Izoglu.

I would also acknowledge the financial support of TENMAK (which used to be TAEK) for my involvement in research at CERN.

LIST OF TABLES

Table 2.1.	Symbols, names, spin, R-parity and hypercharge of MSSM particle content.	16
Table 5.1.	Triggers that are used for different data-taking periods of Run 2.	46
Table 5.2.	Event filters with their usage purposes in the analysis.	48
Table 5.3.	Muon definitions used for muon identification in the analysis for three different working points.	49
Table 5.4.	Electron definitions used for muon identification in the analysis for three working points.	50
Table 5.5.	Identification criteria boosted hadronic objects and working points.	51
Table 5.6.	Identification criteria leptonic boosted and mass-tagged objects	51
Table 5.7.	SRs selection criteria with constraints on objects variables and kinematics.	55
Table 5.8.	CRs selection categorized by their related background processes.	56
Table 5.9.	Photon from $\gamma + jets$ to calculate purity.	59
Table 5.10.	VRs for the CFs used in background estimation.	70
Table 5.11.	Systematic uncertainties for total background in IsoLep SRs.	85
Table 5.12.	Systematics values for signal samples of the TChiWZ simplified model for each isolate lepton SRs.	86
Table A1.	Full list of 2016 dataset collected by CMS which is used in this analysis.	125
Table A2.	Full list of 2016 dataset collected by CMS which is used in this analysis (continuation of previous page).	126
Table A3.	Full list of 2016APV dataset collected by CMS which is used in this analysis.	127
Table A4.	Full list of 2017 dataset collected by CMS which is used in this analysis.	128
Table A5.	Full list of 2018 dataset collected by CMS which is used in this analysis.	129
Table B1.	The full list of 2016 Monte-Carlo samples used in the analysis	130
Table B2.	The full list of 2016 Monte-Carlo samples used in the analysis (continuation of previous page.)	131
Table B3.	The full list of 2016 Monte-Carlo samples used in the analysis (continuation of previous page.)	132
Table B4.	The full list of 2016 Monte-Carlo samples used in the analysis (continuation of previous page.)	133
Table B5.	The full list of 2016APV Monte-Carlo samples used in the analysis.	134
Table B6.	The full list of 2016APV Monte-Carlo samples used in the analysis (continuation of previous page).	135
Table B7.	The full list of 2016APV Monte-Carlo samples used in the analysis (continuation of previous page).	136

Table B8.	The full list of 2016APV Monte-Carlo samples used in the analysis (continuation of previous page).	137
Table B9.	The full list of 2017 Monte-Carlo samples used in the analysis.	138
Table B10.	The full list of 2017 Monte-Carlo samples used in the analysis (continuation of previous page).	139
Table B11.	The full list of 2017 Monte-Carlo samples used in the analysis (continuation of previous page).	140
Table B12.	The full list of 2018 Monte-Carlo samples used in the analysis.	141
Table B13.	The full list of 2018 Monte-Carlo samples used in the analysis (continuation of previous page).	142
Table B14.	The full list of 2018 Monte-Carlo samples used in the analysis (continuation of previous page).	143
Table B15.	MC samples for the signal events	144

LIST OF FIGURES

Figure 2.1.	Schematic representation of Thomson’s apparatus.	4
Figure 2.2.	The simplified signal models used in the analysis for R-parity conserving (RPC) cases. Models with gluino pair production are shown in (a) T5ttcc ($m_{\tilde{t}} = m_{\tilde{\chi}_1^0} + 20$), (b) T5qqqqWH ($m_{\tilde{\chi}} = m_{\tilde{g}} - 50$), and (c) T5bbbbZH ($m_{\tilde{\chi}} = m_{\tilde{g}} - 50$). A model with chargino pair production (d) TChiWW and a model with stop quark production (e) T6ttZH are shown. Chargino-neutralino production is shown in (f) TchiWZ.	17
Figure 2.3.	The simplified signal models used in the analysis for R-parity violating (RPV). The model with gluino pair-production decaying to stop quarks is shown in (a) R2bbqqlv. The model with sbottom quark pair-production decaying to RPV neutralino is shown (b) R5ttbl.	18
Figure 2.4.	Diagrams are shown for representing lab-frame (left), rest-frame (middle) and center of mass frame (right).	19
Figure 2.5.	CMS Summary plots from various search groups for Run-II data with luminosity value of 137 fb^{-1} (CMS Collaboration, 2023). Histograms summarize the exclusion limit results of each SUSY search with different color codes for various simplified models (T1bbbb, T1qqqq, T1tttt, T2bb, T2qq, T2tt from left to right). The histograms are two-dimensional with neutralino mass on the y-axis and gluino, bino, or stop/squark mass on the x-axis.	23
Figure 2.6.	CMS Summary plots from various search groups for Run-II data with luminosity value of 137 fb^{-1} (CMS Collaboration, 2023). Histograms summarize the exclusion limit results of each SUSY search with different color codes for various simplified models (Electroweakino, T5qqqqVV, TChiWH, TChiWZ from left to right). The histograms are two-dimensional with neutralino mass on the y-axis and gluino or chargino mass on the x-axis.	24
Figure 3.1.	Schematic representation of LHC taken from Design Report (Brüning et al., 2004). Two separate beams with opposite directions and the locations of CMS, ATLAS, ALICE, and LHC-b detectors can be seen in the figure.	28
Figure 3.2.	Schematic representation of the CMS detector showcasing the arrangement of sub-detectors, magnet, calorimeters, muon system, yoke, and superconducting magnet. The figure provides an overview of the detector’s layout and includes size information (AC, 1998).	31

Figure 4.1.	Layout of T2 target station from SPS wobbling system (EN, 2017a).	34
Figure 4.2.	Installation of the HGAL and AHAL prototype at PPE172 zone.	35
Figure 4.3.	Side view of H2 beam line taken from G4beamline.	36
Figure 4.4.	Some of the magnetic elements and scintillator on the H2 beam line are shown in these figures. The upper left figure shows the scintillator, beam window and the air gap between two beam pipe, on the upper right figure shows the bending magnet, the lower left figure shows the quadrupole and right figure on the bottom shows the collimator.	38
Figure 4.5.	The momentum distribution of the positron (e^+) beam, represented by the number of events on the y-axis, was generated through simulations using the G4beamline program. The generated plots illustrate the momentum distribution for three different initial energies: 50 GeV/c (left), 120 GeV/c (middle), and 250 GeV/c (right).	39
Figure 4.6.	The momentum distribution of the pion (π^+) beam, represented by the number of events on the y-axis, was generated through simulations using the G4beamline program. The generated plots illustrate the momentum distribution for three different initial energies: 50 GeV/c (left), 120 GeV/c (middle), and 250 GeV/c (right).	40
Figure 4.7.	MIP distribution of the HGAL detector prototype for 100 GeV positron beam with 2018 test beam data, Geant4 simulation, and full beamline simulation information (CMS Collaboration, 2020b).	40
Figure 5.1.	Comparisons of the various background estimates sourced from $\gamma + jets$ events in the $Z \rightarrow (\nu\nu)$ CR in the (M_R, R^2) phase space are shown here for boosted categories; top, W (4-5), and W (>6). The lower pad on the figures shows the distribution of the estimate/MC counts ratio. The upper left plot shows the results for the top category, the upper right plot shows the W (4-5) category, and the lower plot shows the W(>6) category (Sirunyan et al., 2019).	42

Figure 5.2.	Exclusion limits at 95% CL for stop and gluino pair production processes in the $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ planes, respectively. The left plot represents the exclusion limits for stop pair production ($pp \rightarrow \tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0$), T1tt signal model. The right plot represents the exclusion limits for gluino pair production ($pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{\chi}_1^0/t\tilde{c}\tilde{\chi}_1^0$) T5ttcc signal model. In both plots, the solid black line shows the observed limit with $\pm 1\sigma$ theoretical uncertainties, the dashed red line shows the expected limit with $\pm 1\sigma$ experimental uncertainties, and the dashed blue line represents the expected limit for the non-boosted only analysis. The colored background indicates the 95% CL upper limit on the cross-section (pb). The data corresponds to an integrated luminosity of 35.9 fb^{-1} at a center-of-mass energy of 13 TeV (Sirunyan et al., 2019).	43
Figure 5.3.	The 2-D unrolled plot shows efficiency against the E_T and H_T bins. This plot show the hadronic trigger efficiency for the 2018 dataset, using leptonic triggers as an orthogonal trigger set.	47
Figure 5.4.	Hadronic boson SFs in fake object enriched CR, for AK8 momentum bins. The plots located in the upper row show hadronic fake rate SFs for barrel region (2016APV, 2016, 2017, and 2018, respectively). The plots located in the lower row show hadronic fake rate SFs for the endcap regions (2016APV, 2016, 2017, and 2018, respectively).	52
Figure 5.5.	In pre-selection region, jet multiplicities for b-jet, AK4 and AK8, isolated and non-isolated lepton multiplicities, AK8 jet p_T and $M_R \times R^2$ distribution for full Run 2 in respective order top to bottom.	54
Figure 5.6.	$M_R \times R^2$ distribution in G region for each data-taking period.	58
Figure 5.7.	Template fit, fake and prompt photon distribution in bins of $M_R \times R^2$ for data-taking period 2016, for $(pfrelIso.p_T^\gamma)$ on the x and event counts on the y -axis. Upper row shows the barrel region results and lower row shows the endcap region results.	60
Figure 5.8.	Resulting plots show the purity and CF for the 2016 data-taking period. The upper plot shows the purity values for the bins of $M_R \times R^2$ for data and MC comparison. The lower plot shows the CF distribution for the bins of $M_R \times R^2$	61
Figure 5.9.	Template fit, fake and prompt photon distribution in bins of $M_R \times R^2$ for data-taking period 2017, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.	62

Figure 5.10.	Resulting plots show the purity and CF for the 2017 data-taking period. The upper plot shows the purity values for the bins of $M_R \times R^2$ for data and MC comparison. The lower plot shows the CF distribution for the bins of $M_R \times R^2$.	63
Figure 5.11.	Template fit, fake and prompt photon distribution in bins of $M_R \times R^2$ for data-taking period 2018, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.	64
Figure 5.12.	Resulting plots show the purity and CF for the 2018 data-taking period. The upper plot shows the purity values for the bins of $M_R \times R^2$ for data and MC comparison. The lower plot shows the CF distribution for the bins of $M_R \times R^2$.	65
Figure 5.13.	Template fit, fake and prompt photon distribution in bins of n_{AK4} (jet multiplicity) for data-taking period 2016, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.	66
Figure 5.14.	Resulting plots show the purity and CF for the 2016 data-taking period. The upper plot shows the purity values for the bins of n_{AK4} for data and MC comparison, and the lower plot shows the CF distribution.	67
Figure 5.15.	Template fit, fake and prompt photon distribution in bins of n_{AK4} (jet multiplicity) for data-taking period 2017, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.	68
Figure 5.16.	Resulting plots show the purity and CF for the 2017 data-taking period. The upper plot shows the purity values for the bins of n_{AK4} for data and MC comparison, and the lower plot shows the CF distribution.	69
Figure 5.17.	Template fit, fake and prompt photon distribution in bins of n_{AK4} (jet multiplicity) for data-taking period 2018, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.	70
Figure 5.18.	Resulting plots show the purity and CF for the 2018 data-taking period. The upper plot shows the purity values for the bins of n_{AK4} for data and MC comparison, and the lower plot shows the CF distribution.	71

Figure 5.19.	Template fit, fake and prompt photon distribution in bins of $n_{AK8_{m50}}$ (jet multiplicity) for data-taking period 2016, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.	72
Figure 5.20.	Resulting plots show the purity and CF for the 2016 data-taking period. The upper plot shows the purity values for the bins of $n_{AK8_{m50}}$ for data and MC comparison, and the lower plot shows the CF distribution.	73
Figure 5.21.	Template fit, fake and prompt photon distribution in bins of $n_{AK8_{m50}}$ (jet multiplicity) for data-taking period 2017, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.	74
Figure 5.22.	Resulting plots show the purity and CF for the 2017 data-taking period. The upper plot shows the purity values for the bins of $n_{AK8_{m50}}$ for data and MC comparison, and the lower plot shows the CF distribution.	75
Figure 5.23.	Template fit, fake and prompt photon distribution in bins of $n_{AK8_{m50}}$ (jet multiplicity) for data-taking period 2018, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.	76
Figure 5.24.	Resulting plots show the purity and CF for the 2016 data-taking period. The upper plot shows the purity values for the bins of $n_{AK8_{m50}}$ for data and MC comparison, and the lower plot shows the CF distribution.	77
Figure 5.25.	Data and MC comparisons for $M_R \times R^2$ for the W4Z1, T4Z1, W4Z2, T4Z2 CRs used for $W \rightarrow l\nu$ estimation for the 2017 data-taking period.	79
Figure 5.26.	$M_R \times R^2$ distribution with $Z \rightarrow \nu\nu$ MC, background estimation from $\gamma + jets$ and dilepton CRs. The results are from top to bottom in 2016, 2017, and 2018.	80
Figure 5.27.	$M_R \times R^2$ distribution with data/MC comparison in lower pads of the histograms are given for VRs given in Table 5.10. for the 2016 data-taking period.	82
Figure 5.28.	$M_R \times R^2$ distribution with data/MC comparison in the lower pad for non-isolated VRs. Upper row shows the $\Delta\phi^*$ inverted and lower row shows the m_T reverted non-isolated VRs (given in Table 5.10.) for 2016, 2017 and 2018 data-taking period from left to right order.	83

Figure 5.29.	The distribution of event counts across different bin numbers of $(M_R - 800) \times (R^2 - 0.08)$ for various SRs (hadronic SRs on the upper plot, leptonic SRs on the lower plot) with full Run-2 combined. The stacked histograms represent the background processes including $t\bar{t} + \text{ST}$ (green), Multijet (pink), $W(\rightarrow l\nu)$ (red), $Z(\rightarrow \nu\nu)$ (blue), and others (grey). The lower panels show the ratio of observed data to the predicted background, including both statistical and systematic uncertainties.	87
Figure 5.30.	Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the T5ttcc scenario. The plot corresponds to the gluino mass $\tilde{g} = 2000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 400$ GeV, combining the full Run 2 data-taking period.	90
Figure 5.31.	Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the T5bbbbZH scenario. The plot corresponds to the gluino mass $\tilde{g} = 2200$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 400$ GeV, combining the full Run 2 data-taking period.	91
Figure 5.32.	Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the T6ttZH scenario. The plot corresponds to the gluino mass $\tilde{g} = 1000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 100$ GeV, combining the full Run 2 data-taking period.	92
Figure 5.33.	Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the TChiWW scenario. The plot corresponds to the gluino mass $\tilde{g} = 1000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 100$ GeV, combining the full Run 2 data-taking period.	93
Figure 5.34.	Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the TChiWZ scenario. The plot corresponds to the gluino mass $\tilde{g} = 1000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 100$ GeV, combining the full Run 2 data-taking period.	94
Figure 5.35.	Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the T5qqqqWH scenario. The plot corresponds to the gluino mass $\tilde{g} = 2200$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 500$ GeV, combining the full Run 2 data-taking period.	95

Figure 5.36.	Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the R2bbqqlv scenario. The plot corresponds to the gluino mass $\tilde{g} = 1000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 500$ GeV, combining the full Run 2 data-taking period.	96
Figure 5.37.	Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the R5ttbl scenario. The plot corresponds to the gluino mass $\tilde{g} = 1500$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 500$ GeV, combining the full Run 2 data-taking period.	97
Figure 5.38.	Expected upper limits on the gluino mass ($m_{\tilde{g}}$) versus the neutralino mass ($m_{\tilde{\chi}_1^0}$) for the T5ttcc model with an integrated luminosity of 138 fb^{-1} at $\sqrt{s} = 13$ TeV. The plot shows the observed and expected 95% confidence level upper limits on the production cross-section. The solid black line represents the observed exclusion limit with theoretical uncertainties, while the dashed red line represents the expected exclusion limit with experimental uncertainties. The plot indicates the region excluded at next-to-leading order plus next-to-leading logarithm (NLO+NLL) accuracy.	98
Figure 5.39.	Expected upper limits on the gluino mass ($m_{\tilde{g}}$) versus the neutralino mass ($m_{\tilde{\chi}_1^0}$) for the T5bbbbZH model with an integrated luminosity of 138 fb^{-1} at $\sqrt{s} = 13$ TeV. The plot shows the observed and expected 95% confidence level upper limits on the production cross-section. The solid black line represents the observed exclusion limit with theoretical uncertainties, while the dashed red line represents the expected exclusion limit with experimental uncertainties. The plot indicates the region excluded at next-to-leading order plus next-to-leading logarithm (NLO+NLL) accuracy, for T5bbbbZH signal model.	99
Figure 5.40.	The 95% C.L. upper limit on the cross-section for the process $pp \rightarrow \tilde{t}\tilde{t} \rightarrow t\tilde{\chi}_1^0 H/Z \rightarrow t\tilde{\chi}_1^0 \tilde{\chi}_2^0$, as a function of the stop mass m_t and the neutralino mass $m_{\tilde{\chi}_1^0}$, at $\sqrt{s} = 13$ TeV and 138 fb^{-1} . The plot shows the NLO+NLL exclusion limits, with observed and expected limits, including their $\pm 1\sigma$ theoretical and experimental uncertainties, for T6ttZH signal model.	100
Figure 5.41.	The 95% C.L. upper limit on the cross-section for the process $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0 W\tilde{\chi}_1^0$, as a function of the chargino mass $m_{\tilde{\chi}_1^\pm}$ and the neutralino mass $m_{\tilde{\chi}_1^0}$, at $\sqrt{s} = 13$ TeV and 138 fb^{-1} . The plot shows the NLO+NLL exclusion limits, with observed and expected limits, including their $\pm 1\sigma$ theoretical and experimental uncertainties, for TChiWW signal model.	101

Figure 5.42.	The 95% C.L. upper limit on the cross-section for the process $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$, as a function of the chargino mass $m_{\tilde{\chi}_1^\pm}$ and the neutralino mass $m_{\tilde{\chi}_1^0}$, at $\sqrt{s} = 13$ TeV and 138 fb^{-1} . The plot shows the NLO+NLL exclusion limits, with observed and expected limits, including their $\pm 1\sigma$ theoretical and experimental uncertainties for the TChiWZ signal model.	102
Figure 5.43.	The figure shows the exclusion limits at 95% confidence level on the cross-section for the production of gluinos ($\tilde{g}$) in proton-proton collisions at $\sqrt{s} = 13$ TeV with an integrated luminosity of 138.0 fb^{-1} . The observed and expected limits are compared to the theoretical predictions for the T5qqqqWH signal model.	103
Figure 5.44.	The figure illustrates the exclusion limits at 95% confidence level on the cross-section for the production of bottom squarks ($\tilde{b}$) in proton-proton collisions at $\sqrt{s} = 13$ TeV with an integrated luminosity of 138.0 fb^{-1} . The observed and expected limits are shown in comparison to the theoretical predictions for the R2bbqqlv signal model. The plot includes mass ranges for both the bottom squark and the neutralino ($\tilde{\chi}^0$).	104
Figure 5.45.	The 95% C.L. upper limit on the cross section for the process $\tilde{g}\tilde{g} \rightarrow pp \rightarrow \tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t} \rightarrow t\bar{b} \rightarrow \tilde{t}\tilde{b}$, as a function of the gluino mass $m_{\tilde{g}}$ and the stop mass $m_{\tilde{t}_1}$, derived at $\sqrt{s} = 13$ TeV with an integrated luminosity of 138.0 fb^{-1} . The observed limits (solid black line) and the expected limits (dashed black line) are shown along with the theoretical cross section (solid red line). The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ experimental uncertainties, respectively. . .	105
Figure C1.	Systematic uncertainties for total background in hadronic (higgs) signal regions.	145
Figure C2.	Systematic uncertainties for total background in hadronic (V) signal regions. .	146
Figure C3.	Systematic uncertainties for total background in non-isolated leptonic signal regions.	147
Figure D1.	$M_R \times R^2$ distribution with data/MC comparison in lower pads of the histograms are given for validation regions given in Table 5.10. for 2017 data taking period.	148
Figure D2.	$M_R \times R^2$ distribution with data/MC comparison in lower pads of the histograms are given for validation regions given in Table 5.10. for 2017 data taking period.	149

ABBREVIATIONS

σ	: Cross Section
ATLAS	: A Toroidal LHC ApparatuS
CERN	: Conseil Europeenne pour la Recherche Nucleaire
CF	: Correction Factor
CMS	: Compact Muon Solenoid
CR	: Control Region
DAQ	: Data Acquisition
ECAL	: Electromagnetic Calorimeter
HCAL	: Hadronic Calorimeter
HGCAL	: High-Granularity Calorimeter
LHC	: Large Hadronic Collider
LSP	: Lightest Supersymmetric Particle
MC	: Monte Carlo
MSSM	: Minimal Supersymmetric Standart Model
NLL	: Next-to-leading Logarithm
NLO	: Next-to-Leading Order
QCD	: Quantum Chromodynamics
RPC	: R-parity Conserving
RPV	: R-parity Violating
SF	: Scale Factor
SR	: Signal Region
SM	: Standart Model
SMS	: Simplified Signal Model
SUSY	: Supersymmetry
UL	: Ultra Legacy
VR	: Validation Region

1. INTRODUCTION

The questions humankind has asked since the Antique Ages still have fundamental existential philosophical importance. The history of particle physics is full of amazing discoveries with an endless effort by many brilliant scientists who try to enlighten the same fundamental uncertainty about the universe's structure. Supersymmetry (SUSY) is one of the most prolific approaches to answering this unanswered mystery of physics and the beyond. SUSY builds on the very accomplished theory called the Standard Model (SM) of elementary particles, which explains a lot about the behavior of the elementary particles. SM is a well-established theory supported by the many discoveries foreseen by the theory, such as the discovery of the Higgs boson, quarks, and many others. The theory of SM and SUSY will be explained in Chapter 2.

SUSY suggests a potential expansion to the SM of particle physics, which tackles unresolved inquiries concerning dark matter (DM), electroweak-sector fine-tuning, and the $g - 2$ anomaly. It introduces a novel fermion-boson symmetry, leading to a collection of unknown particles, the exploration of which forms a fundamental part of the CERN LHC physics program. This thesis studies data collected by the Compact Muon Solenoid (CMS) experiment, utilizing 137 fb^{-1} of proton-proton collision data accumulated by the CMS experiment at the LHC during Run 2. A brief overview of the CMS experiment and data collection process will be given in Chapter 3. Subsequently, contributions to the upgrade efforts for the maintenance of the CMS detector will be given in Chapter 4.

Exhaustive searches conducted by the ATLAS and CMS Collaborations have yielded no direct evidence for supersymmetric particles. Consequently, this absence of evidence limits masses of SUSY candidate particles and cross-sections. The current limitations indicate that scenarios with higher sparticle masses and lower cross sections necessitate further exploration, thereby motivating the design of these searches.

This document comprehensively explores SUSY, featuring heavy particles (addition of "s" in front of the particle names indicates a SUSY partner of this particle) and substantial disparities in particle masses. Configurations with such mass discrepancies cause heavy particle decays into lighter particles possessing high Lorentz boosts. If these highly energetic decay products are massive, they decay into neighboring particles in the $\eta - \phi$ space, resulting in merged particles. Therefore, the search encompasses final states comprising various boosted SM or SUSY particles. Final states exhibiting substantial mass differences and boosted decay products can manifest across a wide range of SUSY scenarios, particularly those motivated by Naturalness, which predict gluinos and 3rd generation squarks at the order of the TeV scale. Several representative cases involving heavy gluino, top squark, and electroweak gaugino production, followed by subsequent decay into a much lighter, stable lightest SUSY particle (LSP) within models preserving R-parity (RPC). These decays, occur-

ring directly or via a chain, generate boosted heavy SM W, Z, Higgs bosons or top quarks. The final state also incorporates lighter SM leptons and quarks and a significant amount of missing transverse energy from the stable lightest neutralino. Another significant scenario involves R-parity violation (RPV), where the LSP is non-stable and decays into SM particles. In this instance, the boosted object would be a high-momentum RPV LSP significantly heavier than its SM decay products. In both cases, the RPV LSP decays into one or more quarks and a lepton. Similar to the RPC case, boosted RPV final states additionally involve lighter SM leptons and quarks, although the missing transverse energy is low to moderate due to the absence of a neutral, stable heavy sparticle solely comprising SM neutrinos.



2. THEORY OF SUPERSYMMETRY (SUSY)

This chapter includes a brief history of the observation of elementary particles (C. N. Yang, 2015; Hoddeson et al., 1997) and the evaluation of the SM theory. Then the supersymmetric symmetry breaking mechanism will be explained. The motivation for studying SUSY is also explained in this chapter by showing the benefits of theoretical explanation of the questions such as hierarchy problem, dark matter, etc. The minimal supersymmetric standard model (MSSM) and the simplified SUSY models will be introduced. The razor kinematic variables used in chapter 5 are described in a theoretical manner to understand the inclusive razor boost analysis' main strategy better. Next, the experimental results for the beyond the standard model (BSM) physics will also be discussed for Run-II.

2.1. Standard Model of Particles

The history of the SM theory itself coincides with the history of the theories such as relativity, quantum mechanics, and the effort given by scientists to explain the structure of the atoms at the beginning of the 20th century; and also it is significantly related to technological growth over the years which help us to discover elementary particles. However, it is hard to give a complete history of such a big theory that has been studied for over a century; instead, I will try to give a brief history of the SM. I believe this effort in this chapter helps to understand the motivation of this thesis.

As our focus of interest, elementary particles are the key concept to building substantial knowledge about nature. The history of particle physics keeps back many scientists' efforts since the end of the 19th century, and these extensive efforts have helped us understand the universe's underlying nature ever since. In the 19th century, electromagnetism was a well-known physics phenomenon with various applications such as X-rays and electricity in daily life; however, the atomic structure of the electric charge was unclear until J.J. Thomson's famous experiments. In his experiment, he used an apparatus filled with gases, magnets, and cathode rays, as shown in Figure 2.1. . In conclusion, this experiment shows that the particle (first called "corpuscles") with a negative charge has a charge/mass ratio lighter than a thousand times than hydrogen atoms (Thomson, 2011). We now know these particles as electrons with a negative charge and half-spin quantum number. After the discovery of electrons, atom models were shaped at the beginning of the last century. The next breakthrough was Rutherford's experiment, which led the physicist to consider that atoms have a nucleus with positive charges.

The first couple of decades of the century was also the golden age of quantum theory. Quantum mechanics helped scientists to model the subatomic world; one of them is Bohr, whose atomic model (Bohr, 1913) describes the behaviour of electrons and nuclei inside an atom. It follows Schrödinger's wave equation and de Broglie's matter wave (Broglie, 1924) explanations which unfold a new path

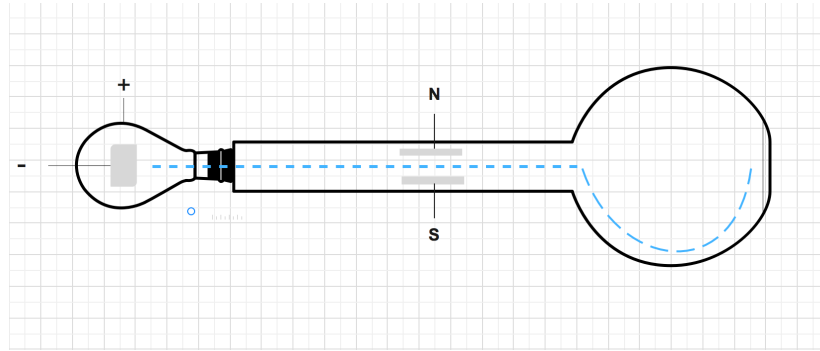


Figure 2.1. Schematic representation of Thomson's apparatus.

to particle physics. The subsequent discovery by J. Chadwick (Chadwick, 1932a; Chadwick, 1932b) suggested that the nuclei of an atom also have neutral particles alongside the protons, called "neutrons." It later became evident that nuclei have almost the same number of protons and neutrons, and the existence of the neutrons explains the β -decay known way before the discovery of the neutron. Works on β -decay also led to the offer of new particles called neutrino (first named by Fermi as "little neutral one"), which theoretically explains the excess of energy in the decay mode of neutron (Bethe and Peierls, 1934); $n \rightarrow p + e^- + \bar{\nu}$ and is detected experimentally (Cowan Jr et al., 1956). Again theoretically, this disintegration of the neutron can produce positively charged electrons, which was first suggested by Dirac (P. A. Dirac, 1933a; P. A. M. Dirac, 1930), and observed in cosmic ray experiments (Anderson, 1932). It is a so-called positron, an anti-particle of the electron, with equal spin and mass but a different charge; it is described as floating in infinite negative energy 'sea' (P. A. Dirac, 1933b). Like β disintegration, the nuclear force that keeps protons and neutrons in nuclei and interaction between them was a subject of interest in the 1930s. Since the proton and neutron interact in such a close range, the mediator particle must have high momentum, according to de Broglie's theory. Yukawa makes the first explanation of such a mediator particle, called U-particle, the mediator of the U-field (Yukawa, 1935), same as the photon in an electromagnetic field described in quantum electrodynamics (QED). That U-particle is called 'mesotrons' or mesons later to be discovered in cosmic ray photographic emulsion experiments (Lattes, Occhialini, and Powell, 1947), and π -meson (or pions) suggested as Yukawa meson with positive, negative and neutral charges. Besides the μ -particle (or muon) also discovered in this experiment. In the 1940s and 1950s, many other "strange particles" were observed by the cosmic ray cloud chamber experiments (Rochester, 1989), so called baryons. Besides the cosmic ray experiments, particle accelerators helped scientists comprehend these new particles as new technology.

Even if both works on β decay and nuclear forces (as we know now that these are related to weak and strong interactions, respectively) are precious, it was not enough to explain the complete notion. With the effect of new high-energy accelerators, more particles and strange behaviour of some

of them arose, and a beautiful mathematical explanation was needed. The Standard Model (SM) of particles is a solid theory to meet this need: a quantum field theory representation for the elementary particles. SM theories are also called the gauge theories first used by C.N. Yang and R.L. Mills to describe nuclei forces in isotopic spin space (C.-N. Yang and Mills, 1954).

Non-Abelian Gauge Theories

This bring us to a very important notion called non-Abelian gauge invariance of a system of elementary particles. Let's define a transformation of a matter field $\psi_l(x)$

$$\delta\psi_l(x) = i\epsilon^\alpha(x)(t_\alpha)_l^m\psi_m(x) \quad (2.1)$$

This makes the Lagrangian of the system invariant (Weinberg, 1995). Here $\epsilon^\alpha(x)$ is infinitesimal parameter, t_α is constant matrices or generators. Commutation relation between generators

$$[t_\alpha, t_\beta] = iC_{\alpha\beta}^\gamma t_\gamma \quad (2.2)$$

Here $C_{\alpha\beta}^\gamma$ is called structure constants. This real constants are anti-symmetric $C_{\alpha\beta}^\gamma = -C_{\beta\alpha}^\gamma$.

From Jacobi identity and from equation 2.2, we get a commutation relation with structure constants.

$$[t_\alpha^A, t_\beta^A] = iC_{\alpha\beta}^\gamma t_\gamma^A \quad (2.3)$$

This is called the adjoint representation of the Lie algebra (For any generator g_α and g_β , if the commutation relation $[g_\alpha, g_\beta] = 0$, it is called Abelian, e.g. QED is an Abelian gauge theory under the U(1) symmetry group).

Differentiation of the infinitesimal transformation of the matter field in equation 2.1 gives

$$\delta(\partial_\mu\psi_l(x)) = i\epsilon^\alpha(x)(t_\alpha)_l^m(\partial_\mu\psi_m(x)) + i(\partial_\mu\epsilon^\alpha(x))(t_\alpha)_l^m\psi_m(x) \quad (2.4)$$

We can define a vector field A_μ^β to make the Lagrangian invariant under the gauge transformation,

$$\delta A_\mu^\beta = \partial_\mu\epsilon^\beta + i\epsilon^\alpha(t_\alpha)^\beta_\gamma A_\mu^\gamma \quad (2.5)$$

This transformation of field represents a Lie group with n parameters. Now we can write the gauge covariant derivative (Sogami, 1995);

$$(D_\mu \Psi(x))_l = \partial_\mu \Psi_l(x) - iA_\mu^\beta(x)(t_\beta)^m_l \Psi_m(x) \quad (2.6)$$

Commutation relation related to two different coordinates of the covariant derivative gives

$$[D_\nu, D_\mu] \Psi_l = -it_\mu^m F_{\nu\mu}^\gamma \Psi_m \quad (2.7)$$

Here, $F_{\nu\mu}^\gamma$ is a tensor such as strength of the gauge field

$$F_{\nu\mu}^\gamma \equiv \partial_\nu A_\mu^\gamma - \partial_\mu A_\nu^\gamma + C_{\alpha\beta}^\gamma A_\nu^\alpha A_\mu^\beta \quad (2.8)$$

We can now define a Lagrangian density that is invariant under gauge transformation

$$\mathcal{L} = \mathcal{L}(\Psi, D_{\nu,\mu} \Psi, F_{\nu,\mu}^\alpha F_{\nu,\mu}^\alpha) \quad (2.9)$$

as a function of matter field, covariant derivative and the field strength. Thus the invariance requirement is

$$\frac{\partial \mathcal{L}}{\partial \Psi} it_\alpha \Psi + \frac{\partial \mathcal{L}}{\partial (D_\mu \Psi)} it_\alpha (D_\mu \Psi) + \frac{\partial \mathcal{L}}{\partial F_{\mu\nu}^\beta} C_{\gamma\alpha}^\beta F_{\nu\mu}^\gamma + \frac{\partial \mathcal{L}}{\partial (D_\rho F_{\mu\nu}^\beta)} C_{\gamma\alpha}^\beta (D_\rho F_{\nu\mu}^\gamma) = 0 \quad (2.10)$$

So the general form of Lagrangian density can be written as invariant under the gauge transformation

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}^\alpha F_{\mu\nu}^\alpha + \mathcal{L}_K(\Psi, D_{\nu\mu} \Psi) \quad (2.11)$$

The first part of the equation 2.11 is for the free particle in vacuum; second term defines the kinetic part of the Lagrangian. The sufficient condition to define a new field A_μ^α , there must be a conservation law (Utiyama, 1956). To have such a conservation law, we need to define the current of the new field

$$J_\alpha^\mu = \frac{\partial \mathcal{L}_K}{\partial A_\mu^\alpha} \quad (2.12)$$

From these differential equation, current can be defined in terms of matter field, field strength, and gauge field

$$J_\alpha^\mu = -F_{\mu\nu}^\gamma C_{\gamma\alpha\beta} A_{\alpha\beta} - i \frac{\partial \mathcal{L}_K}{\partial D_\nu \Psi} t_\alpha \Psi \quad (2.13)$$

and the conservation of current is $D_\nu J_\alpha^\nu = 0$ where $\alpha = 1, 2, \dots, n$.

For the quantization of the theory, one can choose a gauge ("axial" for these cases; $A_{\alpha 3} = 0$) similar to Coloumb gauge in QED. So, we can define the Hamiltonian density

$$\mathcal{H} = \mathcal{H}(P_{\alpha i}, q_l, \psi_l, A_{\alpha i}) \quad (2.14)$$

Here, the canonical variables are $P_{\alpha i} = \partial \mathcal{L} / \partial (\partial A_{\alpha i})$ and $q_l = \partial \mathcal{L} / \partial (\partial \psi_l)$. Thus, the scattering matrix (S-matrix) can be written with respect to Hamiltonian density (Faddeev, Slavnov, and Pontecorvo, 2018)

$$\mathcal{S} = e^{i\mathcal{H}_0 t''} e^{-i\mathcal{H}(t''-t')} e^{-i\mathcal{H}_0 t'} \quad (2.15)$$

in the limit of $t', t'' \rightarrow \infty$.

Broken Symmetries

Broken symmetries were first introduced in the theory of superconductivity and applied to elementary particle physics (Nambu and Jona-Lasinio, 1961). Any system with continuous global symmetry is broken by an excited vacuum state, creating a mass less boson in the unbroken subgroup (Goldstone, 1961; Nambu, 1960). Candidate particle for such a mass less bosons (or Goldstone bosons) was considered to be pion particle in the 1960s; however, later development in this broken symmetry phenomenon shows that a broken local symmetry generates mass for these vector bosons (Englert and Brout, 1964; Higgs, 1964; Guralnik, Hagen, and Kibble, 1964). This mechanism is known as Higgs mechanism, and it can be described over the classical Lagrangian density

$$\mathcal{L} = -\frac{1}{4} F_{\nu\mu} F^{\nu\mu} + (D_\mu \phi_i)^\dagger (D^\mu \phi_i) - V(\phi) \quad (2.16)$$

Here, $\phi_i(x)$ is set of local scalar fields which keeps Lagrangian invariant with the transformation $\phi_i \rightarrow (1 + i\alpha^{a(x)} t^{a(x)})_{ij} \phi_j$ under the symmetry group of the system (Peskin and Halzen, 1995). Then, the covariant derivative is

$$D_\mu \phi_i = (\partial_\mu + g A_\mu^a T^a) \phi_i \quad (2.17)$$

We choose $t^a = iT^a$ since the generators of the group have complex-valued matrix elements. Kinetic energy term of the equation 2.16 then becomes

$$(D_\mu \phi_i) = (\partial_\mu \phi_i)^2 + g A_\mu^a (\partial_\mu \phi_i T_{ij}^a \phi_j) + (g^2 A_\mu^a A^{b\mu}) (T^a \phi_i) (T^b \phi_i) \quad (2.18)$$

For a set of non-zero (degenerated) vacuum expectation value $\langle \phi_i \rangle = (\phi_0)_i$, we can ex-

pand the scalar field around the $(\phi - \phi_0)_i$ and get a new kinetic term in the Lagrangian density $g^2 A_\mu^a A^{b\mu} (T^a \phi_0)_i (T^b \phi_0)_i$. So, the mass matrix for the gauge bosons

$$m_{ab}^2 = g^2 (T^a \phi_0)_i (T^b \phi_0)_i \quad (2.19)$$

And interaction term from the expansion between the gauge field and the vacuum expectation value is

$$g A_\mu^a \partial_\mu \phi_i (T^a \phi_0)_i. \quad (2.20)$$

The Electroweak Theory (GWS Theory)

By symmetry breaking mechanism, electromagnetism and weak interactions are considered the same natural forces of the universe. In this so-called electroweak or GWS (Glashow-Weinberg-Salam) theory (A. Salam, 1994; Glashow, 1961; Weinberg, 1967), the U(1) symmetry group of QED is the sub-group of the larger group SU(2) of the weak isospin space. The vector bosons of the SU(2) group gain masses by Higgs mechanism such that a doublet of a scalar field with the transformation

$$\phi \rightarrow e^{i\alpha^a \sigma^a / 2} e^{i\beta / 2} \phi \quad (2.21)$$

Here, σ^a are the Pauli matrices. To break the symmetry SU(2) × U(1), vacuum expectation value can be chosen as unitary gauge (Hamilton, 2017)

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \mathcal{U} + H(x) \end{pmatrix} \quad (2.22)$$

This term with shifted degenerate vacuum expectation value, and by the expansion around the Higgs potential, potential term in equation 2.16 become $V(\phi) = -\mu^\dagger \phi \phi + \lambda (\dagger \phi \phi)^2$. From this potential, the mass term for the Higgs boson (gaining by coupling itself) can be written as $m_H = \mathcal{U} \sqrt{2\lambda}$.

So the covariant derivative for both gauge fields according to SU(2) and U(1)

$$D_\mu = \partial_\mu - ig A_\mu^a T^a - \frac{i}{2} g' B_\mu \quad (2.23)$$

Here, g and g' are the charges (or the coupling constants) of the gauge fields of weak and electromagnetic interactions, respectively. By recalling the previous chapter, from the kinetic energy term of the Lagrangian one can define the vector bosons of the system

$$\begin{aligned}
W_\mu^\pm &= \frac{1}{\sqrt{2}}(A_\mu^1 \mp iA_\mu^2), \\
Z_\mu^0 &= \frac{1}{\sqrt{g^2 + g'^2}}(gA_\mu^3 - g'B_\mu)
\end{aligned}
\tag{2.24}$$

with the masses $m_W = g\mathcal{U}/2$ and $m_Z = \sqrt{g^2 + g'^2}\mathcal{U}/2$. With the mass coefficients and the bosons, the covariant derivative becomes

$$\begin{aligned}
D_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}(W_\mu^+ T^+ + W_\mu^- T^-) - i\frac{1}{\sqrt{g^2 + g'^2}}Z_\mu(g^2 T^3 - g'^2 Y) \\
- i\frac{gg'}{\sqrt{g^2 + g'^2}}A_\mu(T^3 + Y)
\end{aligned}
\tag{2.25}$$

Here, Y is the hypercharge and T^3 is isospin. Last term of the 2.25 belongs to mass less gauge bosons of the $U(1)$ symmetry, so electric charge can be described as $e = gg'/\sqrt{g^2 + g'^2}$ and the quantum number related to the charge is given by the Gell-Mann-Nishijima (Gell-Mann, 1956; Nishijima, 1955) formula

$$Q = T^3 + Y \tag{2.26}$$

By spontaneous symmetry-breaking mechanism, fermions and Higgs bosons gain mass. To describe this mechanism, we need to consider the chiral gauge theories, which include left- and right-handed fields

$$\Psi_L = \frac{1}{2}(1 - \gamma^5)\Psi, \quad \Psi_R = \frac{1}{2}(1 + \gamma^5)\Psi \tag{2.27}$$

Here, γ^5 is the product of Dirac matrices. Left-handed particles are represented by doublet concerning flavor and charge conservation

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}
\tag{2.28}$$

and right-handed particles are described by the singlet u_R , d_R , e_R where u stands for up-type quarks, d for down-type quarks and l stands for the leptons.

For these multiplets of the electroweak symmetry, we can write the covariant derivatives in terms of chirality

$$\begin{aligned}
D_\mu \Psi_L &= (\partial_L + igT^a A_\mu^a + ig'YB_\mu)\Psi_L, \\
D_\mu \Psi_R &= (\partial_L + ig'YB_\mu)\Psi_R
\end{aligned}
\tag{2.29}$$

Since we know experimentally that A_μ does not couple with right-handed particles, the second equation in 2.29 doesn't include this part.

Recalling that non-Abelian gauge theories have got conservation law for the current $\partial_\mu J^\mu = 0$, we can write the interaction part of the Lagrangian for the $SU(2) \times U(1)$ symmetry (Buchmüller and Lüdeling, 2006)

$$\mathcal{L}_{Int} = -gJ_\mu^T A^\mu - g'J_\mu^Y B_\mu \tag{2.30}$$

Here, J_μ^T and J_μ^Y can be defined as

$$J_\mu^T = \frac{1}{2}\bar{q}_L\gamma_\mu\sigma q_L + \frac{1}{2}\bar{l}_L\gamma_\mu\sigma l_L \tag{2.31}$$

and

$$\begin{aligned}
J_\mu^Y &= \frac{1}{6}\bar{q}_L\gamma_\mu q_L - \frac{1}{2}\bar{l}_L\gamma_\mu l_L + \frac{2}{3}\bar{u}_R\gamma_\mu u_R \\
&\quad - \frac{1}{3}\bar{d}_R\gamma_\mu d_R - \bar{e}_R\gamma_\mu e_R
\end{aligned}
\tag{2.32}$$

Thus, the interaction part of the Lagrangian can be written with the help of 2.31 and 2.32 such that

$$\begin{aligned}
\mathcal{L}_{Int} &= -\frac{g}{\sqrt{2}}(\bar{u}_{L,i}\gamma^\mu d_{L,i})W_\mu^+ - \sum_i \bar{\Psi}_i\gamma^\mu Q_i\Psi_i \\
&\quad - \frac{e}{\sin 2\theta_W}J_{Z,\mu}Z^\mu
\end{aligned}
\tag{2.33}$$

The first term of 2.33 belongs to charged current and last two terms belong to neutral current with electromagnetic and Z^μ . Summation indices i runs over the generations of the fermion families, θ_W is called mixing angle (or "Weinberg angle") $\theta_W = \arctan(g'/g) \in [0, \pi/2)$.

The predictions of the electroweak theory were observed precisely by the experiments, and the neutral current discovery was the most important of these SM confirmations (Hasert et al., 1973). The subsequent significant finding was the gluon (Brandelik et al., 1979), the mass less vector boson of the $SU(3)$ symmetry group of the strong nuclear force, widely known as quantum chromodynamics (QCD) (Ne'eman, 1961; Gell-Mann, 1964). QCD is also a non-Abelian gauge theory with additional color flavour to satisfy the statistic of quarks with the six flavours (u,d,s,t,b,c) of color space and eight 3×3 Gell-Mann matrices as the generators of the symmetry group $SU(3)$ (Politzer, 1973; Gross and Wilczek, 1973).

2.2. SUSY

The SUSY theory is an extension of the SM, which attempts to explain some unsolved challenges of particle physics, such as the hierarchy problem about the scalar boson mass and the unification of the coupling constants of the SM (or GUT). The hierarchy problem (Barbieri and Giudice, 1988) occurs since the two energy scales (Planck and electroweak symmetry breaking) have a tremendous difference in the order of $\sim 10^{16}$, which breaks the naturalness of the SM theory (Susskind, 1979). SUSY is the candidate theory to solve the hierarchy problem by suggesting TeV scale superpartner particles of the SM and the light mass for the scalar bosons, which is assumed by the theory close to Z boson mass. Since the discovery of the Higgs boson at CERN with a mass 125 GeV (Aad et al., 2015), expectation for an extension of the SM with SUSY increased. On the other hand, SUSY is not the only theory for locating a solution to the hierarchy problem; technicolor theory with no need of scalar fields (Dimopoulos and Susskind, 1979), and the theories with extra dimensions (Arkani-Hamed, Dimopoulos, and Dvali, 1998; Randall and Sundrum, 1999) also provides approaches to solve the problem. Supersymmetric extensions of the SM also help us to construct a grand unified theory that unifies the coupling constants of the gauge group $SU(3) \times SU(2) \times U(1)$ at the 10^{16} GeV energy scale (Amaldi, Boer, and Fürstenau, 1991) by enlarging the number of particles of the SM.

For continuity throughout the chapter, we can briefly discuss the history of SUSY from here on. The first SUSY-like explanation comes from the string theories in the 1970s, such that two-dimensional field theory with the symmetry of infinitesimal transformations (keeps the action-integral invariant) (Gervais and Sakita, 1971) was defined to transform bosonic fields to fermionic fields. Henceforth, a 4-dimensional approach to these theories made the supersymmetric ideas more realistic in 1974 by Wess and Zumino (Wess and Zumino, 1974b). Later, a Lagrangian model was also suggested by the same authors (Wess and Zumino, 1974a). And another approach for the Wess-Zumino model was proposed using "superfields" by Salam-Strathdee (Strathdee, 1987). Around the same time, there was an effort to identify neutrinos as Goldstone fermion (Volkov and Akulov, 1973), which now we can say that is the first glance at supersymmetric symmetry breaking. However, way before these improvements, the Coleman-Mandula theorem (Coleman and Mandula, 1967) suggested that the Poincare group generators are commutative with S-matrix, which yields an internal symmetry. But later, it is shown in an extension of this theorem that to build a supersymmetric algebra, one must also consider anti-commutation relations (Gol'fand and Likhtman, 1989). So it can be said that the SUSY generators satisfy the graded Lie algebra (Fayet and Ferrara, 1977).

Now we should construct the main idea of the SUSY to understand better the concept of the "sparticles" (supersymmetric partners of the SM particles) and fields in the light of previous chapter. An invariant action integral under some transformation can be given as (Martin, 1998)

$$S = \int d^4x (\mathcal{L}_{scal} + \mathcal{L}_{ferm}) \quad (2.34)$$

Here, $\mathcal{L}_{scal} = -\partial^\mu \phi^* \partial_\mu \phi$ and $\mathcal{L}_{ferm} = i\psi^\dagger \bar{\sigma}^\mu \partial_\mu \psi$ are Lagrangian for scalar and fermionic field respectively, without any mass and interaction part include. So the supersymmetric transformation between the scalar and fermionic field describe by the two component Weyl spinor $\delta\phi = \epsilon\psi$ with its complex conjugate $\delta\phi^* = \epsilon^\dagger \psi^\dagger$, and thus differentiation of the Lagrangian gives

$$\delta\mathcal{L}_{scal} = -\epsilon\partial^\mu \psi \partial_\mu \phi^* - \epsilon^\dagger \partial^\mu \psi^\dagger \partial_\mu \phi \quad (2.35)$$

Here ϵ^α ($\alpha = 1, 2$) is an infinitesimal Weyl object. Under this transformation, action integral should be invariant $\delta S = 0$, so $\delta\mathcal{L}_{scal}$ and $\delta\mathcal{L}_{ferm}$ terms inside the integral must cancel each other, so the differentiation of fermionic field is $\delta\psi_\alpha = -i(\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \phi$. Thus

$$\begin{aligned} \delta\mathcal{L}_{ferm} &= \epsilon\partial^\mu \psi \partial_\mu \phi^* + \epsilon^\dagger \partial^\mu \psi^\dagger \partial_\mu \phi \\ &\quad - \partial_\mu (\epsilon\sigma^\nu \bar{\sigma}^\mu \psi \partial_\nu \phi^* + \epsilon\psi \partial^\mu \psi^* + \epsilon^\dagger \psi^\dagger \partial^\mu \phi) \end{aligned} \quad (2.36)$$

First two term cancels $\delta\mathcal{L}_{scal}$ and remaining part has no effect on δS so it is invariant under this type of transformations for both scalar and fermionic fields. Additionally, we need to define a scalar field called "auxiliary" as an additional term to free Lagrangian ($\mathcal{L}_{aux} = F \times F$) to have a closed algebra. Where the infinitesimal transformation, according to this field is

$$\delta F = -i\epsilon^\dagger \bar{\sigma}^\mu \partial_\mu \psi \quad (2.37)$$

with the contribution to the Lagrangian

$$\delta\mathcal{L}_{aux} = \delta(F \times F) = -i\epsilon^\dagger \bar{\sigma}^\mu \partial_\mu \psi F^* + i\partial_\mu \psi^\dagger \bar{\sigma}^\mu \epsilon^\dagger F \quad (2.38)$$

Therefore, the transformations are

$$\begin{aligned} \delta\phi &= \epsilon\psi \\ \delta\psi_\alpha &= -i(\sigma^\mu \epsilon^\dagger)_\alpha \partial_\mu \phi + \epsilon_\alpha F_i \\ \delta F &= -i\epsilon^\dagger \bar{\sigma}^\mu \partial_\mu \psi \end{aligned} \quad (2.39)$$

Now, to have renormalizable interaction, we can define the Lagrangian up to the quadratic term

$$\mathcal{L}_{Int} = (-\frac{1}{2}W^{ij}\psi_i\psi_j + W^i F_i) + (-\frac{1}{2}W_{ij}^\dagger\psi^{\dagger i}\psi^{\dagger j} + W_i^* F^{*i}) \quad (2.40)$$

Here, W^{ij} is "super-potential" (Martin, 1998) with mass matrix and Yukawa coupling constant of scalar fields

$$W = \frac{1}{2}M^{ij}\phi_i\phi_j + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k \quad (2.41)$$

To exclude the auxiliary field from Lagrangian, we can choose the super-potential $F_i = -W_i^*$. Thus the Lagrangian will have scalar potential $V(\phi, \phi^*) = W^i W_i^*$. We can conclude that the scalar and fermionic fields have the same mass matrix with the same mass term for each supermultiplet. Since there is no evidence for the SUSY particle with the same SM particle mass, it can be concluded that SUSY is a broken symmetry.

The part discussed so far is for the chiral supermultiplet, consisting of two components Weyl spinor and scalar field. Since the SUSY is aiming for an extension to the SM, we also need to define gauge supermultiplets. To do so, first, take the gauge transformation into account.

$$\begin{aligned} A_\mu^a &\rightarrow A_\mu^a + \partial_\mu \Lambda^a + g f^{abc} A_\mu^b \Lambda^c \\ \lambda^a &\rightarrow \lambda^a + g f^{abc} \lambda^b \Lambda^c \end{aligned} \quad (2.42)$$

Here, A_μ^a is gauge field (recall the 2.5), λ^a is a two-component Weyl spinor, and f^{abc} is the set of structure constants similar to the one used on SM gauge theories. Lagrangian density can be described as the same as non-Abelian gauge theories mentioned earlier by

$$\mathcal{L}_{gauge} = -\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu} + i\lambda^{\dagger a} \bar{\sigma}^\mu \mathcal{D}_\mu \lambda^a + \frac{1}{2}D^a D^a \quad (2.43)$$

Here, $F_{\mu\nu}^a$ is field strength and $\mathcal{D}_\mu = \partial_\mu + g f^{abc} A_\mu^b \lambda^c$ is covariant derivative and D^a is the auxiliary field.

As there is such a continuous symmetry described above, there needs to be a current related to it. In our case, it is called "supercurrent", J_α^μ . And according to Noether theorem this current should be conserved $\partial_\mu J_\alpha^\mu = 0$ and $\partial_\mu J_\alpha^{\mu\dagger} = 0$. So, the conserved charge is

$$Q_\alpha = \sqrt{2} \int d^3 J_\alpha^0 \quad (2.44)$$

So for the supermultiplet $\mathcal{S}$, which includes all the scalar, auxiliary, and fermionic fields, one can find the commutation relation in accordance with the momentum operator

$$[P^\mu, S] = i\partial^\mu S \quad (2.45)$$

With the help of this relation, we can construct the supersymmetric algebra (Weinberg, 2005):

$$\begin{aligned} \{Q_\alpha, Q_\alpha^\dagger\} &= -2\sigma_{\alpha\dot{\alpha}}^\mu P_\mu, \\ \{Q_\alpha, Q_\beta\} &= 0, \quad \{Q_\alpha^\dagger, Q_\beta^\dagger\} = 0 \end{aligned} \quad (2.46)$$

And the commutation relations are

$$[Q_\alpha, P^\mu] = 0, \quad [Q_\alpha^\dagger, P^\mu] = 0 \quad (2.47)$$

Commutation relation 2.47 implies that the SUSY generators Q_α are the generator of space-time transformation and also states that the generator Q_α doesn't change the energy (or momentum) of the field. Thus, the Q_α behaves as the symmetry operator that acts on a quantum state or field by differing the spin of the state, so by definition, any supermultiplet includes both fermionic and bosonic states. As a result, SUSY is an internal space-time symmetry that relates fermions and bosons. On the other hand, if we use Majorana spinor instead of Weyl spinor to get the equation 2.39, we would have the additional auxiliary fields F and G and scalar field B, so the original Wess-Zumino model at the end (Wess and Zumino, 1974b). As planned, auxiliary fields are essential for the SUSY breaking mechanism.

R-parity and Spontaneous SUSY Breaking

As discussed above, for each SM particles, SUSY suggests "superpartners" and these particles obey the R-symmetry (or R-parity) conservation instead of the baryon or leptonic number conservation. Accordingly, one can define R-transformation acts on chiral and vector superfields

$$\begin{aligned} \Phi(x, \theta) &\rightarrow e^{R\alpha} \Phi(x, \theta e^{-i\alpha}) \\ V(x, \theta, \bar{\theta}) &\rightarrow V(x, \theta e^{-i\alpha}, \bar{\theta} e^{i\alpha}) \end{aligned} \quad (2.48)$$

R symmetry is an Abelian group generator ($U(1)_R$) and acts on superfields in the same way as the SUSY generator. R quantum number is conserved under the transformation given in equation 2.48, and it is related to baryonic and leptonic numbers (described as $R = 3(B - L)$ or $R = (3B - L)$ (Fayet, 2016). R-symmetry also gives unique parity conservation, which is essential for the SUSY particle detection in experiments such that this parity differentiates SM particles from sparticles by unit. Also, this parity conservation suggests that the lightest sparticle should be stable and makes the

LSP one of the strongest candidates for dark matter.

As discussed earlier in this section, SUSY must be a broken symmetry. To check if the SUSY is spontaneously broken, from gauge interaction Lagrangian 2.43, one can extract the potential term in terms of D and F auxiliary fields and matter fields (Sohnius, 1985)

$$\mathcal{L}_{pot} = \frac{1}{2}D^2 + \frac{1}{2}DA^\dagger \tau A + \frac{1}{2}F^\dagger F \quad (2.49)$$

Here, τ is the generator, thus the potential ($V = -\mathcal{L}_{pot}$) is the sum of the square of D and F terms. This indicates that the vacuum expectation value of the potential is positive if one of the auxiliary field's expectation values is larger than zero. Therefore symmetry breaking can ensue through D-term or F-term. By adding a linear D-term into the equation 2.49, it keeps the Abelian gauge invariant and degenerates the minimum of the scalar potential (Fayet and Iliopoulos, 1974). Another way to breakdown SUSY is through the F-term by defining three component chiral superfield (or a singlet) with the equation without a solution (O'raifeartaigh, 1975)

$$\lambda_i + m_{ij}\phi_j + g_{ijk}\phi_j\phi_k = 0 \quad (2.50)$$

This sits in a local minimum of the scalar potential. Here m_{ij} is mass matrix. R-symmetry is conserved by the breakdown of the SUSY through the F-term (Fayet, 2016).

2.3. MSSM

There are several SUSY theories in terms of the number of SUSY generators given in equation 2.46 and 2.47, $\mathcal{Q}_\alpha^i$ ($\alpha = 1, \dots, 4, i = 1, \dots, N$). Since there is no limit on the number of SUSY generators in theory, it can be extended to higher orders to cover more bases, such as supergravity ($N = 8$). These theorems are called extended SUSY. In light of this scope, the simplest case for the SUSY is for the $N = 1$ theories, called the MSSM. LHC searches for SUSY aims, in general, to locate the minimal content of the MSSM particles, which has the superpartners for each SM particle named after the original name by adding "-ino" (for fermionic superpartners) or "s" (for the bosonic superpartners) to differ superpartners from the SM particles. Table 2.1. shows the spraticles' symbols and their parity, spin, and hypercharges. Since they have the same quantum numbers, winos and binos can mix; general use for this terminology is neutralino ($\chi_i^0, i=1, \dots, 4$) and chargino ($\chi_i^\pm, i=1, 2$). The lightest neutralino is considered stable, so it is a candidate for dark matter.

To make the electroweak symmetry breaking (EWSB) possible, we still need the Higgs mechanism for MSSM, but now there are two doublets of scalar field

Table 2.1. Symbols, names, spin, R-parity and hypercharge of MSSM particle content.

Names/Symbols		spin	R-parity	Hypercharge
squarks	$\begin{pmatrix} \tilde{u}_L & \tilde{d}_L \\ \tilde{u}_R^* & \tilde{d}_R^* \end{pmatrix}$	0	-1	$\begin{matrix} 1/6 \\ -2/3 \\ 1/3 \end{matrix}$
sleptons	$\begin{pmatrix} \tilde{\nu} & \tilde{e}_L \\ \tilde{e}_R^* & \end{pmatrix}$	0	-1	$\begin{matrix} -1/2 \\ 1 \end{matrix}$
higgsinos	$\begin{pmatrix} \tilde{H}_1^+ & \tilde{H}_1^0 \\ \tilde{H}_2^0 & \tilde{H}_2^- \end{pmatrix}$	1/2	-1	$\begin{matrix} 1/2 \\ -1/2 \end{matrix}$
gluino	$\tilde{g}$	1/2	-1	0
winos	$\begin{pmatrix} \tilde{W}^\pm & \tilde{W}^0 \end{pmatrix}$	1/2	-1	0
binos	$\tilde{B}^0$	1/2	-1	0

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^0 \\ H_2^- \end{pmatrix} \quad (2.51)$$

with expectation values

$$\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \quad (2.52)$$

Here one can determine the valuable notion $\arctan(v_2/v_1) = \beta$ for EWSB (Djouadi et al., 1999), which leads the EWSB for the MSSM. In MSSM, superpotential 2.41 requires an additional μ -term, Higgsino mass similar to the Higgs mass discussed in the previous section. It brings us to the notion called naturalness, which describes stabilizing the Higgs mass according to electroweak scale (Tata, 2020)

$$\frac{M_Z^2}{2} = \frac{m_{H_2}^2 - m_{H_1}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \quad (2.53)$$

Here, m_{H_1} and m_{H_2} are soft SUSY breaking parameters.

2.4. Simplified SUSY Models

To minimize the particle spectrum of the MSSM, simplified models are currently used in the LHC searches. Simplified models introduce a minimum set of parameters to set a limit to the masses of sparticles. Pair-produced primary particles from proton collision are considered to decay in a direct or a 1-step cascade way, with intermediate particles decaying to daughter particles in the final state (Alves et al., 2012). Simplified models have the advantage of limiting the parameter, such as the mass of the sparticles and the cross-section related to the signal model. Yet, it's not a complete description

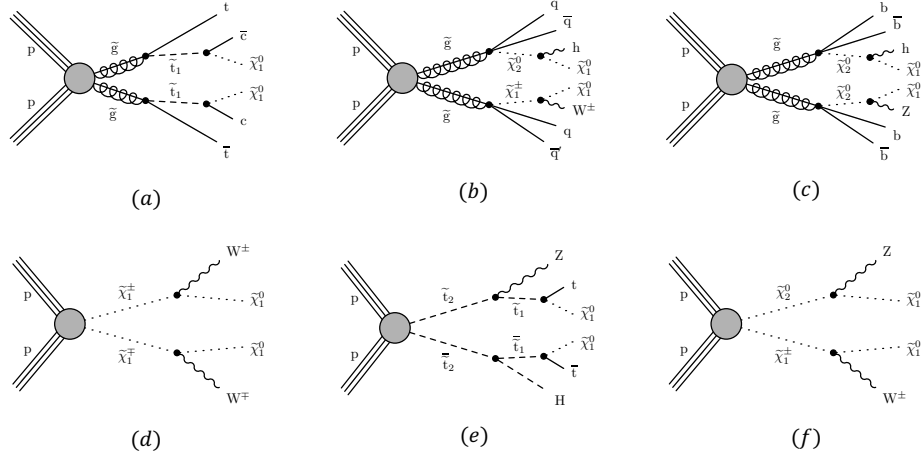


Figure 2.2. The simplified signal models used in the analysis for R-parity conserving (RPC) cases. Models with gluino pair production are shown in (a) T5ttcc ($m_{\tilde{t}} = m_{\tilde{\chi}_1^0} + 20$), (b) T5qqqqWH ($m_{\tilde{\chi}} = m_{\tilde{g}} - 50$), and (c) T5bbbbZH ($m_{\tilde{\chi}} = m_{\tilde{g}} - 50$). A model with chargino pair production (d) TChiWW and a model with stop quark production (e) T6ttZH are shown. Chargino-neutralino production is shown in (f) TchiWZ.

of the particles, only an approach to the theory regarding the most specific point of view that can help us understand the sparticles' behavior.

R-parity conserving (RPC) and R-parity violating (RPV) signal models are also considered by the search groups in high-energy physics to check all the possible SUSY scenarios. Figure 2.2. shows the Feynmann diagrams of the RPC signal models used in this analysis, including pair-produced gluinos, charginos, and stops, decaying various sparticles, and SM particles. Figure 2.3. also shows the signal models that violate the R-parity, i.e., RPV models.

The naming pattern of the simplified models is depicted such as: (Serguei Chatrchyan et al., 2013b)

- **T5-** T5qqqqWH is pair production of gluino which decays to quark-antiquark, and chargino decaying to Higgs, and neutralino decaying to W boson ($p \rightarrow \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0$) with mass difference 50 GeV between gluinos and charginos. T5bbbbZH is pair production of gluino which decays to bottom quarks and neutralinos ($p \rightarrow \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z, H$) with mass difference 50 GeV between gluinos and neutralinos, neutralinos decaying to Z or Higgs boson. T5ttcc is pair production of the gluino decaying to top quark and stop which has daughter charm quark and neutralino ($p \rightarrow \tilde{g} \rightarrow t\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$), with mass difference 20 GeV between stop and neutralino.

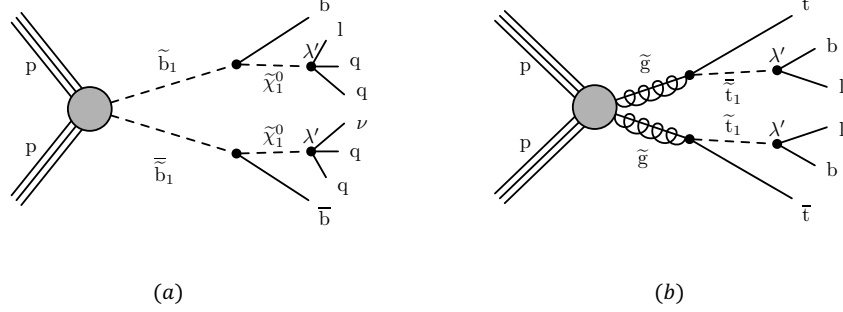


Figure 2.3. The simplified signal models used in the analysis for R-parity violating (RPV). The model with gluino pair-production decaying to stop quarks is shown in (a) R2bbqqlv. The model with sbottom quark pair-production decaying to RPV neutralino is shown (b) R5ttbl.

- **TChi-** TChiWZ is pair production of neutralino and chargino, decaying to Z and neutralino and W and neutralino respectively ($p \rightarrow \chi_2^0 \chi_1^\pm, \chi_2^0 \rightarrow Z \chi_1^0, \chi_1^\pm \rightarrow W \chi_1^\pm$). TChiWW is pair production of the charginos, decaying to W bosons and neutralinos ($p \rightarrow \chi_1^\pm \chi_1^\pm, \chi_1^\pm \rightarrow W \chi_1^0$).
- **T6ttZH** This model is the pair-production of stop, decaying to stop, Z and Higgs boson, stop decay secondarily to top quark and neutralino ($p \rightarrow \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow H/Z \tilde{t}_1, \tilde{t}_1 \rightarrow t \chi_1^0$)
- **RPV** R-parity-violating models considered in this analysis have only SM particles in the final state with low missing energy (Canepa, 2019). This models couples LQD-type in the superpotential. Gluino2RPVstop is the pair production of gluinos, with direct decay of top and cascade decay of stop to bottom quarks and leptons ($p \rightarrow \tilde{g} \rightarrow t \tilde{t}_1, \tilde{t}_1 \rightarrow b l$). SbottomToRPVN1 is pair production of sbottom, with direct decay of bottom quark and cascade decay of neutralinos to two quarks and one lepton in the final state ($p \rightarrow \tilde{b}_1, \tilde{b}_1 \rightarrow b \chi_1^0 \rightarrow q q l, \nu$).

2.5. Razor Kinematic Variables

As an excellent signal-background discriminator, razor variables (M_R and R^2) have proved their value over the years since they were first introduced (Rogan, 2010). Many analyses with different data taken from LHC have been conducted to improve the sparticles' exclusion limits. Its simplicity obliges us to cover the many simplified models in which pair-produced heavy particles and their cascade decay to a final state with missing energy and visible jets.

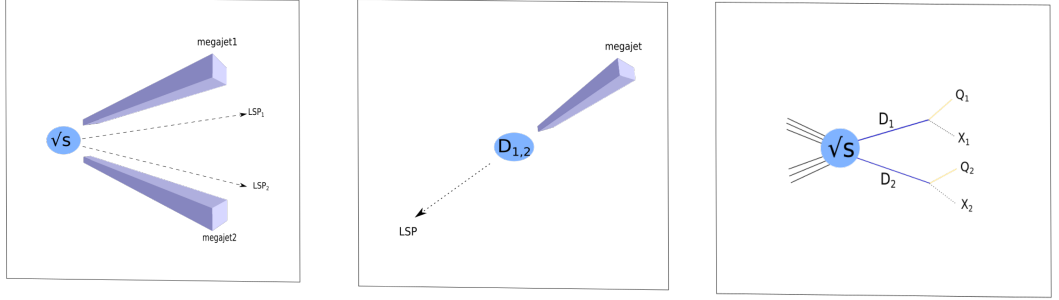


Figure 2.4. Diagrams are shown for representing lab-frame (left), rest-frame (middle) and center of mass frame (right).

A set of assumptions must be considered to determine the razor kinematic variables, such as pair-produced massive particles (D_i) having the same mass and momentum with opposite directions, and their decay products (χ_i and Q_i) have visible and undetected particles with $M_{Q_i} = 0$ and $M_{\chi_i} > 0$. The decay of the daughter particle $D_i \rightarrow Q_i \chi_i$ shown in Figure 2.4. (in the middle frame) is called the rest frame. Four-vector at this frame

$$\begin{aligned} p(Q_i) &\equiv q_i = \{E_{Q_i}, \vec{q}_i\} \\ p(\chi_i) &\equiv r_i = \{E_{\chi_i}, \vec{r}_i\} \end{aligned} \quad (2.54)$$

Considering the conservation of energy and momentum, with additional assumption given above $|\vec{q}_i| = |\vec{r}_i| = |\vec{p}_i|$, we got the relation between the mass of particles and the momentum

$$|\vec{q}_i| = M_{D_i} - \sqrt{M_{\chi_i}^2 + |\vec{r}_i|^2} \quad (2.55)$$

$$|\vec{p}_i| = \frac{M_{D_i}^2 - M_{\chi_i}^2}{2M_{D_i}} = \frac{M_{\Delta}}{2} \quad (2.56)$$

Here M_{Δ} is the mass difference and since $M_{Q_i} = 0$ it is clear that $E_{Q_i} = M_{\Delta}/2$. Again by the conservation of the energy $E_{Q_i} + E_{\chi_i} = M_{D_i}$;

$$E_{\chi_i} = \frac{M_{D_i}^2 + M_{\chi_i}^2}{2M_{D_i}} = \frac{M_{D_i}^2 + M_{\chi_i}^2}{M_{D_i}^2 - M_{\chi_i}^2} \frac{M_{\Delta}}{2} = R_{\chi_i}^2 \frac{M_{\Delta}}{2} \quad (2.57)$$

So the momentum equation 2.54 becomes

$$q_i = \frac{M_{\Delta}}{2} \{1, \hat{u}_i\}, \quad r_i = \frac{M_{\Delta}}{2} \{R_{\chi_i}, -\hat{u}_i\} \quad (2.58)$$

Here $\hat{u}_i$ s are the unit vector and the sign in front of them to represent the opposite direction of the Q_i and χ_i . Equations given above have indices i , which run over the number of LSP and SM particles in the final state. For simplicity, it can be chosen $i = 1, 2$, but, as discussed in the previous chapter, there could be simplified models with more particles in the final state. So, to cover all the possible scenarios, the best way is to cluster these particles into mega jets (see Figure 2.4.).

So far, only the rest frame has been discussed; however, we also need to consider the lab and center of mass frame (see Figure 2.4.) to be able to calculate the kinematic variables with the genuine observables such as missing energy from undetected particles (in our case this is mainly from LSP) and the transverse momentum and energy from visible particles by the detector. Centre of mass (CM) frame simply represents the proton-proton collision picture with the $\sqrt{\hat{s}}$ CM energy. Variables can be transformed from the rest frame to the CM frame by a boost β_{CM} and similarly with another boost $\vec{\beta}_{lab}$ to the lab frame, which includes experimental observables.

$$P(Di) = P_i = M_{D_i} \gamma_{CM} \{1, \pm \vec{\beta}_{CM}\} \quad (2.59)$$

Here, $\sum P_i = \sqrt{\hat{s}}$ and γ_{CM} is the Lorentz factor for the CM frame. Here another assumption is to have D_i particles with mass large enough for $\sqrt{\hat{s}} \approx 2M_{D_i}$ and this indicates that $\gamma_{CM} \approx 1$. Thus, with this approximation, we have $\vec{\beta}_{CM} = 0$ and CM frame becomes the rest frame (Rogan, 2010). Another assumption is for the $\vec{\beta}_{lab} = \{\vec{\beta}_T, \beta_z\}$ which considers the transverse part of the boost to be zero for the large mass of D_i s

$$\vec{\beta}_T \ll \frac{p_T^{ISR}}{2M_{D_i}} \quad (2.60)$$

Here, p_T^{ISR} represents the initial state radiation. The last two assumptions discussed above are called rough-approximation, and the related frame that takes the CM frame to the lab frame is called the R-frame, with only the longitudinal part of the boost of the lab frame. Recall that our aim is to find relation of mass difference M_{Δ} in terms of lab frame kinematics. To do so, we can define the first razor variable such as

$$M_R = 2|\vec{q}_i^R| = M_\Delta \quad (2.61)$$

Here, q_i^R is longitudinal component of the momentum of the Q_i s in the R-frame. Thus, we can drive a relation between energy and momentum for the R-frame and lab frame with a Lorentz transformation from lab frame to R-frame (Strobbe, 2015)

$$\begin{aligned} E_{Q_i}^R &= \gamma^R(E_{Q_i}^l - \beta^R q_i^l) \\ q_i^R &= \gamma^R(q_i^l - \beta^R E_{Q_i}^l) \end{aligned} \quad (2.62)$$

Lab frame and R-frame variables are marked with the letters "l" and "R" respectively. Recalling the conservation of momentum and energy of the Q_i s and considering two mega-jets with equal momenta for simplicity, we have

$$E_{mJ1}^l - \beta^R q_{mJ1}^l = E_{mJ2}^l - \beta^R q_{mJ2}^l \quad (2.63)$$

Now we can define M_R , which can be described as the mass of the R-frame, with lab frame variables only, and by equation 2.61 and 2.62, we have

$$\begin{aligned} M_R &= E_{mJ1}^R + E_{mJ2}^R = 2|\vec{q}_{mJ1}^R| = 2|\vec{q}_{mJ2}^R| \\ &= 2\sqrt{\frac{(q_{mJ1}^l E_{mJ2}^l - q_{mJ2}^l E_{mJ1}^l)^2}{(q_{mJ1}^l - q_{mJ2}^l)^2 - (E_{mJ1}^l - E_{mJ2}^l)^2}} \end{aligned} \quad (2.64)$$

We can now discuss another razor variable, M_T^R , which is another approximation to the mass difference M_Δ . For the M_R variable, we assume that the transverse component of the lab frame velocity is close to zero for large M_{D_i} as seen in equation 2.60, however for the large missing transverse energy (MET) related to final state with LSPs, which is not detected by the experimental tools, one also need to take into account the transpose phase space of the signal events. On this final state we assume that there are two mega-jet with back-to-back four-momentum ($\vec{q}_i^l$) and two LSP with four-momentum ($\vec{r}_i^l$) in the lab frame. Other assumptions are for the LSP four-momentum to assign the half of the MET for both LSPs $E_T^{miss} = 1/2 \cdot |\vec{r}_{iT}^l|$ and $|\vec{r}_{iT}^l|^2 = 0$. Here, we can define the variable

$$M_{2D} = \sqrt{\frac{1}{2} \sum_{i=1}^2 (\vec{q}_i^l + \vec{r}_i^l)^2} \quad (2.65)$$

Equation 2.65 gives the transverse part of the R-frame by defining $M_{2D}^T = (|q_{1T}^l| |r_{1T}^l| - q_{1T}^l r_{1T}^l + |q_{2T}^l| |r_{2T}^l| - q_{2T}^l r_{2T}^l)^{1/2}$. M_Δ has a peak at the endpoint of the M_{2D} , so it benefits our aim to find another approach to mass difference with lab frame variables. As a result of the assumptions

given above, finally, we have M_T^R with transverse variables

$$M_T^R = \sqrt{\frac{E_T^{miss}}{2}(|q_{1T}^l| + |q_{2T}^l|) - \frac{E_T^{miss}}{2}(q_{1T}^l + q_{2T}^l)} \quad (2.66)$$

Thus, the last razor variable R can be defined by the division of M_R and M_T^R ; since both variables are in the unit of GeV, R becomes dimensionless.

2.6. SUSY Searches on LHC, Run-II

For more than ten years, SUSY searches have been carried out by various teams and SUSY groups on LHC experiments, mainly ATLAS and CMS. In contrast to all expectations of finding a signal related to a super-particle, no straightforward observation has been detected. However, almost all the SUSY scenarios have been discussed by these searches, and the exclusion of the masses of some SUSY particles enables us to broaden our understanding of the behavior of the SUSY events in the experiments. Figure 2.5. and Figure 2.6. show the latest CMS summary results with Run-II data over the exclusion limits with a 95% confidence level.

It would be coherent to check the latest published articles from ATLAS and CMS for SUSY searches.

- **ATLAS** The analysis deals with the RPV scenarios with non-zero coupling constant in super-potential and final state with multiple jets decaying from long-lived massive particles covering the gluino and neutralino/chargino production (ATLAS Collaboration, 2023). Another search was conducted for pair production of gluinos for various models with multiple jets (including b-jets) and MET in the final state (ATLAS Collaboration, 2022f). Analysis targeting the RPC pair production of sleptons with leptonic final state and neutralinos and RPC chargino pair production decaying to W, leptons, and neutralino also searched by the collaboration (ATLAS Collaboration, 2022a). Analysis searches are conducted by the collaboration on gauge-mediated SUSY breaking (GMSB) models, in which Higgs and Z boson produced and decay to NLSP (next to LSP), leptons and photons in the final state (ATLAS Collaboration, 2022b). The analysis focuses on the general gauge mediation (GGM) models for pair-produced gluinos with the final states consisting of photons, jets, and MET (from gravitino) (ATLAS Collaboration, 2022e). The analysis searches for LLP pair-production (gluino) with jet and LSP in the final state, chargino pair-production of LLP with pions and LSP in the final state, and sleptons as LLP decaying to gravitino (NLSP) and leptons (ATLAS Collaboration, 2022c). Another analysis searches for electroweak and strong-production of sparticles with GMSB and the second-lightest neutralino model (C1N2) with NLSPs (higgsino) and LSP (gravitino) and leptons/jets

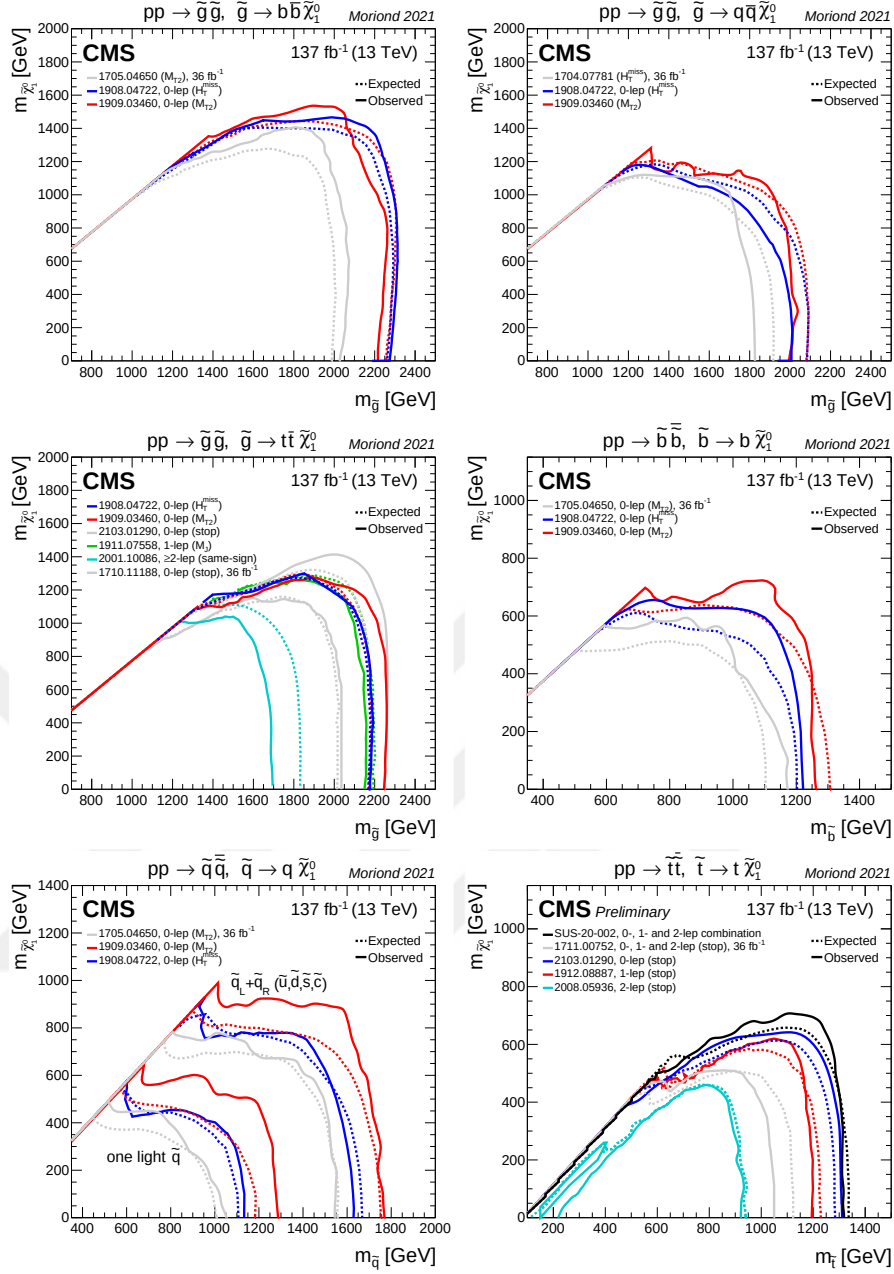


Figure 2.5. CMS Summary plots from various search groups for Run-II data with luminosity value of 137 fb^{-1} (CMS Collaboration, 2023). Histograms summarize the exclusion limit results of each SUSY search with different color codes for various simplified models (T1bbbb, T1qqqq, T1tttt, T2bb, T2qq, T2tt from left to right). The histograms are two-dimensional with neutralino mass on the y-axis and gluino, bino, or stop/squark mass on the x-axis.

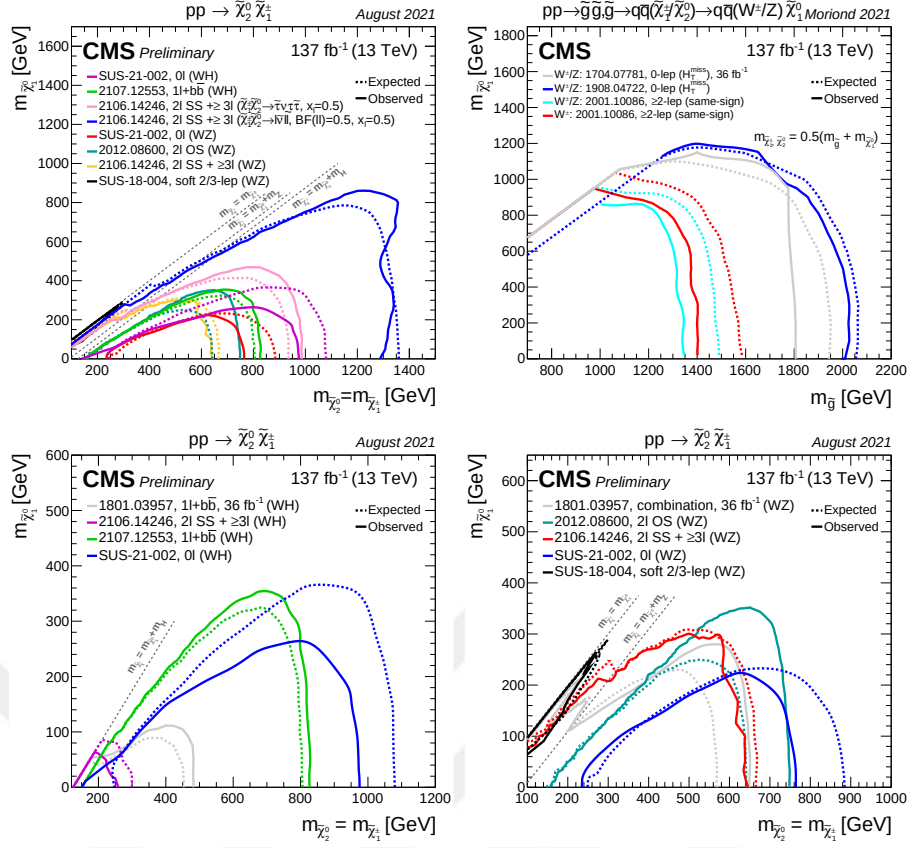


Figure 2.6. CMS Summary plots from various search groups for Run-II data with luminosity value of 137 fb^{-1} (CMS Collaboration, 2023). Histograms summarize the exclusion limit results of each SUSY search with different color codes for various simplified models (Electroweakino, T5qqqqVV, TChiWH, TChiWZ from left to right). The histograms are two-dimensional with neutralino mass on the y-axis and gluino or chargino mass on the x-axis.

in the final states (ATLAS Collaboration, 2022g). The analysis searches for electroweak and strong-production of particles according to the AMSB model (with long-lived chargino) and model with LSP as higgsino (ATLAS Collaboration, 2022d). Another analysis searches for GMSB models for stop pair production with the LSP (as gravitino) and b-jets, tau, and MET in the final states (ATLAS Collaboration, 2021e). The analysis focuses on electroweakino pair production decaying to a lighter electroweakino, bino, wino, higgsino-like chargino or gravitino, axino with the fully hadronic final state (ATLAS Collaboration, 2021d). The analysis focuses on RPV models with gluino/stop pair production decaying to higgsino-type LSP and leptons and jets or neutralino-chargino pair production with many jets in the final state (ATLAS Collaboration, 2021f). The analysis focuses on the models with neutralino pair-production decaying to W, Z and Higgs bosons (which also cascade decay to leptons and neutinos) and neutralino (ATLAS Collaboration, 2021c). Another analysis based on long-lived particles at ATLAS detectors to find a sign of BSM scenarios with R-hadrons which have neutral, charged and double-charged states (ATLAS Collaboration, 2021a). The analysis searches for both RPC (GGM) and RPV models with NLSPs in the final state for wino, bino and slepton or sneutrino-like scenarios. For the RPC case LSP in the final state is considered as gravitino decaying from Z boson or light higgsino (ATLAS Collaboration, 2021h). The analysis searches for sbottom pair-production decaying to bottom quark and second lightest neutralino which also cascade decay to higgsino and tau; and final state also consists of MET from neutralino (ATLAS Collaboration, 2021b). Another analysis considers the RPV models with gluinos and squark pair-production where gluinos decay to quark-antiquark pair and chargino with cascade decay to W boson and neutralino, and squarks decay to quarks and chargino decay in the same way (ATLAS Collaboration, 2021g).

- **CMS** The analysis searches for tau slepton (as NLSP) pair-production, which is hadronically decaying to taus and neutralino or gravitino (CMS Collaboration, 2022a). Another analysis searches for pair-production of electroweakinos (chargino-neutralino or chargino pair-production) decaying to a neutralino and W boson or neutralino and W/Z/H bosons in the final state (CMS Collaboration, 2022b). The analysis searches the RPC models with electroweakino and gluino pair-production with the final state containing Higgs bosons, gravitinos, jets, and MET (CMS Collaboration, 2022d). The analysis searches RPC models with squark pair-production and chargino-neutralino production with the final states containing b-jets, W/Z bosons, and neutralinos (CMS Collaboration, 2022e). The analysis searches for wino-like chargino-neutralino production decaying to the lightest neutralino (considered as MET), W bosons, and Higgs bosons (CMS Collaboration, 2021c). Another analysis conducts a combined search of different SUSY scenarios of stop pair-production with the final states containing top or

bottom quarks neutralinos, charginos (cascade decay to W bosons and neutralino (contributing as MET)) (CMS Collaboration, 2021b). The analysis searches for chargino-neutralino production scenarios with final states with leptons and sleptons decaying to lepton and neutralino, or leptons, sleptons, and sneutrinos decaying to neutralino and leptons or neutrinos (CMS Collaboration, 2022c). Another analysis searches for RPC SUSY models with squark or gluino pair-production with the final states containing b, top, charm quarks and chargino (cascade decay to W boson or neutralino); or b, top (cascade decay to a charm quark and neutralino) and chargino undergoes to W boson or neutralino respectively (CMS Collaboration, 2021f). The analysis searches for RPV and Stealth SUSY models with final states from stop production with top and neutralino undergoes light-flavor quarks; and with scalar particle/anti-particle and its superpartner, top quark and gluinos respectively (CMS Collaboration, 2021g). The analysis searches for RPC models with chargino-neutralino production decaying to WZ, ZZ, HZ, or opposite sign leptons; and with gluino pair-production undergoes to jets and neutralino cascade decay to a Z boson and gravitino; and with sbottom pair-production with the final state containing jets and second lightest neutralino (CMS Collaboration, 2021d). Another analysis searches for RPV stop pair-production with the final states containing top quark/anti-quark and neutralino, or bottom quark/anti-quark and chargino undergoes to W boson and neutralino, or bottom quark/anti-quark, neutrino and opposite sign leptons (CMS Collaboration, 2021e).

3. THE LHC and CMS EXPERIMENT

This chapter introduces general information on the CERN experiments and the tools for discovering the frontier knowledge of humankind. Since the mission of CERN and its goals cover a tremendous number of physics subjects and use complex, state-of-the-art engineering technologies, it is hard to explain all the detailed structures of the LHC and the experiments conducted at CERN. So, the only tip of the iceberg that can be shown in this chapter is the LHC and the CMS detector. Nevertheless, it will help us understand these thesis's central concepts, such as particle collisions, CMS experiments, and data-taking processes.

3.1. The Large Hadron Collider (LHC)

Large Hadron Collider (LHC) is designed to have proton-proton collisions with high luminosity and heavy-ion collisions. The LHC, located in France and Switzerland, uses two separate beam pipes with particles accelerated in opposite directions. There are eight turning points and straight sections. Four of the consecutive sections have interaction regions in which particles collide head-to-head, and at these points, detectors of four large experiments are built for collecting data. Figure 3.1. shows the layout of the LHC and detectors on the beams' intersection points: CMS, ATLAS, LHC-b, and ALICE.(Brüning et al., 2004)

3.2. CMS Experiment

The CMS(Compact Muon Solenoid) (S. Chatrchyan et al., 2008) is a major scientific experiment conducted at the Large Hadron Collider. The CMS experiment aims to investigate the fundamental particles and their interactions by colliding protons and heavy ions at extremely high energies. The primary objective of the CMS experiment was to explore the properties and behaviors of the Higgs boson, discovered in 2012 by the CMS and ATLAS experiments, leading to the Nobel Prize in Physics in 2013. Since then, CMS has been considered the critical instrument for widening our knowledge about BSM physics and more.

The CMS detector is a complex apparatus that captures and measures the particles produced in high-energy proton-proton collisions or heavy-ion collisions. The detector is also used to collect cosmic ray and heavy-ion collision data. It consists of several sub-detectors arranged in layers, each serving a specific purpose in reconstructing the particles' characteristics. Its shape can be compared to an artichoke with its layers of leaves on top of each other. The artichoke's concentric arrangement of leaves mirrors the arrangement of various sub-detectors around the central axis of the CMS detector. The tightly packed inner leaves of the artichoke can be likened to the innermost component of the CMS detector, the silicon tracker. Just as the leaves of an artichoke enclose and protect the tender heart of the

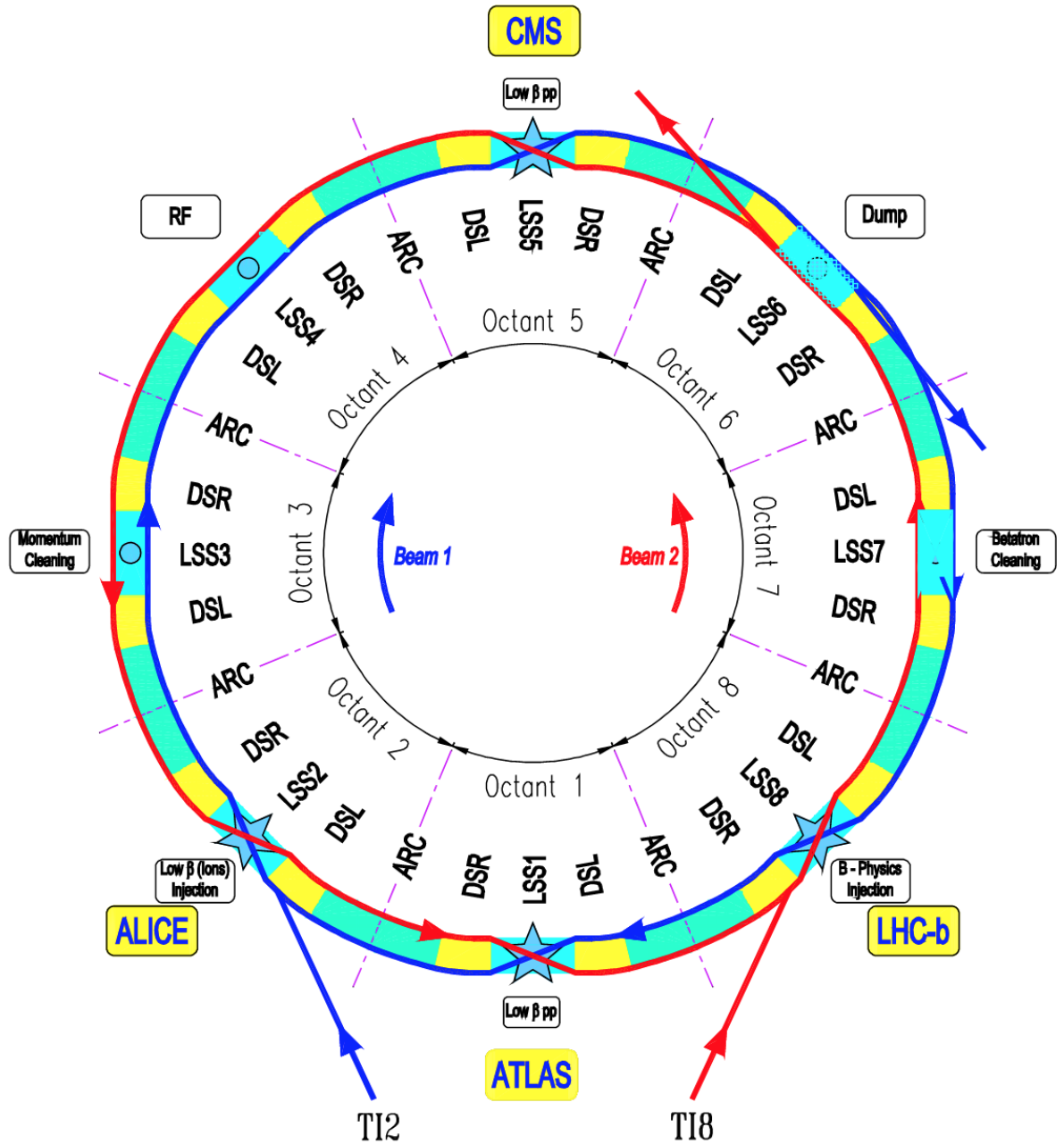


Figure 3.1. Schematic representation of LHC taken from Design Report (Brüning et al., 2004). Two separate beams with opposite directions and the locations of CMS, ATLAS, ALICE, and LHC-b detectors can be seen in the figure.

plant, the silicon tracker encapsulates and traces the paths of charged particles, preserving the delicate information of their trajectories. Moving outward, the fleshy and overlapping leaves of the artichoke correspond to the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL) of the CMS detector. The spiky and protective bracts of an artichoke's outermost layer can be analogically related to the muon chambers of the CMS detector. Like the bracts shielding the artichoke, the muon chambers surround and detect muons, providing crucial information about these elusive particles.

The CMS collaboration comprises a sizeable international community of physicists, engineers, and scientists from institutions worldwide. Collaboration members contribute to various aspects of the experiment, including detector design, data analysis techniques, upgrade of some parts of the detector, and theoretical interpretations.

Through its high-precision measurements and detailed analysis, the CMS experiment aims to deepen our understanding of the fundamental building blocks of matter, the forces governing their interactions, and the fundamental laws that govern the universe at minor scales. The knowledge gained from the CMS experiment has proved the potential to revolutionize our understanding of the behavior of sub-atomic particles and shape our comprehension of the fundamental nature of the universe.

It would be informative to give more details about the CMS sub-systems.

3.2.1. Sub-Systems of CMS

The CMS detector has many sub-systems, each designed to fulfill tasks such as capturing the energy deposits of the objects, tracing the charged and neutral particles, and detecting the muons. The CMS sub-systems also have another crucial task of efficiently collecting the immense number of events generated by the collider, necessitating robust trigger and data acquisition systems. Here, we can give a very brief overview of the sub-systems of the CMS detector:

- **Tracker:** The CMS tracker is the innermost sub-system of the detector. It is designed to trace the paths of charged particles as they pass through it. The tracker consists of silicon pixel and strip detectors, with barrel and endcap regions for both detectors. Barrel regions have a cylindrical shape with many silicon layers, and the endcap region consists of silicon modules perpendicular to the beam axis. The pixel detector is situated in closer proximity to the interaction point compared to the strip detector; nonetheless, both detectors are subjected to radiation-induced degradation owing to their proximity to the collision region (*The Phase-2 Upgrade of the CMS Tracker* 2017).
- **ECAL:** This sub-detector measures the energy of photons and electrons. It comprises lead tungstate crystals (PbWO_4), basically scintillators emitting light when interacting with the particles. ECAL provides exceptional energy resolution for particles that interact electromagnet-

ically. ECAL consists of barrel and endcap regions covering the pseudorapidity $\eta > |3|$ with more than 65.000 crystals for both regions in total. ECAL has a crucial role in detecting various physics processes like Higgs boson decay, BSM events, and electroweak interactions (Serguei Chatrchyan et al., 2013a).

- **HCAL:** This sub-detector measures the energy of particles interacting via strong nuclear force, which can be described as hadrons. The HCAL detector consists of a barrel, endcap, and forward regions to cover all the hadrons produced by collisions. It is located outside the ECAL and consists of layers of dense material incorporated with scintillator tiles. The barrel region contains plastic scintillator tiles interleaved with brass absorbers, while the endcap and forward regions consist of scintillator or silicon sensors coupled with steel absorbers (Mans et al., 2012).
- **Solenoid Magnet:** The CMS detector is immersed in a strong magnetic field created by a superconducting solenoid magnet with a magnetic field of up to 4 Tesla. The magnet produces a uniform magnetic field along the detector's central axis, enabling precise measurements of particle momenta. The magnetic field is crucial for the curvature of charged particles, allowing for particle identification and momentum determination (S. Chatrchyan et al., 2008).
- **Muon Systems:** The CMS's muon system is the outermost sub-system of the CMS detector, with different types of detectors and position alignments. The muon system consists of gas detectors called drift tubes (DT), cathode strip chambers (CSC), and resistive plate chambers (RPC), which identify and measure the trajectories and momenta of muons. The detectors are purposefully designed to accurately detect and measure muons, fundamental particles capable of traversing significant distances with minimal energy loss. This characteristic renders muons indispensable in the search for Beyond the Standard Model (BSM) physics phenomena (*The Phase-2 Upgrade of the CMS Muon Detectors* 2017).
- **Trigger and Data Acquisition :** The CMS detector collects enormous amounts of data with its well-established trigger and DAQ system. The trigger system promptly specifies interesting events for subsequent analysis by rapidly (around 4ms) identifying potentially significant collisions based on the information coming from the sub-detectors. The CMS uses the two-level trigger system: L1 (Level-1) and HLT (High-Level Trigger). The Level-1 (L1) trigger represents the initial stage in reducing the vast amount of data originating from millions of collisions to a more manageable level of several thousand events. This reduction process involves dedicated software tailored to each sub-detector. The L1 trigger selectively gathers and filters data from the calorimeters and muon detectors, then forwards this preliminary data to a global trigger. The global trigger utilizes scaled thresholds to refine event selection further. At the same time, the Data Acquisition (DAQ) system stores the chosen events for offline analysis from the

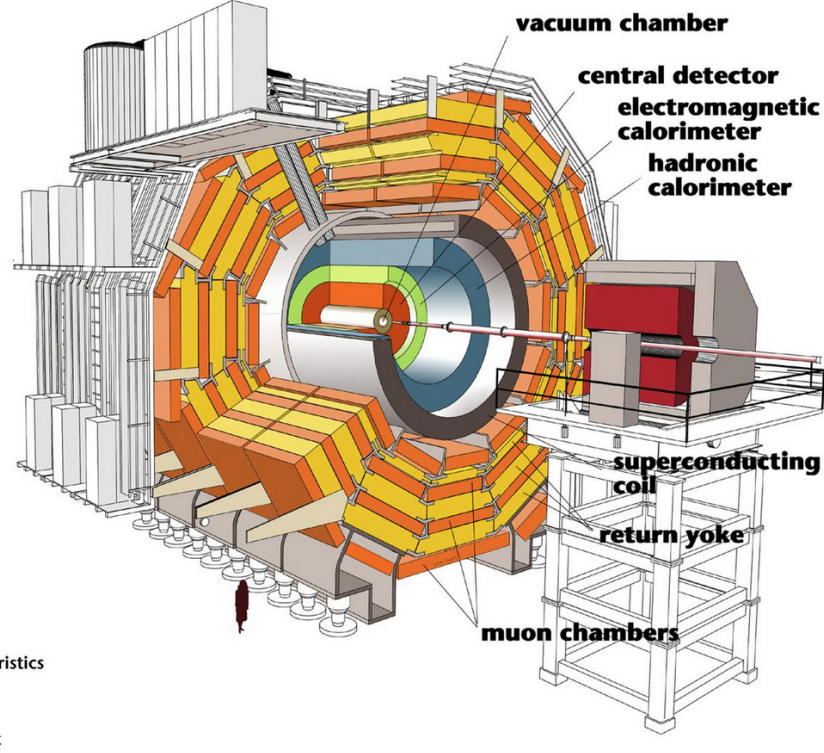


Figure 3.2. Schematic representation of the CMS detector showcasing the arrangement of sub-detectors, magnet, calorimeters, muon system, yoke, and superconducting magnet. The figure provides an overview of the detector's layout and includes size information (AC, 1998).

front-end electronics of sub-detectors to the data storage infrastructures (CMS Collaboration, 2017). HLT applies more complex event selection criteria to reduce the further trigger accept rate; in comparison, L1 has a 100 kHz (up to 750 kHz with Phase-2 upgrades for HL-LHC era) trigger rate, HLT has 1 kHz (up to 7.5 kHz with Phase-2 upgrade for HL-LHC era) (Hegeman, 2018).

3.2.2. Phase-2 Upgrades

HL-LHC era of the LHC will provide more physics data with up to a billion collisions per second and additional radioactivity on the material used for collecting data on the CMS detector. Phase-2 upgrades of the CMS detector itself will be performed during long shutdown-3 (LS3), which will be started from 2024 until 2026 and include upgrades for many sub-systems of the CMS. As part of the upgrade process, the tracker, calorimeters, and muon detectors will undergo renewal, ensuring enhanced performance and capabilities. Furthermore, the trigger and data acquisition (DAQ) systems will undergo improvements to effectively address the demands arising from high luminosity physics events and the challenges associated with data collection. Beyond that, the endcap calorimeters of the HCAL will be replaced with high-granularity calorimeter (HGCAL), which consists of silicon-based

sensors in a total size of more than 600 m², to be able to withstand radiation damage and improve energy resolution with its design to gain high granularity. The HGCal project started in 2016, and the detector is planned to be installed during the LS3. The following chapter will explain my involvement in the HGCal project for the test beam (performed in 2018 at CERN) analysis on the SPS H2 beam line.



4. SPS H2 BEAMLINE SIMULATION

During the autumn of 2018, test beams were conducted in the dedicated test-beam area of CERN's North Area, specifically the H2 beam line, to validate the future CMS HGCAL detector and its various components. The HGCAL prototype was exposed to different high-energy hadron and electron beams with momenta ranging from 20 to 300 GeV/c. These research and development challenges necessitated using data with well-controlled beam quality while considering momentum resolution and contamination. A comprehensive simulation study of the H2 beam line was undertaken to understand better the beam parameters and the factors influencing them. This simulation study encompassed the entire beam trajectory, from the target to the HGCAL module, and included all the materials present along this path. The simulation model, developed using the specialized Geant4-based G4beamline, enabled the examination of virtually all beam characteristics, such as background, momentum resolution, and particle rate. The results from the beam line simulation were then incorporated into the detector simulation. This chapter presents and compares the simulation results for different electron and pion beams with the corresponding test-beam data. The study's findings illustrate the impact of synchrotron radiation on defining the beam momenta in the high-energy range and the energy loss resulting from Bremsstrahlung caused by the presence of beam materials along the beam line.

4.1. Introduction

HGCAL will be replaced with the existing CMS endcap calorimeters during the next long shutdown (LS3), which is designed to be able to deal with the conditions such as expected high pileup and radiation effects of the future High Luminosity LHC (HL-LHC) (Magnan, 2017). For such a challenging task, a lot of test beam data and analysis of this data are required.

HGCAL Test Beam performed during the autumn of 2018 at the North Area Facility of CERN, PPE172 (H2) zone dedicated to CMS HCAL experiments. Super Proton Synchrotron (SPS) H2 beamline provides secondary particles with a wide range of momenta 10-300 GeV/c, which extracts 400 GeV/c primary protons from SPS. This study simulates a full H2 beam line to better comprehend the beam properties used in the HGCAL prototype simulation. All the materials on the beam trajectory are simulated with the G4beamline, a particle tracking program for the beamlines based on Geant4 (Muons Inc., n.d.). The magnetic elements, collimators, and triggers along the beamline and the vacuum pipes and air zones are meticulously simulated with detailed information regarding their apertures, sizes, and precise positions on the beamline. The design of the H2 beamline requires bending magnets to carry particles from the production target to the experimental zone with an extra momentum spread due to synchrotron radiation. The first step of the study was to check the synchrotron radiation effect without

any material (except magnetic elements) on the beamline to be sure that modeling the synchrotron radiation effect by G4beamline was correct. Subsequently, information on materials was incorporated into the model through on-site visits and well-documented H2 beamline properties. The investigation encompasses the study of particle compositions, momentum distribution, and beam emittance.

4.2. Particle Production

A series of bending magnets and beryllium targets carry out the production of secondary particles at the T2 target station. The initial two bending magnets (B1 and B2) facilitate the transfer of primary particles (protons) from the SPS to the target. Subsequently, the remaining bending magnets (B3 and B4) at the T2 station selectively choose secondary particles based on their desired sign, momentum, and particle type (Atherton et al., 1980). Figure 4.1.. shows the layout of the T2 target station with an SPS wobbling system (Charitonidis and Tellander, 2016) with a production angle of 150 GeV secondary particles.

The beam content created by the T2 target varies, such as electrons/positrons, muons, pions, and kaons (Coet and Doble, 1986). In this study, only electron/positron and pion beams are considered. The predominant production mechanism for electrons involves the neutral channel ($\pi^0 \rightarrow \gamma\gamma \rightarrow e^-e^+$), which accounts for approximately 90% of the realistic production rate.

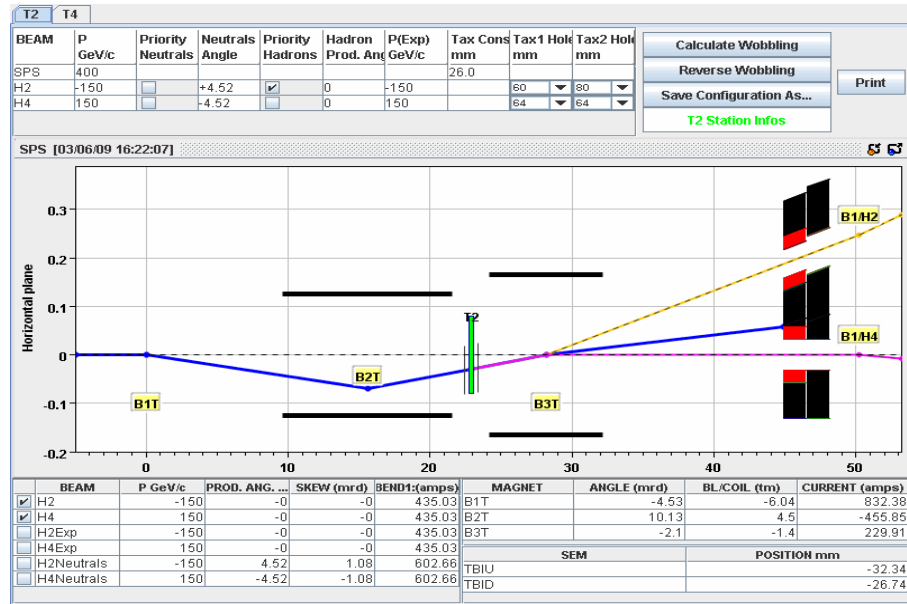


Figure 4.1. Layout of T2 target station from SPS wobbling system (EN, 2017a).

4.3. The HGCAL Test Beams

HGCAL is a high-granularity sampling calorimeter with 50 active layers and around 6 million channels. There are two main sections of the calorimeter: electromagnetic and hadronic sections. Both sections have hexagonal silicon sensors with an area of approximately 1.1 cm^2 and 135 cells in total. Plastic scintillators are also used in conjunction with the silicon sensors in specific regions of the calorimeter's hadronic section where lower radiation effects are expected (Acar et al., 2021).



Figure 4.2. Installation of the HGCAL and AHCAL prototype at PPE172 zone.

The calorimeter prototype was placed at the PPE172 zone of the North Area Facility. In total, 96 prototype silicon modules were installed to be tested; 28 of them belong to the electromagnetic section, and nine layers belong to the hadronic section of the HGCAL. CALICE Analog Hadronic Calorimeter (AHCAL) prototype has 39 active layers upstream of these layers. A picture of the prototypes that were installed at the PPE172 zone is shown in Figure 4.2..

In October 2018, the CMS CE group performed a two-week test beam for the tests of the future endcap calorimeter of the CMS prototype and AHCAL silicon modules. The beams of charged hadrons, electrons, muons, and pions were used within the 20-300 GeV energy range from the SPS H2 beam line.

4.4. Beamline Simulation with G4beamline

A complete and realistic set of simulations of the SPS H2 beam line elements (collimators, bending magnets, wire chambers, etc.) are performed with G4beamline, a single-particle tracking simulation program based on Geant4. The length of the beam path leading to the test zone, the mate-

rial thickness encountered along the beam trajectory during the beam test, and other relevant technical parameters are incorporated as inputs for the simulation. This information is derived from the comprehensive SPS H2 material charts ((EN, 2017b)) and verified through in-situ visits to the beam test zone. The particle production rate for the electron beams is selected as 90% electron and 10% of hadron for the initial beam and 1.2% momentum spread to have a more realistic beam simulation with one million events for generating the H2 beamline conditions. A visualization taken from G4beamline is shown in Figure 4.3..

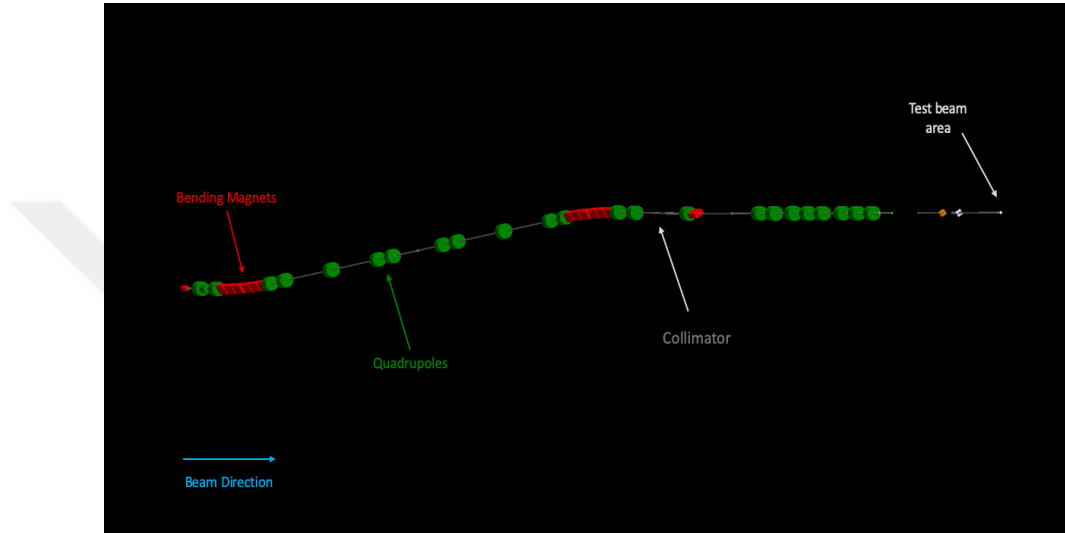


Figure 4.3. Side view of H2 beam line taken from G4beamline.

4.5. Energy Loss and Material Affect

The emission due to the synchrotron radiation highly affects the beam quality, especially for the electron and positron beams. Before considering the material's effect on the beam properties, energy loss due to the synchrotron radiation must be taken into account.

4.5.1. Synchrotron Radiation

Charged particles that move in an orbit lose energy by emitting synchrotron radiation. In our case, H2 has two sets of bending magnets that cause synchrotron radiation through the beam line. To determine the bending angle, we can use the equilibrium of centrifugal and magnetic Lorentz force that affects electrons/positrons in the magnetic field of bending magnet (Wiedemann, 2015).

$$qB = (\gamma m v)/\rho \quad (4.1)$$

where magnetic field vector B is normal to velocity vector and γ is relativistic factor. From

these equations, we can get beam rigidity

$$|B\rho| = \frac{p_0}{e} \quad (4.2)$$

where ρ is the bending radius. Thus, we can define a more generic bending radius formula

$$\frac{1}{\rho} = \frac{e|B|}{p_0} = \frac{ec|B|}{\beta E} \quad (4.3)$$

where B is expressed in Tesla, E in GeV, and $\beta = v/c$, which can be chosen ≈ 1 for relativistic particles.

Finally, the deflection angle of the particle in the magnetic field is

$$\Theta = \int \frac{dz}{\rho} \quad (4.4)$$

which can be written in a uniform field with the effective field length L_{eff} as $\Theta = L_{eff}/\rho$.

Thus, we get deflection angle

$$\Theta = \frac{299.79BL_{eff}}{P} \quad (4.5)$$

where L_{eff} is expressed in m and P in GeV/c.

To define the energy loss due to the synchrotron radiation, one can extract ΔP from the Larmor formula

$$\Delta P = -\frac{2}{3} \frac{r_0}{(m_0c^2)^3} \frac{p^4 \Theta^2}{L_{eff}} \quad (4.6)$$

where p is expressed in GeV/c and Θ in Rad.

4.5.2. Materials on the Beamline

Materials on the H2 beamline can be categorized as magnetic elements on the beamline, such as quadrupole, bending magnets, collimators, and trims; beam counters, such as wire chambers, scintillators, halo/veto counters; materials that are used by the test beam team on the PPE172 zone such as MCPs and extra scintillators used by the team; materials which belong to NA61 experiment upstream of the test zone such as beam position detectors (BPDs) (Abgrall et al., 2014) and targets which are not installed during HGCal test beam so not considered as the materials on this study. In addition to these materials, humidity in the air, vacuum pipes, and beam windows are also implemented in the simulation. Figure 4.4. shows some materials on the beam trajectory that were used during the test beam

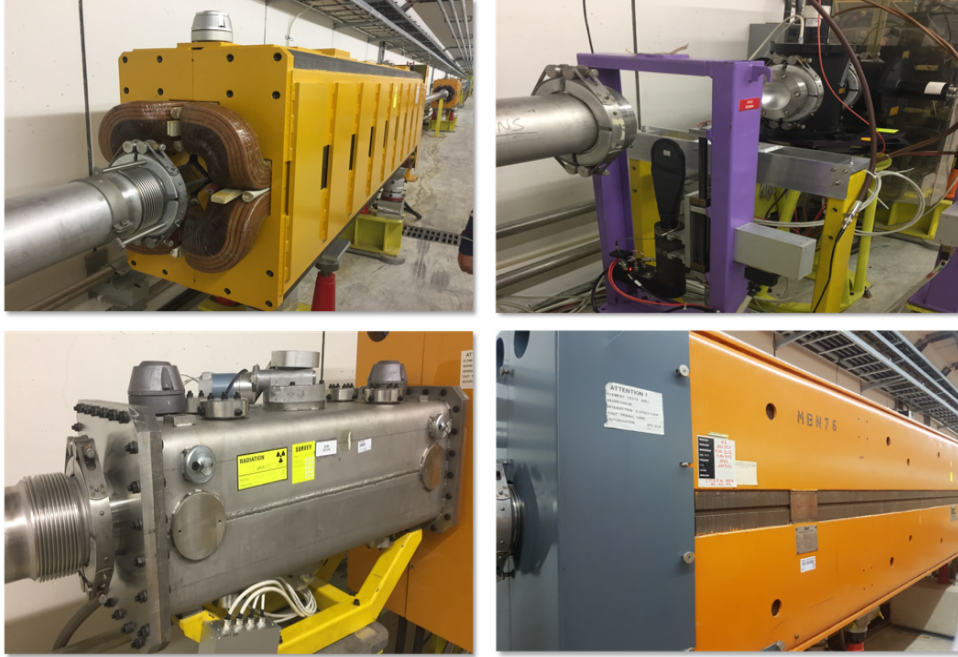


Figure 4.4. Some of the magnetic elements and scintillator on the H2 beam line are shown in these figures. The upper left figure shows the scintillator, beam window and the air gap between two beam pipe, on the upper right figure shows the bending magnet, the lower left figure shows the quadrupole and right figure on the bottom shows the collimator.

4.6. Test Beam Data and MC

A total of one million events were simulated using the G4beamline program, incorporating the complete configuration of beam magnets and materials. The resulting root files contain detailed information on the kinematic variables of each particle generated, offering a comprehensive dataset for further analysis. Figure 4.5. and Figure 4.6. show the momentum distribution of the positron and pion beams, respectively. The presence of materials along the beamline, particularly within the experimental area and the air gaps traversed by the beams, leads to a characteristic tail in the momentum distribution extending towards lower energies from the mean energy. This tail is primarily attributed to the material effects encountered throughout the beamline.

4.7. Results

The results of the H2 beamline simulation are produced as root files for the initial energies range from 20 to 300 GeV and particle content, which is implemented in the CE-E prototype simulation under test by the HGCal simulation group. Figure 4.7. shows the MIP (minimum ionized

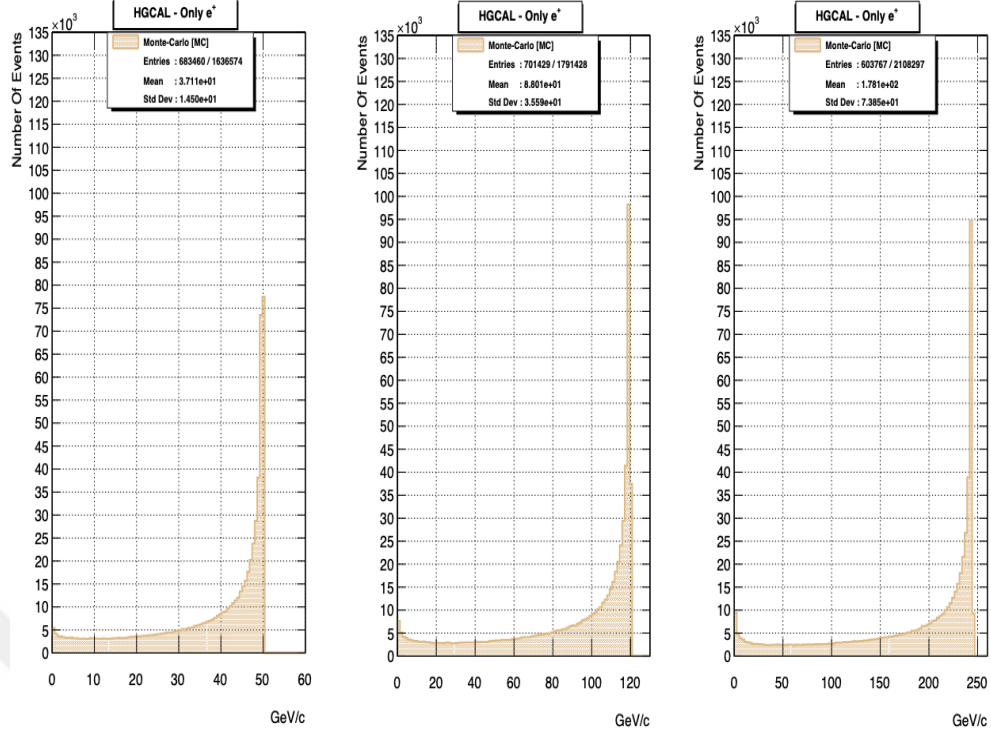


Figure 4.5. The momentum distribution of the positron (e^+) beam, represented by the number of events on the y-axis, was generated through simulations using the G4beamline program. The generated plots illustrate the momentum distribution for three different initial energies: 50 GeV/c (left), 120 GeV/c (middle), and 250 GeV/c (right).

particle) distribution with full beamline simulation results from G4beamline implemented to the detector simulation, 30m beam gun Geant4 simulation, and test beam data. The total radiation length was calculated (Gupta, 2010) as 0.46 X_0 for the full beamline from the production target to the test beam area. Momentum spread due to the Bremsstrahlung and synchrotron radiation emission was calculated as 0.5-0.6% for various beam energy files from the SPS H2 beamline. The results of this study were presented at the 8th BTTB workshop in 2020 on behalf of CMS Collaboration (CMS Collaboration, 2020b).

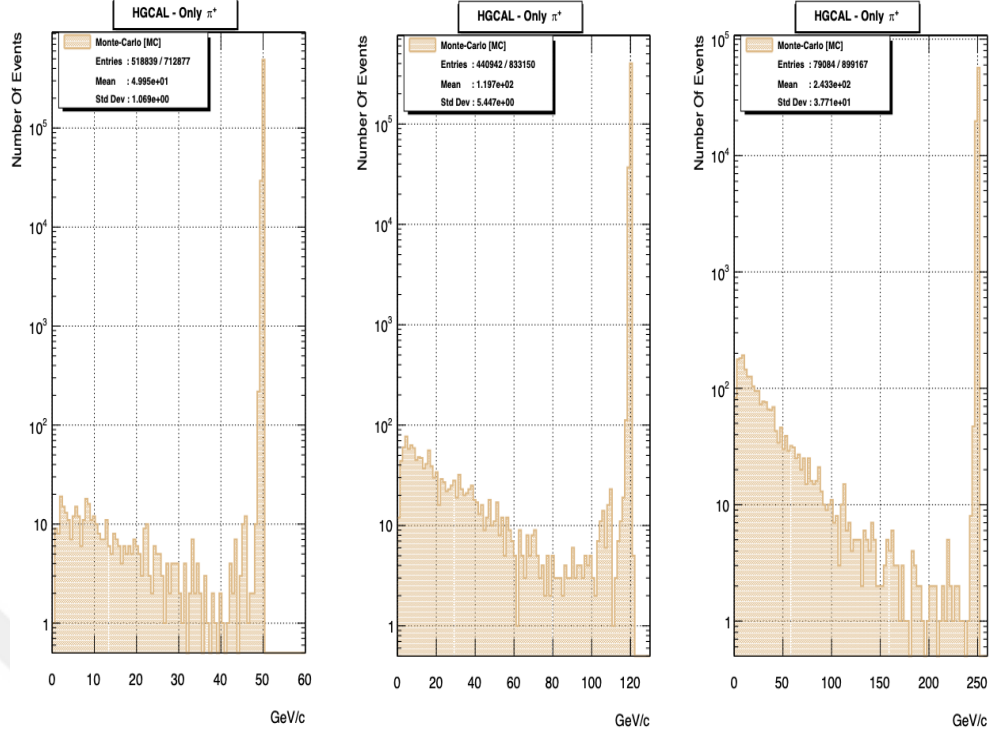


Figure 4.6. The momentum distribution of the pion (π^+) beam, represented by the number of events on the y-axis, was generated through simulations using the G4beamline program. The generated plots illustrate the momentum distribution for three different initial energies: 50 GeV/c (left), 120 GeV/c (middle), and 250 GeV/c (right).

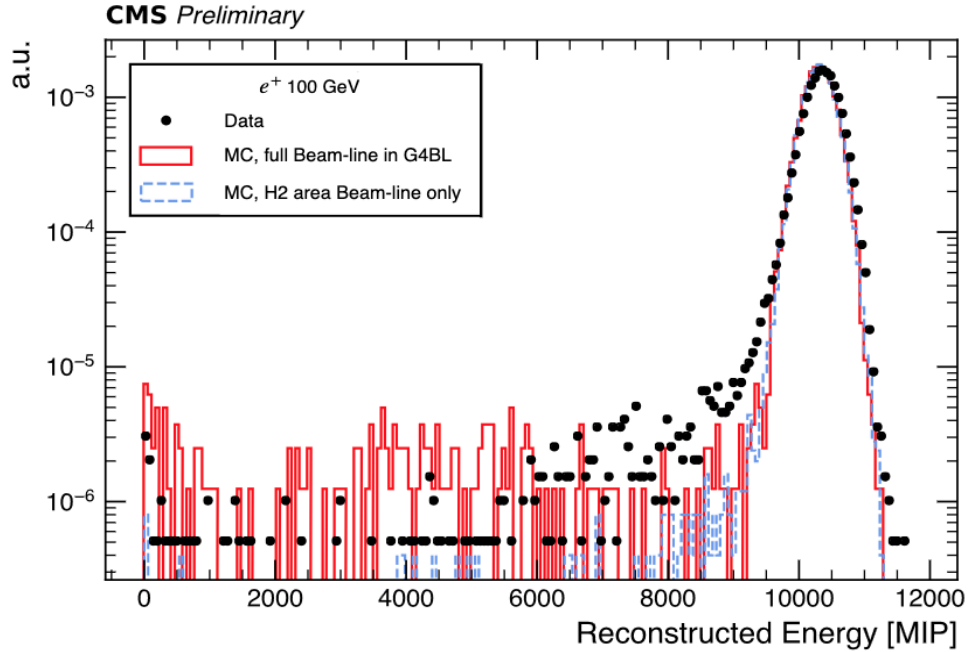


Figure 4.7. MIP distribution of the HGCal detector prototype for 100 GeV positron beam with 2018 test beam data, Geant4 simulation, and full beamline simulation information (CMS Collaboration, 2020b).

5. INCLUSIVE RAZOR BOOST ANALYSIS FOR NEW PHYSICS

As described in the previous chapters, SUSY theory is a solid theoretical tool for our journey to find new physics phenomena. The Minimal Supersymmetric Standard Model (MSSM) has illuminated numerous unresolved questions within the realm of experimental predictions. The Natural MSSM, specifically referenced in (Casas et al., 2015) plays a pivotal role by circumventing the extreme fine-tuning required for the stabilization of the Higgs mass. It also provides insights into the hierarchy problem by addressing why the Higgs mass is relatively small compared to the electroweak scale. On the other hand, exclusion bounds on the LSPs are still agreeing with the natural MSSM theory. LSP is among the strongest candidates for the dark matter explanation in the R-parity conserving scenarios. An expansion comes from additional sparticles on the S-matrix that also theoretically satisfy the gauge coupling unification. Even if the absence of evidence for MSSM particles in the LHC experiments has led to skepticism about the theory, it is still worth tracking the events of SUSY particles in the experiments and calculating the exclusion limits on the masses of the predicted models of SUSY to obtain a deeper acquaintance of the nature.

In this chapter, I aim to present an extensive strategy and outcomes of the Inclusive Razor Boost Analysis within the context of my contribution to the analysis and the implications of the final findings. My involvement with the Razor Boost team aligns with the first Run-II data-taking period in 2016. Firstly, I must emphasize that the new physics searches with razor kinematic variables have a relatively long history. During Run-I and Run-II data-taking eras at the CMS, working with M_R and R^2 showed its powerful effect on the exclusion upper limits of the sparticle masses. The subsequent subsection will briefly outline the outcomes and my contributions to the Inclusive Razor Boost analysis. This analysis is based on the analysis data obtained by CMS at a center-of-mass energy of 13 TeV, accompanied by an integrated luminosity of 35.8 fb, published in 2019. Subsequently, a detailed explanation of Inclusive search with razor kinematic variables for full Run-II data (including 2016, 2017, and 2018 data collected by CMS) at 13 TeV will be given for Ultra Legacy (UL) dataset.

5.1. Inclusive Search for SUSY with M_R and R^2 variables for 2016 CMS Data

Search for SUSY with M_R and R^2 variables at 13 TeV with vetoing lepton or at least one charged lepton in the final state was performed (Sirunyan et al., 2019) with integrated luminosity 35 fb⁻¹. This analysis is categorized by the event categories based on various characteristics of the search strategy, including boosted objects (W boson or top quark), AK8 jets, or b-tagged jet multiplicity. For the boosted categories (where the razor-boost team contributes as a separate team), dedicated control region (CR), signal region (SR), and validation region (VR) are specified, used for background estimation to improve the signal sensitivity further. Background estimation aimed to separate the SM

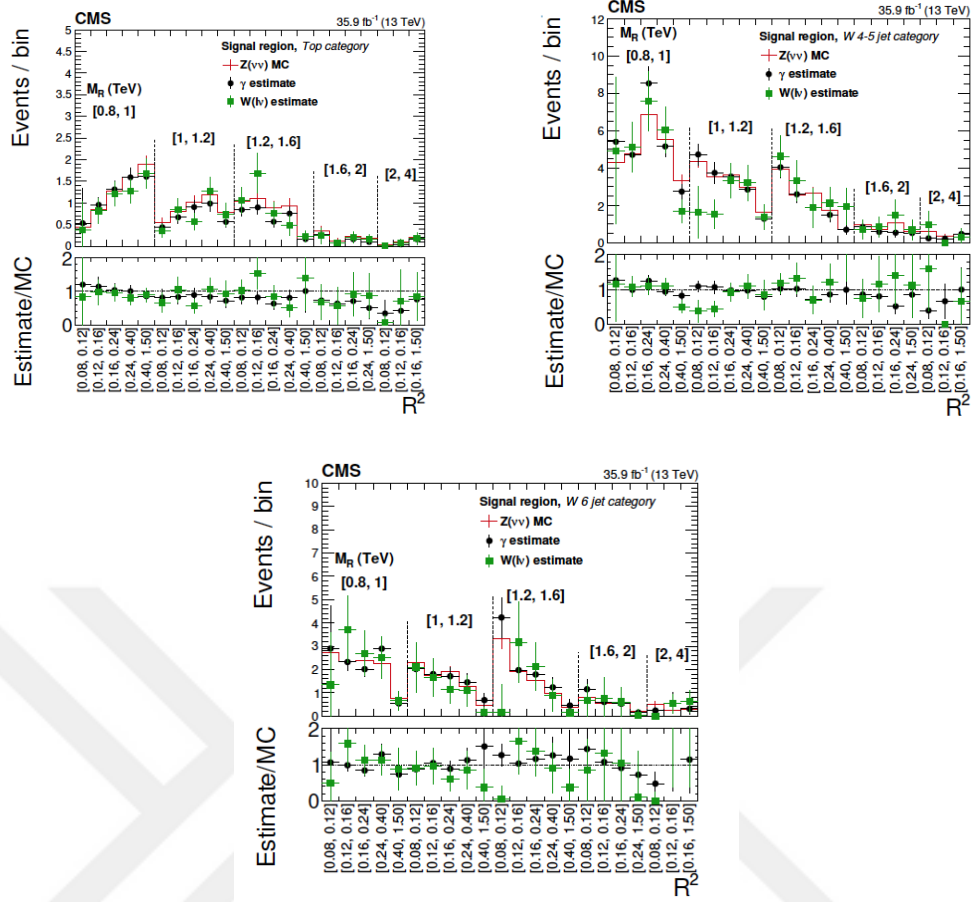


Figure 5.1. Comparisons of the various background estimates sourced from $\gamma + jets$ events in the $Z \rightarrow (\nu\nu)$ CR in the (M_R, R^2) phase space are shown here for boosted categories; top, W (4-5), and W (>6). The lower pad on the figures shows the distribution of the estimate/MC counts ratio. The upper left plot shows the results for the top category, the upper right plot shows the W (4-5) category, and the lower plot shows the W (>6) category (Sirunyan et al., 2019).

processes from the signal events in the circumstances with W+jets, Z boson to invisible events, top enriched, and QCD multijet enriched CRs. SRs are determined to emulate the possible SUSY signal in the events. VRs serve as essential checks to ensure the validity of the background estimation method. Figure 5.1. shows the final background estimation comparison for the various events contributing to the background.

All categories of the analysis combined with the confidence limit (CL) (Favara and Pieri, 1997) technique for the upper limit calculations to improve the signal sensitivity. Figure 5.2. shows the results for the simplified SUSY models of T5ttcc and T1tt with gluino pair production with different final states.

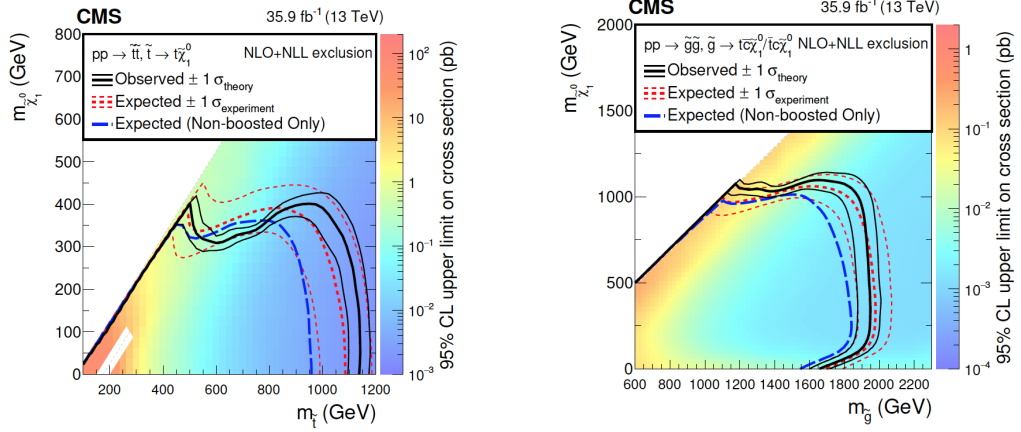


Figure 5.2. Exclusion limits at 95% CL for stop and gluino pair production processes in the $m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ planes, respectively. The left plot represents the exclusion limits for stop pair production ($pp \rightarrow \tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0$), T1tt signal model. The right plot represents the exclusion limits for gluino pair production ($pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{\chi}_1^0/\tilde{t}\tilde{\chi}_1^0$) T5ttcc signal model. In both plots, the solid black line shows the observed limit with $\pm 1\sigma$ theoretical uncertainties, the dashed red line shows the expected limit with $\pm 1\sigma$ experimental uncertainties, and the dashed blue line represents the expected limit for the non-boosted only analysis. The colored background indicates the 95% CL upper limit on the cross-section (pb). The data corresponds to an integrated luminosity of 35.9 fb^{-1} at a center-of-mass energy of 13 TeV (Sirunyan et al., 2019).

5.2. Analysis Strategy

This chapter represents the overall search strategy of the inclusive search of the SUSY with full Run-II data, which is a continuation of the previous analysis conducted with 2016 CMS data discussed in the previous subsection. This analysis is designed to be an inclusive search to cover a wide range of SUSY scenarios, aiming at boosted objects in the final states. It thoroughly investigates both hadronic and leptonic final states involving boosted W, Z, and Higgs bosons and boosted top quarks in hadronic or leptonic decays, along with boosted leptonic jets. The razor kinematic variables (M_R and R^2) discussed in Chapter 2 effectively differentiate the signal from the SM backgrounds. ($M_R \times R^2$) phase space is used to discriminate the background and signal events in the CRs, SRs, and VRs. Background processes are partitioned into CRs based on the selection criteria, such as lepton and jet multiplicities, b-tagged objects, and constraints on transverse mass (m_T) to mimic the SM events. The analysis searches for RPC and RPV simplified models simultaneously with gluino, electroweakino, or stop pair production decaying to various final states with LSPs (for RPC cases); all the RPC cases are shown in the form of Feynmann diagrams in Figure 2.2.. In RPV models, LSP decays to heavier SM particles in the final states; among numerous conceivable RPV configurations, Figure 2.3. illustrates a pair of examples used in the analysis. Dedicated SRs are needed to encompass and enhance the signal sensitivity of a wide range of signal models for hadronic, leptonic, and leptonic

top cases with different jet and b-tag multiplicities selections. Precisely estimating the background stemming from SM processes within the context of SUSY signal events assumes critical significance in our pursuit of novel physics inquiries. A well-established strategy is used for W^+ jets, top, ZtoInv, and QCD processes to address this. Following this, the fidelity of our background estimations is subjected to validation through dedicated VRs designed and reserved for this specific evaluative purpose. All the systematics sources from theory, object definitions, detector uncertainties, and corrections for the MC samples are calculated simultaneously and applied to all the results.

5.3. Dataset and Monte-Carlo

The analysis presented in this chapter uses data collected by CMS during the Run-II era, including 2016 data with 35.8 fb, 2017 data with 41.5 fb, and 2018 data with 59.8 integrated luminosity at 13 TeV. In this specific analysis, NanoAOD (Rizzi, Petrucciani, and Peruzzi, 2019) (v9) data format was used with UL extension. NanoAOD format is a compact and streamlined format derived from the original AOD (Analysis Object Data) format used by the CMS search groups, suitable for usage in CMS software (CMSSW) and ROOT (Antcheva et al., 2009) analysis framework. The primary purpose of NanoAOD is to provide a more condensed and optimized data representation suitable for physics analyses without sacrificing critical information.

Monte-Carlo (MC) samples are produced centrally in the CMS collaboration with various generator tools such as the Geant-4 detector simulation program and PYTHIA (Sjöstrand et al., 2015) event generator to produce background and signal samples.

5.3.1. Datasets

All the datasets, including JetHT, MET, HTMHT, SingleMuon, SingleElectron, SinglePhoton, and EGamma, are used for various purposes in the analysis.

- **JetHT** JetHT dataset collected by the CMS records jets with high transverse momentum using hadronic triggers. It is used by various studies to identify SM processes and searches beyond the SM. This analysis uses these datasets in CRs, SRs and VRs for background estimation and trigger efficiency calculations (lepton and photonic trigger efficiencies).
- **HTMHT** 'High Transverse Momentum/Energy' dataset collected by CMS with events including jets and hadronic processes using hadronic and MET triggers. HTMHT dataset is used in all the regions and performed lepton and photon trigger efficiencies for this analysis.
- **MET** 'Missing Transverse Energy' dataset collected by CMS with the events in the transverse plane causing missing energy. The primary source of the MET is neutrinos and weakly interacting massive particles; also, the BSM processes contribute to the MET. Accurate measurement

of MET is crucial for understanding the properties of W and Z bosons, such as their masses, widths, and production cross-sections. This dataset allows for the precise reconstruction of the boson's decay products and helps in reducing systematic uncertainties. It is also used for lepton and photon trigger efficiencies in this analysis.

- **Leptonic Datasets** SingleMuon, SingleElectron, and SinglePhoton datasets collect events with processes, including triggered leptons in CMS. It is used for computing the hadronic trigger efficiencies in the analysis and CRs with lepton identification.
- **EGamma** This dataset is produced by CMS in collaboration with electron and photon triggers. It is used in the analysis for some lepton-related CRs and computing the hadronic trigger efficiencies.

The complete dataset list for each data-taking period is presented in Appendix A with tables.

5.3.2. Monte-Carlo Samples

A large number of simulated events are required to compare massive amounts of the collision data from LHC realistically. For each data-taking period at the CMS experiment, the physics object groups (POG), physics analysis groups (PAG), and detector performance groups (DPG) collaborate to generate MC samples centrally that align with the current condition, incorporating detector upgrades and requirements of analysis groups. Production of simulated events is constructed by the GEANT4 (*GEANT4* n.d.) simulation program, including all the realistic steps to collect data from the CMS detector and the simulation of CMS's subsystems. For details of Run 2 upgrade on simulation, one can check the reference (Ivanchenko and Banerjee, 2019).

All the MC samples used in this analysis for background and signal events are listed in Appendix B, with tables for each data-taking period.

5.4. Trigger

As given in the previous chapter, a wide variety of data and MC samples are used in the analysis, taking into account the inclusive nature of the study. The list of triggers used in the analysis for various SRs, CRs, and VRs are listed in Table 5.1. with specific energy thresholds according to their object tagging purposes for different data-taking era (2016, 2017 and 2018). This table is classified considering their related datasets, JetHT, HTMHT, MET, SingleMuon, SingleElectron, SinglePhoton, and EGamma, respectively. Hadronic and MET triggers are selected according to the analysis strategy, which aims to have a boosted object in the final state. Leptonic triggers are used as an orthogonal trigger set to calculate the trigger efficiency to scale the MC samples in the CRs and SRs. It is crucial to accurately measure the efficiency of these triggers to ensure that the recorded events represent the actual events produced in the collisions.

Table 5.1. Triggers that are used for different data-taking periods of Run 2.

Trigger	2016	2017	2018
HLT_PFHTX, HLT_AK8PFJetY	900, 450	–	–
HLT_PFHTX	–	1050	1050
HLT_PFHTX_PFMETY	300,110	–	–
HLT_PFMET[NoMu]X_PFMHT[NoMu]Y_IDTight	110,110	–	–
HLT_PFHTX_PFMETY_PFMHTZ_IDTight	–	500,100,100 / 700,85,85 / 800,75,75	500,100,100 / 700,85,85 / 800,75,75
HLT_PFMET[NoMu]X_PFMHT[NoMu]Y_IDTight[_PFHTZ]	–	120,120,60	120,120,60
HLT_Mu15_IsoVVVL_PFHTX	350 / 400 / 450 / 600	350 / 400 / 450 / 600	350 / 400 / 450 / 600
HLT_Iso[Tk]MuX	24	27	27
HLT_[Tk]MuX	50 / 55	50 / 55	50 / 55
HLT_[Old,Tk]MuX	–	100	–
HLT_Ele15_IsoVVVL_PFHT	350 / 400 / 450 / 600	350 / 400 / 450 / 600	350 / 400 / 450 / 600
HLT_EleX_WPTight_Gsf	27 / 28 / 32 / 35 / 38	27 / 28 / 32 / 35 / 38	– –
HLT_EleX_CaloldVT_GsfTrkIdT	105 / 115	105 / 115	–
HLT_PhotonX	175	200	200
HLT_EleX_WPTight_Gsf	–	–	27 / 28 / 32 35 / 38
HLT_EleX_CaloldVT_GsfTrkIdT	–	–	105 / 115
HLT_PhotonX	–	–	200

Baseline event selections are used for calculating the trigger efficiencies depending on the categories given in subsequent sections; hadronic, leptonic, and non-isolated leptonic categories. The primary selection criteria for each case is on the jets tagged with the anti-kt algorithm with different cone sizes and constrain on the razor kinematic variables. The general formula for the trigger efficiency can be described as follows:

$$\epsilon_{trigger} = \frac{N_{baseline+trigger}}{N_{trigger}} \quad (5.1)$$

where $N_{baseline+trigger}$ stands for the event count passing both trigger and baseline selection, and $N_{trigger}$ is the event count with the event-only trigger selection applied. Figure 5.3. shows the distribution of the hadronic trigger efficiency in the H_T (which means the scalar some of transverse momenta) and E_T (which means missing transverse energy) bins for various leptonic orthogonal triggers with only baseline selection (see next section). With different color codes, histogram shows the electron, muon and gamma dataset and MC distribution over the bins of E_T and H_T . As expected, the trigger efficiency for higher bins of H_T and E_T approaches unity, indicating that the trigger system is effectively identifying the specific events. This reassurance allows us to have confidence in the trigger selection criteria used in the analysis.

Table 5.2. Event filters with their usage purposes in the analysis.

Event Filters	Purpose
goodVertices	To satisfy that the event has at least one good primary vertex in p-p collision data.
GlobalSuperTightHalo2016Filter	To avoid the beam-halo effect.
HBHENoiseFilter, HBHENoiseIsoFilter	To avoid the noise sourced from HCAL sub-systems.
EcalDeadCellTrigPrimitiveFilter	To filter out the events from known dead cells from ECAL.
BadPFMuonFilter, BadPFMuonDzFilter	To avoid the muons inconsistently reconstructed
hfNoisyHitsFilter	To avoid noise sourced from HF.
eeBadScFilter, ecalBadCalibFilter	To avoid the events reconstructed from ECAL's problematic super-crystals at end-cap region.
HEMFailure	To filter out High eta-muon 15/16 failure in the HCAL FED (for late 2018 runs).
METExtra	Excluding some events from the JetHT 2018 dataset (CMS Collaboration, 2020a).

In this chapter, we will discuss the physics objects involved in this study in detail, outlining their roles according to the search strategy. Additionally, we will address the search regions used in the analysis. These regions, defined as CRs, SRs and VRs, will be described in terms of their constraints on the physics objects and their specific purposes within the analysis.

5.5.1. Jets

Jets are reconstructed by clustering together PF candidate particles (CMS JMAR POG, 2021). These particles are reconstructed tracks in the tracker, energy deposits in the electromagnetic and hadronic calorimeters, and information from the muon detectors. By combining these different sources of information, the PF jet reconstruction aims to achieve the most accurate estimation of the energy and direction of the jets. The jets used in this analysis are AK4 and AK8 jets constructed with an anti-kt algorithm (Cacciari, G. P. Salam, and Soyez, 2008) with cone size $R=0.4$ and 0.8 , respectively. Selection criteria on jets are by momentum and pseudo-rapidity, which is defined as $p_T > 30$ and $|\eta| < 2.4$ for AK4 jets and $p_T > 200$ and $|\eta| < 2.4$ for AK8. Further, jet energy corrections sourced from the high pile-up effect are applied according to JetMET Group (CMS JetMET POG, 2023) which is taken into account as one of systematic uncertainty sources.

5.5.2. b-tagged Jets

b-tagged jets, also known as b-jets, are identified as originating from the hadronization of a bottom quark. b hadrons have a relatively long lifetime; they can travel a measurable distance before

decaying. B-tagging algorithms exploit the presence of displaced secondary vertices (from B hadron decays) or tracks with high-impact parameters within a jet to differentiate b-jets from light-quark or gluon jets.

To identify of a b-jet, a machine learning-based algorithm called DeepJet (Bols et al., 2020) was used. Medium, Medium-iso, Loose, and Loose-iso working points are selected for better classification and separation from boosted object tagging such as W, Z, or Higgs. The b-tagging process has its own fluctuations detected by further investigation by the b-tag POG, which is applied to MC events as a scale factor (SF) and taken into account as a source of systematic uncertainty.

5.5.3. Leptons

Leptons are widely used in the analysis with different working points (for electrons and muons) according to suggestions of related POGs (CMS Collaboration, 2022f). Electrons, muons, and taus are reconstructed by the PF algorithms (for muons) and MVA-based algorithm (for electrons). Muon identification and SF suggestions for UL were considered for 2018 (MuonPOG, 2021c), 2017 (MuonPOG, 2021b) and 2016 (MuonPOG, 2021a). Table 5.3. and Table 5.4. show the muon and electron definitions, respectively, for different isolation working points. For the muon definition table, the muons classified as Veto-Iso (designed for a looser selection of muons to reject events where muons are not likely part of primary interaction), Select-Iso (designed for identifying muons that are likely part of primary interaction with stricter selections) and NonIso (scenarios where muons may not be isolated, typically in environments with high jet activity). Selection criterias are selected by kinematic (p_T) and spatial ($|\eta|$, d_0 and sigma3D (only for NonIso)) variables, with additional object tagging algorithms. On the other hand, for the electron definition table, the electrons are classified with the same way of the muons but some different object tagging algorithms.

Table 5.3. Muon definitions used for muon identification in the analysis for three different working points.

Variable/Method	Veto-Iso	Select-Iso	NonIso
softId	= 1	--	= 1
mediumPromptId	--	= 1	--
$p_T (GeV)$	≥ 5	≥ 10	≥ 30
$ \eta $	< 2.4	< 2.4	< 2.4
$ d_0 $	< 0.2	< 0.05	< 0.05
$ d_Z $	< 0.5	< 0.1	< 0.1
sigma3D	--	--	< 4
miniPFReliso_all	< 0.4	< 0.2	--
"B2G 2D isolation"	--	--	$\Delta_{\min}(\mu, j) > 0.4$ or $p_T^{rel}(\mu, j) > 15$

For tau object definitions, TauPOG suggestions (TauPOG, 2023) was considered for Run 2 data

Table 5.4. Electron definitions used for muon identification in the analysis for three working points.

Variable/Method	Veto-Iso	Select-Iso	NonIso
mvaFall17V2noIso_WPL	= 1	--	= 1
mvaFall17V2noIso_WP90	--	= 1	--
$p_T (GeV)$	≥ 5	≥ 10	≥ 30
$ \eta $	< 2.5	< 2.5	< 2.5
$ \eta $ (exclusion)	--	$\neq [1.442, 1.556]$	$\neq [1.442, 1.556]$
$ d_0 $	< 0.05	< 0.05	< 0.05
$ d_Z $	< 0.1	< 0.1	< 0.1
miniPFReliso_all	< 0.4	< 0.1	--
"B2G 2D isolation"	--	--	$\Delta_{\min}(\mu, AK4) > 0.4$ or $p_T^{rel} > 15$

and MC. Tau momentum is defined as $p_T \geq 20(GeV)$ and pseudo-rapidity is defined as $|\eta| < 2.3$.

For muon and electron SFs calculations, the "tag-and-probe" method is used to correct the MC samples with leptons, which is data-driven method uses MC and data samples with related triggers (e.g., HLT Ele27 WPTight Gsf v^* / HLT Ele32 WPTight Gsf L1DoubleEG v^* / HLT Ele32 WPTight Gsf v^* for electron SFs in data-taking period order, and HLT IsoMu24 v^* (2016,17) or HLT IsoMu27 v^* (2018) for muon SFs). All the SFs are taken into account as systemic uncertainty in the final results.

5.5.4. Photons

Cut-based identification was used for photon identification considering EGammaPOG suggestions (EGammaPOG, 2020). For photon identification SFs to correct the MC samples with photons, EGammaPOG suggestions (EGammaPOG, 2023) were considered, and the resulting systematic uncertainty was implemented in the results.

Selection criterias for photons are:

$$\begin{aligned}
 p_T &> 80(GeV), \\
 medium_{ID}(cut - based) &\geq 1, \\
 |\eta| &< 2.5, \\
 ele_veto &= 1
 \end{aligned} \tag{5.3}$$

Photons are used for the $Z \rightarrow \nu\nu$ background estimations sourced from the $\gamma + jets$ events. Since this background might contribute to the missing transverse energy with undetected events, it has a crucial role in the analysis. This background estimation will be discussed in detail in subsequent sections.

Table 5.5. Identification criteria boosted hadronic objects and working points.

Object	p_T (GeV)	WP (particleNet)	2016/APV	2017	2018
W	≥ 200	PN WP2 (1%)	$> -/0.93$	> 0.94	> 0.94
Z	≥ 200	PN ZvsQCD >0.95	$> 0.93/0.93$	> 0.94	> 0.94
H ($m_H \in [90, 140]$)	≥ 450	PN (MD) LP WP	$> 0.97/0.97$	> 0.80	> 0.80
top	≥ 400	PN WP2 (1%)	$> 0.73/0.73$	> 0.91	> 0.97

Table 5.6. Identification criteria leptonic boosted and mass-tagged objects

Object	p_T	Mass	non-iso lepton	btagDeepB
lepTop	≥ 300	≥ 50	≥ 1 within $\Delta R < 0.8$	≤ 0.1522 (loose)
lepJet	≥ 300	≥ 50	≥ 1 within $\Delta R < 0.8$	> 0.1522 (loose)
m50 (mass-tagged)	≥ 200	≥ 50	—	—

5.5.5. Boosted Hadronic and Leptonic Objects

Boosted objects are particles produced in collisions that carry significant momentum in the direction of the beamline. These objects are characterized by their high transverse momenta. They are typically associated with the decay of heavy particles, such as the W and Z bosons, top quarks, and Higgs bosons.

Reconstruction of the hadronic boosted objects is carried out by the particleNet algorithm based on the deep neural network (DNN) technique (CMS Collaboration and others, 2020), which is well-suited for capturing complex patterns and correlations in high-dimensional data. The algorithm uses fat jets (i.e., AK8 jets) on the QCD MC training sample, with $p_T > 300$ GeV. In Table 5.5., selection criterias for boosted hadronic objects for working points (for each data-taking period) of ParticleNet (CMS Collaboration, 2024b) algorithm and p_T constraints are shown.

Boosted leptonic objects have additional requirements with the algorithm named bTagDeepB for leptonic-top (lepTop), (which refers to the leptonic decay of a top quark) and leptonic-jet (lepJet) (which refers to a jet decaying a lepton, typically from the decay of a heavy quark or tau lepton inside the jet) with loose identification. Table 5.6. shows the leptonic and mass-tagged object identification criteria for p_T constraints and btagDeepB algorithm selection (CMS Collaboration, 2024a) (for lepTop and lepJet).

Boosted hadronic SFs are produced centrally by the JetMET POG. The SF is calculated as the ratio of the tagging efficiency measured in data to that observed in MC simulations. These factors correct the MC simulation to match data, accounting for any discrepancies in the tagging process modeling and applied to all the search regions with hadronic boosted objects. To calculate the SFs, a fake region, similar to the pre-selection region given in the previous section, is defined with additional lepton and b-tagged jets vetoed objects criteria and hadronic trigger. Resulted in efficiency vs. p_T^{AK8} distribution for each boosted object, in the fake-rate region, applied to the search region and taken into

account as a systematic uncertainty. Figure 5.4. shows the SF efficiencies for the hadronic bosons (W or Z) in the AK8 momentum bins with different η regions, which allows having a more precise understanding of the SFs behavior for different geometry of the detector.

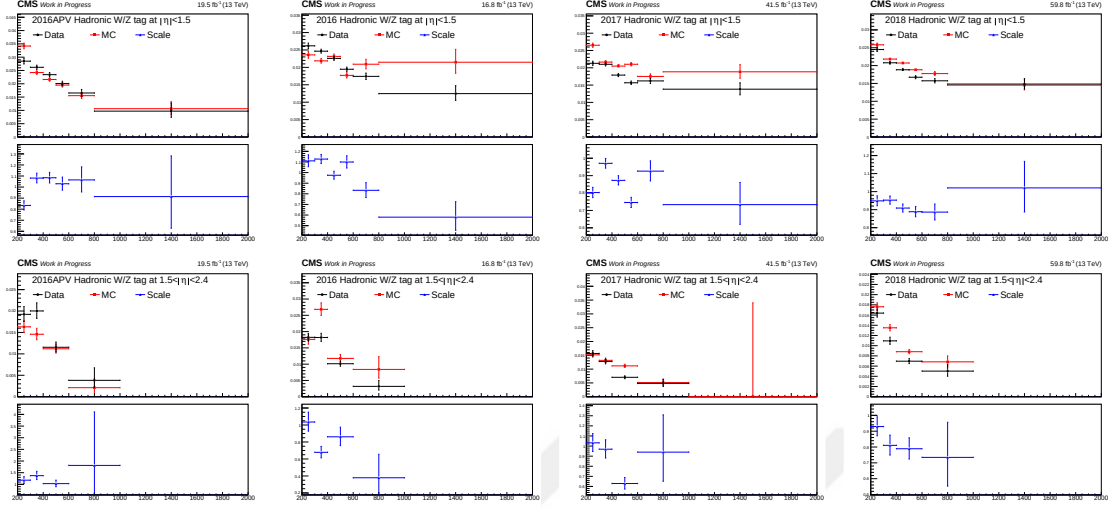


Figure 5.4. Hadronic boson SFs in fake object enriched CR, for AK8 momentum bins. The plots located in the upper row show hadronic fake rate SFs for barrel region (2016APV, 2016, 2017, and 2018, respectively). The plots located in the lower row show hadronic fake rate SFs for the endcap regions (2016APV, 2016, 2017, and 2018, respectively).

5.5.6. Search Regions

Search regions in this analysis are categorized by their various expected properties, and different SRs are designed to achieve specific purposes, such as estimating SM background and maximizing the SUSY signal sensitivity. Additionally, as discussed in the previous section, some search regions can be described for specific calculations, such as object tagging SF, or VRs, to check the sanity of the background estimations. As the primary goal of all SUSY searches, it is crucial to eliminate all the SM contamination from our signal events to maintain a good amount of signal sensitivity, so the definitions on the SRs with specific selections of the objects need to be designed to have an excess of signal events in high $M_R \times R^2$ bins. Following the analysis strategy, which is kinematically similar to SRs, there must be CRs to estimate the background contribution in the SRs, enriched events according to background processes. These CRs are defined by relaxing one or more selection variables and easing the criteria for boosted object selection and jet multiplicity (b-tagged, AK4, or AK8 jets). CFs, calculated from data/MC discrepancies on the CRs, are applied to SM background MC to correct the SRs distribution (see the next section for a detailed explanation). These CFs from various background processes are later considered systematic uncertainty sources. The validity of these CFs is verified in VRs that maintain a similar selection to the CRs, except for imposing stringent criteria on the boosted object selection. Closure tests are conducted in VRs to ensure the reliability of background estimates.

Pre-Selection Regions

As put earlier, in section 5.3.1, selection criteria are applied to all search regions. Due to the further classification of SRs and CRs that is used for discrimination of the signal and background events, there are additional baseline criteria for hadronic, isolated leptonic, and non-isolated leptonic regions, such as:

- **Hadronic** Additional lepton vetos are needed to have a fully hadronic region: at least one veto e, τ, μ .
- **Isolated Leptonic** Isolated leptons are reconstructed by the PF algorithm in which their energy sum is categorized in the defined cone size. For this class of SR, required isolated leptons, one medium ID isolated leptons and exclusion of the leptonic top or jets are selected.
- **Non-Isolated Leptonic** Non-isolated lepton can be defined as leptons originating from a hadronization or jet processes. For this region, at least one or more non-isolated leptons are required.

Figure 5.5. shows the distributions of the some variables used in the search region selection for various background MC and data with data/MC ratios for each variable bins.

The SRs

SRs are categorized based on their respective characteristics, including the presence of isolated leptons, jet multiplicity, b-tagged jets, vector bosons (V), boosted Higgs bosons (h), boosted top quarks (hTop), leptonic top quarks (lepTop), and leptonic jets (lepJet). SRs are defined to target specific event topologies that may indicate the presence of the signal processes. SRs are categorized further as hadronic (hadronic Higgs, hadronic vector boson), isolated leptonic (leptonic Higgs and leptonic vector boson), and non-isolated leptonic SRs to cover the inclusive nature of the analysis.

Table 5.7. gives the selection criteria for each SRs with additional requirements on SR categories such as hadronic, leptonic, and non-isolated leptonic. This table gives the additional criterion at the bottom of the table, which is imposed for the hadronic SRs to mitigate the presence of SM backgrounds further, particularly those arising from multijet QCD production. This criterion requires the angular separation between two megajets employed in calculating the razor kinematic variables.

In the leptonic regions, a strategy is adopted to amplify the signal in contrast to backgrounds originating from top or W decays in a leptonic manner. This strategy entails the imposition a transverse mass condition, necessitating that m_T exceeds 120 GeV.

For the non-isolated leptonic SRs, a refined approach is taken to distinguish between backgrounds arising from leptonic W/top processes and multijet events. This approach is realized through

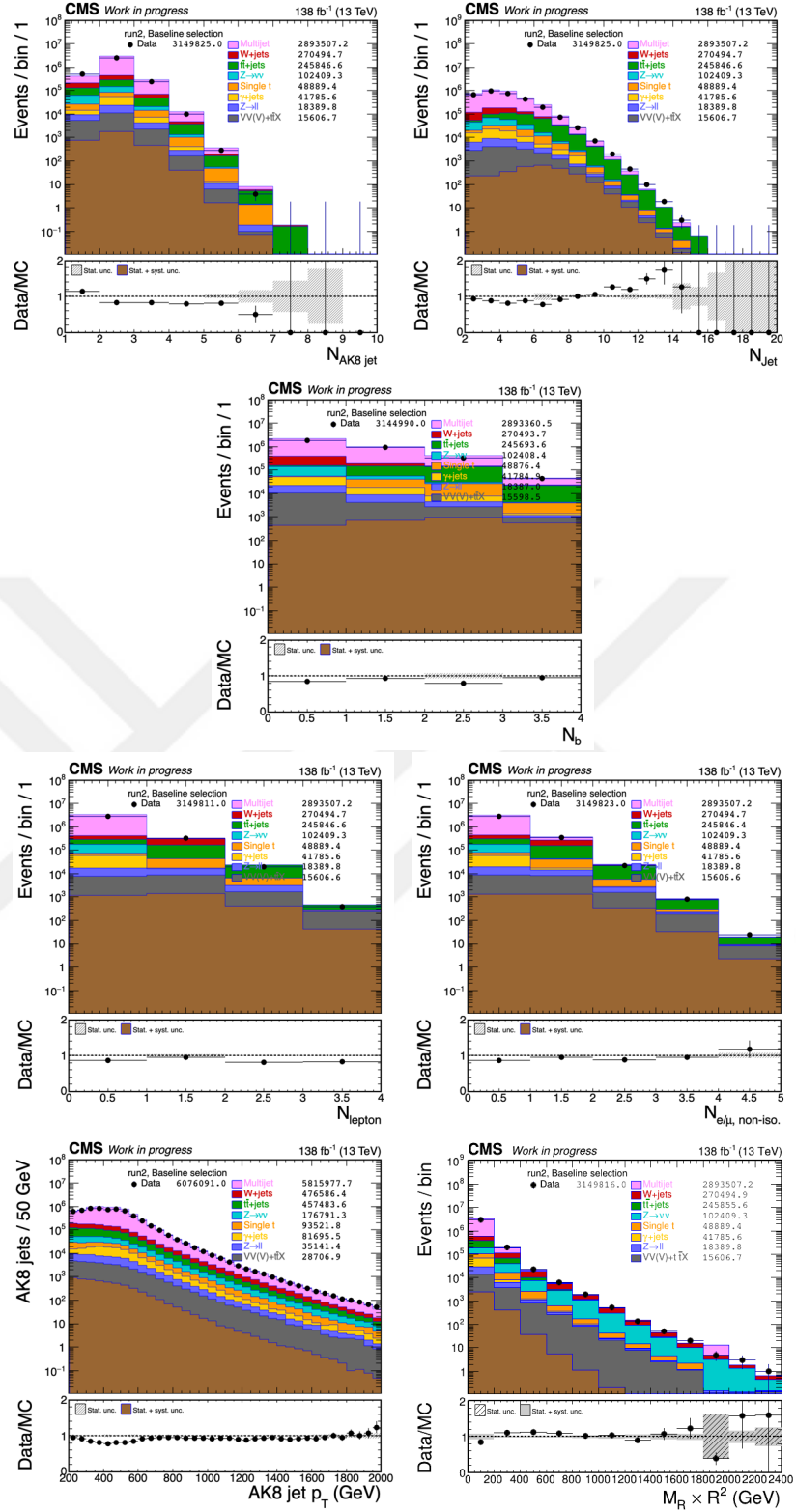


Figure 5.5. In pre-selection region, jet multiplicities for b-jet, AK4 and AK8, isolated and non-isolated lepton multiplicities, AK8 jet p_T and $M_R \times R^2$ distribution for full Run 2 in respective order top to bottom.

two distinct requirements: First, a transverse mass criterion is enforced, mandating that m_T surpasses 140 GeV. Second, a condition is placed on $\Delta\phi$, defined as the angle between the leading boosted jet and the W boson. The latter is identified as the leading non-isolated lepton accompanied by the missing transverse momentum (E_T^{miss}), ensuring $\Delta\phi$ is greater than 0.8.

Table 5.7. SRs selection criteria with constraints on objects variables and kinematics.

	Category	Isolep	jets	b	V	h	hTop	lepTop	lepJet
*	had H b 45j	0	4-5	≥ 1	--	≥ 1	--	0	0
	had H b 6j	0	≥ 6	≥ 1	--	≥ 1	--	0	0
	had HV b 6j	0	≥ 6	≥ 1	1	1	--	0	0
	had H 0b 34j	0	3-4	0	--	≥ 1	--	0	0
	had H 0b 5j	0	≥ 5	0	--	≥ 1	--	0	0
	had HV 0b 24j	0	2-4	0	≥ 1	≥ 1	--	0	0
	had HV 0b 5j	0	≥ 5	0	≥ 1	≥ 1	--	0	0
*	had 1hTop	0	≥ 5	--	--	0	1	0	0
	had 2hTop	0	≥ 2	--	--	0	≥ 2	0	0
	had V b 45j	0	4-5	≥ 1	≥ 1	0	0	0	0
	had V b 6j	0	≥ 6	≥ 1	≥ 1	0	0	0	0
	had 1V 0b 34j	0	3-4	0	1	0	0	0	0
	had 1V 0b 5j	0	≥ 5	0	1	0	0	0	0
	had 2V 0b 24j	0	2-4	0	≥ 2	0	0	0	0
	had 2V 0b 5j	0	≥ 5	0	≥ 2	0	0	0	0
**	lep 1hTop	1	≥ 3	--	--	0	1	0	0
	lep V b	1	≥ 4	≥ 1	≥ 1	0	0	0	0
	lep V 0b	1	≥ 2	0	≥ 1	0	0	0	0
**	lep H b 3j	1	≥ 3	≥ 1	--	≥ 1	--	0	0
	lep H 0b 2j	1	≥ 2	0	--	≥ 1	--	0	0
***	lepTop 0hTop	--	≥ 3	--	--	--	0	≥ 1	0
	lepTop hTop	--	≥ 3	--	--	--	≥ 1	≥ 1	0
	lepJet 0V 24j	--	2-4	--	0	--	0	0	≥ 1
	lepJet 0V 5j	--	≥ 5	--	0	--	0	0	≥ 1
	lepJet 1V 24j	--	2-4	--	1	--	0	0	≥ 1
Additional * : $\Delta\phi_R < 2.8$ ** : $m_T > 120$ *** : $m_T > 140, \Delta\phi > 0.8$									

The CRs

The CRs are defined subsets of the events used in our analysis to estimate the contributions from different background processes. These regions are designed to be enriched in specific background components while minimizing the contamination from signal events. The selection criteria for these CRs are summarized in Table 5.8., where each CR is categorized by its related background process.

Table 5.8. presents the various CRs and their associated background processes and selection criteria. Each CR is identified by a unique label, such as Q1, T2, G', and more. The corresponding background processes are specified, including QCD, Top, W, and Zinv as dominant background sources.

The selection criteria for each CR are outlined in terms of specific variables. These variables include the number of AK8 jets ($AK8_{m50}$), non-isolated leptons (ℓ_{niso}), b-tagged loose jets (b_l), b-tagged medium jets (b_m), veto leptons (ℓ_{veto}), selected leptons (ℓ_{sel}), photons (γ), azimuthal angle separation ($d\phi$), azimuthal angle separation in a star-based coordinate system ($d\phi^*$), and transverse mass (m_T).

As discussed earlier, each CR is defined slightly differently from the corresponding SR, which is used to estimate the background and calculate the CF to adjust the SRs. QCD-enriched CRs (Q1 and Q2) were used for hadronic, leptonic, and non-isolated leptonic regions. For the top-enriched CR category, we have three different CRs, where T1 and T2 are used for correction on hadronic and leptonic SRs, while Tnl is used only for non-isolated leptonic SRs. As top CRs, W-enriched CRs (W1 and W2) are used for hadronic and leptonic SRs, while Wnl is used only for non-isolated SRs.

Table 5.8. CRs selection categorized by their related background processes.

	CR	BG	$AK8_{m50}$	ℓ_{niso}	b_l	b_m	ℓ_{veto}	ℓ_{sel}	γ	$d\phi$	$d\phi^*$	m_T
1	Q1	QCD	1	--	0	--	0	--	--	≥ 2.8	--	--
2	Q2	QCD	≥ 2	--	0	--	0	--	--	≥ 2.8	--	--
3	T1	Top	1	--	--	≥ 1	--	1	0	< 2.8	--	< 120
4	T2	Top	≥ 2	--	--	≥ 1	--	1	0	< 2.8	--	< 120
5	Tnl	Top	≥ 1	≥ 1	--	≥ 1	--	--	0	--	< 0.8	< 140
6	W1	W	1	--	0	--	--	1	0	< 2.8	--	30-100
7	W2	W	≥ 2	--	0	--	--	1	0	< 2.8	--	30-100
8	Wnl	W	≥ 2	≥ 1	0	--	--	--	0	--	< 0.8	< 140
9	G'	Zinv	≥ 1	--	--	--	0	--	≥ 1	< 2.8	--	--
10	DY'''	Zinv	≥ 1	--	0	--	--	2,OS	0	--	< 2.8	--
11	W4Z1''	Zinv	1	--	0	--	1	--	0	< 2.8	--	30-100
12	W4Z2''	Zinv	≥ 2	--	0	--	1	--	0	< 2.8	--	30-100
13	T4Z1''	Zinv	1	--	--	≥ 1	1	--	0	< 2.8	--	< 120
14	T4Z2''	Zinv	≥ 2	--	--	≥ 1	1	--	0	< 2.8	--	< 120

5.6. Background Estimation Strategy and CFs

Accurately estimating the SM backgrounds is crucial to ensure the validity and sensitivity of our SRs in the analysis. A comprehensive methodology that employs CRs to estimate and correct the backgrounds that could mimic or interfere with our signal processes was designed. The dominant SM backgrounds are W+jets, top related backgrounds (tt+jets), QCD (multijets), and $Z \rightarrow \nu\nu$. Additionally, lost leptons originating from W bosons or top quarks leptonic decay are considered as the source of background, which might be reconstructed as missing energy by the detector.

5.6.1. BG Estimation Strategy

The BG estimation strategy revolves around extrapolating the knowledge from the CRs to the SRs. We determine data-to-MC CFs that quantify the discrepancies between data and MC simulations in the CRs. Subsequently, these factors were employed to correct the background predictions in the SRs. For dominant background processes, an MC-assisted data-driven background estimation was held.

The data-to-MC CFs are derived by comparing data and simulation yields in the CRs. A series of CFs are iteratively computed for each distinct background across varying event variables, favoring an iterative paradigm over multi-dimensional calculations for reduced statistical uncertainties. The iterative process involves applying obtained CFs to the CR in each step before evaluating the next CF for subsequent variables. Across all scenarios of background estimation, CFs are initially determined concerning $M_R \times R^2$, followed by AK4 jet count, and as a particular case, for $Z \rightarrow \nu\nu$ background estimation, a mass-tagged jet (which is identified as AK8 jet with mass greater than 50 GeV) multiplicity is used as a final step to compute the CFs. Once we have obtained the data-to-MC CFs, we apply them to the MC background distribution in the SRs. This scaling process adjusts the expected backgrounds to match the observed data, based on the differences identified in the CRs. Minor backgrounds, which contribute only at the percentile level, are predicted using direct MC counts. While the overall strategy is consistent, there are nuances in background prediction for SRs due to variations in the preselection groups.

5.6.2. BG Estimation for $Z \rightarrow \nu\nu$ Process

$Z \rightarrow \nu\nu$ process can be mimicked by eighter γ +jets or Drell-Yann (DY) events. Therefore, instead of defining a CR dedicated to $Z \rightarrow \nu\nu$ background to compute the CF, separate CRs need to be defined for the background estimation. In Table 5.8, CRs for $Z \rightarrow \nu\nu$ background estimation were denoted as G (gamma enriched region) and DY. Additionally, supplementary CRs enriched with W events featuring single leptons contribute to a second set of CFs, aiding cross-validation efforts and quantifying systematic uncertainties.

The main selection procedure for the G region is to have zero lepton, at least one mass-tagged AK8 jet, and at least one prompt photon. Figure 5.6. shows the $M_R \times R^2$ distributions for each data-taking period in G CR. Specific to the G region, razor kinematic variables are redefined such that photons are removed from megajets, used for the M_R definition, and added to the missing transverse energy. The modified E_T and megajet definitions are employed to define particular razor kinematic variables. So, additional $M_R > 800$ and $R^2 < 0.08$ constraints are applied to mimic the missing photons'

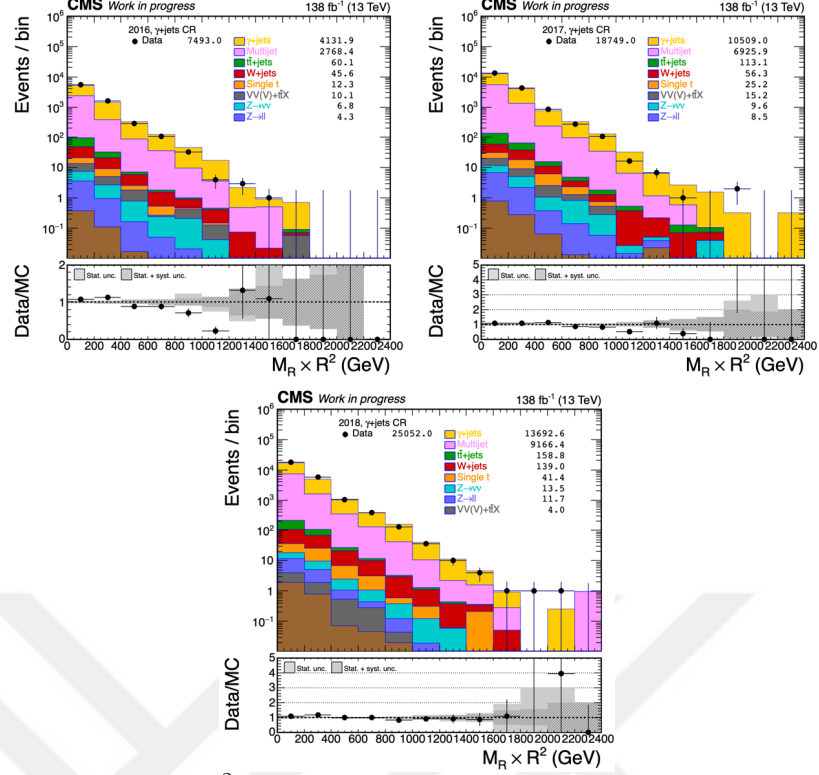


Figure 5.6. $M_R \times R^2$ distribution in G region for each data-taking period.

kinematics in the $Z \rightarrow \nu\nu$ process.

The primary contributor to the G region, alongside γ +jets, is the QCD multijet process wherein a jet is mistakenly identified as a photon. The γ +jets events contain a combination of direct photons and fragmentation photons. A data-driven assessment of photon purity is undertaken to mitigate the reliance on simulation for subtracting the multijet (or QCD) background. This involves scaling the data in the G region using the purity factor, thereby eliminating the multijet background originating from fake and fragmentation photons. Photons identified mistakenly from QCD events are labeled as "fake," which is taken from data directly with inverting $\sigma_{i\eta i\eta}$. Mass-tagged jets and photon multiplicity constraints in the G region are excluded for calculating the fake photon events. Photons within the MC events in the G region are called "prompt" photons with the same exclusion procedure as fake photons in the G region. Data in G regions are scaled with purity to remove the multijet background from γ +jets events. Table 5.9. gives all the details to calculate the purity over template fit over target photons. On this table, $\sigma_{i\eta i\eta}$ measures the spread of the particle shower in the pseudorapidity η dimension across the ECAL regions (barrel and endcap), and $pfRelIso3chg$ ensures that the candidate lepton is not part of a jet or produced in a dense environment of other particles, which could imply a different origin (such as decay from a b-quark).

So the purity can be defined as:

Table 5.9. Photon from $\gamma + jets$ to calculate purity.

Photon	Source	G Region	$\sigma_{\eta\eta}$ (EB/EE)	pfRelIso03_chg (EB/EE)
fake	Data	<i>excl_1Pho_1M</i>	$> 0.01015/0.0272$	$< 1.141/1.051$
prompt	MC	<i>excl_1Pho_1M</i>	$> 0.01015/0.0272$	$< 1.141/1.051$
target fit	MC	<i>excl_1Pho</i>	$> 0.01015/0.0272$	$< 1.141/1.051$

$$p_\gamma = \frac{prompt + fake}{prompt} \quad (5.4)$$

Purity calculation from the G region for $\gamma + jets$ background is calculated iteratively in the bins of $M_R \times R^2$, n_{jet} , and mass-tagged jets, respectively, for endcap and barrel region separately. Then CFs are derived as follows:

$$C_\gamma = \frac{N_G^{data} \times p_\gamma \times f}{N_G^{MC}} \quad (5.5)$$

Here N_G^{data} and N_G^{MC} are the event counts from data and MC in the G region, respectively, and f is the fragmentation photons from gen-level photons. To calculate the photon purity, a template fit method was used based on the ROOT class for fraction fitting (ROOT, 2011), on the bins of $M_R \times R^2$, AK4 jet multiplicity, and mass-tagged AK8 jet multiplicity iteratively. For the $M_R \times R^2$, the binning strategy is to enlarge the last bin to improve statistical values and get more precise purity values. The jet multiplicity is binned based on the number of jets per event. The broader bins in jet multiplicity help mitigate low statistics while still providing a reasonable estimate of purity. Mass-tagged AK8 jets correspond to boosted, large-radius jets often used to identify heavy particles such as top quarks or W/Z bosons. PF relative isolation with cone size $R = 0.3$ photon distribution ($pfRelIso03_chg \times p_T^\gamma$) is used for the template fit. This process is performed for different data-taking periods of Run-2 and regions of the detector (endcap and barrel).

Figure 5.7., 5.9., 5.11. shows the template fit distributions for purity calculation in bins of $M_R \times R^2$, figure 5.13., 5.15., 5.17. shows n_{AK4} and figure 5.19., 5.21., 5.23. shows the template fit distribution in bins of $n_{AK8_{m50}}$ for each data-taking period respectively. Figure 5.8., 5.10., 5.12. shows the purity and CFs on bins of $M_R \times R^2$ for each data-taking period, figure 5.14., 5.16., 5.18. shows the same distribution for the bins of n_{AK4} and figure 5.20., 5.22., 5.24. shows the purity and CFs in bins of mass-tagged AK8 jets. Each template fit distribution is in agreement with the data overall. This is evidenced by the consistency between the data points and the fitted curves, reflecting the reliability

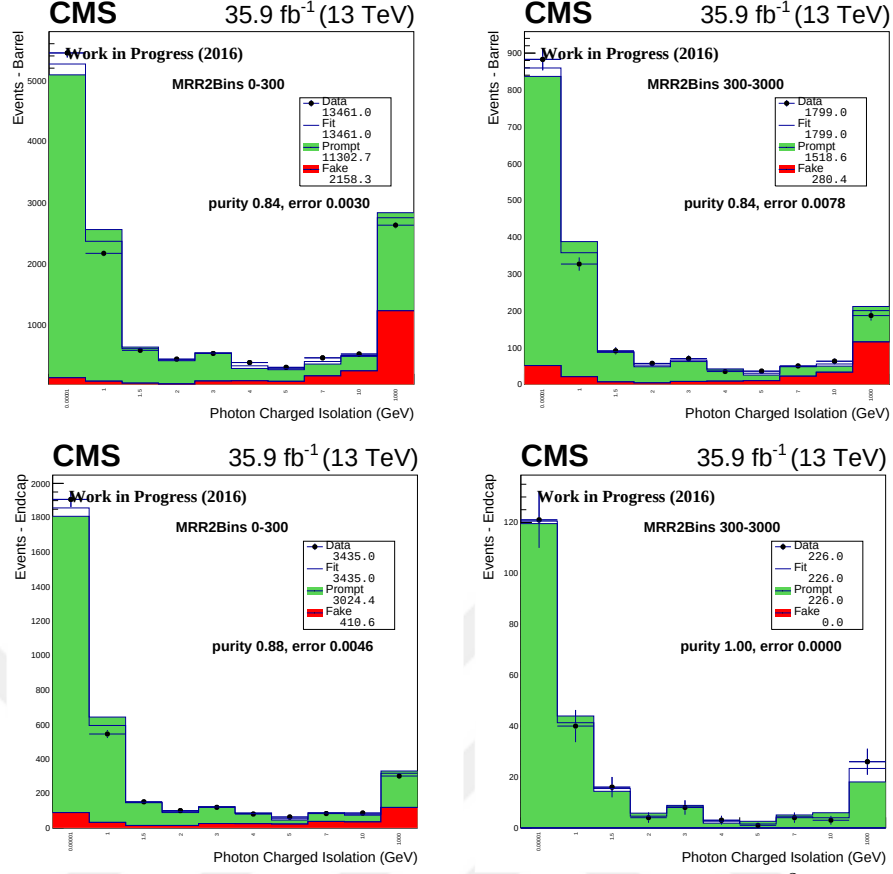


Figure 5.7. Template fit, fake and prompt photon distribution in bins of $M_R \times R^2$ for data-taking period 2016, for $(pfrelIso.p_T^\gamma)$ on the x and event counts on the y -axis. Upper row shows the barrel region results and lower row shows the endcap region results.

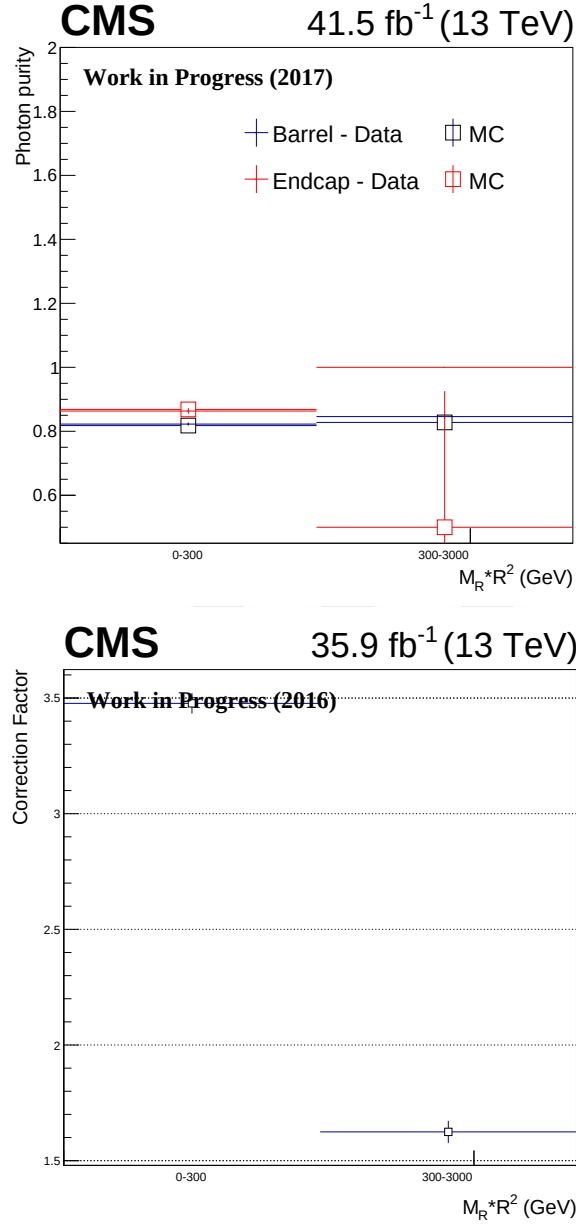


Figure 5.8. Resulting plots show the purity and CF for the 2016 data-taking period. The upper plot shows the purity values for the bins of $M_R \times R^2$ for data and MC comparison. The lower plot shows the CF distribution for the bins of $M_R \times R^2$.

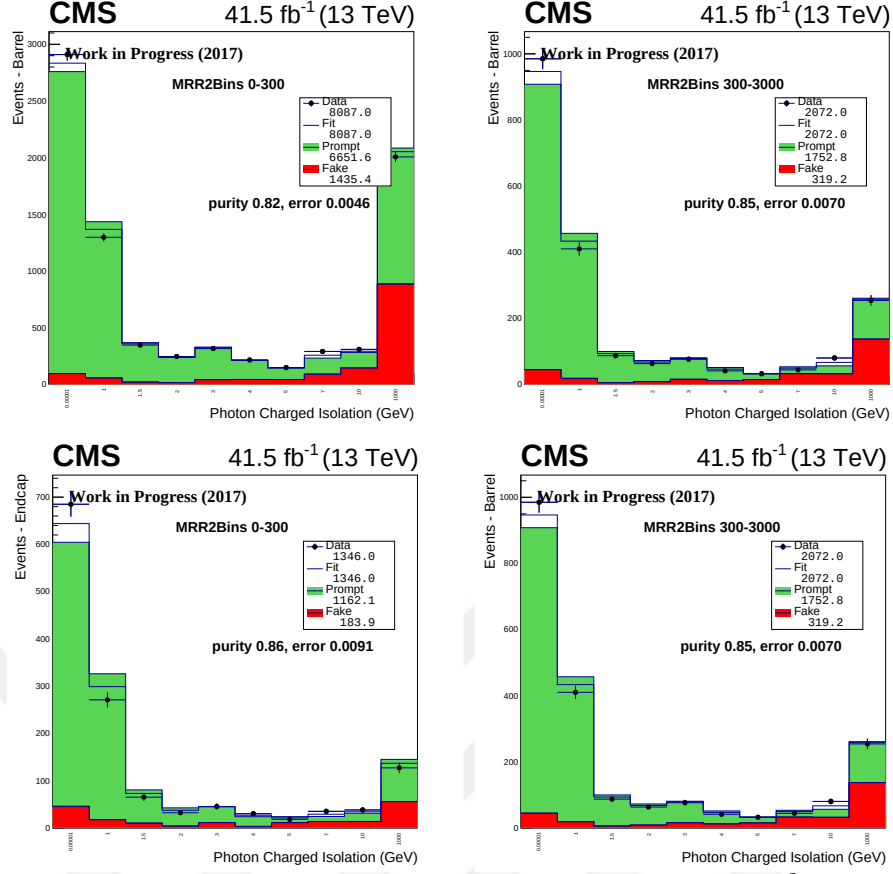


Figure 5.9. Template fit, fake and prompt photon distribution in bins of $M_R \times R^2$ for data-taking period 2017, for $(pfrelIso, p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.

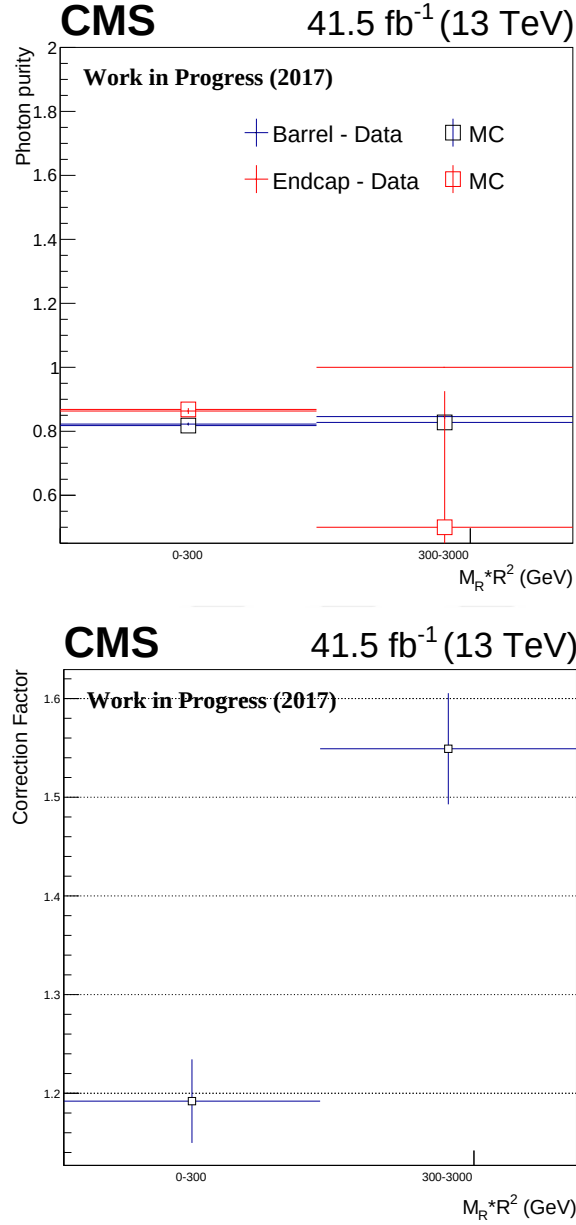


Figure 5.10. Resulting plots show the purity and CF for the 2017 data-taking period. The upper plot shows the purity values for the bins of $M_R \times R^2$ for data and MC comparison. The lower plot shows the CF distribution for the bins of $M_R \times R^2$.

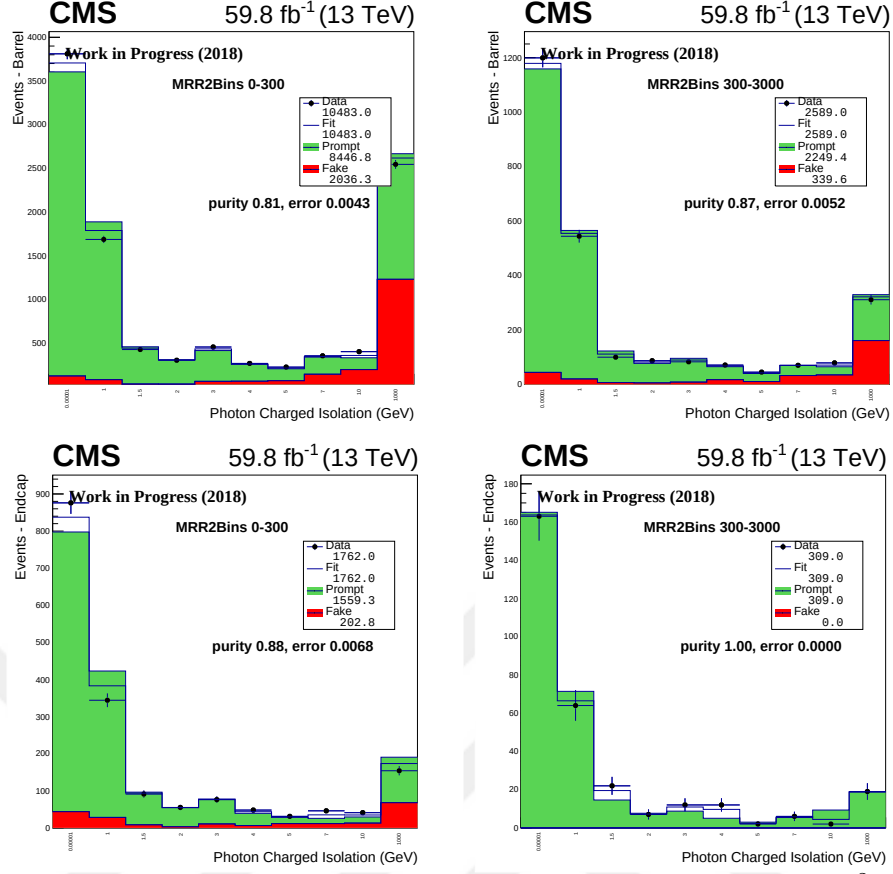


Figure 5.11. Template fit, fake and prompt photon distribution in bins of $M_R \times R^2$ for data-taking period 2018, for $(pfrelIso, p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.

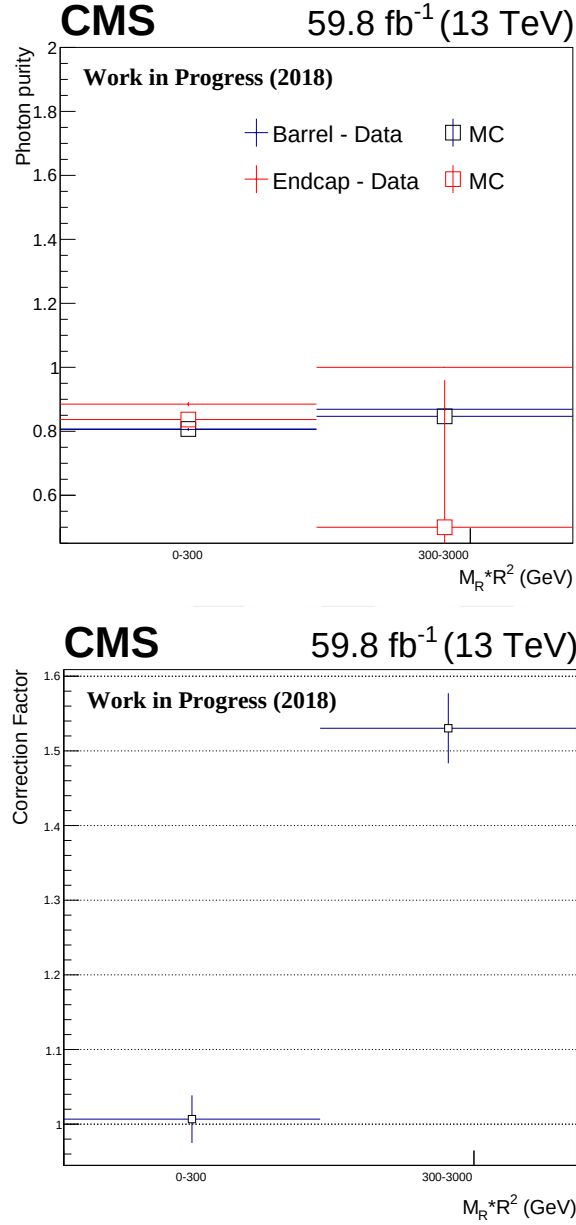


Figure 5.12. Resulting plots show the purity and CF for the 2018 data-taking period. The upper plot shows the purity values for the bins of $M_R \times R^2$ for data and MC comparison. The lower plot shows the CF distribution for the bins of $M_R \times R^2$.

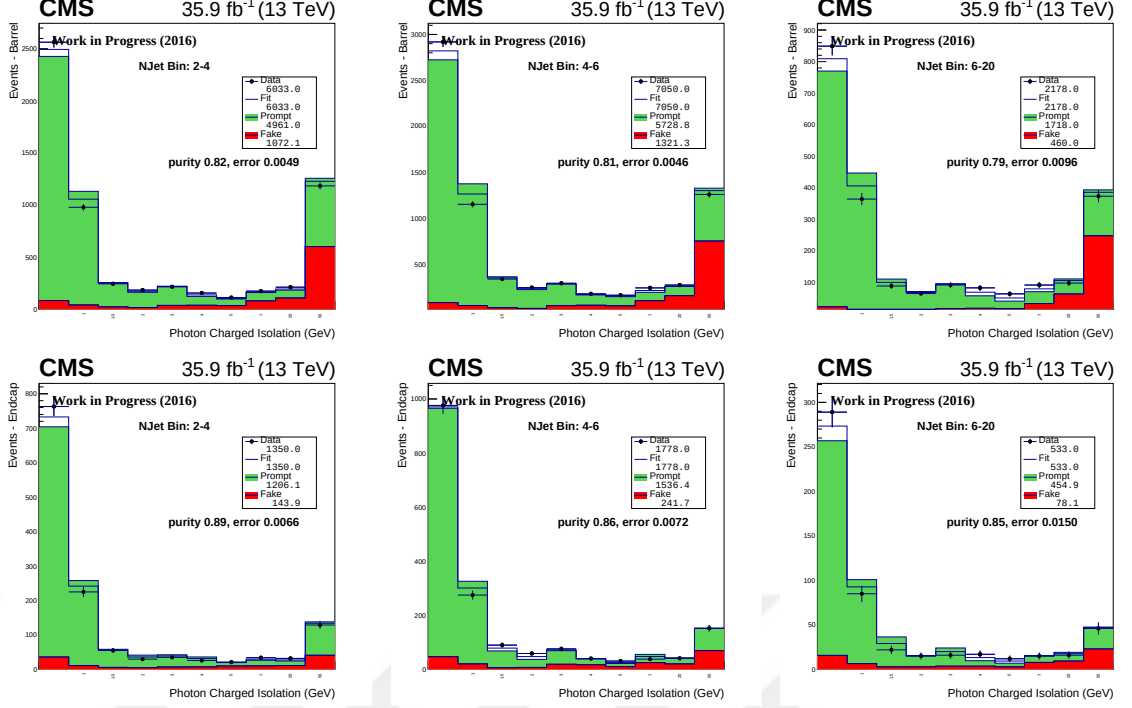


Figure 5.13. Template fit, fake and prompt photon distribution in bins of n_{AK4} (jet multiplicity) for data-taking period 2016, for $(pfrelIso, p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.

of the modeling approach. It also gives a reasonable amount of photon purity and purity error values (located on the plots under the legends with the number of entries included for each Data, Fit values, and Prompt and Fake photon event counts).

Subsequently, $Z \rightarrow ll$ CR (DY) is employed to refine the CF of $Z \rightarrow \nu\nu$ background. The DY CR, detailed in Table 5.8., mandates the presence of 2 opposite-charge, same-flavor leptons whose invariant mass falls within a 10 GeV window around the Z boson mass. In the case of electron-positron pair, any extra veto muons are excluded, while for $\mu^+ - \mu^-$ events, additional veto electrons are disregarded. The momentum of the dilepton system is incorporated into E_{miss}^T , which, in turn, is employed to modify the M_R and R^2 variables computation. Furthermore, zero loosely b-tagged jets are required to eliminate the top backgrounds effectively.

To complete the $Z \rightarrow \nu\nu$ background estimation, dilepton CR is used to compute the double-ratio as a factor. It is basically a ratio between data and MC in the CRs of G and DY :

$$R_\gamma^{ll} = \left| \frac{N_{data}^{DY}}{N_{MC}^{DY}} \right| \times \left| \frac{N_{MC}^G}{N_{data}^G} \right| \quad (5.6)$$

This double ratio is computed for each data-taking period, which is:

- **2016:** 0.531 ± 0.0158
- **2017:** 0.850 ± 0.0240

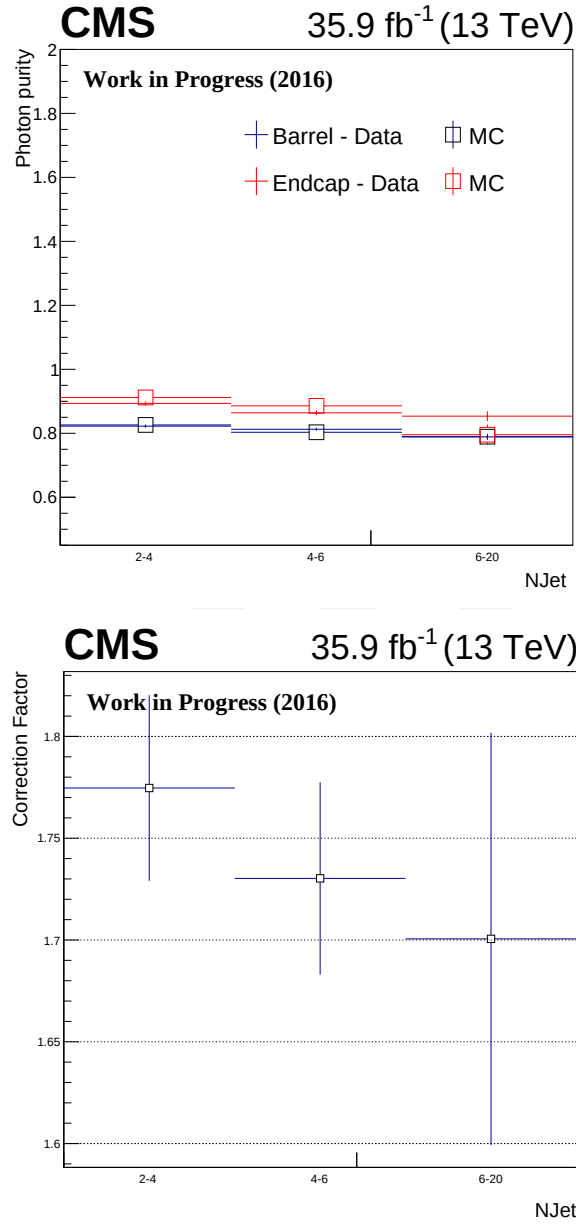


Figure 5.14. Resulting plots show the purity and CF for the 2016 data-taking period. The upper plot shows the purity values for the bins of n_{AK4} for data and MC comparison, and the lower plot shows the CF distribution.

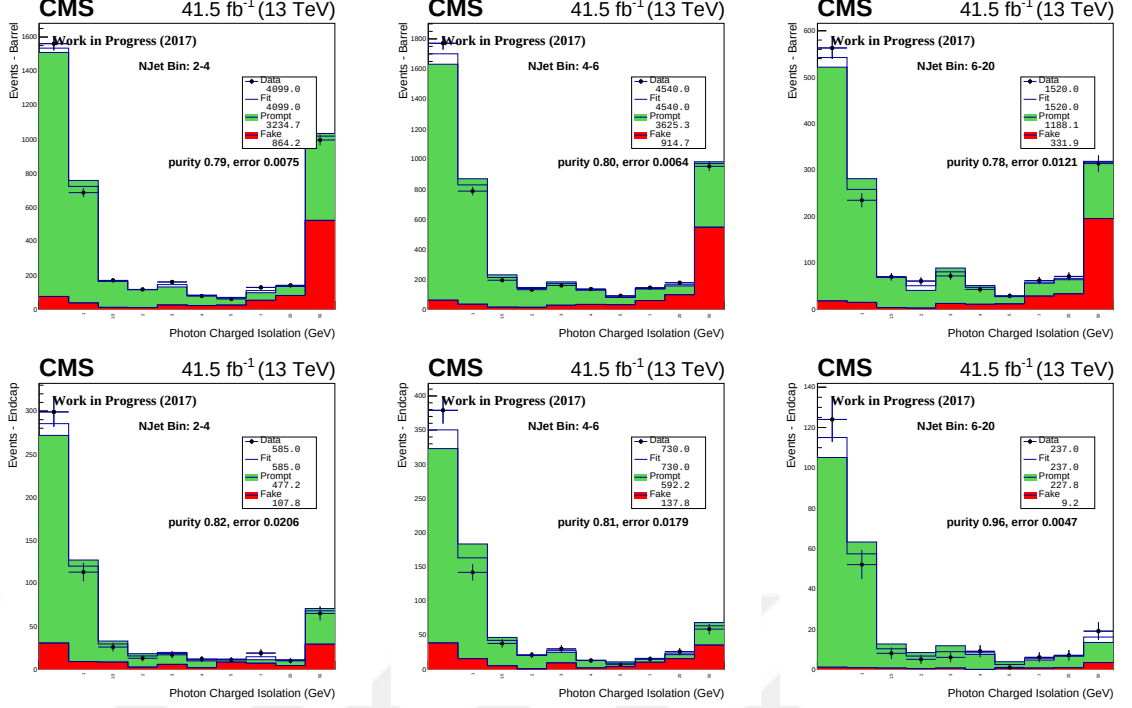


Figure 5.15. Template fit, fake and prompt photon distribution in bins of n_{AK4} (jet multiplicity) for data-taking period 2017, for $(p_{frelIso}, p_T^\gamma)$ on the x-axis and event counts on the y-axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.

- **2018:** 0.487 ± 0.0128

The resulting CFs calculated for $Z \rightarrow \nu\nu$ are applied to correct the SRs and calculated as systematic uncertainty.

5.6.3. Validation Regions to Check Background Estimation

CFs undergo validation by being applied across various VRs that serve varying purposes. Table 5.10. provides an overview of all VRs, including their selection criteria and contextual validation purpose. The selection criteria are based on variables such as $AK8_{m50}$ (number of mass-tagged AK8 jets for the mass higher than 50 GeV); number of bosons, hadronic top quarks, Higgs boson, non-isolated leptons, vetoed leptons, number of gamma and azimuthal angle ($\Delta\phi$). For some regions, additional selections are needed, such as m_T and M_{T2}

The initial collection of VRs is employed to ascertain the credibility of CFs when dealing with identified boosted objects. The CRs, utilized to derive CFs, do not impose explicit criteria regarding boosted object multiplicity. Instead, they mandate the presence of AK8 jets with a mass exceeding 50 GeV. The constraint is in place to ensure sufficient statistical viability.

A subsequent batch of VRs is harnessed to validate CFs under diverse kinematic circumstances. By mimicking a selection to CRs and subsequently reversing specific selection criteria, these VRs sim-

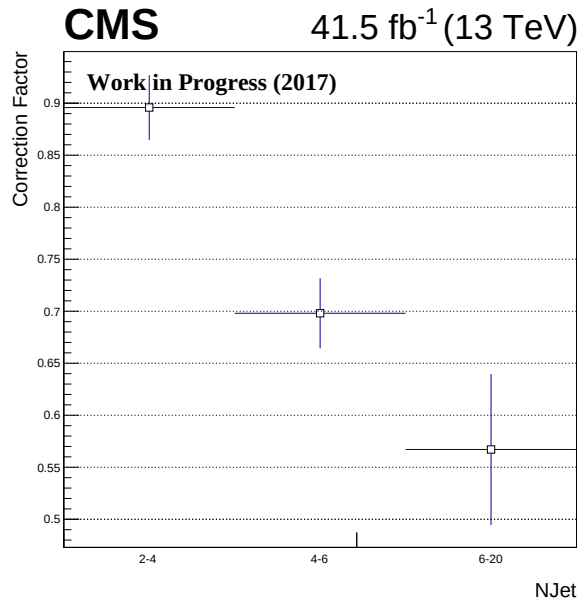
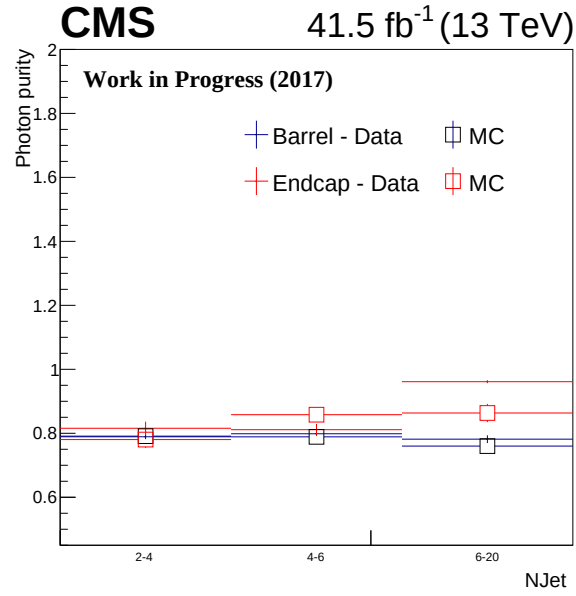


Figure 5.16. Resulting plots show the purity and CF for the 2017 data-taking period. The upper plot shows the purity values for the bins of n_{AK4} for data and MC comparison, and the lower plot shows the CF distribution.

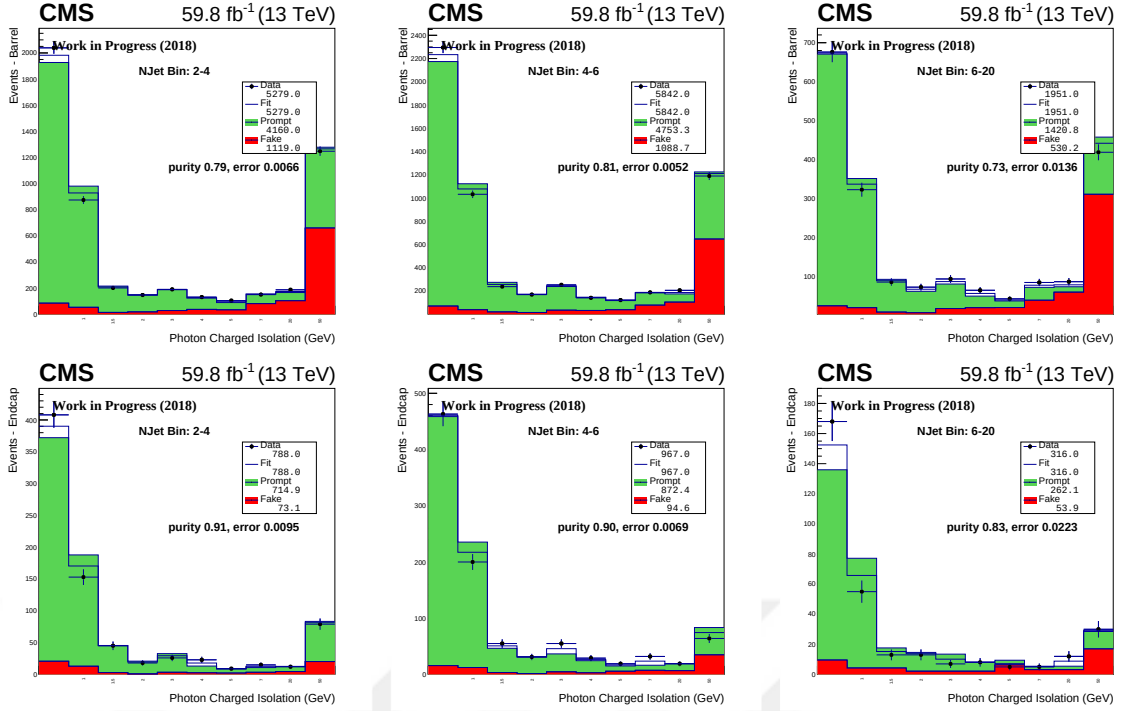


Figure 5.17. Template fit, fake and prompt photon distribution in bins of n_{AK4} (jet multiplicity) for data-taking period 2018, for $(pfrelIso, p_T^\gamma)$ on the x-axis and event counts on the y-axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.

Table 5.10. VRs for the CFs used in background estimation.

	VR	AK8 _{m50}	V	hTop	H	ℓ_{niso}	b_l	b_m	ℓ_{veto}	γ	$\Delta\phi$
Validate had and lep SR BG estimate											
	QV	–	≥ 1	–	–	0	0	–	0	0	≥ 2.8
	Qtop	–	–	≥ 1	–	0	0	–	0	0	≥ 2.8
	QH	–	–	–	≥ 1	0	0	–	0	0	≥ 2.8
*	TV	–	≥ 1	–	–	0	–	≥ 1	1	0	< 2.8
	Ttop	–	–	≥ 1	–	0	–	≥ 1	1	0	< 2.8
	TH	–	–	–	≥ 1	0	–	≥ 1	1	0	< 2.8
**	WV	–	≥ 1	–	–	0	0	–	1	0	< 2.8
	Wtop	–	–	≥ 1	–	0	0	–	1	0	< 2.8
	WH	–	–	–	≥ 1	0	0	–	1	0	< 2.8
Validate had and lep SR BG estimate											
	S'	≥ 1	–	–	–	0	0	–	0	0	≥ 2.8
	Q'	≥ 1	–	–	–	0	0	–	0	0	< 2.8
Validate the Top CF for dilepton backgrounds											
***	Tll	≥ 1	–	–	–	–	–	≥ 1	2	0	< 2.8
Validate noniso lep SR BG estimate											
****	low $d\phi^*$	≥ 1	–	–	–	≥ 1	–	–	–	0	–
	low M_T	≥ 1	–	–	–	≥ 1	–	–	–	0	–
Extra Selections:											
* : $m_T < 120$											
** : $m_T \in [30, 100]$											
*** : $M_{T2} < 200$											
**** : $M_{T2} < 140, \Delta\phi^* > 0.8$											

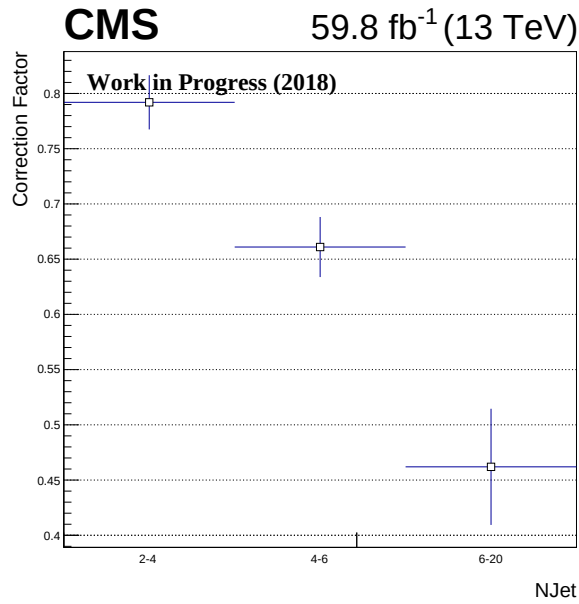
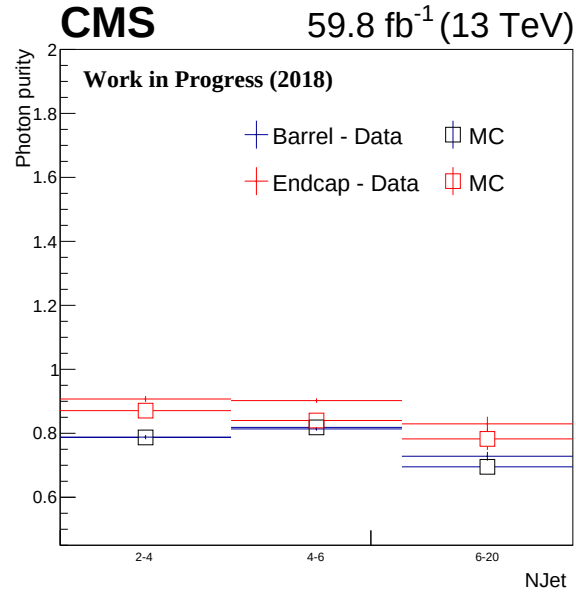


Figure 5.18. Resulting plots show the purity and CF for the 2018 data-taking period. The upper plot shows the purity values for the bins of n_{AK4} for data and MC comparison, and the lower plot shows the CF distribution.

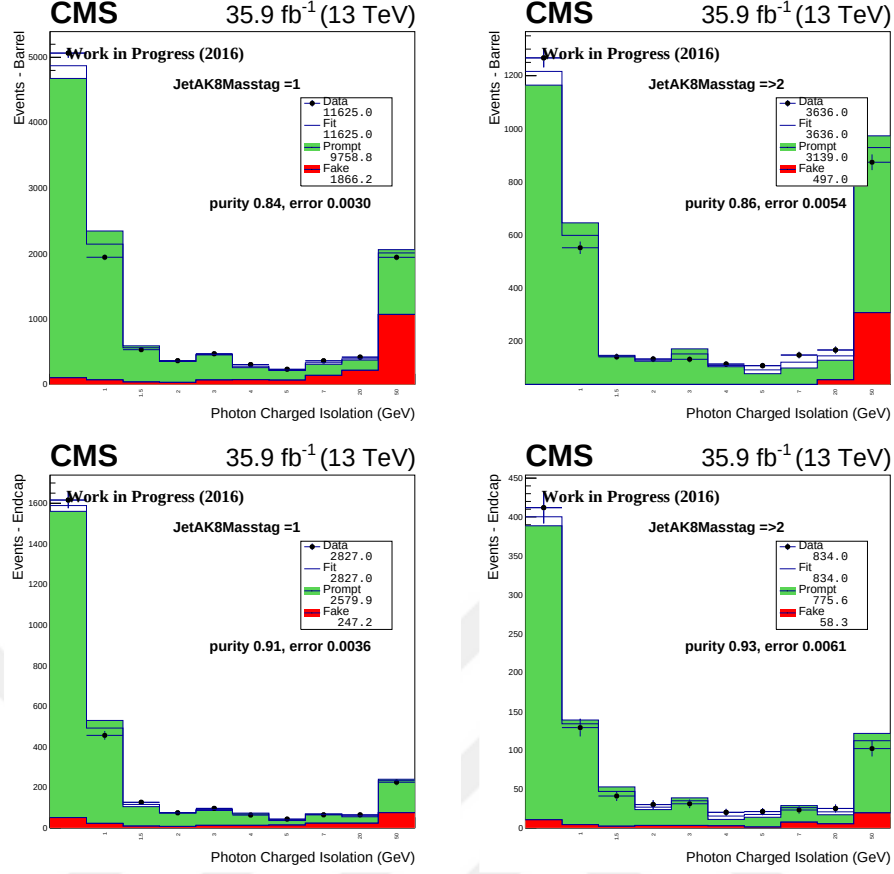


Figure 5.19. Template fit, fake and prompt photon distribution in bins of n_{AK8m50} (jet multiplicity) for data-taking period 2016, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.

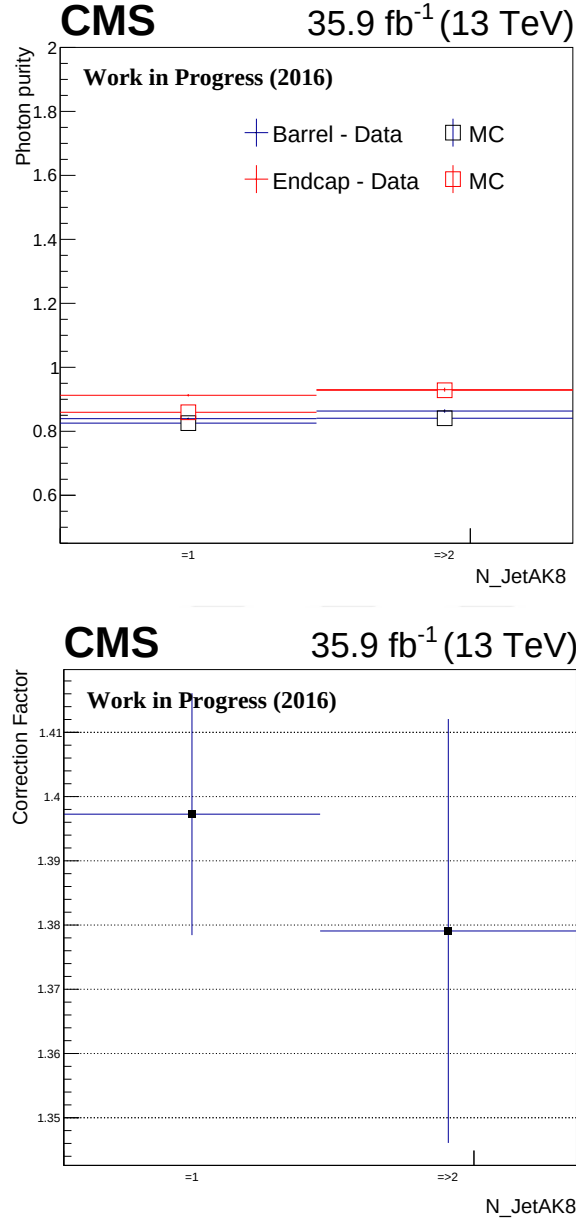


Figure 5.20. Resulting plots show the purity and CF for the 2016 data-taking period. The upper plot shows the purity values for the bins of $n_{AK8_{m50}}$ for data and MC comparison, and the lower plot shows the CF distribution.

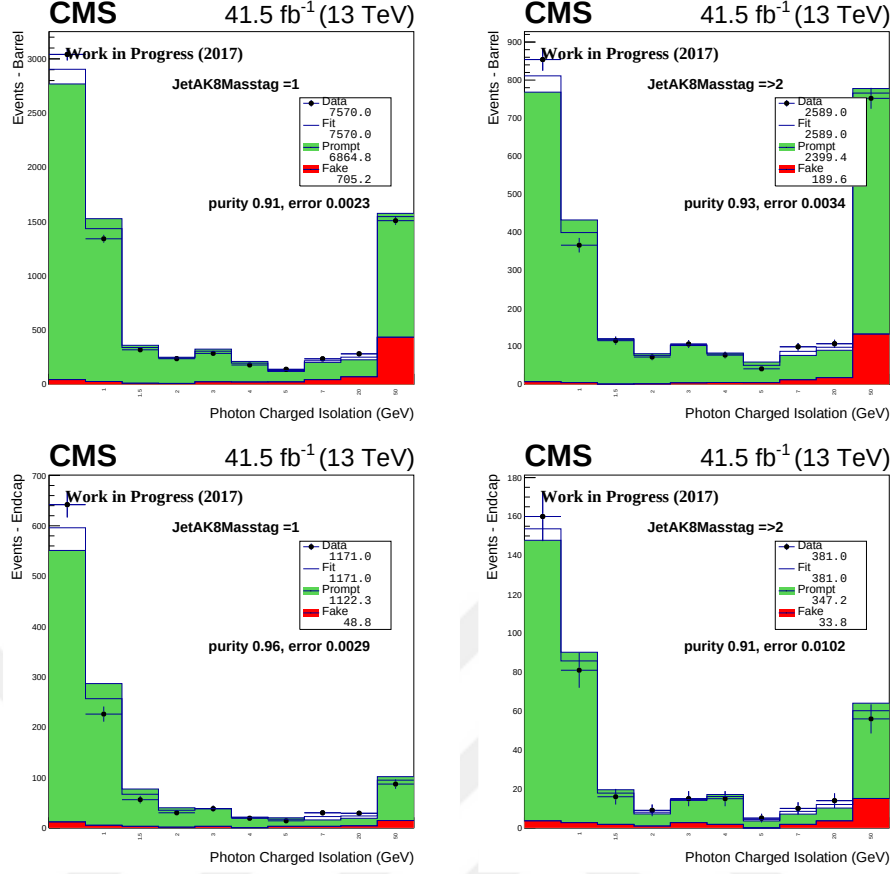


Figure 5.21. Template fit, fake and prompt photon distribution in bins of n_{AK8m50} (jet multiplicity) for data-taking period 2017, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.

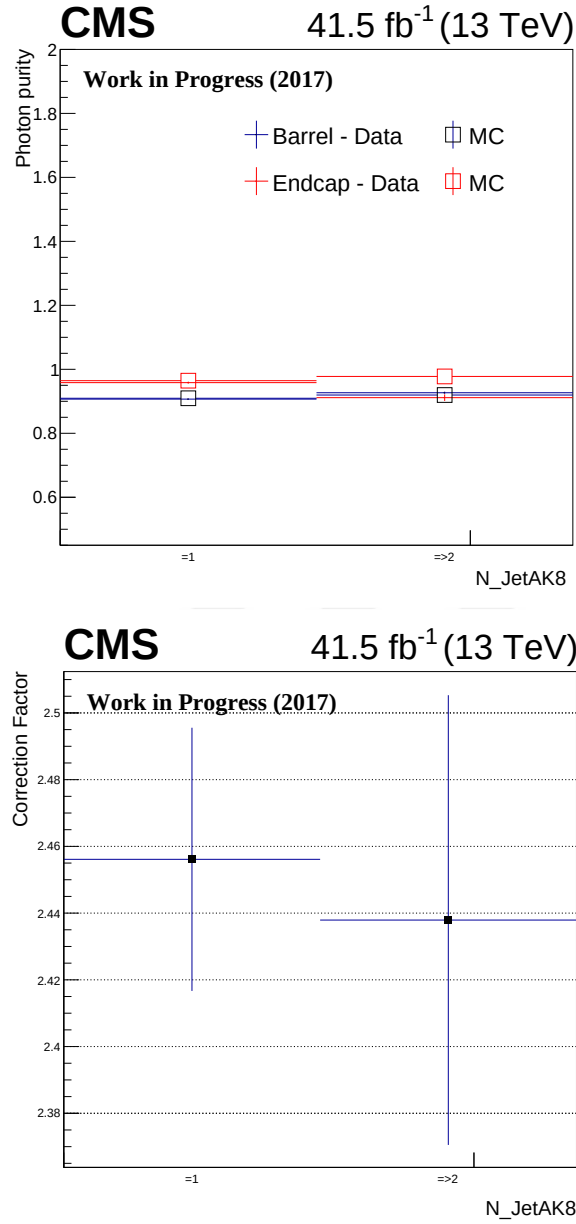


Figure 5.22. Resulting plots show the purity and CF for the 2017 data-taking period. The upper plot shows the purity values for the bins of $n_{AK8_{m50}}$ for data and MC comparison, and the lower plot shows the CF distribution.

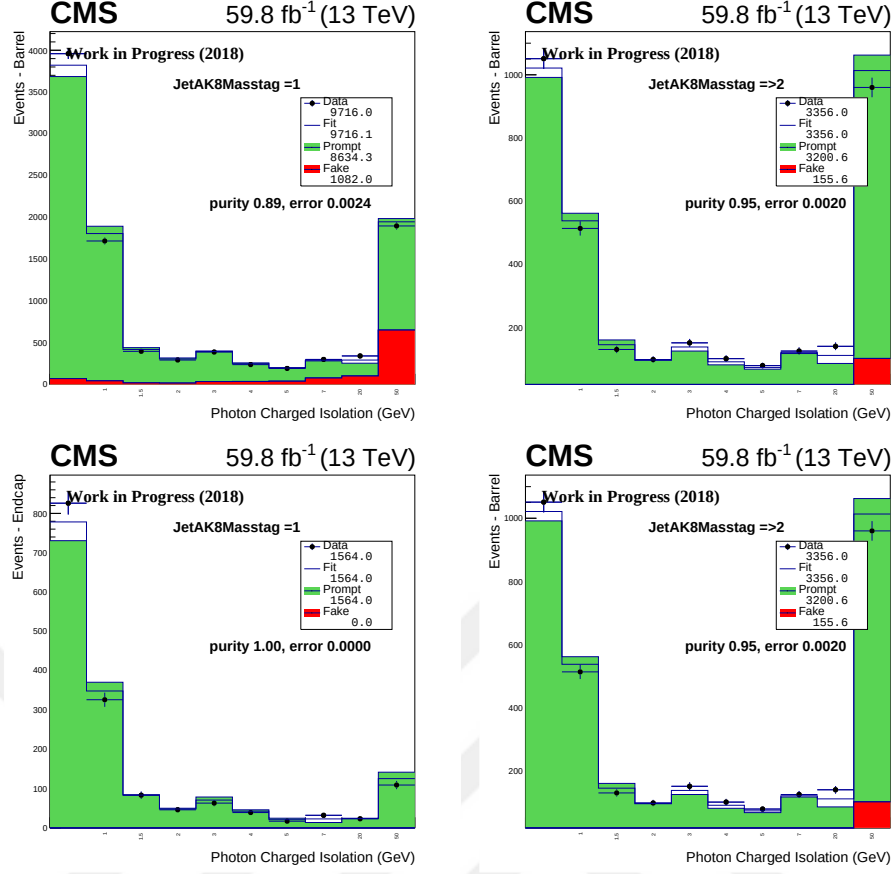


Figure 5.23. Template fit, fake and prompt photon distribution in bins of n_{AK8m50} (jet multiplicity) for data-taking period 2018, for $(pfrelIso.p_T^\gamma)$ on the x -axis and event counts on the y -axis. The upper row shows the barrel region results, and the lower row shows the endcap region results.

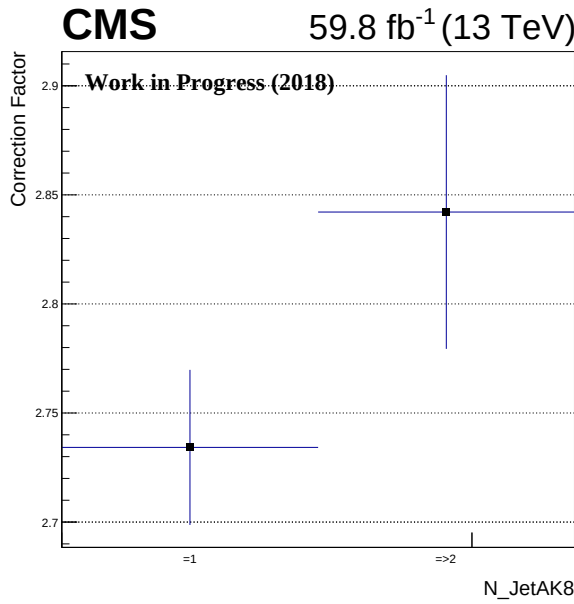
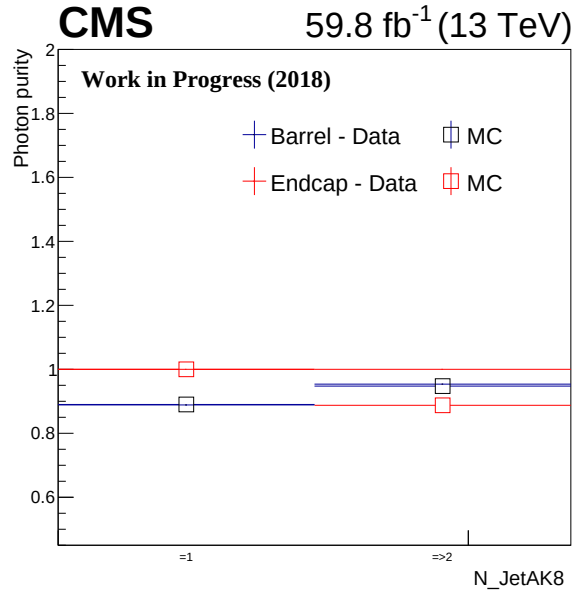


Figure 5.24. Resulting plots show the purity and CF for the 2016 data-taking period. The upper plot shows the purity values for the bins of $n_{AK8_{m50}}$ for data and MC comparison, and the lower plot shows the CF distribution.

ulate SR-like conditions. They aim to examine the applicability of CFs derived in CRs within kinematic domains resembling SRs. These VRs function as validators for estimations within the hadronic and leptonic SRs.

An additional VR is designed to justify the utilization of top CFs. These CFs are derived within a CR where $t\bar{t}$ decays manifest through the single lepton channel. They are then employed within SRs where top backgrounds originate from single lepton and dilepton $t\bar{t}$ decays.

The concluding assortment of VRs is enlisted to verify the validity of CFs for non-isolated lepton regions. The methodology closely resembles that of the preceding set. These VRs serve to validate estimations within the non-isolated leptonic SRs.

5.6.4. Validation of $Z \rightarrow \nu\nu$ Background Estimation with $W \rightarrow l\nu$

The similar CRs ($W \rightarrow l\nu$ and semileptonic top enriched CRs), which can emulate $\gamma + jets$ events, are defined to validate the estimation from G and DY CR, so the estimations from both approaches need to be close. These CRs, denoted as W4Z and T4Z (see Table 5.8.), are established separately for cases of at least one or more than one mass-tagged AK8 jets.

Based on this selection, the m_T variable is computed using the actual E_T^{miss} in the event after isolating $W \rightarrow l\nu + jets$ events. To account for the second neutrino originating from $Z \rightarrow \nu\nu$ decays, lepton's contribution are added to E_T^{miss} . The adjusted E_T^{miss} is then employed to recalculate M_R and R^2 variables.

Figure 5.25. shows the $M_R \times R^2$ distribution for the CRs used for validation of the $Z \rightarrow \nu\nu$ background estimation in the bins of $M_R \times R_{nolep}^2$ to mimic the $W \rightarrow l\nu$ process. In this plot, the Data/MC agreement for each VRs is quite reasonable with the event count for each SM process given on the legends. As expected, $W + jets$ is the dominant SM background in the W4Z1 and W4Z2 VRs; $t\bar{t} + jets$ are the dominant for the T4Z1 and T4Z2 VRs. The figures 5.26. shows the comparison of the $Z \rightarrow \nu\nu$ background estimation for validation SR in $M_R \times R^2$ bins with $\gamma + jets$ and $W \rightarrow l\nu$ estimation inputs from $\gamma + jets$ and $W(\rightarrow l\nu)$ background processes in the bins of $M_R \times R^2$. The black line on the histograms indicates the $Z \rightarrow \nu\nu$ MC event count, and the estimates are represented with blue and red dots for the contribution from $\gamma + jets$ and $W \rightarrow l\nu$ to the $Z \rightarrow \nu\nu$ background estimations. The figure aims to validate the accuracy of two different background estimation methods against Monte Carlo (MC) simulations.

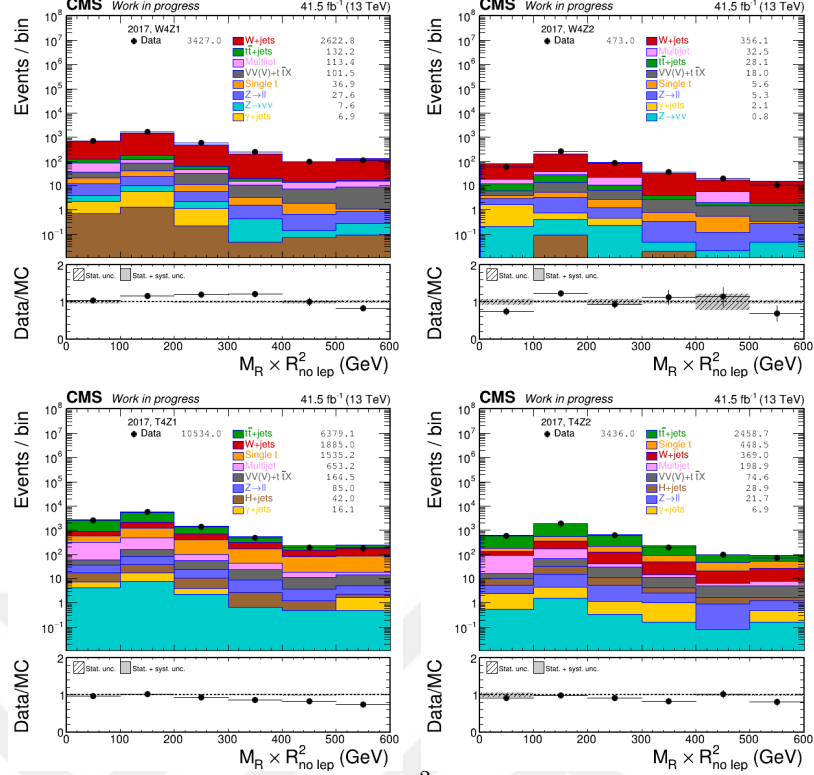


Figure 5.25. Data and MC comparisons for $M_R \times R^2$ for the W4Z1, T4Z1, W4Z2, T4Z2 CRs used for $W \rightarrow l\nu$ estimation for the 2017 data-taking period.

5.6.5. Other Background Estimations: Dilepton and QWT

In the previous section, the particular background estimation case of $Z \rightarrow \nu\nu$ is given with estimation methodology and results with its validation with different CRs. This section discusses other dominant background estimation methods and results, such as QCD, top, and W+jets. Dedicated CRs were already given in the table.

The CFs for clusters of two or three background processes from CRs are computed together rather than using the conventional method. In the traditional approach, the purest CR is identified first, background contributions are subtracted, and then CFs are determined and applied iteratively to MC samples across different bins of $M_R \times R^2$ and AK4 jet multiplicity, repeating this process for each additional background.

Data and MC distributions are gathered for the variable against which the CF will be developed. Within each CR, all minor backgrounds designated for direct MC-based estimation are subtracted from the data, leaving only contributions from the significant backgrounds such as QCD, top, or W+jets for which CFs are aimed.

Assuming that the CF for a specific background remains consistent across regions, in each bin 'i' of the distribution, a set of N equations with N unknowns is established. The unknowns correspond to the CFs. This method interconnects data yields, MC counts, and CFs, permitting the simultaneous

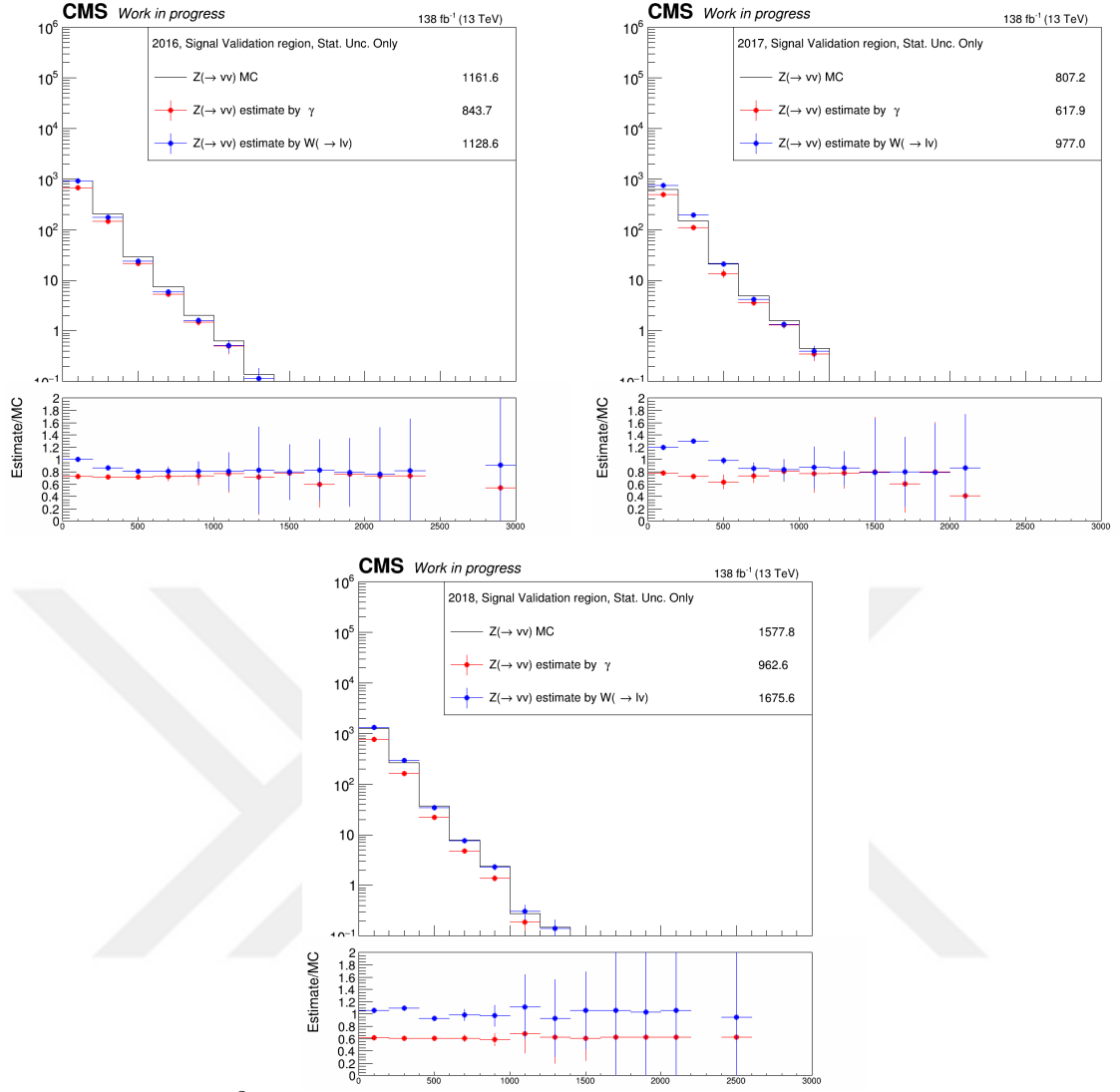


Figure 5.26. $M_R \times R^2$ distribution with $Z \rightarrow \nu\nu$ MC, background estimation from $\gamma + jets$ and dilepton CRs. The results are from top to bottom in 2016, 2017, and 2018.

determination of CFs for various backgrounds.

This method can be formulated for the major backgrounds' simultaneous estimation as:

$$\begin{bmatrix} CF_Q^i \\ CF_T^i \\ CF_W^i \end{bmatrix} \begin{bmatrix} MC_Q^{Q_i} & MC_T^{Q_i} & MC_W^{Q_i} \\ MC_Q^{T_i} & MC_T^{T_i} & MC_W^{T_i} \\ MC_Q^{W_i} & MC_T^{W_i} & MC_W^{W_i} \end{bmatrix} = \begin{bmatrix} Data^{Q_i} \\ Data^{T_i} \\ Data^{W_i} \end{bmatrix} \quad (5.7)$$

Here i runs over the 1 and 2 representing two different CRs of the same background processes reverted over m_T and $\Delta\phi$, as coded in Table 5.8., e.g. Q1, Q2, W1, W2, T1, T2. In equation 5.8, CFs are solved for various MC and data event counts in different CRs. Firstly, CFs are solved in bins of $M_R \times R^2$ and applied to all the related CRs, and secondly, CFs are recalculated in bins of AK4 jet multiplicity and reapplied to the CRs and SRs.

In the same way, CFs from non-isolated leptonic CRs are calculated. The main contributors of these regions are $t\bar{t} + jets$ and W+jets background processes (see Table 5.8.). CFs from these non-isolated CRs are calculated in a similar simultaneous way formulated as:

$$\begin{bmatrix} CF_{T,no-isoLep}^i \\ CF_{W,no-isoLep}^i \end{bmatrix} \begin{bmatrix} MC_T^{Tnl} & MC_W^{Tnl} \\ MC_T^{Wnl} & MC_W^{Wnl} \end{bmatrix} = \begin{bmatrix} Data^{Tnl} \\ Data^{Wnl} \end{bmatrix} \quad (5.8)$$

Here CFs are calculated simultaneously and applied to non-isolated CRs and SRs event by event in bins of $M_R \times R^2$ and AK4 jet multiplicity iteratively.

5.7. Systematic Uncertainties

Systematic uncertainties arise from various sources and reflect our limited knowledge or control over certain aspects of the analysis. They are essential for accurately quantifying the precision of a measurement or the significance of a signal under interest. The analysis identifies all potential sources of uncertainty that could affect the measurement. These can include effects from experimental apparatus, theoretical models, data analysis techniques, and more.

The statistical analysis takes as input a collection of histograms plotted in the bins of $M_R \times R^2$ or jet multiplicity, encompassing systematic uncertainties inherent in the simulated signal and background MC datasets. The distinct systematic influences, explained below, are concurrently sampled. A Gaussian-distributed variate with zero mean and unit variance is uniformly employed to induce a randomized shift in the systematic effect across all signal and background models for every sampled systematic influence. Based on the suggestion of the CMS SUS group (CMS SUS, 2022), we ignore the parton distribution function (PDF) effect for our Run-2 UL samples while determining systematic uncertainties of the analysis. The systematic uncertainties primarily originate from scale and CFs applied to simulated (MC) samples to correct modeling discrepancies. The following bullets explain the

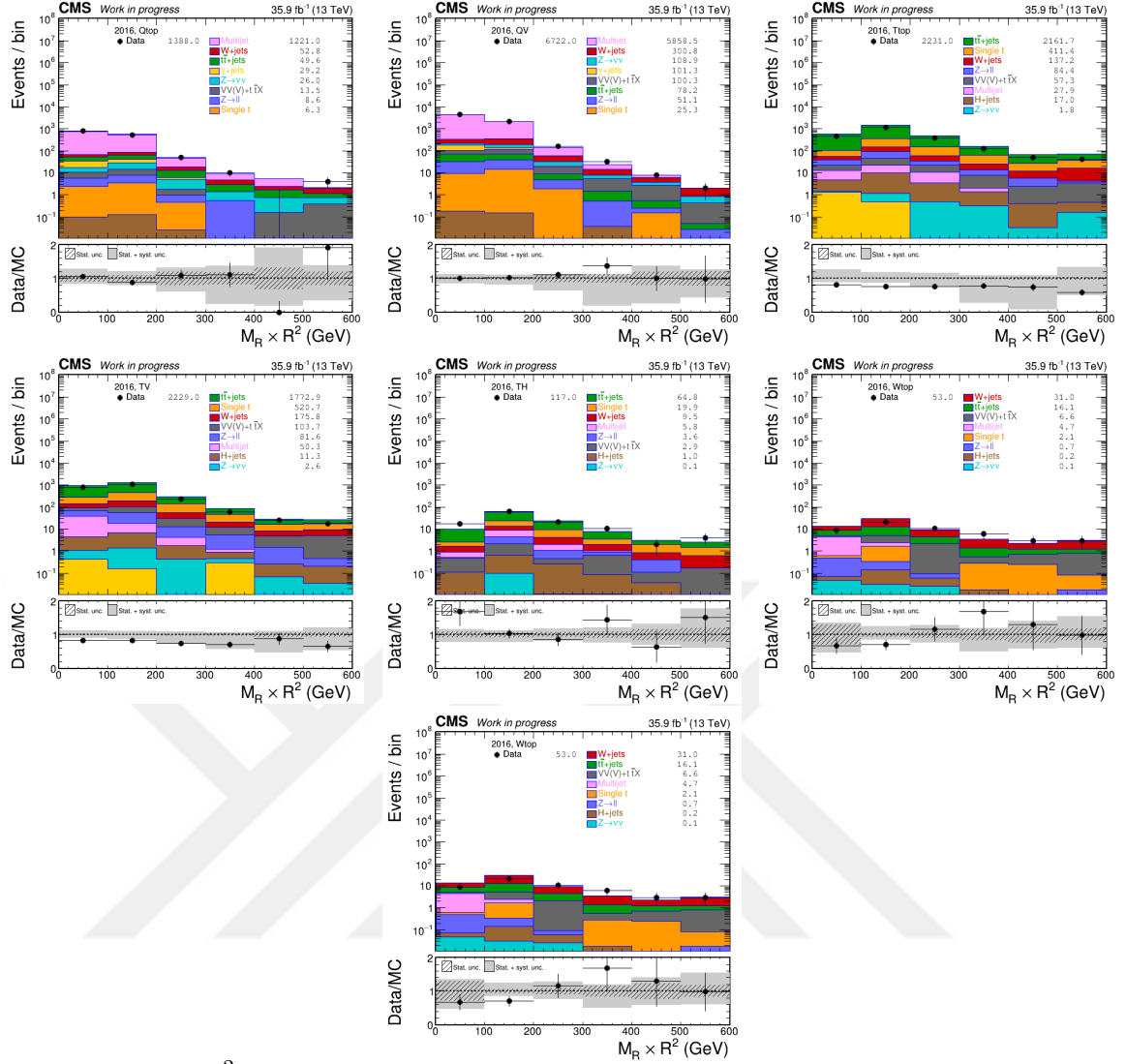


Figure 5.27. $M_R \times R^2$ distribution with data/MC comparison in lower pads of the histograms are given for VRs given in Table 5.10. for the 2016 data-taking period.

sources considered in the analysis:

- **toppt:** Systematic uncertainty from toppt reweighting refers to the uncertainty associated with modeling the transverse momentum distribution of top quarks in simulated events. This uncertainty accounts for variations in the simulation's ability to predict the top quark momenta distribution accurately. The one sigma down variation corresponds to no reweighting; the one sigma up variation corresponds to applying the reweighting twice. These uncertainties are propagated to the Data/MC ratio to estimate the TTjets background.
- **ISR:** The "ISR" systematic uncertainty is related to Initial State Radiation. It accounts for uncertainties in modeling the additional particles (radiation) produced by the incoming particles before they collide. These additional particles can affect the kinematic properties of the final state particles detected in the CMS detector. The ISR reweighting is applied to signal samples following the recommendations of the CMS SUS group (CMS SUS, 2022).
- **L1prefiring:** The Level-1 (L1) trigger decides which events to keep for further analysis in the CMS trigger system. The uncertainties about the L1 ECal and muon prefiring rates in 2016 and 2017 datasets have been included as shape uncertainties for all MC samples following the recommendations from this reference (CMS Collaboration, 2021a).
- **lostlep:** The "lostlep" systematic uncertainty accounts for the background of events in which leptons (electrons or muons) from the decays of certain particles are not efficiently identified or reconstructed in the CMS detector. This can lead to misestimating the actual event properties, particularly when reconstructing events with missing energy (e.g., from neutrinos).
- **JES:** "JES" stands for Jet Energy Scale. These systematic uncertainties in the analyses relate to the calibration of jets, which are collimated sprays of particles resulting from quarks and gluons.
- **JER:** "JER" stands for Jet Energy Resolution. These systematic uncertainties in the analysis relate to the calibration of jets, which are collimated sprays of particles resulting from quarks and gluons. It is applied to all MC samples as shape uncertainties following the recommendations from JetMET group (CMS JME Group, 2023).
- **puid:** The "puid" uncertainty accounts for the efficiency of correctly identifying and removing pileup contributions from the primary interaction. Pileup reweighting is applied as a shape uncertainty using up/down (UL) variations.
- **BoostTag/BoostTagFastsim:** Boosted object SFs and fake rates for boosted object data in the FullSim and FullSim/FatSim contexts are employed to account for uncertainties in SFs, introduced variations by increasing and decreasing the SFs and subsequently recalculating the event weight, effectively incorporating these uncertainties as shape variations.
- **Lepton Fullsim and FastSim SFs:** Uncertainties on electron and muon SFs are applied to MC

Table 5.11. Systematic uncertainties for total background in IsoLep SRs.

syst/SRs	Lep_V_b	Lep_V_0b	Lep_H_b	Lep_H_0b
toppt	4.9%/-4.9%	3.2%/-3.2%	5.6%/-5.6%	3.6%/-3.6%
isr	0.7%/-0.7%	0.9%/-0.9%	1.8%/-1.8%	0.6%/-0.6%
pileup	2.9%/-2.9%	2.2%/-2.2%	2.1%/-2.1%	1.7%/-1.7%
L1PreFiring	1.0%/-1.0%	0.6%/-0.6%	0.1%/-0.1%	0.0%/-0.0%
alphas	0.9%/-0.9%	0.4%/-0.4%	1.0%/-1.0%	0.2%/-0.2%
scale	0.9%/-0.9%	1.0%/-1.0%	0.4%/-0.4%	0.5%/-0.5%
lostlep	1.9%/-1.9%	0.6%/-0.6%	1.0%/-1.0%	0.3%/-0.3%
trigger	0.8%/-0.8%	1.0%/-1.0%	0.4%/-0.4%	0.2%/-0.2%
jes	3.7%/-3.7%	4.8%/-4.8%	1.4%/-1.4%	2.4%/-2.4%
jer	2.6%/-2.6%	3.6%/-3.6%	4.1%/-4.1%	2.4%/-2.4%
puid	3.5%/-3.5%	2.2%/-2.2%	2.4%/-2.4%	1.5%/-1.5%
BoostTag	3.1%/-3.1%	2.5%/-2.5%	3.4%/-3.4%	1.6%/-1.6%
BoostTagFastsim	4.3%/-4.3%	3.3%/-3.3%	5.0%/-5.0%	0.4%/-0.4%
EleFullsim	2.8%/-2.8%	2.2%/-2.2%	3.5%/-3.5%	1.8%/-1.8%
EleFastsim	3.2%/-3.2%	3.6%/-3.6%	5.3%/-5.3%	1.0%/-1.0%
MuonFullsim	3.9%/-3.9%	2.5%/-2.5%	5.6%/-5.6%	0.8%/-0.8%
MuonFastsim	3.5%/-3.5%	3.8%/-3.8%	5.8%/-5.8%	0.6%/-0.6%
BTag	1.8%/-1.8%	9.9%/-9.9%	6.8%/-6.8%	3.9%/-3.9%
BTagFastsim	3.2%/-3.2%	2.9%/-2.9%	4.9%/-4.9%	0.8%/-0.8%
cf_QTW	19.4%/-19.4%	16.7%/-16.7%	19.0%/-19.0%	38.7%/-38.7%
cf_NonIso	3.3%/-3.3%	3.1%/-3.1%	3.4%/-3.4%	1.6%/-1.6%
cf_Z	3.0%/-3.0%	3.0%/-3.0%	5.9%/-5.9%	0.5%/-0.5%

samples as event weight.

- **Btag and BtagFastsim:** These uncertainties account for the differences in modeling the b-tagging efficiency between the full simulation and fast simulation approaches.
- **CFs:** CFs depicted from background estimation, described in previous section, applied to MC samples as up/down variation. Difference between data/MC in CRs sourced this uncertainties.

Systematic uncertainty effects on the total background for each SRs (isolated lepton SRs) is given in Table 5.11. and the for the TChiWZ model in Table 5.12., where the average systematic values are used for each mass bins. For other SR, one can check the Appendix C.

The next section discusses systematic uncertainties as nuisance parameters for calculating the upper limits of the signal models.

Table 5.12. Systematics values for signal samples of the TChiWZ simplified model for each isolate lepton SRs.

syst/SRs	Lep_1htop	Lep_V_b	Lep_V_0b	Lep_H_b	Lep_H_0b
toppt	0.0%/-0.0%	0.0%/-0.0%	0.0%/-0.0%	0.0%/-0.0%	4.1%/-4.1%
isr	0.0%/-0.0%	0.8%/-0.8%	0.8%/-0.8%	2.6%/-2.6%	7.2%/-7.2%
pileup	0.0%/-0.0%	0.0%/-0.0%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
L1PreFiring	0.0%/-0.0%	0.0%/-0.0%	0.0%/-0.0%	2.5%/-2.5%	7.2%/-7.2%
alphas	0.0%/-0.0%	0.0%/-0.0%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
scale	0.0%/-0.0%	0.0%/-0.0%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
lostlep	0.0%/-0.0%	0.0%/-0.0%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
trigger	0.0%/-0.0%	0.1%/-0.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
jes	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	4.2%/-4.2%
jer	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	4.2%/-4.2%
puid	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
BoostTag	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
BoostTag_Fastsim	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
BoostmisTag	0.0%/-0.0%	4.2%/-4.2%	3.6%/-3.6%	1.6%/-1.6%	6.9%/-6.9%
EleFullsim	0.0%/-0.0%	1.4%/-1.4%	1.2%/-1.2%	2.4%/-2.4%	7.1%/-7.1%
EleFastsim	0.0%/-0.0%	1.4%/-1.4%	0.4%/-0.4%	2.4%/-2.4%	7.1%/-7.1%
MuonFullsim	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
MuonFastsim	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
BTag	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
BTagFastsim	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
cf_QTW	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
cf_NonIso	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%
cf_Z	0.0%/-0.0%	1.1%/-1.1%	0.0%/-0.0%	2.4%/-2.4%	7.2%/-7.2%

5.8. Results and Limit Calculations on Simplified Models

Simplified Signal Models (or SMSs) are given for RPV cases in figure 2.3. and RPC cases in figure 2.2.. Limits on sparticle masses are determined by employing a binned maximum likelihood fit, using the same binning scheme shown in figure 5.29. across a variety of search regions and their combination in unrolled $M_R \times R^2$ bins.

Systematic uncertainties explained in the previous section are used as nuisance parameters of the likelihood functions. Production cross sections are computed with (combine limit) CLs technique (Junk, 1999), and signal cross sections for expected particles are collected by the centrally produced values (Fuks et al., 2013), (Fuks et al., 2012). The expected limits obtained using the asymptotic CLs method for the simplified models of T5ttcc, T5bbbbZH, T6ttZH, TChiWW, TChiWZ, T5qqqqWH, R2bbqqlv and R5ttbl are shown respectively on the next pages.

The T5ttcc model, featuring the production of top squarks that subsequently decay into top quarks and a lighter charm squark, sheds light on SUSY mechanisms affecting the third-generation quarks. Figure 5.38. displays the 95% CL upper limits on the production cross-section as a function of the stop and charm squark masses. This preliminary plot with blinded data exclusively presents

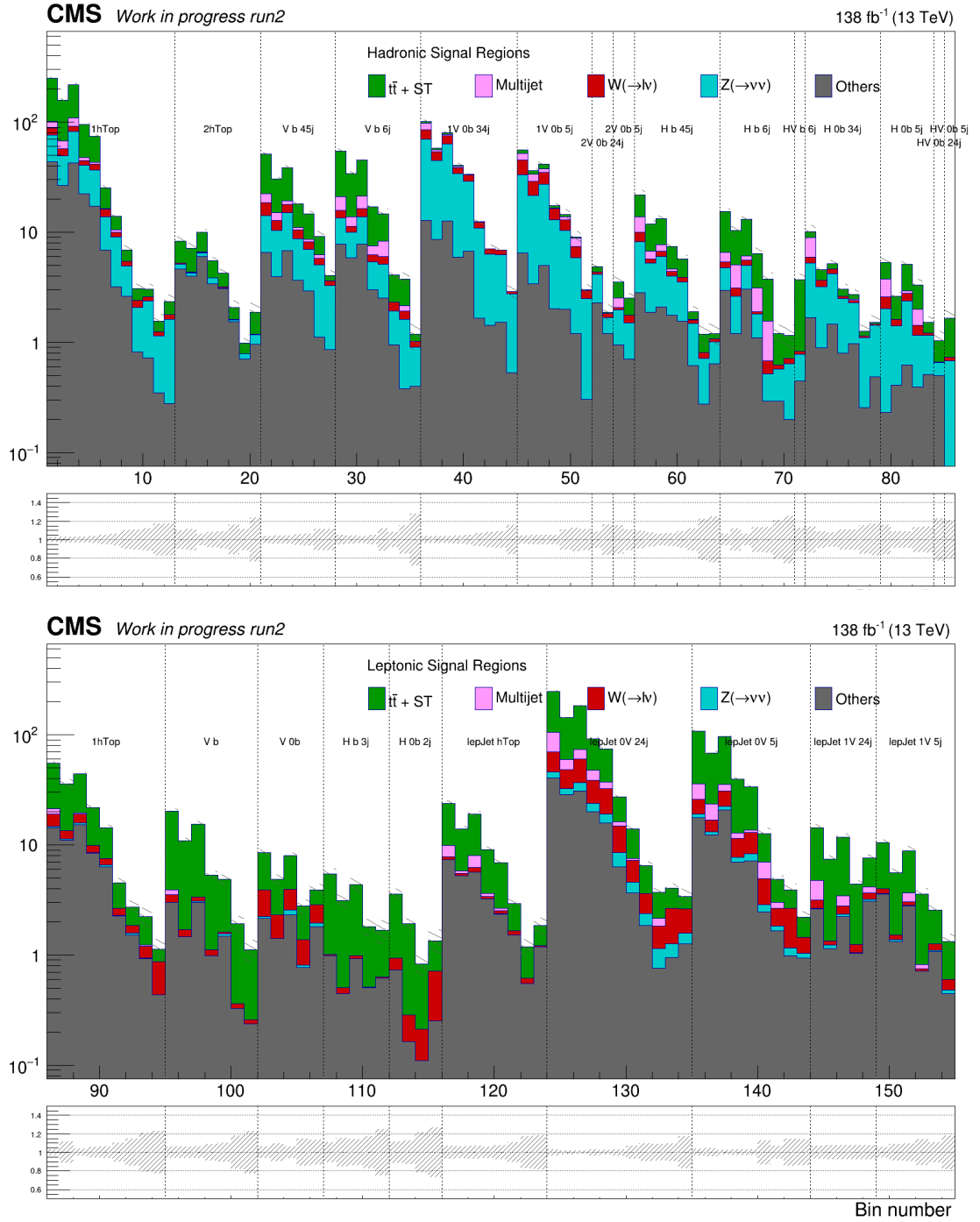


Figure 5.29. The distribution of event counts across different bin numbers of $(M_R - 800) \times (R^2 - 0.08)$ for various SRs (hadronic SRs on the upper plot, leptonic SRs on the lower plot) with full Run-2 combined. The stacked histograms represent the background processes including $t\bar{t} + \text{ST}$ (green), Multijet (pink), $W(\rightarrow l\nu)$ (red), $Z(\rightarrow \nu\nu)$ (blue), and others (grey). The lower panels show the ratio of observed data to the predicted background, including both statistical and systematic uncertainties.

the expected masses of the stop and charm squarks, incorporating insights from NLO+NLL exclusion calculations.

The T5bbbbZH model involves the production of gluino pairs that decay into bottom quark pairs and the lightest neutralino, providing a rich context for studying SUSY processes involving heavy-flavor quarks. Figure 5.39. presents the 95% CL upper limits on the gluino production cross-section as a function of the gluino and neutralino masses. This focuses exclusively on the expected masses for gluinos and neutralinos, showcasing results from NLO+NLL exclusion calculations. The displayed exclusion limits are critical for constraining possible gluino masses in scenarios where these heavy particles decay predominantly into bottom quarks, accompanied by the production of a Z boson and the lightest neutralino.

The T6ttZH model involves the production of third-generation squarks, specifically stop squarks, which then decay into top quarks and a subsequent emission of a Z boson along with the lightest neutralino. Figure 5.40. delineates the 95% CL upper limits on the production cross-section as a function of the stop squark and neutralino masses. The analysis highlights critical exclusion zones that are essential for testing the viability of the T6ttZH model within SUSY frameworks, providing key insights into the interaction dynamics of third-generation squarks, Z bosons, and neutralinos under the current experimental constraints.

The TChiWW model explores scenarios within charginos and the lightest neutralinos are produced in pairs and subsequently decay into pairs of W bosons. Figure 5.41. presents the 95% CL upper limits on the production cross-section of these processes, depicted as a function of the chargino and neutralino masses. The results are instrumental for delineating the mass constraints of charginos and neutralinos and for evaluating the potential discovery of electroweak SUSY particles, providing valuable insights into the nature of these elusive particles under the Standard Model extensions.

The TChiWZ model, involving the production of charginos and neutralinos decaying into bosons (W and Z) and the lightest neutralino, provides insights into the electroweak SUSY breaking mechanisms. Figure 5.42. illustrates the 95% CL upper limits on the production cross-section as a function of the chargino and neutralino masses. For this preliminary plot with blinded data, shows only expected neutralino and chargino mass with NLO+NLL exclusion insights.

The T5qqqqWH model addresses scenarios with gluinos are produced in pairs and decay into two quarks accompanied by a Higgs boson and the lightest neutralino, highlighting interactions that probe both the strong and electroweak sectors. Figure 5.43. illustrates the 95% CL upper limits on the gluino production cross-section as a function of the gluino and neutralino masses. These results are particularly crucial for validating the SUSY predictions involving the coexistence of strong and electroweak interactions, offering valuable insights into potential new physics beyond the Standard

Model.

The R2bbqqlv model focuses on scenarios involving R-parity violating (RPV) decays where gluinos are produced and subsequently decay into a pair of bottom quarks and a lepton, bypassing the typical missing energy signature associated with R-parity conserving models. Figure 5.44. showcases the 95% CL upper limits on the gluino production cross-section as a function of the gluino mass derived from NLO+NLL calculations, highlighting crucial mass ranges where gluino decays into this particular final state are either likely or ruled out.

The R5ttbl model explores another facet of R-parity violating SUSY, where top squarks ($\tilde{t}$) decay into a top quark, a bottom quark, and a lepton (ℓ), offering a unique perspective on top squark decays without the conventional missing energy component. Figure 5.45. depicts the 95% CL upper limits on the top squark production cross-section, plotting it against the top squark mass. The data, collected by the CMS experiment at a center-of-mass energy of 13 TeV, reveals expected mass exclusion zones through NLO+NLL analytical methods. This plot is crucial for assessing the probability of top squark decays within RPV models, and it aids in delineating the parameter space where such decay channels are plausible, thereby contributing to broader searches for deviations from R-parity conserving predictions within the SUSY framework.

The R5ttbl model explores another facet of R-parity violating SUSY, where top squarks decay into a top quark, a bottom quark, and a lepton, offering a unique perspective on top squark decays without the conventional missing energy component. Figure 5.45. depicts the 95% CL upper limits on the top squark production cross-section, plotting it against the top squark mass. This plot is crucial for assessing the probability of top squark decays within RPV models, and it aids in delineating the parameter space where such decay channels are plausible, thereby contributing to broader searches for deviations from R-parity conserving predictions within the SUSY framework.

The impact plots (see figures 5.30., 5.31., 5.32., 5.33., 5.34., 5.35., 5.36., 5.37.) depict the relative importance and influence of various parameters on the fitted model outcome, represented by the central value r and its associated uncertainties. Each entry shows the pull (deviation from the nominal value) and impact (effect on the model's prediction) for individual parameters. Parameters are ordered by their influence, with uncertainties displayed as horizontal bars, indicating the confidence interval of each parameter's impact. The plot also highlights different types of constraints applied during the model fitting process, providing a comprehensive view of the model's sensitivity to each parameter. The central value r is precisely constrained within -0.22 to $+0.24$, demonstrating the robustness of the model under various parameter adjustments.

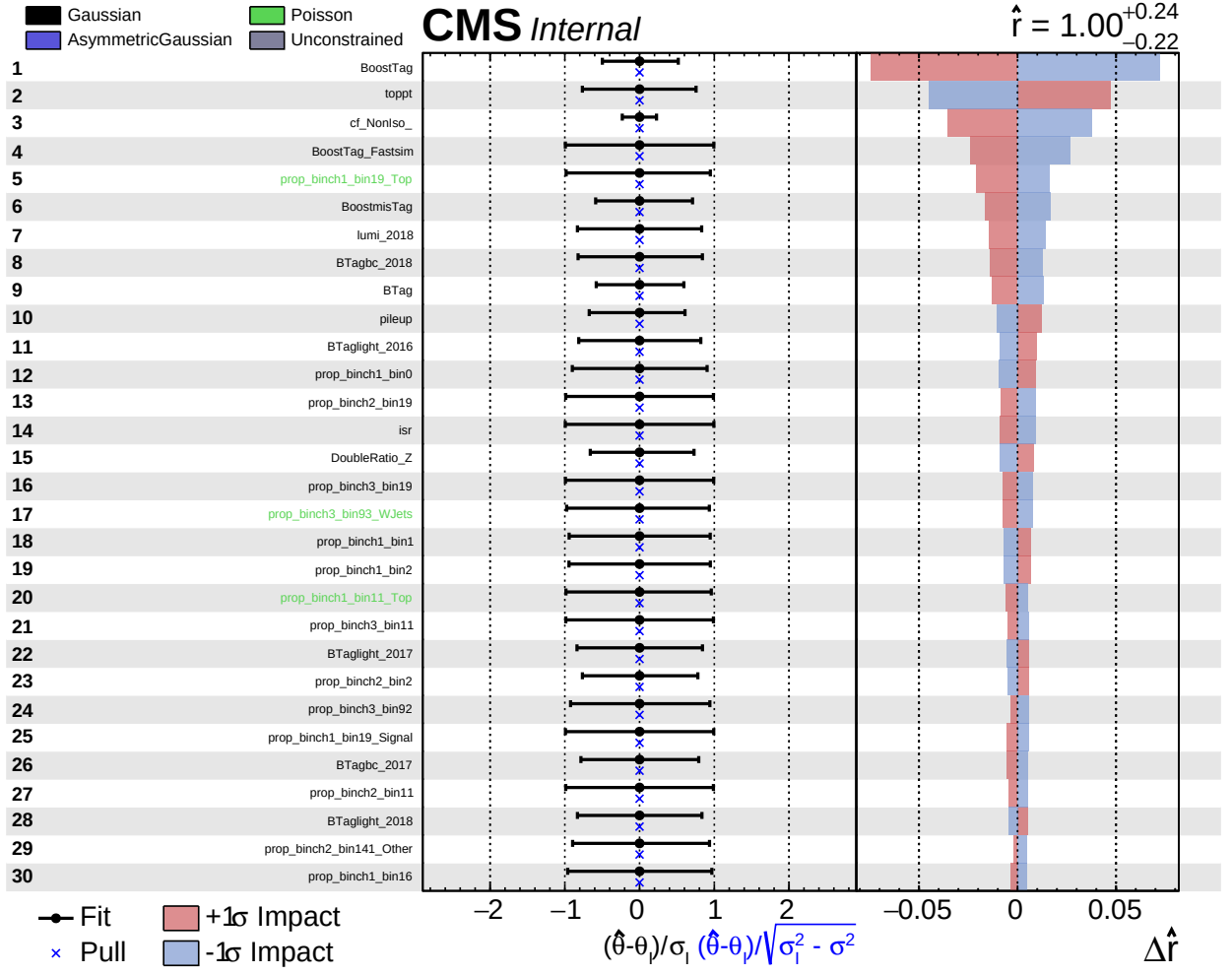


Figure 5.30. Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the T5ttcc scenario. The plot corresponds to the gluino mass $\tilde{g} = 2000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 400$ GeV, combining the full Run 2 data-taking period.

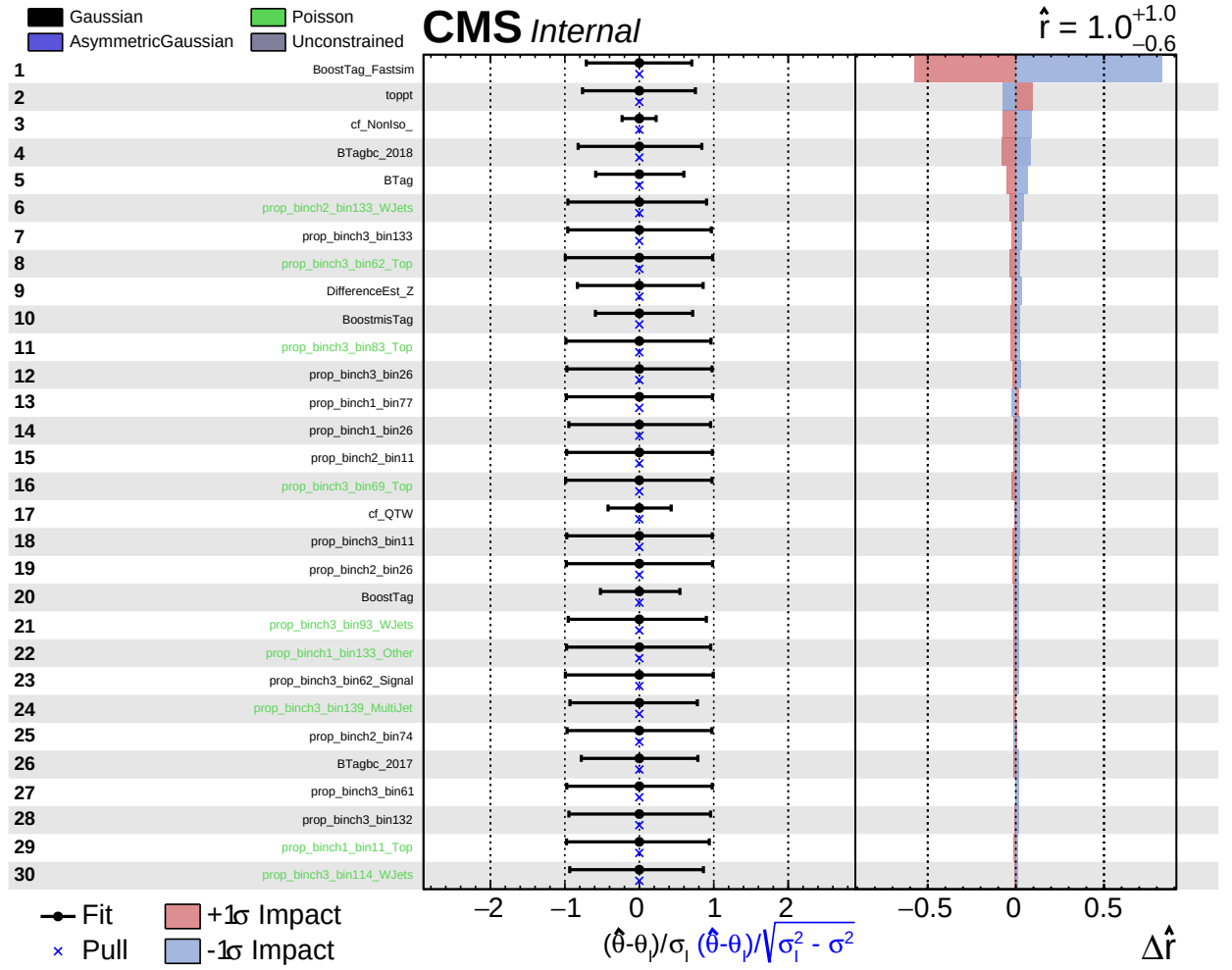


Figure 5.31. Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the T5bbbbZH scenario. The plot corresponds to the gluino mass $\tilde{g} = 2200$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 400$ GeV, combining the full Run 2 data-taking period.

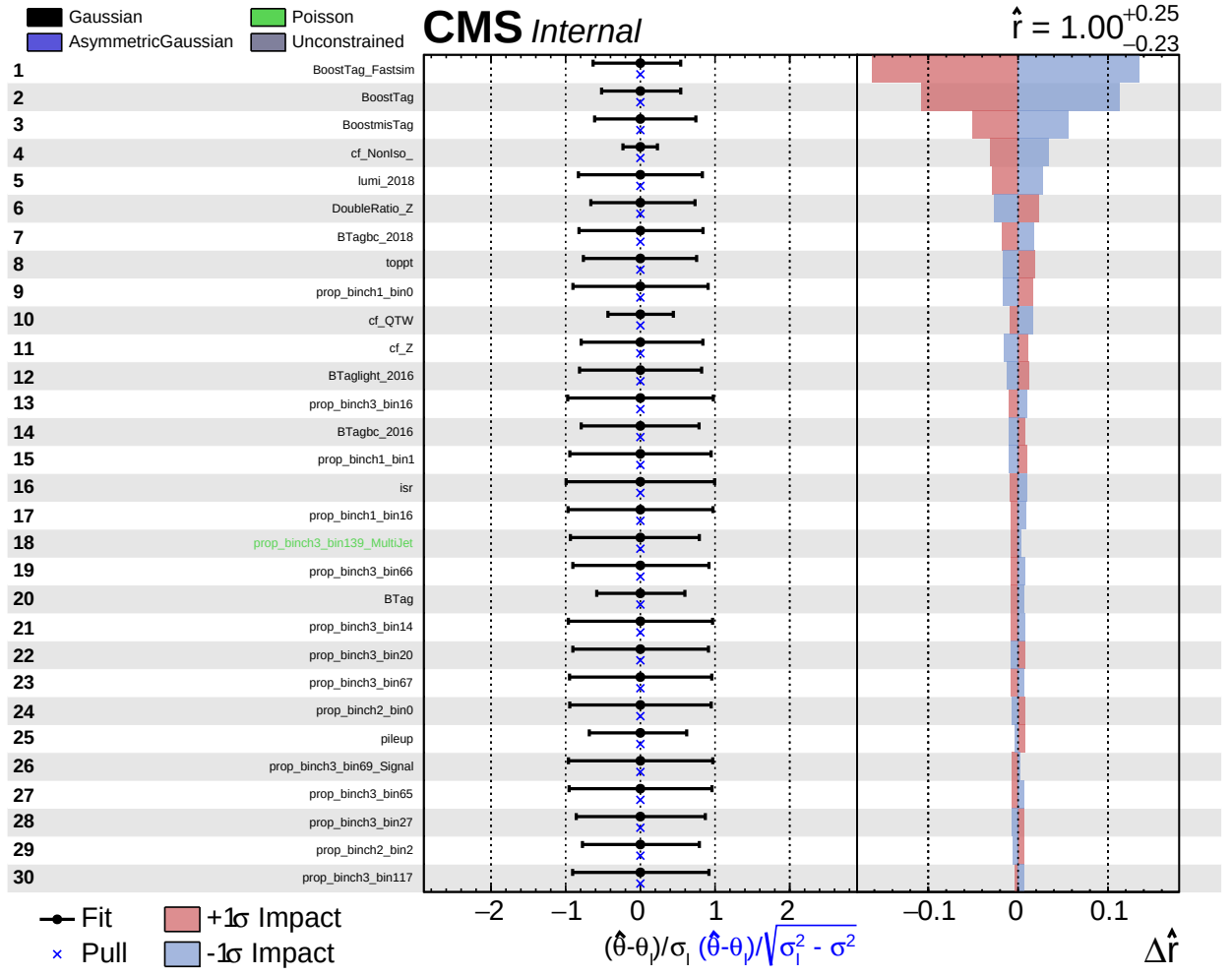


Figure 5.32. Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the T6ttZH scenario. The plot corresponds to the gluino mass $\tilde{g} = 1000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 100$ GeV, combining the full Run 2 data-taking period.

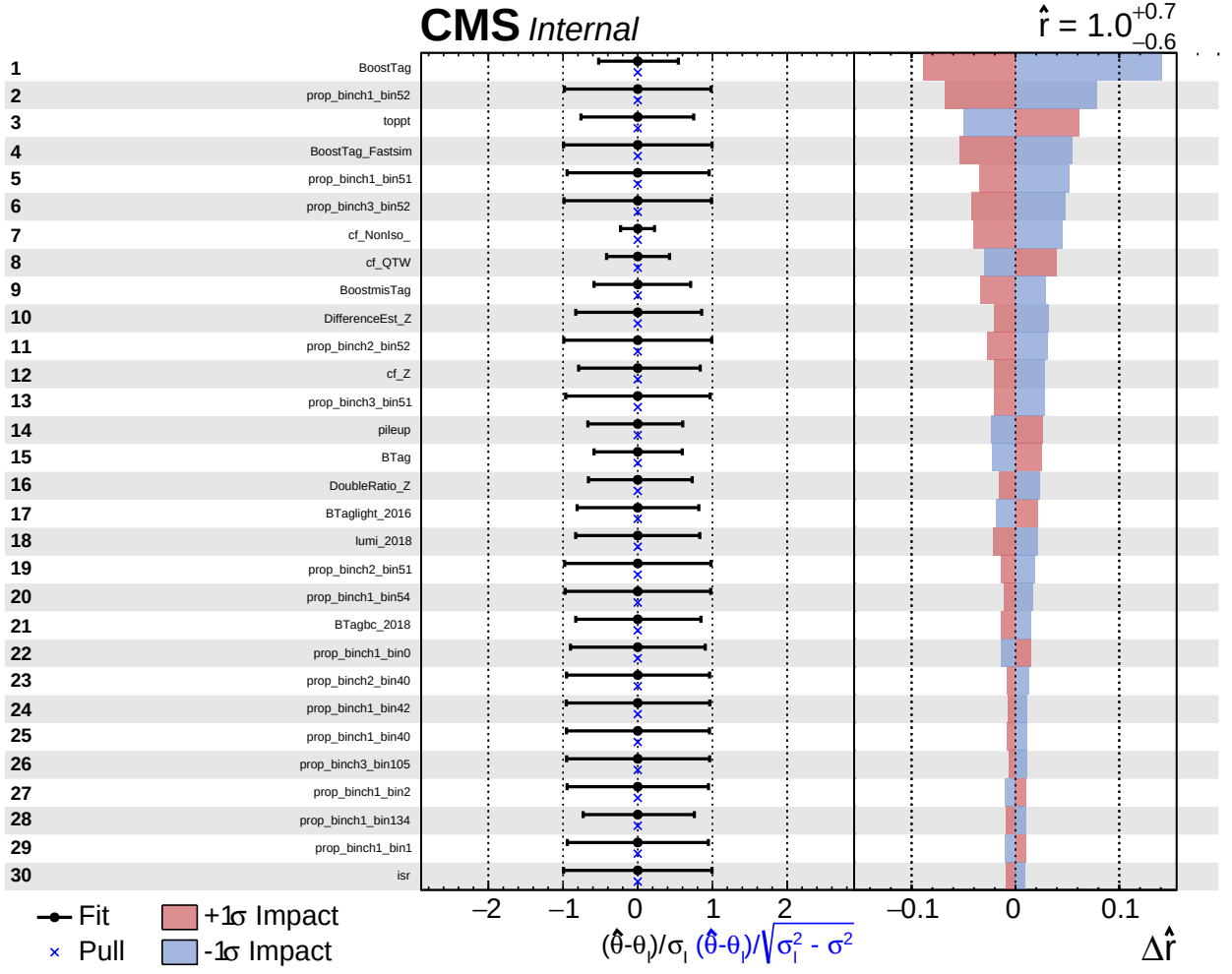


Figure 5.33. Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the TChiWW scenario. The plot corresponds to the gluino mass $\tilde{g} = 1000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 100$ GeV, combining the full Run 2 data-taking period.

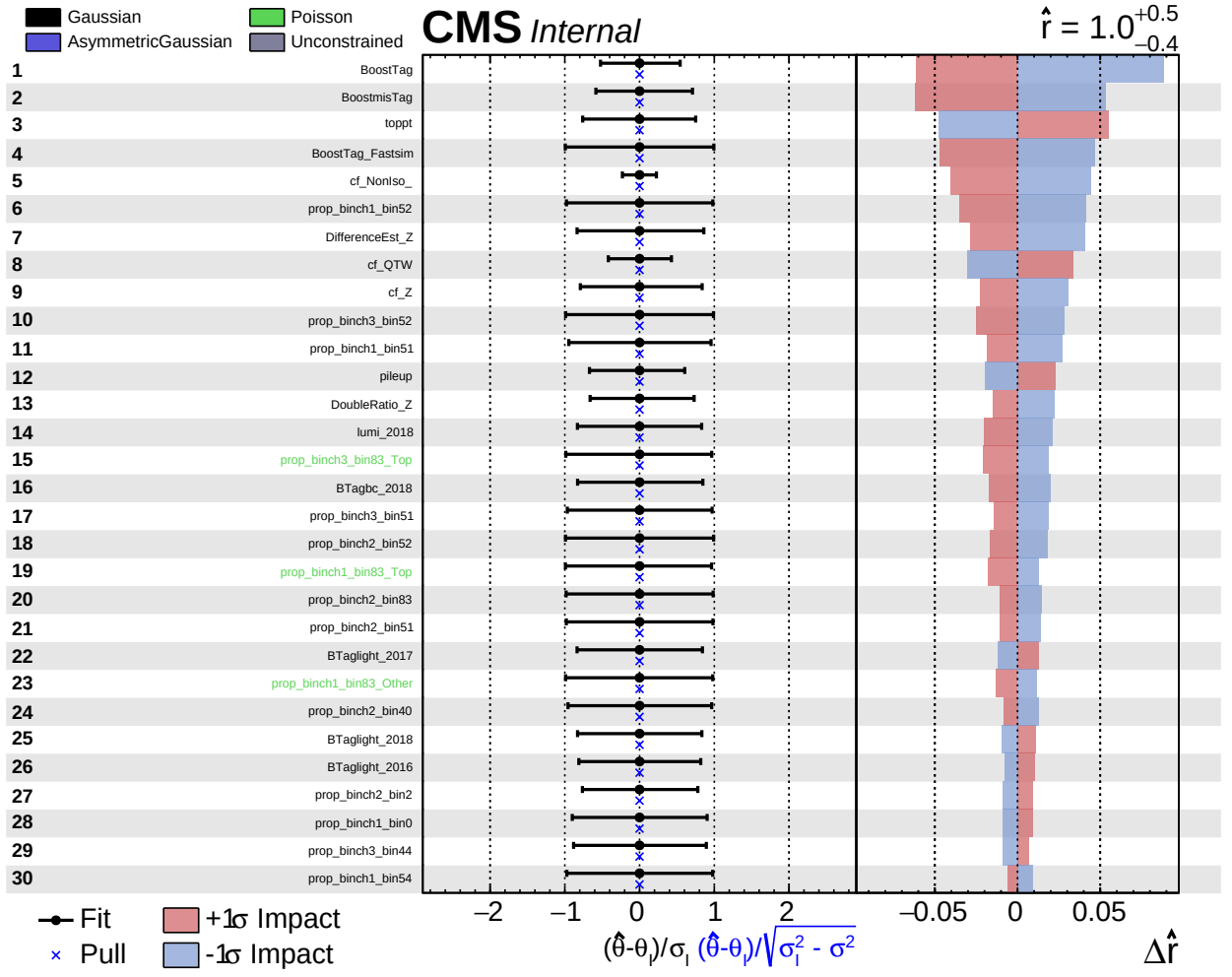


Figure 5.34. Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the TChiWZ scenario. The plot corresponds to the gluino mass $\tilde{g} = 1000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 100$ GeV, combining the full Run 2 data-taking period.

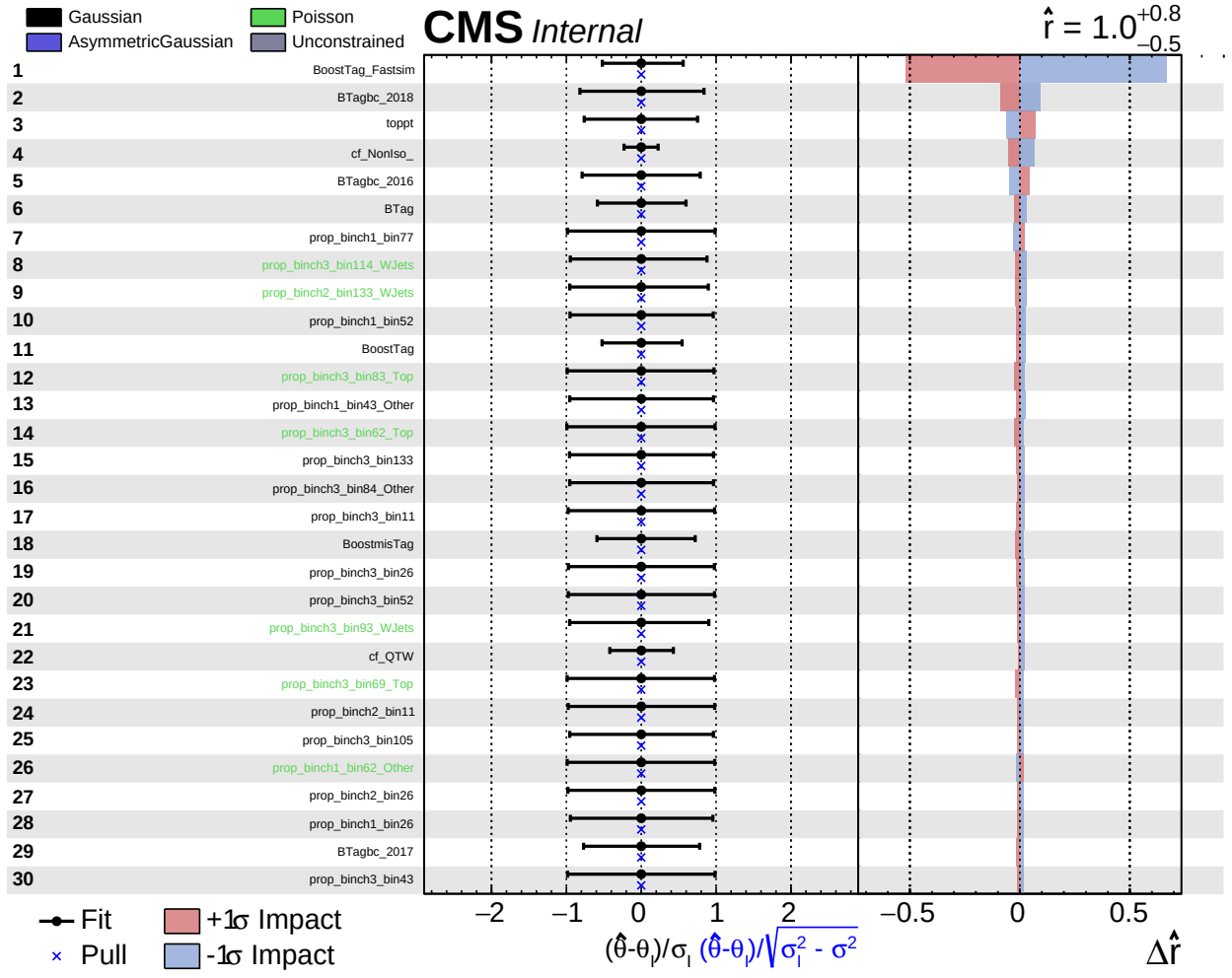


Figure 5.35. Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the T5qqqqWH scenario. The plot corresponds to the gluino mass $\tilde{g} = 2200$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 500$ GeV, combining the full Run 2 data-taking period.

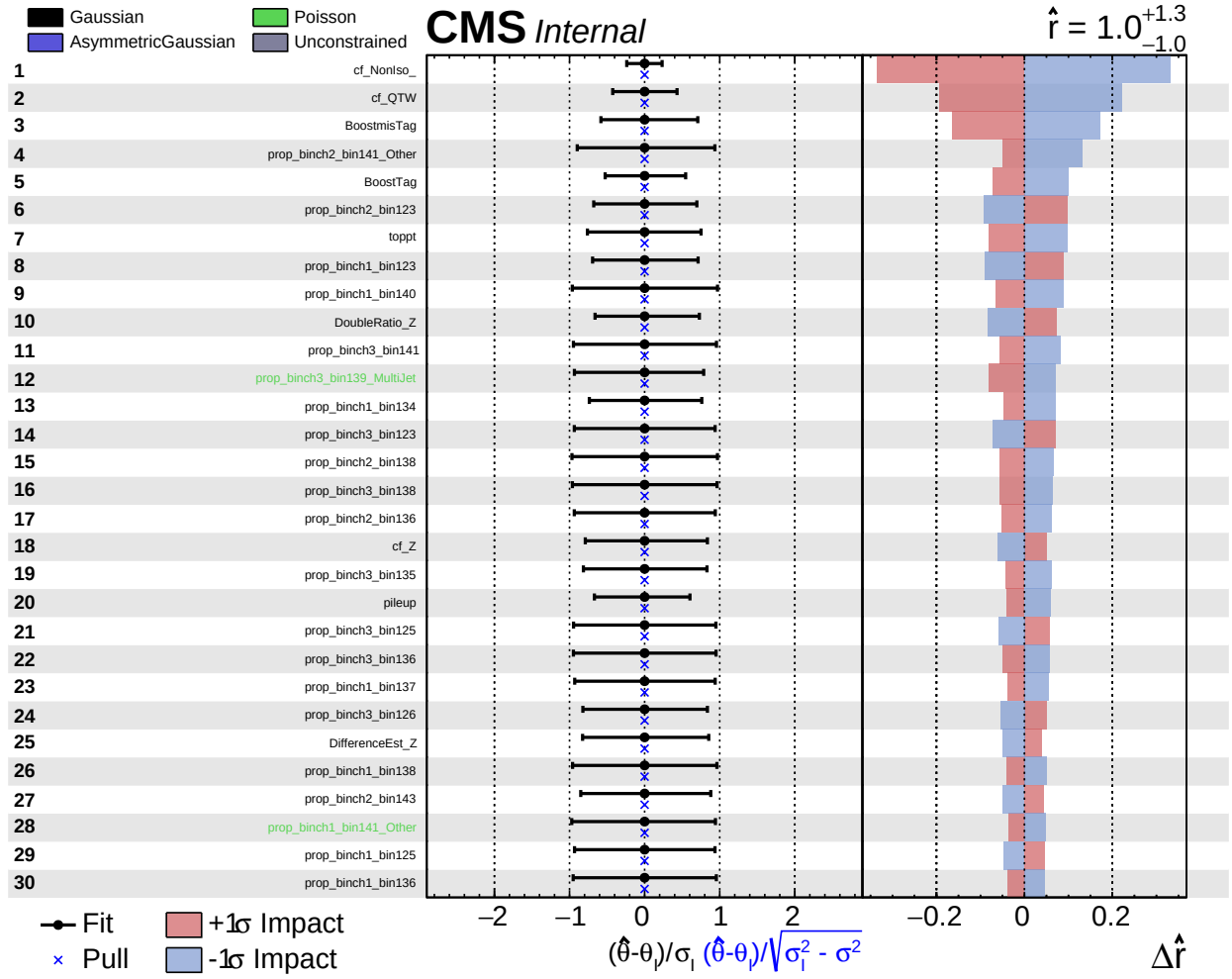


Figure 5.36. Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the R2bbqq ν scenario. The plot corresponds to the gluino mass $\tilde{g} = 1000$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 500$ GeV, combining the full Run 2 data-taking period.

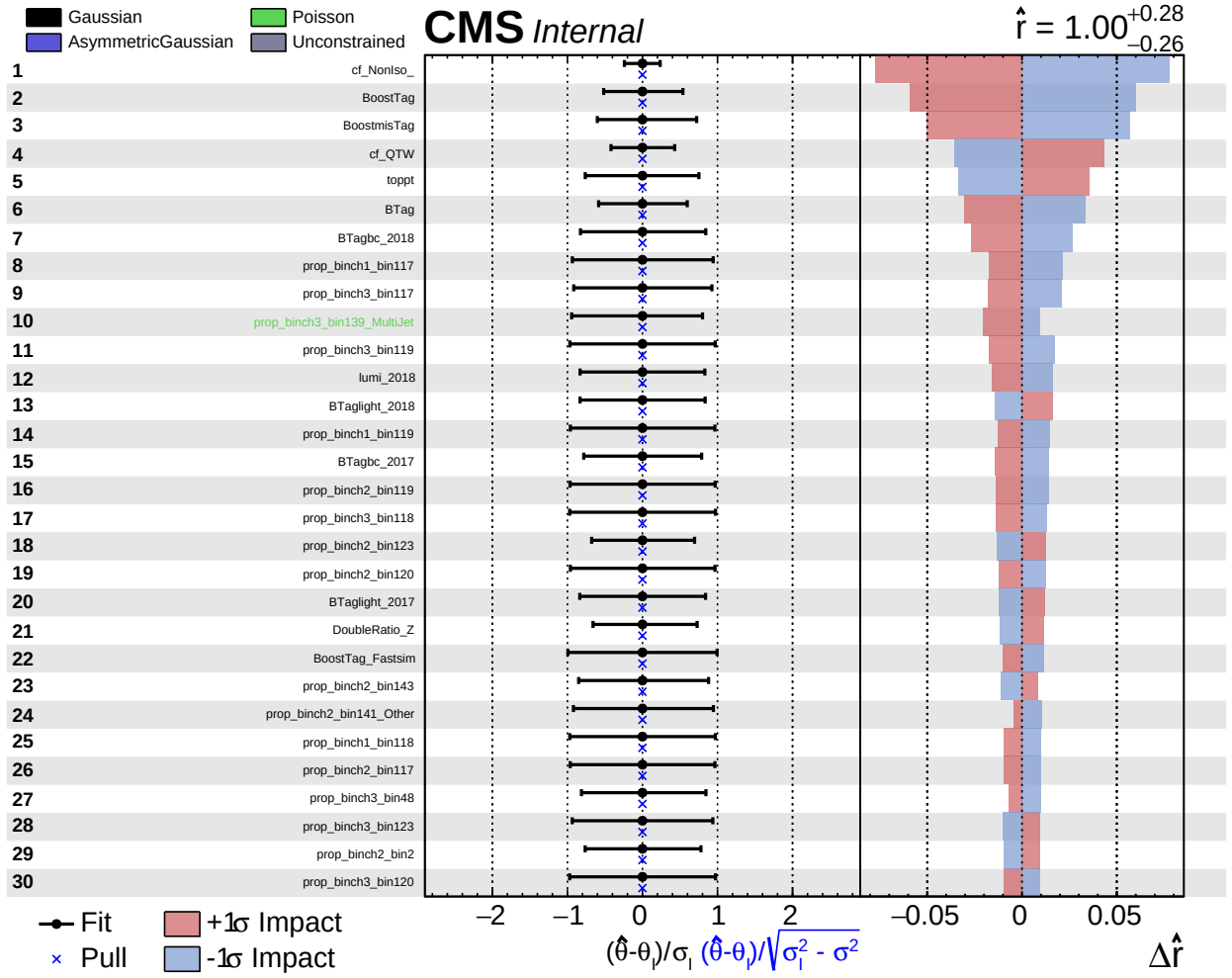


Figure 5.37. Impact of systematic uncertainties on the signal strength, ordered by the highest impact, when fit to $\mu = 1$ Asimov dataset for the R5ttbl scenario. The plot corresponds to the gluino mass $\tilde{g} = 1500$ GeV and the neutralino mass $\tilde{\chi}_1^0 = 500$ GeV, combining the full Run 2 data-taking period.

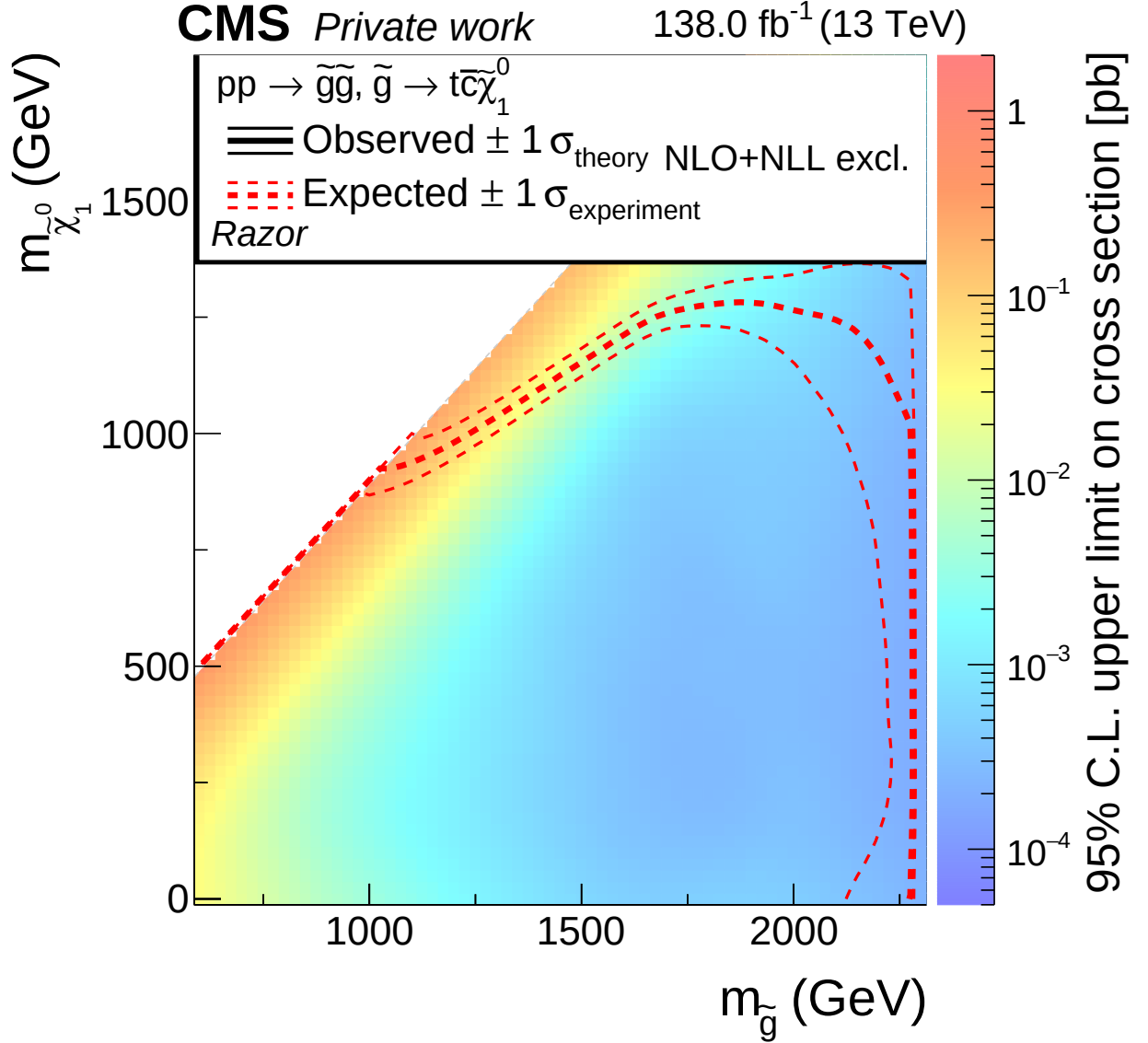


Figure 5.38. Expected upper limits on the gluino mass ($m_{\tilde{g}}$) versus the neutralino mass ($m_{\tilde{\chi}_1^0}$) for the T5ttcc model with an integrated luminosity of 138 fb⁻¹ at $\sqrt{s} = 13$ TeV. The plot shows the observed and expected 95% confidence level upper limits on the production cross-section. The solid black line represents the observed exclusion limit with theoretical uncertainties, while the dashed red line represents the expected exclusion limit with experimental uncertainties. The plot indicates the region excluded at next-to-leading order plus next-to-leading logarithm (NLO+NLL) accuracy.

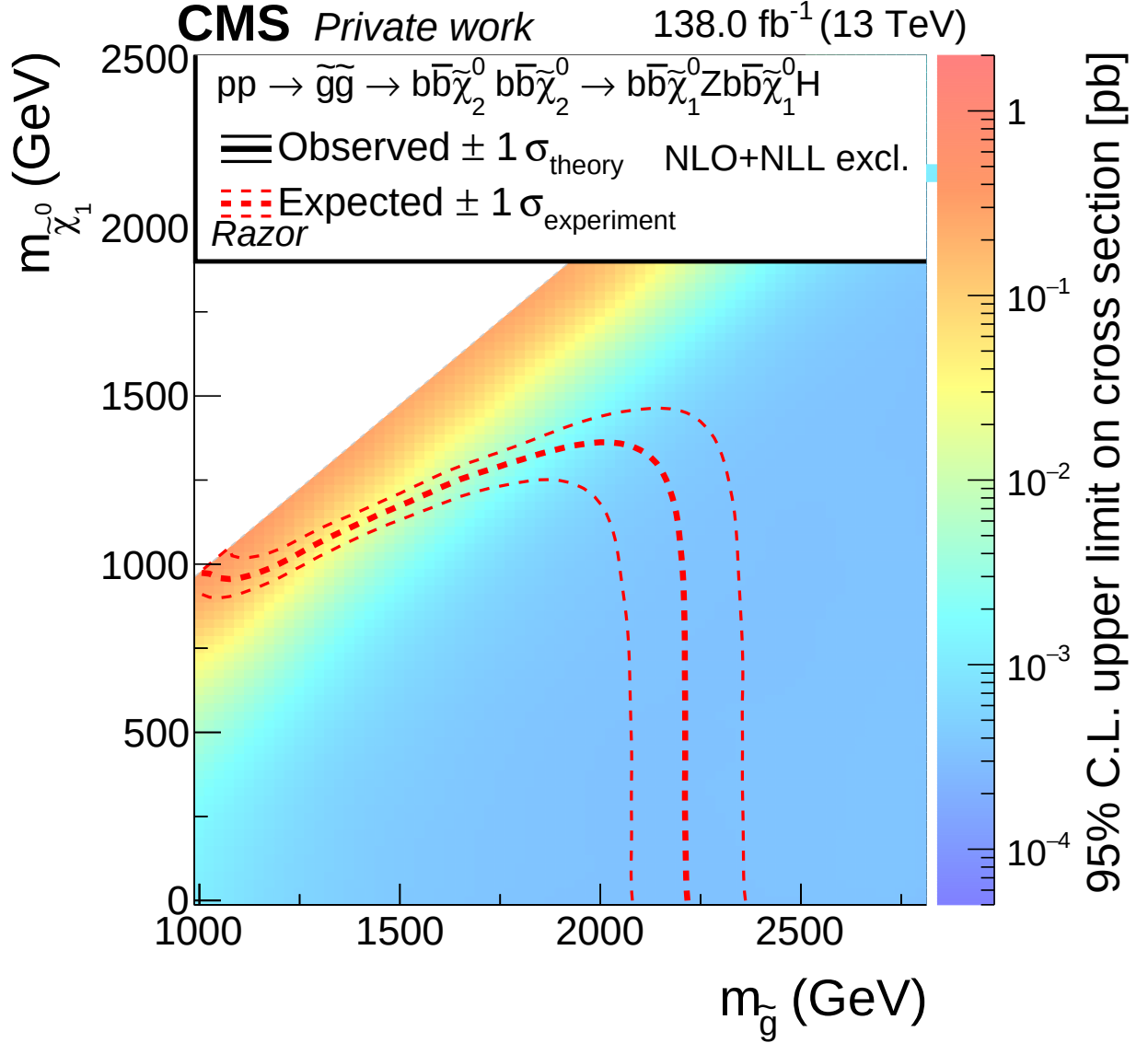


Figure 5.39. Expected upper limits on the gluino mass ($m_{\tilde{g}}$) versus the neutralino mass ($m_{\tilde{\chi}_1^0}$) for the T5bbbbZH model with an integrated luminosity of 138 fb⁻¹ at $\sqrt{s} = 13$ TeV. The plot shows the observed and expected 95% confidence level upper limits on the production cross-section. The solid black line represents the observed exclusion limit with theoretical uncertainties, while the dashed red line represents the expected exclusion limit with experimental uncertainties. The plot indicates the region excluded at next-to-leading order plus next-to-leading logarithm (NLO+NLL) accuracy, for T5bbbbZH signal model.

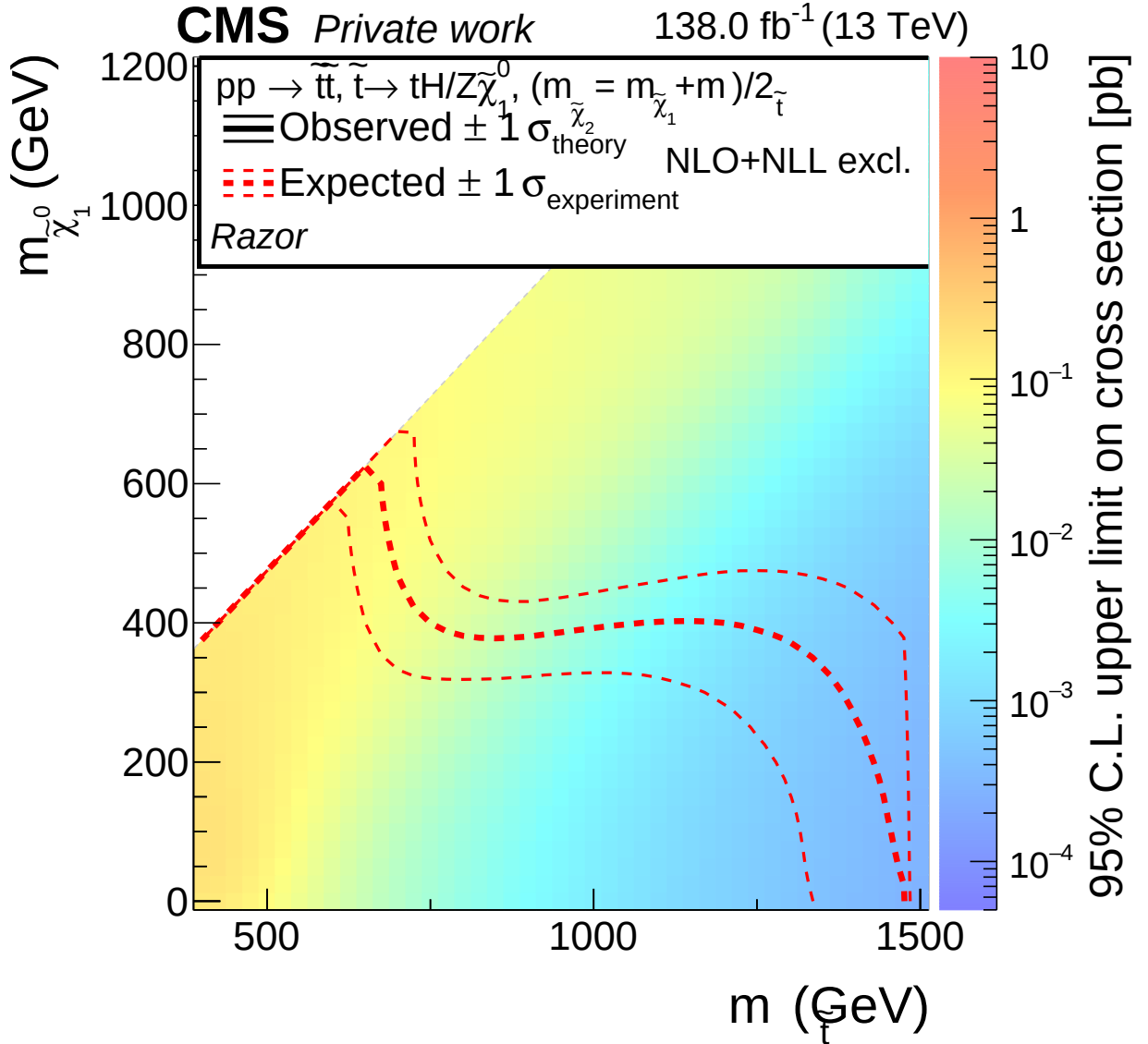


Figure 5.40. The 95% C.L. upper limit on the cross-section for the process $pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 H/Z \rightarrow t\tilde{\chi}_1^0 \tilde{\chi}_2^0$, as a function of the stop mass $m_{\tilde{t}}$ and the neutralino mass $m_{\tilde{\chi}_1^0}$, at $\sqrt{s} = 13$ TeV and 138 fb⁻¹. The plot shows the NLO+NLL exclusion limits, with observed and expected limits, including their $\pm 1\sigma$ theoretical and experimental uncertainties, for T6ttZH signal model.

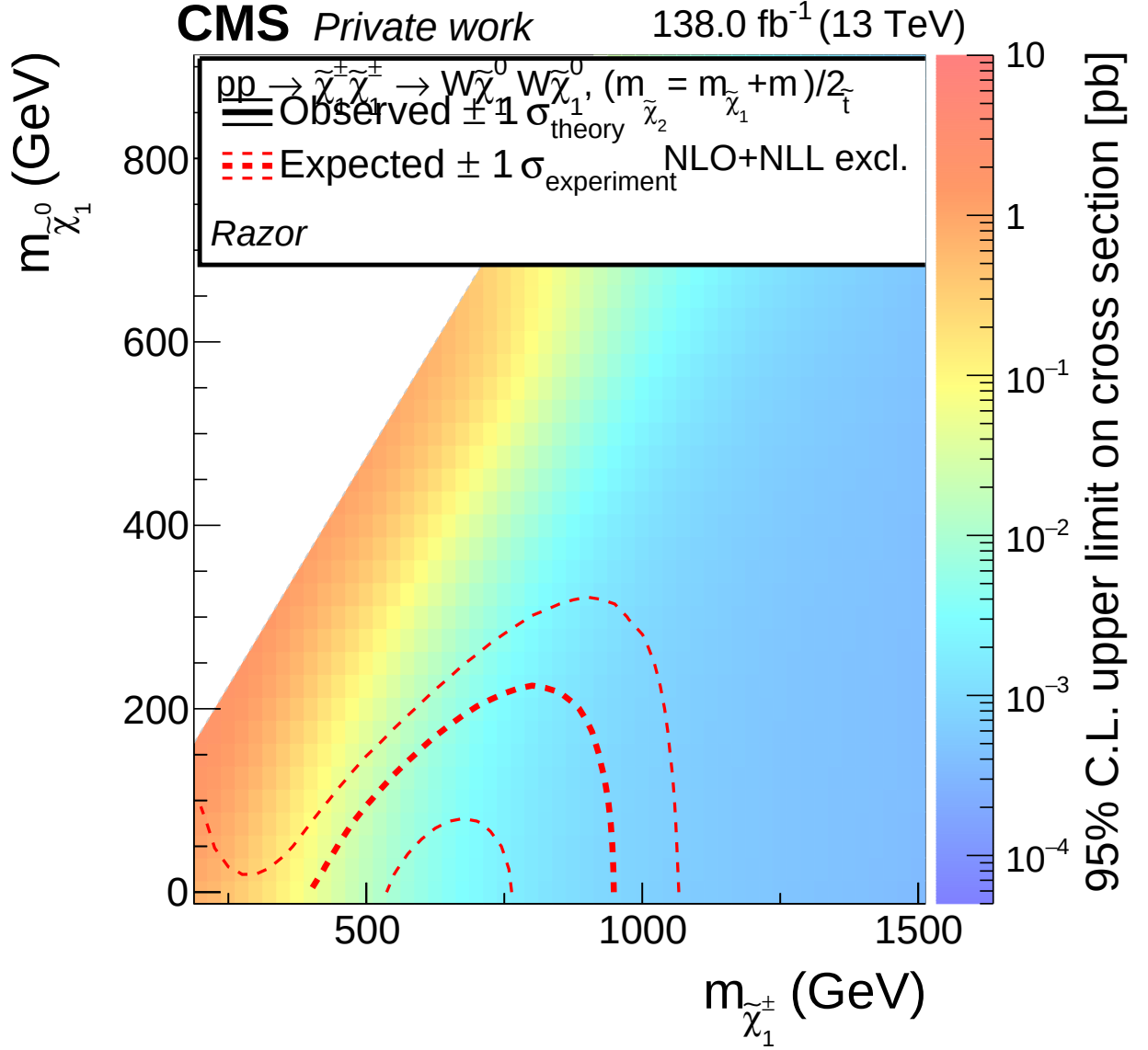


Figure 5.41. The 95% C.L. upper limit on the cross-section for the process $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm \rightarrow W \tilde{\chi}_1^0 W \tilde{\chi}_1^0$, as a function of the chargino mass $m_{\tilde{\chi}_1^\pm}$ and the neutralino mass $m_{\tilde{\chi}_1^0}$, at $\sqrt{s} = 13$ TeV and 138 fb^{-1} . The plot shows the NLO+NLL exclusion limits, with observed and expected limits, including their $\pm 1\sigma$ theoretical and experimental uncertainties, for TChiWW signal model.

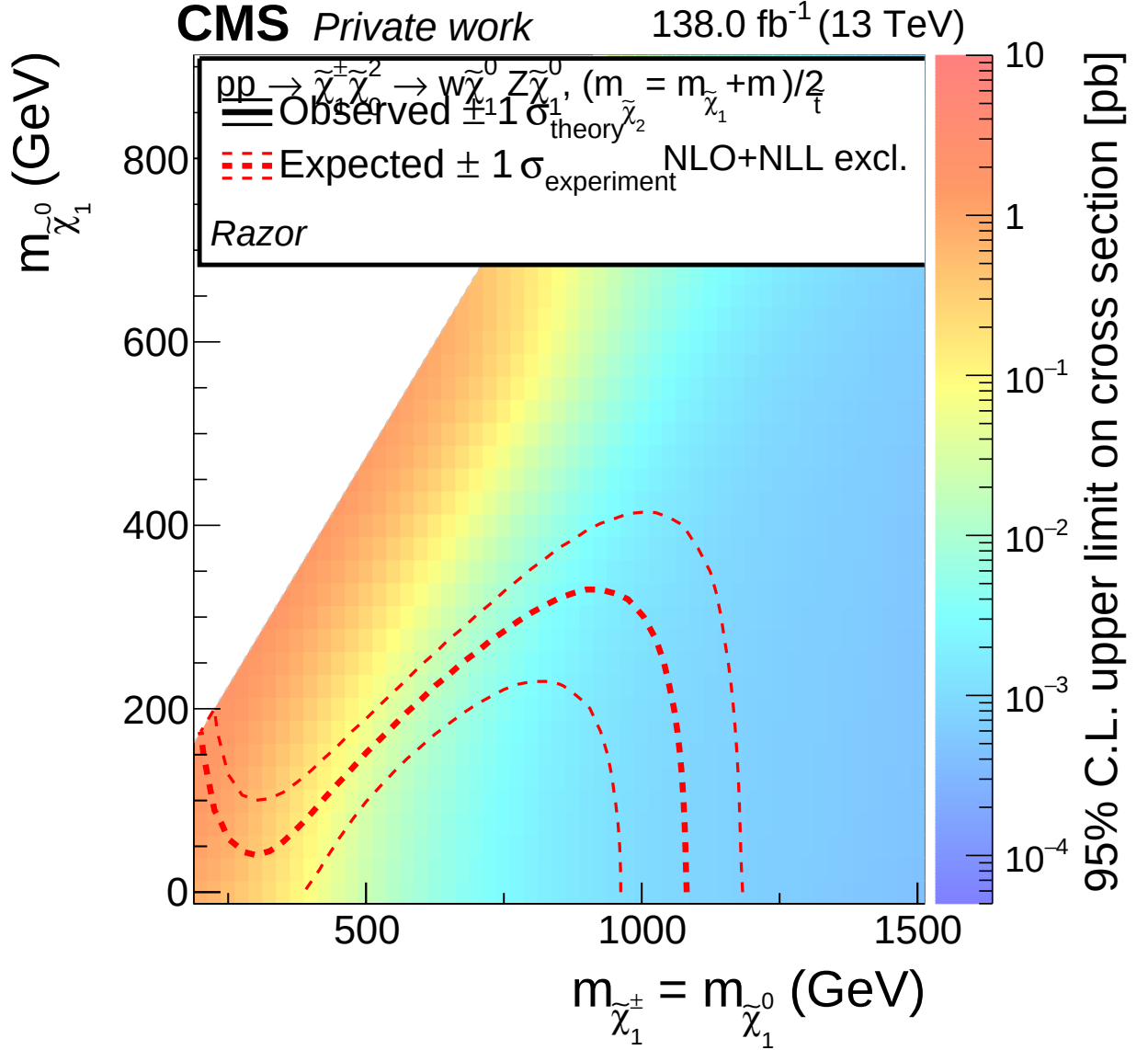


Figure 5.42. The 95% C.L. upper limit on the cross-section for the process $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$, as a function of the chargino mass $m_{\tilde{\chi}_1^\pm}$ and the neutralino mass $m_{\tilde{\chi}_1^0}$, at $\sqrt{s} = 13$ TeV and 138 fb^{-1} . The plot shows the NLO+NLL exclusion limits, with observed and expected limits, including their $\pm 1\sigma$ theoretical and experimental uncertainties for the TChiWZ signal model.

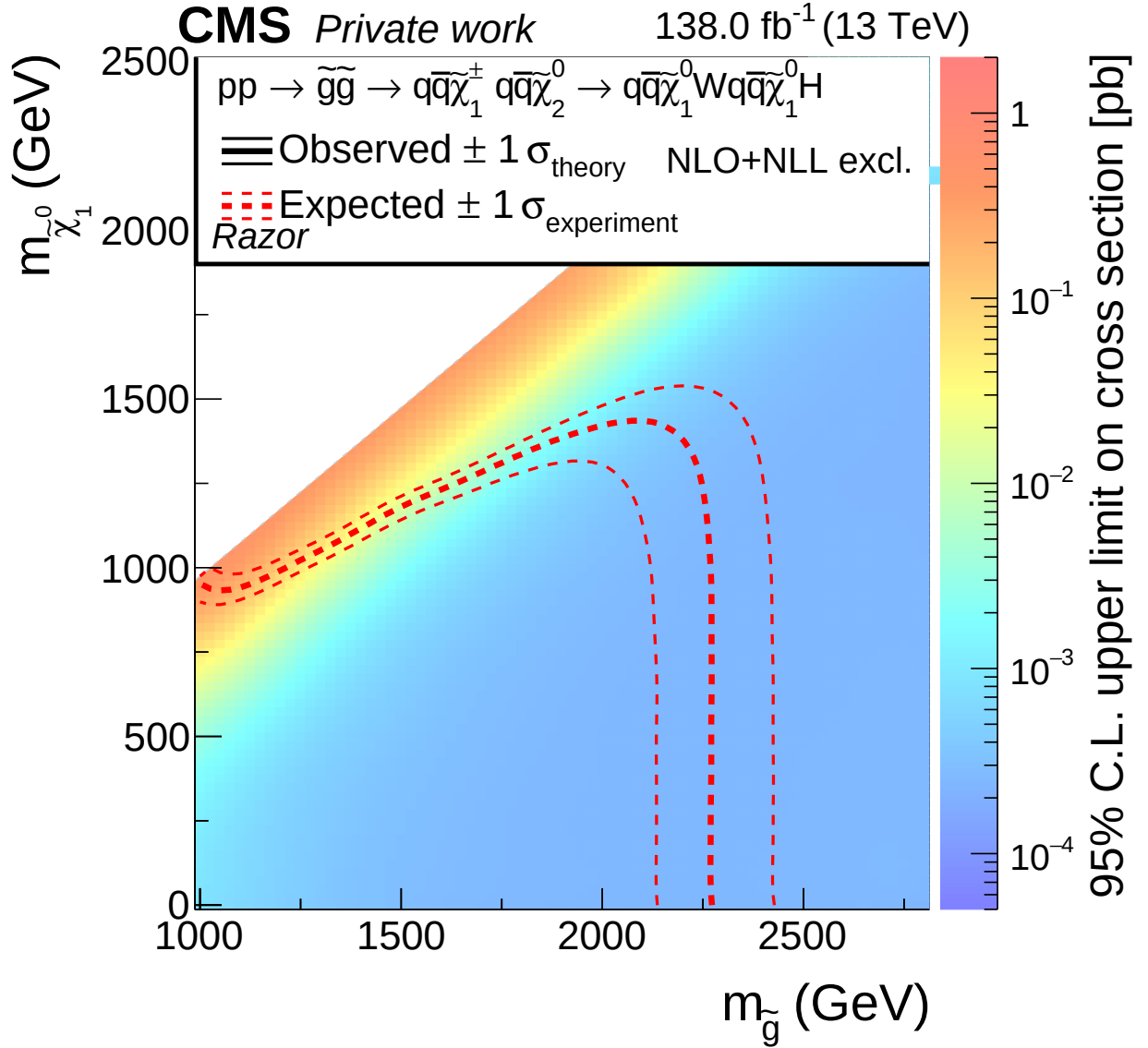


Figure 5.43. The figure shows the exclusion limits at 95% confidence level on the cross-section for the production of gluinos ($\tilde{g}$) in proton-proton collisions at $\sqrt{s} = 13$ TeV with an integrated luminosity of 138.0 fb⁻¹. The observed and expected limits are compared to the theoretical predictions for the T5qqqqWH signal model.

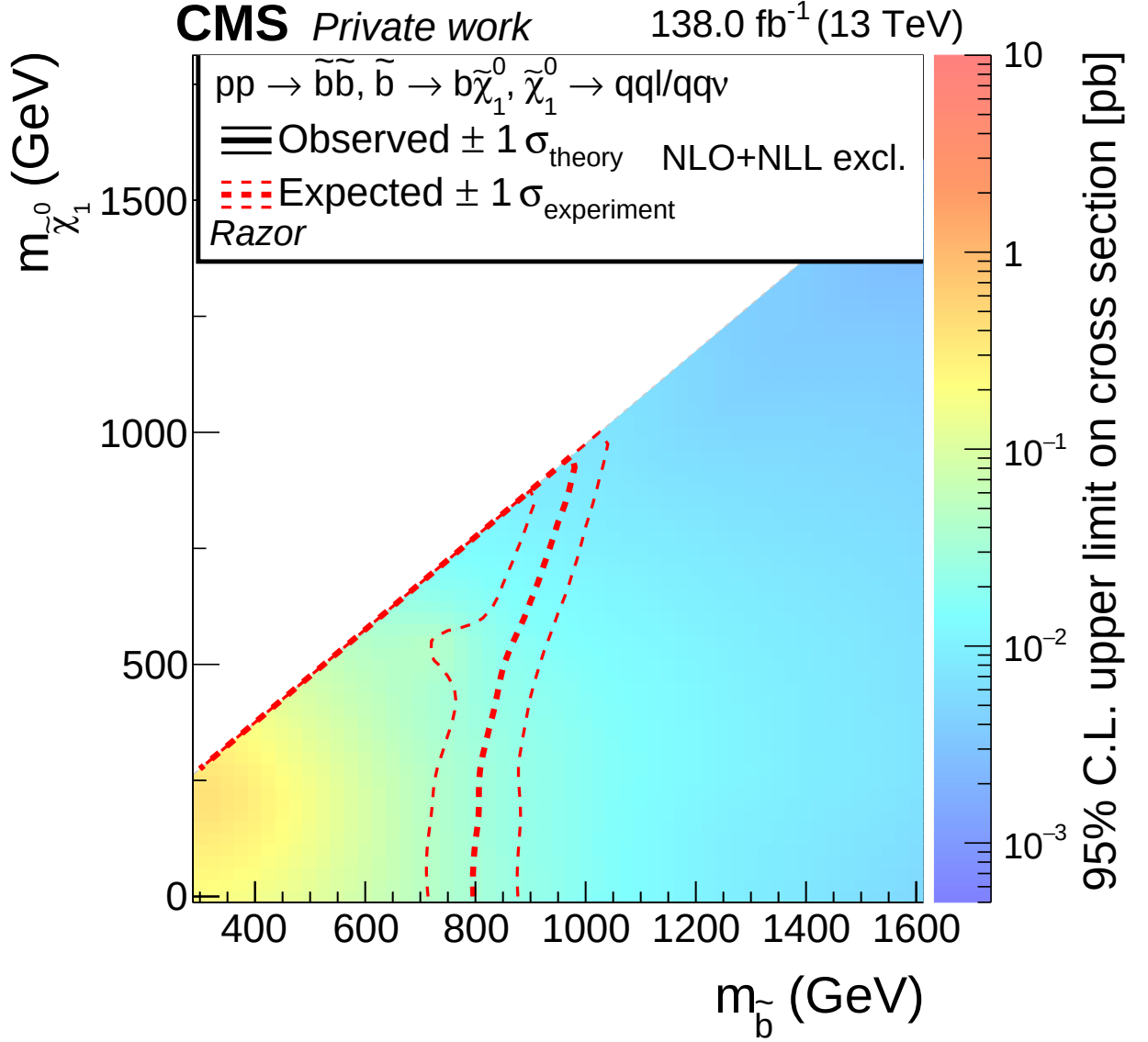


Figure 5.44. The figure illustrates the exclusion limits at 95% confidence level on the cross-section for the production of bottom squarks ($\tilde{b}$) in proton-proton collisions at $\sqrt{s} = 13$ TeV with an integrated luminosity of 138.0 fb⁻¹. The observed and expected limits are shown in comparison to the theoretical predictions for the R2bbqq $\ell\nu$ signal model. The plot includes mass ranges for both the bottom squark and the neutralino ($\tilde{\chi}^0$).

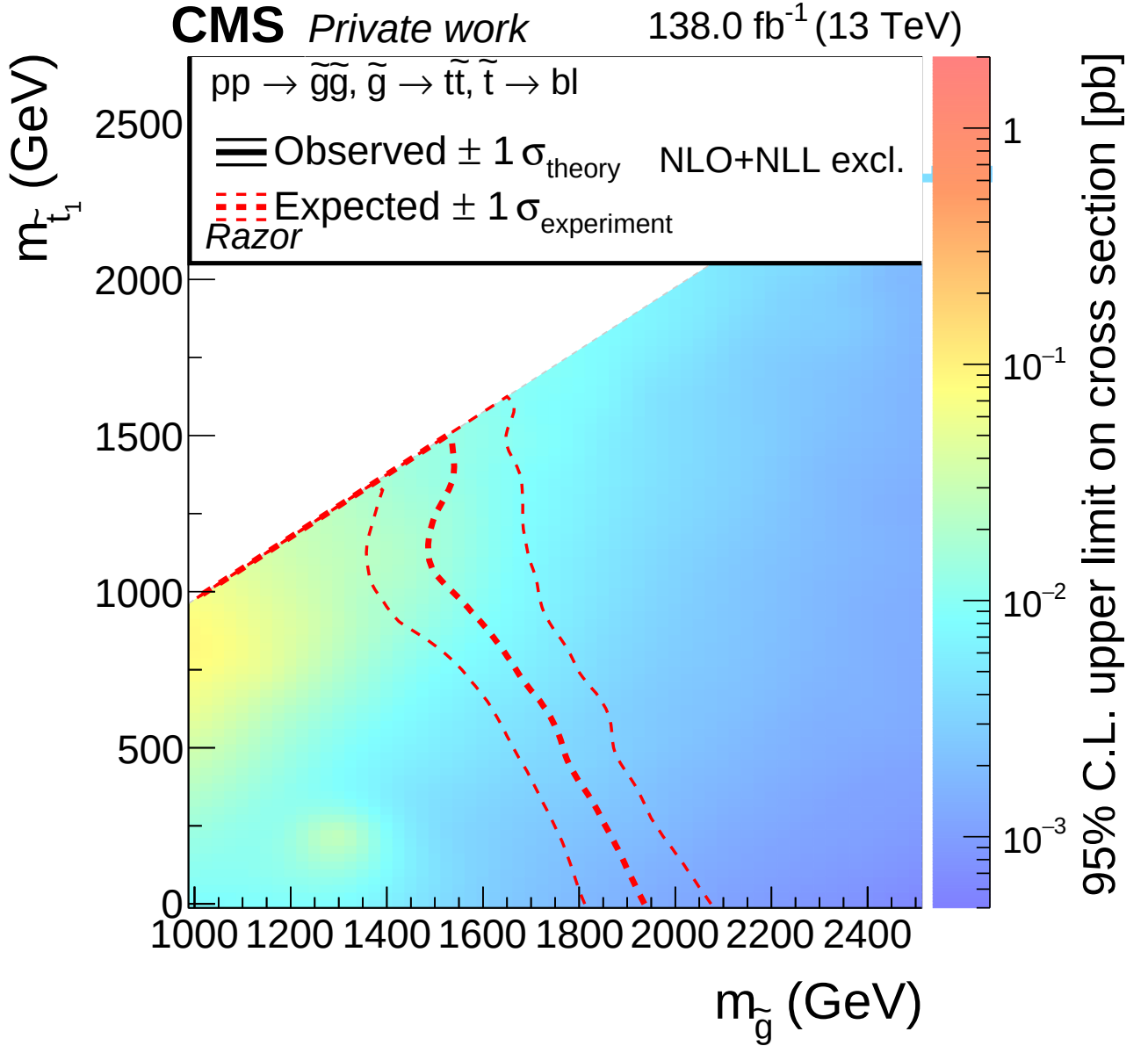


Figure 5.45. The 95% C.L. upper limit on the cross section for the process $\tilde{g}\tilde{g} \rightarrow pp \rightarrow \tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t} \rightarrow t\bar{b} \rightarrow \bar{l}\bar{b}$, as a function of the gluino mass $m_{\tilde{g}}$ and the stop mass $m_{\tilde{t}_1}$, derived at $\sqrt{s} = 13$ TeV with an integrated luminosity of 138.0 fb⁻¹. The observed limits (solid black line) and the expected limits (dashed black line) are shown along with the theoretical cross section (solid red line). The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ experimental uncertainties, respectively.



6. CONCLUSION

This thesis discusses the fascinating features of SUSY and its relevance in high-energy physics. By using Ultra-Legacy data collected by the CMS experiment during the Run 2 data-taking period at the LHC, a comprehensive investigation into the SUSY landscape, focusing mainly on the razor kinematic variables were conducted. Our journey began with a thorough review of the theoretical framework underpinning SUSY, highlighting its potential to address several unresolved questions in particle physics, such as the hierarchy problem and the nature of dark matter. Then the data collection processes of the CMS and the author's contribution to the effort were given.

The core of the research involved using razor kinematic variables, which have proven essential tools for constraining and interpreting SUSY scenarios. These variables, namely the Razor variables, M_R , and R^2 , offer a unique perspective on event kinematics, enabling the discrimination between signal and background processes. Through a detailed analysis of these variables, we analyzed various search regions and optimized the analysis's strategies to enhance the sensitivity to SUSY signals. Also, the first publication of the SUSY searches with razor kinematic variables with Run 2 data collected in 2016 was given, which showed that the limit exclusion for the gluino mass reached the 2 TeV border.

The thesis presented a detailed account of the data analysis methodology, encompassing data selection criteria, background estimation techniques, and systematic uncertainties. Especially the $Z \rightarrow \nu\nu$ background estimation and the systematic uncertainties were the main focus of the thesis.

The culmination of the efforts for yielded results presented in the previous chapters, which provided valuable insights into the search for SUSY particles. While it is not observes any significant excess over the Standard Model expectations, the findings of the research contribute to the global effort to unravel the mysteries of the universe. The absence of evidence for SUSY at the energy scales probed by the analysis places constraints on the parameter space of SUSY models, excluding certain regions and guiding theoretical developments.

This work reflects the collaborative spirit of the international particle physics community and represents a crucial step in refining our understanding of fundamental physics. Looking ahead, the upcoming High-Luminosity LHC era promises to extend the sensitivity of SUSY searches, offering new opportunities to explore previously inaccessible regions of parameter space. As we continue the quest to discover the universe's hidden secrets, this research lays a strong foundation for future investigations, guiding theoretical and experimental efforts to push the frontiers of high-energy physics.

In conclusion, our exploration of SUSY with razor kinematic variables using Ultra-Legacy data from CMS during Run 2 has deepened our understanding of the universe's fundamental building blocks. While we have not yet unraveled the enigma of new physics, our research has pushed the boundaries of knowledge and opened new avenues for future investigations. Looking ahead, the

upcoming High-Luminosity LHC era promises to extend the sensitivity of SUSY searches, offering new opportunities to explore previously inaccessible regions of parameter space.

Additionally, Chapter 4 highlighted the benefits and outcomes of the full beamline simulation for the SPS H2 beamline during the 2016 HGCal test beam. This simulation provided a more realistic foundation for the HGCal test beam analysis and offered valuable insights for optimizing the SPS H2 beamline setup for future test beams.



REFERENCES

- Aad, Georges et al. (2015). “Combined Measurement of the Higgs Boson Mass in p p Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments”. In: *Physical review letters* 114.19, p. 191803.
- Abgrall, Nicolas et al. (2014). “NA61/SHINE facility at the CERN SPS: beams and detector system”. In: *Journal of Instrumentation* 9.06, P06005.
- AC, CERN (1998). “Layout of CMS”. URL: <https://cds.cern.ch/record/39040>.
- Acar, B et al. (2021). “Construction and commissioning of CMS CE prototype silicon modules”. In: *Journal of Instrumentation* 16.04, T04002.
- Alves, Daniele et al. (2012). “Simplified models for LHC new physics searches”. In: *Journal of Physics G: Nuclear and Particle Physics* 39.10, p. 105005.
- Amaldi, Ugo, Wim de Boer, and Hermann Fürstenau (1991). “Comparison of grand unified theories with electroweak and strong coupling constants measured at LEP”. In: *Physics Letters B* 260.3-4, pp. 447–455.
- Anderson, Carl D (1932). “The apparent existence of easily deflectable positives”. In: *Science* 76.1967, pp. 238–239.
- Antcheva, I. et al. (2009). “ROOT — A C++ framework for petabyte data storage, statistical analysis and visualization”. In: *Computer Physics Communications* 180.12. 40 YEARS OF CPC: A celebratory issue focused on quality software for high performance, grid and novel computing architectures, pp. 2499–2512. ISSN: 0010-4655. DOI: <https://doi.org/10.1016/j.cpc.2009.08.005>. URL: <https://www.sciencedirect.com/science/article/pii/S0010465509002550>.
- Arkani-Hamed, Nima, Savas Dimopoulos, and Gia Dvali (1998). “The hierarchy problem and new dimensions at a millimeter”. In: *Physics Letters B* 429.3-4, pp. 263–272.
- Atherton, Henry W et al. (1980). *Precise measurements of particle production by 400 GeV/c protons on beryllium targets*. Tech. rep. CERN.
- ATLAS Collaboration (2021a). “A search for the decays of stopped long-lived particles at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: *JHEP* 07, p. 173. DOI: 10.1007/JHEP07(2021)173. arXiv: 2104.03050 [hep-ex].
- (2021b). “Search for bottom-squark pair production in pp collision events at $\sqrt{s} = 13$ TeV with hadronically decaying τ -leptons, b -jets and missing transverse momentum using the ATLAS detector”. In: *Phys. Rev. D* 104.3, p. 032014. DOI: 10.1103/PhysRevD.104.032014. arXiv: 2103.08189 [hep-ex].

- ATLAS Collaboration (2021c). “Search for chargino–neutralino pair production in final states with three leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”. In: *Eur. Phys. J. C* 81.12, p. 1118. DOI: 10.1140/epjc/s10052-021-09749-7. arXiv: 2106.01676 [hep-ex].
- (2021d). “Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: *Phys. Rev. D* 104.11, p. 112010. DOI: 10.1103/PhysRevD.104.112010. arXiv: 2108.07586 [hep-ex].
 - (2021e). “Search for new phenomena in pp collisions in final states with tau leptons, b-jets, and missing transverse momentum with the ATLAS detector”. In: *Phys. Rev. D* 104.11, p. 112005. DOI: 10.1103/PhysRevD.104.112005. arXiv: 2108.07665 [hep-ex].
 - (2021f). “Search for R-parity-violating supersymmetry in a final state containing leptons and many jets with the ATLAS experiment using $\sqrt{s} = 13\text{TeV}$ proton–proton collision data”. In: *Eur. Phys. J. C* 81.11, p. 1023. DOI: 10.1140/epjc/s10052-021-09761-x. arXiv: 2106.09609 [hep-ex].
 - (2021g). “Search for squarks and gluinos in final states with one isolated lepton, jets, and missing transverse momentum at $\sqrt{s} = 13$ with the ATLAS detector”. In: *Eur. Phys. J. C* 81.7. [Erratum: *Eur.Phys.J.C* 81, 956 (2021)], p. 600. DOI: 10.1140/epjc/s10052-021-09748-8. arXiv: 2101.01629 [hep-ex].
 - (2021h). “Search for supersymmetry in events with four or more charged leptons in 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”. In: *JHEP* 07, p. 167. DOI: 10.1007/JHEP07(2021)167. arXiv: 2103.11684 [hep-ex].
 - (Sept. 2022a). “Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W -boson mass in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”. In: arXiv: 2209.13935 [hep-ex].
 - (Sept. 2022b). “Search for displaced photons produced in exotic decays of the Higgs boson using 13 TeV pp collisions with the ATLAS detector”. In: arXiv: 2209.01029 [hep-ex].
 - (May 2022c). “Search for heavy, long-lived, charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment and the full Run 2 dataset”. In: arXiv: 2205.06013 [hep-ex].
 - (2022d). “Search for long-lived charginos based on a disappearing-track signature using 136 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: *Eur. Phys. J. C* 82.7, p. 606. DOI: 10.1140/epjc/s10052-022-10489-5. arXiv: 2201.02472 [hep-ex].

- ATLAS Collaboration (June 2022e). “Search for new phenomena in final states with photons, jets and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: arXiv: 2206.06012 [hep-ex].
- (Nov. 2022f). “Search for supersymmetry in final states with missing transverse momentum and three or more b -jets in 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: arXiv: 2211.08028 [hep-ex].
- (Apr. 2022g). “Searches for new phenomena in events with two leptons, jets, and missing transverse momentum in 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”. In: arXiv: 2204.13072 [hep-ex].
- (Jan. 2023). “Search for long-lived, massive particles in events with displaced vertices and multiple jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: arXiv: 2301.13866 [hep-ex].
- Barbieri, Riccardo and Gian Francesco Giudice (1988). “Upper bounds on supersymmetric particle masses”. In: *Nuclear Physics B* 306.1, pp. 63–76.
- Bethe, Hans and Rudolph Peierls (1934). “The neutrino”. In: *Nature* 133.3366, pp. 689–690.
- Bohr, Niels (1913). “I. On the constitution of atoms and molecules”. In: *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 26.151, pp. 1–25.
- Bols, Emil et al. (2020). “Jet flavour classification using DeepJet”. In: *Journal of Instrumentation* 15.12, P12012.
- Brandelik, R et al. (1979). “Evidence for planar events in $e^+ e^-$ annihilation at high energies”. In: *Physics Letters B* 86.2, pp. 243–249.
- Broglie, Louis de (1924). “XXXV. A tentative theory of light quanta”. In: *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 47.278, pp. 446–458.
- Brüning, Oliver Sim et al. (2004). *LHC Design Report*. CERN Yellow Reports: Monographs. Geneva: CERN. DOI: 10.5170/CERN-2004-003-V-1. URL: <https://cds.cern.ch/record/782076>.
- Buchmüller, Wilfried and Christoph Lüdelling (2006). “Field theory and standard model”. In: *arXiv preprint hep-ph/0609174*.
- Cacciari, Matteo, Gavin P Salam, and Gregory Soyez (2008). “The anti-kt jet clustering algorithm”. In: *Journal of High Energy Physics* 2008.04, p. 063.
- Canepa, Anadi (2019). “Searches for supersymmetry at the Large Hadron Collider”. In: *Reviews in Physics* 4, p. 100033.
- Casas, J Alberto et al. (2015). “What is a Natural SUSY scenario?” In: *Journal of High Energy Physics* 2015.6, pp. 1–45. DOI: [https://doi.org/10.1007/JHEP03\(2019\)031](https://doi.org/10.1007/JHEP03(2019)031).

- Chadwick, James (1932a). “Possible existence of a neutron”. In: *Nature* 129.3252, pp. 312–312.
- (1932b). “The existence of a neutron”. In: *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character* 136.830, pp. 692–708.
- Charitonidis, Nikolaos and Felix Tellander (2016). *Tertiary particle production and target optimization of the H2 beam line in the SPS North Area*. Tech. rep. Geneva: CERN. arXiv: 1610.09066. URL: <https://cds.cern.ch/record/2226558>.
- Chatrchyan, S. et al. (2008). “The CMS Experiment at the CERN LHC”. In: *JINST* 3, S08004. DOI: 10.1088/1748-0221/3/08/S08004.
- Chatrchyan, Serguei et al. (2013a). “Energy Calibration and Resolution of the CMS Electromagnetic Calorimeter in pp Collisions at $\sqrt{s} = 7$ TeV”. In: *JINST* 8, P09009. DOI: 10.1088/1748-0221/8/09/P09009. arXiv: 1306.2016 [hep-ex].
- Chatrchyan, Serguei et al. (2013b). “Interpretation of searches for supersymmetry with simplified models”. In: *Physical Review D* 88.5, p. 052017.
- CMS Collaboration (Jan. 2017). “The CMS trigger system”. In: *Journal of Instrumentation* 12.01, P01020–P01020. DOI: 10.1088/1748-0221/12/01/p01020.
- (2020a). “MET News”. https://indico.cern.ch/event/884106/contributions/3725350/attachments/1977822/3292861/MET_news_slides.pdf. Accessed: 2023-08-12.
- (2020b). “SPS H2 Beam Line Simulation: Energy Loss and Material Impact at HGCal Test Beam”. URL: <https://indico.cern.ch/event/813822/contributions/3648319/>.
- (2021a). Reweightings to emulate Level-1 ECAL and Muon pre-firing.. Accessed: 2023-08-19.
- (2021b). “Combined searches for the production of supersymmetric top quark partners in proton–proton collisions at $\sqrt{s} = 13$ TeV”. In: *Eur. Phys. J. C* 81.11, p. 970. DOI: 10.1140/epjc/s10052-021-09721-5. arXiv: 2107.10892 [hep-ex].
- (2021c). “Search for chargino-neutralino production in events with Higgs and W bosons using 137 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: *JHEP* 10, p. 045. DOI: 10.1007/JHEP10(2021)045. arXiv: 2107.12553 [hep-ex].
- (2021d). “Search for supersymmetry in final states with two oppositely charged same-flavor leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: *JHEP* 04, p. 123. DOI: 10.1007/JHEP04(2021)123. arXiv: 2012.08600 [hep-ex].
- (2021e). “Search for top squark pair production using dilepton final states in pp collision data collected at $\sqrt{s} = 13$ TeV”. In: *Eur. Phys. J. C* 81.1, p. 3. DOI: 10.1140/epjc/s10052-020-08701-5. arXiv: 2008.05936 [hep-ex].

- CMS Collaboration (2021f). “Search for top squark production in fully-hadronic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: *Phys. Rev. D* 104.5, p. 052001. DOI: 10.1103/PhysRevD.104.052001. arXiv: 2103.01290 [hep-ex].
- (2021g). “Search for top squarks in final states with two top quarks and several light-flavor jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: *Phys. Rev. D* 104.3, p. 032006. DOI: 10.1103/PhysRevD.104.032006. arXiv: 2102.06976 [hep-ex].
 - (July 2022a). “Search for direct pair production of supersymmetric partners of τ leptons in the final state with two hadronically decaying τ leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: arXiv: 2207.02254 [hep-ex].
 - (May 2022b). “Search for electroweak production of charginos and neutralinos at $\sqrt{s} = 13$ TeV in final states containing hadronic decays of WW, WZ, or WH and missing transverse momentum”. In: arXiv: 2205.09597 [hep-ex].
 - (2022c). “Search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: *JHEP* 04, p. 147. DOI: 10.1007/JHEP04(2022)147. arXiv: 2106.14246 [hep-ex].
 - (2022d). “Search for higgsinos decaying to two Higgs bosons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: *JHEP* 05, p. 014. DOI: 10.1007/JHEP05(2022)014. arXiv: 2201.04206 [hep-ex].
 - (2022e). “Search for supersymmetry in final states with two or three soft leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”. In: *JHEP* 04, p. 091. DOI: 10.1007/JHEP04(2022)091. arXiv: 2111.06296 [hep-ex].
 - (2022f). “SUSY Leptons selection and Data/MC Scale Factors”. <https://twiki.cern.ch/twiki/bin/view/CMS/SUSLeptonSF>. Accessed: 2023-08-13.
 - (2023). “CMS SUS Physics Results”. URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Links_to_the_list_of_all_CMS_SUS.
 - (2024a). “CMS B-Tagging and Vertexing Results”. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBTV#DeepJet_algorithm_description. Accessed: 2024-09-12.
 - (2024b). “ParticleNet - CMS Machine Learning Documentation”. <https://cms-ml.github.io/documentation/inference/particlenet.html>. Accessed: 2024-09-12.
- CMS Collaboration and others (2020). “Identification of heavy, energetic, hadronically decaying particles using machine-learning techniques”. In: *Journal of Instrumentation*.

- CMS JetMET POG (2019). “MET Filters Recommendations for Run-II”. https://twiki.cern.ch/twiki/bin/viewauth/CMS/MissingETOptionalFiltersRun2?rev=137Analysis_Recommendations_for_ana. Accessed: 2023-08-12.
- (2023). “Jet Energy Resolution and Corrections (JERC) Subgroup.” <https://twiki.cern.ch/twiki/bin/view/CMS/JetEnergyScale>. Accessed: 2023-08-12.
- CMS JMAR POG (2021). “JETMET Algorithms and Reconstruction (JMAR) Group.” . Accessed: 2023-08-12.
- CMS JME Group (2023). “Jet Energy Resolution and Corrections (JERC) Subgroup”. <https://twiki.cern.ch/twiki/bin/view/CMS/JetEnergyScale>. Accessed: 2023-08-19.
- CMS SUS (2022). “SUS recommendations for analyses combining 2016, 2017, and 2018 UL data”. <https://twiki.cern.ch/twiki/bin/viewauth/CMS/SUSRecommendationsRun2UltraLegacy>. Accessed: 2023-08-18.
- Coet, P and Niels T Doble (1986). *An introduction to the design of high-energy charged particle beams*. Tech. rep. CM-P00061390.
- Coleman, Sidney and Jeffrey Mandula (1967). “All possible symmetries of the S matrix”. In: *Physical Review* 159.5, p. 1251.
- Cowan Jr, Clyde L et al. (1956). “Detection of the free neutrino: a confirmation”. In: *Science* 124.3212, pp. 103–104.
- Dimopoulos, Savas and Leonard Susskind (1979). “Mass without scalars”. In: *Nuclear Physics B* 155.1, pp. 237–252.
- Dirac, Paul Adrien Maurice (1930). “A theory of electrons and protons”. In: *Proceedings of the Royal Society of London. Series A, Containing papers of a mathematical and physical character* 126.801, pp. 360–365.
- Dirac, Paul AM (1933a). “Theory of electrons and positrons”. In: *Nobel Lecture* 12, pp. 320–325.
- (1933b). “Theory of electrons and positrons”. In: *Nobel Lecture* 12, pp. 320–325.
- Djouadi, Abdelhak et al. (1999). “The Minimal supersymmetric standard model: Group summary report”. In: *arXiv preprint hep-ph/9901246*.
- Dordevic, Milos (2018). “The cms particle flow algorithm”. In: *EPJ Web of Conferences*. Vol. 191. EDP Sciences, p. 02016. DOI: <https://doi.org/10.1051/epjconf/201819102016>.
- EGammaPOG (2020). “Cut Based Photon ID for Run 2”. <https://twiki.cern.ch/twiki/bin/view/CMS/CutBasedPhotonIdentificationRun2>. Accessed: 2023-08-13.
- (2023). “A note about IDs in UL”. <https://twiki.cern.ch/twiki/bin/view/CMS/EgammaUL2016To2018>. Accessed: 2023-08-13.
- EN, CERN (2017a). “Layout of T2”. URL: <https://sba.web.cern.ch/sba/>.

- EN, CERN (2017b). “Secondary Beams and Areas, CERN Engineering Department”. URL: <http://sba.web.cern.ch/sba/BeamsAndAreas/h2/H2manual.html>.
- Englert, François and Robert Brout (1964). “Broken symmetry and the mass of gauge vector mesons”. In: *Physical review letters* 13.9, p. 321.
- Faddeev, Ljudvig D, Andrei Alekseevich Slavnov, and GB Pontecorvo (2018). *Gauge fields: introduction to quantum theory*. CRC Press.
- Favara, A and M Pieri (1997). “Confidence level estimation and analysis optimization”. In: *arXiv preprint hep-ex/9706016*.
- Fayet, Pierre (2016). *The Supersymmetric Standard Model*. World Scientific, pp. 397–454.
- Fayet, Pierre and Sergio Ferrara (1977). “Supersymmetry”. In: *Physics Reports* 32.5, pp. 249–334.
- Fayet, Pierre and J Iliopoulos (1974). “Spontaneously broken supergauge symmetries and Goldstone spinors”. In: *Physics Letters B* 51.5, pp. 461–464.
- Fuks, Benjamin et al. (2012). “Gaugino production in proton-proton collisions at a center-of-mass energy of 8 TeV”. In: *JHEP* 10, p. 081. DOI: 10.1007/JHEP10(2012)081. arXiv: 1207.2159 [hep-ph].
- (2013). “Precision predictions for electroweak superpartner production at hadron colliders with Resummino”. In: *Eur. Phys. J. C* 73, p. 2480. doi: 10.1140/epjc/s10052-013-2480-0. arXiv: 1304.0790 [hep-ph].
- “GEANT4” (n.d.). <https://geant4.web.cern.ch/>. Accessed: 2023-08-12.
- Gell-Mann, Murray (1956). “The interpretation of the new particles as displaced charge multiplets”. In: *Il Nuovo Cimento (1955-1965)* 4.2, pp. 848–866.
- (1964). “A schematic model of baryons and mesons”. In: *Phys. Letters* 8.
- Gervais, J-L and Bunji Sakita (1971). “Field theory interpretation of supergauges in dual models”. In: *Nuclear Physics B* 34.2, pp. 632–639.
- Glashow, Sheldon L (1961). “Partial-symmetries of weak interactions”. In: *Nuclear physics* 22.4, pp. 579–588.
- Gol’fand, Yuri A and Evgeny P Likhtman (1989). “Extension of the algebra of Poincaré group generators and violation of p invariance”. In: *Supergravities in diverse dimensions. Volume 1*.
- Goldstone, Jeffrey (1961). “Field theories with «Superconductor» solutions”. In: *Il Nuovo Cimento (1955-1965)* 19.1, pp. 154–164.
- Gross, David J and Frank Wilczek (1973). “Ultraviolet behavior of non-abelian gauge theories”. In: *Physical Review Letters* 30.26, p. 1343.
- Gupta, Mukund (2010). *Calculation of radiation length in materials*. Tech. rep.

- Guralnik, Gerald S, Carl R Hagen, and Thomas WB Kibble (1964). “Global conservation laws and massless particles”. In: *Physical Review Letters* 13.20, p. 585.
- Hamilton, Mark JD (2017). *Mathematical gauge theory*. Springer, pp. 445–524.
- Hasert, FJ et al. (1973). “Search for elastic muon-neutrino electron scattering”. In: *Physics letters B* 46.1, pp. 121–124.
- Hegeman, Jeroen Guido (2018). *The CMS Data Acquisition System for the Phase-2 Upgrade*. Tech. rep. Geneva: CERN. url: <http://cds.cern.ch/record/2629375>.
- Higgs, Peter W (1964). “Broken symmetries and the masses of gauge bosons”. In: *Physical Review Letters* 13.16, p. 508.
- Hoddeson, Lillian et al. (1997). *The rise of the standard model: A history of particle physics from 1964 to 1979*. Cambridge University Press.
- Ivanchenko, Vladimir and Sunanda Banerjee (2019). *Upgrade of CMS full simulation for Run 2*. Tech. rep. Geneva: CERN. doi: 10.1051/epjconf/201921402012. url: <http://cds.cern.ch/record/2650711>.
- Junk, Thomas (1999). “Confidence level computation for combining searches with small statistics”. In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 434.2-3, pp. 435–443.
- Lattes, Cesare Mansueto Giulio, Giuseppe PS Occhialini, and Cecil Frank Powell (1947). “Observations on the tracks of slow mesons in photographic emulsions”. In: *Nature* 160.4067, pp. 486–492.
- Magnan, A-M (2017). “HGCal: a High-Granularity Calorimeter for the endcaps of CMS at HL-LHC”. In: *Journal of Instrumentation* 12.01, p. C01042.
- Mans, J et al. (2012). *CMS Technical Design Report for the Phase I Upgrade of the Hadron Calorimeter*. Tech. rep. Additional contact persons: Jeffrey Spalding, Fermilab, spalding@cern.ch, Didier Contardo, Universite Claude Bernard-Lyon I, contardo@cern.ch. url: <https://cds.cern.ch/record/1481837>.
- Martin, Stephen P (1998). “A supersymmetry primer”. In: *Perspectives on supersymmetry*. World Scientific, pp. 1–98.
- MuonPOG (2021a). “Muon recommendations for 2016 Ultra Legacy data and Monte Carlo”. <https://twiki.cern.ch/twiki/bin/view/CMS/MuonUL2016>. Accessed: 2023-08-13.
- (2021b). “Muon recommendations for 2017 Ultra Legacy data and Monte Carlo”. <https://twiki.cern.ch/twiki/bin/view/CMS/MuonUL2017>. Accessed: 2023-08-13.
- (2021c). “Muon recommendations for 2018 Ultra Legacy data and Monte Carlo”. <https://twiki.cern.ch/twiki/bin/view/CMS/MuonUL2018>. Accessed: 2023-08-13.

- Muons Inc. (n.d.). “G4beamline”. <http://www.muonsinternal.com/muons3/G4beamline>. Accessed on: [23/05/2023].
- Nambu, Yoichiro (1960). “Axial vector current conservation in weak interactions”. In: *Physical Review Letters* 4.7, p. 380.
- Nambu, Yoichiro and Giovanni Jona-Lasinio (1961). “Dynamical model of elementary particles based on an analogy with superconductivity. I”. In: *Physical review* 122.1, p. 345.
- Ne’eman, Yuval (1961). “Derivation of strong interactions from a gauge invariance”. In: *Nuclear physics* 26.2, pp. 222–229.
- Nishijima, Kazuhiko (1955). “Charge independence theory of V particles”. In: *Progress of Theoretical Physics* 13.3, pp. 285–304.
- O’raifeartaigh, L (1975). “Spontaneous symmetry breaking for chirals scalar superfields”. In: *Nuclear Physics B* 96.2, pp. 331–352.
- Peskin, Michael E and F Halzen (1995). “AN INTRODUCTION TO QUANTUM FIELD THEORY, by Michael E. Peskin and Daniel V. Schroeder”.
- Politzer, H David (1973). “Reliable perturbative results for strong interactions?” In: *Physical Review Letters* 30.26, p. 1346.
- Randall, Lisa and Raman Sundrum (1999). “Large mass hierarchy from a small extra dimension”. In: *Physical review letters* 83.17, p. 3370.
- Rizzi, Andrea, Giovanni Petrucciani, and Marco Peruzzi (2019). “A further reduction in CMS event data for analysis: the NANOAOOD format”. In: *EPJ Web of Conferences*. Vol. 214. EDP Sciences, p. 06021.
- Rochester, GD (1989). “Cosmic-ray cloud-chamber contributions to the discovery of the strange particles in the decade 1947-1957”. In: *Pions to quarks: particle physics in the 1950s*.
- Rogan, Christopher (2010). “Kinematical variables towards new dynamics at the LHC”. In: *arXiv preprint arXiv:1006.2727*.
- ROOT (2011). “class TFractionFitter”. <https://root.cern.ch/root/html532/TFractionFitter.html>. Accessed: 2023-08-16.
- Salam, Abdus (1994). “Weak and electromagnetic interactions”. In: *Selected Papers Of Abdus Salam: (With Commentary)*. World Scientific, pp. 244–254.
- Sirunyan, Albert M et al. (2019). “Inclusive search for supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV using razor variables and boosted object identification in zero and one lepton final states”. In: *Journal of High Energy Physics* 2019.3, pp. 1–64.
- Sjöstrand, Torbjörn et al. (2015). “An introduction to PYTHIA 8.2”. In: *Computer Physics Communications* 191, pp. 159–177. issn: 0010-4655. doi: <https://doi.org/10.1016/j.cpc.2015.06.025>.

- cpc.2015.01.024. url: <https://www.sciencedirect.com/science/article/pii/S0010465515000442>.
- Sogami, Ikuo S (1995). “Generalized covariant derivative with gauge and Higgs fields in the standard model”. In: *Progress of Theoretical Physics* 94.1, pp. 117–123.
- Sohnius, Martin F (1985). “Introducing supersymmetry”. In: *Physics reports* 128.2-3, pp. 39–204.
- Strathdee, J (1987). “Super-gauge transformations”. In: *Supersymmetry: Lectures And Reprints (In 2 Volumes)* 76, p. 35.
- Strobbe, Nadja Catharina (2015). “The Razor Boost analysis-Another step in the hunt for new physics at CMS”. PhD thesis. Fermilab.
- Susskind, Leonard (1979). “Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory”. In: *Physical Review D* 20.10, p. 2619.
- Tata, Xerxes (2020). “Natural supersymmetry: status and prospects”. In: *The European Physical Journal Special Topics* 229, pp. 3061–3083.
- TauPOG (2023). “Tau Identification Physics Object Group”. <https://twiki.cern.ch/twiki/bin/view/CMS/Tau>. Accessed: 2023-08-13.
- The Phase-2 Upgrade of the CMS Muon Detectors* (2017). Tech. rep. This is the final version, approved by the LHCC. Geneva: CERN. url: <https://cds.cern.ch/record/2283189>.
- The Phase-2 Upgrade of the CMS Tracker* (2017). Tech. rep. Geneva: CERN. doi: 10.17181/CERN.QZ28.FLHW. url: <https://cds.cern.ch/record/2272264>.
- Thomson, Joseph John (2011). *Recollections and reflections*. Cambridge University Press, pp. 323, 343.
- Utiyama, Ryoyu (1956). “Invariant theoretical interpretation of interaction”. In: *Physical Review* 101.5, p. 1597.
- Volkov, DV and VP Akulov (1973). “Is the neutrino a Goldstone particle?” In: *Physics Letters B* 46.1, pp. 109–110.
- Weinberg, Steven (1967). “A model of leptons”. In: *Physical review letters* 19.21, p. 1264.
- (1995). *The quantum theory of fields*. Vol. 2. Cambridge university press.
- (2005). *The quantum theory of fields: volume 3, supersymmetry*. Cambridge university press.
- Wess, Julius and Bruno Zumino (1974a). “A Lagrangian model invariant under supergauge transformations”. In: *Physics Letters B* 49.1, pp. 52–54.
- (1974b). “Supergauge transformations in four dimensions”. In: *Nuclear Physics B* 70.1, pp. 39–50.
- Wiedemann, Helmut (2015). *Particle accelerator physics*. Springer Nature.
- Yang, Chen Ning (2015). *Elementary particles*. Vol. 2181. Princeton University Press.

- Yang, Chen-Ning and Robert L Mills (1954). “Conservation of isotopic spin and isotopic gauge invariance”. In: *Physical review* 96.1, p. 191.
- Yukawa, Hideki (1935). “On the interaction of elementary particles. I”. In: *Proceedings of the Physico-Mathematical Society of Japan. 3rd Series* 17, pp. 48–57.





CURRICULUM VITAE

Ufuk Güney TOK, started his integrated Ph.D. education in 2015 at Cukurova University. After successfully giving his qualification exams, he first went to CERN in 2017 to work on hadronic forward calorimeter (HF) upgrades. The same year he joined the razor boost physics analysis team to work on new physics searches with razor kinematic variables. The First Run-2 data collected by the CMS detector in 2016 was used for the razor boost team's first publication. He contributed to the team by calculating the closure test to validate the background estimation results. Then the razor boost team started a considerable effort to analyzing complete Run-2 data inclusively with a relatively small group, and he was involved in almost all the analyzing processes, which helped him to increase his knowledge/experience about the CMS experiment and CERN environment. At the same time, he also worked on the HGCAL upgrade project from 2019 to 2020, in which he worked with the HGCAL simulation group and managed to simulate the full SPS H2 secondary beam line to be used for the test beam studies of the HGCAL's CE-E prototype performed in 2018 by the HGCAL collaboration. It helped him increase his experience with the test beam and beamlines and become an expert in the G4beamline program, a particle tracking program built on Geant4 libraries specialized for beamlines. Last year of his Ph.D., he also worked on the ZDC experiment to install and test the ZDC detector at the CMS Point-5, SX5 RP (radiation protection) area, contributing to calculating the dark current of the PMTs of the ZDC's RPD detector.





APPENDIX



A Datasets for Each Data Taken Periods for Run 2

Table A1. Full list of 2016 dataset collected by CMS which is used in this analysis.

Data Samples
/JetHT/Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/JetHT/Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/JetHT/Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/JetHT/Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/JetHT/Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/JetHT/Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/HTMHT/Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/HTMHT/Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/HTMHT/Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/HTMHT/Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/HTMHT/Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/HTMHT/Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAO

Table A2. Full list of 2016 dataset collected by CMS which is used in this analysis (contuniation of previous page).

Data Samples
/SingleElectron/Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleElectron/Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleElectron/Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleElectron/Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleElectron/Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleMuon/Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleMuon/Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleMuon/Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleMuon/Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleMuon/Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SingleMuon/Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SinglePhoton/Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SinglePhoton/Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SinglePhoton/Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SinglePhoton/Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SinglePhoton/Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD
/SinglePhoton/Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9-v2/NANOAOD

Table A3. Full list of 2016APV dataset collected by CMS which is used in this analysis.

Data Samples
/JetHT/Run2016F-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/JetHT/Run2016G-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/JetHT/Run2016H-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/HTMHT/Run2016F-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/HTMHT/Run2016G-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/HTMHT/Run2016H-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/MET/Run2016F-UL2016_MiniAODv2_NanoAODv9-v2/NANOAOB
/MET/Run2016G-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/MET/Run2016H-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleElectron/Run2016F-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleElectron/Run2016G-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleElectron/Run2016H-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleMuon/Run2016F-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleMuon/Run2016G-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleMuon/Run2016H-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/SinglePhoton/Run2016F-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB
/SinglePhoton/Run2016G-UL2016_MiniAODv2_NanoAODv9-v2/NANOAOB
/SinglePhoton/Run2016G-UL2016_MiniAODv2_NanoAODv9-v2/NANOAOB
/SinglePhoton/Run2016H-UL2016_MiniAODv2_NanoAODv9-v1/NANOAOB

Table A4. Full list of 2017 dataset collected by CMS which is used in this analysis.

Data Samples
/JetHT/Run2017B-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/JetHT/Run2017C-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/JetHT/Run2017D-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/JetHT/Run2017E-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/JetHT/Run2017F-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/HTMHT/Run2017B-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/HTMHT/Run2017C-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/HTMHT/Run2017D-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/HTMHT/Run2017E-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/HTMHT/Run2017F-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/MET/Run2017B-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/MET/Run2017C-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/MET/Run2017D-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/MET/Run2017E-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/MET/Run2017F-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleElectron/Run2017B-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleElectron/Run2017C-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleElectron/Run2017D-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleElectron/Run2017E-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleElectron/Run2017F-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleMuon/Run2017B-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleMuon/Run2017C-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleMuon/Run2017D-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleMuon/Run2017E-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SingleMuon/Run2017F-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SinglePhoton/Run2017B-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SinglePhoton/Run2017C-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SinglePhoton/Run2017D-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SinglePhoton/Run2017E-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB
/SinglePhoton/Run2017F-UL2017_MiniAODv2_NanoAODv9-v1/NANOAOB

Table A5. Full list of 2018 dataset collected by CMS which is used in this analysis.

Data Samples
/JetHT/Run2018A-UL2018_MiniAODv2_NanoAODv9-v2/NANOAO
/JetHT/Run2018B-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/JetHT/Run2018C-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/JetHT/Run2018D-UL2018_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2018A-UL2018_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2018B-UL2018_MiniAODv2_NanoAODv9-v2/NANOAO
/MET/Run2018C-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/MET/Run2018D-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/SingleMuon/Run2018A-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/SingleMuon/Run2018B-UL2018_MiniAODv2_NanoAODv9-v2/NANOAO
/SingleMuon/Run2018C-UL2018_MiniAODv2_NanoAODv9-v2/NANOAO
/SingleMuon/Run2018D-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/EGamma/Run2018A-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/EGamma/Run2018B-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/EGamma/Run2018C-UL2018_MiniAODv2_NanoAODv9-v1/NANOAO
/EGamma/Run2018D-UL2018_MiniAODv2_NanoAODv9-v3/NANOAO

B Monte-Carlo Samples for Background and Signal

Table B1. The full list of 2016 Monte-Carlo samples used in the analysis

Dataset	cross section [pb]
/DYJetsToLL_M-4to50_HT-100to200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	204.0
/DYJetsToLL_M-4to50_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	45.743700
/DYJetsToLL_M-4to50_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	45.743700
/DYJetsToLL_M-4to50_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	5.697
/DYJetsToLL_M-4to50_HT-600toInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	1.85
/DYJetsToLL_M-4to50_HT-70to100_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	145.50
/DYJetsToLL_M-50_HT-100to200_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	160.7
/DYJetsToLL_M-50_HT-1200to2500_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	0.1937
/DYJetsToLL_M-50_HT-200to400_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	48.63
/DYJetsToLL_M-50_HT-2500toInf_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	0.003514
/DYJetsToLL_M-50_HT-400to600_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	6.993
/DYJetsToLL_M-50_HT-600to800_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	1.761
/DYJetsToLL_M-50_HT-70to100_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	146.5
/DYJetsToLL_M-50_HT-800to1200_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	0.8021
/GJets_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	8644.000000
/GJets_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	2183.000000
/GJets_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	260.200000
/GJets_HT-40To100_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	18540.000000
/GJets_HT-600ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	93.380000
/QCD_HT100to1500_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	1127.000000
/QCD_HT100to200_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	23590000.000000
/QCD_HT1500to2000_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	119.900000
/QCD_HT2000toInf_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	21.980000
/QCD_HT200to300_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	1555000.000000
/QCD_HT300to500_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	324500.000000
/QCD_HT500to700_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	30310.000000
/QCD_HT50to100_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	187300000.000000
/QCD_HT700to1000_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	6444.000000
/ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOADSIM	3.549000
/ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8/***-v1/NANOADSIM	69.09
/ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8/***-v1/NANOADSIM	115.3
/ST_tW_antitop_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOADSIM	32.510000
/ST_tW_top_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOADSIM	32.450000
**=Run2016H-UL2016_MiniAODv2_NanoAODv9	
***=RunII Summer20UL16NanoAODv9-106X_mcRun2_asymptotic_v17	
****=RunII Summer20UL16NanoAODv9-4cores5k_106X_mcRun2_asymptotic_v17	
*****=Run2016G-UL2016_MiniAODv2_NanoAODv9	

Table B2. The full list of 2016 Monte-Carlo samples used in the analysis (continuation of previous page.)

Dataset	cross section [pb]
/TTGJets_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/***-v1/NANOAOBSIM	3.757000
/TTHH_TuneCP5_13TeV-madgraph-pythia8/***-v2/NANOAOBSIM	0.0006655
/TTTT_TuneCP5_13TeV-amcatnlo-pythia8/***-v2/NANOAOBSIM	0.008213
/TTTW_TuneCP5_13TeV-madgraph-pythia8/***-v2/NANOAOBSIM	0.0007314
/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	88.29
/TTToHadronic_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	377.96
/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	365.34
/TTWH_TuneCP5_13TeV-madgraph-pythia8/***-v2/NANOAOBSIM	0.001141
/TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/***-v1/NANOAOBSIM	0.216000
/TTWJetsToQQ_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/***-v1/NANOAOBSIM	0.437700
/TTWW_TuneCP5_13TeV-madgraph-pythia8/***-v1/NANOAOBSIM	0.007003
/TTWZ_TuneCP5_13TeV-madgraph-pythia8/***-v1/NANOAOBSIM	0.002453
/TTZH_TuneCP5_13TeV-madgraph-pythia8/***-v2/NANOAOBSIM	No value
/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.2432
/TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.5104
/TTZZ_TuneCP5_13TeV-madgraph-pythia8/***-v1/NANOAOBSIM	0.001386
/VBFHTtoBB_M-125_TuneCP5_13TeV-powheg-pythia8/***-v2/NANOAOBSIM	3.873000
/VBFHTtoBB_M-125_TuneCP5_13TeV-powheg-pythia8/***-v2/NANOAOBSIM	3.873000
/VBFHTtoWWTo2L2Nu_M-125_TuneCP5_13TeV-powheg-jhugen727-pythia8/***-v2/NANOAOBSIM	3.892000
/WJetsToLNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	1256.000000
/WJetsToLNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	1.160000
/WJetsToLNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	335.5
/WJetsToLNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	0.008001
/WJetsToLNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	45.25
/WJetsToLNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	10.97
/WJetsToLNu_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	1264.0
/WJetsToLNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	4.933
/WJetsToQQ_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	2549.0
/WJetsToQQ_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	276.5
/WJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	59.25
/WJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	28.75
*=Run2016H-UL2016_MiniAODv2_NanoAODv9	
**=Run2016F-UL2016_MiniAODv2_NanoAODv9	
***=RunIIISummer20UL16NanoAODv9-106X_mcRun2_asymptotic_v17	
****=RunIIISummer20UL16NanoAODv9-4cores5k_106X_mcRun2_asymptotic_v17	
*****=Run2016G-UL2016_MiniAODv2_NanoAODv9	

Table B3. The full list of 2016 Monte-Carlo samples used in the analysis (continuation of previous page.)

Dataset	cross section [pb]
/WWTo1LL1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	80.74000
/WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	11.09
/WWTo4Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	51.723000
/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.2158
/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8/***_ext1-v1/NANOAOBSIM	0.2158
/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.1707
/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8/***_ext1-v1/NANOAOBSIM	0.1707
/WZTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	10.710000
/WZTo1L3Nu_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	3.033000
/WZTo3LNU_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	5.213
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.05709
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/***_ext1-v1/NANOAOBSIM	0.05709
/WminusH_HToBB_WToLNU_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.033700
/WminusH_HToBB_WToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.034922
/WminusH_WToQQ_HToInvisible_M125_TuneCP5_13TeV_powheg_pythia8/***-v2/NANOAOBSIM	0.3674
/WplusH_HToBB_WToLNU_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.053100
/WplusH_HToBB_WToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.055037
/WplusH_WToQQ_HToInvisible_M125_TuneCP5_13TeV_powheg_pythia8/***-v2/NANOAOBSIM	0.5884
/ZH_HToBB_ZToBB_M-125_TuneCP5_13TeV-powheg-pythia8/***-v2/NANOAOBSIM	0.554000
/ZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.048600
/ZH_HToBB_ZToNuNu_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.089100
/ZH_HToBB_ZToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.309931
/ZJetsToNuNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	267.0
/ZJetsToNuNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	0.2497
/ZJetsToNuNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	73.08
/ZJetsToNuNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	0.005618
/ZJetsToNuNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	9.904
/ZJetsToNuNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	2.413
/ZJetsToNuNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	1.071
/ZJetsToQQ_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	1012.0
/ZJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	25.34
/ZJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	190.2
*=Run2016H-UL2016_MiniAODv2_NanoAODv9	
**=Run2016F-UL2016_MiniAODv2_NanoAODv9	
***=RunIISummer20UL16NanoAODv9-106X_mcRun2_asymptotic_v17	
****=RunIISummer20UL16NanoAODv9-4cores5k_106X_mcRun2_asymptotic_v17	
*****=Run2016G-UL2016_MiniAODv2_NanoAODv9	

Table B4. The full list of 2016 Monte-Carlo samples used in the analysis (continuation of previous page.)

Dataset	cross section [pb]
/ZZTo2L2Nu_TuneCP5_13TeV_powheg_pythia8/***.v1/NANOADSIM	0.6008
/ZZTo2Nu2Q_5f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***.v1/NANOADSIM	4.040000
/ZZTo4L_TuneCP5_13TeV_powheg_pythia8/***.v1/NANOADSIM	1.325
/ZZTo4Q_5f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***.v1/NANOADSIM	6.842000
/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8/***.v1/NANOADSIM	0.01398
/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8/***.ext1-v1/NANOADSIM	0.01398
/ggZH_HToBB_ZToBB_M-125_TuneCP5_13TeV-powheg-pythia8/***.v2/NANOADSIM	0.043200
/ggZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8/***.v1/NANOADSIM	0.007800
/ggZH_HToBB_ZToNuNu_M-125_TuneCP5_13TeV-powheg-pythia8/***.v1/NANOADSIM	0.014400
/ggZH_HToBB_ZToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/***.v1/NANOADSIM	0.04319
/ggZH_ZToQQ_HToInvisible_M125_TuneCP5_13TeV_powheg_pythia8/***.v1/NANOADSIM	0.04319
/ttHJetToNonbb_M125_TuneCP5_13TeV_amcatnloFXFX_madspin_pythia8/***.v1/NANOADSIM	0.507
/ttHJetToTobb_M125_TuneCP5_13TeV_amcatnloFXFX_madspin_pythia8/***.v1/NANOADSIM	0.211800
*=Run2016H-UL2016_MiniAODv2_NanoAODv9	
**=Run2016F-UL2016_MiniAODv2_NanoAODv9	
***=RunIISummer20UL16NanoAODv9-106X_mcRun2_asymptotic_v17	
****=RunIISummer20UL16NanoAODv9-4cores5k_106X_mcRun2_asymptotic_v17	
*****=Run2016G-UL2016_MiniAODv2_NanoAODv9	

Table B5. The full list of 2016APV Monte-Carlo samples used in the analysis.

Dataset	cross section [pb]
/DYJetsToLL_M-4to50_HT-100to200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v3/NANOADSIM	204.0
/DYJetsToLL_M-4to50_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v3/NANOADSIM	45.743700
/DYJetsToLL_M-4to50_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v3/NANOADSIM	5.697
/DYJetsToLL_M-4to50_HT-600toInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	1.85
/DYJetsToLL_M-4to50_HT-70to100_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	145.50
/DYJetsToLL_M-50_HT-100to200_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	160.7
/DYJetsToLL_M-50_HT-1200to2500_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	0.1937
/DYJetsToLL_M-50_HT-200to400_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	48.63
/DYJetsToLL_M-50_HT-2500toInf_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	0.003514
/DYJetsToLL_M-50_HT-400to600_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	6.993
/DYJetsToLL_M-50_HT-600to800_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	1.761
/DYJetsToLL_M-50_HT-70to100_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	146.5
/DYJetsToLL_M-50_HT-800to1200_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	0.8021
/GJets_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/*****-v1/NANOADSIM	8644.000000
/GJets_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	2183.000000
/GJets_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	260.200000
/GJets_HT-40To100_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	18540.000000
/GJets_HT-600ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	86.58
/QCD_HT1000to1500_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	1127.000000
/QCD_HT100to200_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	23590000.000000
/QCD_HT1500to2000_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	119.900000
/QCD_HT2000toInf_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	21.980000
/QCD_HT200to300_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	1555000.000000
/QCD_HT300to500_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	324500.000000
/QCD_HT500to700_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	30310.000000
/QCD_HT50to100_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	187300000.000000
/QCD_HT700to1000_TuneCP5_PSWeights_13TeV-madgraph-pythia8/***-v1/NANOADSIM	6444.000000
/ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOADSIM	3.549000
/ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8/***-v1/NANOADSIM	69.09
/ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8/***-v1/NANOADSIM	115.3
/ST_tW_antitop_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOADSIM	32.510000
/ST_tW_top_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOADSIM	32.450000
*=Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9	
**=Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9	
***=RunIISummer20UL16NanoAODAPV9-106X_mcRun2_asymptotic_preVFP_v11	
****=Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=RunIISummer20UL16NanoAODAPV9-4cores5k_106X_mcRun2_asymptotic_preVFP_v11	

Table B6. The full list of 2016APV Monte-Carlo samples used in the analysis (continuation of previous page).

Dataset	cross section [pb]
/TTGJets_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/***-v2/NANOADSIM	3.757000
/TTHH_TuneCP5_13TeV-madgraph-pythia8/***-v2/NANOADSIM	0.0006655
/TTTT_TuneCP5_13TeV-amcatnlo-pythia8/***-v2/NANOADSIM	0.008213
/TTTW_TuneCP5_13TeV-madgraph-pythia8/***-v2/NANOADSIM	0.0007314
/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOADSIM	88.29
/TTToHadronic_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOADSIM	377.96
/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOADSIM	365.34
/TTWH_TuneCP5_13TeV-madgraph-pythia8/***-v2/NANOADSIM	0.001141
/TTWJetsToLNU_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/***-v2/NANOADSIM	0.216000
/TTWJetsToQQ_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/***-v2/NANOADSIM	0.437700
/TTWW_TuneCP5_13TeV-madgraph-pythia8/***-v1/NANOADSIM	0.007003
/TTWZ_TuneCP5_13TeV-madgraph-pythia8/***-v1/NANOADSIM	0.002453
/TTZH_TuneCP5_13TeV-madgraph-pythia8/***-v2/NANOADSIM	0.00113
/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOADSIM	0.2432
/TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOADSIM	0.5104
/TTZZ_TuneCP5_13TeV-madgraph-pythia8/***-v1/NANOADSIM	0.001386
/WJetsToLNU_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	1256.000000
/WJetsToLNU_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	1.160000
/WJetsToLNU_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/***_ext1-v2/NANOADSIM	1.160000
/WJetsToLNU_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	335.5
/WJetsToLNU_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	0.008001
/WJetsToLNU_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/***_ext1-v2/NANOADSIM	0.008001
/WJetsToLNU_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	45.25
/WJetsToLNU_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/***_ext1-v1/NANOADSIM	45.25
/WJetsToLNU_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	10.97
/WJetsToLNU_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/***_ext1-v2/NANOADSIM	10.97
/WJetsToLNU_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	1264.0
/WJetsToLNU_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOADSIM	4.933
/WJetsToLNU_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8/***_ext1-v2/NANOADSIM	4.933
/WJetsToQQ_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	2549.0
/WJetsToQQ_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	276.5
/WJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	59.25
/WJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOADSIM	28.75
*=Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9	
**=Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9	
***=RunIISummer20UL16NanoAODAPVv9-106X_mcRun2_asymptotic_preVFP_v11	
****=Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=RunIISummer20UL16NanoAODAPVv9-4cores5k_106X_mcRun2_asymptotic_preVFP_v11	

Table B7. The full list of 2016APV Monte-Carlo samples used in the analysis (continuation of previous page).

Dataset	cross section [pb]
/VBFHToWWTo2L2Nu_M-125_TuneCP5_13TeV-powheg-jhugen727-pythia8/***-v1/NANOAOBSIM	3.892000
/WWTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	80.74000
/WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	11.09
/WWTo4Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v3/NANOAOBSIM	51.723000
/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.2158
/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8/***_ext1-v1/NANOAOBSIM	0.2158
/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.1707
/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8/***_ext1-v1/NANOAOBSIM	0.1707
/WZTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	10.710000
/WZTo1L3Nu_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	3.033000
/WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	5.213
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.05709
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/***_ext1-v1/NANOAOBSIM	0.05709
/WminusH_HToBB_WToLNU_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.033700
/WminusH_WToQQ_HToInvisible_M125_TuneCP5_13TeV_powheg_pythia8/***-v2/NANOAOBSIM	0.3674
/WplusH_HToBB_WToLNU_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.053100
/WplusH_WToQQ_HToInvisible_M125_TuneCP5_13TeV_powheg_pythia8/***-v3/NANOAOBSIM	0.5884
/ZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.048600
/ZH_HToBB_ZToNuNu_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.089100
/ZH_HToBB_ZToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.309931
*==Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9	
**=Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9	
***=RunIISummer20UL16NanoAODAPVv9-106X_mcRun2_asymptotic_preVFP_v11	
****=Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=RunIISummer20UL16NanoAODAPVv9-4cores5k_106X_mcRun2_asymptotic_preVFP_v11	

Table B8. The full list of 2016APV Monte-Carlo samples used in the analysis (continuation of previous page).

Dataset	cross section [pb]
/ZJetsToNuNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	267.0
/ZJetsToNuNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	0.2497
/ZJetsToNuNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v1/NANOAOBSIM	73.08
/ZJetsToNuNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	0.005618
/ZJetsToNuNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	9.904
/ZJetsToNuNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	2.413
/ZJetsToNuNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	1.071
/ZJetsToQQ_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	1012.0
/ZJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	25.34
/ZJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8/***-v2/NANOAOBSIM	190.2
/ZZTo2L2Nu_TuneCP5_13TeV_powheg_pythia8/***-v1/NANOAOBSIM	0.6008
/ZZTo2Nu2Q_5f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	4.040000
/ZZTo4L_TuneCP5_13TeV_powheg_pythia8/***-v1/NANOAOBSIM	1.325
/ZZTo4Q_5f_TuneCP5_13TeV-amcatnloFXFX-pythia8/***-v1/NANOAOBSIM	6.842000
/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8/***-v1/NANOAOBSIM	0.01398
/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8/***_ext1-v1/NANOAOBSIM	0.01398
/ggZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.007800
/ggZH_HToBB_ZToNuNu_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.014400
/ggZH_HToBB_ZToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/***-v1/NANOAOBSIM	0.04319
/ggZH_ZToQQ_HToInvisible_M125_TuneCP5_13TeV_powheg_pythia8/***-v2/NANOAOBSIM	0.04319
/ttHJetToNonbb_M125_TuneCP5_13TeV_amcatnloFXFX_madspin_pythia8/***-v1/NANOAOBSIM	0.507
/ttHJetToTobb_M125_TuneCP5_13TeV_amcatnloFXFX_madspin_pythia8/***-v1/NANOAOBSIM	0.211800
**=Run2016F-HIPM_UL2016_MiniAODv2_NanoAODv9	
***=Run2016D-HIPM_UL2016_MiniAODv2_NanoAODv9	
****=RunIISummer20UL16NanoAODAPVv9-106X_mcRun2_asymptotic_preVFP_v11	
*****=Run2016B-ver2_HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016B-ver1_HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016C-HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=Run2016E-HIPM_UL2016_MiniAODv2_NanoAODv9	
*****=RunIISummer20UL16NanoAODAPVv9-4cores5k_106X_mcRun2_asymptotic_preVFP_v11	

Table B9. The full list of 2017 Monte-Carlo samples used in the analysis.

Dataset	cross section [pb]
/DYJetsToLL_M-4to50_HT-100to200_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	204.0
/DYJetsToLL_M-4to50_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	54.39
/DYJetsToLL_M-4to50_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	5.696000
/DYJetsToLL_M-4to50_HT-600toInf_TuneCP5_13TeV-madgraphMLM-pythia8/**-v3/NANOAOBSIM	1.85
/DYJetsToLL_M-4to50_HT-70to100_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	145.5
/DYJetsToLL_M-50_HT-100to200_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	160.7
/DYJetsToLL_M-50_HT-1200to2500_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	0.1937
/DYJetsToLL_M-50_HT-200to400_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	48.63
/DYJetsToLL_M-50_HT-2500toInf_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	0.003514
/DYJetsToLL_M-50_HT-400to600_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	6.993
/DYJetsToLL_M-50_HT-600to800_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	1.761
/DYJetsToLL_M-50_HT-70to100_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	146.50
/DYJetsToLL_M-50_HT-800to1200_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	0.8021
/GJets_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/*****-v1/NANOAOBSIM	8640.0000
/GJets_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	2185.0000
/GJets_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	277.4000
/GJets_HT-40To100_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	394583.0000
/QCD_HT1000to1500_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	1127.0
/QCD_HT100to200_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	23590000.0
/QCD_HT1500to2000_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	109.8
/QCD_HT2000toInf_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	21.98
/QCD_HT200to300_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	1555000.0
/QCD_HT300to500_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	324500.0
/QCD_HT500to700_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	30310.0
/QCD_HT50to100_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	187300000.0
/QCD_HT700to1000_TuneCP5_PSWeights_13TeV-madgraph-pythia8/**-v1/NANOAOBSIM	6444.0
/ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8/**-v1/NANOAOBSIM	3.549
/ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8/**-v1/NANOAOBSIM	69.09
/ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8/**-v1/NANOAOBSIM	115.3
/ST_tW_antitop_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	34.97
/ST_tW_top_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	34.91
/VBFHTtoBB_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	3.873
/VBFHTtoWWto2L2Nu_M-125_TuneCP5_13TeV-powheg-jhugen727-pythia8/**-v2/NANOAOBSIM	3.892
*Run2017B-UL2017_MiniAODv2_NanoAODv9	
**=RunIISummer20UL17NanoAODv9-106X_mc2017_realistic_v9	
***=Run2017C-UL2017_MiniAODv2_NanoAODv9	
****=Run2017E-UL2017_MiniAODv2_NanoAODv9	
*****=Run2017D-UL2017_MiniAODv2_NanoAODv9	
*****=RunIISummer20UL17NanoAODv9-4cores5k_106X_mc2017_realistic_v9	
*****=Run2017F-UL2017_MiniAODv2_NanoAODv9	

Table B10. The full list of 2017 Monte-Carlo samples used in the analysis (continuation of previous page).

Dataset	cross section [pb]
/TTGJets_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/**-v1/NANOADSIM	4.078
/TTHH_TuneCP5_13TeV-madgraph-pythia8/**-v2/NANOADSIM	0.0006655
/TTTT_TuneCP5_13TeV-amcatnlo-pythia8/**-v2/NANOADSIM	0.008213
/TTTW_TuneCP5_13TeV-madgraph-pythia8/**-v2/NANOADSIM	0.0007314
/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOADSIM	88.29
/TTToHadronic_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOADSIM	377.96
/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOADSIM	365.34
/TTWH_TuneCP5_13TeV-madgraph-pythia8/**-v2/NANOADSIM	0.001141
/TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/**-v1/NANOADSIM	0.2149
/TTWJetsToQQ_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/**-v1/NANOADSIM	0.4316
/TTWW_TuneCP5_13TeV-madgraph-pythia8/**-v1/NANOADSIM	0.006979
/TTWZ_TuneCP5_13TeV-madgraph-pythia8/**-v1/NANOADSIM	0.002441
/TTZH_TuneCP5_13TeV-madgraph-pythia8/**-v2/NANOADSIM	0.00113
/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8/**-v1/NANOADSIM	0.2432
/TTZToNuNu_TuneCP5_13TeV-amcatnlo-pythia8/**-v1/NANOADSIM	0.1476
/TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8/**-v1/NANOADSIM	0.5104
/TTZZ_TuneCP5_13TeV-madgraph-pythia8/**-v1/NANOADSIM	0.001386
/WWTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/**-v1/NANOADSIM	49.997
/WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/**-v2/NANOADSIM	10.48
/WWTo4Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/**-v1/NANOADSIM	51.723000
/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8/**-v1/NANOADSIM	0.2086
/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8/**-v1/NANOADSIM	0.1651
/WZTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/**-v1/NANOADSIM	10.710000
/WZTo1L1Nu2Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/**-v1/NANOADSIM	10.710000
/WZTo1L3Nu_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/**-v1/NANOADSIM	3.033
/WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8/**-v2/NANOADSIM	5.052
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/**-v1/NANOADSIM	0.05565
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/**_ext1-v2/NANOADSIM	0.05565
/WminusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOADSIM	0.033700
/WminusH_HToBB_WToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOADSIM	0.034922
/WplusH_HToBB_WToLNu_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOADSIM	0.053100
/WplusH_HToBB_WToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOADSIM	0.055037
/WplusH_WToQQ_HToInvisible_M125_TuneCP5_13TeV_powheg_pythia8/**-v1/NANOADSIM	No value
*Run2017B-UL2017_MiniAODv2_NanoAODv9	
**=RunIISummer20UL17NanoAODv9-106X_mc2017_realistic_v9	
***=Run2017C-UL2017_MiniAODv2_NanoAODv9	
****=Run2017E-UL2017_MiniAODv2_NanoAODv9	
*****=Run2017D-UL2017_MiniAODv2_NanoAODv9	
*****=RunIISummer20UL17NanoAODv9-4cores5k_106X_mc2017_realistic_v9	
*****=Run2017F-UL2017_MiniAODv2_NanoAODv9	

Table B11. The full list of 2017 Monte-Carlo samples used in the analysis (continuation of previous page).

Dataset	cross section [pb]
/WJetsToLNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	1395.0
/WJetsToLNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	1.074
/WJetsToLNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	407.9
/WJetsToLNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	0.008001
/WJetsToLNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	57.48
/WJetsToLNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	12.87
/WJetsToLNu_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	1292.0
/WJetsToQQ_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	2549.0
/WJetsToQQ_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	276.5
/WJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	59.25
/WJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	28.75
/ZH_HToBB_ZToBB_M-125_TuneCP5_13TeV-powheg-pythia8/**-v2/NANOAOBSIM	0.048600
/ZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.048600
/ZH_HToBB_ZToNuNu_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.148200
/ZH_HToBB_ZToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.309931
/ZH_ZToQQ_HToInvisible_M125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.5561
/ZJetsToNuNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	267.0
/ZJetsToNuNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	0.2497
/ZJetsToNuNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	73.08
/ZJetsToNuNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	0.005618
/ZJetsToNuNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	9.904
/ZJetsToNuNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	2.413
/ZJetsToNuNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8/**-v1/NANOAOBSIM	1.071
/ZJetsToQQ_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	114.2
/ZJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	25.34
/ZJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8/**-v2/NANOAOBSIM	190.2
/ZZTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.6008
/ZZTo2Nu2Q_5f_TuneCP5_13TeV-amcatnloFXFX-pythia8/**-v1/NANOAOBSIM	4.033000
/ZZTo4L_M-1toInf_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	13.74
/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8/**-v1/NANOAOBSIM	0.01398
/ggZH_HToBB_ZToBB_M-125_TuneCP5_13TeV-powheg-pythia8/**-v2/NANOAOBSIM	0.007800
/ggZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.007800
/ggZH_HToBB_ZToNuNu_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.014400
/ggZH_HToBB_ZToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.049959
/ggZH_ZToQQ_HToInvisible_M125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.04319
/ttHJetTobb_M125_TuneCP5_13TeV-amcatnloFXFX_madspin-pythia8/**-v1/NANOAOBSIM	0.5086
/ttHToNonbb_M125_TuneCP5_13TeV-powheg-pythia8/**-v2/NANOAOBSIM	0.5638
/ttH_HToInvisible_M125_TuneCP5_13TeV-powheg-pythia8/**-v1/NANOAOBSIM	0.4916
**=Run2017B-UL2017_MiniAODv2_NanoAODv9	
***=RunII Summer20UL17NanoAODv9-106X_mc2017_realistic_v9	
***=Run2017C-UL2017_MiniAODv2_NanoAODv9	
***=Run2017E-UL2017_MiniAODv2_NanoAODv9	
****=Run2017D-UL2017_MiniAODv2_NanoAODv9	
*****=RunII Summer20UL17NanoAODv9-4cores5k_106X_mc2017_realistic_v9	
*****=Run2017F-UL2017_MiniAODv2_NanoAODv9	

Table B12. The full list of 2018 Monte-Carlo samples used in the analysis.

Dataset	cross section [pb]
/DYJetsToLL_M-4to50_HT-100to200_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOAOBSIM	204.0
/DYJetsToLL_M-4to50_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/*-v3/NANOAOBSIM	54.06000
/DYJetsToLL_M-4to50_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOAOBSIM	5.696000
/DYJetsToLL_M-4to50_HT-600toInf_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOAOBSIM	1.85
/DYJetsToLL_M-50_HT-100to200_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	181.3020
/DYJetsToLL_M-50_HT-1200to2500_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	0.1937
/DYJetsToLL_M-50_HT-200to400_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	48.63
/DYJetsToLL_M-50_HT-2500toInf_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	0.003514
/DYJetsToLL_M-50_HT-400to600_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	6.993
/DYJetsToLL_M-50_HT-600to800_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	1.761
/DYJetsToLL_M-50_HT-70to100_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	146.5
/DYJetsToLL_M-50_HT-800to1200_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	0.8021
/GJets_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	8640.0000
/GJets_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	2185.0000
/GJets_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	277.4000
/GJets_HT-40To100_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	18700.0000
/GJets_HT-600ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	85.310000
/QCD_HT100to1500_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	1127.0
/QCD_HT100to200_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	23590000.0
/QCD_HT1500to2000_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	109.8
/QCD_HT2000toInf_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	21.98
/QCD_HT200to300_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	1555000.0
/QCD_HT300to500_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	324500.0
/QCD_HT500to700_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	30310.0
/QCD_HT50to100_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	187300000.0
/QCD_HT700to1000_TuneCP5_PSWeights_13TeV-madgraph-pythia8/*-v2/NANOAOBSIM	6444.0
/ZH_HToBB_ZToBB_M-125_TuneCP5_13TeV-powheg-pythia8/*-v2/NANOAOBSIM	0.048600
/ZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	0.048600
/ZH_HToBB_ZToNuNu_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	0.089100
/ZH_HToBB_ZToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	0.309931
/ZH_ZToQQ_HToInvisible_M125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	0.5561
/ZZTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	0.6008
/ZZTo2Q2Nu_TuneCP5_13TeV-amcatnloFXFX-pythia8/*-v1/NANOAOBSIM	4.033000
/ZZTo4L_M-1toInf_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	13.74
/ZZTo4Q_TuneCP5_13TeV-amcatnloFXFX-pythia8/*-v2/NANOAOBSIM	No value
/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8/*-v1/NANOAOBSIM	0.01398
**=RunIISummer20UL18NanoAODv9-106X_upgrade2018_realistic_v16_L1v1	
***=RunIISummer20UL18NanoAODv9-4cores5k_106X_upgrade2018_realistic_v16_L1v1	
****=Run2018A-UL2018_MiniAODv2_NanoAODv9	
*****=Run2018D-UL2018_MiniAODv2_NanoAODv9	
*****=Run2018B-UL2018_MiniAODv2_NanoAODv9	
*****=Run2018C-UL2018_MiniAODv2_NanoAODv9	

Table B13. The full list of 2018 Monte-Carlo samples used in the analysis (continuation of previous page).

Dataset	cross section [pb]
/ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8/*-v1/NANOAOBSIM	3.74
/ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8/*-v1/NANOAOBSIM	69.09
/ST_t-channel_top_4f_InclusiveDecays_TuneCP5_13TeV-powheg-madspin-pythia8/*-v1/NANOAOBSIM	115.3
/ST_tW_antitop_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	34.97
/ST_tW_top_5f_NoFullyHadronicDecays_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	34.91
/TTGJets_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/*-v1/NANOAOBSIM	3.757
/TTHH_TuneCP5_13TeV-madgraph-pythia8/*-v2/NANOAOBSIM	0.0006655
/TTTT_TuneCP5_13TeV-amcatnlo-pythia8/*-v2/NANOAOBSIM	0.008213
/TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	88.29
/TTToHadronic_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	377.96
/TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOAOBSIM	365.34
/TTWH_TuneCP5_13TeV-madgraph-pythia8/*-v2/NANOAOBSIM	0.001141
/TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/*-v1/NANOAOBSIM	0.2149
/TTWJetsToQQ_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8/*-v1/NANOAOBSIM	0.4316
/TTWW_TuneCP5_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	0.007003
/TTWZ_TuneCP5_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	0.002453
/TTZH_TuneCP5_13TeV-madgraph-pythia8/*-v2/NANOAOBSIM	0.00113
/TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8/*-v1/NANOAOBSIM	0.2439
/TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8/*-v1/NANOAOBSIM	0.5104
/TTZZ_TuneCP5_13TeV-madgraph-pythia8/*-v1/NANOAOBSIM	0.001386
/VBFHToBB_M125_TuneCP5_13TeV-powheg-pythia8/*-v2/NANOAOBSIM	3.873
/VBFHToWWTo2L2Nu_M125_TuneCP5_13TeV_powheg2_JHUGenV714_pythia8/*-v2/NANOAOBSIM	3.879
/WJetsToLNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	1395.0
/WJetsToLNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	1.16
/WJetsToLNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	407.9
/WJetsToLNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOAOBSIM	0.008001
/WJetsToLNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	57.48
/WJetsToLNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	12.87
/WJetsToLNu_HT-70To100_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	1292.0
/WJetsToLNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOAOBSIM	5.366
/WJetsToQQ_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOAOBSIM	2549.0
/WJetsToQQ_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOAOBSIM	276.5
/WJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOAOBSIM	59.25
/WJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOAOBSIM	28.75
/tHJetToNonbb_M125_TuneCP5_13TeV_amcatnloFXFX_madspin_pythia8/*-v1/NANOAOBSIM	0.507
/tHJetToTobb_M125_TuneCP5_13TeV_amcatnloFXFX_madspin_pythia8/*-v1/NANOAOBSIM	0.5086
/tHTToNonbb_M125_TuneCP5_13TeV-powheg-pythia8/*-v2/NANOAOBSIM	0.5638
/tHTToNonbb_M125_TuneCP5_13TeV-powheg-pythia8/*-v2/NANOAOBSIM	0.5638
/tHTTobb_M125_TuneCP5_13TeV-powheg-pythia8/*-v2/NANOAOBSIM	0.5269
/tH_HToInvisible_M125_TuneCP5_13TeV_powheg_pythia8/*-v1/NANOAOBSIM	0.4916
/tWJets_TuneCP5_13TeV_madgraphMLM_pythia8/*-v2/NANOAOBSIM	0.4611
/tZJets_TuneCP5_13TeV_madgraphMLM_pythia8/*-v2/NANOAOBSIM	0.5407
*=RunIISummer20UL18NanoAODv9-106X_upgrade2018_realistic_v16_L1v1	
**=RunIISummer20UL18NanoAODv9-4cores5k_106X_upgrade2018_realistic_v16_L1v1	
***=Run2018A-UL2018_MiniAODv2_NanoAODv9	
****=Run2018D-UL2018_MiniAODv2_NanoAODv9	
*****=Run2018B-UL2018_MiniAODv2_NanoAODv9	
*****=Run2018C-UL2018_MiniAODv2_NanoAODv9	

Table B14. The full list of 2018 Monte-Carlo samples used in the analysis (continuation of previous page).

Dataset	cross section [pb]
/WWTo1L1Nu2Q_TuneCP5_13TeV-amcatnloFXFX-pythia8/*-v1/NANOADSIM	80.74000
/WWTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/*-v2/NANOADSIM	11.09
/WWTo4Q_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/*-v1/NANOADSIM	51.723000
/WWW_4F_TuneCP5_13TeV-amcatnlo-pythia8/*-v1/NANOADSIM	0.2086
/WWZ_4F_TuneCP5_13TeV-amcatnlo-pythia8/*-v1/NANOADSIM	0.1651
/WZTo1L1Nu2Q_TuneCP5_13TeV-amcatnloFXFX-pythia8/*-v2/NANOADSIM	10.710000
/WZTo1L3Nu_4f_TuneCP5_13TeV-amcatnloFXFX-pythia8/*-v1/NANOADSIM	3.033
/WZTo2Q2Nu_TuneCP5_13TeV-amcatnloFXFX-pythia8/*-v1/NANOADSIM	6.858000
/WZTo3L3Nu_TuneCP5_13TeV-amcatnloFXFX-pythia8/*-v2/NANOADSIM	5.052
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/*-v1/NANOADSIM	0.05565
/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/*_ext1-v2/NANOADSIM	0.05565
/WminusH_HToBB_WToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.034922
/WminusH_WToQQ_HToInvisible_M125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.3674
/WplusH_HToBB_WToLNU_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.053100
/WplusH_HToBB_WToLNU_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.053100
/WplusH_HToBB_WToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.055037
/WplusH_WToQQ_HToInvisible_M125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.5884
/ZJetsToNuNu_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOADSIM	267.0
/ZJetsToNuNu_HT-1200To2500_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOADSIM	0.2497
/ZJetsToNuNu_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOADSIM	73.08
/ZJetsToNuNu_HT-2500ToInf_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOADSIM	0.005618
/ZJetsToNuNu_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOADSIM	9.904
/ZJetsToNuNu_HT-600To800_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOADSIM	2.413
/ZJetsToNuNu_HT-800To1200_TuneCP5_13TeV-madgraphMLM-pythia8/*-v1/NANOADSIM	1.071
/ZJetsToQQ_HT-200to400_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOADSIM	1012.0
/ZJetsToQQ_HT-400to600_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOADSIM	114.2
/ZJetsToQQ_HT-600to800_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOADSIM	25.34
/ZJetsToQQ_HT-800toInf_TuneCP5_13TeV-madgraphMLM-pythia8/*-v2/NANOADSIM	190.2
/ggZH_HToBB_ZToBB_M-125_TuneCP5_13TeV-powheg-pythia8/*-v2/NANOADSIM	0.007800
/ggZH_HToBB_ZToLL_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.007800
/ggZH_HToBB_ZToNuNu_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.014400
/ggZH_HToBB_ZToQQ_M-125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.049959
/ggZH_ZToQQ_HToInvisible_M125_TuneCP5_13TeV-powheg-pythia8/*-v1/NANOADSIM	0.04319
*RunIIISummer20UL18NanoAODv9-106X_upgrade2018_realistic_v16_L1v1	
***=Run2018A-UL2018_MiniAODv2_NanoAODv9	
****=Run2018D-UL2018_MiniAODv2_NanoAODv9	
*****=Run2018B-UL2018_MiniAODv2_NanoAODv9	
*****=Run2018C-UL2018_MiniAODv2_NanoAODv9	

Table B15. MC samples for the signal events

MC Samples
The list of 2016 M0nte-Carlo signal samples
/SMS-T5bbbbZH_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
/SMS-T5ttcc_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
/SMS-T6ttZH_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
/SMS-TChiHH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
/SMS-TChiWH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
/SMS-TChiWWpm-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
/SMS-TChiWZ-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
/SMS-TChiZH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
/SMS-TChiZZ-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/*/NANOADSIM
The list of 2017 M0nte-Carlo signal samples
/SMS-T5bbbbZH_TuneCP5_13TeV-madgraphMLM-pythia8/**/NANOADSIM
/SMS-T6ttZH_TuneCP5_13TeV-madgraphMLM-pythia8/**/NANOADSIM
/SMS-TChiHH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/**/NANOADSIM
/SMS-TChiWH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/**/NANOADSIM
/SMS-TChiWWpm-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/**/NANOADSIM
/SMS-TChiWZ-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/**/NANOADSIM
/SMS-TChiZH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/**/NANOADSIM
/SMS-TChiZZ-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/**/NANOADSIM
The list of 2018 M0nte-Carlo signal samples
/SMS-T5bbbbZH_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
/SMS-T5bbbbZH_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
/SMS-T6ttZH_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
/SMS-TChiHH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
/SMS-TChiWH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
/SMS-TChiWWpm-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
/SMS-TChiWZ-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
/SMS-TChiZH-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
/SMS-TChiZZ-mNLS200To1500_mLSP0To600_TuneCP5_13TeV-madgraphMLM-pythia8/***/NANOADSIM
*=RunIISummer20UL16NanoAODv9-FSUL16 FSUL16 106X_mcRun2_asymptotic_v17-v1
**=RunIISummer20UL17NanoAODv9-FSUL17 FSUL17 106X_mc2017_realistic_v9-v1
***=RunIISummer20UL18NanoAODv9-FSUL18 FSUL18 106X_upgrade2018_realistic_v16_L1v1-v1

C Systematic Uncertainties

Figure C1. Systematic uncertainties for total background in hadronic (higgs) signal regions.

syst./SRs	Had_1htop	Had_2htop	Had_H_b_6j	Had_H_0b_34j	Had_H_0b_5j	Had_HV_0b_24j	Had_HV_0b_5j
toppt	5.0%/-5.0%	4.0%/-4.0%	7.2%/-7.2%	1.4%/-1.4%	3.4%/-3.4%	2.5%/-2.5%	7.2%/-7.2%
isr	0.7%/-0.7%	0.7%/-0.7%	0.9%/-0.9%	0.2%/-0.2%	0.1%/-0.1%	0.2%/-0.2%	0.0%/-0.0%
pileup	1.7%/-1.7%	2.4%/-2.4%	0.7%/-0.7%	0.6%/-0.6%	0.9%/-0.9%	2.0%/-2.0%	0.1%/-0.1%
L1Prefiring	0.3%/-0.3%	0.8%/-0.8%	1.1%/-1.1%	0.1%/-0.1%	0.0%/-0.0%	0.7%/-0.7%	0.2%/-0.2%
alphas	0.6%/-0.6%	0.3%/-0.3%	1.1%/-1.1%	0.1%/-0.1%	0.0%/-0.0%	0.2%/-0.2%	0.5%/-0.5%
scale	0.3%/-0.3%	0.8%/-0.8%	1.0%/-1.0%	0.1%/-0.1%	1.0%/-1.0%	0.2%/-0.2%	0.2%/-0.2%
lostlep	0.4%/-0.4%	0.4%/-0.4%	0.9%/-0.9%	0.1%/-0.1%	0.1%/-0.1%	0.1%/-0.1%	0.2%/-0.2%
trigger	0.5%/-0.5%	0.5%/-0.5%	1.1%/-1.1%	0.4%/-0.4%	0.8%/-0.8%	0.3%/-0.3%	0.0%/-0.0%
jes	7.0%/-7.0%	7.7%/-7.7%	4.3%/-4.3%	0.1%/-0.1%	1.3%/-1.3%	3.9%/-3.9%	14.3%/-14.3%
jer	7.3%/-7.3%	8.8%/-8.8%	3.9%/-3.9%	0.1%/-0.1%	1.4%/-1.4%	4.0%/-4.0%	13.8%/-13.8%
puid	6.3%/-6.3%	9.5%/-9.5%	4.0%/-4.0%	0.2%/-0.2%	5.1%/-5.1%	4.0%/-4.0%	13.6%/-13.6%
BoostTag	5.8%/-5.8%	10.3%/-10.3%	5.7%/-5.7%	0.4%/-0.4%	6.7%/-6.7%	5.0%/-5.0%	15.2%/-15.2%
BoostTagFastsim	5.6%/-5.6%	10.3%/-10.3%	6.6%/-6.6%	0.2%/-0.2%	5.7%/-5.7%	4.7%/-4.7%	14.0%/-14.0%
EleFullsim	5.7%/-5.7%	10.7%/-10.7%	5.7%/-5.7%	0.1%/-0.1%	7.7%/-7.7%	5.0%/-5.0%	14.0%/-14.0%
EleFastsim	5.9%/-5.9%	10.3%/-10.3%	4.9%/-4.9%	0.1%/-0.1%	6.9%/-6.9%	5.0%/-5.0%	15.0%/-15.0%
MuonFullsim	5.7%/-5.7%	10.6%/-10.6%	6.7%/-6.7%	0.2%/-0.2%	6.1%/-6.1%	5.0%/-5.0%	15.4%/-15.4%
MuonFastsim	5.5%/-5.5%	10.4%/-10.4%	5.2%/-5.2%	0.2%/-0.2%	6.8%/-6.8%	5.3%/-5.3%	14.1%/-14.1%
BTag	3.5%/-3.5%	10.2%/-10.2%	0.6%/-0.6%	0.2%/-0.2%	9.2%/-9.2%	4.0%/-4.0%	13.3%/-13.3%
BTagFastsim	5.7%/-5.7%	10.3%/-10.3%	6.2%/-6.2%	0.4%/-0.4%	6.0%/-6.0%	4.5%/-4.5%	15.7%/-15.7%
cf_QTW	20.2%/-20.2%	9.9%/-9.9%	16.0%/-16.0%	7.9%/-7.9%	11.0%/-11.0%	37.5%/-37.5%	4.1%/-4.1%
cf_NonIso	4.5%/-4.5%	9.3%/-9.3%	2.4%/-2.4%	9.2%/-9.2%	7.6%/-7.6%	2.0%/-2.0%	7.7%/-7.7%
cf_Z	5.7%/-5.7%	10.7%/-10.7%	4.0%/-4.0%	0.1%/-0.1%	6.4%/-6.4%	4.7%/-4.7%	14.0%/-14.0%

Figure C2. Systematic uncertainties for total background in hadronic (V) signal regions.

syst/SRs	Had_V_b_45j	Had_V_b_6j	Had_1V_0b_34j	Had_1V_0b_5j	Had_2V_0b_24j	Had_2V_0b_5j	Had_H_b_45j
toppt	1.8%/-1.8%	4.9%/-4.9%	0.5%/-0.5%	1.3%/-1.3%	0.2%/-0.2%	4.0%/-4.0%	3.5%/-3.5%
isr	2.1%/-2.1%	1.0%/-1.0%	0.6%/-0.6%	0.9%/-0.9%	0.3%/-0.3%	0.6%/-0.6%	1.2%/-1.2%
pileup	2.0%/-2.0%	1.6%/-1.6%	0.9%/-0.9%	1.6%/-1.6%	1.9%/-1.9%	0.3%/-0.3%	3.3%/-3.3%
L1PreFiring	1.2%/-1.2%	0.9%/-0.9%	0.6%/-0.6%	1.7%/-1.7%	0.1%/-0.1%	0.6%/-0.6%	1.6%/-1.6%
alphas	1.7%/-1.7%	1.5%/-1.5%	0.6%/-0.6%	1.2%/-1.2%	1.4%/-1.4%	0.0%/-0.0%	1.0%/-1.0%
scale	1.0%/-1.0%	1.3%/-1.3%	0.3%/-0.3%	0.3%/-0.3%	0.7%/-0.7%	0.2%/-0.2%	1.0%/-1.0%
lostlep	1.5%/-1.5%	2.2%/-2.2%	0.5%/-0.5%	1.2%/-1.2%	0.4%/-0.4%	0.5%/-0.5%	0.9%/-0.9%
trigger	1.5%/-1.5%	1.0%/-1.0%	0.7%/-0.7%	1.1%/-1.1%	1.6%/-1.6%	0.4%/-0.4%	0.9%/-0.9%
jes	4.4%/-4.4%	5.5%/-5.5%	2.9%/-2.9%	6.8%/-6.8%	4.4%/-4.4%	14.2%/-14.2%	2.2%/-2.2%
jer	4.0%/-4.0%	6.0%/-6.0%	2.9%/-2.9%	6.9%/-6.9%	5.0%/-5.0%	2.2%/-2.2%	2.5%/-2.5%
puid	3.8%/-3.8%	5.9%/-5.9%	3.8%/-3.8%	5.3%/-5.3%	3.8%/-3.8%	4.4%/-4.4%	2.4%/-2.4%
BoostTag	4.5%/-4.5%	4.0%/-4.0%	3.5%/-3.5%	3.0%/-3.0%	6.0%/-6.0%	6.2%/-6.2%	1.3%/-1.3%
BoostTag_Fastsim	4.2%/-4.2%	4.1%/-4.1%	3.6%/-3.6%	2.8%/-2.8%	6.6%/-6.6%	5.8%/-5.8%	2.4%/-2.4%
EleFulsim	4.3%/-4.3%	5.0%/-5.0%	3.7%/-3.7%	2.6%/-2.6%	6.7%/-6.7%	6.8%/-6.8%	2.6%/-2.6%
EleFastsim	4.2%/-4.2%	4.5%/-4.5%	3.5%/-3.5%	3.3%/-3.3%	5.7%/-5.7%	6.5%/-6.5%	2.6%/-2.6%
MuonFulsim	3.8%/-3.8%	4.7%/-4.7%	3.4%/-3.4%	2.9%/-2.9%	5.2%/-5.2%	3.5%/-3.5%	1.9%/-1.9%
MuonFastsim	4.2%/-4.2%	4.5%/-4.5%	3.4%/-3.4%	2.4%/-2.4%	5.3%/-5.3%	5.6%/-5.6%	2.0%/-2.0%
BTag	2.6%/-2.6%	3.2%/-3.2%	8.4%/-8.4%	9.1%/-9.1%	7.6%/-7.6%	7.6%/-7.6%	5.3%/-5.3%
BTagFastsim	4.5%/-4.5%	4.8%/-4.8%	3.4%/-3.4%	3.0%/-3.0%	6.2%/-6.2%	5.2%/-5.2%	1.2%/-1.2%
cf_QTW	19.8%/-19.8%	19.0%/-19.0%	14.0%/-14.0%	18.3%/-18.3%	21.3%/-21.3%	18.0%/-18.0%	19.8%/-19.8%
cf_NonIso	4.5%/-4.5%	2.1%/-2.1%	20.0%/-20.0%	22.4%/-22.4%	5.4%/-5.4%	3.4%/-3.4%	6.8%/-6.8%
cf_Z	5.1%/-5.1%	4.4%/-4.4%	3.2%/-3.2%	3.2%/-3.2%	6.4%/-6.4%	5.3%/-5.3%	1.8%/-1.8%

Figure C3. Systematic uncertainties for total background in non-isolated leptonic signal regions.

syst/SRs	Lepton_0htop	Lepton_1htop	Lepjet_0V_24j	Lepjet_0V_5j	Lepjet_1V_24j	Lepjet_1V_5j
toppt	5.8%/-5.8%	5.1%/-5.1%	2.0%/-2.0%	3.9%/-3.9%	8.4%/-8.4%	1.1%/-1.1%
isr	0.8%/-0.8%	0.9%/-0.9%	1.1%/-1.1%	1.4%/-1.4%	1.3%/-1.3%	0.0%/-0.0%
pileup	1.8%/-1.8%	2.0%/-2.0%	1.4%/-1.4%	2.9%/-2.9%	0.5%/-0.5%	2.4%/-2.4%
L1PreFiring	0.8%/-0.8%	0.9%/-0.9%	0.9%/-0.9%	2.0%/-2.0%	0.9%/-0.9%	0.2%/-0.2%
alphas	0.8%/-0.8%	0.6%/-0.6%	0.6%/-0.6%	2.3%/-2.3%	1.6%/-1.6%	0.0%/-0.0%
scale	0.6%/-0.6%	0.5%/-0.5%	1.3%/-1.3%	2.5%/-2.5%	1.9%/-1.9%	0.1%/-0.1%
lostlep	0.8%/-0.8%	1.0%/-1.0%	1.0%/-1.0%	1.7%/-1.7%	0.6%/-0.6%	0.3%/-0.3%
trigger	0.5%/-0.5%	1.1%/-1.1%	1.1%/-1.1%	1.9%/-1.9%	0.2%/-0.2%	0.1%/-0.1%
jes	1.6%/-1.6%	7.5%/-7.5%	3.9%/-3.9%	8.3%/-8.3%	3.1%/-3.1%	0.2%/-0.2%
jer	1.7%/-1.7%	4.5%/-4.5%	4.2%/-4.2%	8.0%/-8.0%	5.3%/-5.3%	0.2%/-0.2%
puid	1.5%/-1.5%	5.0%/-5.0%	2.4%/-2.4%	6.2%/-6.2%	3.6%/-3.6%	0.0%/-0.0%
BoostTag	1.1%/-1.1%	4.6%/-4.6%	1.8%/-1.8%	7.1%/-7.1%	3.3%/-3.3%	0.3%/-0.3%
BoostTagFastsim	1.6%/-1.6%	4.0%/-4.0%	2.2%/-2.2%	7.4%/-7.4%	3.4%/-3.4%	0.4%/-0.4%
EleFullsim	1.4%/-1.4%	4.6%/-4.6%	2.2%/-2.2%	6.8%/-6.8%	4.0%/-4.0%	0.0%/-0.0%
EleFastsim	1.6%/-1.6%	4.6%/-4.6%	1.9%/-1.9%	6.3%/-6.3%	3.5%/-3.5%	0.1%/-0.1%
MuonFullsim	1.8%/-1.8%	4.7%/-4.7%	2.0%/-2.0%	8.1%/-8.1%	3.1%/-3.1%	0.4%/-0.4%
MuonFastsim	2.0%/-2.0%	4.7%/-4.7%	2.2%/-2.2%	7.4%/-7.4%	4.2%/-4.2%	0.2%/-0.2%
BTag	3.0%/-3.0%	1.8%/-1.8%	7.7%/-7.7%	13.2%/-13.2%	10.2%/-10.2%	1.7%/-1.7%
BTagFastsim	1.8%/-1.8%	4.2%/-4.2%	2.0%/-2.0%	6.8%/-6.8%	4.5%/-4.5%	0.3%/-0.3%
cf_QTW	1.1%/-1.1%	4.6%/-4.6%	2.0%/-2.0%	8.1%/-8.1%	5.0%/-5.0%	0.0%/-0.0%
cf_NonIso	1.3%/-1.3%	4.2%/-4.2%	2.1%/-2.1%	7.5%/-7.5%	3.1%/-3.1%	0.2%/-0.2%
cf_Z	25.5%/-25.5%	13.8%/-13.8%	29.0%/-29.0%	23.0%/-23.0%	24.5%/-24.5%	56.1%/-56.1%

D Validation Results

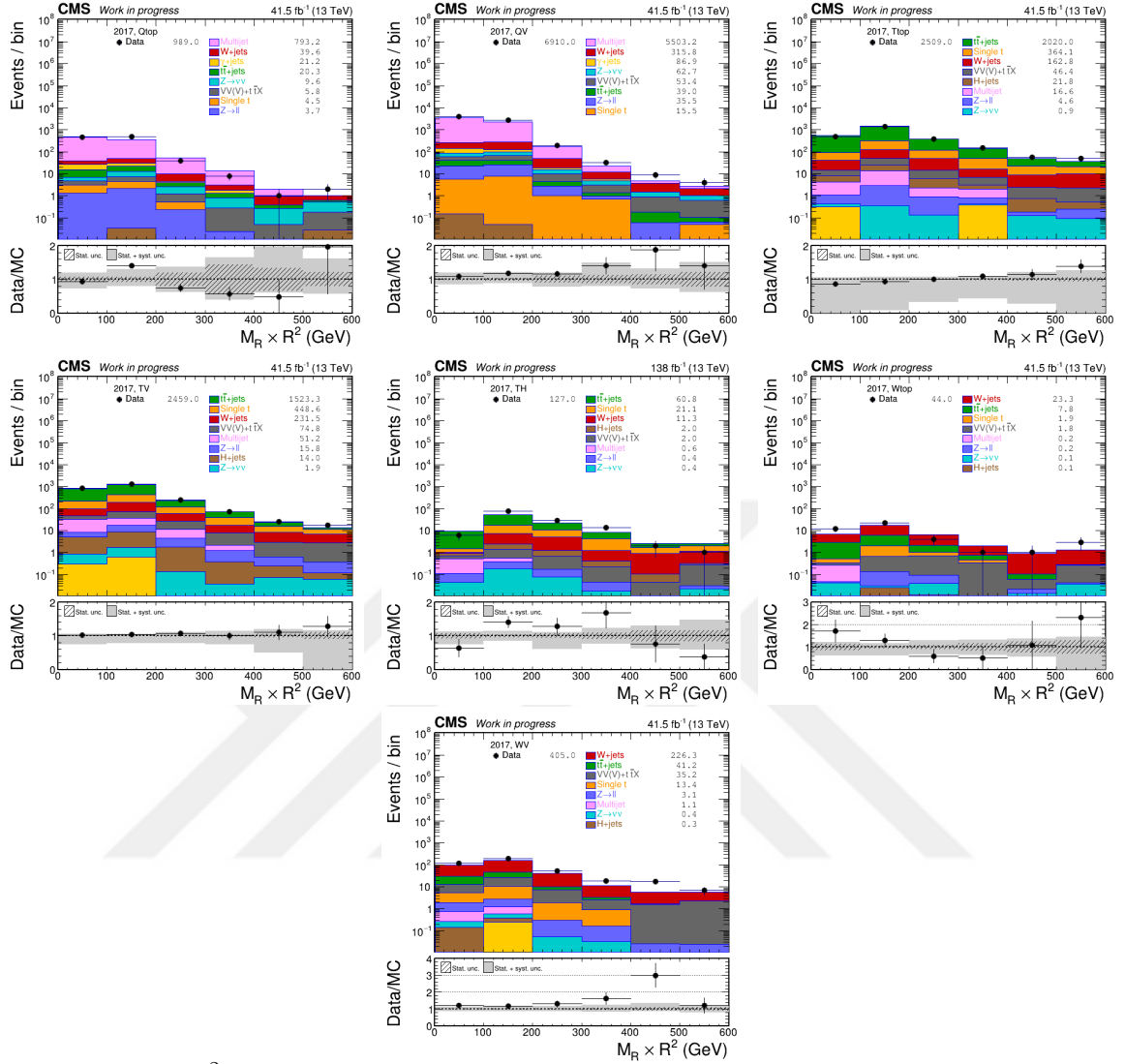


Figure D1. $M_R \times R^2$ distribution with data/MC comparison in lower pads of the histograms are given for validation regions given in Table 5.10. for 2017 data taking period.

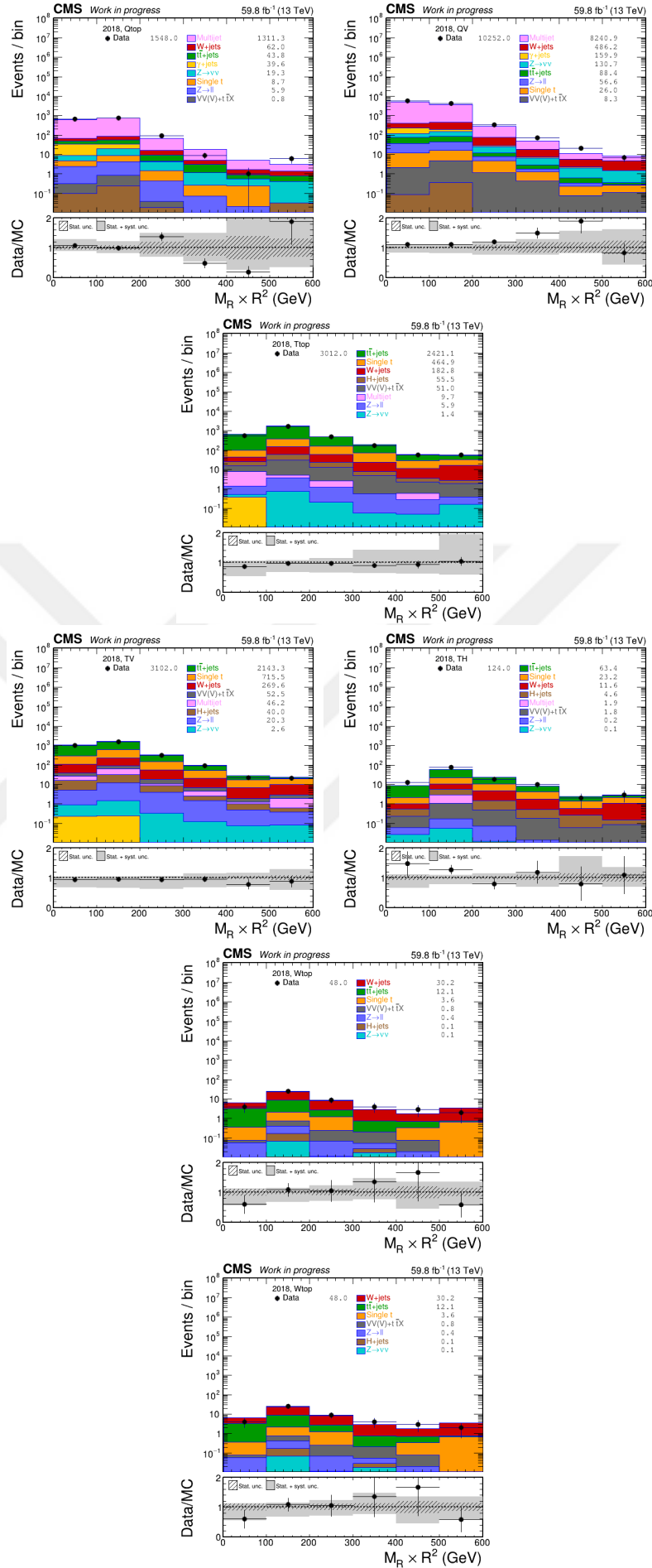


Figure D2. $M_R \times R^2$ distribution with data/MC comparison in lower pads of the histograms are given for validation regions given in Table 5.10. for 2017 data taking period.