

Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV using CMS 2017 and 2018 data

Author:

Deepak KUMAR

Supervisor:

Prof. Jyothsna Rani
KOMARAGIRI

A thesis submitted in fulfillment
of the requirements for the degree of
Doctor of Philosophy

Center For High Energy Physics



Indian Institute Of Science
Bangalore-560012, India

March 2023



Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV using CMS 2017 and 2018 data, © March 2023

Author:

Deepak KUMAR

Supervisor:

Prof. Jyothsna Rani KOMARAGIRI

Institute:

Indian Institute Of Science

CONTENTS

List of Figures	8
List of Tables	28
Abstract	30
Declaration	31
Acknowledgments	32
Publications	33
Acronyms	34
1 INTRODUCTION	36
2 STANDARD MODEL	39
2.1 Overview of Standard Model	39
2.2 Particles of Standard Model	39
2.3 Gauge Symmetry and Fundamental Interactions	42
2.3.1 Quantum Chromodynamics	43
2.3.2 Electroweak Interaction	44
2.3.3 Higgs Mechanism	44
2.4 The SM Lagrangian	46
2.5 Open Points of Standard Model	47
3 DARK MATTER	49
3.1 Evidence of Dark Matter	49
3.1.1 Rotational Curves	49
3.1.2 Gravitational Lensing and Bullet Cluster	50
3.1.3 Cosmic Microwave Background	51
3.2 Dark Matter Candidates	52

3.3	Dark Matter Detection	54
3.3.1	Direct Detection	55
3.3.2	Indirect Detection	56
3.3.3	Dark Matter Searches at Collider Experiment	57
3.4	mono-Higgs signature	59
3.5	Signal Model	60
3.5.1	2HDM+a	61
3.5.2	Baryonic- Z' Model	63
3.5.3	Z' -2HDM Model	64
4	THE LHC AND CMS EXPERIMENT	67
4.1	The Large Hadron Collider	67
4.1.1	LHC Experiments	68
4.1.2	Journey of protons; acceleration to collision	69
4.1.3	Luminosity	69
4.1.4	Events at LHC	70
4.1.5	Pile-up	72
4.2	The CMS Experiment	73
4.2.1	Coordinate System	75
4.2.2	The Tracking System	76
4.2.3	Electromagnetic Calorimeter	78
4.2.4	Hadron Calorimeter	80
4.2.5	The Muon System	81
4.2.6	The Trigger System	86
4.2.7	Data Quality Monitoring	88
5	PHYSICS OBJECT RECONSTRUCTION	89
5.1	Tracks	89
5.2	Vertex Reconstruction	91
5.3	Jets	91
5.3.1	Jets Reconstruction	92
5.3.2	Jets Energy Correction	94
5.3.3	Jet Identification	95
5.4	Electrons	96
5.5	Muons	98
5.6	Photons	99

5.7	Taus	100
5.8	Missing Transverse Energy	100
5.8.1	The E_T^{miss} ϕ corrections	101
6	BUILDING BLOCKS FOR THE ANALYSIS	102
6.1	Data And Simulation	102
6.1.1	Data	102
6.1.2	Monte-Carlo Simulation	103
6.1.3	Signal Samples	106
6.2	Triggers	109
6.2.1	E_T^{miss} triggers	111
6.2.2	Electron Triggers	114
6.3	Object Selection For Analysis	115
6.3.1	Electron Selection	115
6.3.2	Muon Selection	117
6.3.3	Tau Selection	118
6.3.4	Photon Selection	119
6.3.5	AK4jets Selection	119
6.3.6	b-jet Identification	120
6.3.7	AK8jets Selection	122
6.3.8	Identification of b-jets in boosted topology	123
6.3.9	Missing Transverse Energy	125
6.4	Monte Carlo Re-weighting	126
6.4.1	Pileup re-weighting	126
6.4.2	Trigger scale-factors	126
6.4.3	Lepton reconstruction and identification scale factors	127
6.4.4	b-tagging scale factors	128
6.4.5	DeepDoubleBvL scale factors	128
6.4.6	Top p_T re-weighting	130
6.4.7	L1 prefiring	130
6.5	Reconstructed Higgs boson mass correction	132
6.5.1	Softdrop mass correction	132
6.5.2	Dijet invariant mass correction	132
7	BOOSTED ANALYSIS	135
7.1	Introduction	135

7.2	Event Selection	135
7.3	Signal Region	136
7.4	Control Region	136
7.4.1	Top Control Region	137
7.4.2	Z Control region	139
7.5	Signal Extraction And Background Estimation	144
7.5.1	Statistical Concepts	144
7.5.2	Background Estimation	147
7.6	Systematic Uncertainty	149
7.7	Results	151
7.7.1	Interpretations	152
8	RESOLVED ANALYSIS	155
8.1	Introduction	155
8.2	Event Selection	155
8.3	Signal Region	156
8.4	Control Region	157
8.4.1	Top Control region	157
8.4.2	Z Control region	158
8.4.3	QCD Control region	158
8.5	Background Estimation	168
8.6	Systematic Uncertainty	168
8.7	Results	169
8.7.1	Interpretations	169
9	COMBINED RESULTS OF BOOSTED AND RESOLVED ANALYSES	173
9.1	Systematic Uncertainty	173
9.2	Asimov fit : Impacts and pulls	174
9.3	Interpretations	178
10	PROJECTION FOR RUN-3 AND HL-LHC	181
11	SUMMARY AND OUTLOOK	184
11.1	Summary	184
11.2	Outlook	185
	APPENDICES	187

A	APPENDIX 1	187
A.1	HEM15/16 Issue	187
B	APPENDIX 2	189
B.1	Other contribution at CMS	189
C	APPENDIX 3	190
c.1	Generator level study of 2HDM+a for the analysis "Search for dark matter produced in association with b-jets"	190
c.2	E_T^{miss} trigger scale factor measurement	191
c.3	NLO QCD k-factor measurement for W + jets LO samples	192
c.4	Optimizing b-tagging working point	193
D	APPENDIX 4	195
E	APPENDIX 5	220
	BIBLIOGRAPHY	223

LIST OF FIGURES

Figure 2.1	Elementary particle of standard model [29]	40
Figure 2.2	Higgs potential [32]	45
Figure 2.3	Loop-level correction to the mass of the Higgs boson by a fermion.	48
Figure 3.1	The rotation curve of galaxy NGC 6503 [44]. The dark matter halo contribution is shown by dashed-dotted line. The expected velocity of an object is shown by dashed line. Dotted line represents gas velocity.	51
Figure 3.2	"The gravitational lensing map (blue), overlaid over the optical and X-ray (pink) data of the Bullet cluster" [45].	52
Figure 3.3	Different approaches to the hunt for DM are represented schematically. In direct detection, DM interacts with ordinary matters such as nucleons. In indirect detection , DM self-annihilate or decay into Standard model particles in outer space. In DM searches at collider, DM candidates are produced at laboratory[64].	55
Figure 3.4	Upper limits on spin-independent WIMP-nucleon cross section at 90 % confidence level for XENONnT (represented as "this work" in black line)[74], LZ [75] (purple lines, preprint), PandaX-4T [76] (red lines) and XENON1T [77] (blue lines). For PandaX and LZ, dashed lines represent their published result, for XENON results the dashed lines represent limits without a power- constraint applied. Full lines for each experiment represent a limit that is power-constrained to always lie at or above the median un-constrained limit.	56

Figure 3.5	95% CL observed and expected exclusion regions in $m_{\text{med}}\text{-}m_{\text{DM}}$ plane for di-jet searches and different MET based DM searches from CMS in the lepto-phobic Vector model. Following the recommendation of the LHC DM working group ([90, 91]), the exclusions are computed for a universal quark coupling of $g_q = 0.25$ and for a DM coupling of $g_{\text{DM}} = 1.0$. It should also be noted that the absolute exclusion of the different searches as well as their relative importance, will strongly depend on the chosen coupling and model scenario. Therefore, the exclusion regions, relic density contours, and unitarity curve shown in this plot are not applicable to other choices of coupling values or model[92].	57
Figure 3.6	Feynman diagram for mono-X(Fig(a)) and resonance search(Fig(b)).	58
Figure 3.7	95% CL observed and expected exclusion regions in $m_{\text{med}}\text{-}m_{\text{DM}}$ plane for di-jet and di-lepton searches from CMS in the Vector model. Following the recommendation of the LHC DM working group ([90, 91]), the exclusions are computed for a universal quark coupling of $g_q = 0.1$, lepton coupling $g_l = 0.01$, and for a DM coupling of $g_{\text{DM}} = 1.0$. It should also be noted that the absolute exclusion of the different searches as well as their relative importance, will strongly depend on the chosen coupling and model scenario. Therefore, the exclusion regions, relic density contours, and unitarity curve shown in this plot are not applicable to other choices of coupling values or model[92].	59
Figure 3.8	The upper limits at 95% CL on the observed and expected $\sigma/\sigma^{\text{th}}$ for the $Z'\text{-2HDM}$ (left) and baryonic Z' (right) model for the five individual decay modes of the Higgs boson, and for their combination [104]. The distributions are shown as a function of m'_Z for $m_A = 300$ GeV ($Z'\text{-2HDM}$) and $m_\chi = 1$ GeV (baryonic Z' model). The inner and outer shaded bands show the 68 and 95% CL uncertainties in the expected limit, respectively.	60
Figure 3.9	Left: feynman diagram for gg fusion process. Right: feynman diagram for bb initiated process. Both processes give rise to a Higgs + $E_{\text{T}}^{\text{miss}}$ signature	62
Figure 3.10	Feynman diagram for Z' 2HDM (left), and for Baryonic Z' (right). Both processes give rise to a Higgs + $E_{\text{T}}^{\text{miss}}$ signature	63
Figure 4.1	Schematic view of CERN accelerator complex [113]	68

Figure 4.2	(a) Total Integrated luminosity delivered to CMS from LHC during Run I and Run II data taking [124]. Total Integrated luminosity recorded and validated by CMS is shown in (b) and (c) for physics analysis [125].	71
Figure 4.3	Standard model cross-section at the Tevatron and LHC colliders [126].	72
Figure 4.4	Distribution of the average number of interactions per crossing (pileup) for pp collisions [124].	73
Figure 4.5	Sketch of an interesting interaction happening together with a pileup interaction in the detector. The particles coming from the pileup interaction should be removed. The two steps of the pileup removal are depicted.	74
Figure 4.6	A cutaway diagram of the CMS detector with all of the principal components labelled. This detector configuration was used for the 2017–18 data taking years, where the coverage of the pixel detectors in the silicon tracker were upgraded. Image taken from Ref. [127].	74
Figure 4.7	The CMS Coordinate system [128].	75
Figure 4.8	Schematic cross-section through the CMS tracker in the r-z plane [129]	77
Figure 4.9	View of the CMS silicon pixel sub-detector geometry. In the middle there are three layers of the barrel pixels, and on either end of the barrel are three end-cap disks[132].	78
Figure 4.10	The CMS Electromagnetic Calorimeter [134]	79
Figure 4.11	CMS ECAL [133]	79
Figure 4.12	CMS HCAL [137]	82
Figure 4.13	CMS Muon system [138]	83
Figure 4.14	CMS Drift tubes [134]	84
Figure 4.15	CMS Cathode strip chamber [138]	84
Figure 4.16	muon tracks [138]	85
Figure 4.17	A summary of CMS Level 1 trigger system from the hits recorded by subsystem to Global trigger[140].	87
Figure 5.1	Jet reconstruction in a simulated dijet event [144].	93
Figure 5.2	Reconstructed jet using anti- k_t algorithm [152].	93
Figure 5.3	CMS jet energy correction procedure performed in multistep factorize procedure [156]	94

Figure 5.4	JEC uncertainties as a function of jet p_T ($\eta = 0$) at left, and as a function of jet η ($p_T = 30$) using 2017 CMS data [157].	95
Figure 6.1	Representation of hadron-hadron collision as simulated by a Monte-Carlo event generator [170]. The hard collision is represented by the red blob in the center, which is surrounded by a tree-like structure showing Bremsstrahlung as simulated by parton showers. A subsequent hard scattering event is represented by the purple blob. Parton-to-hadron transitions are depicted by light green blob, hadron decays by dark green blob, and soft photon emission by yellow lines.	104
Figure 6.2	Generator level missing transverse energy distribution. Top plots show the distribution for m_A and m_a scans while bottom plots show the distribution for $\sin\theta$ and $\tan\beta$. Missing energy is calculated by summing the momentum vector of dark matter candidates.	110
Figure 6.3	Generator level missing transverse energy distribution. Left plot is for Z' -2HDM and right plot is for Baryonic- Z' model. Missing energy is calculated by summing the momentum vector of dark matter candidates.	111
Figure 6.4	E_T^{miss} trigger turn-on curve measured in single muon events and single electron for 2017 and 2018 (Upper and middle left plots are for single muon events and right plots for single electron events). The trigger turn-on is computed as a function of the recoil (E_T^{miss} without including the muon) in single muon events and as a function of E_T^{miss} in single electron events. Efficiency in simulation is measured using W+jets samples. Lower plot shows scale factor in single electron and single muon events. Bottom pad shows the ratio of curve between electron region and muon region.	113
Figure 6.5	Comparison of E_T^{miss} trigger scale-factor curve for resolved and boosted categories. Scale-factors are same for both categories.	114
Figure 6.6	Electron trigger efficiency for 2017 (left) and 2018 (right) [176].	115

Figure 6.7	b-jet identification efficiency vs misidentification probability for c jet and light jets for various b tagging algorithms (JP, CSV, CSVv2(AVR), CSVv2, DeepCSV, cMVA2) in $t\bar{t}$ events. The DeepCSV tagger outperforms all the other b jet identification algorithms, when discriminating against c jets or light-flavour jets, except for b jet identification efficiencies above 70% where the cMVA2 tagger performs better when discriminating against light-flavour jets [181].	122
Figure 6.8	DeepDoubleBvL performance for $H \rightarrow b\bar{b}$ efficiency versus QCD misidentification probabilities, compared to previous double-b tagger [186]. There are five working points; loose (L), medium 1 (M1), medium 2 (M2), tight 1 (T1) and tight 2 (T2).	124
Figure 6.9	Distribution of the number of vertices in $Z \rightarrow \mu\mu + \text{jets}$ events in data and simulation before pileup re-weighting (left) and after pileup re-weighting (right) in the resolved category. The Monte Carlo is normalized to the luminosity of 41.5 and 59.6 fb^{-1} for 2017 and 2018, respectively.	127
Figure 6.10	Left plot shows DeepDoubleBvL tagger distribution for data and all backgrounds, and the right plot shows the distribution for subtracted data and $t\bar{t}$ background only. The "Top" templates contain contributions from $t\bar{t}$ samples. They are split up into different quark content of the fat jet. Matching with b-quark and light quarks is performed with $\text{DR} < 0.8$. The main contribution comes from events with "unmatched" top quarks.	129
Figure 6.11	Inclusive scale-factor measured for $t\bar{t}$ samples.	130
Figure 6.12	L1 prefiring effect in signal region for boosted (left) and resolved (right) category.	131
Figure 6.13	Fig(a) shows the effect of b-jet regression on single. Fig(b) shows the validation of correction in the Top Control Region	133
Figure 6.14	Effect of b-jet regression correction in signal mass point of 2HDM+a for $m_A = 600$ and $m_a = 150$ GeV.	134
Figure 7.1	Background contribution in the signal region.	136

Figure 7.2	A comparison of distribution of events observed in data and expected background for electron and muon regions. The two left plots are shown for the recoil distribution and two right plots are shown for softdrop mass distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.	138
Figure 7.3	A comparison of distribution of events observed in data and expected background. The left two plots are shown for the fatjet p_T distribution and two right plots are shown for fatjet η mass distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.	139
Figure 7.4	A comparison of distribution of events observed in data and expected background for fatjet ϕ distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.	140
Figure 7.5	A comparison of distribution of events observed in data and expected background for electron and muon regions. The two left plots are shown for the recoil distribution and two right plots are shown for softdrop mass distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.	141
Figure 7.6	A comparison of distribution of events observed in data and expected background for electron and muon regions. The two left plots are shown for the fatjet p_T distribution and two right plots are shown for fatjet η mass distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.	142
Figure 7.7	A comparison of distribution of events observed in data and expected background for fatjet ϕ . The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.	143
Figure 7.8	Sketch of method used to connect the signal region background to control regions through a scale factor. A common rateParam has been used for electron and muon region.	147

Figure 7.9	A comparison of distribution of events observed in data and expected post fit background in the signal region. Mass distribution is filled in three E_T^{miss} bins. The last MET bin includes all events with $E_T^{\text{miss}} > 500$ GeV. One signal hypothesis ($m_a=150$ GeV, $m_A=600$ GeV, $\tan\beta=1$, $\sin\theta=0.35$) for 2HDM+a model is also shown overlaid. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The black band in bottom pad corresponds to the combined effect of systematic and statistical uncertainty in the background expectation.	152
Figure 7.10	The 95% CL upper limit on signal strength for the boosted analysis as a function of: (a) heavier pseudoscalar mediator for 2HDM+a (b and c) vector mediator for Z' -2HDM and Baryonic- Z'	154
Figure 8.1	Sketch of events flow. If event does not pass the boosted selections then the resolved selections are checked. Exact selections are discussed in next section.	155
Figure 8.2	Background contribution in the signal region.	156
Figure 8.3	A comparison of distribution of events observed in data and expected background in electron and muon of the top control region for resolved category. Left plot is shown for Recoil distribution and right plot is shown for inclusive distribution of m_{jj} . Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.	159
Figure 8.4	A comparison of distribution of events observed in data and expected background in electron and muon region of the top control region for resolved category. Left plot is shown for Jet1 p_T distribution and right plot is shown for jet2 p_T . Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.	160

Figure 8.5	A comparison of distribution of events observed in data and expected background in electron and muon region of the top control region for resolved category. Left plot is shown for Jet1 η distribution and right plot is shown for jet2 η . Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.	161
Figure 8.6	A comparison of distribution of events observed in data and expected background in electron and muon region of the top control region for resolved category. Left plot is shown for Jet1 ϕ distribution and right plot is shown for jet2 ϕ . Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.	162
Figure 8.7	A comparison of distribution of events observed in data and expected background in electron and muon region of the Z control region for resolved category. Left plot is shown for Recoil distribution and right plot is shown for m_{jj} distribution. Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.	163
Figure 8.8	A comparison of distribution of events observed in data and expected background in electron and muon region of the Z control region for resolved category. Left plot is shown for jet1 p_T distribution and right plot is shown for jet2 p_T distribution. Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.	164

Figure 8.9	A comparison of distribution of events observed in data and expected background in electron and muon region of the Z control region for resolved category. Left plot is shown for jet1 η distribution and right plot is shown for jet2 η distribution. Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.	165
Figure 8.10	A comparison of distribution of events observed in data and expected background in electron and muon region of the Z control region for resolved category. Left plot is shown for jet1 ϕ distribution and right plot is shown for jet2 ϕ distribution. Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.	166
Figure 8.11	The estimated QCD background for the signal region is displayed in the plots. The top plot displays the estimation for 2017, while the bottom plot displays it for 2018.	167
Figure 8.12	Mass distribution in five E_T^{miss} bins. The last MET bin includes all events with $E_T^{\text{miss}} > 420$ GeV. One signal hypothesis for 2HDM+a model is also shown overlaid where m_a is fixed 150 GeV, $\tan\beta = 1$, $\sin\theta = 0.35$. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.	171
Figure 8.13	The 95% CL upper limit on signal strength for the resolved analysis as a function of: (a) heavier pseudoscalar mediator for 2HDM+a (b and c) vector mediator for Z' -2HDM and Baryonic- Z' .	172
Figure 9.1	Impact of nuisances for combination of resolved and boosted with combined 2017 and 2018 data.	176
Figure 9.2	Pulls for Asimov fit.	177
Figure 9.3	The comparison of expected upper limits at 95% CL on the production cross-section for resolved and boosted analysis.	178

Figure 9.4	Exclusion limits at 95% CL on m_Z - m_χ plane in context of Baryonic- Z' model (a). The coupling to DM candidates is set to $g_\chi = 1$, the coupling to quarks is set to $g_q = 0.25$. The limit on m_Z - m_A plane in right plot is in context of Z' -2HDM(b). The mediator Z' coupling strength is fixed at 0.8, and $\tan\beta$ is fixed at 1.0. Color code represents the limit on the signal strength modifier.	179
Figure 9.5	Exclusion limits at 95% CL on dark matter production as a function of heavier pseudoscalar mediator m_A (Fig. a), $\sin\theta$ (Fig. b) and $\tan\beta$ (Fig. c).	180
Figure 10.1	LHC future plan for HL-LHC [197]	181
Figure 10.2	The expected upper limits at 95% CL on the DM production cross-section for Run3 and HL-LHC. (a) shows sensitivity for m_A and while (b) and (c) present sensitivity for $\sin\theta$ and $\tan\beta$	183
Figure A.1	Electron η and ϕ distribution in single electron region of resolved category. In top two plots HEM veto is not applied. In bottom two plots jet based HEM veto is applied	188
Figure C.1	Generator level plots for $\sin\theta$ (left) and $\tan\beta$ (right) scans.	190
Figure C.2	Generator level plots for m_a scan.	191
Figure C.3	Trigger efficiency for Monte-Carlo (left) and Data (right).	192
Figure C.4	Trigger scale-factor used to correct the simulation.	192
Figure C.5	Generator level vector boson p_T distribution for DY + jets (left) and W + jets (right) processes at LO and NLO. Bottom pad shows ratio of NLO and LO.	193
Figure C.6	b-tagging working point optimization.	194
Figure D.1	The impact of b-tagging systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.	196

Figure D.2	The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers uncertainty is shifted up and down, respectively	196
Figure D.3	The impact of L1-prefiring systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the L1-prefiring uncertainty is shifted up and down, respectively	197
Figure D.4	The impact of pile-up reweighting systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting uncertainty is shifted up and down, respectively	197
Figure D.5	The impact of top reweighting systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the top reweighting uncertainty is shifted up and down, respectively	198
Figure D.6	The impact of pdf systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf uncertainty is shifted up and down, respectively	198

Figure D.7	The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale uncertainty is shifted up and down, respectively	199
Figure D.8	The impact of b-tagging systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.	199
Figure D.9	The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers systematic uncertainty is shifted up and down, respectively.	200
Figure D.10	The impact of prefiring systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the prefiring systematic uncertainty is shifted up and down, respectively.	201

Figure D.11	The impact of pile-up reweighting systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting systematic uncertainty is shifted up and down, respectively.	201
Figure D.12	The impact of top p_T reweighting systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the top p_T reweighting systematic uncertainty is shifted up and down, respectively.	202
Figure D.13	The impact of pdf systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf systematic uncertainty is shifted up and down, respectively.	202
Figure D.14	The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale systematic uncertainty is shifted up and down, respectively.	203

Figure D.15	The impact of electron identification scale systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron identification scale systematic uncertainty is shifted up and down, respectively.	203
Figure D.16	The impact of electron reconstruction scale systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron reconstruction scale systematic uncertainty is shifted up and down, respectively.	204
Figure D.17	The impact of electron trigger scale systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron trigger scale systematic uncertainty is shifted up and down, respectively.	204
Figure D.18	The impact of b-tagging systematic uncertainty on the mass distribution in the Top(μ) control region. The center shape of the distribution represents the total expected background in the Top(μ) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.	205

Figure D.19	The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers systematic uncertainty is shifted up and down, respectively.	205
Figure D.20	The impact of prefiring systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the prefiring systematic uncertainty is shifted up and down, respectively.	206
Figure D.21	The impact of pile-up reweighting systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting systematic uncertainty is shifted up and down, respectively.	206
Figure D.22	The impact of p_T reweighting systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the p_T reweighting systematic uncertainty is shifted up and down, respectively.	207
Figure D.23	The impact of pdf systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf systematic uncertainty is shifted up and down, respectively.	207

Figure D.24	The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale systematic uncertainty is shifted up and down, respectively.	208
Figure D.25	The impact of muon identification scale systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the muon identification systematic uncertainty is shifted up and down, respectively.	208
Figure D.26	The impact of muon isolation scale systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the muon isolation systematic uncertainty is shifted up and down, respectively.	209
Figure D.27	The impact of b-tagging systematic uncertainty on the mass distribution in the $\text{Z}(\text{ee})$ control region. The center shape of the distribution represents the total expected background in the $\text{Z}(\text{ee})$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.	209

Figure D.28	The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers systematic uncertainty is shifted up and down, respectively.	210
Figure D.29	The impact of prefiring systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the prefiring systematic uncertainty is shifted up and down, respectively.	211
Figure D.30	The impact of pile-up reweighting systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting systematic uncertainty is shifted up and down, respectively.	211
Figure D.31	The impact of p_T reweighting systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the p_T reweighting systematic uncertainty is shifted up and down, respectively.	212
Figure D.32	The impact of pdf systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf systematic uncertainty is shifted up and down, respectively.	212

Figure D.33	The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the $Z(ee)$ control region. The center shape of the distribution represents the total expected background in the $Z(ee)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale systematic uncertainty is shifted up and down, respectively.	213
Figure D.34	The impact of electron identification scale systematic uncertainty on the mass distribution in the $Z(ee)$ control region. The center shape of the distribution represents the total expected background in the $Z(ee)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron identification scale systematic uncertainty is shifted up and down, respectively.	213
Figure D.35	The impact of electron reconstruction scale systematic uncertainty on the mass distribution in the $Z(ee)$ control region. The center shape of the distribution represents the total expected background in the $Z(ee)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron reconstruction scale systematic uncertainty is shifted up and down, respectively.	214
Figure D.36	The impact of b-tagging systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.	214

Figure D.37	The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers systematic uncertainty is shifted up and down, respectively.	215
Figure D.38	The impact of prefiring systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the prefiring systematic uncertainty is shifted up and down, respectively.	216
Figure D.39	The impact of pile-up reweighting systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting systematic uncertainty is shifted up and down, respectively.	216
Figure D.40	The impact of top p_T reweighting systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the top p_T reweighting systematic uncertainty is shifted up and down, respectively.	217

Figure D.41	The impact of pdf systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf systematic uncertainty is shifted up and down, respectively.	217
Figure D.42	The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale systematic uncertainty is shifted up and down, respectively.	218
Figure D.43	The impact of muon identification systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the muon identification systematic uncertainty is shifted up and down, respectively.	218
Figure D.44	The impact of muon isolation systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the muon isolation systematic uncertainty is shifted up and down, respectively.	219
Figure E.1	Impact of nuisances for boosted analysis with combined 2017 and 2018 data.	221
Figure E.2	Pulls of nuisances in boosted category with real data.	222

LIST OF TABLES

Table 2.1	The list of force carriers (gauge bosons), their mass, charge, and the force they mediate. Masses are obtained from Ref [30].	41
Table 2.2	A list of fermionic particles of the standard model, their masses and charge. Masses are obtained from Ref [30].	41
Table 3.1	Phase space for m_a and m_A scans	62
Table 3.2	Phase space for $\tan\beta$ scan	63
Table 3.3	Phase space for $\sin\theta$ scan	63
Table 3.4	Signal mass points used to generate official signal samples.	64
Table 3.5	Signal mass points used to generate official signal samples.	66
Table 5.1	Cuts applied in the JetID for 2017 and 2018	96
Table 6.1	Integrated luminosity recorded in 2017 and 2018 data taking and the certified	102
Table 6.2	Primary datasets name used in the analysis for 2017 and 2018 data taking	103
Table 6.3	Background dataset names and corresponding cross-section for 2017 simulation samples. Cross-section contains the branching fraction.	107
Table 6.4	Background dataset names and corresponding cross-section for 2018 simulation samples. Cross-section contains the branching fraction.	108
Table 6.5	Parameter scans for the signal models	109
Table 6.6	List of HLT paths used in the analysis.	111
Table 6.7	Loose electron identification criteria[177]. In the table ρ represents the median of the transverse energy density per unit area in the event. $\sigma_{i\eta i\eta}$ represents the energy spread along the η direction in the ECAL . It is commonly used as a discriminant to distinguish between genuine electrons and background sources such as jets or photons.	116

Table 6.8	Tight electron identification criteria. In the table ρ represents the median of the transverse energy density per unit area in the event. $\sigma_{i\eta i\eta}$ represents the energy spread along the η direction in the ECAL . It is commonly used as a discriminant to distinguish between genuine electrons and background sources such as jets or photons.	117
Table 6.9	Photon identification criteria	119
Table 6.10	Global tags summary for Data and MC for 2017 and 2018 data-taking periods	120
Table 6.11	cuts applied in the JetID for 2017 and 2018	121
Table 6.12	Table shows deep CSV working points and corresponding mistag rate.	123
Table 6.13	MET filters used in this analysis for 2017 and 2018	125
Table 7.1	Signal and Control region selections of the boosted category. Here "a" is for "additional", l is for lepton and j is for AK4jet	137
Table 7.2	Normalisation factor measured for $t\bar{t}$ and Z+Jets processes in Top and Z control region for 2017 and 2018.	148
Table 8.1	Selection cuts applied in the resolved category. Here "a" is for "additional", l is for lepton and j is for ak4jet	157
Table 8.2	Normalisation factor measured for $t\bar{t}$ and Z+Jets processes in Top and Z control region for 2017 and 2018.	169
Table 8.3	List of systematic Uncertainty. Some of the uncertainties denoted by "YAER" indicate that they are uncorrected between the 2017 and 2018 data periods.	170

ABSTRACT

The discovery of the Higgs boson has opened a new portal to search for Dark Matter(DM). Since DM does not interact in the CMS detector, searches rely on the missing transverse energy in association with a visible SM particle. The final state of the Higgs boson+DM is known as "mono-Higgs". In this thesis, mono-Higgs analysis has been performed in two categories; Boosted and Resolved.

In the first part of the thesis, we present a search for DM when it is produced in association with a highly boosted Higgs boson decaying to a pair of bottom quarks using data collected at CMS detector in 2017 and 2018, corresponding to a total luminosity of 101.3 fb^{-1} . The Higgs boson is reconstructed using a fatjet (AK8 jet), and its decay to bb quarks is identified using the DeepDoubleB tagger algorithm. This category targets the phase space where the DM-SM mediator mass is high. Two sensitive observables, missing energy and mass of Higgs boson, are used for this search. Finally, we compare observed and expected events and interpret results in terms of the upper limit in the context of three signal models: 2HDM+a, Z' -2HDM and Baryonic- Z' .

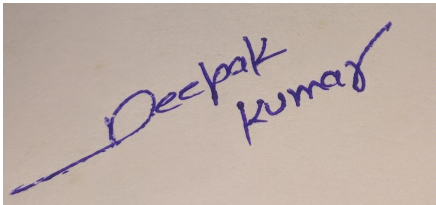
In the second part of the thesis, we present a search for DM when it is produced in association with a low or medium-boosted Higgs boson decaying to a pair of bottom quarks using data collected at CMS detector in 2017 and 2018 corresponding to a total luminosity of 101.3 fb^{-1} . Higgs is reconstructed using two narrow jets (AK4 jets), and deepCSV algorithm is used to identify b quarks. This category targets the phase space where DM-SM mediator mass is low. Missing energy and Higgs boson's mass observables are used for this search. Results are interpreted in terms of the upper limit in the context of three signal models: 2HDM+a, Z' -2HDM and Baryonic- Z' .

Finally, we present the combination of resolved and boosted categories results for all three models and show a projection of this search for Run3 and HL-LHC in the context of 2HDM+a model.

DECLARATION

I, **Deepak Kumar**, declare that this thesis titled **Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV using CMS 2017 and 2018 data** and the work presented in it are my own. I confirm that this work was done mainly while in candidature for a research degree at **Indian Institute of Science, Bangalore**.

Except where reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis accepted for the award of any other degree or diploma. No other person's work has been used without due acknowledgment in the main text of the thesis. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.



Deepak Kumar

March 6, 2023

ACKNOWLEDGMENTS

I would like to thank all the people who helped me through my journey in the PhD, and Please forgive me if I missed some names.

First of all, I would like to express my grateful to my supervisor Dr. Jyothsna Rani Komaragiri for her suggestion, invaluable discussions, sharing expertise and support she had given me throughout this work. Thank you for all of the advice and allowing me to pursue my own ideas. I would like to express deepest gratitude to my collaborator Dr. Raman Khurana for his help and support. Thank you for teaching me how to do an analysis and your dedication to this search . Many thanks for the help with the code development, the suggestions on talks and presentations. I would like to extend my sincere thanks to my colleagues Praveen and Lata. They have been kind and helpful to me all the time in these years. I would also like to thank to mono-Hbb team; Monika Mittal, Raman Khurana, Fasya Khuzaimah, Kung-Hsiang Chen, Praveen Chandra Tiwari, Eiko for their support, contributions and the interesting discussions during the meetings. Thanks to Marino, Milos, Pallabi and Scarlet for their support in CMS EPR task. Thanks to Prof. Justin for the responsibilities as chairman and thank to all faculties for teaching all the courses nicely and the office staff for taking care of administrative work. Thank you to all my seniors and juniors for their help and very fruit full discussion throughout this journey. I also want to thank Saurabh Srivastav, Bhaskar, Saumya, Saurav Majumdar, Ayan, Shyantana, Parth, Rishabh, Gauri, Shipaz, Parthiv, Amandeep, Lata for helping and being friendly classmate during the course work. Thanks to my friends Saurav Srivastav, Harshvardhan, Alam, Prabhat, Amandeep, Ashish, Navneet, Dhanpal and Sujeet. Special thanks to My Family members: parents, sisters, brothers.

From depth of heart: Whatever I was able to do, it was all because of your grace my Lord(Narayan Sakar Hari) and my mother. You never let me feel alone. You have always been with me in this journey. Please you always stay with me my lord (my God).

PUBLICATIONS

- Deepak Kumar Bangalore, Indian Inst. Sci. or the collaboration. "41st International Conference on High Energy Physics, 6-13 Jul 2022, Bologna (Italy) - PoS(ICHEP2018)" **"Search for Dark Matter with mono-X Signatures in CMS"** doi = [10.22323/1.414.0260](https://doi.org/10.22323/1.414.0260).
- Other CMS paper with co-authorship: [Inspire Link](#)

ACRONYMS

2HDM	Two-Higgs-Doublet Model
ALICE	A Large Ion Collider Experiment
APD	Avalanche Photodiode
ATLAS	A Toroidal LHC ApparatuS
BSM	Beyond Standard Model
BTV	B-Tagging Vetexing
CERN	European Organization For Nuclear Research
CMS	Compact Muon Solenoid
CR	Control Region
DQM	Data Quality Monitoring
ECAL	Electromagnetic Calorimeter
FASER	Farward Search ExpeRiment
HCAL	Hadron Calorimeter
LHCb	Large Hadron Collider Beauty
LHCf	Large Hadron Collider Forward
LINAC	LINEAR ACCELERATOR
MC	Monte-Carlo
MET	Missing Transverse Energy
MoEDAL	Mnople And Exotics Detector At The LHC
NLO	Next-to-Leading Order
PSB	Proton Synchrotron Booster
PUPPI	Per Particle Identification
QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics

RPC	Resistive Plate Chamber
SLAC	Stanford Linear Accelerator Center
SM	Standard Model
SPS	Super Proton Synchrotron
SR	Signal Region
SSB	Spontaneous Symmetry Breaking
TOTEM	TOTal Elastic And Differactive Measurement
VEV	Vacuum Expectation Value
WIMP	Weakly Interacting Massive Particle
AK	Anti-Kt
CSC	Cathode Resistive Chamber
EPR	Experimental Physics Responsibilities
FIMPs	Feebly Interacting Massive Particles
HE	Hadron Calorimeter Endcap
JEC	Jet Energy Calibration
LO	Leading Order

INTRODUCTION

The universe is vast and filled with mysteries. The most important question comes in the mind that "What is the universe made of?". Over the many years large number of fundamental particles were discovered. All these particles and interactions between them are described very well in the theory known as Standard Model (SM) of particle physics [1–4].

At very early stage of particle physics, J.J. Thomson discovered that cathode rays are made up of negative light charged particles called electrons[5]. He proposed a model called "plum pudding model", in which negatively-charged electrons are floating in a sea of positive-charge in the atom, therefore total charge is neutral. Rutherford's experiment of the scattering of alpha particles from a thin gold foil in 1911 led to the discovery that an atom is made up of a solid, positively charged nucleus that is orbited by a cloud of negatively charged electrons [6, 7]. The final piece to the atom's puzzle was the discovery of neutrons by J. Chadwick in 1932 [8]. Until Gell-Mann and Zweig proposed the quark model in 1964, protons, neutrons, and electrons were considered as the fundamental particles. According to this model, protons and neutrons consist of more fundamental particles called "quarks". In 1968, a series of electron-proton scattering experiments by MIT-SLAC collaboration at the Stanford Linear Accelerator Center (SLAC) in US showed that nucleons have inner structure and they are consists of three quarks. Afterwards, more elementary particles were discovered, the $W^{\pm}$ and Z bosons discovered in 1983 by UA1 and UA2 Collaboration at CERN [9–13]. In 1964, three physicists "Robert Brout" and "Francois Englert", and "Peter Higgs" proposed a mechanism in which SM particles gain mass by interaction with a field called "Higgs field" [14, 15]. The Higgs boson, quantum of the Higgs field, was discovered on July 2012 at Large Hadron Collider (LHC) [16, 17]. With this "last missing piece" of SM, SM theory is considered as one of the most successful theory.

All these discovered particles represent visible matter, a number of macroscopic observations suggests the existence of Dark Matter particles (invisible particles). The existence of dark matter (DM) is known from a variety of astrophysical and cosmological experiments. Although it is measured to be about 26.4% [18] of the total energy density of the Universe via indirect observations, the exact nature of DM particles is still unknown. All we know is that it is electrically neutral, participates only in gravitational interactions, and does not interact with ordinary baryonic matter. These properties make weakly interacting massive particle (WIMP) the primary candidate for DM particles.

If DM can be produced at hadron colliders, then Large Hadron Collider (LHC) is the best place to do so. However, due to not interacting nature of the DM with ordinary matter, it is almost impossible to detect it in the normal particle detector. DM particle if produced in the proton-proton collisions at LHC will leave the detector undetected, hence becomes source of large transverse momentum imbalance. DM particles can be detected through their association with the particles from the Standard Model (SM), denoted as X , which can be photons (γ), gluons (g), quarks (q), or weak bosons (Z or W). Such interactions, which are observed at collider as particles or jets recoiling against invisible particle are called “mono- X ” interactions. Large missing transverse momentum E_T^{miss} with SM particle(s) is the common detector signature for these searches.

The SM particle X could be emitted directly from a quark as initial state radiation or as part of a new effective vertex coupling of DM to SM. The discovery of an SM-like Higgs boson [16, 17] extended the possibility to search the dark matter in “mono-Higgs” final state. The Higgs boson production from initial state radiation is highly suppressed because of the mass dependence of its coupling strength to fermions and its loop-suppressed coupling to gluons. Hence such a signal could probe directly the structure of the effective DM-SM coupling.

This analysis presents the search for DM produced in association with a Higgs boson, h , decaying into a pair of bottom quarks. The Higgs boson considered is the newly observed scalar compatible with the SM Higgs boson. The bb decay mode has the largest branching fraction of all the Higgs boson decay channels and provide highest signal yield. The search for dark matter using mono-Higgs channel has been performed by the ATLAS¹ and CMS² Collaborations in several final states using data collected at 8 [19]

¹ Details of ATLAS and CMS are discussed in chapter 4

² 1

and 13 TeV [20–27]. So far, none of these searches has observed a significant excess of events over the SM expectations.

Results are interpreted in terms of three simplified models predicting the mono-Higgs signal following the recommendations of the ATLAS-CMS Dark Matter working group [28]. Figure 1 shows the representative Feynman diagrams corresponding to these three models.

In this thesis I present the work done during my journey as a PhD student. Along with physics analysis, I also worked on CMS EPR tasks. The analysis focuses on search for Dark Matter associated with Higgs boson and Higgs decays to a pair of bottom quarks. Within my CMS EPR tasks, I worked as a BTV MC (Monte-Carlo) contact, I worked on HCAL Depth studies, HBHE Noise Filter study, Jet energy response and resolution. The thesis is organized in the chapters as following:

Chapter 2 provides the overview of Standard Model. The fundamental particles and interactions between them have been explained with lagrangian. Some points are also discussed which Standard Model does not explain including Dark Matter.

Chapter 3 describes the evidence of DM and possible DM candidates. The DM detection methods and latest results from different experiments have been shown. mono-Higgs channel and models for interpretation have also been discussed.

Chapter 4 describes the LHC accelerator and its experiments. Data used in this thesis has been collected by the CMS experiment, therefore a detailed description of CMS detector and sub-detector have been discussed.

Chapter 5 details the reconstruction of the physics objects. Only important physics objects are discussed in the details.

Chapter 6 provides information on the background samples, data, and triggers used in the analysis, including the discussion of physical objects and the corresponding selection criteria. Additionally, it covers the necessary corrections applied to the simulation to enhance its alignment with the observed data.

Chapter 7 and **8** describe the boosted and resolved analyses, respectively. **Chapter 9** presents the combination of the resolved and boosted analyses.

Chapter 10 presents the projection for the Run-3 and HL-LHC, while **Chapter 11** provide the summary of overall findings.

STANDARD MODEL

2.1 Overview of Standard Model

The standard model of particle physics is a consistent and computable theory that describes all the known elementary particles and their interactions at the fundamental level. It explains three of four fundamental forces that govern the universe: strong force, weak force and electromagnetic force. The last two forces appear very different at low energies but above the electro-weak scale, on the order of 100 GeV, both forces would merge into a single force: electro-weak force. Elementary particles included in the models are quarks, leptons, gauge bosons and Higgs Boson. A key element of the theory is the Higgs field which gives mass to vector bosons and fermions together with spontaneous symmetry breaking. More details of forces or interactions are explained in the Sec [2.3](#).

2.2 Particles of Standard Model

The standard model contains all elementary particles. Based on their internal property of spin, they can be divided into two distinct categories: fermions and bosons. Fermions with a half-integer spin occur in two basic types called quarks and leptons, which make up matter while bosons with 0 or 1 spin mediate the interactions between quarks and leptons.

The standard model has a total of 12 elementary fermions along with their antiparticles. And six fermions are quarks and six fermions are leptons. They are arranged in pairs and form three generations such that masses of particles are in increasing order as shown in Fig. [2.1](#). First-generation particles and neutrinos do not decay. In the quark sector, first-row quarks are called up-type quarks with an electric charge of $2/3$ and second-row quarks

are called down-type quarks with an electric charge of $1/3$. up quark, charm quark and top quark are up-type quarks. Down quark, strange quark and bottom quark are down-type quarks.

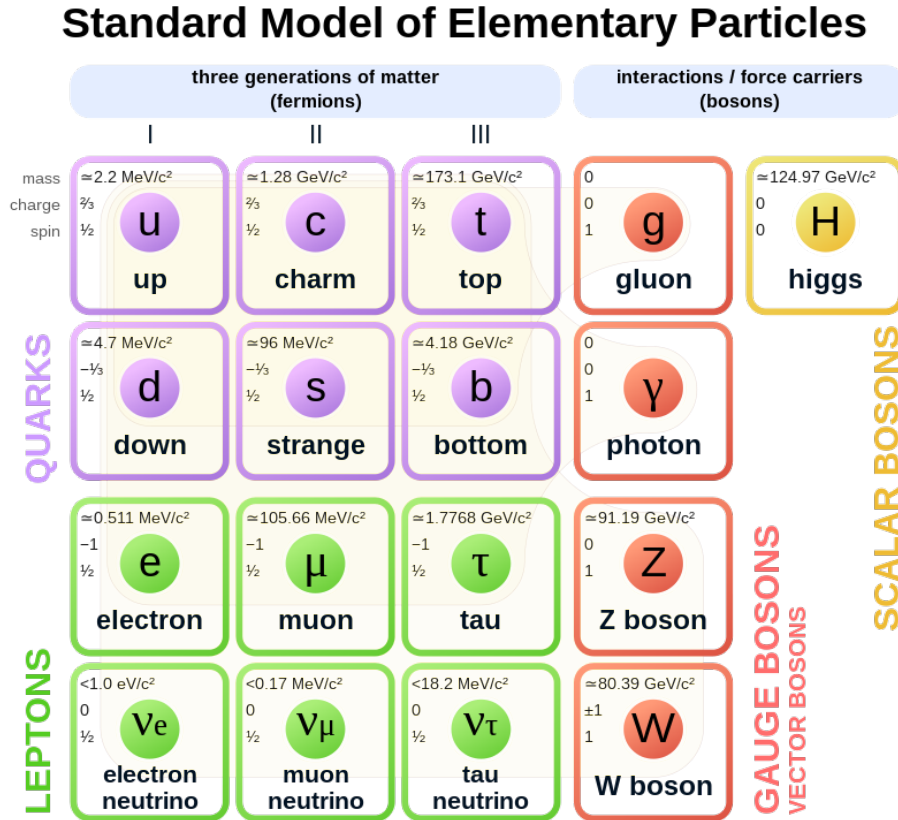


Figure 2.1: Elementary particle of standard model [29]

All quarks carry a color charge, and they are combined to form color-neutral composite hadrons particles such as protons and neutrons. Each generation also consists of a massive lepton particle and extremely light neutrino. Leptons carry $-1e$ electron charge and neutrinos are neutral. The first-generation consists of the electron(e) and electron neutrino (ν_e), the second generation consists of muon (μ) and muon neutrino (ν_μ), and the third generation consists of tau (τ) and tau neutrino (ν_τ). The lepton interacts via electromagnetism and weak force while neutrinos interact via the weak force due to a lack of electric charge. Each force is carried by gauge bosons also known as the force carriers or intermediate particles. The chargeless photons γ mediate the electromagnetic interaction, the eight flavours of massless and electrically neutral gluon g mediate the strong force,

and the charged $W^\pm$ and neutral Z bosons mediate the weak interaction. The Higgs boson, spin-0 particle, is the excitations of the Higgs field that gives mass to fundamental particles. The list of particles that mediate the forces is given in Table 2.1. And the list of particles that interact via electromagnetism, and weak and strong forces are given in the Table 2.2.

Particle	Mass[GeV]	Charge[e]	EM	Weak	Strong
photon(γ)	0	0	Yes	No	No
$W^\pm$	80.38	± 1	No	Yes	No
Z	91.19	0	No	Yes	No
gluon(g)	0	0	No	No	Yes

Table 2.1: The list of force carriers (gauge bosons), their mass, charge, and the force they mediates. Masses are obtained from Ref [30].

Particle	Mass	Charge(e)	EM	Weak	Strong
Quarks					
up (u)	2.2 MeV	+2/3	Yes	Yes	Yes
down(d)	4.7 MeV	-1/3	Yes	Yes	Yes
charm(c)	1.28 GeV	+2/3	Yes	Yes	Yes
strange(s)	95 MeV	-1/3	Yes	Yes	Yes
top(t)	173.2 GeV	+2/3	Yes	Yes	Yes
bottom(b)	4.18 GeV	-1/3	Yes	Yes	Yes
Leptons					
electron(e)	0.511 MeV	-1	Yes	Yes	No
muon(μ)	106 MeV	-1	Yes	Yes	No
tau(τ)	1.777 GeV	-1	Yes	Yes	No
electron neutrino(ν_e)	-	0	No	Yes	No
muon neutrino(ν_μ)	-	0	No	Yes	No
tau neutrino(ν_τ)	-	0	No	Yes	No

Table 2.2: A list of fermionic particles of the standard model, their masses and charge. Masses are obtained from Ref [30].

2.3 Gauge Symmetry and Fundamental Interactions

Gauge theories are important field theories that explain the dynamics of elementary particles. The SM is a gauge quantum field theory, in which particles are characterized by quantum field excitations and interactions by continuous gauge symmetry group. A symmetry is a property of a theory in which a quantity is preserved when subjected to specific transformations. The interaction of SM is defined by the $SU(3) \times SU(2) \times U(1)$, where $SU(3)$ gauge group describes the strong interaction and the color symmetry, $SU(2)$ gauge group describes the weak interaction and the isospin symmetry, and $U(1)$ gauge group describes the electromagnetic interaction and the hypercharge symmetry. The combination of weak interaction and electromagnetic interaction is represented as $SU(2) \times U(1)$, known as electroweak interaction.

The Gauge principle can be understood from quantum electrodynamics (QED). This theory describes phenomena of electrically charged particles and their interactions.

A Lagrangian density $\mathcal{L}$ defines the dynamics of a physical system in general. If ψ is Dirac field with spin $\frac{1}{2}$, electric charge q and mass m , then Lagrangian density for QED can be written as :

$$\mathcal{L} = \bar{\psi}(x)(i\partial_\mu\gamma^\mu - m)\psi(x) \quad (2.1)$$

where $\gamma^\mu (\in 0,1,2,3)$ are Dirac matrices. For a phase change $\psi(x) \rightarrow e^{q\theta}\psi(x)$ the lagrangian is invariant, this is called global $U(1)$ symmetry. If the phase change depends on the space-time then equation is not invariant due to the presence of derivatives:

$$\psi(x) \rightarrow e^{q\theta(x)}\psi(x) \quad \partial_\mu(e^{q\theta(x)}\psi(x)) = e^{q\theta(x)}(\partial_\mu\psi(x) + i\partial_\mu\theta(x)\psi(x)) \quad (2.2)$$

In order to assure invariance of the Lagrangian $\mathcal{L}$ under local phase transformations, an additional term is required to compensate for $\partial_\mu\theta(x)$ term. This can be done by modifying the derivative as:

$$D_\mu = \partial_\mu - iqA_\mu \quad (2.3)$$

where the new field A_μ is transformed as $A_\mu \rightarrow A_\mu + \frac{1}{q}\partial_\mu\theta(x)$ under gauge transformations. The new Lagrangian becomes :

$$\mathcal{L} = \bar{\psi}(iD_\mu\gamma^\mu - m)\psi \quad (2.4)$$

This contains a term of $\bar{\psi}qA_\mu\gamma^\mu\psi$, which represents an interaction between the field ψ and the new vector field A_μ . This new field is a physical photon field where photon is massless. So by demanding local U(1) gauge symmetry, interaction has been generated. If we add kinetic term of the photon field, full Lagrangian of QED can be written as:

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(iD_\mu\gamma^\mu - m)\psi - \frac{1}{4}F_{\mu\nu}(x)F^{\mu\nu}(x) \quad (2.5)$$

where the field tensor $F_{\mu\nu}(x)$ defined as

$$F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x) \quad (2.6)$$

2.3.1 Quantum Chromodynamics

In Quantum chromodynamics (QCD) U(1) gauge group is replaced by SU(3) group of phase transformations on the quark color fields. The free Lagrangian of QCD is

$$\mathcal{L}_{\text{QCD}} = \bar{q}(i\gamma^\mu\partial_\mu - m)q \quad (2.7)$$

where q denotes the quark field.

In order to make Lagrangian invariance under local gauge transformations, the modified covariant derivative is defined as

$$D_\mu q = (\partial_\mu - ig_s \frac{\lambda_a}{2} G_\mu^a(x))q, \quad (2.8)$$

where g_s is the strong coupling constant, λ_a are the SU(3) generators and $G_\mu^a(x)$ represents the eight gluon fields($a = 1, 2, 3, \dots$). And gluon field transforms under SU(3) as

$$G_\mu^a(x) \rightarrow G_\mu^a(x) - \frac{1}{g_s} \partial_\mu \theta^a(x) + f^{abc} \theta_b(x) G_{\mu c}(x) \quad (2.9)$$

where f^{abc} are real constant, called the structure constants of the SU(3) group.

The final gauge invariant QCD Lagrangian with a gauge invariant kinematic energy term is

$$\mathcal{L} = \bar{q}(i\gamma^\mu\partial_\mu - m)q - g_s(\bar{q}\gamma^\mu\lambda_a q)G_\mu^a - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} \quad (2.10)$$

The additional term $g_s(\bar{q}\gamma^\mu\lambda_a q)G_\mu^a$ in the Lagrangian shows interaction between colored quarks q and vector gluons G_μ , with coupling constant g_s .

2.3.2 Electroweak Interaction

Based on the $SU(2) \times U(1)$ symmetry group, electroweak interaction describes an interaction between quarks and leptons. In order to assure invariance of the Lagrangian under phase transformations, the modified covariant derivative corresponding to $SU(2) \times U(1)$ is

$$D_\mu f = (\partial_\mu - igT_i W_\mu^i - ig' \frac{Y}{2} B_\mu) f \quad (2.11)$$

where g and g' are the gauge coupling constants of the weak and the EM interaction. $T_i = \frac{\sigma_i}{2}$ ($i = 1, 2, 3$) are $SU(2)$ generators and $\frac{Y}{2}$ is $U(1)$ generator.

The physical gauge bosons are obtained from the mixing of electroweak eigenstates, called mass eigenstates

$$W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \quad (2.12)$$

$$Z^\mu = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu \quad (2.13)$$

$$A^\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu \quad (2.14)$$

where θ_W represents Weinberg angle and $\sin\theta_W \equiv \frac{g'^2}{g^2 + g'^2}$.

An important note here is that the electroweak gauge group $SU(2) \times U(1)$ under local symmetry has massless gauge boson. So symmetries in the standard model requires the massless gauge bosons. On the other hand, the bosons mediating the weak force have been found to be massive in the experiment [11, 31]. The solution to this problem is spontaneous symmetry breaking. It is discussed in the next section.

2.3.3 Higgs Mechanism

In order to obtain the mass of the gauge boson, the concept of spontaneous symmetry breaking (SSB) has been introduced. If the interactions of a system respect the symmetry but the system's ground state does not, the symmetry is said to be spontaneously broken. To obtain SSB, a new field is introduced in addition to the SM lagrangian.

$$\mathcal{L} = (D^\mu \phi)^\dagger (D_\mu \phi) - V(\phi) \quad (2.15)$$

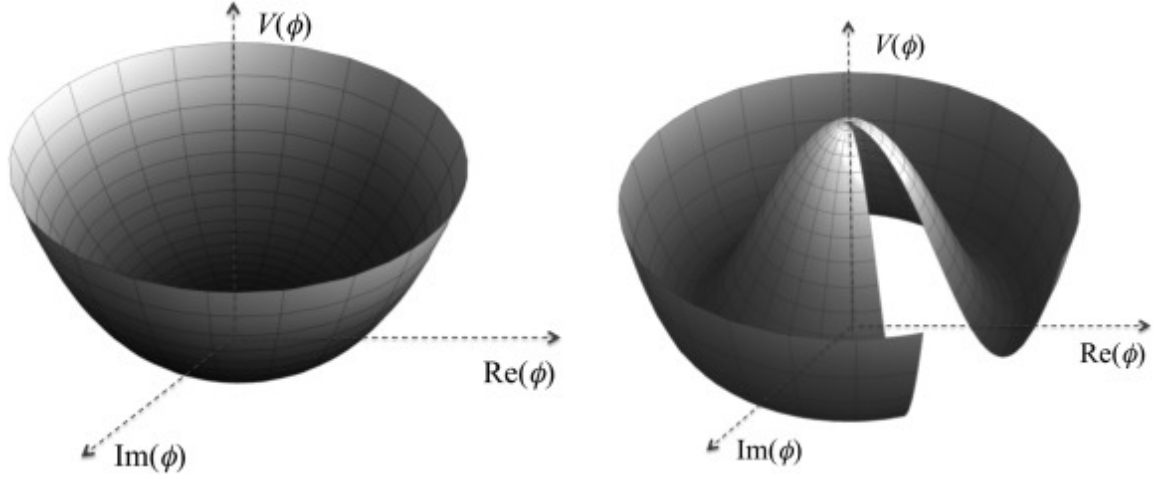


Figure 2.2: Higgs potential [32]

where ϕ represents a complex scalar field and $V(\phi)$ is its potential, and D_μ is same as Eq. 2.11. New field must give mass to the $W^\pm$ and Z^0 bosons and let the photon be massless. So, we need at least 3 additional degrees of freedom. A new field having 4 degrees of freedom is written as :

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.16)$$

The potential $V(\phi)$ is written as

$$V(\phi) = \mu^2(\phi^\dagger \phi) + \lambda(\phi^\dagger \phi)^2 \quad (2.17)$$

In order to ensure the presence of a ground state, λ is required to be > 0 . Fig. 2.2 (left) shows minimum of potential at $\phi = 0$ for $\mu^2 > 0$, and for $\mu^2 < 0$ Fig. 2.2 (right) shows minimum at :

$$\phi^\dagger \phi = -\frac{\mu^2}{2\lambda} \equiv \frac{1}{2}v^2 \quad (2.18)$$

where v is the vacuum expectation value (VEV) of the field ϕ . The SSB is achieved in second case. The selected ground state is:

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.19)$$

Expanding the field around the minima, we get:

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.20)$$

where h denotes the physical Higgs boson. After taking this expression for field ϕ and solving the kinematic part of Eq 2.15, we get mass terms for the electroweak bosons of Eqs 2.12 and 2.13. At tree level, the predicted masses are

$$m_W = \frac{gv}{2}, \quad m_Z = v \frac{\sqrt{g^2 + g'^2}}{2} \quad (2.21)$$

while the photon is massless.

The interesting feature of this field is that it also produces the mass terms needed for fermions. The masses are generated via the Yukawa coupling between the fermion fields and the Higgs field.

$$\mathcal{L} = \sum_f -g_Y^f (\bar{\psi}_L^f \phi \psi_R^f + \bar{\psi}_R^f \bar{\phi} \psi_L^f) \quad (2.22)$$

where g_Y^f represents the Yukawa coupling constants for fermions. The fermion masses are given by:

$$m_f = \frac{v g_Y^f}{\sqrt{2}} \quad (2.23)$$

The potential term in Eq 2.15 gives a mass term of the form $\mu^2 h^2$ for the leftover degree of freedom of the field, and this is known as the Higgs boson particle.

The electroweak bosons and elementary fermions obtain their mass by interacting with the Higgs field. This process is known as the Higgs mechanism [33–35]

2.4 The SM Lagrangian

The SM Lagrangian is formed by the combination of the various elements outlined in the preceding sections:

$$\mathcal{L}_{SM} = \mathcal{L}_{QCD} + \mathcal{L}_{EWK} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} \quad (2.24)$$

where $\mathcal{L}_{QCD}$ and $\mathcal{L}_{EWK}$ describe the strong sector and the electroweak sector, respectively. $\mathcal{L}_{Higgs}$ describes the Higgs potential, which provides the mass terms for the electroweak

bosons with SSB. $\mathcal{L}_{Yukawa}$ takes into account the interactions between the Higgs field and fermions, and provide mass terms for fermions.

2.5 Open Points of Standard Model

As stated at the beginning of this section, the SM has proven to be a successful theory, but it is considered incomplete. There are still some open points that SM does not explain. A short summary is given below:

- **Dark Matter:** Cosmological observations indicate that SM explains about 5% of energy of the universe [18, 36]. About 25% of energy is unseen, which interacts weakly with SM. Yet the SM does not offer any candidates for dark matter. Therefore, an extension of the SM theory is required to explain the existence of dark matter. In this thesis, detailed studies of dark matter searches are presented.
- **Neutrino masses:** In standard model, neutrinos are massless, while various experiments [37, 38] found a contradictory result with observation of neutrino oscillations.
- **Matter anti-matter asymmetry:** The SM predicts that matter and anti-matter should have been created in an equal amount in the early stages of the universe. But the universe is made up of mostly matter. Yet, there is no mechanism in the SM to explain the matter and anti-matter asymmetry.
- **Gravity:** The standard model explains the electroweak and the strong forces, but it does not describe gravity, which is the fourth fundamental force.
- **Hierarchy problem:** The Hierarchy problem refers to the large difference between the Higgs boson mass $O(125\text{ GeV})$ and the Planck mass $O(10^{17})$. Fig. 2.3 shows the loop-level correction diagram, which needs to be considered for the tree-level mass. This gives following correction term to the mass:

$$\Delta m_h^2 = \frac{\lambda_f^2}{8\pi} \Lambda^2$$

where λ_f represents the coupling parameters to the respective fermion and Λ represents the energy scale above which the SM theory expected to no longer valid. If Λ is Planck mass, this huge term needs to cancel in order to arrive at the observed mass of 125 GeV at the electroweak scale. Such effect is not considered to be a reasonable feature of a theory, and in the literature this called fine tuning.

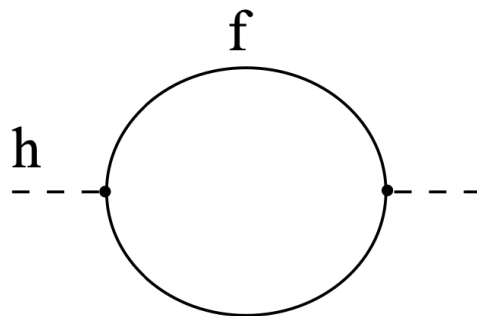


Figure 2.3: Loop-level correction to the mass of the Higgs boson by a fermion.

DARK MATTER

A large number of cosmological observations and measurements from various scales point to the existence of an invisible matter called dark matter, which interacts through gravitational force. These observations are based on the gravitational effects of dark matter on astrophysical objects. The most recent result from Plank experiment[39] indicates that our universe contains 4.9% of ordinary matter, 26.8% of dark matter and 68.3% of dark energy. It is still unknown whether dark matter is made up of particles and whether it interacts with baryonic matter via forces other than gravity. There have been various books and articles written that go into great detail describing the various pieces of evidence for dark matter. This chapter provides a brief overview of the most compelling and well-known ones, followed by a list of the main DM candidates and a brief description of the current detection techniques.

3.1 Evidence of Dark Matter

The first evidence was claimed by Fritz Zwicky in 1933 [40, 41], when he observed that measured velocities of galaxies in the Coma cluster are too high to keep them stable. This shows that there is additional non-luminous matter in the cluster.

This observation was supported by Vira Rubin et al. [42, 43] in 1970 with their measurement of rotation of galaxies.

3.1.1 Rotational Curves

The observation of rotation curves of galaxies, particularly spiral galaxies, provides the most convincing evidence of DM. In galaxies, most of the visible mass is clustered at the

center of the galaxy. From Newtonian mechanism, the velocity v of an object at a distance r from the galactic center can be described by

$$v(r) = \sqrt{\frac{GM(r)}{r}} \quad (3.1)$$

where G is gravitational constant and $M(r)$ is total mass contained in a sphere of a radius r and integrated mass $M(r)$ can be written as $M(r) = 4\pi \int \rho(r)r^2 dr$. The density profile $\rho(r)$ decreases as one moves away from the galactic center, and the total mass $M(r)$ becomes constant within the radius r sphere. As a result, the velocity is expected to decrease as a function of $\frac{1}{\sqrt{r}}$. However, the observed velocities far from the center are approximately constant, a phenomenon called the flat rotation curve. This is shown in the Fig. 3.1.

The observations show that the galaxy's mass distribution is continuous with radius like $M(r) \propto r$, which cannot be explained by gas alone outside the luminous part of the galactic disk. This gives strong evidence of spherical halos around the galaxies, which consists of invisible matter, known as Dark Matter.

3.1.2 Gravitational Lensing and Bullet Cluster

According to Einstein's general theory of relativity, A Gravitational lensing is a mass distribution between a distant light source and an observer that bends the light around the mass distribution, travelling towards the observable. If gravitational lensing is strong and the source of light and observable are perfectly aligned, this leads to a ring structure called the Einstein ring. If gravitational lensing is weak, this results in a small shape distortion around the outer region. The angular radius of Einstein's ring is related to mass through the formula [45]:

$$\theta_E = \sqrt{\frac{4GM}{c^2} \frac{(D_S - D_L)}{D_S D_L}} \quad (3.2)$$

where θ_E is Einstein angular radius, M mass of the lens, D_L distance to lens and D_S distance to source. Astronomers use gravitational lensing to weigh clusters of galaxies.

Second strong evidence of DM comes from the bullet cluster [46]. An image of a bullet cluster is shown in Fig. 3.2, which is composed of two clusters of galaxies that collided and moved apart. The red color shows hot gas observed by Chandra X-ray Observatory and the blue color shows the major part of mass measured using gravitational lensing. The major components of this cluster of galaxies are stars and gas. The stars of galaxies are

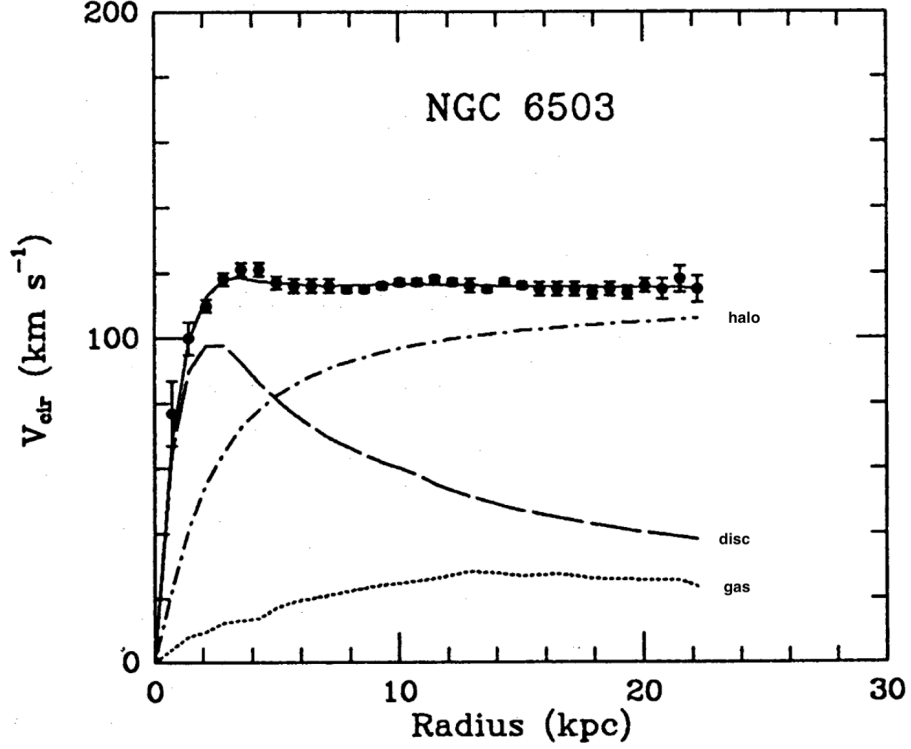


Figure 3.1: The rotation curve of galaxy NGC 6503 [44]. The dark matter halo contribution is shown by dashed-dotted line. The expected velocity of an object is shown by dashed line. Dotted line represents gas velocity.

not greatly affected by collisions. The hot gases interact via electro-magnetic interaction, and they slow down with respect to stars. The visible mass of the cluster is composed of galaxies and gases, but from gravitational lensing it comes out that major part of mass is separated from the gas. This shows that there is invisible matter which does not interact with visible matter via electro-magnetic.

3.1.3 Cosmic Microwave Background

The Cosmic Microwave Background (CMB)[47] is the study of radiation that originated from the early universe. The universe was incredibly hot and dense in the earliest seconds following the Big Bang. When the universe had expanded sufficiently and the temperature dropped enough, the atoms could be formed, and the photons could decouple and travel freely (called photon decoupling). These photons reach the Earth at microwave

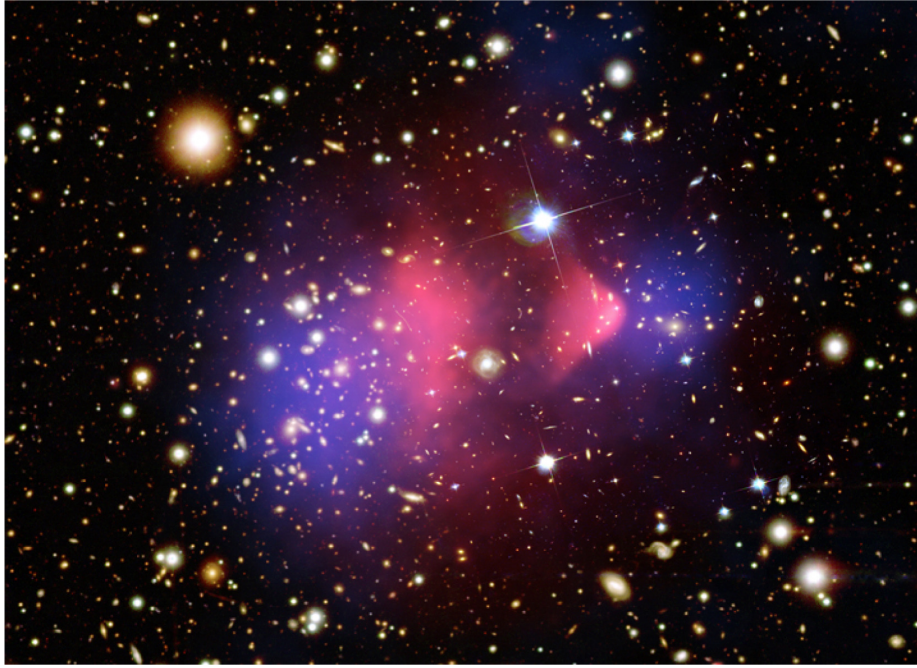


Figure 3.2: "The gravitational lensing map (blue), overlaid over the optical and X-ray (pink) data of the Bullet cluster" [45].

wavelengths. Since they are Big Bang remnants, they provide knowledge about the creation of the universe and the formation of matter. The CMB is isotropic, corresponding to a black-body radiation of 2.7K. However, the CMB spectrum shows slight temperature variations. When simulating the universe, these anisotropies are used to predict its matter concentration. With the use of this knowledge, the Planck collaboration has made predictions about the universe's composition of baryonic matter, dark matter (DM), and dark energy [39]. The results show that just 26.8% of the universe is made up of Dark matter, with the remaining 68.3 % being dark energy and 4.9% visible matter.

3.2 Dark Matter Candidates

Despite the fact that Dark Matter exists, very little is known about its physical nature. The DM theories may be divided into three categories based on the relativity of the DM particles, each of which makes a different prediction.

- **Cold Dark Matter:** In this scenario, the DM candidates were non-relativistic when they decoupled with ordinary matter. This occurred during the "freeze-out" process,

an early stage of cosmic evolution. This theory has strong support from measurements of the CMB radiation and the structure-formation process in galaxy clusters.

- **Warm Dark Matter:** It's also plausible that the DM particles were relativistic at the time of the decoupling between DM and ordinary matter, but gradually cooled down in step with the expansion of the universe and turned out to be non-relativistic. The galaxy density may be predicted with reasonable accuracy by this theory [48], and sterile neutrinos are the most plausible candidates for warm dark matter.
- **Hot Dark Matter:** If the DM particles are light (<1 eV), the cosmic expansion cannot cool them down to a non-relativistic state. The well-known example of hot dark matter is neutrinos, which have almost zero mass. However, simulation shows that neutrinos alone can not account for the inferred DM mass density in the galaxies [49].

The Cold Dark Matter (CDM) hypothesis is currently the most popular DM hypothesis. In recent decades, a variety of CDM theories and DM candidates have been proposed, as discussed below:

- **Axions:** Axions [50, 51] are interesting DM candidates because they can explain the strong CP problem. These particles are predicted to have extremely weak coupling to photons and negligible mass. Their cosmological and astrophysical measurements set bounds on axion mass, $10^{-6} \text{ eV} < m_a < 10^{-2} \text{ eV}$ [51].
- **Massive Compact Halo Objects:** MACHOs are astronomical bodies made of baryonic matter that are condensed and non-luminous, such as black holes, neutron stars, and planets that are not associated with any planetary systems. MACHOs can only be seen by gravitational lensing because they produce (virtually) no radiation. However, Big Bang nucleosynthesis theory and observations of the cosmic microwave background set restrictions on the amount of baryonic matter in the Universe, ruling out MACHOs as the dominant dark matter component.
- **Weakly Interacting Massive Particles:** These particles, also referred to as WIMPs. They arise in BSM (Beyond Standard Model) theories, e.g. the lightest supersymmetric particle in Supersymmetry [52]. These DM candidates are denoted by χ and are assumed to be massive. The upper bound on mass (m_χ) is set at 100 TeV from the perturbative unitarity [53]. The thermal production of WIMPs with weak scale

cross section naturally leads to the observed DM relic abundance¹ $\Omega_\chi h^2 \approx 0.1$, often referred to as the ‘WIMP miracle’, which motivates the experimental searches.

Inelastic Dark Matter(iDM):Dark matter as a weakly interacting massive particle (WIMP) is predicted in many extensions of the SM. In the search for dark matter, it is assumed that dark matter particles can scatter elastically off detector nuclei. So far, there are no unambiguous signals for a detection of DM scattering, leading to strong bounds on WIMPs with weak scale interactions[54]. This motivates theoretical exploration of modifications of the standard picture. For example, if dark matter is required to scatter inelastically into a state heavier than the initial WIMP by $>\approx 1$ MeV, typical WIMPs in the Milky Way halo will have insufficient energy to upscatter, explaining the null results of direct detection experiments[55]. This introduce a new model called inelastic dark matter (iDM) model. In our analysis, we will not use this model for the search for DM.

Feebly Interacting Massive Particles (FIMPs):Another intriguing possibility gaining attention in the scientific community for the origin of dark matter is the freeze-in mechanism. This mechanism involves the production of feebly interacting massive particles (FIMPs) by the Standard Model (SM) bath through out-of-equilibrium processes [56, 57]. Freeze-in offers the appealing feature of providing viable candidates for dark matter with a wide range of masses, from a few keV [58–60] up to the scale of the maximum temperature of universe [61, 62].

In this analysis, the search for Dark Matter was performed under the WIMPs scenario. The DM candidates will be restricted to WIMPs from here. Thermal (WIMP) DM, although the relevant scenario for this thesis, is not the only DM scenario discussed in recent literature[63].

3.3 Dark Matter Detection

Even though there is solid evidence that DM exists, we still know very little about the characteristics of these particles. There are several searches that aim to detect DM particles in order to give some information on their real nature. Depending on how they interact with the SM particles, there are three methods to detect them: direct detection, indirect

¹ The relic abundance of DM particle is a measure of the present quantity of DM particle remaining from the Big Bang. From the Boltzmann equation, it is given by $\Omega_\chi h^2 = 3 \times 10^{-27} \text{cm}^3 \text{s}^{-1} \langle \sigma v \rangle^{-1}$, where $\langle \sigma v \rangle$ is the DM annihilation cross section and h is the Hubble constant.

detection, and searches in particle colliders. In Fig. 3.3, a schematic representation of DM detection is presented.

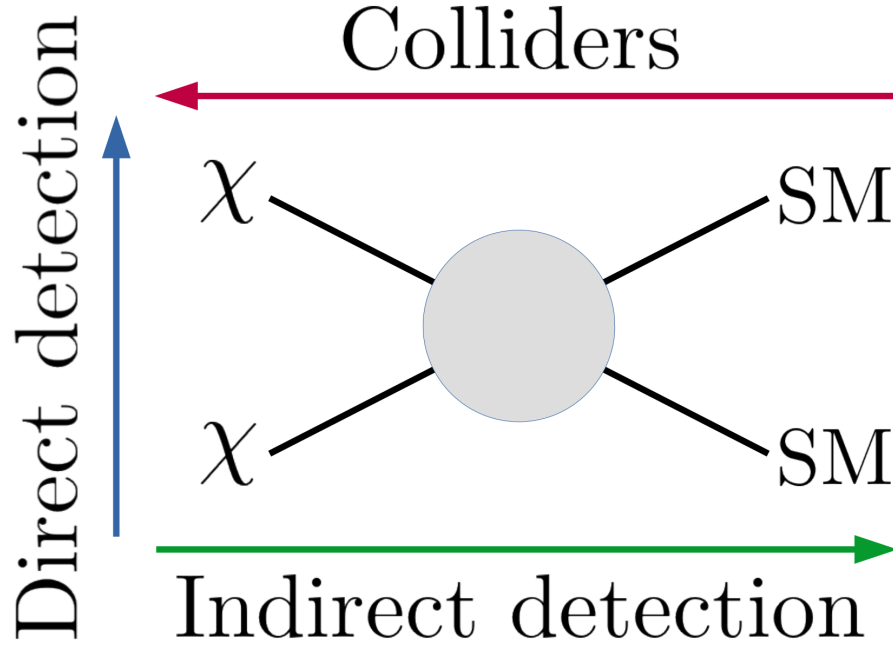


Figure 3.3: Different approaches to the hunt for DM are represented schematically. In direct detection, DM interacts with ordinary matters such as nucleons. In indirect detection, DM self-annihilate or decay into Standard model particles in outer space. In DM searches at collider, DM candidates are produced at laboratory[64].

3.3.1 Direct Detection

As shown in the schematic diagram 3.3, direct detection experiments look for nuclear recoil produced by the elastic scattering of DM particles from atomic nuclei in highly sensitive detection medium. The DM particles, coming from space, can travel through the earth and interact with the material nucleus. If DM moves through the detector and scatters off a recoiling atomic nucleus, it deposits a small amount of energy. The interaction of DM particles with atomic nuclei depends on the cross-section of DM and nuclei (σ_χ) and the mass of the DM particle m_χ . From the galaxy's rotation curve, the velocity of DM particles is in the order of a few hundred km/s. At this velocity, the deposited energy in DM-nucleon scattering is in the range of 1-100 KeV with the mass of between 10 GeV

to 10 TeV. DM-nucleon scattering is a rare process and it requires thousands of kilogram of target material. Therefore, these experiments are built underground to reduce background from cosmic rays. Various direct detection experiments, such as DAMA [65, 66], LUX [67, 68], PICASSO [69, 70], XENON[71, 72] and LUX-ZEPILIN(LZ)[73] placed exclusion limits on cross-section and DM mass. Fig. 3.4 shows the results from direct detection experiments on the DM-nucleon cross-section as a function of DM mass.

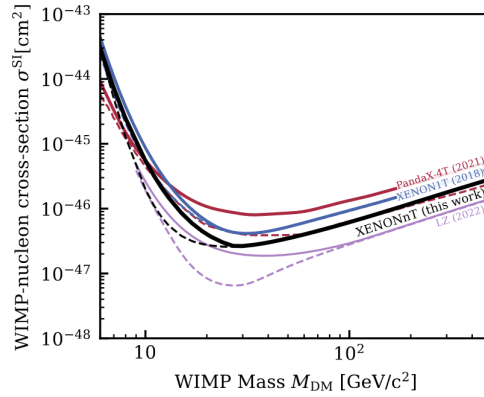


Figure 3.4: Upper limits on spin-independent WIMP-nucleon cross section at 90 % confidence level for XENONnT (represented as "this work" in black line)[74], LZ [75] (purple lines, preprint), PandaX-4T [76] (red lines) and XENON1T [77] (blue lines). For PandaX and LZ, dashed lines represent their published result, for XENON results the dashed lines represent limits without a power-constraint applied. Full lines for each experiment represent a limit that is power-constrained to always lie at or above the median unconstrained limit.

3.3.2 Indirect Detection

As shown in schematic diagram 3.3, Indirect experiments study look for the standard model particles from the annihilation of DM particles. The DM particles decays into the SM particles such as gamma rays, charged particles (electron, positron, etc) and neutrinos. The flux of these particles depends on the DM density. The DM density is high at center of the galaxy, the sun, these regions are best regions to perform such search. Signal such as gamma ray produced from DM annihilation is expected to have mono-energetic lines in the photon spectrum. Signal would not be compatible with astrophysical gamma rays background source. Some experiments such as HESS[78], MAGIC[79] and Fermi Gamma-ray Space Telescope [80] look for gamma ray events like signal. Fermi telescope

has detected excess of energetic gamma rays (1-3 GeV) from the center of Milky Way [81, 82], results are compatible with DM particles of mass range 36-51 GeV, more data is required to confirm. Some other experiments such as ATIC [83], PAMELA[84], AMS[85] and Auger [86] search for charged particles produced from DM annihilation. Neutrino telescopes are designed to detect high-energy neutrinos originating from the annihilation of dark matter (DM) particles in the vicinity of massive objects like the Sun or the Galactic Center. These telescopes, such as Super-Kamiokande (Super-K) [87, 88] and IceCube [89], are typically situated underground or under ice to minimize background noise and maximize detection sensitivity.

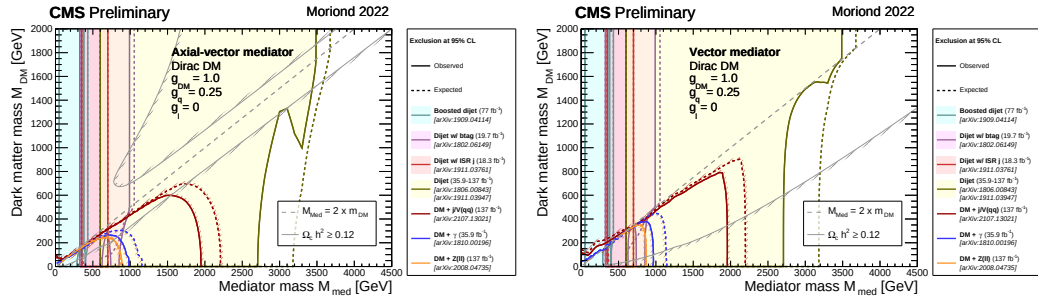


Figure 3.5: 95% CL observed and expected exclusion regions in $m_{\text{med}}-m_{\text{DM}}$ plane for di-jet searches and different MET based DM searches from CMS in the leptophobic Vector model. Following the recommendation of the LHC DM working group ([90, 91]), the exclusions are computed for a universal quark coupling of $g_q = 0.25$ and for a DM coupling of $g_{\text{DM}} = 1.0$. It should also be noted that the absolute exclusion of the different searches as well as their relative importance, will strongly depend on the chosen coupling and model scenario. Therefore, the exclusion regions, relic density contours, and unitarity curve shown in this plot are not applicable to other choices of coupling values or model[92].

3.3.3 Dark Matter Searches at Collider Experiment

In these experiments, DM particles are produced at a laboratory such as the Large Hadron Collider(LHC) from the collisions of SM particles. Due to its property, DM would not interact with ordinary matter, it is almost impossible to detect it in a normal particle detector. A DM particle produced in proton-proton collisions at the LHC will escape detection and become a source of large transverse momentum imbalance. DM particles can not be detected directly, but they can be observed if they are produced in association with a visible standard model particle X. Such interactions, which are observed at CMS

and ATLAS as particles or jets recoiling against invisible particle, are called "mono-X" or $E_T^{\text{miss}} + X$ interactions, where E_T^{miss} is called missing transverse energy. Here X can be a jet [93, 94], photon [95, 96], vector boson [97, 98], lepton [99, 100] and heavy flavor quark [101–103]. The SM particle X could be emitted directly from a quark as initial state radiation or as part of a new effective vertex coupling of DM to the Standard Model (SM).

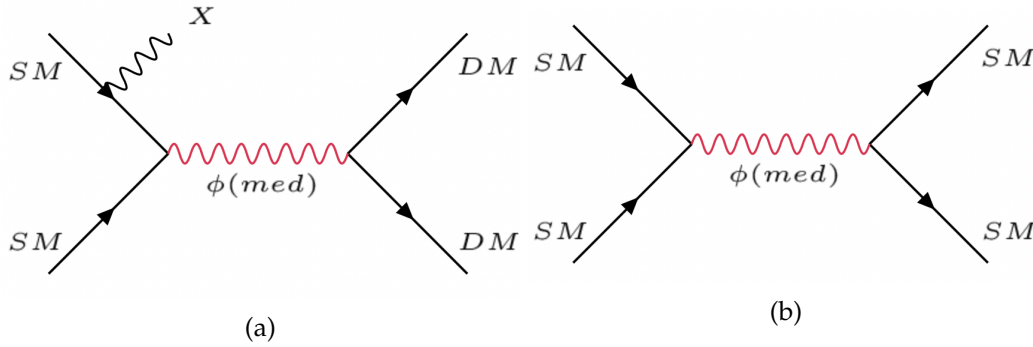


Figure 3.6: Feynman diagram for mono-X(Fig(a)) and resonance search(Fig(b)).

The DM search is performed based on beyond SM theory, such as supersymmetry and simplified models, which are extensions of SM with DM particles. In these models, mediators interact with SM particles and DM particles as shown in figure 3.6a. The coupling constants are chosen to give the highest cross-section without violating any previous results. The mediator in the models can be a scalar, pseudo-scalar, vector, or axial vector. In addition to E_T^{miss} based (mono-X) DM searches, resonance based DM searches are also performed in CMS and ATLAS. In resonance based DM searches, the mediator decays into a pair of standard model particles and signal peak is expected in the invariant mass of two visible final state particles over the SM background as shown in figure 3.6b.

Fig. 3.5 shows the latest DM searches results from CMS collaboration. 95% CL observed and expected exclusion regions in $m_{\text{med}} - m_{\text{DM}}$ plane for di-jet searches and different E_T^{miss} based DM searches is shown. Here, m_{med} represents the mass of the dark matter mediator, and m_{DM} represents the mass of the dark matter itself. The best sensitivity is given by dijet search. However, results depends on coupling constant, lepton coupling is set to zero here. Fig. 3.7 shows comparison of dijet and dilepton resonance results after introducing lepton coupling.

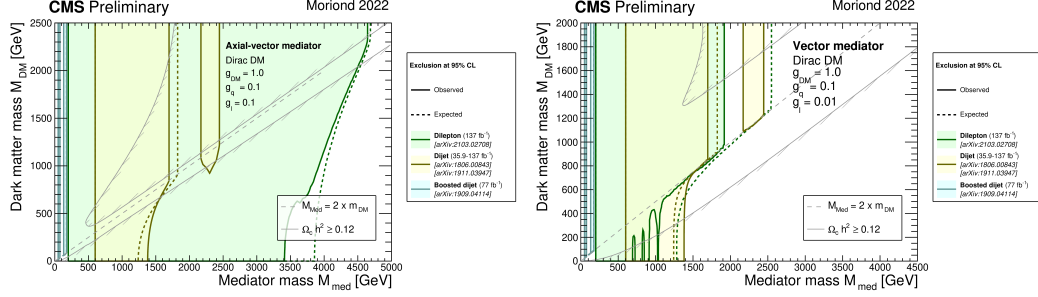


Figure 3.7: 95% CL observed and expected exclusion regions in $m_{\text{med}}\text{-}m_{\text{DM}}$ plane for di-jet and di-lepton searches from CMS in the Vector model. Following the recommendation of the LHC DM working group ([90, 91]), the exclusions are computed for a universal quark coupling of $g_q = 0.1$, lepton coupling $g_l = 0.01$, and for a DM coupling of $g_{\text{DM}} = 1.0$. It should also be noted that the absolute exclusion of the different searches as well as their relative importance, will strongly depend on the chosen coupling and model scenario. Therefore, the exclusion regions, relic density contours, and unitarity curve shown in this plot are not applicable to other choices of coupling values or model[92].

3.4 mono-Higgs signature

The discovery of Higgs boson [16, 17, 22] has opened a new portal to search for DM particles. The final state of the Higgs boson + $E_{\text{T}}^{\text{miss}}$ is known as "mono-Higgs". The mono-Higgs has an advantage over the mono-X. The SM particle X could be emitted directly from a quark as an initial state radiation or as part of a new effective vertex coupling of DM to SM, but the Higgs boson production from initial state radiation is highly suppressed because of the mass dependence of its coupling strength to fermions and its loop-suppressed coupling to gluons. Hence, such a signal could probe directly into the structure of the effective DM-SM coupling.

This search can be carried out in five Higgs decay modes: $H \rightarrow b\bar{b}$, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, and $H \rightarrow \tau\tau$. In this thesis, we present an analysis searching for dark matter production in association with the SM Higgs boson decaying into a pair of bottom quarks. The advantage of $b\bar{b}$ channel is that it has the highest branching ratio, so this channel is more sensitive than other channels. At 13 TeV, mono-Higgs searches have been performed for all decay modes: $b\bar{b}$ [25, 26], ZZ , WW , $\gamma\gamma$ [27] and $\tau\tau$ with 2016 CMS data taking. No significant excess is observed over the SM background in any of the five decay channels or in their combination. Fig. 3.8 shows the upper limit plot from

the combination of all decay channels for Z' -2HDM (left) and baryonic Z' (right) models [104]. The best limit is set by $b\bar{b}$ for high mass phase space. However, $H \rightarrow \gamma\gamma$ seems better in low mass phase space.

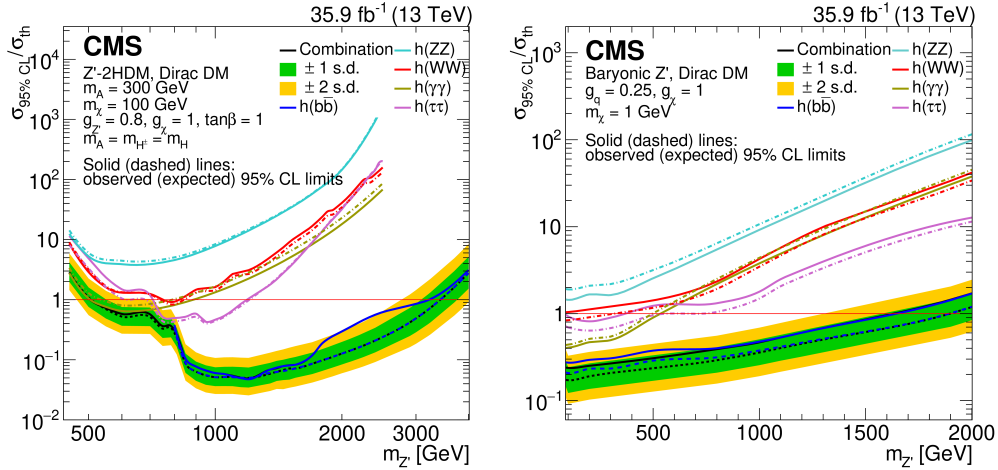


Figure 3.8: The upper limits at 95% CL on the observed and expected σ/σ^{th} for the Z' -2HDM (left) and baryonic Z' (right) model for the five individual decay modes of the Higgs boson, and for their combination [104]. The distributions are shown as a function of $m'_{Z'}$ for $m_A = 300$ GeV (Z' -2HDM) and $m_\chi = 1$ GeV (baryonic Z' model). The inner and outer shaded bands show the 68 and 95% CL uncertainties in the expected limit, respectively.

This analysis is performed in the $H \rightarrow b\bar{b}$ channel with 2017 and 2018 CMS data. In order to improve sensitivity in low mass phase space, the resolved category has been added to the analysis. Because the boosted and resolved categories target different phase spaces, high mass and low mass, respectively, a combination of both will have the power to exclude large phase spaces of the model if no excess of events is found. Details will be discussed in the coming sections.

3.5 Signal Model

The interpretation of dark matter signal is performed with three benchmark simplified models: 2HDM+a, Baryonic- Z' model, and Z' -2HDM model.

3.5.1 2HDM+a

2HDM stands for "Two Higgs Doublet Model". It is an extension of the Standard Model of particle physics, where instead of one Higgs doublet, there are two Higgs doublets. This leads to the existence of five Higgs bosons, instead of one in the Standard Model.

The "a" in 2HDM+a stands for "pseudo-scalar, spin-0 mediator". It refers to the mediator particle that connects the dark matter and the Standard Model particles. In this model, the dark matter particle is assumed to be a fermion, and it interacts with the Standard Model particles through the pseudo-scalar mediator.

2HDM+a[105, 106] is a type-II two-Higgs-doublet model (2HDM) containing an additional pseudo-scalar boson. The Type-II 2HDM couples the up-type quarks to one Higgs doublet, and the down-type quarks and charged leptons to the other. In 2HDM+a, the coupling of the new spin-0 mediator to SM gauge bosons is strongly suppressed, hence this model becomes interesting for this analysis.

The model has several parameters, which are as follows:

- $v = \sqrt{v_1^2 + v_2^2}$: the vacuum expectation value of the Higgs field
- $\tan\beta$: the ratio of the vacuum expectation values of the two Higgs doublets, which determines the strength of the couplings of the Higgs bosons to fermions and gauge bosons.
- m_H : the mass of the CP-even neutral Higgs boson that is heavier than the SM-like Higgs boson.
- m_h : the mass of the light CP-even Higgs boson (SM-like Higgs boson).
- (m_A, m_a) : the masses of the two CP-odd Higgs bosons (mass of heavier pseudoscalar, lighter pseudoscalar).
- $m_{H^\pm}$: the mass of the charged Higgs bosons.
- m_χ : the mass of dark matter candidate.
- $\sin\theta$: (θ) is the mixing angle between the two CP-odd Higgs bosons.
- α : the mixing angle between the CP-even scalars h and H .
- y_χ : the coupling strength between the dark matter particle and the mediator.
- $\lambda_3, \lambda_{P1}, \lambda_{P2}$: The quartic couplings among the CP-odd and CP-even Higgs bosons.

Following parameters are constrained in this model:

- $\cos(\beta - \theta)=0$: this is constrained by Higgs coupling strength measurements, called alignment limit of the 2HDM[107].
- $m_H = m_{H^\pm} = m_{A0}$: to ensure the stability of the vacuum, the masses of the neutral Higgs bosons are related by $m_H = m_{H^\pm} = m_{A0}$.

As (θ) is the mixing angle between the two pseudoscalar mediators (a, A) hence, both mediators couple with dark matter particles as shown in a term from lagrangian:

$$-iy_\chi(A\sin\theta + a\cos\theta)\bar{\chi}\gamma_5\chi \quad (3.3)$$

The Feynman diagram for the signal process is shown in Fig. 3.9, depicting both the gluon-gluon fusion and bb -initiated processes.

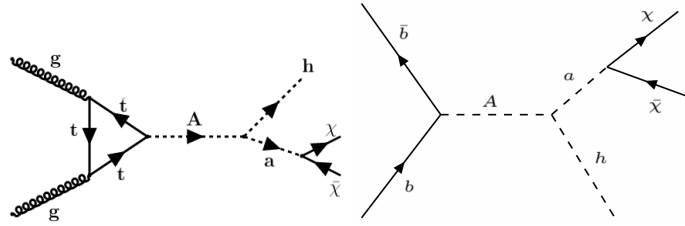


Figure 3.9: Left: feynman diagram for gg fusion process. Right: feynman diagram for bb initiated process. Both processes give rise to a Higgs + E_T^{miss} signature

In this search, the parameters have been selected based on either benchmark points suggested in reference [108] or through scanning. We have chosen $\lambda_3 = \lambda_{p1} = \lambda_{p2} = 3$ as given in the Ref. [106] and fixed the mass of Dark Matter at 10 GeV.

For the free parameters, several scans have been performed in this analysis, which are outlined in Tables [3.1, 3.2, 3.3].

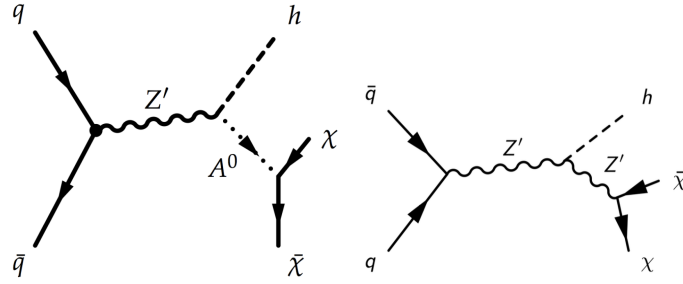
	Range							Fixed parameters			
								$\sin\theta$	$\tan\beta$	m_a [GeV]	m_χ [GeV]
m_A [GeV]	200	400	600	800	1000	1200	1600	0.35	1	150	10
		400	600	800	1000	1200	1600	0.35	1	250	10
			600	800	1000	1200	1600	0.35	1	350	10

Table 3.1: Phase space for m_a and m_A scans

	Range								Fixed parameters			
									$\sin\theta$	m_a [GeV]	m_A [GeV]	m_χ [GeV]
$\tan\beta$	0.5	1	1.5	2	4	8	20	50	0.35	150	600	10
									0.35	250	600	10

Table 3.2: Phase space for $\tan\beta$ scan

	Range										Fixed parameters			
											$\tan\beta$	m_a [GeV]	m_A [GeV]	m_χ [GeV]
$\sin\theta$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	200	600	10	10

Table 3.3: Phase space for $\sin\theta$ scanFigure 3.10: Feynman diagram for Z' 2HDM (left), and for Baryonic Z' (right). Both processes give rise to a Higgs + E_T^{miss} signature

3.5.2 Baryonic- Z' Model

The Feynman diagram on the Fig. 3.10(right) shows the production mechanism for the baryonic- Z' model [109], where the Z' is a vector boson mediator and can radiate a Higgs boson before decaying to a pair of Dirac fermionic dark matter particles. In this case, the baryonic gauge boson Z' arises from a new $U(1)_B$ baryon number symmetry. The stable baryonic states in this model are the candidate DM particles. A baryonic Higgs boson (h_B) is introduced to spontaneously break the new symmetry and generate the Z' boson mass via a coupling that is dependent on the h_B vacuum expectation value. The Z' couplings to quarks and DM are proportional to the $U(1)_B$ gauge couplings. There is mixing between h_B and h , allowing the Z' to radiate an SM-like Higgs boson and results in SM-like Higgs boson decays.

In this model, the mediator-DM coupling(g_χ) is fixed to 1 and the mediator-quark coupling (g_q) is fixed to 0.25. The mixing angle between the baryonic Higgs boson and the SM-like Higgs boson is set to 0.3 and the coupling between the Z' boson and SM-like Higgs boson is proportional to the mass of the Z' boson. For both models, the SM-like Higgs boson is assumed to have a mass of 125 GeV. Details on the choice of the parameters are given in [28]. Parameter values used in this analysis are given in the Table 3.4.

m_χ [GeV]	M_{Zp} [GeV]								
1	100	200	500	1000	1500	2000	2500	3000	3500
50	100	200	350	650	800				
100	200	500	1000	1500	2000	2500	3500		
150	200	300							
200	500	1000	1500	2000	2500	3500			
400	500	1000	1500	2000	2500				
600	1000	1500	2000	2500					
800	1000	1500	2000	2500					

Table 3.4: Signal mass points used to generate official signal samples.

3.5.3 Z' -2HDM Model

In the 2HDM model of Ref [110], a type-2 Higgs doublet is assumed, where Φ_u couples to up-type quarks and Φ_d couples to down-type quarks and leptons. The gauge symmetry of the SM is extended by $U(1)_{Z'}$, with a new Z' gauge boson. In this 2HDM model, only Φ_u and right-handed up-type quarks (u_R) are charged under the $U(1)_{Z'}$ while Φ_d and all the other SM fermions are neutral.

After electroweak symmetry breaking, the Higgs doublets attain vacuum expectation values v_u and v_d , and in unitary gauge, the doublets are parametrized as

$$\Phi_d = \frac{1}{\sqrt{2}} \begin{pmatrix} -H^+ \sin\beta \\ v_d - h \sin\alpha + H \cos\alpha - iA^0 \sin\beta \end{pmatrix}$$

$$\Phi_u = \frac{1}{\sqrt{2}} \begin{pmatrix} -H^+ \cos\beta \\ v_u + h \cos\alpha + H \sin\alpha + iA^0 \cos\beta \end{pmatrix}$$

where h, H are neutral CP-even scalars, $H^\pm$ is a charged scalar, and A^0 is a neutral CP-odd scalar. In this framework, $\tan\beta = v_u/v_d$, and α is the mixing angle that diagonalizes the h - H mass squared matrix. This model also contains an additional scalar singlet ϕ that leads to spontaneous symmetry breaking. The α is assigned to be $\alpha = \beta - \pi/2$, in the limit where the h has SM-like couplings to fermions and gauge bosons, and $\tan\beta \geq 0.3$ as implied from the perturbativity of the top Yukawa coupling.

The model is described by five parameters:

- the pseudoscalar mass M_{A^0}
- the DM mass m_χ
- the Z' mass $M_{Z'}$
- $\tan\beta$
- the Z' coupling strength g_z

The kinematic distributions were checked in 2015 analyses for each of masses M_{A^0} , $M_{Z'}$ and $\tan\beta$, and it has been shown that only the masses M_{A^0} and M_Z affect the kinematic distributions. Hence, g_z and $\tan\beta$ are fixed at 0.8 and 1.

Parameter values for this model used in this analysis are given in the Table [3.5].

$M_{A0}[\text{GeV}]$	$M_{Z'}[\text{GeV}]$														
300	450	550	600	800	1000	1200	1400	1700	2000	2500	3000	3500	4000	4500	6000
400	550	600	800	1200	1700	2500	3500	4000	4500	5000	5500	6000			
500	800	1200	1400	1700	2500	3000	3500	4000	4500	5000	6000				
600	800	1400	2500	3000	3500	4000	5500	5000	6000						
700	2000	2500	3000	3500	4000	4500	5000	6000							
800	1000	1400	1700	2500	3000	3500	4000	45000	5000	5500	6000				
900	1200	1700	2500	3000	3500	4000	5000	5500	6000						
1000	1200	1400	1700	2500	3000	3500	4000	4500	6000						
1200	1400	17000	2000	2500	3000	3500	4000	4500	6000						
1400	1700	2000	3000	3500	4000	4500	5000								
1600	2000	2500	3000	3500	4000	4500	5500	6000							

Table 3.5: Signal mass points used to generate official signal samples.

THE LHC AND CMS EXPERIMENT

The data used in this analysis has been produced by the Large Hadron Collider(LHC) through proton-proton collisions with a center of mass energy of 13 TeV. The CMS experiment at the Large Hadron Collider collected data during Run 2 from 2016 to 2018. For this analysis, we are using the data from 2017 and 2018 because the analysis using the 2016 data has already been published.

This chapter provides an overview of the LHC and the CMS experiment, explaining how the data used in this analysis was produced and collected. The chapter is divided into two parts. In the first half of the chapter, the details of the LHC have been discussed. This includes information about how the LHC accelerates particles, the collisions of protons, the amount of data collected (luminosity), and a concept called "pileup" where multiple collisions occur in a single event. We also talk about the different experiments conducted at the LHC. The second part of the chapter focuses on the CMS detector. We explain how the CMS detector is set up in a coordinate system, the different sub-detectors that make up the CMS detector, the triggers used to select interesting events, and the data quality monitoring (DQM) process to ensure the data's integrity and reliability.

4.1 The Large Hadron Collider

The LHC [111, 112] is the largest and most powerful collider in the world, and it is situated at European Organization for Nuclear Research (CERN), on the border between France and Switzerland. It is a 27 km ring in circumference and lies 100 m under the Earth (50-175 m), as shown in Fig. 4.1. The LHC is designed for proton-proton collisions at a maximum center of mass energy of $\sqrt{s} = 14$ TeV with instantaneous luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. LHC accelerates not only protons but also heavy ions such as lead (Pb) and Xenon (Xe) for heavy ion studies. Lead-Lead(Pb-Pb), Lead-Xenon(Pb-Xe) and Xenon-

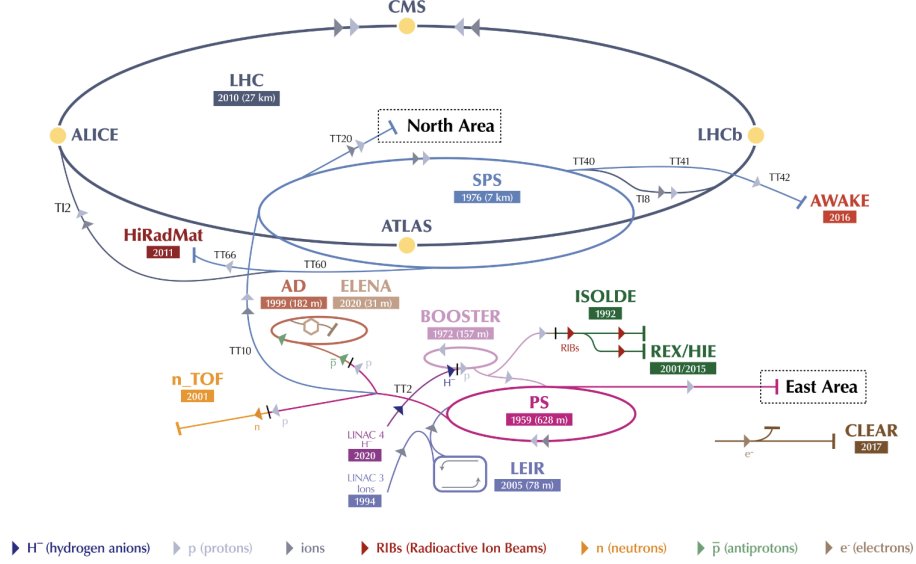


Figure 4.1: Schematic view of CERN accelerator complex [113]

Xenon(Xe-Xe) collide at $\sqrt{s} = 5.02, 8.16$ and 5.44 TeV. Particles collide at four different crossing points where the detectors are placed. The details of the detector have been discussed in Sec 4.1.1. The LHC's goal is to search for new physics and test the predictions of different theories or models of particle physics, such as SM and BSM.

4.1.1 LHC Experiments

There are four crossing points on the ring where four experiments take place: A Toroidal LHC ApparatuS(ATLAS)[114], Compact Muon Solenoid (CMS)[115], A Large Ion Collider Experiment(ALICE)[116], and a Large Hadron Collider beauty (LHCb)[117]. ATLAS and CMS experiments are the two biggest experiments and general-purpose detectors to study new physics. Two independently designed detectors are important to the cross-confirmation of any new discoveries. LHCb is designed to understand the difference between matter and anti-matter by studying b quarks and CP violation [118], and ALICE is designed to study heavy-ion physics and the physics of strongly interacting matter, leading to the formation of a new state of matter called quark-gluon plasma [119]. In addition to the main LHC experiments, there are other experiments that focus on specific tasks. These experiments are TOTAL Elastic and diffractive cross-section Measurement (TOTEM) [120], Large Hadron Collider forward(LHCf)[121], Forward Search Ex-

periment(FASER)[122], and Monopole and Exotics Detector At the LHC(MoEDAL)[123]. TOTEM performs proton structure and inelastic cross-section studies; LHCf performs the measurement in the beam direction and provides an estimate of the energy of ultra-high energy cosmic rays, FASER studies light and extremely weakly interacting particles; and neutrinos and MoEDAL aims to detect magnetic monopole and highly ionising stable massive particles.

4.1.2 Journey of protons; acceleration to collision

The journey of proton particles goes through the accelerator complex at CERN 4.1. It is a chain of machines that accelerate particles to increasingly higher energies. Each machine boosts the energy of a beam of particles before injecting it into the next machine in the sequence, and the last element in the chain is the LHC.

First, hydrogen atoms are stripped of their electrons. They are then propelled to the linear accelerator LINAC4. Protons gain 50 MeV of energy and are then fed from LINAC4 into the Proton Synchrotron Booster (PSB), which increases the energy of protons to 1.4 GeV and separates protons into bunches. The protons are then passed to the Proton Synchrotron (PS) and gain energy of 26 GeV. Protons are then sent to the Super Proton Synchrotron (SPS) where they are accelerated up to 450 GeV. After the SPS, protons are finally injected into the beam pipes of the LHC. It takes 4 minutes and 20 seconds to fill each LHC ring and 20 minutes to reach its maximum energy of 6.5 TeV. Each beam with 2800 proton bunches circulates in the opposite direction with a spacing of 25 nanoseconds apart, and 3×10^{14} protons are supplied to each beam in the LHC.

The LHC uses 1232 liquid helium-cooled superconducting dipole magnets to achieve the final energy of protons. Each magnet length is 15m, with a peak dipole field of 8.3T. And 492 quadrupole magnet of length 5-7 m is used to focus the beam.

4.1.3 Luminosity

Luminosity is a very important parameter at CMS. The higher luminosity means more probability of observing rare events in the collisions. The luminosity - a measure of how many collisions are occurring in the detector- is related to the number of events observed by an experiment. There are two kinds of luminosity: instantaneous luminosity and integrated luminosity.

The instantaneous luminosity L that characterizes an accelerator is defined as the number of collisions per unit cross-sectional area of beams and per unit time:

$$L = \frac{N_1 N_2 n_b f}{A} \quad (4.1)$$

where N_1 and N_2 represent the number of particles in two bunches colliding at a frequency f , n_b represents the number of bunches in each beam, and A represents the area of the two bunches in the beam. The LHC is designed to operate with an incredibly high instantaneous luminosity of $L = 1034 \text{ cm}^2 \text{ s}^{-1}$.

Integrated luminosity is the accumulation of instantaneous luminosity over a period of the time. It can be defined as:

$$\mathcal{L} = \int L dt \quad (4.2)$$

The integrated luminosity of a detector is measured in units of fb^{-1} and represents the total amount of data collected. More integrated luminosity indicates that a physical process with smaller cross section is accessible in the given period of time.

Every year, CMS collects more luminosity during the data taking-periods. CMS integrated luminosity delivered during the data collection period in runs I (2010-2012) and II (2015-2018) is shown in Fig. 4.2(a). In this analysis, 2017 and 2018 data collected by CMS is analyzed, and Fig. shows integrated luminosity for 2017 and 2018.

4.1.4 Events at LHC

For any specific physics process, the number of events can be calculated using two main parameters: the integrated luminosity ($\mathcal{L}$) recorded by the detector and the cross-section of the physics process ($\sigma_{process}$). It is defined as

$$N = \mathcal{L} \sigma_{process} \quad (4.3)$$

In proton-proton collisions, interesting physics processes like Higgs physics and BSM (beyond the standard model) are projected to suffer from low production cross-section. The predicted cross-section for certain significant SM processes at proton-proton and proton-antiproton colliders is shown in Figure 4.3. From the Figure, Higgs production cross-section is lower than vector boson (Z/W) production cross, but the cross-section

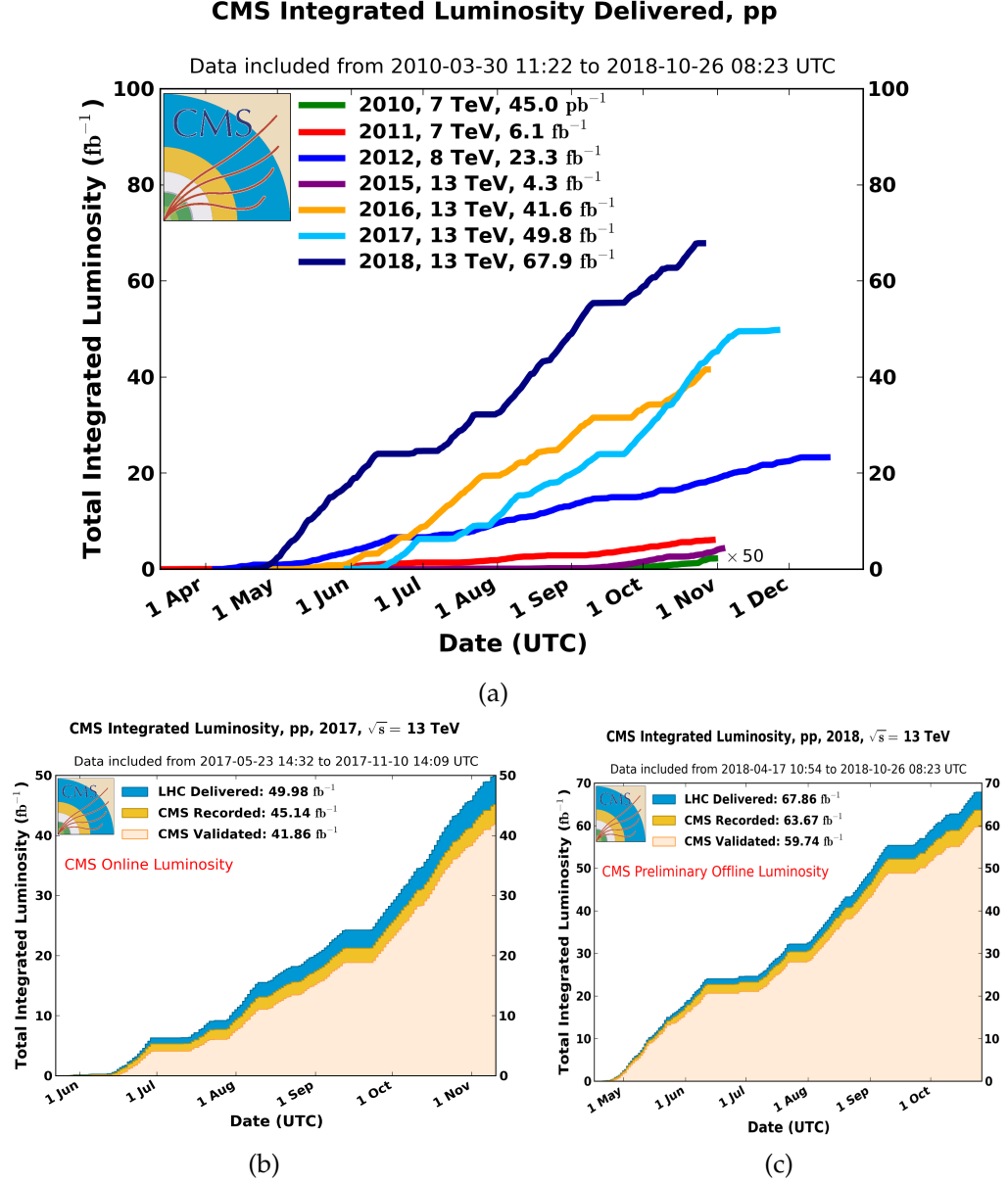


Figure 4.2: (a) Total Integrated luminosity delivered to CMS from LHC during Run I and Run II data taking [124]. Total Integrated luminosity recorded and validated by CMS is shown in (b) and (c) for physics analysis [125].

increases when the center of mass energy increases. Because of this, the colliders tend to increase the center-of-mass energy and luminosity so that the event rate can be increased.

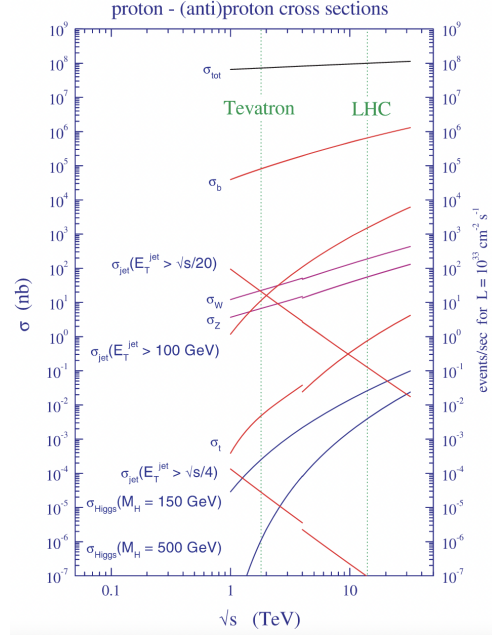


Figure 4.3: Standard model cross-section at the Tevatron and LHC colliders [126].

4.1.5 Pile-up

At the Large Hadron Collider (LHC), proton collisions do not happen with individual protons but rather with bunches of protons colliding simultaneously. Due to the substantial number of protons involved in each collision, multiple interactions can take place within the CMS detector. Consequently, particles stemming from the primary interaction (the interaction of interest) are recorded along with particles originating from additional interactions, known as pileup interactions.

In order to separate out interesting particles from a large number of particles produced in the pileup interactions, advanced techniques have been used at CMS. The distribution of pileup interactions in CMS during Run-2 is shown in Fig. 4.4.

The classical approach to mitigate the pileup uses CMS tracker system, which can identify the charge particle interaction vertex and remove charged particles from pileup vertices. This method fixed 60% of the pileup energy because 60% of particles from proton-proton collisions are charge particles. The remaining energy from the neutral particles, assuming

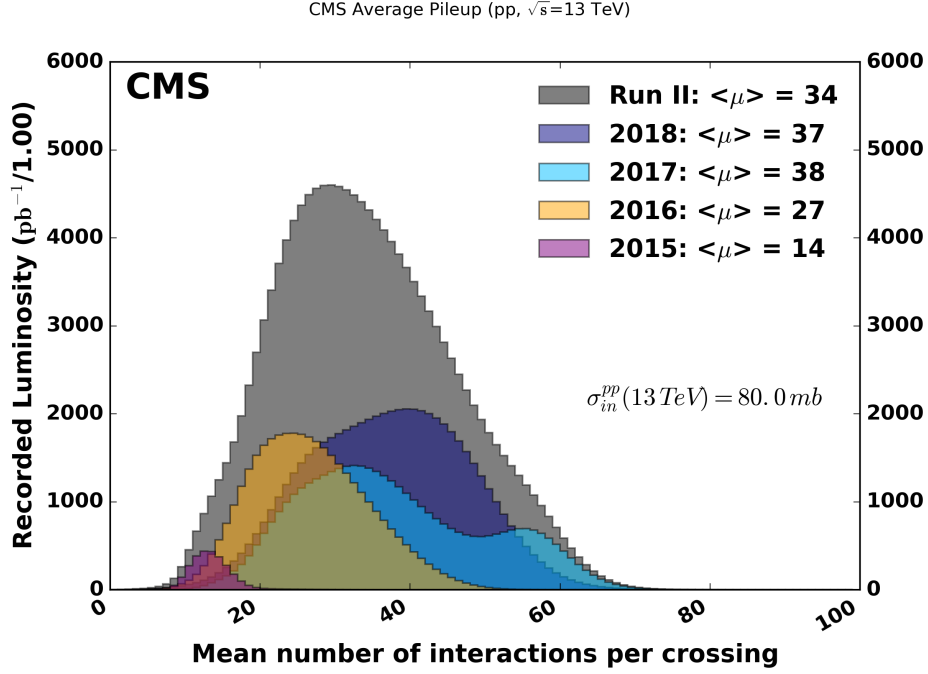


Figure 4.4: Distribution of the average number of interactions per crossing (pileup) for pp collisions [124].

that neutral particles are distributed uniformly in the detector. CMS has a new approach called PileUp Per Particle Identification (PUPPI), where neutral particles originating from pileup are also estimated (Fig. 4.5). The technique is shown in Fig. 4.5, where neutral particle from the interaction of interest is typically aligned with charged particles originating from the interaction of interest, while neutral particle originating from pileup vertices are more uniformly distributed in all directions. So based on its surrounding charged particles, neutral particle from pileup collision can be identified.

4.2 The CMS Experiment

The Compact Muon Solenoid (CMS) is a general-purpose detector to operate at the Large Hadron Collider (LHC) at CERN. This chapter describes the design and sub-detectors of the CMS detector. CMS is installed about 100 meters underground between Lake Geneva and the Jura mountains.

The CMS detector is designed with the following requirements to meet the goals of the LHC Physics program:

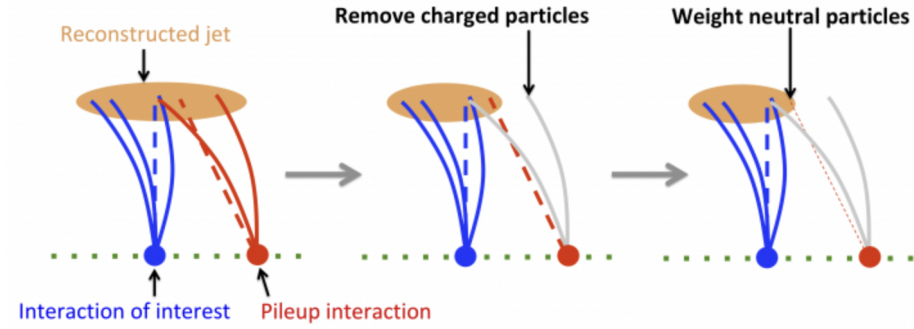


Figure 4.5: Sketch of an interesting interaction happening together with a pileup interaction in the detector. The particles coming from the pileup interaction should be removed. The two steps of the pileup removal are depicted.

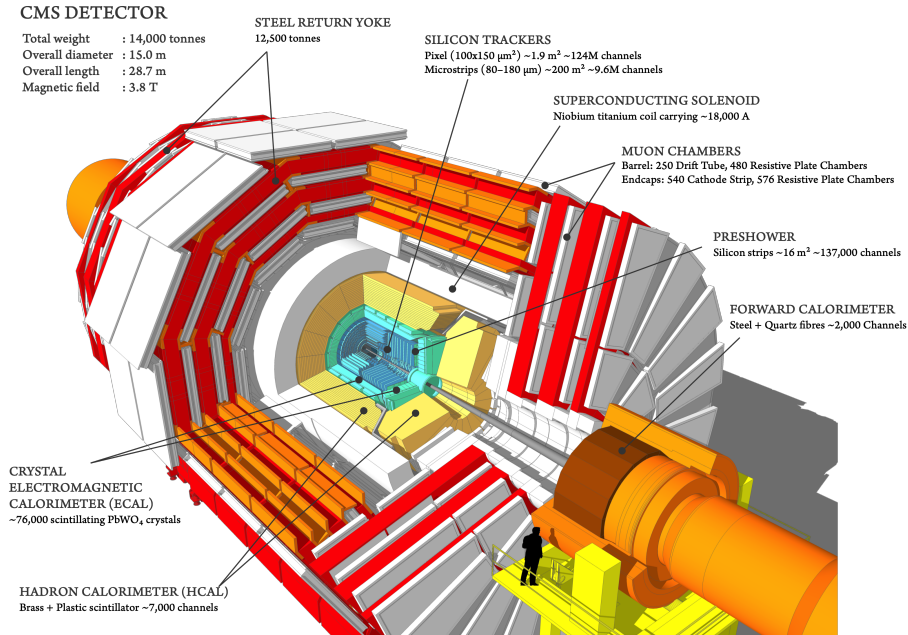


Figure 4.6: A cutaway diagram of the CMS detector with all of the principal components labelled. This detector configuration was used for the 2017–18 data taking years, where the coverage of the pixel detectors in the silicon tracker were upgraded. Image taken from Ref. [127].

- Good muon identification and momentum resolution over a wide range of momenta and angles, good dimuon mass resolution ($\approx 1\%$ at 100 GeV), and the ability to determine the charge of muons with $p_T < 1$ TeV without ambiguity.
- Good charged-particle momentum resolution and reconstruction efficiency in the inner tracker. Efficient triggering and offline tagging of τ 's and b-jets, requiring pixel detectors close to the interaction region;
- Good electromagnetic energy resolution, good diphoton and dielectron mass resolution ($\approx 1\%$ at 100 GeV), wide geometric coverage, π^0 rejection, and efficient photon and lepton isolation at high luminosities.
- Good missing-transverse-energy and dijet-mass resolution, requiring hadron calorimeters with a large hermetic geometric coverage and with fine lateral segmentation.

A high-field solenoid, a full-silicon-based inner tracking system, and a homogeneous scintillating-crystals-based electromagnetic calorimeter are the main distinguishing features of CMS.

4.2.1 Coordinate System

The standard coordinate system is used by CMS. The origin is centered at the nominal collision point inside the experiment, and x-axis points radially inward toward the center of the LHC, and y-axis points toward the sky, and the z-axis points along the beam direction as shown in the Fig. 4.6. The azimuthal angle, called ϕ is measured in the x-y

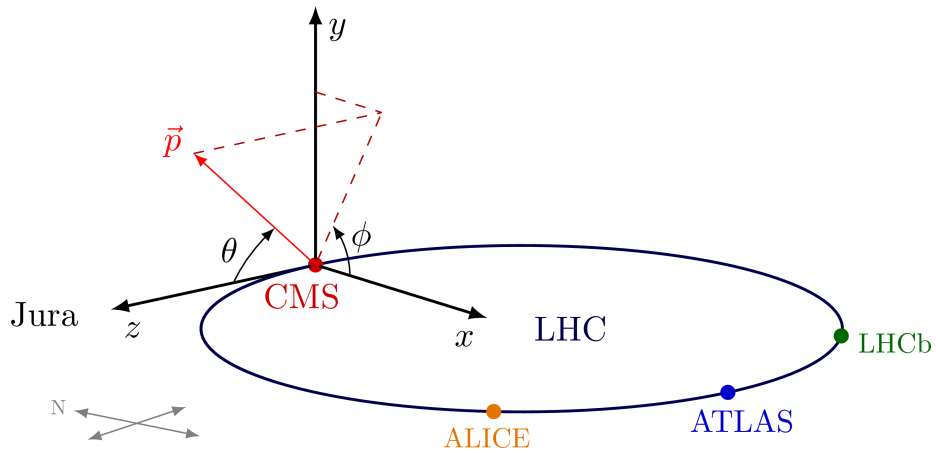


Figure 4.7: The CMS Coordinate system [128].

plane, $\phi = 0$ corresponds to the positive x-axis. The polar angle, called θ , is measured in y-z the plane where $\theta = 0$ corresponds to the positive z-axis. However, pseudorapidity, η , is used more often than polar angle θ , because it is invariant at the limit of momenta much larger than the mass of particle. It is defined as

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \quad (4.4)$$

where θ is polar angle. $\eta = 0$ represents particles lying on the perpendicular x-y plane and $\eta = \pm\infty$ represents particle lying in a direction parallel to the beam axis. The transverse momentum p_T and transverse energy are computed on x-y plane using x, y components. According to momentum conservation law, the particle's p_T should be the same before and after the collision; if there is an imbalance of energy, it is referred to as "missing transverse energy" (E_T^{miss}) and measured in the transverse plane.

Another common variable used to denote the angular separation between two particles is defined as

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad (4.5)$$

4.2.2 The Tracking System

The silicon tracker is the first sub-detector located in close proximity to the interaction point. As a result, it necessitates a highly radiation-resistant material. With a diameter of 2.5 m, total length of 5.8 m, and pseudorapidity range of $|\eta| < 2.5$, this tracking system enables the precise measurement of charge and momentum for all charged particles as they emanate outward from the collision point. Its design aims to minimize energy loss encountered by the particles when traversing through matter. By reconstructing the trajectories of charged particles originating from the collision point, except for tracks stemming from the decay of short-lived particles, the tracker facilitates the identification of primary and secondary vertices with exceptional precision [129].

The tracking system is comprised of two components: the silicon pixel sub-detector positioned at the inner radius, and the silicon strip sub-detector located at the outer radius. Figure 4.8 provides a comprehensive overview of the CMS tracker system, illustrating its subsystems: Pixel, Tracker Inner Barrel (TIB), Tracker Inner Disks (TID), Tracker Outer Barrel (TOB), and Tracker Endcaps (TEC).

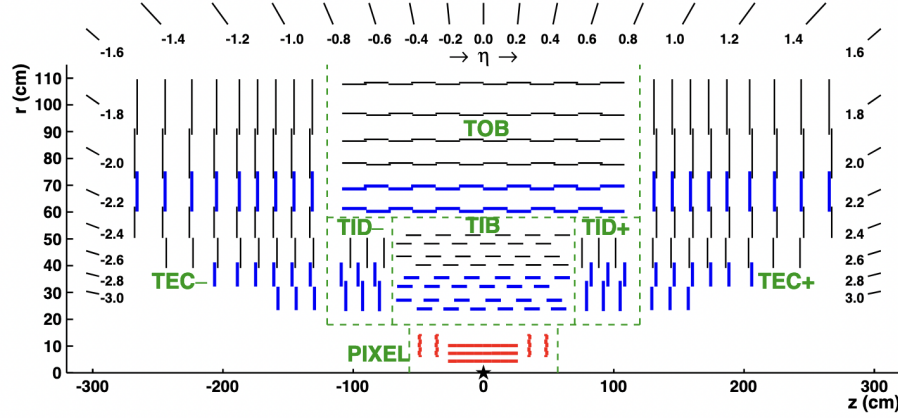


Figure 4.8: Schematic cross-section through the CMS tracker in the r - z plane [129]

4.2.2.1 The silicon pixel sub-detector

The silicon pixel detector serves as the initial sub-detector positioned near the interaction point, comprising four Barrel Pixel (BPix) layers encircling the beam-pipe, along with three endcap disks (EPix) in each end-cap region, as depicted in figure 4.9.

During operation, silicon pixels are connected in reverse-bias. As charged particles traverse through the pixels, the silicon's electrons transition from the valence to the conduction band of the semiconductor, resulting in small currents. These currents are then amplified by the electronics. If these amplified currents meet the trigger condition, the corresponding data is transmitted to the data acquisition (DAQ) system. Otherwise, if no trigger is received, the data is overwritten.

In order to precisely reconstruct particle tracks and determine their momentum, it is crucial to accurately ascertain the particle's origin, whether from a primary or secondary vertex. This becomes particularly significant for identifying decays involving b quarks and τ leptons, as they possess lifetimes allowing them to travel several millimeters from the primary vertex before decaying. The pixel detector plays a vital role in distinguishing these secondary vertices from the primary collision points.

However, as time progresses, the pixel detector experiences a degradation of resolution due to radiation damage. To maintain its high performance, a "Phase Pixel Upgrade" was conducted during the technical stop at the end of 2016 [130, 131]. The pixel upgrade phase involved the addition of a fourth layer in the barrel and a third disk in the end-cap, enhancing the pixel detector's capabilities.

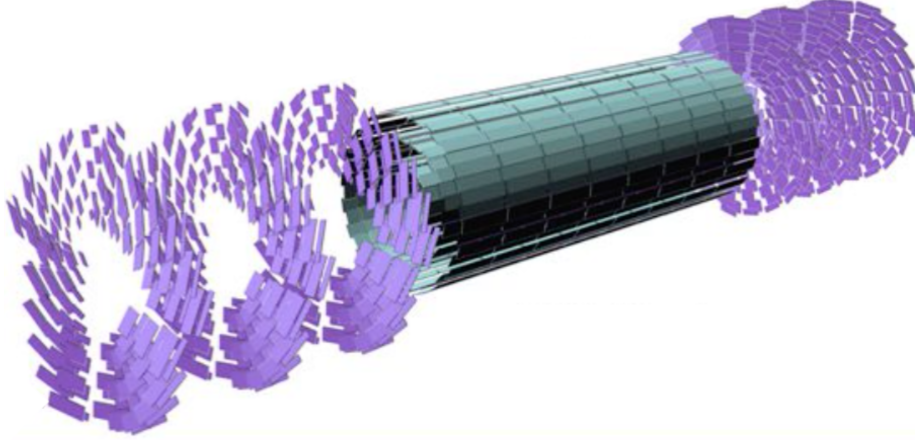


Figure 4.9: View of the CMS silicon pixel sub-detector geometry. In the middle there are three layers of the barrel pixels, and on either end of the barrel are three end-cap disks[132].

4.2.2.2 The silicon strip sub-detector

Following the silicon pixel sub-detector, and continuing beyond the tracker, is the strip sub-detector. This particular system employs modules consisting of silicon microstrips instead of pixels. The strip sub-detector encompasses various components, including 10 cylinder layers in the barrel region encircling the pixel sub-detector: a four-layer Tracker Inner Barrel (TIB), a six-layer Tracker Outer Barrel (TOB), and 24 disk-shaped endcap modules, with 12 located on each end of the barrel cylinders. Specifically, there are three disk-shaped Tracker Inner Disks (TID) and nine disk-shaped Tracker Endcaps (TEC). The coverage extends to $|\eta| < 1.6$ within the barrel region and $|\eta| < 2.5$ in the end-cap region. The operation principle of the silicon strip detector modules is similar to that of the pixel modules. The transverse momentum resolution for tracks ranges from 0.7% to 1.5% for track momenta between 1 GeV and 100 GeV, respectively.

4.2.3 Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL [133]) starts after the tracking system. The purpose of the ECAL in the CMS experiment is to measure and precisely reconstruct the energy of electromagnetic particles, such as electrons and photons. CMS has a scintillating crystal calorimeter that provides good energy resolution due to the fact that almost all of the energy of photons and electrons is deposited within the scintillating crystal volume.

CMS ECAL is made of lead tungstate (PbWO_4) crystals. The lead tungstate crystal has a high density, a small Molière radius¹ and a short radiation length, and this makes a very compact calorimeter system.

CMS ECAL consists of 76,832 lead-tungstate crystals as shown in Fig. 4.10 with a preshower in front of the endcap crystals (Fig. 4.11). Avalanche photodiodes (APDs) are used in the barrel (EB), and vacuum photodiodes are used in the endcap (EE). The use of high-density crystals has allowed the design of a calorimeter which is fast, has fine granularity and is radiation resistant, all important characteristics in the LHC environment.

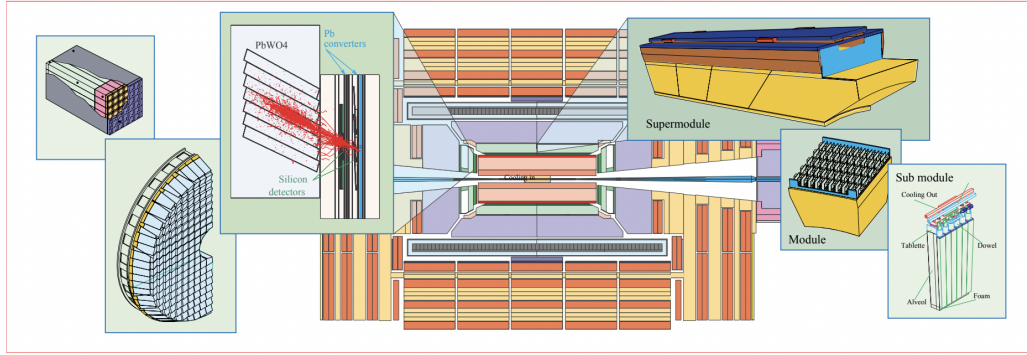


Figure 4.10: The CMS Electromagnetic Calorimeter [134]

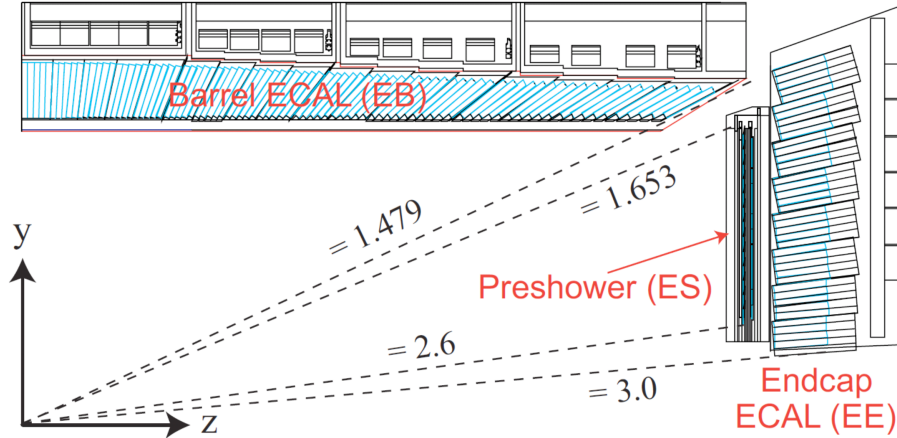


Figure 4.11: CMS ECAL [133]

¹ It is the radius of a cylinder containing on average 90% of the shower's energy deposition, and defined as $R_M = 0.0265X_0(Z + 1.2)$, where Z is atomic number and X_0 is radiation length

The ECAL barrel (EB) covers the pseudorapidity range $|\eta| < 1.479$. The crystals are organized into supermodules, and each supermodule contains 1700 crystals, 20 along ϕ and 85 along η . The crystals have a truncated pyramid shaped with some variation in η position. To avoid cracks aligned with particle trajectories, they are mounted in a quasi-projective geometry, so they are tilted with a small angle (3°) with respect to the nominal interaction vertex, in both the η and ϕ projections. Each crystal has a front face of about 0.0174×0.0174 in $\eta - \phi$ or $22 \times 22 \text{ mm}^2$ and rear face of $26 \times 26 \text{ mm}^2$, front face matches with Molière radius of 22 mm. The crystal has a total thickness of 26 radiation lengths, corresponding to 23 cm in length. This length limits fluctuations in the longitudinal shower leakage of high-energy electrons and photons.

The ECAL endcap (EE) covers a pseudorapidity range of $1.479 < |\eta| < 3.0$. The longitudinal distance between the interaction point and the endcap envelope is 315.4 cm, which includes a 1.6 cm shift toward the interaction point when the 4 T magnetic field is turned on. The endcap is made up of identically shaped crystals grouped into mechanical units of 5×5 supercrystals(SCs) consisting of a carbon-fibre alveola structure. The crystals and SCs are set up in a rectangular $x - y$ grid, with the crystals pointing at a focus 1300 mm beyond the interaction point. Each crystal has a front face of $28.62 \times 28.62 \text{ mm}^2$, rear face of $30 \times 30 \text{ mm}^2$ and a length of 220 mm, corresponding to 24.7 radiation length.

One of the design goals was to detect Higgs boson decays to pairs of photons ($H \rightarrow \gamma\gamma$). A scintillating crystal calorimeter's high energy resolution enhances this capability. The CMS ECAL energy resolution has been measured on a super [135], can be defined as :

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 \oplus \left(\frac{12\%}{\sqrt{E}}\right) \oplus (0.3\%) \quad (4.6)$$

where E is in GeV. A resolution of 0.5% was achieved for electrons with 120 GeV energy. The scintillator light from the crystals is captured by a photodiode. This data is transported off the detector via optical fibres to the readout and trigger system.

4.2.4 Hadron Calorimeter

The CMS detector is designed to investigate a wide range of high-energy phenomena involving a variety of final state signatures. The Hadron Calorimeter(HCAL[136]) detectors

are particularly useful for detecting hadron jets, neutrinos, and other exotic particles with apparent missing transverse energy.

The HCAL is made up of alternating layers of dense material, usually made of brass (as absorber) and plastic fluorescent scintillator (acts as an active material). When a hadron passes through the brass it creates a shower of secondary particles, such as pions and muons, which in turn create a cascade of lower-energy particles. These particles interact with the scintillators, causing them to emit light which is then detected by photodetectors. The amount of light detected by the photodetectors is proportional to the amount of energy deposited by the hadron in the HCAL. By summing up the signals from all the layers, the total energy of the hadron can be determined with high precision. The HCAL is also designed to be hermetic, which means that the detector is designed to fully surround and enclose the interaction region where particle collisions occur, so that it can detect all the hadrons produced in the collision. The CMS HCAL detector is shown in longitudinal view in Fig. 4.12.

The HCAL is divided into four parts: the Hadron Barrel (HB), the Hadron Endcap (HE), the Hadron Outer (HO), and the Hadron Forward (HF) detectors.

The HB is composed of two half-barrels that cover the region $|\eta| < 1.3$. It consists of 18 layers of brass absorber interleaved with plastic scintillator tiles. The HE, located outside the HB, covers the range $1.3 < |\eta| < 3.0$. It also consists of brass absorber plates, but the scintillator tiles are replaced with wavelength shifting (WLS) fibers that are read out by hybrid photodiodes (HPDs).

The HO is located outside the magnet coil and covers the region $|\eta| < 1.3$. It is designed to improve the energy measurement in the barrel region by sampling the energy deposited in the tail of the shower that penetrates the HB. The HO consists of one layer of scintillator tiles placed behind the outermost layer of the HB absorber.

The HF is located in the forward region and covers the range $3.0 < |\eta| < 5.0$. It is composed of steel absorber plates, with embedded quartz fibers that collect Cherenkov light from the shower particles. The Cherenkov light is detected by photomultiplier tubes (PMTs) located at the end of the fibers.

4.2.5 The Muon System

As the name "The Muon System" tells that this part of the detector is designed to have the capability of reconstructing the charge and momentum of muons very well at the LHC.

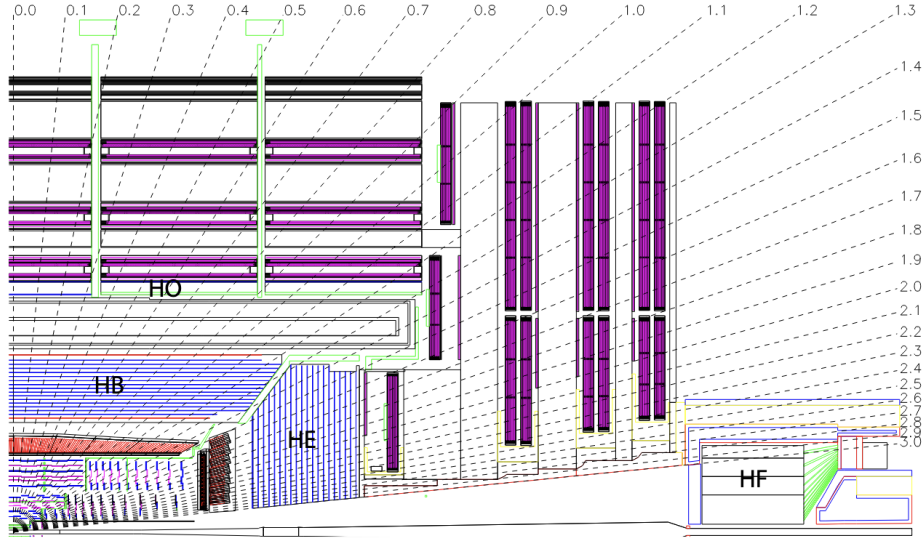


Figure 4.12: CMS HCAL [137]

The CMS muon detector [138] detects muons with precise energy measurement over a large energy range and at high luminosities. A schematic view of the muon detector is shown in Fig. 4.13.

The muon detector covers the pseudorapidity range of $|\eta| < 2.4$. There are four stations of gas-ionization muon detectors installed outside the solenoid and sandwiched between the layers of the steel return yoke. It is divided into three sub-detectors: Drift tube (DT) chambers, cathode strip chambers (CSC), and resistive plate chambers (RPC). DT reconstructs and identifies muons in the η regions of $|\eta| < 0.9$, and CSC detects muons in the η regions of $0.9 < |\eta| < 2.4$, and both chambers are complemented by RPC covering the pseudorapidity range of $|\eta| < 1.6$. The important characteristic of the DTs and CSCs sub-system is that they provide good position resolution. The RPCs produce a fast response, with good time resolution but coarser position resolution than the DTs and CSCs. In muon detector, three different η regions are defined, barrel region ($|\eta| < 0.9$), overlap ($0.9 < |\eta| < 1.2$), and endcap ($1.2 < |\eta| < 2.4$). Muon reconstruction is also performed using the all-silicon inner tracker, electromagnetic calorimeter (ECAL), hadronic calorimeter (HCAL), and outer hadronic calorimeter (HO).

In muons measurement, the most important part is a magnetic field configuration choice. A high-field Solenoid provides large the magnetic flux to saturate a sufficient amount of steel in the return yoke. This provides efficient muon measurement up-to pseudorapidity of $|\eta| < 2.4$.

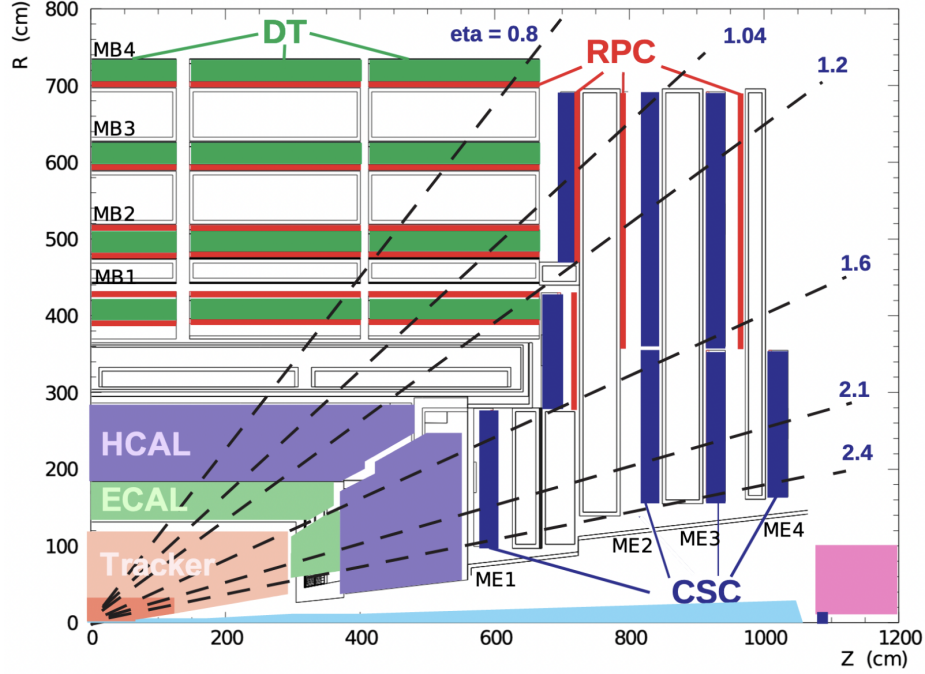


Figure 4.13: CMS Muon system [138]

4.2.5.1 Drift tubes

DT system consists of 4 stations. They are cylindrical; the first three inner cylinders have 60 drift chambers, the last cylinder has 70 drift chambers, and around 1172000 sensitive wires are used in the drift chamber to track the muons in the barrel muon system.

The wire has a length of around 2.4 m in the chamber, it is measured in an $r - \phi$ projection, and it is constrained by longitudinal segmentation of the iron yoke. The maximum drift path is 21 mm, and the drift time is 380 ns in a gas mixture of 85% Ar + 15% CO₂. Each DT chamber is made of 3 or 2 superlayers, as shown in Fig. 4.14, and each SL is made of 4 layers of rectangular drift cells staggered by half a cell. As we can see from the figure, in the 2 outer SLs, the wires are parallel to the beamline and provide a track measurement in the magnetic bending ($r - \phi$) plane. In the inner SL, wires are orthogonal to the beamline and measure the z position in the direction of the beam. The fourth station does not have this third z measurement. Therefore it measures only the ϕ coordinate. A muon emitted from the interaction point encounters a ϕ measuring SL, then passes through the honeycomb plate before crossing the z -measuring SL and the second ϕ measuring SL. A muon may only pass through two stations instead of the maximum four due to discontinuities in design.

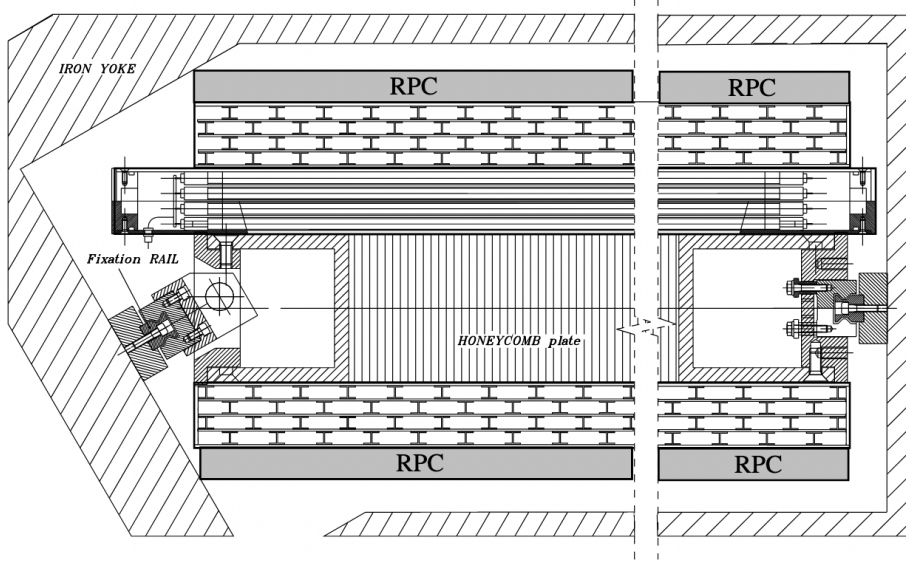


Figure 4.14: CMS Drift tubes [134]

4.2.5.2 Cathode strip chamber

Cathode strip chambers(CSCs) are used in endcap disks with a pseudorapidity range of $0.9 < |\eta| < 2.4$, where the magnetic field is not completely smooth, and particle rates are high. There are four stations, namely ME1, ME2, ME3, and ME4. The chambers are placed perpendicular to the beamline and interspersed between the magnetic flux return plates.

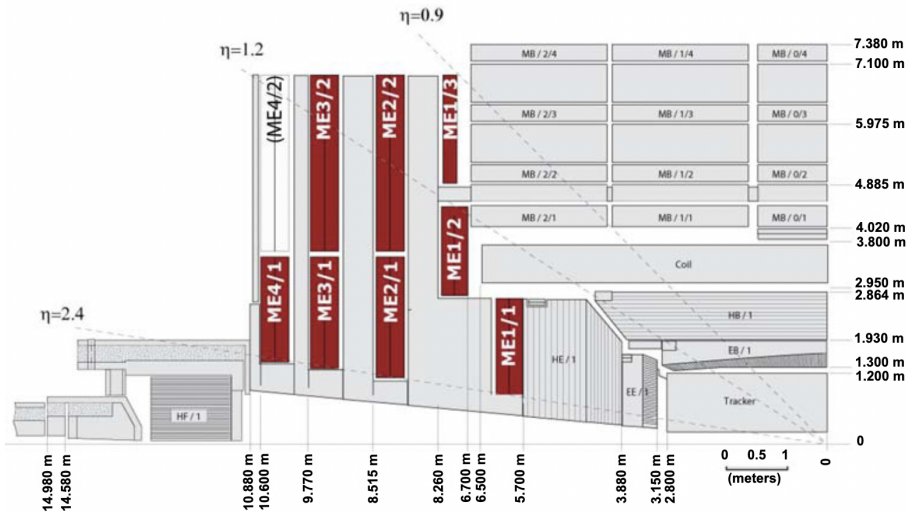


Figure 4.15: CMS Cathode strip chamber [138]

CSCs are multiwire proportional chambers, and each chamber has six anode wire planes and seven cathode panels with strips. Wires that run azimuthally define the radial coordinate of a track. On cathode panels, strips are milled and run lengthwise at a constant width ($\Delta\phi$). The CSCs can operate in large, noneven magnetic fields and at high rates, and they provide precise space and time information. The CSCs fast detector is suitable for triggering because of its closely spaced wires.

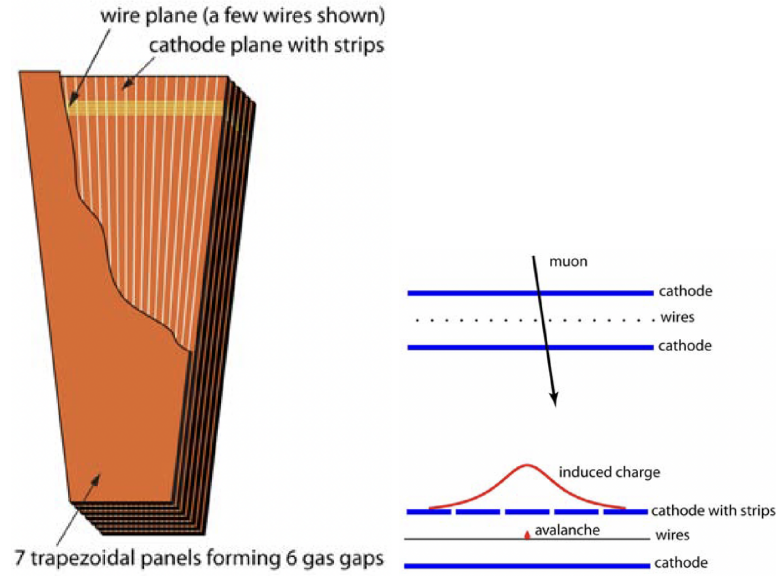


Figure 4.16: muon tracks [138]

The muons passing through the chambers knock the electrons out of the gas atoms, and electrons move towards anode wires, creating an avalanche of electrons. Positive ions move opposite the electron direction. They move towards the copper cathode and away from the wire. Strip and wires are perpendicular. Therefore we get two positions coordinated for each passing muon.

4.2.5.3 Resistive plate chambers

Resistive plate chambers (RPCs) are fast gaseous parallel-plate detectors. They are located in both the barrel (along with DTs) and endcaps (along with CSCs), as shown in Fig. 4.13. In Each muon station, one RPC is attached except for two innermost barrel stations, 1 and 2, which are equipped with two RPC planes. This helps to identify low momentum muons ($< 5\text{-}6\text{ GeV}$) which can not reach the outer stations, for which a special low momentum trigger is designed. The RPC readout is segmented into strips, and each strip has 1-2 cm

width and 30-130 cm length. In the endcaps, strips are radial, and in the barrel, they are running to the beam. Each strip covers $\Delta\phi = (5/16^\circ)$ and $\Delta\eta \approx 0.1$ in angular units. An RPC can tag the time of an ionizing event in a very shorter time than the time between two consecutive LHC bunch crossings (BX), which is 25 ns. Therefore, a muon trigger based on RPCs is capable of identifying unambiguously the relevant BX to which a muon track is associated, even at a high rate and background.

4.2.6 The Trigger System

The trigger system is the first step in selecting which physics events to analyze from the large number of events created by collisions at the LHC[139]. The LHC produces many events every second, with each bunch of particles colliding at a rate of 40 million times per second. This means there are about 800 million collisions happening in one second. To distinguish particles from the same event and avoid mixing them up with particles from different events, the detectors need to have precise timing, and the signals from millions of electronic channels must be synchronized.

Storing all this data would require a massive amount of memory, about 40 terabytes per second. It's not feasible to store such a huge amount of data, so a reduction process is necessary. The trigger system is responsible for quickly deciding which events to keep and which ones to discard. It has to make this decision within a very short time, around 25 nanoseconds, as required by the LHC.

The trigger system consists of two levels: the Level-1 (L1) trigger and the High-Level Trigger (HLT). These two levels work independently to analyze the data and make the selection. The L1 trigger operates very quickly and performs a basic analysis of the events, while the HLT performs a more detailed analysis to identify specific physics processes. Their combined efforts help to select the most interesting events for further analysis, while discarding the majority of less relevant events.

4.2.6.1 Level 1 Trigger

Level 1 is the first-level decision and completely hardware based system. It reduces the event rate from the initial 40 MHz to 100 kHz. The data are moved or assigned to a buffer for readout only if the level 1 trigger accepts the event. Figure shows a schematic of the L1 trigger.

The L1 calorimeter trigger, the L1 muon trigger, and the L1 global trigger are three major subsystems of the L1 trigger system. The muon trigger is organized into three muon

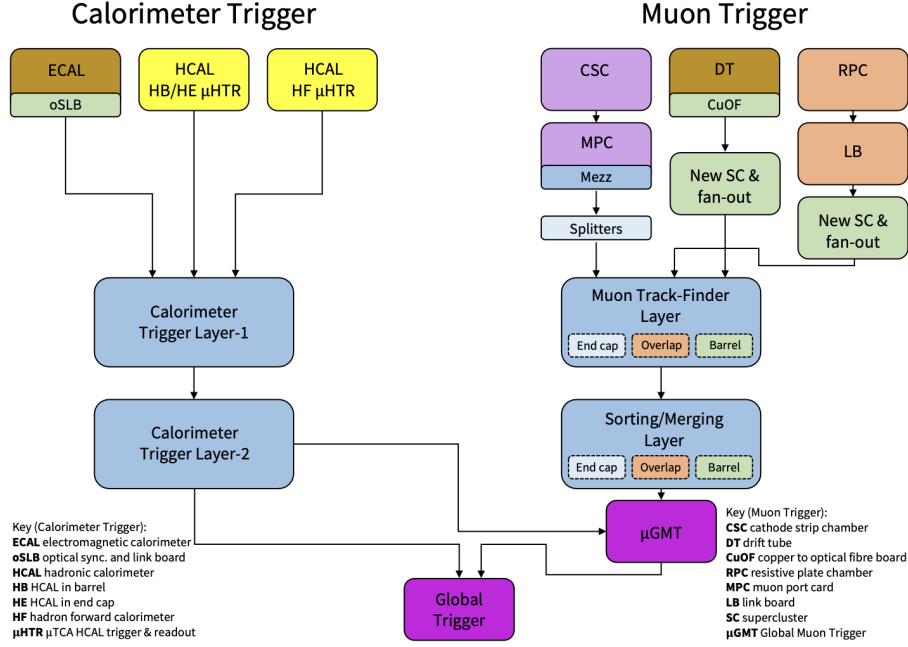


Figure 4.17: A summary of CMS Level 1 trigger system from the hits recorded by sub-system to Global trigger[140].

detector systems, namely, Drift Tube (DT) trigger, Cathode Strip Chamber (CSC) trigger, and Resistive Plate Chamber (RPC). The L1 muon trigger also contains a global muon trigger which uses the trigger information from the DT, CSC, and RPC trigger systems, and this information is sent to the L1 global trigger.

The input data of the L1 trigger system are transmitted to the DAQ for storage along with the event readout data. This input data also includes the input data to the global muon trigger, global calorimeter trigger, and global trigger. All trigger objects found are also sent. The L1 decision to keep or reject depends on the presence of trigger objects such as electrons, muons, photons, jets, and global sums of E_T and missing E_T . The L1 trigger can also monitor and control trigger rate, dead channels, and other pathological conditions. It is designed to keep a maximum trigger rate of 100kHz and minimum rejection rate of 10^4 at the luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$.

4.2.6.2 High Level Trigger

After the L1 trigger, an event is processed further by High-Level Trigger (HLT) [141], which is software based. It uses powerful software consisting of appropriately 22,000

CPU cores computers. HLT triggers filter the events from 100 kHz to 1 kHz. HLT menu consists of a list of paths, and each path has some selections. An event needs to pass at least one of the HLT paths. If the event passes the HLT, then it is recorded permanently on the disk by the DAQ system and then transferred to CERN Tier0 (T0) storage system. The collected data undergoes data quality monitoring (DQM) to assess its quality, resulting in the classification of datasets as either "good" or "bad." The certified datasets, derived from this process, are subsequently utilized for physics analysis.

4.2.7 Data Quality Monitoring

In the CMS experiment, the Data Quality Monitoring group (DQM)[142] serves several important purposes. Firstly, it monitors the detector to quickly identify any malfunctions and raise alarms when necessary. Secondly, it provides data certification by recording the portions of data that were affected by detector faults. Lastly, it aids in debugging by offering detailed information that helps experts troubleshoot and resolve issues. The output of DQM varies depending on the task: for monitoring and certification, a single bit indicating "good" or "bad" data quality suffices, while debugging requires a larger number of plots known as monitor elements. These monitor elements, presented as histograms in ROOT[143] format, allow detector experts to analyze the behavior of detector. The DQM group collaborates with CMS subsystems, including detectors and trigger systems, to collect and display relevant data. The DQM system comprises modules within the CMS data processing software and independent applications running on dedicated hardware. It involves data collection, visualization of monitor elements, metadata management, and user interfaces. User interaction poses a significant challenge for the DQM team, and their findings are communicated through interfaces and APIs to the collaboration.

PHYSICS OBJECT RECONSTRUCTION

This chapter describes essential physics object reconstruction, such as missing transverse energy and jets, which are this analysis's final state for Dark Matter Search. The corrections applied to them have also been discussed in this chapter.

The raw information from different sub-detectors, such as "hits" from the tracker and muon system, "energy" deposited in the electromagnetic calorimeter, and hadron calorimeter, is used to reconstruct the physics object. The reconstruction process is done by the particle flow (PF) algorithm [144], which performs a global event reconstruction using the raw information from all the sub-detectors. The particle-flow algorithm generates a list of particle-flow candidates, namely, electrons, muons, photons, and neutral and charged hadron particles. Before talking about object reconstruction, tracks and vertex reconstruction have been discussed first in the next sections [5.1,5.2].

5.1 Tracks

Charged particles from the interaction point leave their signatures in various sub-detectors. They leave hits in the tracker and deposit energy in the calorimeters. Due to the presence of the magnetic field, charged particles make a helical trajectory in the detector. Dedicated algorithms are used to perform track reconstruction from hits. The track reconstruction [129] occurs in the following steps:

- hit reconstruction
- seed generation
- track finding
- track fitting
- final selection

Hits are reconstructed in the pixel and strip tracker. In the pixel detector, any pixel above its single pixel threshold are read out, others are zero-suppressed. Pixel clusters are formed by adjacent above-threshold pixels. The cluster position is determined using a charge-weighted average of the individual pixel positions. For the strip detector, the threshold value is set to five times the channel noise, or if the strip and one of its neighbors have a charge more than two times the channel noise, then it is accepted. Strip clusters are formed by adding neighboring strips which are above the threshold value. Clusters are seeded by the channel that has a charge of at least three times channel noise [134]. In each cluster, a hit is reconstructed by taking the charge-weighted average of its strip positions.

An iterative tracking procedure [129] is used to reconstruct the trajectories. The first step focuses on finding the easiest tracks to identify, such as those with high momentum. Once these tracks are identified, the hits associated with them are removed to simplify the search for more challenging tracks, like those that are displaced or have missing hits or low momentum. In each iteration, initial track candidates, known as seeds, are identified by considering three hits with three-dimensional positions. To fully describe the helical trajectory of a charged particle, five track parameters are required: p_T , η (pseudorapidity), the angle (ϕ_0) at the point of closest approach, the z position (z_0) at the closest approach, and the x - y distance (impact parameter or d_0) at the closest approach. Seeds provide an initial estimate of these track parameters along with their associated uncertainties.

Track is reconstructed using the hits from the tracker. A CMS software Combinatorial Track Finder(CTF), which is an adaptation of the combinatorial Kalman filter [145–147] (an extension of Kalman filter [148]), is used for pattern recognition and track fitting. It produces a collection of reconstructed tracks. In this process, multiple iterations take place; this is called iterative tracking. The filtering and smoothing procedure uses the Runge-Kutta propagator [149, 150]. The Runge-Kutta propagator employs a detailed magnetic field map to ensure accurate extrapolation of track trajectory.

The track-finding procedure yields a significant fraction of fake tracks, which are not associated with any charged particle. The fake tracks are further reduced by applying selections on tracks.

5.2 Vertex Reconstruction

A vertex is reconstructed using the collection of tracks. The point where hard interaction happens is called the primary vertex (PV), and additional interactions are called pile-up (PU). The goal of primary-vertex reconstruction [151] is to find the location and the associated uncertainty of all proton-proton interaction vertices in each event, including the ‘signal’ vertex and any vertices from pile-up collisions, using the available reconstructed tracks. This measurement happens in three steps:

- Some selections are applied to filter the fake tracks. Tracks are required to be the maximum value of significance of the transverse impact parameter (<5) relative to the center of the beam spot, and the number of the strip and pixel hits associated with a track should be ≥ 2 for pixel layers and 5 for pixel+strip, and normalized χ^2 from a fit to the trajectory should be < 20 .
- The selected tracks are clustered based on their z-coordinates at their closest approach to the beam spot’s center.
- Performing fit on each vertex using associated tracks.

In order to ensure quality vertices, additional selections are applied to all reconstructed vertices.

- All the reconstructed vertices are required to have the number of degrees of freedom(N_{PV}) of vertex greater than 4.
- The z position of the vertex should be less than 24 cm
- The distance from the interaction point in the x-y plane should be less than 2 cm.

Suppose there are more than one reconstructed primary vertices. In that case, the vertex with associated tracks with the highest sum of the square of the transverse momenta is selected as the primary vertex.

5.3 Jets

Proton-proton collisions produce quarks and gluons. As quarks and gluons have a net color charge, they can not be isolated due to color confinement and can not be directly observed in nature. Quarks and gluons combine to form neutral-color hadrons; the process

of formation of hadrons is called hadronization; a collimated spray of hadrons is called a jet, which can be detected in the detector.

When Jets go through the CMS detector, they leave signals in sub-detectors like the tracker and the electromagnetic and hadronic calorimeter. The signals from various sub-detectors are combined to reconstruct the jet using jet algorithms. The energy of reconstructed jets does not match with true generator-level energy; therefore, jets are further corrected. Details about the jet algorithm are discussed in Sec 5.3.1. Jets are present in the final state, so they are important objects in this analysis.

5.3.1 Jets Reconstruction

Jets are reconstructed using the anti- k_t algorithm [152, 153]. The algorithm clusters either all the particles reconstructed by the PF algorithm (PF jets) or the sum of the ECAL and HCAL energies deposited in the calorimeter towers¹ (Calo jets) or all stable particles produced by the event generator excluding neutrinos (reference jet)[144]. In this analysis, jets are reconstructed using PF algorithm. Simulation and reconstruction of a dijet event are shown in Fig. 5.1. In PF jets, 90% of measured jet energy is reconstructed as charge hadrons and photons, which are measured dominantly with a high-resolution tracker and ECAL, while only the remaining 10% are reconstructed as neutral hadrons, which are measured with the HCAL alone[154].

The anti- k_t algorithm uses the distance d_{ij} between the two objects i, j , and the distance d_{iB} between the object and the beam. They are defined as:

$$d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2}) \frac{\Delta_{ij}^2}{R^2} \quad (5.1)$$

$$d_{iB} = k_{ti}^{-2}, \quad (5.2)$$

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and k_{ti} , y_i and ϕ_i represent the transverse momentum, the rapidity, and the azimuthal angle of the object i , respectively, and radius parameter R represents the radius of the cone and determines the jet cone size. Two types of jets with standard cone size $R=0.4$ and $R=0.8$ are reconstructed.

The algorithm proceeds by finding the smallest distance, and if it is a d_{ij} , then objects i, j are combined, while if it is d_{iB} , i called a jet, and it is removed from the list of objects. The

¹ When particle energy summed up over many layers of tiles in depth, called a "tower". A calorimeter tower is composed of an HCAL tower and the 25 underlying ECAL crystals.

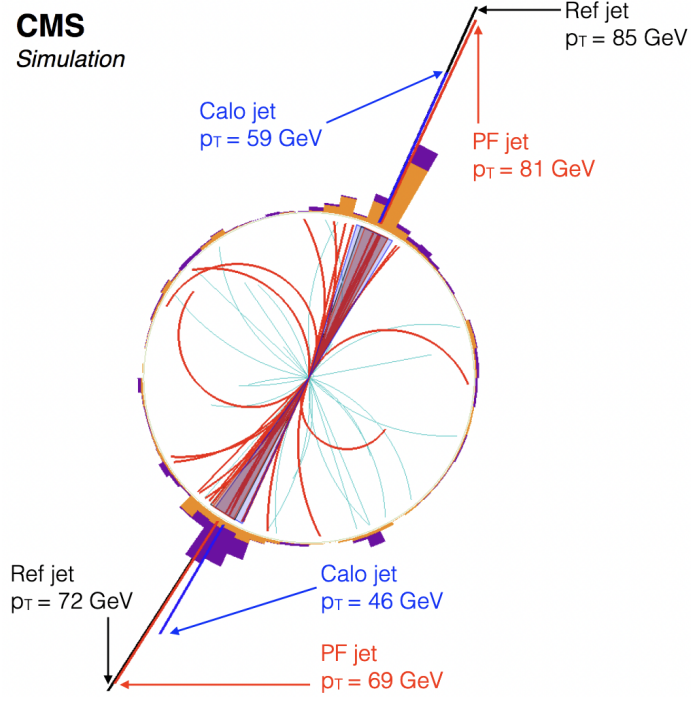


Figure 5.1: Jet reconstruction in a simulated dijet event [144].

distances are recalculated, and the procedure is repeated until no entities are left. Fig. 5.2 shows a jet reconstructed by the anti- k_t algorithm.

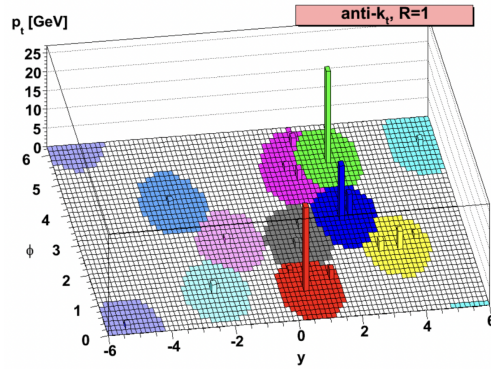


Figure 5.2: Reconstructed jet using anti- k_t algorithm [152].

5.3.2 Jets Energy Correction

In order to match reconstructed jet energy to the true energy of the jet, many corrections are applied to the jet detected in the detector. This difference is mainly due to the nonuniform and non-linear response of the calorimeter detectors, the pileup, and electronic noise. During the jet clustering, pileup mitigation is done with the Charge Hadron Subtraction (CHS) algorithm. This algorithm removes the charge hadron inside the jet, which comes from the pileup events. 50% of the pileup is reduced by the CHS algorithm. The energy of reconstructed jets is calibrated as a function of jet p_T and η [155]. The Correction flow is shown in Fig. 5.3. In jet energy calibration, each component of the raw jet

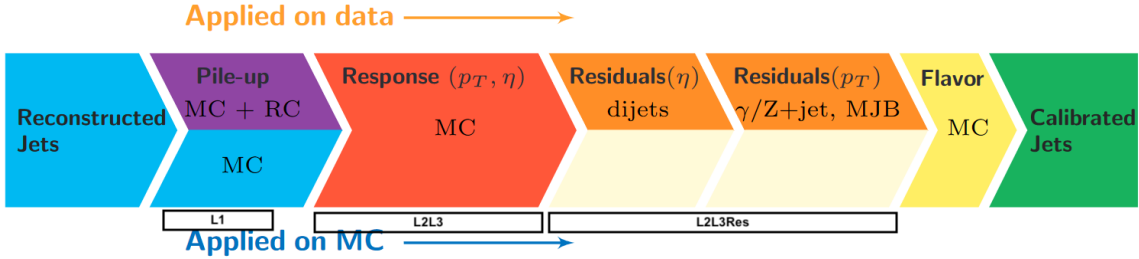


Figure 5.3: CMS jet energy correction procedure performed in multistep factorize procedure [156] .

four-momentum vector (p_μ^{raw}) is corrected by applying a multiplicative factor C :

$$p_\mu^{cor} = C \cdot p_\mu^{raw} \quad (5.3)$$

The correction factor C is composed of the following factors:

- C_{offset} : offset correction removes the extra energy due to noise and pileup.
- C_{MC} : the MC correction removes the bulk of the non-uniformity in η and non-linearity in p_T .
- C_{rel} and C_{abs} : The residual corrections account for the small differences between data and simulation.

As shown in Fig. 5.4, the uncertainties in the jet energy estimation due to simulation modeling are combined into six groups: absolute scale, relative scale, pileup, method, jet flavor and time stability. Pileup and flavor uncertainty dominates at low p_T .

The measurement shows that the jet energy resolution (JER) in the data is worse than in the simulation; therefore, the jets in the simulation need to be smeared to describe the

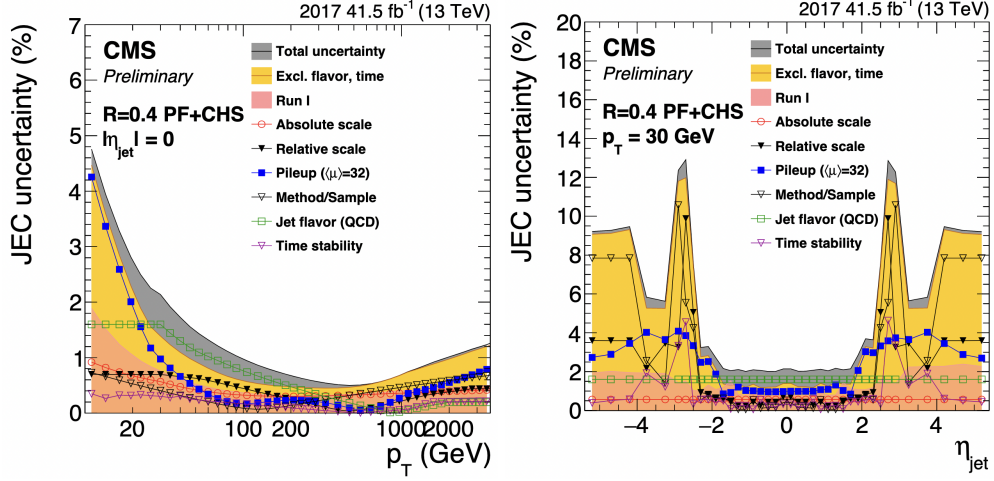


Figure 5.4: JEC uncertainties as a function of jet p_T ($\eta = 0$) at left, and as a function of jet η ($p_T = 30$) using 2017 CMS data [157].

data. The scaling method is used to rescale the corrected four-momentum of a reconstructed jet with a factor.

$$C_{\text{JER}} = 1 + (s_{\text{JER}} - 1) \frac{p_T - p_T^{\text{gen}}}{p_T} \quad (5.4)$$

where p_T is reconstructed jet transverse momentum, p_T^{gen} is the transverse momentum of the corresponding jet clustered from generator-level particles, and s_{JER} is the data-to-simulation core resolution scale factor. A reconstructed jet is required to match with a generator level jet with the following two conditions:

$$\Delta R < R_{\text{cone}}/2, |p_T - p_T^{\text{gen}}| < 3\sigma_{\text{JER}} p_T \quad (5.5)$$

here R_{cone} is the jet radius parameter, and σ_{JER} is the relative p_T resolution as measured in simulation.

5.3.3 Jet Identification

In the jet collections, there can be some fake jets due to noisy calorimeter cells or electronic noise. These fake jets are reduced by applying jet identification criteria based on the hadron and electromagnetic components of PF jets. The PF jets are required to have a charge hadron fraction greater than zero and charged multiplicity greater than zero if the tracking fiducial region of $|\eta|$ is less than 2.4. If the tracking fiducial region of $|\eta|$ is

less than 2.7, then the neutral hadron fraction is required to be less than 0.90, and the neutral electromagnetic(EM) fraction is required to be 0.90, the number of constituents is required to be greater than 1. The Details of cuts for all $|\eta|$ regions are shown in Table 5.1.

PF JetID	Tight ID			
	$ \eta < 2.7$		$2.7 < \eta < 3.0$	$ \eta > 3.0$
	$ \eta < 2.6$	$2.6 < \eta < 2.7$ (2018)		
Neutral Hadron Fraction	<0.90		-	>0.02
Neutral EM Fraction	<0.90	<0.99	>0.02 & <0.99	<0.90
Number of Constituents	>1		-	-
Number of Neutral Particles	-		>2	>10
In addition for $ \eta < 2.4$				
Charged Hadron Fraction	>0		-	-
Charged Multiplicity	>0		-	-
Charged EM Fraction	-		-	-

Table 5.1: cuts applied in the JetID for 2017 and 2018

5.4 Electrons

Electrons are reconstructed by combining the information from the tracker and the ECAL sub-detectors. This is achieved by associating a track reconstructed in the silicon detector with a cluster of energy deposited in the ECAL. During their traversal through the silicon material, electrons undergo energy loss due to Bremsstrahlung radiation and ionization processes. To accurately measure the energy of the electrons, it is necessary to collect the energy of the radiated photons.

The energy of the radiated photon is distributed across multiple crystals in the ϕ direction, resulting from the bending of the electron trajectory in the magnetic field. However, there is negligible spread in the η direction. Two clustering algorithms, namely the "hybrid" and the "multi- 5×5 " algorithms, are employed for clustering the energy of electrons and photons in the barrel and endcap regions, respectively [158, 159].

The hybrid algorithm begins by identifying a seed crystal, which is the crystal containing the highest energy deposition within a given region and surpassing a specified threshold.

Surrounding the seed crystal, an array of 5×1 crystals in the $\eta \times \phi$ space is added, extending over a range of N_{steps} crystals in both directions of ϕ . These additional crystals are included in the clustering process if their energies exceed a minimum threshold. The contiguous arrays are then grouped into clusters, with each distinct cluster requiring a seed array that surpasses a threshold energy in order to be included in the final global cluster known as the supercluster seed-array (SC).

In the endcap region, the multi- 5×5 algorithm is utilized, where crystals do not follow an $\eta \times \phi$ arrangement. Similarly, the algorithm initiates by identifying seed crystals, which are characterized as having the highest local energy compared to their four immediate neighbors and surpassing a defined threshold value. Starting with the seed crystals and considering the largest transverse energy (ET), the energy is accumulated in clusters of 5×5 crystals, which can partially overlap. These clusters are subsequently grouped into a supercluster (SC) if the total transverse energy of the clusters exceeds a specific threshold within a range of η and ϕ surrounding each seed crystal. The SC energy corresponds to the sum of energies from all its constituent clusters. The position of the SC is determined by calculating the energy-weighted mean of the cluster positions.

When an electron traverses the tracker detector, it loses the energy due to the substantial material present in the pixel detector. This energy loss, particularly from bremsstrahlung photon emission, leads to a deviation or "kink" in the electron's trajectory, rendering the electron track reconstruction using the Kalman Filter (KF) approach unsuitable. Even if the standard KF approach manages to track the path of electron, the quality of the track fit can be compromised.

To address this issue, a dedicated track algorithm specifically designed for electron track reconstructions is employed. The Gaussian Sum Filter (GSF) tracking [160], which builds upon the KF approach, is utilized for electron tracking. Unlike the KF approach, which relies solely on Gaussian probability density functions, the GSF algorithm accounts for the highly non-Gaussian distribution of energy loss resulting from bremsstrahlung. The GSF algorithm models the distribution of bremsstrahlung energy loss using a Gaussian mixture instead of a single Gaussian function. By doing so, the GSF track fit effectively considers the abrupt curvature in the track of electron caused by bremsstrahlung photon emission.

The selection criteria for electrons employed in the analysis will be discussed in section 6.3.1.

5.5 Muons

Muons have a lifetime of approximately $2.2 \mu s$ and move at a speed near the speed of light. As a result, muons can easily escape the CMS detector before decaying. Therefore, muons are considered as stable particles by the reconstruction algorithms. Since they are charged particles, they interact in the tracker silicon detector and in the specifically-designed muon chambers. By combining the information obtained from the inner tracker and the muon system, the CMS detector achieves highly efficient reconstruction of muon tracks, ensuring accurate momentum measurements with good resolution.

The process of muon reconstruction [161, 162] begins with the independent local reconstruction of muon tracks in the inner tracking system (tracker track) and the muon systems (standalone muon track) as follows:

- **Standalone tracks:** These are muons reconstructed using only the information from the muon system. The hits from the DT and CSC chambers are clustered to form track segments called "track stubs," which are then matched together to form seeds. The seeds are further matched with the RPC hits to build a standalone muon track.
- **Tracker tracks:** These are muons reconstructed using only the information from the inner tracker. The hits in the silicon tracker are clustered to form a tracker track, also known as an inner track or a silicon track.

Based on the aforementioned local reconstruction processes, two distinct reconstruction algorithms are defined:

- **Global Muon Reconstruction:** A matching process is conducted between each standalone muon track and the tracker track reconstructed in the inner tracking system. The best-matching tracker track is selected for each standalone muon track. Subsequently, a track fit is performed using all hits from both tracks through the application of the Kalman filter technique. It is observed that for muons with $p_T > 200 \text{ GeV}$, the global muon reconstruction yields improved momentum resolution compared to tracker muon reconstruction.
- **Tracker Muon Reconstruction:** In this approach, potential muon candidates are identified among all tracker tracks with $p_T > 0.5 \text{ GeV}$ and total momentum $p > 2.5 \text{ GeV}$ by searching for at least one compatible segment in the muon stations. These tracker tracks that are identified as muons using this method are referred to

as "tracker muons". This method demonstrates a better energy resolution for low momentum muons with $p_T < 5$ GeV, as these muons may not always traverse the CMS detector up to the muon system. However, it is important to note that the criteria used to define a tracker track as a "tracker muon" are very loose and should not be utilized without additional requirements.

The selection criteria for muons employed in the analysis will be discussed in section 6.3.2. Loose and Tight Identification criteria are used to select the muon object for the analysis. Loose Identification requires following set of cuts:

- Muon objects are reconstructed as a global or tracker muon
- Muon objects are reconstructed as a particle flow muon

And Tight Identification requires following set of cuts:

- Muon reconstructed as a Global Muon
- Muon reconstructed as Particle-Flow muon
- Normalized χ^2 of the global track less than 10
- At least one muon-chamber hit included in the global-muon track fit
- Muon segments in at least two muon stations
- Muon's tracker track has transverse impact parameter $d_{xy} < 2$ mm
- The longitudinal distance of the tracker track w.r.t the primary vertex is $d_z < 5$ mm
- Number of pixel hits > 0
- Hits on at least 5 tracker layers

5.6 Photons

Photon candidates are reconstructed by analyzing the energy deposits in the ECAL. Specific algorithms are used to ensure that the clusters have the size and shape expected for a photon[163]. The identification of photon candidates relies on various variables related to the shower shape and isolation. The criteria for identification differ based on whether the energy deposit is in the ECAL barrel or endcaps. In the case of isolated photons, the

scalar sums of the transverse momenta (p_T) of PF candidates within a cone of radius $\Delta R < 0.3$ around the photon candidate must fall below certain predefined limits. The isolation sums only consider PF candidates that do not overlap with the electromagnetic (EM) shower of the photon candidate. In this analysis, the photon candidates are used for vetoing purposes. Exact selection on photon will be discussed in section 6.3.4

5.7 Taus

The reconstruction of taus[164, 165] starts with the identification and reconstruction of their decay products. To reconstruct hadronic tau decays, a specific algorithm called the hadron plus strips (HPS)[166] algorithm is employed. The HPS algorithm combines charged hadrons and photons in the vicinity of the tau candidate to reconstruct the tau's energy and direction. It takes into account the properties of tau decays, such as narrow jets of charged particles (tracks) and electromagnetic showers. The reconstruction of tau decays involving electrons or muons requires the identification and reconstruction of the associated leptons. Electrons are reconstructed using the tracker and ECAL information, while muons are reconstructed using the muon system. The identified electrons and muons are then matched to the tau candidates to reconstruct the tau leptons. In this analysis, the tau candidates are used for vetoing purposes. Exact selection on tau will be discussed in section 6.3.3

5.8 Missing Transverse Energy

The missing transverse energy (E_T^{miss}) is the most important observable in the physics searches for beyond the standard model, such as dark matter and supersymmetry. A precise measurement of all reconstructed physics objects (electron, muon, tau, photon, jet, etc) are used to determine the E_T^{miss} [167].

The E_T^{miss} is defined as the imbalance in the transverse momentum of all detectable and reconstructed particles in the detector. As transverse momentum should be conserved before and after the proton-proton collisions, therefore E_T^{miss} is carried by weakly interacting particles like neutrinos. The E_T^{miss} is computed as the inverse of the vectorial sum of the transverse momenta of all PF particles, which known as PF E_T^{miss} .

$$\text{PF } \vec{E}_T^{\text{miss}} = - \sum_{\text{PF obj}} \vec{p}_T^{\text{PF obj}} \quad (5.6)$$

The nonlinearity of calorimeter response to hadronic particles, minimum energy thresholds in calorimeter, p_T thresholds, and tracker inefficiency can all contribute to erroneous E_T^{miss} estimation [167]. The estimation of E_T^{miss} is improved by applying jet energy correction (JEC) on the reconstructed jet as described in Sec 5.3.2, and propagating these corrections to E_T^{miss} as given below:

$$\text{Type-I } \vec{E}_T^{\text{miss}} = \vec{E}_T^{\text{miss}} - \sum_{\text{jets}} (\vec{p}_{T,\text{jet}}^{\text{corr}} - \vec{p}_{T,\text{jet}}) \quad (5.7)$$

Here Type-I E_T^{miss} refers to the corrected E_T^{miss} value.

5.8.1 The E_T^{miss} ϕ corrections

The E_T^{miss} distribution is independent of ϕ and should be flat as a function of ϕ because of the rotational symmetry of the collisions around the beam axis. However, it is noticed that the ϕ distribution is not symmetry, and it has a sinusoidal curve with a period of 2π . The possible causes of this asymmetry can be due to anisotropic detector responses, inactive calorimeter cells or tracking regions, detector misalignment, the displacement of the beam spot.

The ϕ -asymmetry has been seen in both collision data and Monte Carlo simulated events. The observed ϕ -asymmetry can alternatively be represented as a shift in the x and y projection of E_T^{miss} (E_x^{miss} , E_y^{miss} components). In order to determine the ϕ -asymmetry corrections for both data and simulated events, linear functions are fitted to the correlation of E_x^{miss} and E_y^{miss} as a function of the number of PF candidates in various η bins.

$$\begin{aligned} E_x^{\text{corr}} &= E_x^{\text{miss}} - (c_{x_0} \cdot x + c_{x_s} \cdot x^2) \\ E_y^{\text{corr}} &= E_y^{\text{miss}} - (c_{y_0} \cdot y + c_{y_s} \cdot y^2). \end{aligned} \quad (5.8)$$

where the coefficients c_{x_0} , c_{x_s} , and c_{y_s} are determined from tt, W and Z candidate events in data and simulation samples.

BUILDING BLOCKS FOR THE ANALYSIS

This chapter provides an overview of the essential components of the analysis. Section 6.1 focuses on the data and simulation, detailing their importance in the study. Moving on to Section 6.2, we delve into the trigger selection process and the measurement of its efficiency. The subsequent Section 6.3 explores the physical objects utilized in the analysis and the criteria applied to them. Finally, Sections 6.4 and 6.5 delve into the subjects of simulation reweighting and Higgs boson mass correction, respectively. Together, these sections form the foundational elements of the analysis.

6.1 Data And Simulation

In this section, we have talked about both the real data collected from experiments and the Monte Carlo simulation samples.

6.1.1 Data

The analysis described in this thesis focuses on data collected during the 2017 and 2018 CMS data-taking campaigns at a center-of-mass energy of 13 TeV. The dataset for the analysis corresponds to an integrated luminosity of 41.5 fb^{-1} for 2017 and 59.6 fb^{-1} for 2018. To ensure the reliability and quality of the data, certified runs provided in JSON files are utilized, and the specific JSON files used in this analysis are listed in Table 6.1.

Year	JSON file	Integrated Lumi
2017	Cert_294927-306462_13TeV_PromptReco_Collisions17_JSON.txt	41.5 fb^{-1}
2018	Cert_314472-325175_13TeV_PromptReco_Collisions18_JSON.txt	59.7 fb^{-1}

Table 6.1: Integrated luminosity recorded in 2017 and 2018 data taking and the certified

JSON file	
2017	2018
/MET/Run2017B-31Mar2018-v1/MINIAOD	/MET/Run2018A-17Sep2018-v1/MINIAOD
/MET/Run2017C-31Mar2018-v1/MINIAOD	/MET/Run2018B-17Sep2018-v1/MINIAOD
/MET/Run2017D-31Mar2018-v1/MINIAOD	/MET/Run2018C-17Sep2018-v1/MINIAOD
/MET/Run2017E-31Mar2018-v1/MINIAOD	/MET/Run2018D-17Sep2018-v1/MINIAOD
/MET/Run2017F-31Mar2018-v1/MINIAOD	
/SingleElectron/Run2017B-31Mar2018-v1/MINIAOD	/EGamma/Run2018A-17Sep2018-v2/MINIAOD
/SingleElectron/Run2017C-31Mar2018-v1/MINIAOD	/EGamma/Run2018B-17Sep2018-v1/MINIAOD
/SingleElectron/Run2017D-31Mar2018-v1/MINIAOD	/EGamma/Run2018C-17Sep2018-v1/MINIAOD
/SingleElectron/Run2017E-31Mar2018-v1/MINIAOD	/EGamma/Run2018D-17Sep2018-v2/MINIAOD
/SingleElectron/Run2017F-31Mar2018-v1/MINIAOD	

Table 6.2: Primary datasets name used in the analysis for 2017 and 2018 data taking

In the analysis, two primary datasets are considered for the 2017 data: the MET dataset and the SingleElectron dataset. The MET dataset consists of events that exhibit at least one or two high-energy jets along with significant missing transverse energy. On the other hand, the SingleElectron dataset comprises events characterized by the presence of at least one or two high-energy electrons.

For the 2018 data, two primary datasets are used: the MET dataset and the EGamma dataset. The EGamma dataset is formed by combining the SingleElectron and DoubleEG datasets. It includes events that have at least one or two high-energy electrons or photons. The specific dataset names can be found in Table 6.2.

In terms of data format, the analysis relies on the MINIAOD format, which is a condensed version of the full AOD (Analysis Object Data) format. MINIAOD contains crucial information about reconstructed particles, such as electrons, muons, photons, and jets, including their relevant properties like momentum, energy, and charge. Additionally, it provides details about the primary vertices, which represent the points of origin for particle tracks. The MINIAOD format also includes essential event-level information, such as trigger decisions, run numbers, and event numbers.

6.1.2 Monte-Carlo Simulation

Monte-Carlo(MC) simulated events are used to evaluate the signal and background contribution, model the background, optimize event selection and estimate the systematic uncertainty.

Different MC generators are used to generate the simulation events. The MC simulation of signal and background processes has been performed in two steps, i.e., event generation and detector simulation. In the event generation, the matrix elements (MEs) of hard-scattering are calculated with the proton substructure described by parton distribution functions (PDFs) implemented via "Les Houches Accord PDF Interface" (LHAPDF[168]) library. The shower and hadronization processes are then simulated with several adjustable parameter sets while the decaying partons begin to produce colour-neutral bound states. An example event is shown in Fig. 6.1. The resulting generated events are then sent into detector simulation, which simulates the interactions of the final particles with detector materials. This is done with the use of the Geant4 toolbox [169]. And then particles are reconstructed and saved as a reconstructed physical object as discussed in Sec 5.

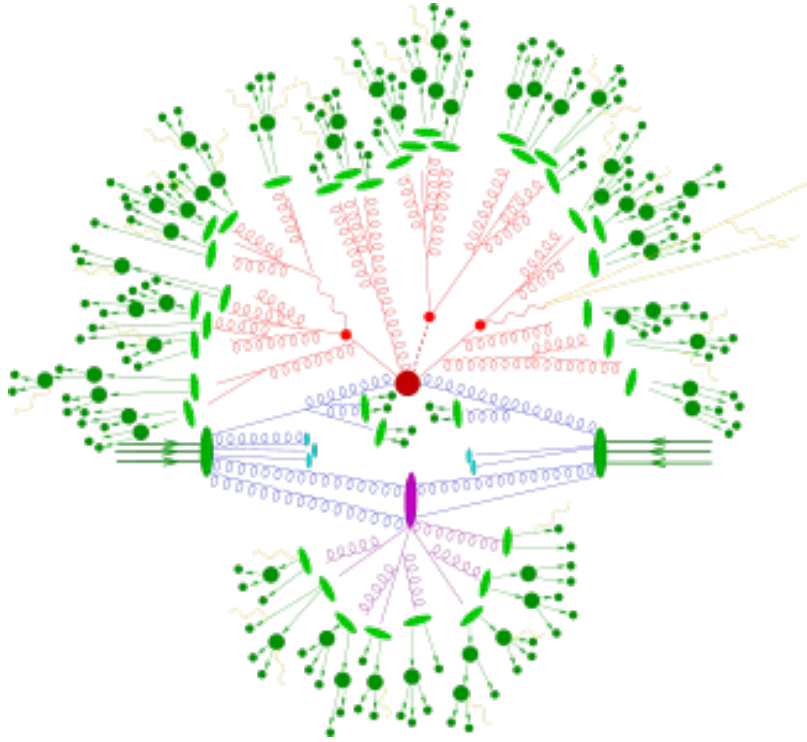


Figure 6.1: Representation of hadron-hadron collision as simulated by a Monte-Carlo event generator [170]. The hard collision is represented by the red blob in the center, which is surrounded by a tree-like structure showing Bremsstrahlung as simulated by parton showers. A subsequent hard scattering event is represented by the purple blob. Parton-to-hadron transitions are depicted by light green blob, hadron decays by dark green blob, and soft photon emission by yellow lines.

6.1.2.1 Background Samples

Several standard model processes pose as backgrounds to the dark matter signal in this analysis. Simulation datasets for these backgrounds are listed in Table 6.3 and Table 6.4. Table contains cross-section values for corresponding simulated sample with branching fraction included.

Background samples cover the following processes: $Z(\nu\nu) + \text{jets}$, $W + \text{jets}$, $DY + \text{jets}$, top quark pair production ($t\bar{t}$), single top production (ST), the production of the single top quark in association with W boson (tW), Diboson (WW , WZ , ZZ), the associated production of a Higgs Boson with vector bosons (WH and ZH).

- **$Z(\nu\nu) + \text{jets}$:** $Z(\nu\nu) + \text{jets}$ is a significant background in this analysis, wherein the Z boson decays into two neutrinos. It is considered an irreducible background, meaning it cannot be easily distinguished from the signal we are interested in. To simulate this background, samples are generated using the MadGraph5_aMC@NLO[171] generator at the next-to-leading order (NLO) in quantum chromodynamics (QCD). The Z boson momentum is divided into several bins to provide a more accurate representation. This background is modeled using the dedicated control region in the analysis.
- **Top:** Top backgrounds are also major backgrounds in this analysis. $t\bar{t}$ samples and single top production samples are generated using POWHEG[172] generator at NLO. In three $t\bar{t}$ production modes, semi-leptonic $t\bar{t}$ production is a dominant source of background in the analysis where lepton from W boson produced in a top quark is lost either due to detector acceptance or does not pass the selection criteria. Top backgrounds are modeled using the dedicated control regions in the analysis.
- **W+jets and DY+jets:** These two samples are produced using MadGraph5_aMC@NLO[171] generator at next to leading order in QCD. Samples are generated in two bins of jet multiplicity and several bins of boson momentum (p_T). The W+jets background contributes to the analysis when a lepton is lost in the event. It involves the W boson decaying into a lepton and a neutrino, along with additional jets. On the other hand, the DY+jets samples involve the vector boson Z decaying into two leptons. These samples are particularly useful for modeling the $Z(\nu\nu) + \text{jets}$ backgrounds, where the Z boson decays into two neutrinos.

- **Diboson(VV):** Diboson backgrounds also contribute background events to this analysis when one of the vector bosons (W or Z) decays leptonically, and other vector boson decays hadronically. Furthermore, if leptons are lost this produces E_T^{miss} + jets in the final state. Diboson samples are generated using Pythia8[173] at leading order (LO).
- **QCD:** QCD Multijet can contribute background events to this analysis if high momentum jet is mismeasured or goes undetected. Samples have a very large cross-section, so a very small fraction of events can serve as background to this analysis. QCD multi-jets are generated using MadGraph5_aMC@NLO[171] at leading order (LO) in bins of HT(transverse momentum sum of jets).
- **SM h:** Standard model Higgs Boson (SM h) decays to bottom quarks can also contribute background events to this analysis. Simulation samples for SM Higgs production have been generated using POWHEG[172] at next to leading order (NLO)

Samples produced by Pythia8 or MadGraph5_aMC@NLO with tune parameter CP5[174] use the NNPDF3.1[175] parton distribution function (PDF). Here, tuning is for underlying events. Parton shower, hadronization, and the simulation of the underlying event (UE) are provided by Pythia8 [173]. All events passed through the CMS detector are simulated with GEANT 4 [169]. Simulated events used the same version of the CMS event reconstruction software as used for data.

6.1.3 Signal Samples

mono-H(bb) search is performed in context of three different models as follows:

- 2HDM+a
- Z'-2HDM
- Baryonic-Z'

A detailed description of the signal model is discussed already in the Sec. 3.5. 2HDM+a is the main model in this search because the phase space of this model is not much excluded yet. In 2HDM+a mode, four parameter scans have been performed, while in Z'-2HDM and Baryonic-Z' model, 2 parameter scans have been performed. The scan

Dataset Name	Cross Section (pb)
DY1JetsToLL_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	315.1
DY1JetsToLL_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	9.5
DY1JetsToLL_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	1.097
DY1JetsToLL_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.1207
DY2JetsToLL_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	169.
DY2JetsToLL_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	15.73
DY2JetsToLL_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	2.74
DY2JetsToLL_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.4492
W1JetsToLNu_LHEWpT_100-150_TuneCP5_13TeV-amcnloFXFX-pythia8	284.06
W1JetsToLNu_LHEWpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	71.71
W1JetsToLNu_LHEWpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	8.06
W1JetsToLNu_LHEWpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.89
W2JetsToLNu_LHEWpT_100-150_TuneCP5_13TeV-amcnloFXFX-pythia8	281.63
W2JetsToLNu_LHEWpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	108.59
W2JetsToLNu_LHEWpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	18.03
W2JetsToLNu_LHEWpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	3.0
Z1JetsToNuNu_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	598.9
Z1JetsToNuNu_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	18.04
Z1JetsToNuNu_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	2.051
Z1JetsToNuNu_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.2251
Z2JetsToNuNu_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	326.3
Z2JetsToNuNu_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	29.6
Z2JetsToNuNu_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	5.174
Z2JetsToNuNu_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.8472
ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	35.85
ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	35.85
ST_t-channel_top_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8	136.02
ST_t-channel_antitop_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8	80.95
ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8	10.32
WZ_TuneCP5_13TeV-pythia8	27.6
WW_TuneCP5_13TeV-pythia8	75.8
ZZ_TuneCP5_13TeV-pythia8	12.14
TTToSemiLeptonic_TuneCP5_PSweights_13TeV-powheg-pythia8	365.34
TTTo2L2Nu_TuneCP5_PSweights_13TeV-powheg-pythia8	88.29
TTToHadronic_TuneCP5_PSweights_13TeV-powheg-pythia8	377.96
QCD_HT500to700_TuneCP5_13TeV-madgraph-pythia8	32100
QCD_HT700to1000_TuneCP5_13TeV-madgraph-pythia8	6831
QCD_HT1000to1500_TuneCP5_13TeV-madgraph-pythia8	1207
QCD_HT1500to2000_TuneCP5_13TeV-madgraph-pythia8	119.9
QCD_HT2000toInf_TuneCP5_13TeV-madgraph-pythia8	25.24
GJets_HT-40To100_TuneCP5_13TeV-madgraphMLM-pythia8	20790
GJets_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8	9238
GJets_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8	2305
GJets_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8	274.4
GJets_HT-600ToInf_TuneCP5_13TeV-madgraphMLM-pythia8	93.46
ZH_HToBB_ZToNuNu_M125_13TeV_powheg_pythia8	0.1565
ZH_HToBB_ZToLL_M125_13TeV_powheg_pythia8	0.07924
ggZH_HToBB_ZToNuNu_M125_13TeV_powheg_pythia8	0.01222
ggZH_HToBB_ZToLL_M125_13TeV_powheg_pythia8	0.006185
WplusH_HToBB_WToLNu_M125_13TeV_powheg_pythia8	0.2819
WminusH_HToBB_WToQQ_M125_13TeV_powheg_pythia8	0.3654

Table 6.3: Background dataset names and corresponding cross-section for 2017 simulation samples. Cross-section contains the branching fraction.

Dataset Name	Cross Section (pb)
DYJetsToLL_Pt-0To50_TuneCP5_13TeV-amcatnloFXFX-pythia8	106300.0
DYJetsToLL_Pt-100To250_TuneCP5_13TeV-amcatnloFXFX-pythia8	407.9
DYJetsToLL_Pt-250To400_TuneCP5_13TeV-amcatnloFXFX-pythia8	96.8
DYJetsToLL_Pt-400To650_TuneCP5_13TeV-amcatnloFXFX-pythia8	3.774
DYJetsToLL_Pt-50To100_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.5164
DYJetsToLL_Pt-650ToInf_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.04796
WJetsToLNu_Pt-50To100_TuneCP5_13TeV-amcatnloFXFX-pythia8	3570.0
WJetsToLNu_Pt-100To250_TuneCP5_13TeV-amcatnloFXFX-pythia8	779.1
WJetsToLNu_Pt-250To400_TuneCP5_13TeV-amcatnloFXFX-pythia8	27.98
WJetsToLNu_Pt-400To600_TuneCP5_13TeV-amcatnloFXFX-pythia8	3.604
WJetsToLNu_Pt-600ToInf_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.5545
Z1JetsToNuNu_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	598.9
Z1JetsToNuNu_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	18.04
Z1JetsToNuNu_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	2.051
Z1JetsToNuNu_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.2251
Z2JetsToNuNu_M-50_LHEZpT_50-150_TuneCP5_13TeV-amcnloFXFX-pythia8	326.3
Z2JetsToNuNu_M-50_LHEZpT_150-250_TuneCP5_13TeV-amcnloFXFX-pythia8	29.6
Z2JetsToNuNu_M-50_LHEZpT_250-400_TuneCP5_13TeV-amcnloFXFX-pythia8	5.174
Z2JetsToNuNu_M-50_LHEZpT_400-inf_TuneCP5_13TeV-amcnloFXFX-pythia8	0.8472
ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	35.85
ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	35.85
ST_t-channel_top_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8	136.02
ST_t-channel_antitop_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8	80.95
ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8	10.32
WZ_TuneCP5_13TeV-pythia8	27.6
WW_TuneCP5_13TeV-pythia8	75.8
ZZ_TuneCP5_13TeV-pythia8	12.14
TTToSemiLeptonic_TuneCP5_PSweights_13TeV-powheg-pythia8	365.34
TTTo2L2Nu_TuneCP5_PSweights_13TeV-powheg-pythia8	88.29
TTToHadronic_TuneCP5_PSweights_13TeV-powheg-pythia8	377.96
QCD_HT500to700_TuneCP5_13TeV-madgraph-pythia8	32100
QCD_HT700to1000_TuneCP5_13TeV-madgraph-pythia8	6831
QCD_HT1000to1500_TuneCP5_13TeV-madgraph-pythia8	1207
QCD_HT1500to2000_TuneCP5_13TeV-madgraph-pythia8	119.9
QCD_HT2000toInf_TuneCP5_13TeV-madgraph-pythia8	25.24
GJets_HT-40To100_TuneCP5_13TeV-madgraphMLM-pythia8	20790
GJets_HT-100To200_TuneCP5_13TeV-madgraphMLM-pythia8	9238
GJets_HT-200To400_TuneCP5_13TeV-madgraphMLM-pythia8	2305
GJets_HT-400To600_TuneCP5_13TeV-madgraphMLM-pythia8	274.4
GJets_HT-600ToInf_TuneCP5_13TeV-madgraphMLM-pythia8	93.46
ZH_HToBB_ZToNuNu_M125_13TeV_powheg_pythia8	0.1565
ZH_HToBB_ZToLL_M125_13TeV_powheg_pythia8	0.07924
ggZH_HToBB_ZToNuNu_M125_13TeV_powheg_pythia8	0.01222
ggZH_HToBB_ZToLL_M125_13TeV_powheg_pythia8	0.006185
WplusH_HToBB_WToLNu_M125_13TeV_powheg_pythia8	0.2819
WminusH_HToBB_WToQQ_M125_13TeV_powheg_pythia8	0.3654

Table 6.4: Background dataset names and corresponding cross-section for 2018 simulation samples. Cross-section contains the branching fraction.

parameters are listed in Table 6.5 for each model.

model	scan parameters			
2HDM+a	m_a	m_A	$\sin\theta$	$\tan\beta$
Z'-2HDM	m_A		$m_{Z'}$	
Baryonic-Z'	m_A		m_χ	

Table 6.5: Parameter scans for the signal models

Simulated samples of gluon-gluon fusion process for 2HDM+a are generated using MadGraph5_aMC@NL0[171] at leading order (LO) with LHAPDF ID 305800 (NNPDF31), while bb initiated process is generated at Next-to-leading order(NLO). Parton showers and hadronization were simulated with Pythia8 using the CP3[174] set of tuned parameters. The Baryonic-Z' model and Z'-2HDM model follow the same principle. Samples are generated using MadGraph5_aMC@NL0[171]. LHAPDF ID 315200 is used to generate the samples for Baryonic-Z', and the Z'-2HDM model. Parton showers and hadronization were simulated with Pythia8[173] using CP2[174] set of tuned parameters. All the generated events passed through the CMS detector are simulated with GEANT 4 [169].

The generator level study has been performed to understand the shape variation of E_T^{miss} due to the change in the parameter values for all three models. Fig. 6.2(top left) shows that the distribution of E_T^{miss} changes when the value of m_A is changed. Other three parameters m_a , $\tan\beta$ and $\sin\theta$ of 2HDM+a also represent similar trend as shown in Fig. 6.2(bottom plots), shape changes for the different value of parameter. Fig. 6.3 shows that m_A and $m'_{Z'}$ scan of Z'-2HDM also have different shape for different values. m_χ does not affect the shape in these two models. However, it does affect the shape in Baryonic-Z' model as shown in Fig. 6.3.

6.2 Triggers

The trigger part is very important part of this analysis. Triggers are used to select the interesting events for the analysis and reject those events which are not needed. The data and simulation events used in this analysis are required to pass E_T^{miss} and single electron triggers. The events for the signal region¹ are collected with the help of the dedicated

¹ Signal and control region are discussed in the Sec 8.2

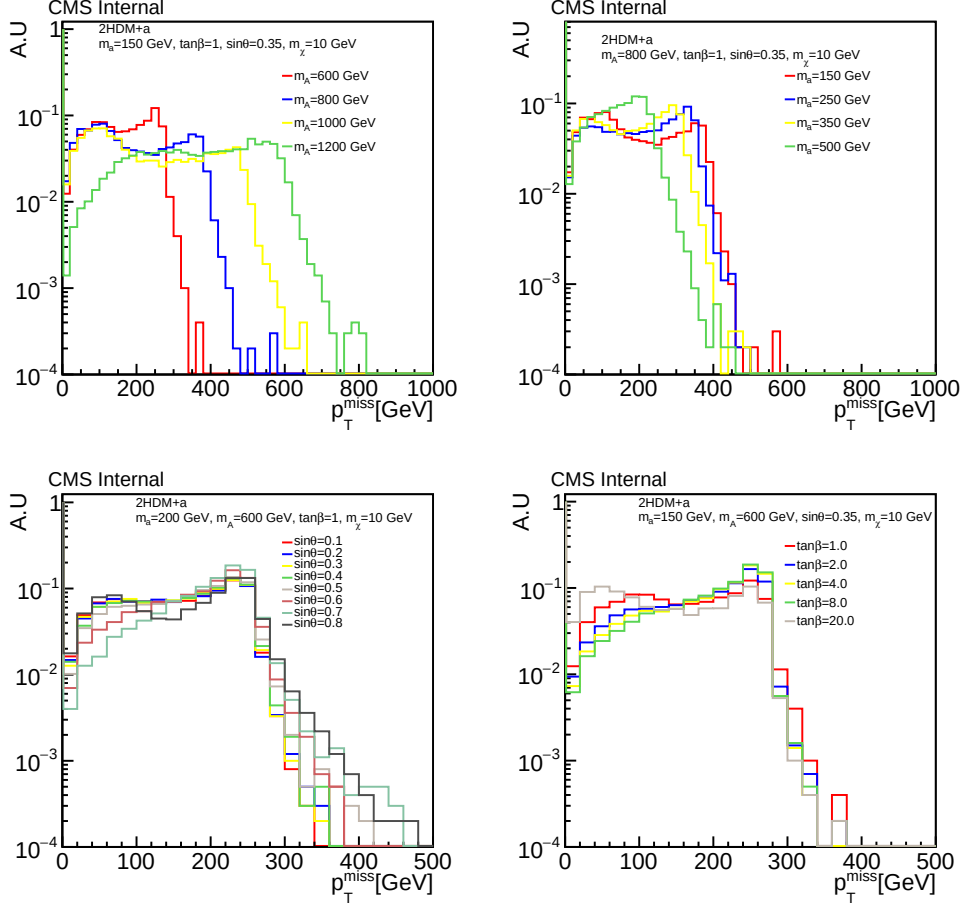


Figure 6.2: Generator level missing transverse energy distribution. Top plots show the distribution for m_A and m_a scans while bottom plots show the distribution for $\sin\theta$ and $\tan\beta$. Missing energy is calculated by summing the momentum vector of dark matter candidates.

E_T^{miss} triggers, these E_T^{miss} triggers are designed to select the events with large E_T^{miss} and large H_T^{miss} which come from the online version of the particle-flow algorithm. In the trigger algorithms, identified particle flow muons are removed from the event before the E_T^{miss} , and H_T^{miss} objects are calculated. So using the same E_T^{miss} triggers, we also select single muon and double muons events in the muon control regions¹. Events selected in the single electron region and double electrons region are required to pass single-electron trigger(s). Trigger details and performance are given in the Secs. 6.2.1 and 6.2.2.

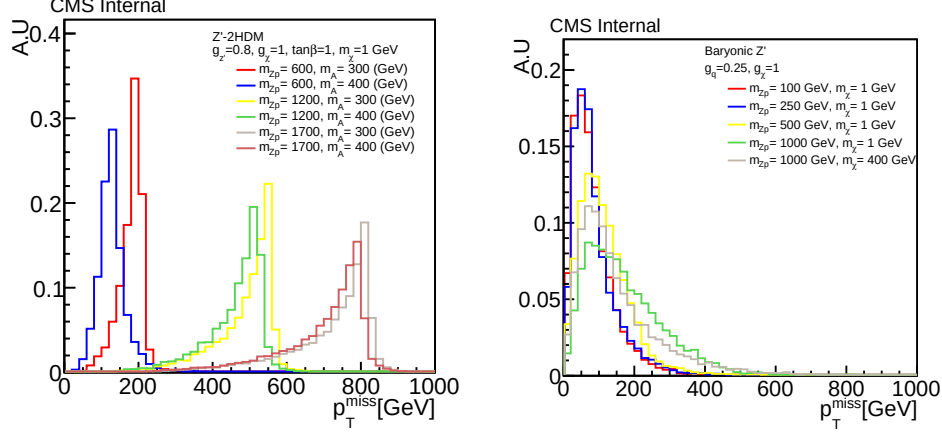


Figure 6.3: Generator level missing transverse energy distribution. Left plot is for Z'-2HDM and right plot is for Baryonic-Z' model. Missing energy is calculated by summing the momentum vector of dark matter candidates.

6.2.1 E_T^{miss} triggers

E_T^{miss} triggers are used in the CMS detector to select events that have missing transverse energy (MET). Table 6.6 shows the list of High-Level Trigger (HLT) paths. These High-Level Trigger (HLT) paths used in the CMS detector to select events that have missing transverse energy (MET) and missing transverse momentum (MHT) with no muon (NoMu) with high identification efficiency (IDTight).

HLT path
HLT_PFMETNoMu120_PFMHTNoMu120_IDTight_PFH60
HLT_PFMETNoMu120_PFMHTNoMu120_IDTight
HLT_PFMETNoMu140_PFMHTNoMu140_IDTight

Table 6.6: List of HLT paths used in the analysis.

HLT path requires events to have a reconstructed MET with no contribution from identified muons above a threshold 120 GeV (OR 140 GeV). It also requires the reconstructed MHT, which is the vector sum of all jet(with $p_T > 20$ GeV and $|\eta| < 5$) momenta in the event, to be greater than 120 GeV (OR 140 GeV). First HLT path in the Table requires the presence of sum of the jet with(with $p_T > 30$ GeV and $|\eta| < 2.5$) transverse momenta

greater than or equal to 60 GeV (PFHT60).

The performance of the E_T^{miss} triggers (in an OR) is measured using single muon events ($W \rightarrow \mu\nu$ decays) after requiring the full selections of the analysis. In particular, single muon events are selected from the Single Muon dataset, and events are required to pass the following selections:

- Tight ID for Muon Identification ²
- Tight Isolation (PFIsoTight)
- Muon momentum (p_T) greater than 30 GeV and pseudorapidity ($|\eta|$) less than 2.4.
- Muon trigger HLT_IsoMu27 for 2017 and HLT_IsoMu24 for 2018
- Central AK4jet with momentum(p_T) larger than 50 GeV
- Additional AK4jets with momentum(p_T) larger than 30 GeV.

The trigger efficiency is computed as a function of the E_T^{miss} recoil i.e. E_T^{miss} computed without including the muon. The definition of trigger efficiency is given in the Eq. 6.1.

$$E_T^{\text{miss}} \text{ trigger efficiency} = \frac{(\text{OR of } E_T^{\text{miss}} \text{ triggers) and (selections)}}{(\text{selections})} \quad (6.1)$$

The efficiency has also been measured in the single electron region, where events are required to have an exact one electron, and the electron should pass tight identification criteria³. The efficiency is computed in data and simulation events as shown in Fig. 6.4 for the both categories. The difference in the efficiency has been observed on data and Monte-Carlo for both years. We calculated scale-factors by taking the ratio of data and MC and applying them in the analysis. Scale-factors are also shown in Fig. 6.4(bottom plots). The full difference between single muon events ($W \rightarrow \mu\nu$) and single electron events ($W \rightarrow e\nu$) scale factor curve is used as systematic uncertainty due to the E_T^{miss} triggers.

We also checked trigger scale-factor for boosted case by replacing AK8jet with $p_T > 200$ GeV and $|\eta| < 2.5$, scale-factor curves look same for $E_T^{\text{miss}} > 250$ GeV ($E_T^{\text{miss}} > 250$ GeV is used for boosted category). Fig. 6.5 shows comparison of E_T^{miss} trigger scale-factors in resolved and boosted categories.

² Muon selection is explained in coming Sec 6.3.2

³ Electron identification is explained in coming Sec. 6.3.1

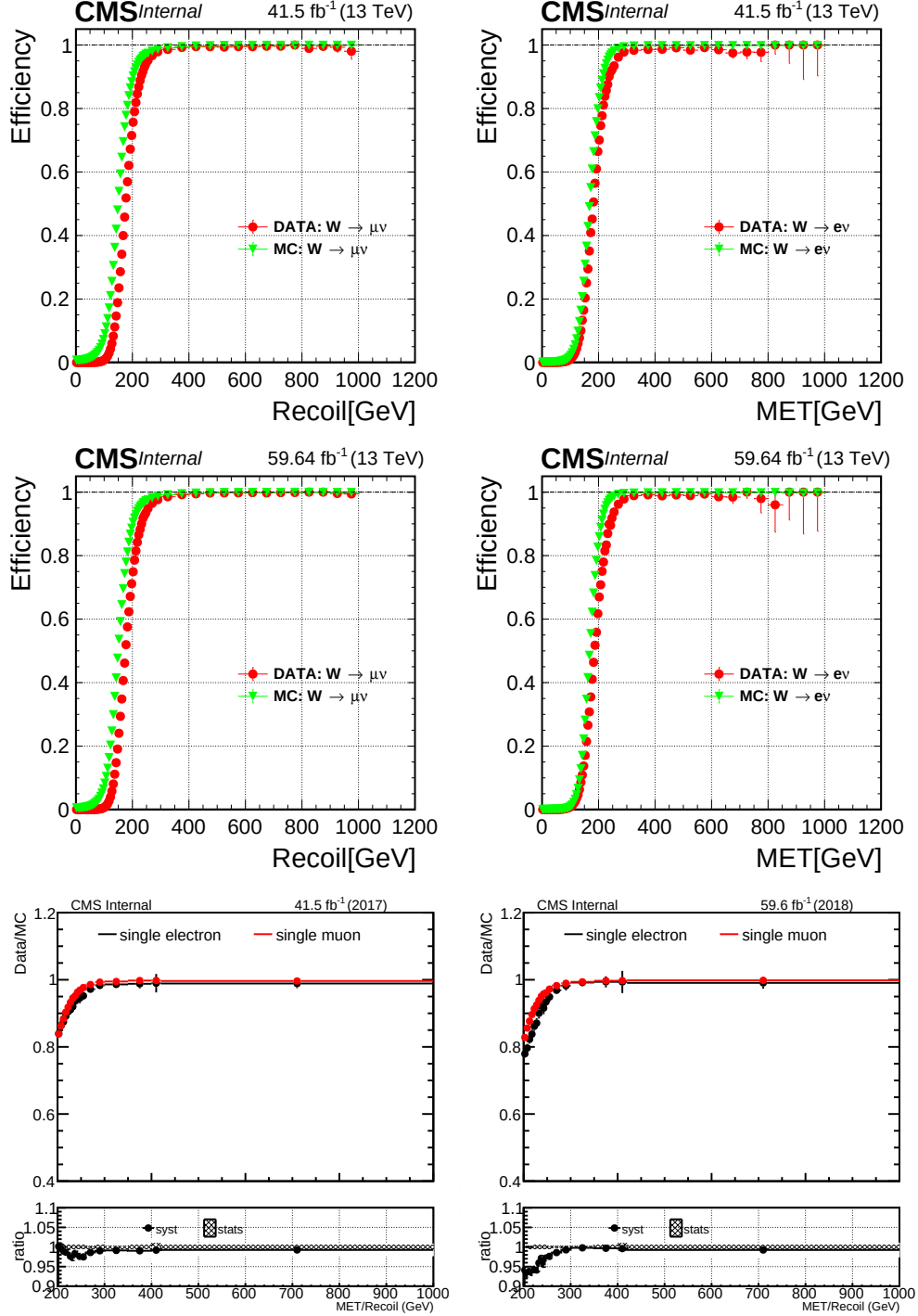


Figure 6.4: E_T^{miss} trigger turn-on curve measured in single muon events and single electron for 2017 and 2018 (Upper and middle left plots are for single muon events and right plots for single electron events). The trigger turn-on is computed as a function of the recoil (E_T^{miss} without including the muon) in single muon events and as a function of E_T^{miss} in single electron events. Efficiency in simulation is measured using W +jets samples. Lower plot shows scale factor in single electron and single muon events. Bottom pad shows the ratio of curve between electron region and muon region.

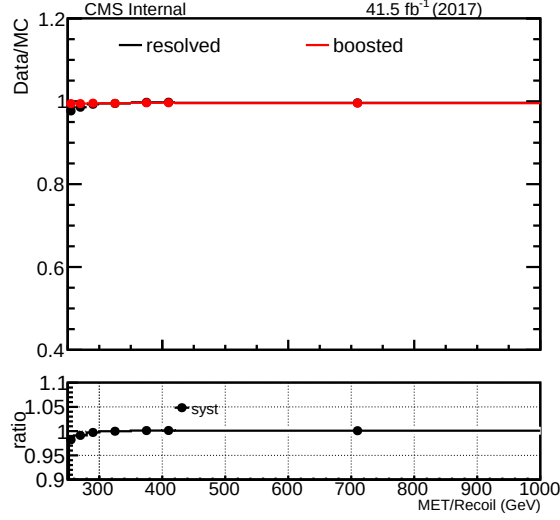


Figure 6.5: Comparison of E_T^{miss} trigger scale-factor curve for resolved and boosted categories. Scale-factors are same for both categories.

6.2.2 Electron Triggers

Following single electron triggers are used to select events in single electron and double electron regions for 2017 and 2018 :

- HLT_Ele32_WPTight_Gsf_L1DoubleEG for 2017.
- HLT_Ele32_WPTight_Gsf for 2018: standard single-electron trigger with tight identification and isolation requirements. The electron E_T^{HLT} is required to be above 32 GeV in 2017-2018

2017 trigger is seeded by the normal single L1 EG seeds and the double EG seeds. This trigger is super-set of HLT_Ele32_WPTight_Gsf_v* and exits only after run 302026, the start of Run2017D. So the trigger is turned into a HLT_Ele32_WPTight_Gsf_v trigger, by requiring the trigger object to pass hltEle32L1DoubleEGWPTightGsfTrackIsoFilter and hltEGL1SingleEG0rFilter, because hltEle32L1DoubleEGWPTightGsfTrackIsoFilter is the last filter of HLT_Ele32_WPTight_Gsf_L1DoubleEG and after making a trigger object hltEGL1SingleEG0rFilter, we directly get the trigger object that passes HLT_Ele32_WPTight_Gsf_v.

Efficiency for the electron trigger is taken from mono-jet analysis[176], and it is measured in data and MC using a "tag and probe". The efficiency is shown in Fig. 6.6 for 2017 and 2018.

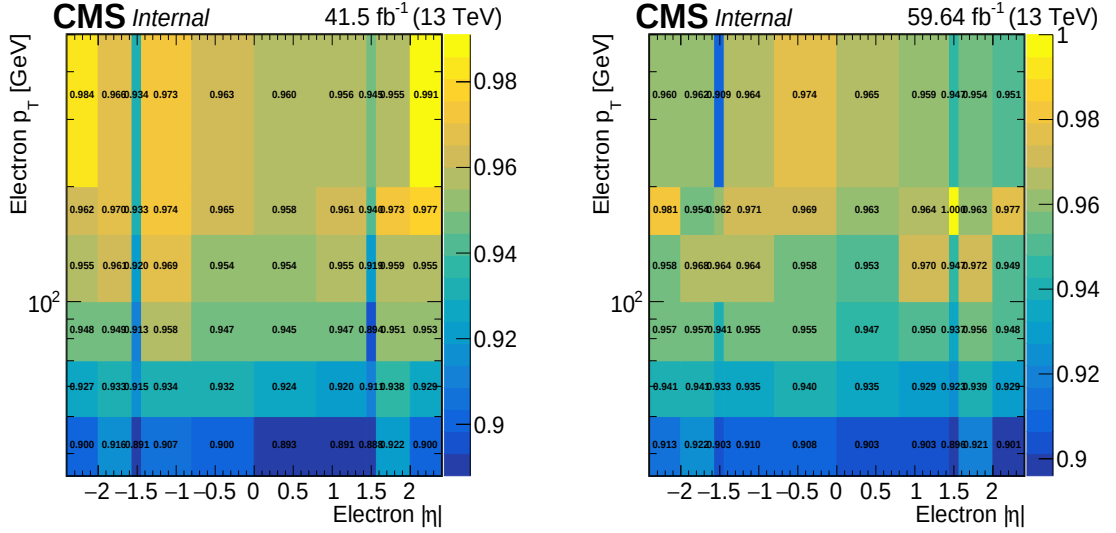


Figure 6.6: Electron trigger efficiency for 2017 (left) and 2018 (right) [176].

6.3 Object Selection For Analysis

In the analysis, a variety of physics objects are employed to identify signal-like events, suppress the background, and define the control region for background estimation. A selection criterion is applied to those reconstructed objects to identify the genuine object for the analysis. The selection of each object is described in this section.

6.3.1 Electron Selection

Electrons are used to remove electroweak backgrounds and to define control regions in this analysis. The reconstructed electron can be a real or fake electron, therefore, some off-line selections are applied to select well-reconstructed electrons for the analysis. Two type of selections are imposed to identify the electrons, loose selections and tight selections. Electrons passing the loose choices are referred to as "Loose Electrons," whereas electrons passing the tight selections are referred to as "Tight Electrons". The loose electron selections are as follows:

- Electron momentum (p_T) greater than 10 GeV
- Absolute pseudo-rapidity($|\eta|$) less than 2.5: The electrons which are reconstructed in the gap between the ECAL barrel and endcaps ($1.4442 < |\eta| < 1.566$ region) are excluded in the analysis.
- Loose ID: This has a set of cuts which are mentioned in the Table 6.7.

Variable	Selection (Barrel)	Selection (Endcap)
Full 5x5 $\sigma_{\eta\eta}$	< 0.0112	< 0.0425
$ \Delta\eta_{\text{scd}} $ (difference in η between the supercluster and track)	< 0.00377	< 0.00674
$ \Delta\phi_{\text{in}} $ (difference in ϕ between the supercluster and track)	< 0.0884	< 0.169
H/E(Hadronic over Electromagnetic energy)	$< 0.05 + 1.16/E_{\text{SC}}(\text{GeV}) + 0.0324\rho/E_{\text{SC}}(\text{GeV})$	$< 0.0441 + 2.54/E_{\text{SC}}(\text{GeV}) + 0.183 * \rho/E_{\text{SC}}(\text{GeV})$
Relative isolation (ρ correction)	$< 0.112 + 0.506/p_T(\text{GeV})$	$0.108 + 0.963/p_T(\text{GeV})$
$1/E(\text{Super Cluster energy GeV}) - 1/p(\text{track momentum GeV})$	< 0.193	< 0.111
Expected Missing Inner Hits	≤ 1	≤ 1
Pass Conversion Veto	Yes	Yes

Table 6.7: Loose electron identification criteria[177]. In the table ρ represents the median of the transverse energy density per unit area in the event. $\sigma_{\eta\eta}$ represents the energy spread along the η direction in the ECAL . It is commonly used as a discriminant to distinguish between genuine electrons and background sources such as jets or photons.

In the signal region⁴, events with these well-reconstructed electrons are rejected to suppress the electroweak backgrounds.

The tight electron selections are as follows:

- Electron momentum (p_T) greater than 40 GeV
- Absolute pseudo-rapidity($|\eta|$) less than 2.5: The electrons which are reconstructed in the gap between the ECAL barrel and endcaps ($1.4442 < \eta < 1.566$ region) are excluded in the analysis.
- Tight ID: A set of cuts of tight ID are mentioned in the Table 6.8.

The electrons with tight identification criteria are used in defining certain control regions⁴ for estimating the major backgrounds using a data-driven manner in the analysis.

⁴ Signal region and control region are discussed in the Sec 8.2

Variable	Selection (Barrel)	Selection (Endcap)
Full $5 \times 5 \sigma_{i\eta i\eta}$	< 0.0104	< 0.0353
$ \Delta\eta_{seed} $ (difference in η between the supercluster and track)	< 0.00255	< 0.00501
$ \Delta\phi_{in} $ (difference in ϕ between the supercluster and track)	< 0.022	< 0.0236
H/E(Hadronic over Electromagnetic energy)	$< 0.026 + 1.15/E_{SC}(GeV) + 0.0324\rho/E_{SC}(GeV)$	$< 0.0188 + 2.06/E_{SC}(GeV) + 0.183 * \rho/E_{SC}(GeV)$
Relative isolation (ρ correction)	$< 0.0287 + 0.506/p_T(GeV)$	$0.0445 + 0.963/p_T(GeV)$
$1/E(\text{Super Cluster energy GeV}) - 1/p(\text{track momentum GeV})$	< 0.159	< 0.0197
Expected Missing Inner Hits	≤ 1	≤ 1
Pass Conversion Veto	Yes	Yes

Table 6.8: Tight electron identification criteria. In the table ρ represents the median of the transverse energy density per unit area in the event. $\sigma_{i\eta i\eta}$ represents the energy spread along the η direction in the ECAL. It is commonly used as a discriminant to distinguish between genuine electrons and background sources such as jets or photons.

6.3.2 Muon Selection

Same as electrons, reconstructed muons can be fake muons. Offline selection is applied to select well-reconstructed muons for the analysis. Two types of muons are selected, "loose muons" with loose selection and "tight muons" with tight selection.

In order to identify loose muons in the event, we use the following selections.

- Muon momentum (p_T) greater than 10 GeV and pseudo-rapidity ($|\eta|$) less than 2.4.
- Loose ID for muon identification
- Loose Isolation: Muon isolation is strong variable to distinguish between real muons and fake muons. The muon isolation cut is defined as :

$$I_{iso}^{PF} = \frac{\sum P_T^{chad} + \max[0, \sum E_T^{neuthad} + \sum E_T^\gamma - \Delta\beta]}{P_T^{muon}} \quad (6.2)$$

where P_T^{chad} represents the transverse momentum of the PF change hadrons which are not originating from primary vertex. And $E_T^{neuthad}$ represents the neutral hadron particles. $\Delta\beta$ Correction represents pileup correction and defined as

$$\Delta\beta = \frac{1}{2} \sum_{PU}^{chad} P_T \quad (6.3)$$

Loose Isolation has relative PF-isolation value < 0.25 and $\Delta\beta$ correction 0.4.

Loose muons in this analysis are used to remove electroweak background, loose muon veto is applied in the signal region and electron regions.

In order to identify tight muons in the event, we use the following selections.

- Muon momentum (p_T) greater than 20 GeV and pseudo-rapidity ($|\eta|$) less than 2.4.
- Tight ID for Muon Identification
- Tight Isolation : Tight Isolation has relative PF-isolation value < 0.15 .

These tight muons are used to define certain control regions (single muon and double muons) to estimate major backgrounds in a data-driven manner.

6.3.3 Tau Selection

In this analysis, taus are primarily utilized to reduce electroweak backgrounds. The selection criteria for taus are defined as follows:

- Tau momentum(p_T) greater than 20 GeV and pseudorapidity $|\eta|$ less than 2.3
- "DecayModeFinding" should be true. The "DecayModeFinding" discriminator is designed for identifying the hadronic decay mode of tau leptons.
- A loose isolation required (byLooseIsolationMVArun2017v2DBoldDMwLT2017)
- Loose discriminator against Electron(againstElectronLooseMVA6): It is designed to discriminate against electrons and reject tau candidates that exhibit electron-like characteristics.
- Loose discriminator against Muon (againstMuonLoose3): The purpose of the againstMuonLoose3 discriminator is to suppress the misidentification of tau candidates as muons, as muons and taus can have similar signatures in the detector. By applying the "againstMuonLoose3" discriminator, tau candidates that pass certain criteria are considered "loose" against muons, meaning they are less likely to be misidentified as muons

Tau are selected based on the above selection.

6.3.4 Photon Selection

A photon veto is applied in the analysis to suppress the backgrounds $(Z(\nu\nu) + \gamma + \text{jet}, W(\ell\nu) + \gamma + \text{jet})$. The following selections are applied to select the photon candidates:

- Photon loose Identification
- Photon momentum (p_T) greater than 30 GeV and pseudo-rapidity($|\eta|$) less than 2.5.

Details of cuts for loose photon identification are given in Table 6.9. The isolation value is computed in an ΔR cone of 0.3 and is corrected for pileup using the ρ -correction.

Variable	Selection (Barrel)	Selection(EndCap)
H/E(Hadronic over Electromagnetic energy)	0.04596	0.0590
Full 5X5 σ_{min}	0.0106	0.0272
PF charged hadron isolation	1.694	2.089
PF neutral hadron isolation	$24.032 + 0.01512 * p_T(\text{GeV}) + 2.259\text{e-}05 * p_T^2(\text{GeV})$	$19.722 + 0.0117 * p_T(\text{GeV}) + 2.3\text{e-}05 * p_T^2(\text{GeV})$
PF photon isolation	$2.876 + 0.004017 * p_T(\text{GeV})$	$4.162 + 0.0037 * p_T(\text{GeV})$

Table 6.9: Photon identification criteria

In addition to the above selections, photons are required to not overlap with electrons, muons, and AK4jets within $\Delta R > 0.4$

6.3.5 AK4jets Selection

As we discussed in jet reconstruction Sec. 5.3.1, jets are reconstructed using the anti- k_T algorithm [178] with a distance parameter $R = 0.4$, referred to as "AK4jets". In AK4jet clustering, pileup mitigation is done with the Charge Hadron Subtraction (CHS) algorithm, which removes charged particles coming from pileup vertices. The energy of reconstructed jets is calibrated as a function of jet p_T and $|\eta|$ [179]. In order to compensate for pileup effects, corrections based on jet area and energy density [152, 180] are applied. The combination of jet energy calibration and pileup corrections is referred to as jet-energy corrections (JEC). The global tags are used to apply the JEC to data and simulated events for 2017 and 2018 data-taking periods. In addition to JEC, jet energy resolution (JER) corrections are also applied. The summary of global tags is given in the Table 6.10.

This analysis uses only those jets which pass the tight jet identification for both years. For those jets, the set of cuts are given in Table 6.11. Selected jets are required to satisfy the

conditions $p_T > 30$ GeV and $|\eta| < 2.5$. They are further required not to overlap with loose electrons and loose muons.

6.3.6 b-jet Identification

AK4jets originating from the hadronization of b quarks are identified by the "DeepCSV" algorithm [181]. This algorithm, a new version of the "CSVv2 tagger"[182], was developed by employing a deep neural network with more hidden layers, more nodes per layer, and simultaneous training in all vertex categories and jet flavors. The algorithm exploits high and low-level observables related to the long lifetime of b hadrons and the high particle multiplicity and mass of b-jets compared to light quark and gluon jets. The following input variables are used in training:

- SV 2D flight distance significance
- Number of SV
- Track η_{rel}
- Corrected SV mass
- Number of tracks from SV
- SV energy ratio
- 3D IP significance of the first four tracks
- $\Delta R(track, jet)$
- Track($p_{T,rel}$ ratio)
- Track distance
- Track decay length

Year	Data	MC
2017	94X_dataRun2_v11	94X_mc2017_realistic_v17
2018(ABC)	102X_dataRun2_v14	102X_upgrade2018_realistic_v21
2018(D)	102X_dataRun2_Prompt_v16	

Table 6.10: Global tags summary for Data and MC for 2017 and 2018 data-taking periods

PF JetID	Tight ID			
	$ \eta < 2.7$		$2.7 < \eta < 3.0$	$ \eta > 3.0$
	$ \eta < 2.6$	$2.6 < \eta < 2.7$ (2018)		
Neutral Hadron Fraction	<0.90		-	>0.02
Neutral EM Fraction	<0.90	<0.99	>0.02 & <0.99	<0.90
Number of Constituents	>1		-	-
Number of Neutral Particles	-		>2	>10
In addition for $ \eta < 2.4$				
Charged Hadron Fraction	>0		-	-
Charged Multiplicity	>0		-	-
Charged EM Fraction	-		-	-

Table 6.11: cuts applied in the JetID for 2017 and 2018

- Summed tracks E_T ratio
- $\Delta R(\text{summed tracks, jet})$
- First track 2D IP significance above c threshold
- Number of selected tracks
- Jet p_T
- Jet η

Training is done using the jets with p_T ranging from 20 GeV to 1000 GeV and within the tracker's acceptance. For b:c:udsg jets, the proportional ratio of the number of jets of each flavor is set at 2:1:4. To minimize the dependency of the training on the heavy-flavor quark production process, a combination of $t\bar{t}$, and multijet events are used. The performance of the DeepCSV was checked in the simulated pp collision events. Fig. 6.7 shows the b-jet identification efficiency versus the misidentification probability for light jets (udsg) or c jets with jet $p_T > 20$ GeV and $|\eta| < 2.4$ in $t\bar{t}$ events. Performance is compared with previous taggers.

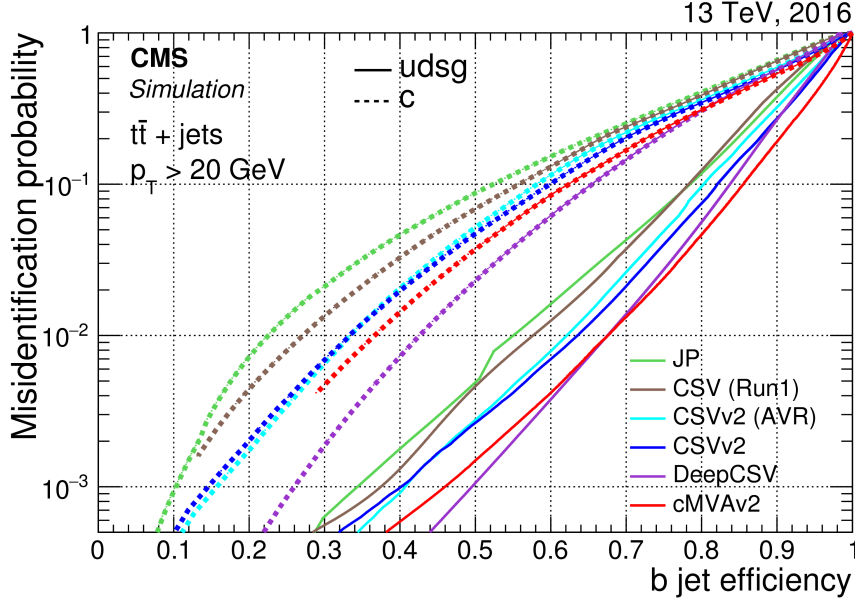


Figure 6.7: b-jet identification efficiency vs misidentification probability for c jet and light jets for various b tagging algorithms (JP, CSV, CSVv2(AVR), CSVv2, DeepCSV, cMVA2) in $t\bar{t}$ events. The DeepCSV tagger outperforms all the other b jet identification algorithms, when discriminating against c jets or light-flavour jets, except for b jet identification efficiencies above 70% where the cMVA2 tagger performs better when discriminating against light-flavour jets [181].

The standard loose/medium/tight working points⁵ defined by the BTV POG based on the b-jet selection efficiency and misidentification rates are listed in Table 6.12. In this analysis, b-jets are required to pass the standard medium working point (0.4941 for 2017, 0.4184 for 2018) for the resolved category and loose working point (0.1522 for 2017, 0.1241 for 2018) for the boosted category.

6.3.7 AK8jets Selection

At high energy, the Higgs boson decaying to b quarks can be produced with a large Lorentz boost. Because of the strong boost of the parent particle, the decay products often produce overlapping jets. Such jets are reconstructed with a distance parameter of $R = 0.8$ to catch all of the decay products. These jets reconstructed using the anti- k_T

⁵ Standard working points are defined for each b tagging algorithm using jets with $p_T > 30$ GeV. These working points, “loose” (L), “medium” (M), and “tight” (T), correspond to thresholds on the discriminator after which the misidentification probability is around 10%, 1%, and 0.1%, respectively, for light-flavour jets

WP Name	deepCSV	Year	mistag-efficiency
loose	0.1522	2017	10%
medium	0.4941	2017	1%
tight	0.8001	2017	.1%
loose	0.1241	2018	10%
medium	0.4184	2018	1%
tight	0.7527	2018	.1%

Table 6.12: Table shows deep CSV working points and corresponding mistag rate.

algorithm are referred to as “AK8jets”. Contributions of pileup are reduced by filtering the collections of PF particles used as input to the reconstruction of AK8jets with the “pileup per particle identification” (PUPPI) algorithm [183]. The energy of AK8jets is calibrated and corrected for pileup effects using a dedicated set of JEC that has been specifically determined for AK8jets [184]. In addition to JEC, jet energy resolution (JER) corrections are also applied. The global tags for AK8jets are the same as those for AK4jets, given in Table 6.10. The soft drop mass⁶ (m_{SD}) of the AK8jet is reconstructed using the “modified mass drop tagger” algorithm, also known as the “soft-drop” (SD) algorithm [185].

This analysis uses only those jets which pass the tight jet identification. The AK8jets are required to satisfy the conditions $p_T > 200$ GeV and $|\eta| < 2.5$. They are further required not to overlap with loose electrons and loose muons within $\Delta R < 0.8$.

6.3.8 Identification of b-jets in boosted topology

For the boosted analysis, AK8jet is used to identify the Higgs boson, and b-tagging of the AK8jet ($H \rightarrow b\bar{b}$) is checked using the DeepDoubleBvL tagger. This algorithm is based on a deep neural network and is used for the identification of the boosted object decays to pair of b quarks (e.g., $H \rightarrow b\bar{b}$). The algorithm is trained on 37 input parameters. This exploits the correlations between the flight directions of b quarks by using the N-subjettiness⁷ axes to associate tracks and vertex to the sub-jets and building-related input observables [186].

⁶ Soft drop is a jet grooming algorithm which removes soft and wide angle radiation from a jet.

⁷ N-subjettiness is an effective discriminating variable for tagging boosted objects and rejecting the background of QCD jets with large invariant mass.

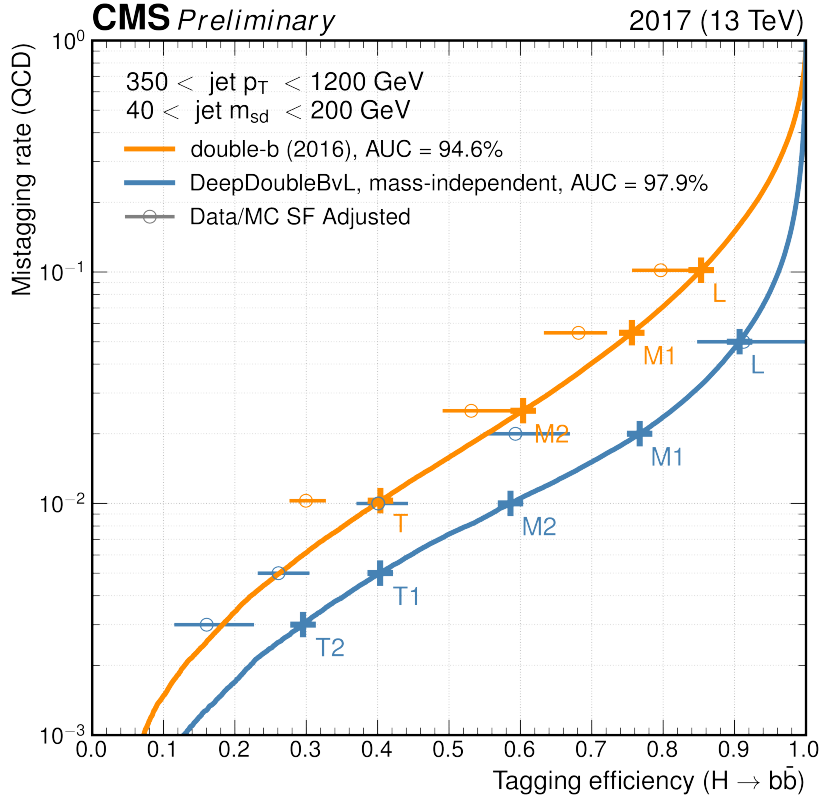


Figure 6.8: DeepDoubleBvL performance for $H \rightarrow b\bar{b}$ efficiency versus QCD misidentification probabilities, compared to previous double-b tagger [186]. There are five working points; loose (L), medium 1 (M1), medium 2 (M2), tight 1 (T1) and tight 2 (T2).

The performance of the DeepDoubleBvL algorithm in discrimination of $H \rightarrow b\bar{b}$ jets from QCD multijet background is shown in Fig. 6.8. Jets are selected with a mass window of $20 < m_{sd} < 200$ GeV and a p_T window of $300 < p_T < 1200$ GeV. DeepDoubleBvL shows better performance compared to previous double-b tagger. Lower curve shows less mistag efficiency which means better performance. It has five working points (L, M1, M2, T1, and T2), and we use M1 (0.86) working point to identify the Higgs boson decaying to a pair of bottom quarks, which corresponds to a signal efficiency of 86% and a mistag rate of 1%.

6.3.9 Missing Transverse Energy

The missing transverse energy (E_T^{miss}) is main observable in this analysis, it is computed as the negative sum of the transverse momentum vectors of all the particle flow candidates reconstructed in a given event as discussed in the Sec 5.8. The difference in momentum between uncalibrated jets and calibrated jets is further applied to E_T^{miss} as a correction (Type-1 Corrections). In 2017 data taking, there was an issue of EE noise in the ECAL at high $|\eta|$ that increased the fake E_T^{miss} tail in data. So, to reduce the effect of EE noise in the ECAL endcap at high $|\eta|$, the EE noise mitigation technique⁸ has been applied.

To mimic E_T^{miss} in control regions, hadronic recoil has been computed by removing the p_T of the leptons from the E_T^{miss} . The hadronic recoil is defined as

$$\vec{U} = \vec{E}_T^{\text{miss}} + \vec{p}_T^{ll,l} \quad (6.4)$$

where p_T^l or p_T^{ll} is single or double lepton p_T depending on the control region. Events in data can end up with large spurious E_T^{miss} due to detector noise, miss-reconstruction, and beam backgrounds. To remove these problematic events several E_T^{miss} filters listed in the Table [6.13] have been implemented in the Analysis.

MET Filters	Year
goodVertices	2017 and 2018
globalSuperTightHalo2016Filter	2017 and 2018
HBHENoiseFilter	2017 and 2018
HBHENoiseIsoFilter	2017 and 2018
EE Bad SC Filter	2017 and 2018
EcalDeadCellTriggerPrimitiveFilter	2017 and 2018
BadPFMuonFilter	2017 and 2018
ecalBadCalibReducedMINIAODFilter	2017 and 2018

Table 6.13: MET filters used in this analysis for 2017 and 2018

⁸ The EE noise mitigation technique aims to reduce the impact of various sources of noise that can affect the ECAL energy measurements, particularly in the endcap regions. This noise can arise from electronic noise, spurious signals, or other instrumental effects.

6.4 Monte Carlo Re-weighting

Monte Carlo (MC) simulation does not match exactly with the real data due to several effects, including varying run conditions, detector inefficiencies, and theoretical uncertainties on physics processes. Therefore, several corrections are applied to the simulation in order to match its prediction to the data. In this section, we discuss all the corrections and weights that are applied to several simulation processes.

6.4.1 Pileup re-weighting

The pileup condition present in the Monte Carlo samples does not exactly match the pileup present in the data. The difference is corrected by reweighting simulated events to match the PU distribution in the data.

We calculated the ratio between the distribution of the number of inelastic collisions in data and the pileup profile in simulation. Proton-proton inelastic cross-section value of $(69.2 \pm 4.6\%)$ mb is used to derive the distribution of the number of collisions in data. Moreover, this ratio is applied as a function of the true number of generated inelastic collisions in the event.

Fig. 6.9 shows the comparison between the distribution of the number of vertices in $Z \rightarrow \mu\mu + \text{jets}$ events in data and simulation before and after the pileup reweighting. These events are required to pass resolved analysis selection for the Z control region.

6.4.2 Trigger scale-factors

The first selection of events is to pass trigger(s) condition. Signal and muon regions are required to pass E_T^{miss} triggers. E_T^{miss} trigger efficiency is not same for data and simulation. Hence, we measured trigger efficiency in data and MC and applied the ratio of data and MC directly to the simulation as discussed in section 6.2.1.

Single electron and double electron regions are required to pass electron trigger(s). The scale-factors to account for the difference in data and simulation has been used. Details of trigger(s) and scale-factors are given the Sec 6.2.2.

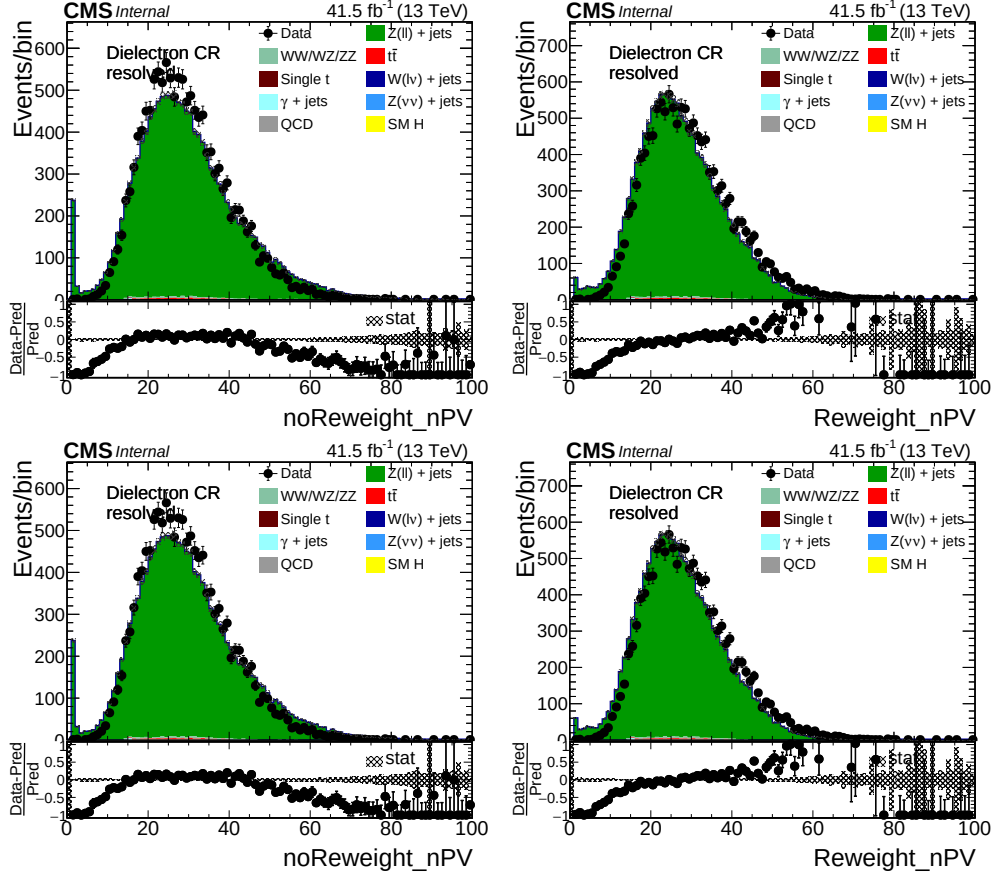


Figure 6.9: Distribution of the number of vertices in $Z \rightarrow \mu\mu + \text{jets}$ events in data and simulation before pileup re-weighting (left) and after pileup re-weighting (right) in the resolved category. The Monte Carlo is normalized to the luminosity of 41.5 and 59.6 fb^{-1} for 2017 and 2018, respectively.

6.4.3 Lepton reconstruction and identification scale factors

The reconstruction and identification algorithms may not perfectly reproduce the efficiencies observed in real data due to various factors like detector effects, modeling limitations, and mismodeling of the underlying physics processes. To account for these discrepancies, scale factors are applied to adjust the efficiencies in simulation to match those in data. The scale factors are typically derived as functions of lepton (electron or muon) kinematics, such as transverse momentum (p_T) and pseudorapidity (η).

6.4.4 b-tagging scale factors

The efficiency of identifying b-tagged and non-b-tagged jets is known to differ between data and simulation. In order to account for these differences, scale factors are applied to the simulated data to correct for the disparities.

The BTV (B-Tagging and Vertexing) Physics Object Group (POG) provides the necessary scale factors and their associated uncertainties for b-tagging of AK4jets for the specific years, such as 2017 and 2018. These jet scale factors are then incorporated into the calculation of event scale factors. To compute the event weight, the probability of the event satisfying the b-tagging selection is first determined.

$$P(\text{DATA}) = \prod_{i=\text{tagged}} \varepsilon_i \prod_{j=\text{non tagged}} (1 - \varepsilon_j) \quad (6.5)$$

$$P(\text{MC}) = \prod_{i=\text{tagged}} \text{SF}_i \varepsilon_i \prod_{j=\text{non tagged}} (1 - \text{SF}_j \varepsilon_j) \quad (6.6)$$

where ε_i and SF_i are b-tagging efficiency and scale factor of i^{th} jet as a function of jet p_T , η and flavor. The event weight is calculated as the ratio of the probability of the event in data ($P(\text{DATA})$) to the probability of the event in the Monte Carlo simulation ($P(\text{MC})$).

$$w = \frac{P(\text{DATA})}{P(\text{MC})} \quad (6.7)$$

This event weight is then applied to re-weight the simulation, adjusting it to better match the characteristics and distributions observed in the data.

The provided scale factors for AK4jets are applicable to the jet transverse momentum (p_T) range of 20 GeV to 1000 GeV. For this specific analysis, a minimum p_T requirement of 30 GeV is imposed on the jets. If a p_T of jet exceeds 1000 GeV, it is recommended to use the scale factor provided for the upper boundary of 1000 GeV and double the associated uncertainty.

6.4.5 DeepDoubleBvL scale factors

The DeepDoubleBvL scale factors play a critical role in boosted analysis. The DeepDoubleBvL scale factors are provided for signal samples by the BTV Physics Object Group (POG).

Misidentification rate for top quark faking as Higgs jet can be different in Data and Simulation. Therefore, we have conducted dedicated measurement specifically for this analysis to derive the mistag scale factors for $t\bar{t}$ events.

6.4.5.1 Mistagging scale-factor measurement for top quark jets

In order to calculate the differences between data and MC in misidentification rate for top quark faking as Higgs jets. We performed this study based on the $t\bar{t}$ background sample. We defined a control region that is orthogonal to our top control region. In this region, the additional jet condition is inverted ($n_{\text{jets}} > 2$), and the mass window range (50-250) is increased to get more statistics. In this region, selected events are largely enriched with $t\bar{t}$ events, and other background contributions are from W +jets, single top, and diboson production in association with jets and single top quark production. The DeepDoubleBvL distribution for selected data and simulation is shown in Fig. 6.10(left).

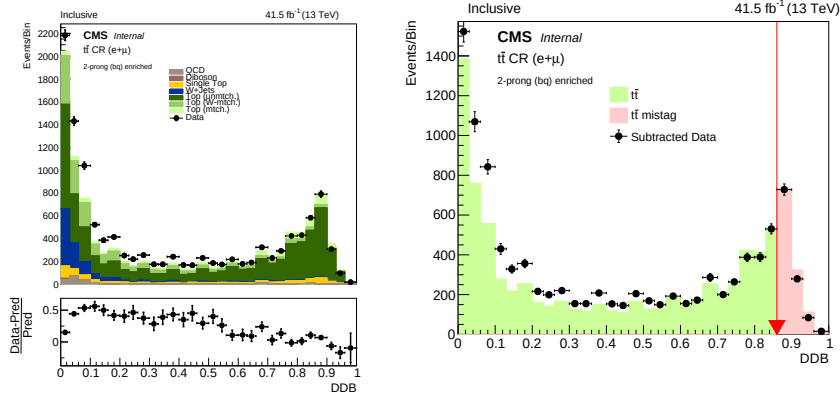
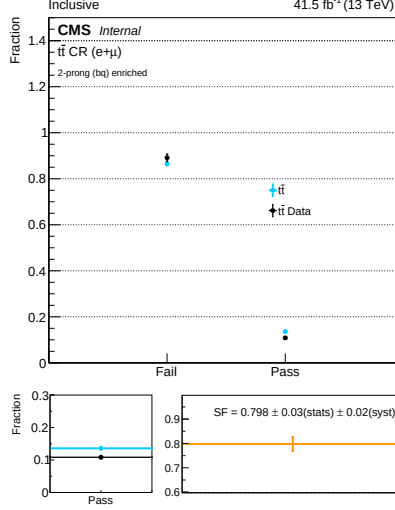


Figure 6.10: Left plot shows DeepDoubleBvL tagger distribution for data and all backgrounds, and the right plot shows the distribution for subtracted data and $t\bar{t}$ background only. The "Top" templates contain contributions from $t\bar{t}$ samples. They are split up into different quark content of the fat jet. Matching with b-quark and light quarks is performed with $DR < 0.8$. The main contribution comes from events with "unmatched" top quarks.

The non - $t\bar{t}$ backgrounds are subtracted from data, before calculating the scale factor. The DDBvL distribution for subtracted data and $t\bar{t}$ background is shown in Fig. 6.10. Scale factors for the mistag rate from top quark jets are evaluated by comparing the efficiency in subtracted data and $t\bar{t}$ background. The scale factor is evaluated inclusively and shown in Fig. 6.11. We can see from the plot that the inclusive mistag scale-factor is 20%.

Figure 6.11: Inclusive scale-factor measured for $t\bar{t}$ samples.

6.4.6 Top p_T re-weighting

The p_T spectra of top quarks in data are significantly softer than those predicted by the various MC simulations based on either LO or NLO matrix elements interfaced with parton shower. Hence, top p_T spectrum in simulation is re-weighted as given below.

$$SF(p_T) = 0.103 * \exp(0.0118 p_T(\text{GeV})) - 0.000134 * p_T(\text{GeV}) + 0.973 \quad (6.8)$$

This top p_T reweighting function is based on the parton-level results of Ref. [187] and defined as the ratio of the top p_T measured in data with respect to the theory predictions at NNLO and from Powheg+Pythia8.

6.4.7 L1 prefiring

During the 2017 data taking, it was found that ECAL trigger primitives (TPs), located in the most inner rings of the endcap region ($2 < |\eta| < 3.0$), exhibit a timing drift. And because of this a significant fraction of high η TP being mistakenly associated to the previous bunch crossing. And this increases of the L1 pre-firing rate for the calorimeter based trigger.

Since Level 1 rules forbid two consecutive bunch crossings to fire, an consequence of this (in addition to not finding the TP in the BX0) is that events can be self vetoed if

a significant amount of ECAL energy is found in the region of $2 < |\eta| < 3$. The main consequence of the pre-firing is an inefficiency in recording potentially interesting event by the L1 trigger system.

To check the effect of the L1 pre-firing in the analysis, the analysis is repeated by removing events with jets with $p_T > 100$ and $2.25 < |\eta| < 3.0$. E_T^{miss} distribution in signal region is used to check the effect.

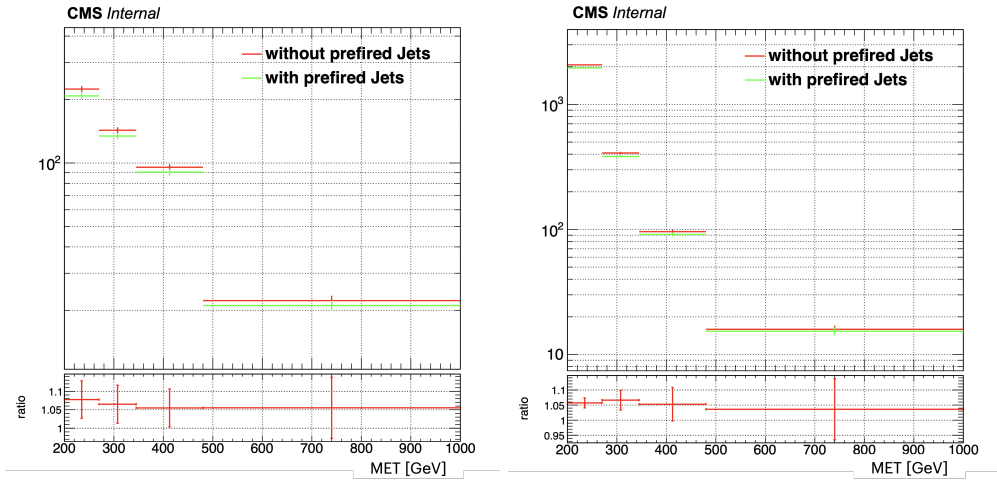


Figure 6.12: L1 prefiring effect in signal region for boosted (left) and resolved (right) category.

From the Fig. 6.12 we can see that the effect is around 2-6% in both categories. Hence, a recipe provide by JETMET group has been applied to get the pre-firing weight for 2017 MC.

The prefiring weight is the final event weight, obtained as the product of the non prefiring probability of all objects as shown in the equation:

$$w = 1 - P(\text{prefiring}) = \prod_{i=\text{photons,jets}} (1 - \epsilon_i^{\text{pref}}(\eta, p_T^{(EM)})) \quad (6.9)$$

6.5 Reconstructed Higgs boson mass correction

Mass is very important observable to identify Higgs boson in this analysis. Therefore, we correct mass peak in both resolved and boosted categories.

6.5.1 Softdrop mass correction

This analysis uses AK8 PUPPI softdrop[185] mass to tag Higgs boson in the boosted category. In order to correct the Higgs boson mass peak, we applied puppi corrections recommended by JMAR group. The soft drop jet mass(m_{SD}) is calculated from the sum of the four-momenta of the constituents that survived the grooming algorithm; it is then corrected by a factor derived in simulated signal samples to ensure a p_T and η independent jet mass distribution. Two corrections are derived:

- Correction for generator level: mass peak shifts with p_T , so corrections are computed by performing fit to M_{PDG}/M_{Gen} as a function of p_T of vector boson.
- Correction for reconstruction effects after gen level corrections applied: corrections are computed by performing fit to M_{Gen}/M_{Reco} as a function of p_T and η .

Both corrections are applied to uncorrected PUPPI softdrop mass:

$$M_{SD-Corr} = M_{SD-Uncorr} \times GenCorr \times RecoCorr \quad (6.10)$$

The final corrected softdrop mass is independent of p_T and η .

Fig. 6.13a shows the shift in the signal peak due to the soft drop mass correction. With this correction, the average gain in signal efficiency is 1-2 % depending on the phase space of 2HDM+a, but there is no overall gain in the sensitivity because the background also changes. We also checked the effect on data/MC agreement as shown in Fig. 6.13b region; the agreement does not change much after applying the correction.

6.5.2 Dijet invariant mass correction

Dijet invariant mass is constructed using two AK4jets and used to identify the Higgs boson in the resolved category where, both AK4jets are required to pass the criteria of b-tagging algorithm[181]. As we discussed in Sec 6.3.6, AK4jet originates from the

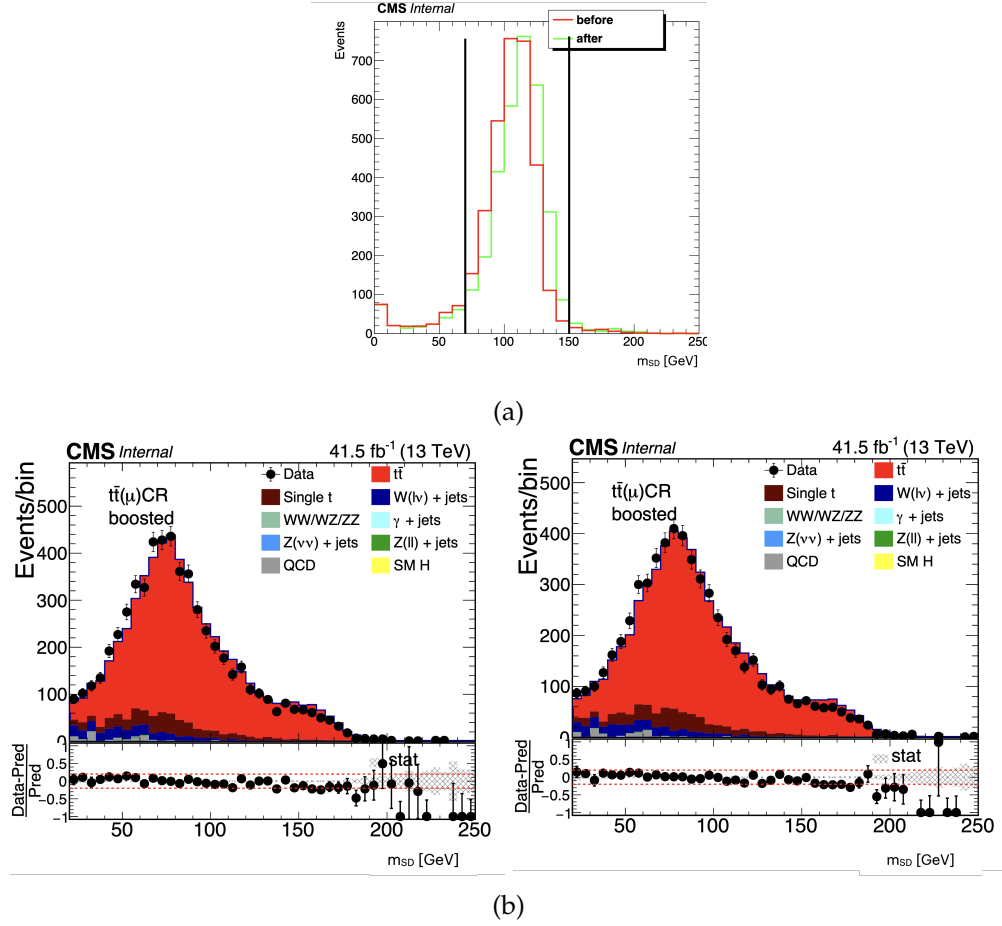


Figure 6.13: Fig(a) shows the effect of b-jet regression on single. Fig(b) shows the validation of correction in the Top Control Region

hadronization of b quark. B hadron (meson) can decay hadronically and semileptonically. Semileptonic decays lead to mismeasured energy due to escaping neutrino worsening the b-jet resolution; thus it is important to improve b-jet energy scale and resolution. b-jet energy regression is performed to correct the b-jet energy scale using a multidimensional correction and information at the generator level. Correction is computed based on the recommended recipe [188] for individual jets that attempts to more accurately estimate the true b-jet energy. This improves the resolution of the dijet mass and also corrects the mass peak, as shown in Fig. 6.14 for a single mass point of 2HDM+a. Corrections improve the resolution, and the Higgs boson mass peak is shifted from 118 GeV to 121 GeV.

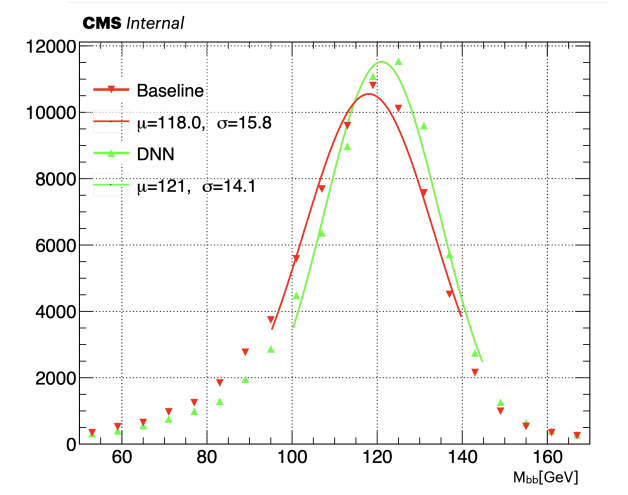


Figure 6.14: Effect of b-jet regression correction in signal mass point of 2HDM+a for $m_A = 600$ and $m_a = 150$ GeV.

BOOSTED ANALYSIS

7.1 Introduction

This analysis presents the search for dark matter produced in association with a boosted Higgs boson decaying to a pair of bottom quarks. Due to a highly boosted Higgs, both jets originated from b-quark overlap and reconstructed as a single fatjet (AK8jet). Higgs to bb decay mode has been identified using the DeepDoubleBvL algorithm. The boosted analysis aims for the phase space where the Higgs boson is highly boosted, and the DM mediator is massive. The final results are interpreted in terms of three benchmark models, 2HDM+a, Z'-2HDM, and Baryonic-Z', which are described in the previous Sec 3.5.

7.2 Event Selection

This section describes the event selections of the boosted analysis. The boosted topology targets boosted Higgs boson p_T above 200 GeV. The boosted measurement employs a single fatjet (AK8jet) with DeepDoubleBvL tagger algorithm[186] applied. This accounts for the kinematics of the event where two AK4jets start to overlap. The event topology of boosted analysis is characterized by the presence of large transverse missing energy and an AK8jet recoiling against missing energy.

The E_T^{miss} is required to be larger than 250 GeV. AK8jet is required to have p_T greater than 200 GeV, $|\eta|$ less than 2.5 and soft-drop mass within [70,150] GeV mass window. Photon veto and tau veto are applied to reduce the electro-weak backgrounds. The number of

additional AK4jets with p_T greater than 30 GeV and $|\eta|$ less than 2.5 are allowed to be a maximum of two and outside the AK8jet ($\Delta R > 0.8$).

7.3 Signal Region

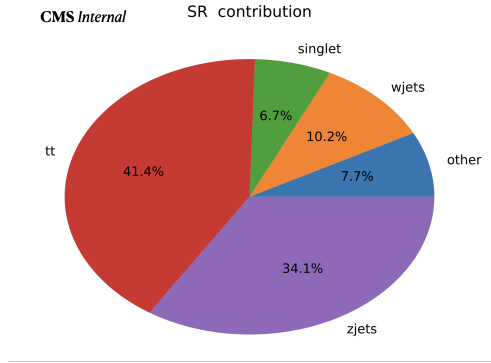


Figure 7.1: Background contribution in the signal region.

In addition to common selection, there are a few extra selections in the signal region. AK8jet is also required to have DeepDoubleBvL tagger discriminator larger than 0.86. Events with additional b-jets outside the AK8jet are vetoed. Loose medium working point criteria of DeepCSV is used to tag isolated b-jet. The number of electrons and muons is required to be zero to reduce the $t\bar{t}$ and $W + \text{jets}$ backgrounds. In order to reduce QCD multijet background, anti-QCD requirement of $\Delta\phi(E_T^{\text{miss}}, \text{AK4jet})$ greater than 0.4 is applied. The Table 7.1 provides a summary of event selection. Dominant backgrounds are $t\bar{t}$ and $Z(\nu\nu) + \text{jets}$ as shown in Fig. 7.1.

7.4 Control Region

We use control regions to perform data-driven estimates of the two largest SM backgrounds, $t\bar{t}$ and $Z(\nu\nu) + \text{jets}$ backgrounds. Here we define the dedicated control regions to estimate these two SM backgrounds. The rest of the backgrounds hereafter referred to **minor backgrounds**, will be taken directly from the simulation.

Variable	Selections		
	SR	Z control region	tt control region
Recoil(U)	-	250 GeV	250 GeV
E_T^{miss}	250 GeV	-	>50 GeV
N_{AK8jet}	1 ($p_T > 200$ GeV, $70 < m_{SD} < 150$ GeV, DDBvL >0.86)	1 ($p_T > 200$ GeV, $70 < m_{SD} < 150$ GeV, DDBvL not applied)	1 ($p_T > 200$ GeV, $70 < m_{SD} < 150$ GeV, DDBvL >0.86)
N_{bj}	0	0	1
N_{aj}	≤ 2	≤ 2	≤ 2
N_l	0	2	1
m_{ll}	-	[60-120] GeV	-
anti QCD $\Delta\phi(E_T^{\text{miss}}, AK4jet)$	>0.4	-	-
$N_{a\gamma}$	0	0	0
N_{atau}	0	0	0

Table 7.1: Signal and Control region selections of the boosted category. Here "a" is for "additional", l is for lepton and j is for AK4jet

7.4.1 Top Control Region

We defined Top control region by requiring one lepton in addition to common selection. DeepDoubleBvL score of AK8jet is required to be greater than 0.86. One additional b-jet is required to increase the purity of this control region, this b-jet should be outside the AK8jet ($\Delta R > 0.8$). E_T^{miss} greater than 50 GeV is applied to reduce the W + jets background. The set of cuts used to define Top control regions are listed in Table 7.1. Two control regions are defined based on lepton flavor.

Electron region of Top control region is required exact one tight electron¹ and the number of loose muons² to be zero. We refer to electron region of Top control region as **Top(e)**.

Similarly, muon region of Top control region is required exact one tight muon and the number of loose electrons to be zero.

Many kinematic and diagnostic plots are presented for the combination of 2017 and 2018 data to understand data-mc agreement. The MC expected distribution and observed data

¹ Definition of tight electron is explained in the Sec 6.3.1

² Definition of loose muon is explained in the Sec 6.3.2

for Recoil and Jet mass (m_{sd}) are shown in Fig. 7.2. Figure 7.3 shows the distributions for fatjet p_T and η . Figure 7.4 shows distribution for fatjet ϕ . Top background seems modelled well as data and MC agreement is fine.

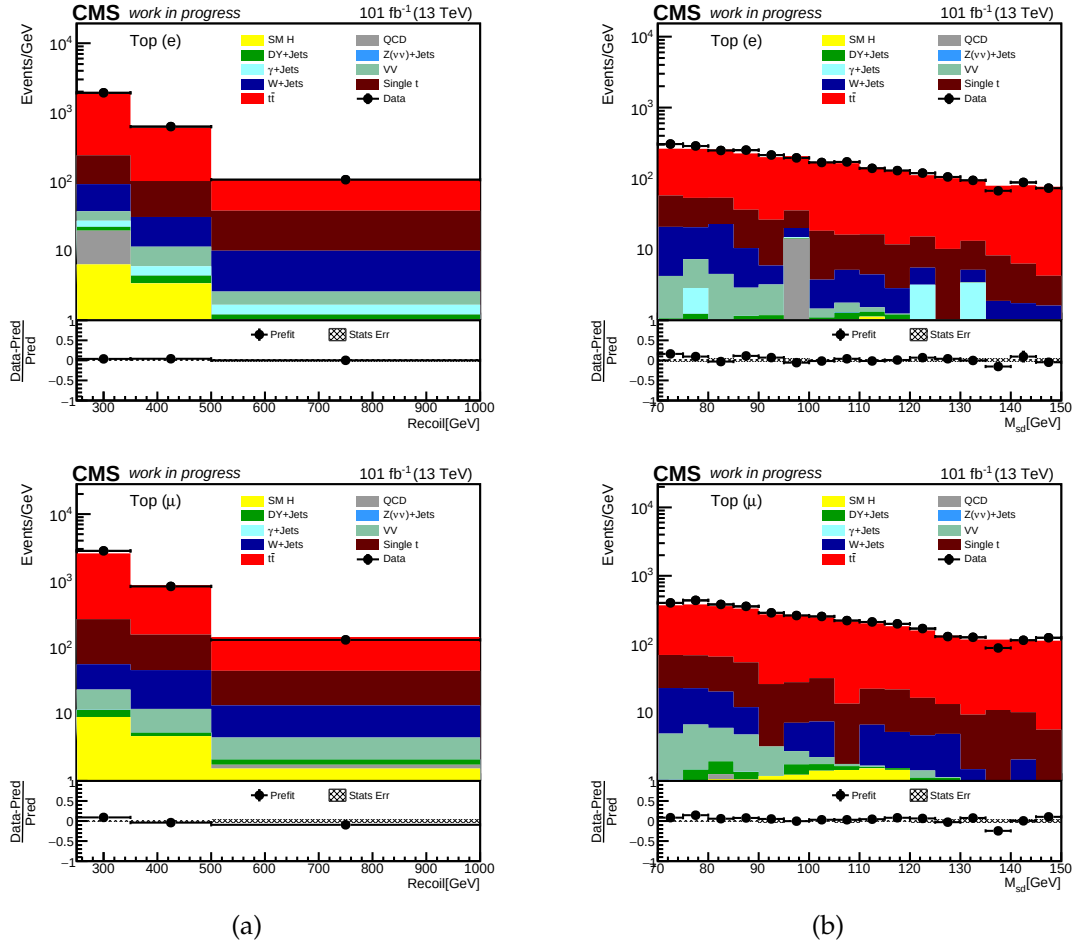


Figure 7.2: A comparison of distribution of events observed in data and expected background for electron and muon regions. The two left plots are shown for the recoil distribution and two right plots are shown for softdrop mass distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.

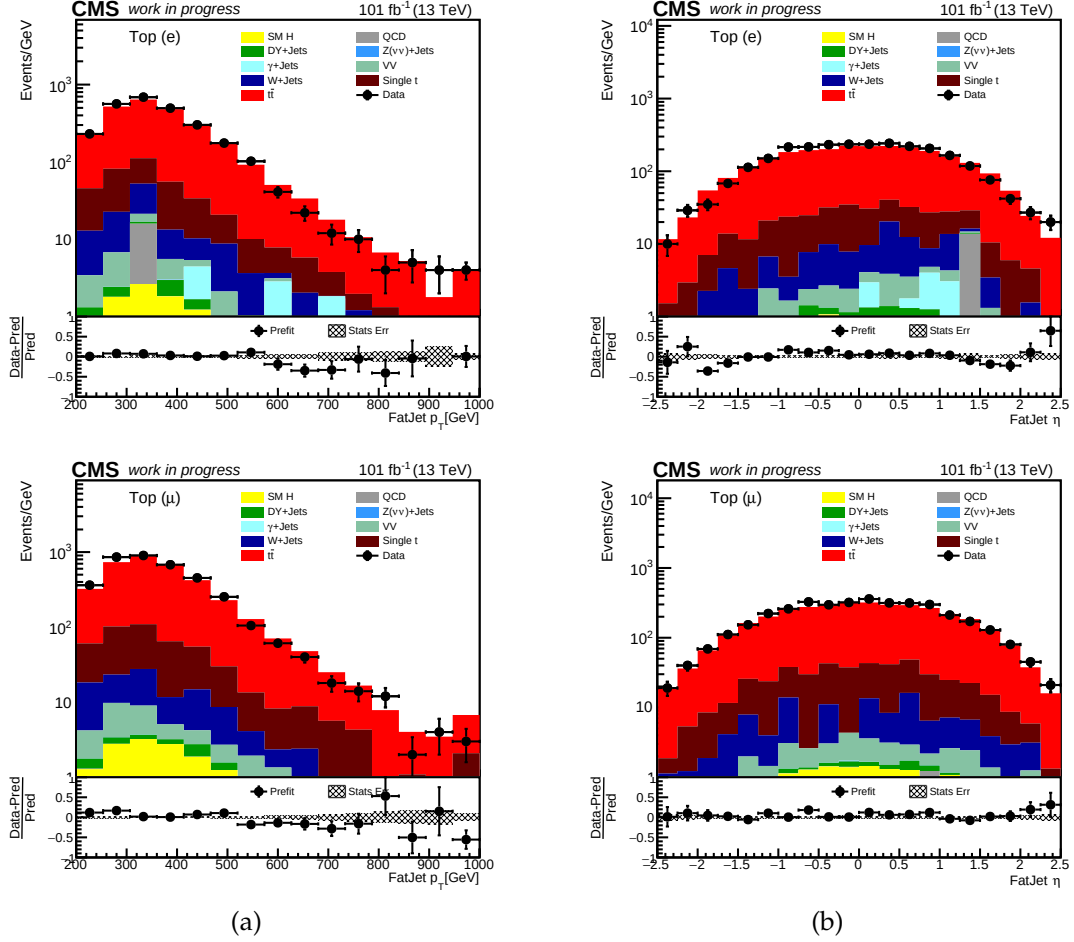


Figure 7.3: A comparison of distribution of events observed in data and expected background. The left two plots are shown for the fatjet p_T distribution and two right plots are shown for fatjet η mass distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.

7.4.2 Z Control region

We defined the Z control region to model irreducible $Z(\nu\nu) + \text{jets}$ background by requiring exact two leptons. This region does not have enough statistics; therefore, AK8jet is not required to pass DeepDoubleBvL score to gain enough statistics. Only p_T , η and mass selections are required as mentioned in common selection. In addition to common selec-

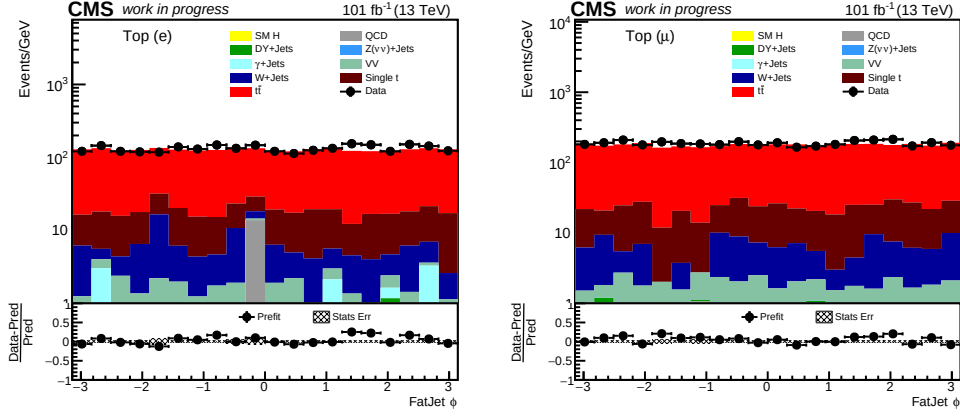


Figure 7.4: A comparison of distribution of events observed in data and expected background for fatjet ϕ distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.

tion, b-jet veto is applied. And di lepton invariant mass (m_{ll}) window between 60 and 120 GeV is applied to select the Z candidate. The exact set of cuts is listed in Table 7.1.

The electron region of the Z control region is required to have two electrons, and at least one of them should be tight electron. And Loose muon veto is applied. We refer double electron control region as **Z(ee)**.

Similarly muon region of Z control region is required to have two muons and at least one of them should be tight muon. And Loose electron veto is applied. We refer double muons control region as **Z($\mu\mu$)**.

The MC expected distribution and observed data for Recoil and m_{sd} are shown in Fig. 7.5. Figure 7.6 shows the distributions for fatjet p_T and η . Figure 7.7 shows distribution for fatjet ϕ . Top background seems modelled well as data and MC agreement is fine.

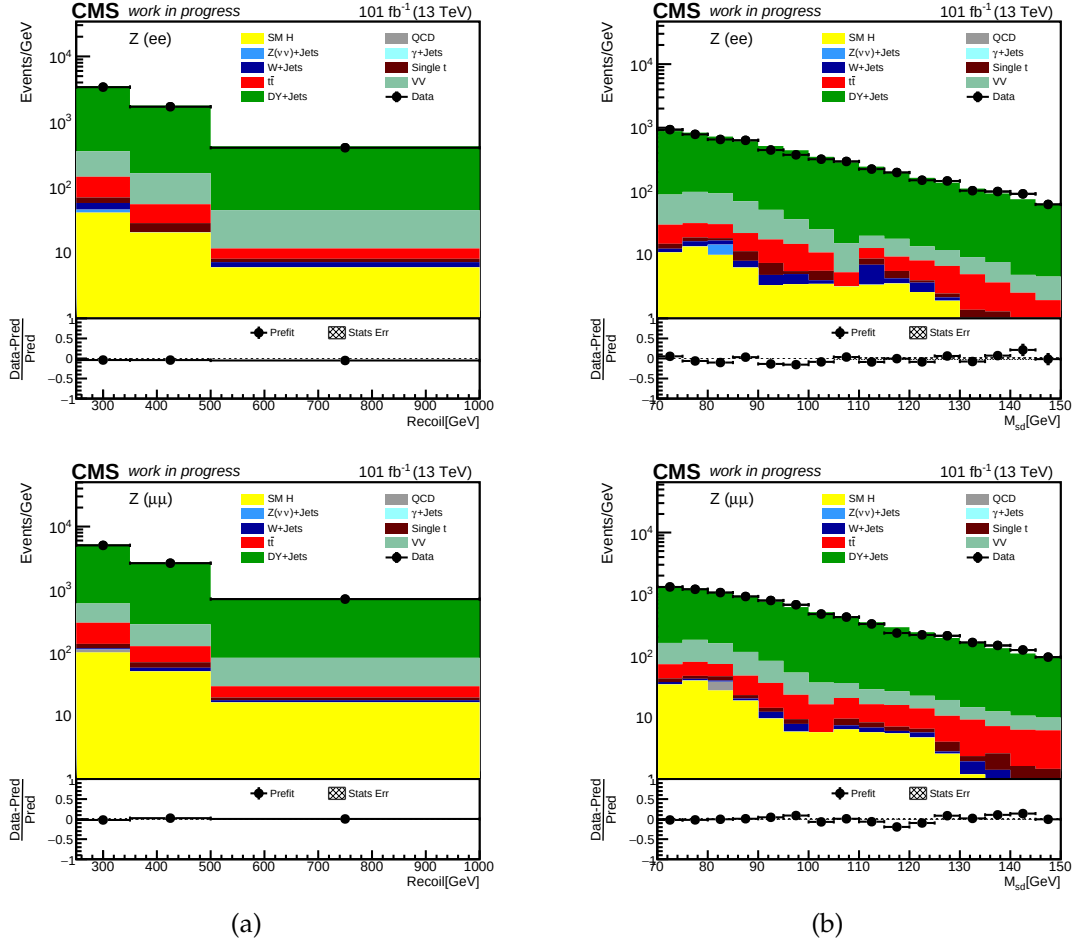


Figure 7.5: A comparison of distribution of events observed in data and expected background for electron and muon regions. The two left plots are shown for the recoil distribution and two right plots are shown for softdrop mass distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.

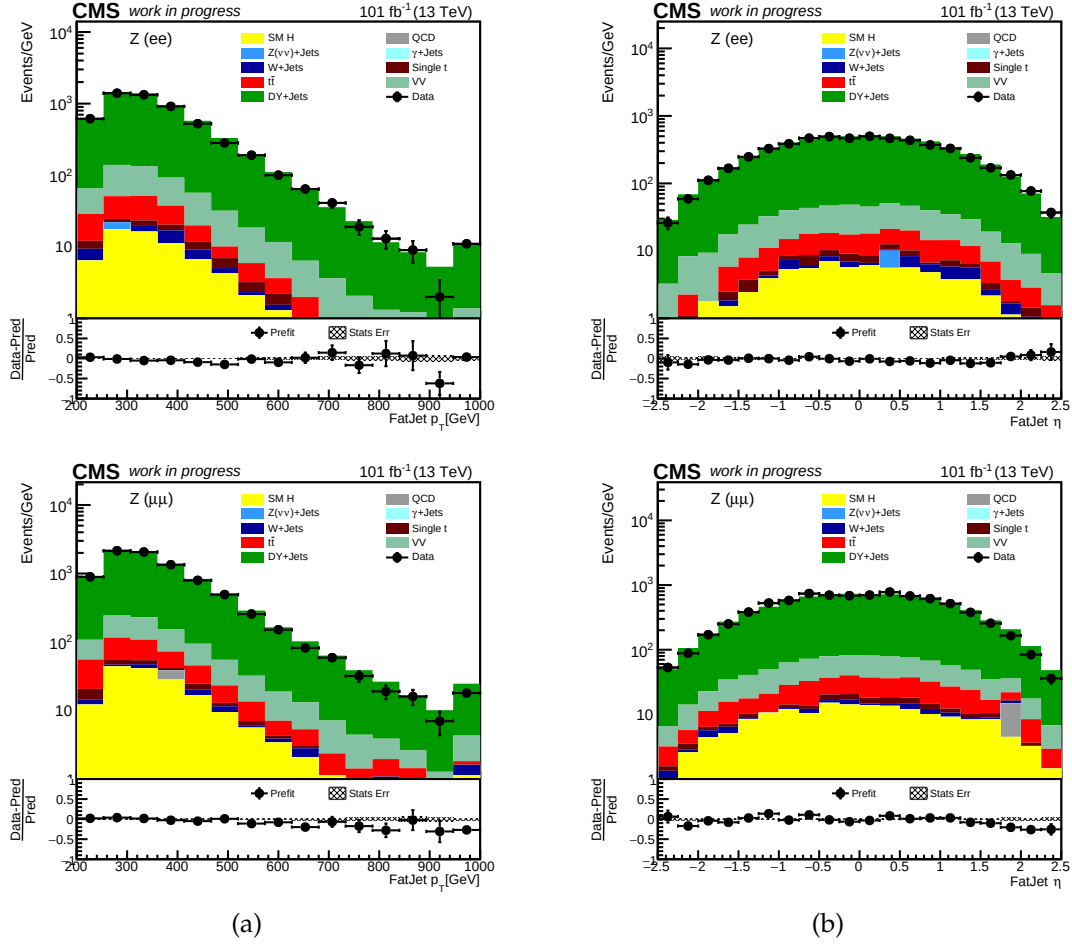


Figure 7.6: A comparison of distribution of events observed in data and expected background for electron and muon regions. The two left plots are shown for the fatjet p_T distribution and two right plots are shown for fatjet η mass distribution. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.

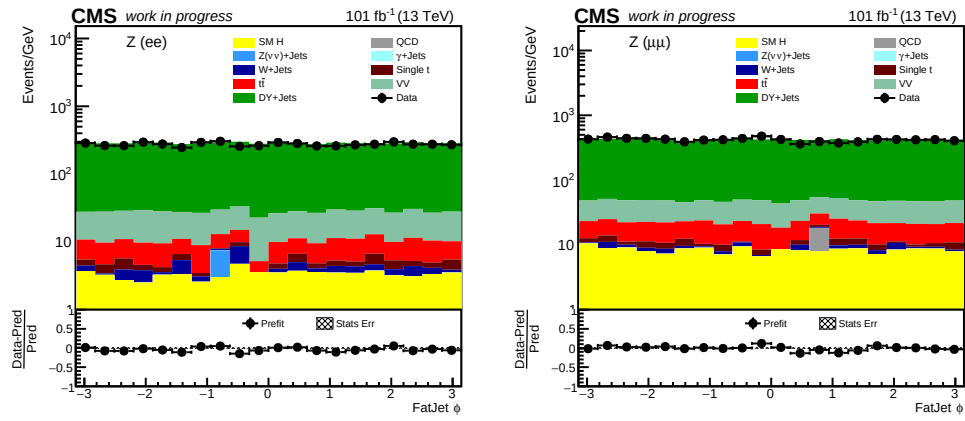


Figure 7.7: A comparison of distribution of events observed in data and expected background for fatjet ϕ . The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.

7.5 Signal Extraction And Background Estimation

In this chapter the fundamentals of the statistical treatment [189], the analysis likelihood fit model are described. And simultaneous fit of signal and control region have been discussed.

7.5.1 Statistical Concepts

The search for DM candidates in this analysis is performed with profile likelihood fit using binned distributions of mass observable in form of histograms based on background predictions, observed data and signal model. The expected event yield can be written as:

$$N^{\text{exp}}(\mu, \theta) = \mu \cdot S(\theta) + B(\theta), \quad (7.1)$$

where the μ is signal strength, S and B represents signal and background events, and θ are nuisance parameters (NPs), including the systematic uncertainties which may affect the expected yields. The signal strength μ is chosen such that

$$\mu = \begin{cases} 0, \text{background - only model} \\ 1, \text{signal model} \end{cases} \quad (7.2)$$

The best values of μ and θ are obtained in a profile maximum likelihood fit. The likelihood of observing data events (N^{obs}) given N^{exp} is constructed by the product of poisson probabilities

$$\mathcal{L}(N_i^{\text{obs}} | \mu, \theta) = \prod_i P(N_i^{\text{obs}} | \mu \cdot S_i(\theta) + B_i(\theta)) \times \prod_j G(0 | \theta_j, \Delta\theta_j) \quad (7.3)$$

where i runs over each bins in signal region, and $B_i(\theta)$ is estimated from the control region. The gaussian distribution is used to model the NPs, θ_j which can be constrained, the systematic uncertainty j can affect the prediction in bin i. The log normal distribution is used for some uncertainties, but it is not shown in likelihood function. The statistical uncertainties are also used as additional NPs. The uncertainties in the statistical model reduces the sensitivity w.r.t POI μ and improves the data and monte-carlo prediction.

The maximisation of binned likelihood fit gives the value of μ , and NPs θ that maximise the likelihood function written as $\hat{\mu}$ and $\hat{\theta}$. These maximum likelihood estimators are the

collection of parameters that provide the best overall agreement between the prediction and the data under consideration of systematic and statistical uncertainties.

A value of particular NP θ corresponds to a $\pm 1\sigma$ variation. A nuisance parameter (NP) is a parameter that represents a source of uncertainty in the analysis, typically arising from systematic effects or experimental uncertainties. The value of the NP is denoted by θ . When the value of the nuisance parameter is set to $\theta = 0$, it corresponds to the central or nominal value. When the value of the nuisance parameter is set to $\theta = -1\sigma$, it represents a variation by one standard deviation below the nominal value. This value is typically associated with the lower bound or downward uncertainty of the nuisance parameter. Conversely, when the value of the nuisance parameter is set to $\theta = +1\sigma$, it represents a variation by one standard deviation above the nominal value. This value corresponds to the upper bound or upward uncertainty of the nuisance parameter. By varying the value of the nuisance parameter between $\theta = -1\sigma$, $\theta = 0$, and $\theta = +1\sigma$, the analysis explores the impact of systematic uncertainties on the final result or measurement.

If the post fit value of a nuisance has a central value different from zero, it is said to be *pulled*. And if post fit value is lower than 1σ , it is said to be *constrained*.

In order to test a particular value of a hypothesis μ , the profile likelihood ratio is build

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \quad (7.4)$$

where numerator is maximised for all NPs θ for specific μ and denominator is maximised for total phase space in μ and θ . $\hat{\hat{\theta}}$ represents the value of NPs that maximise the likelihood for given μ known as conditional maximum-likelihood, while $\hat{\mu}, \hat{\theta}$ are unconditional maximum likelihood estimators. The λ close to 1 shows good agreement between data and hypothesized value of μ .

To establish upper exclusion limits on cross-sections for a signal-plus-background hypothesis, the goal is to find the highest value of μ that ensures the signal-plus-background model agrees with the observed data within a specific confidence level (CL) The following test statistic is build from the profile likelihood ratio:

$$q_\mu = \begin{cases} -2\ln\lambda(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} \quad (7.5)$$

This test statistic is performed to determine the existence or absence of a signal in the observed data. To determine how well the observed data matches the expected results, we often use a measure called the p-value. The p-value represents the likelihood that if we were to repeat the experiment multiple times, we would observe results as extreme or more extreme than what we currently have. In other words, it calculates the probability of observing a greater discrepancy between the expected and observed data, denoted as $q'_\mu > q_\mu$. To calculate the p-values, we can utilize Wilks' theorem[190], which states that for nested hypotheses, the log-likelihood ratio test statistic in Equation 7.5 will, asymptotically for large samples sizes, follow a χ^2 -distribution with one degree of freedom, corresponding here to the signal strength parameter μ .

With these findings, we can use the test statistic q_μ to calculate the p-value for a specific signal strength μ . The formula for computing the p-value based on the q_μ test statistic is given by

$$p_\mu = \int_{-\infty}^{q_\mu^{obs}} f(q_\mu|b) dq_\mu, \quad (7.6)$$

$$p_{s+b} = \int_{q_\mu^{obs}}^{-\infty} f(q_\mu|s+b) dq_\mu, \quad (7.7)$$

If $p_{s+b} < 0.05$, signal model is excluded at 95% confidence level (CL).

However, if the expected number of signal is much lower than the background prediction, the probability density function $f(q_\mu|b)$ and $f(q_\mu|s+b)$ will mostly overlap and the signal hypothesis might be rejected when sufficiently large downward fluctuation in data takes place. To avoid this CL_s probability [191] is introduced:

$$CL_s = \frac{P_{s+b}}{1 - p_b} \quad (7.8)$$

The 95% confidence level upper limit on μ is calculated as the value of μ corresponding to $CL_s (1-\alpha) = 0.05 (1-0.95)$.

In addition to the previously discussed observed upper limit, the expected upper limit can be determined through the following steps.

- Pseudo-data samples are generated based on the background model and systematic uncertainties defined in the datacard.
- Each pseudo-data sample is fitted to the likelihood function, similar to the observed data fitting.

- The likelihood ratio distributions are constructed from the ensemble of fitted pseudo-data samples, representing the distribution of the test statistic under the background-only hypothesis.
- Quantiles are calculated from the likelihood ratio distributions, corresponding to the desired confidence level (e.g., 95% confidence level).
- The median of the likelihood ratio distribution represents the median expected limit, which gives the expected upper limit on the signal strength at the chosen confidence level.
- Additional quantiles used to determine the 1σ or 2σ uncertainty bands around the expected limit.

7.5.2 Background Estimation

Dominant backgrounds are estimated using control region. Two of the sensitive variables, E_T^{miss} and Higgs boson candidate mass are used for signal extraction through maximum likelihood fit. The search is performed in three bin of E_T^{miss} . In each E_T^{miss} bin the m_{sd} distribution is used for signal extraction. The ranges of E_T^{miss} bins and number of bins are:

- first 12 m_{sd} bins corresponds to E_T^{miss} range: 250-350 GeV
- next 10 m_{sd} bins corresponds to E_T^{miss} range: 350-500 GeV
- last 3 m_{sd} bins corresponds to E_T^{miss} range: > 500 GeV

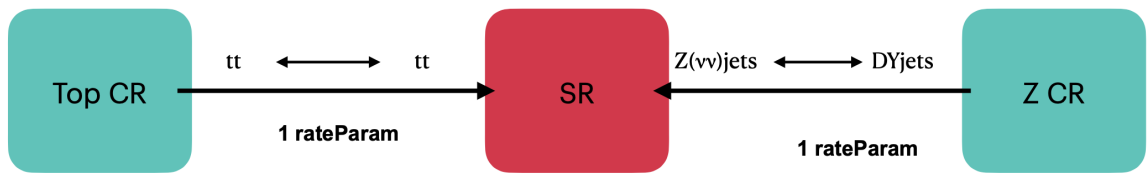


Figure 7.8: Sketch of method used to connect the signal region background to control regions through a scale factor. A common rateParam has been used for electron and muon region.

The maximum binned likelihood fit is performed in the signal region and control regions (Top(e), Top(μ), Z(ee) and Z($\mu\mu$)). The major backgrounds, $Z(\nu\nu) + \text{jets}$ and $t\bar{t}$, are connected through rateParam commands between the signal and control regions.

The normalizations of these backgrounds in the signal region are modified using rate parameters (rateParams). RateParams provide a way to incorporate uncertainties in the expected event yields for specific processes. The calculation of the rate parameter is done by performing a likelihood fit in the control regions. The best-fit values within the allowed ranges of the rate parameters maximize the agreement between the observed data and the expected predictions and used as the scaling factor for the corresponding background in signal region.

It is worth noting that common rateParams are used for both the electron and muon flavors of the control regions. This ensures a consistent treatment of the rate uncertainties across the different control regions.

The likelihood functions for control region and signal region are as following:

$$\mathcal{L}(n|R^s, \theta) = P(n_i|R^s B(\theta) + B'(\theta)) \times \Pi_{j \in syst} G(\theta_j, \Delta\theta_j) \quad (7.9)$$

$$\mathcal{L}(n|\mu, \theta) = \Pi_{i \in bins} P(n_i|\mu \cdot S_i(\theta) + \sum_s R^s B_i^s(\theta) + B'(\theta)) \times \Pi_{j \in syst} G(\theta_j, \Delta\theta_j) \quad (7.10)$$

where i represent bin number of histogram, n represent observed events, B represent dominant background, B' represent minor background and R represent the rateParam. Systematic uncertainty (j) is added as a gaussian distribution of nuisance parameter $NP(\theta)$. The rateParams are also different for each year dataset. Total four scale factors are used to control the normalisation of the major backgrounds. The rateParams estimated from the fit are given in the Table 7.2. All the systematic uncertainties discussed in the next section are added in the fit.

Control Region	Process	Normalisation Factor	YEAR
Top	$t\bar{t}$	0.993 ± 0.032	2017
	$t\bar{t}$	1.078 ± 0.0313	2018
Z	Z+Jets	1.014 ± 0.0194	2017
	Z+Jets	0.933 ± 0.0161	2018

Table 7.2: Normalisation factor measured for $t\bar{t}$ and Z+Jets processes in Top and Z control region for 2017 and 2018.

7.6 Systematic Uncertainty

In the analysis, systematic uncertainties are considered to account for various sources of uncertainty that can affect the measurement. These uncertainties are essential in assessing the robustness and reliability of the analysis results. Systematic uncertainties arise from different aspects, including experimental measurements and theoretical assumptions.

Systematic uncertainties are typically parameterized and treated as nuisance parameters in the analysis. They are varied simultaneously with the likelihood fit or limit calculation to explore the range of possible outcomes given the uncertainties. The impact of each systematic uncertainty is quantified by evaluating its effect on the measured observables and determining the corresponding uncertainty on the final results. Following are the list of systematic uncertainties which are used in the fit:

- **Integrated luminosity:** All monte-carlo samples are scaled with the integrated luminosity. In order to reflect the uncertainty on the integrated luminosity measurement in 2017 and 2018 datasets, an uncertainty of 2.5% [192, 193] are used for the normalization of Monte-Carlo samples.
- **Electron reconstruction and identification:** Electron reconstruction and identification scale factors are used to correct the simulation in single and double electron control regions. Therefore, systematic uncertainty for these scale factors is taken into account.
- **Electron trigger:** Electron trigger uncertainty has been considered in Top(e) and Z(ee) control regions. The shape based systematic uncertainty is used in the analysis. An average uncertainty of electron trigger is 1%.
- **Muon identification and isolation:** The systematic uncertainty for muon identification and isolation have been taken into account. Uncertainty for loose ID and tight ID is taken into account in double muon region while tight ID is taken for single muon region only.
- **Tau veto:** Tau systematic uncertainty is calculated by defining new signal region with the tau. The measured systematic uncertainty is $\approx 6\%$ and taken as $\ln N$.
- **E_T^{miss} trigger:** The difference of scale-factor curve in single electron and single muon region is taken as a systematic uncertainty.

- **b tagging:** We ask for a b-tagged jet in Top control region. Therefore, b-tagging scale-factors are applied in top control region. Shape based uncertainty is calculated for real b jets (b flavor) and fake b-jets (light jets). The average uncertainty is 5%.
- **DeepDoubleBvL:** BTV provides systematic uncertainty for DeepDoubleBvL SF for the range 250-850 GeV. For jet $p_T < 250$ GeV and > 850 GeV, the scale factor is taken from the neighbouring bin is taken with inflated systematic uncertainty (doubled), i.e. for < 250 GeV SF from 250-350 GeV is used, and for > 850 GeV, SF from 350-850 GeV is used. For mistag rate 4% is used as $\ln N$, this includes statistical and systematic uncertainties.
- **Jet Energy Calibration (JEC):** Total 11 JEC source uncertainties are used for signal and control regions. Maximum uncertainty is less than 3%. Following are the name of JEC sources:
 - JECAbsolute
 - JECAbsolute_YEAR
 - JECBBEC1
 - JECBBEC1_YEAR
 - JECEC2
 - JECEC2_YEAR
 - JECFlavorQCD
 - JECHF
 - JECHF_YEAR
 - JECRelativeBal
 - JECRelativeSample_YEAR
- **Jet Energy Resolution (JER):** Jets are smeared to match monte-carlo resolution with data, hence 5% uncertainty taken into account for JER.
- **Pile-up:** The pileup re-weight scale factors are derived using 69.2 mb minimum bias cross-section. Up and down uncertainties on scale factors are calculated by varying 4.5% minimum cross-section. A shape based systematic uncertainty is used.
- **Parton distribution function (PDF):** PDF affects the distribution and cross-section of process. The uncertainty is calculated as positive square root of variance using 101 set of PDF weights.

- **QCD renormalization and scale factorization:** For signal and SM h , we propagate the alternative variations of renormalization and factorization scale which directly affect the normalization and shape of M_{jj} distribution. It is represented as μ_scale in the table. Each process has separate μ_scale nuisance.
- **The QCD multijet background:** An uncertainty of 50% is used for qcd normalization in all regions for boosted and resolved categories.
- **L1 prefiring:** The shape based uncertainty is used for l1 prefiring.
- **Muon prefiring:** The recommended size of 0.5% uncertainty is used for l1 prefiring.
- **Backgrounds taken directly from simulation prediction:** An uncertainty of 10% is assumed for the normalization of single top (approximately the uncertainty on the measured cross-section), 20% on SM Higgs and diboson (assumed to have the same uncertainty as SM Higgs).
- **Monte Carlo Statistics:** We considered finite Monte-Carlo statistical uncertainty [194] such that it affects each bin of the final fitted distributions independently from the other bins.

7.7 Results

Unrolled mass distribution of signal regions is shown in Fig. 7.9. Data is matching well with SM expectations. No signal peak is observed over the SM backgrounds hence results are interpreted in terms of upper limits.

A simultaneous fit of the signal and control regions is performed to extract the expected upper limit on signal production. The simultaneous fit of signal and background regions control the normalization of the background processes by adjusting the prediction of background yields in the control regions. The fit will, therefore, constrain the value of normalization scale factors for each background in such a way that the data and simulation matches. This is equivalent to measuring the data to simulation scale factor in the control region and then applying them to the signal region. However, a simultaneous fit is preferable because it takes care of the systematic uncertainties when propagating these scale factor from control regions to the signal region.

The study of impact of each nuisance on parameter interest and pulls of each nuisance is shown in Appendix E.

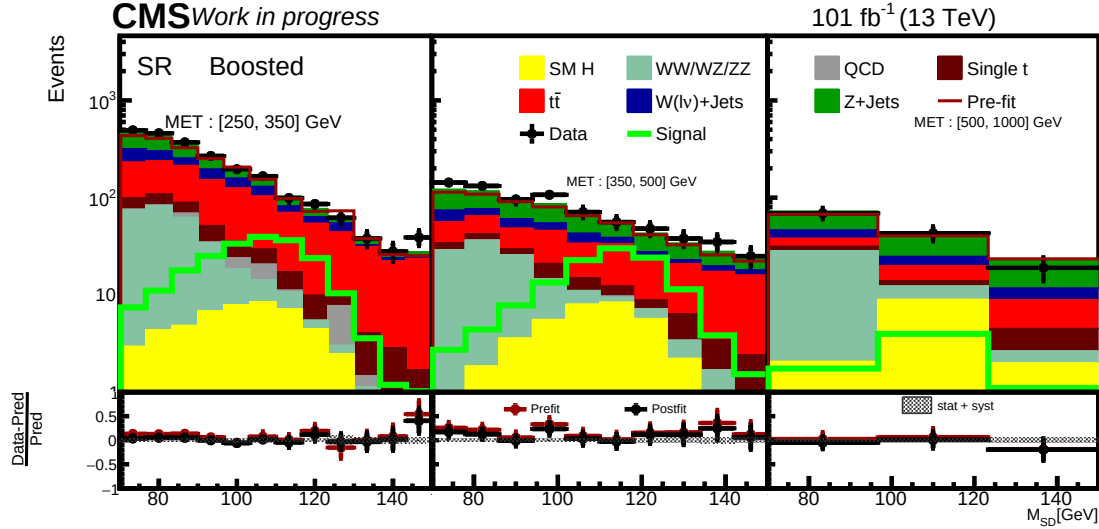


Figure 7.9: A comparison of distribution of events observed in data and expected post fit background in the signal region. Mass distribution is filled in three E_T^{miss} bins. The last MET bin includes all events with $E_T^{\text{miss}} > 500$ GeV. One signal hypothesis ($m_a=150$ GeV, $m_A=600$ GeV, $\tan\beta=1$, $\sin\theta=0.35$) for 2HDM+a model is also shown overlaid. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The black band in bottom pad corresponds to the combined effect of systematic and statistical uncertainty in the background expectation.

7.7.1 Interpretations

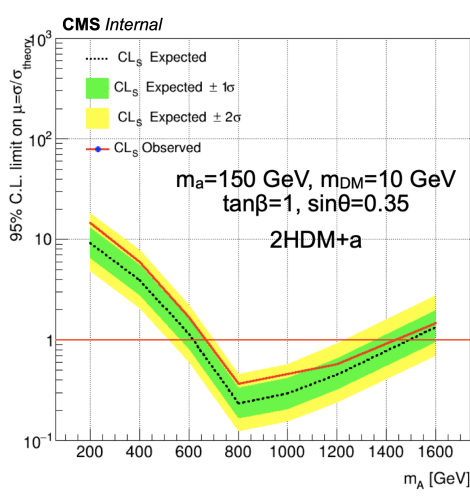
No significant excess over the expected Standard Model (SM) background is observed in the Signal Region (SR). The results of the search are therefore interpreted in terms of upper limits on the signal strength modifier, denoted as $\mu = \sigma_{\text{obs}}/\sigma_{\text{th}}$. Here, σ_{th} represents the predicted production cross-section of Dark Matter (DM) candidates in association with a Higgs boson, and σ_{obs} represents the upper limit on the observed cross-section. The upper limits on μ are calculated at a 95% confidence level (CL) using a modified frequentist method[191, 195] with an asymptotic approximation[196].

The 95% CL upper limits on the signal strength, as a function of the mass of the heavy pseudoscalar mediator (m_A), are presented in Figure 7.10(a) for the 2HDM+a model. In this model, m_a is fixed at 150 GeV, $\tan\beta$ is set to 1, and $\sin\theta$ is 0.35. The results combine data collected in 2017 and 2018. The observed limit is represented by the red line, the

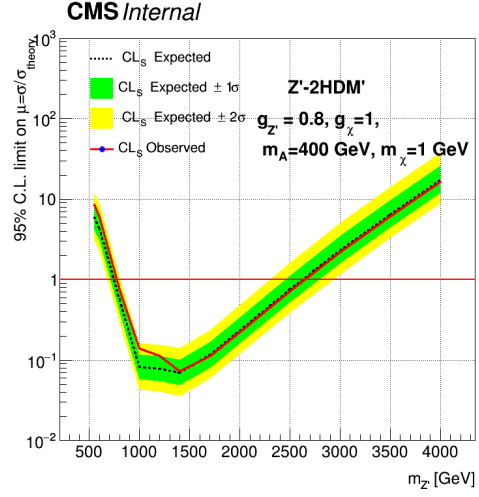
expected limit by the black dotted line, the $\pm 1\sigma$ uncertainty band by the green color, and the $\pm 2\sigma$ uncertainty band by the yellow color. The expected limit suggests that the mass range from 600 to 1450 GeV is excluded.

Figure 7.10(b) displays the upper limit on the signal strength as a function of the vector mediator for the Z' -2HDM model. The limit indicates that vector mediators with masses ranging from 0.8 TeV to 2.6 TeV are excluded for $m_A = 400$ GeV and $m_\chi = 1$ GeV.

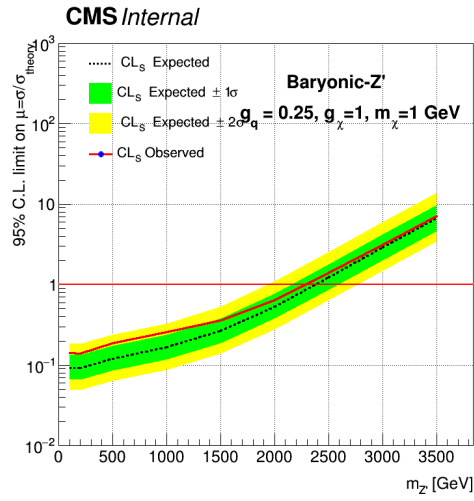
Lastly, Figure 7.10(c) represents the upper limit on the signal strength for the Baryonic- Z' model. It reveals that vector mediators with masses below 2.3 TeV are excluded when $m_\chi = 1$ GeV.



(a)



(b)



(c)

Figure 7.10: The 95% CL upper limit on signal strength for the boosted analysis as a function of: (a) heavier pseudoscalar mediator for 2HDM+a (b and c) vector mediator for Z'-2HDM and Baryonic-Z'.

RESOLVED ANALYSIS

8.1 Introduction

In addition to the boosted analysis, this study also includes a resolved analysis to explore the search for dark matter in association with a low boosted Higgs boson that decays into a pair of bottom quarks. The resolved analysis is specifically designed to be sensitive to the phase space where the mass of the DM mediator is relatively low. The final results obtained from the resolved category are interpreted and analyzed within the framework of three benchmark models: 2HDM+a, Z' -2HDM, and Baryonic- Z' , which have been comprehensively described in Section 3.5.

8.2 Event Selection

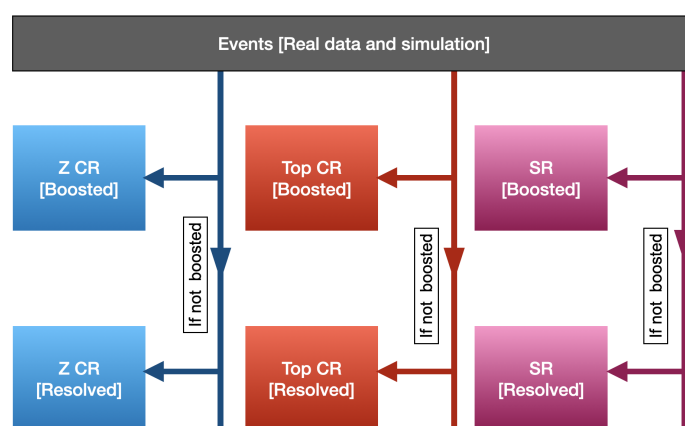


Figure 8.1: Sketch of events flow. If event does not pass the boosted selections then the resolved selections are checked. Exact selections are discussed in next section.

This section gives a general overview of the resolved analysis and common selections in signal and control regions. The resolved topology is included in the measurement in addition to boosted analysis. If event does not pass boosted analysis selections, then resolved category selections are checked as shown in the chart 8.1. The event topology of the resolved category is characterized by the presence of large missing transverse energy E_T^{miss} and a pair of b-jets from the Higgs boson decay recoiling against missing transverse energy. Additional jet activity is expected to be low.

The E_T^{miss} is required to be larger than 200 GeV. Higgs candidate is reconstructed using two AK4jets passing medium working point criteria of DeepCSV algorithm [181]. And among those two bjets, the first jet with the highest transverse momentum is required to have p_T greater than 50 GeV, while the second jet is required to have p_T greater than 30 GeV. The dijet p_T is required to be greater than 100 GeV. The dijet invariant mass is required to be larger than 100 GeV and less than 150 GeV. No photon and tau are allowed in the events. The final events of the resolved analysis are split into signal and control regions.

8.3 Signal Region

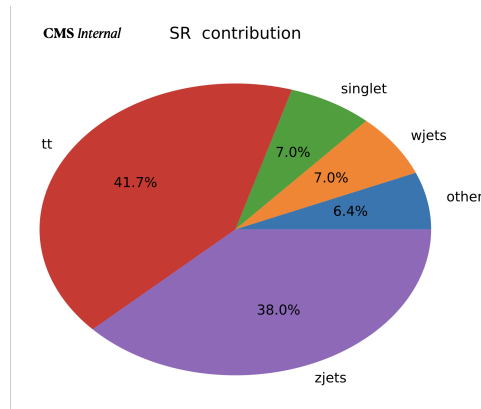


Figure 8.2: Background contribution in the signal region.

The SR selections are applied in addition to common selection to estimate the contamination background in the resolved category. Presence of loose electron and loose muons are not allowed in the events. This additional lepton veto helps to reduce the $W + \text{jets}$ and $t\bar{t}$ backgrounds. Number of additional jets with p_T greater than 30 GeV and $|\eta|$ less

than 2.5 is required to be 0,1 or 2. To reduce the QCD multijet background, minimum $\Delta\phi(E_T^{\text{miss}}, \text{jet})$ is required to be greater than 0.4. The summary of the selection is given in table 8.1. Dominant backgrounds are $t\bar{t}$ and $Z(\nu\nu) + \text{jets}$ as shown in chart 8.2.

Variable	signal region	Z control region	tt control region
Recoil	-	>200 GeV	>200 GeV
E_T^{miss}	>200 GeV	<100 GeV	>50 GeV
$p_T^{l1}(\text{b-tagged})$	50 GeV	50 GeV	50 GeV
$p_T^{l2}(\text{b-tagged})$	30 GeV	30 GeV	30 GeV
m_{jj}	[100-150] GeV	[100-150] GeV	[100-150] GeV
p_T^{jj}	>100 GeV	>100 GeV	>100 GeV
$N_{a\gamma}$	0	0	0
$N_{a\text{Tau}}$	0	0	0
anti QCD $\Delta\phi(E_T^{\text{miss}}, \text{jet})$	>0.4	-	-
N_{aj}	<=2	<=2	>1
N_{al}	0	2	1
m_{ll}	-	[60-120] GeV	-

Table 8.1: Selection cuts applied in the resolved category. Here "a" is for "additional", l is for lepton and j is for ak4jet

8.4 Control Region

We use control regions to perform data-driven estimates of the two largest SM backgrounds, $t\bar{t}$ and $Z(\nu\nu) + \text{jets}$ backgrounds. Here we define the dedicated control regions to estimate these two SM backgrounds. The rest of the backgrounds hereafter referred to **minor backgrounds**, will be taken directly from the simulation.

8.4.1 Top Control region

Same as boosted analysis, top control region is defined to model the $t\bar{t}$ background by requiring one lepton in addition to common selection. In order to reduce the $W + \text{jets}$ background and to increase the purity of this control region, E_T^{miss} greater than 50 GeV and additional jets greater than 0 are applied. Based on lepton flavour, this

control region is also divided into two regions; electron region and muon region. Details of cuts are given in Table 8.1 In single electron region, exact one tight electron is required and loose muons are vetoed. We refer to the single electron top control region as **Top(e)**. In single muon region, loose electrons are vetoed and exact one tight muon is selected. We refer to the single muon top control region as **Top(μ)**.

A comparison of distribution of events observed in data and expected background for Recoil, M_{jj} , $\text{Jet}1p_T$, $\text{Jet}1\eta$, $\text{Jet}1\phi$, $\text{Jet}2p_T$, $\text{Jet}2\eta$, and $\text{Jet}2\phi$ is shown in Figs. 8.3, 8.4, 8.5, 8.6. Bottom pad shows the difference of Data and MC. Data-MC agreement is good in all distributions.

8.4.2 Z Control region

The definition of Z Control regions is same as described in boosted category. Two leptons are required to define Z Control region where one of them should pass tight identification criteria. Loose muon veto is applied in electron region and electron veto is applied in muon region. In order to reduce the $t\bar{t}$ background and to increase the purity of this control region, E_T^{miss} less than 100 GeV are applied. Details of selection are given in the same Table 8.1.

Data-MC agreement is shown in Figs. 8.7, 8.8, 8.9 and 8.10 for Recoil, M_{jj} , $\text{Jet}p_T$, $\text{Jet}\eta$, $\text{Jet}\phi$. Control region is dominated by DY + jets background, and it seems modelled well.

8.4.3 QCD Control region

In the resolved category, the modeling of the QCD background is not good. To overcome this, we have introduced an additional QCD control region where we estimate the QCD contribution using a data-driven method. This control region is defined by inverting the $\Delta\phi(E_T^{\text{miss}}, \text{jet})$ cut to be less than 0.4, while keeping other selections the same as the signal region. The QCD estimation is performed by fitting an exponential function to the $\Delta\phi(E_T^{\text{miss}}, \text{jet})$ distribution (up to 0.4) in the QCD region. The integral of the fit function from 0.4 to 3.14 provides the estimated number of QCD events in the signal region. This estimation is done separately for each bin of the main observable, which is the mass distribution consisting of 43 bins.

The estimated QCD contribution, obtained using the data-driven method, is shown in Figure 8.11, where the x-axis represents the bin number of the main observable and

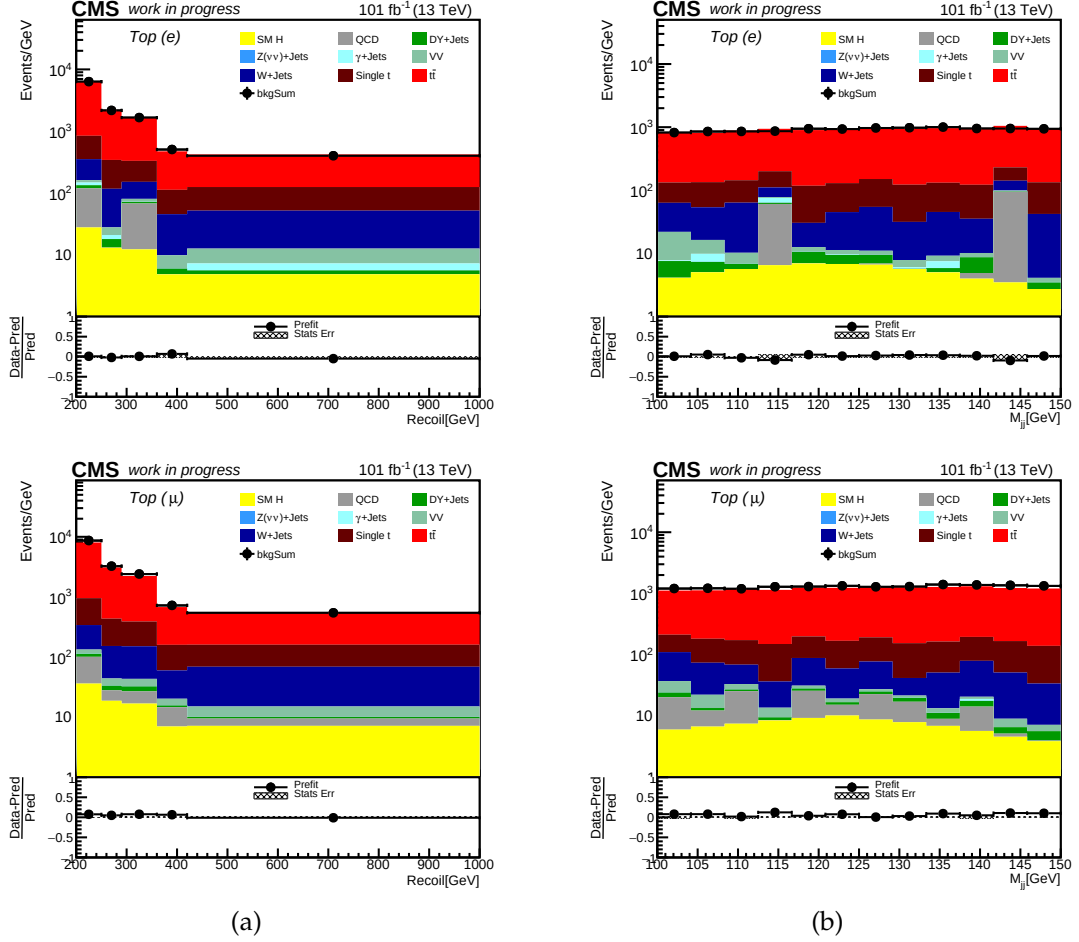


Figure 8.3: A comparison of distribution of events observed in data and expected background in electron and muon of the top control region for resolved category. Left plot is shown for Recoil distribution and right plot is shown for inclusive distribution of m_{jj} . Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.

y-axis represents the number of events estimated from data driven method. The main observable will be discussed in the next section. The plots depict the estimated QCD events in the signal region, which have been added to the respective bins of the mass distribution.

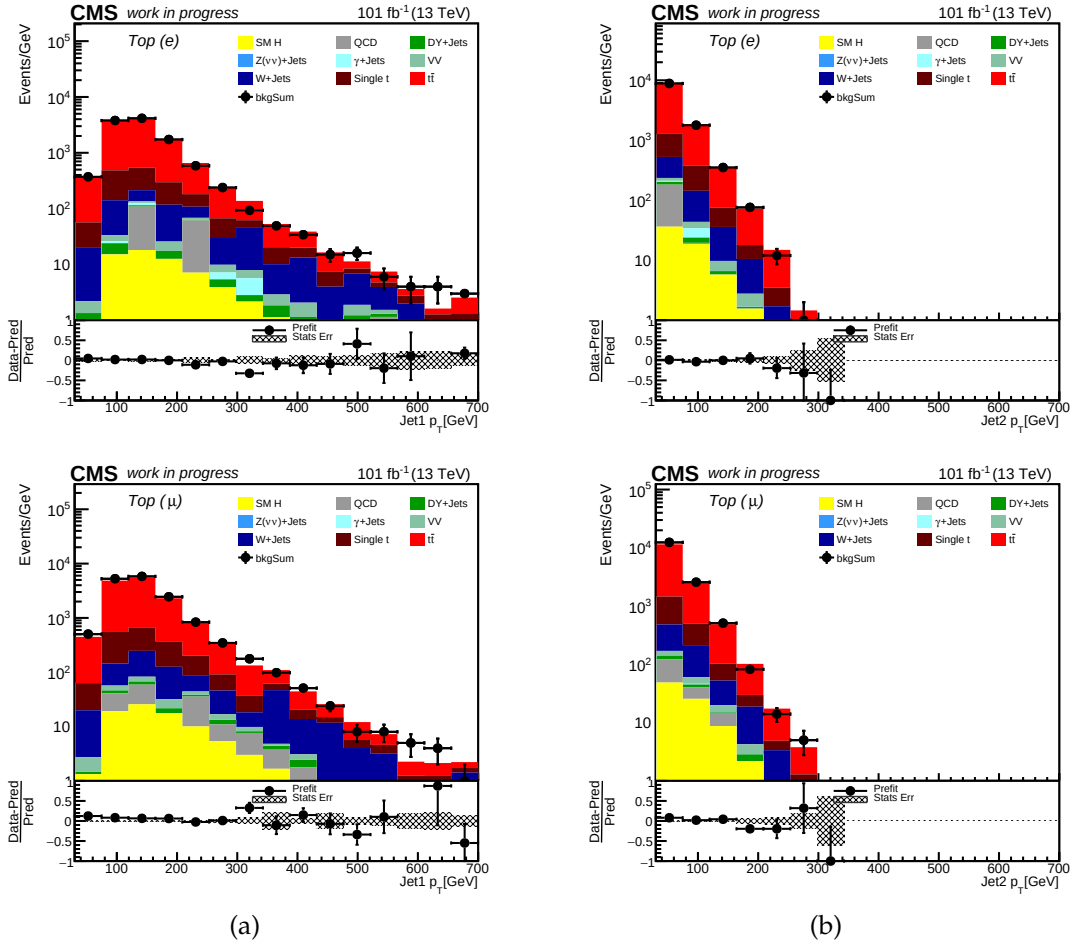


Figure 8.4: A comparison of distribution of events observed in data and expected background in electron and muon region of the top control region for resolved category. Left plot is shown for Jet1 p_T distribution and right plot is shown for jet2 p_T . Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.

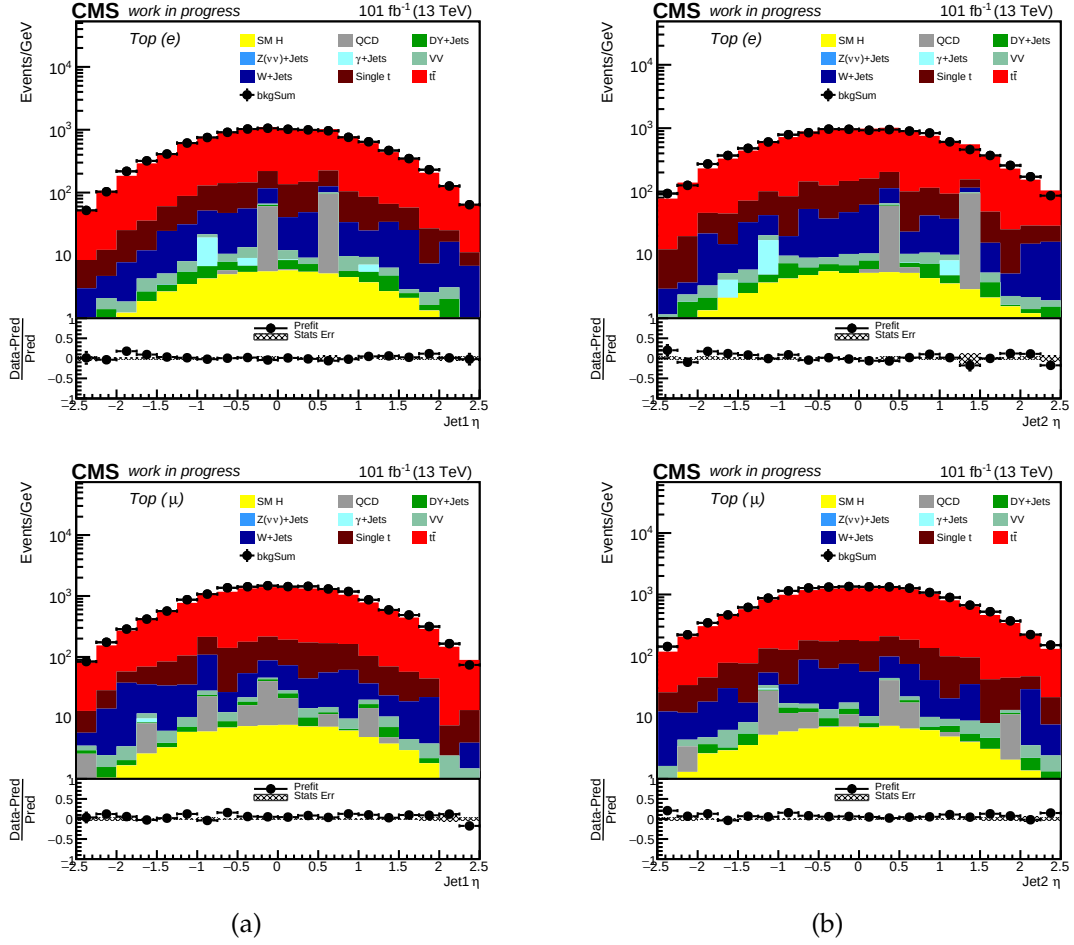


Figure 8.5: A comparison of distribution of events observed in data and expected background in electron and muon region of the top control region for resolved category. Left plot is shown for Jet1 η distribution and right plot is shown for Jet2 η . Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.

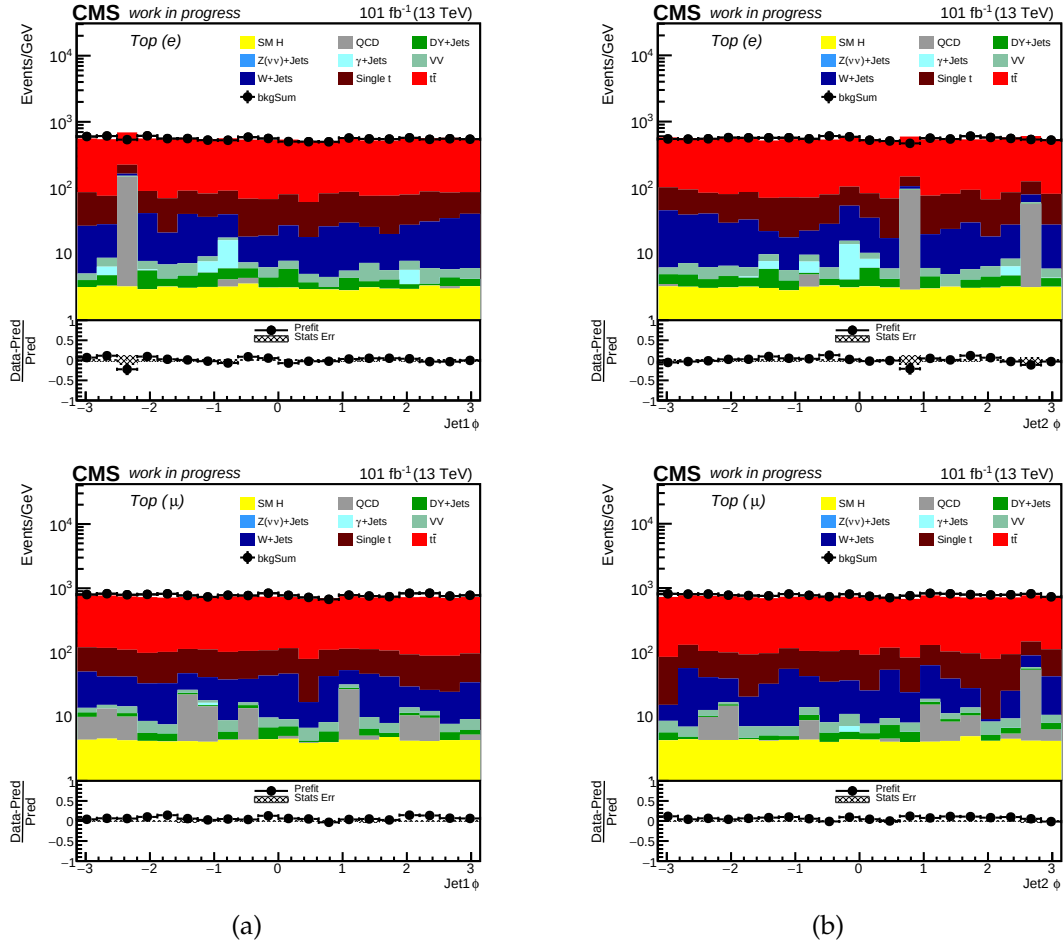


Figure 8.6: A comparison of distribution of events observed in data and expected background in electron and muon region of the top control region for resolved category. Left plot is shown for Jet1 ϕ distribution and right plot is shown for Jet2 ϕ . Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.

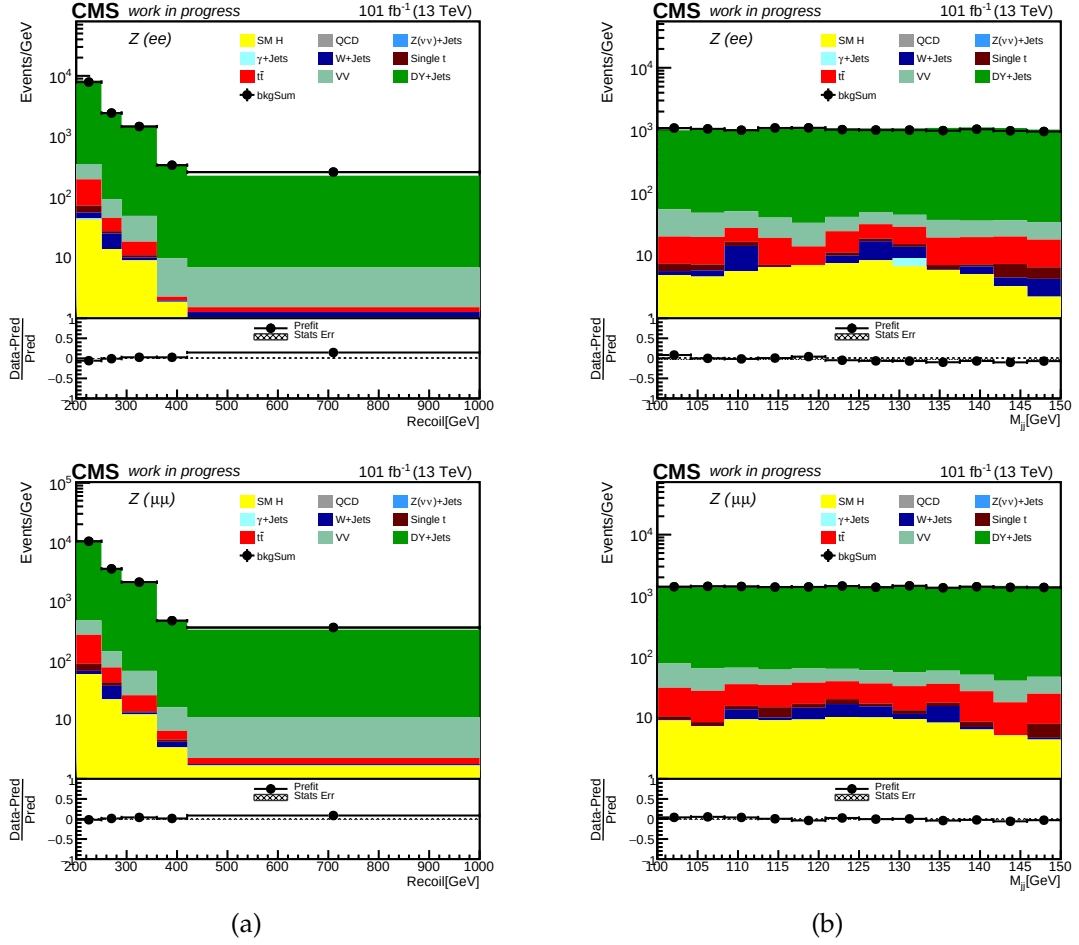


Figure 8.7: A comparison of distribution of events observed in data and expected background in electron and muon region of the Z control region for resolved category. Left plot is shown for Recoil distribution and right plot is shown for m_{jj} distribution. Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.

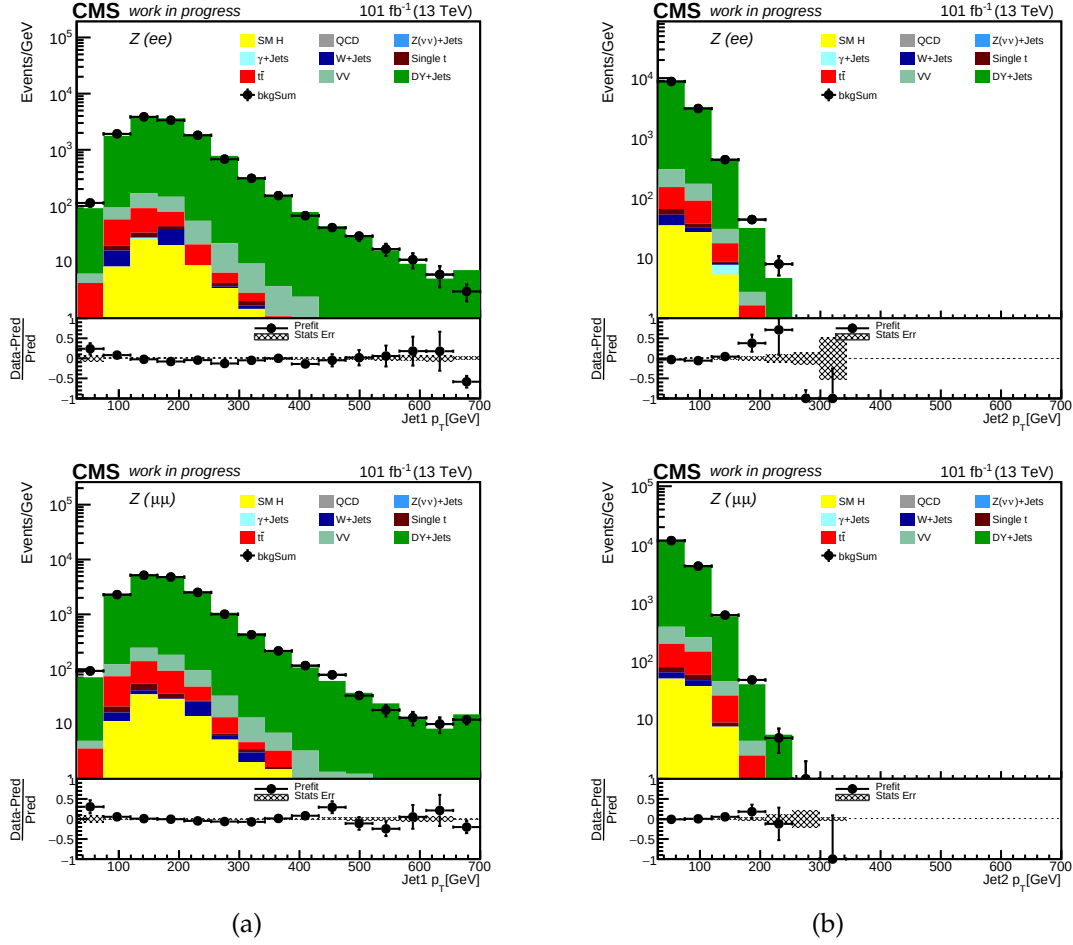


Figure 8.8: A comparison of distribution of events observed in data and expected background in electron and muon region of the Z control region for resolved category. Left plot is shown for jet1 p_T distribution and right plot is shown for jet2 p_T distribution. Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.

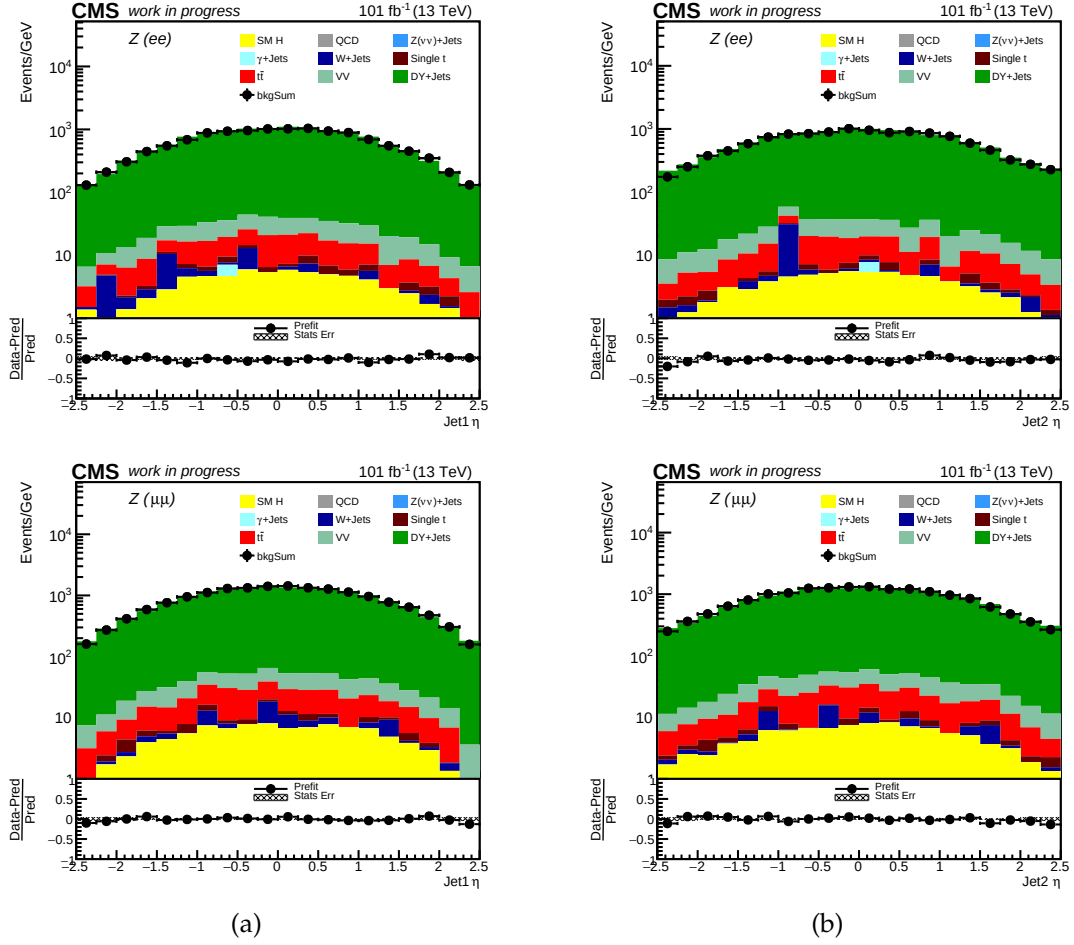


Figure 8.9: A comparison of distribution of events observed in data and expected background in electron and muon region of the Z control region for resolved category. Left plot is shown for jet1 η distribution and right plot is shown for jet2 η distribution. Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.

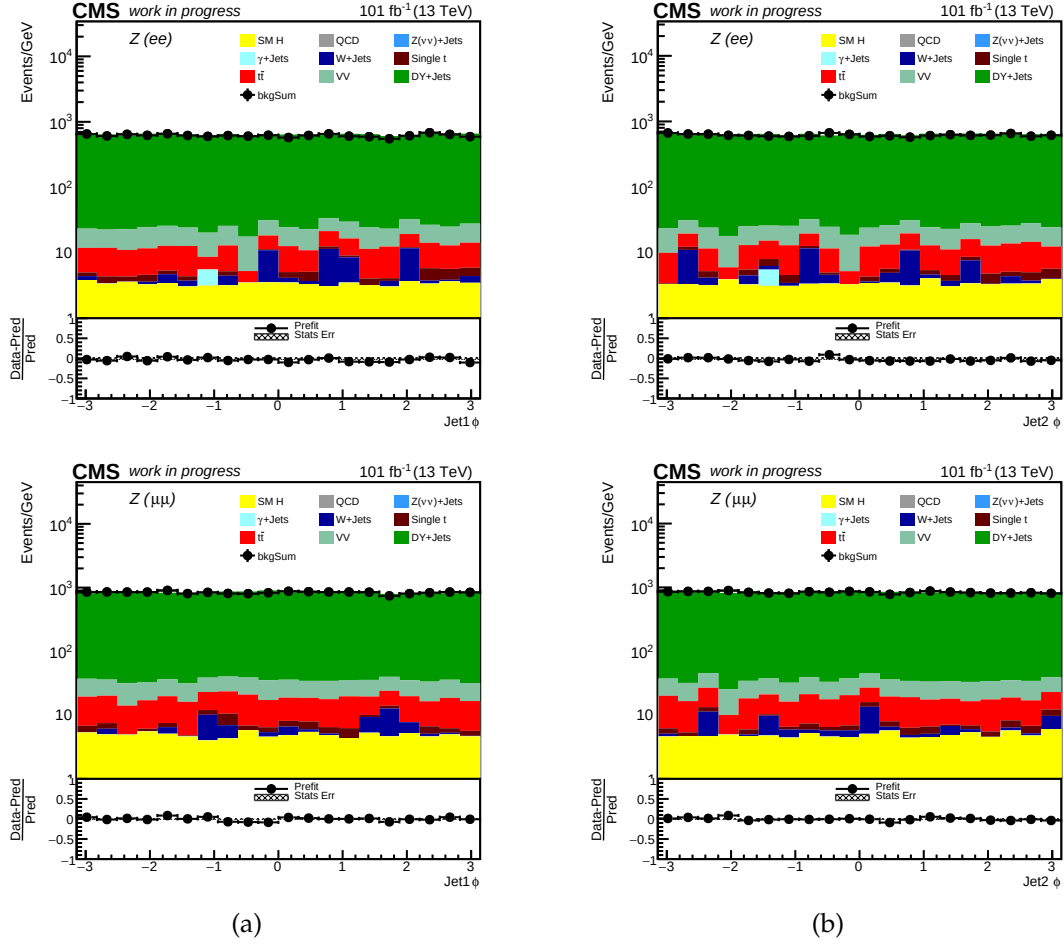


Figure 8.10: A comparison of distribution of events observed in data and expected background in electron and muon region of the Z control region for resolved category. Left plot is shown for jet1 ϕ distribution and right plot is shown for jet2 ϕ distribution. Top plots are for electron region and bottom plots are for muon region. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation. The shaded band corresponds to the statistical uncertainty in the background expectation.

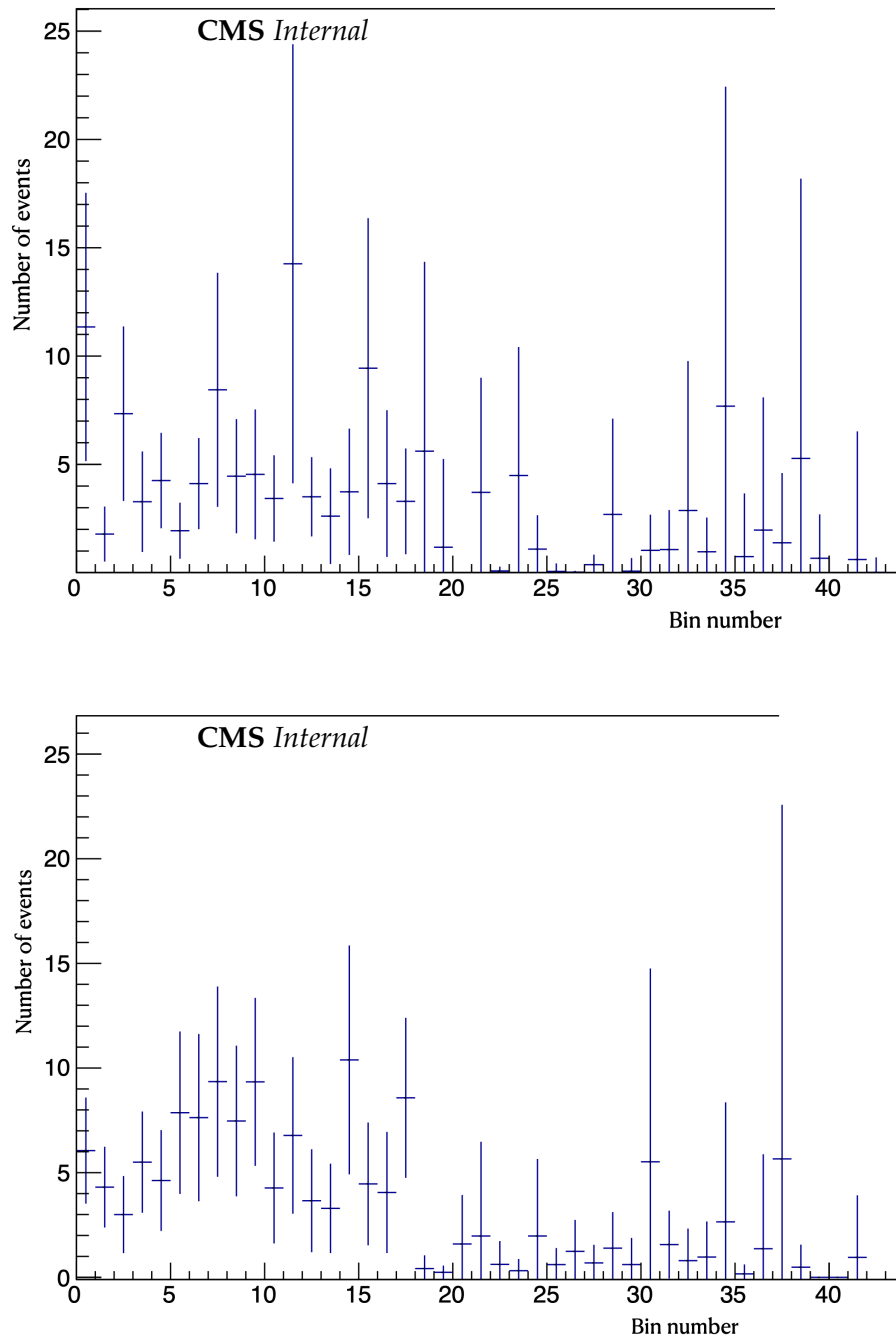


Figure 8.11: The estimated QCD background for the signal region is displayed in the plots. The top plot displays the estimation for 2017, while the bottom plot displays it for 2018.

8.5 Background Estimation

For the resolved analysis, the search is performed in four bins of E_T^{miss} . In each E_T^{miss} bin the m_{jj} distribution is used for signal extraction. The m_{jj} and E_T^{miss} binning are kept same for SR and CRs. The ranges of E_T^{miss} bins and number of bins are:

- first 18 mass bins are corresponds to E_T^{miss} range: 200-250 GeV
- next 11 mass bins are corresponds to E_T^{miss} range: 250-290 GeV
- next 7 mass bins are corresponds to E_T^{miss} range: 290-360 GeV
- next 4 mass bins are corresponds to E_T^{miss} range: 360-420 GeV
- last 3 mass bins are corresponds to E_T^{miss} range : > 420 GeV

Fit strategy is same as discussed in boosted analysis. The maximum binned likelihood fit is performed in signal region and control regions. The normalisation of the dominant backgrounds $Z(\nu\nu) + \text{jets}$ and $t\bar{t}$ in the signal region and in the control regions are simultaneously connected using rateParams. A common rateParam is used for electron and muon flavour of the control regions. The likelihood functions for control region and signal region are as following:

$$\mathcal{L}(n|R^s, \theta) = P(n_i|R^s B(\theta) + B'(\theta)) \times \Pi_{j \in \text{syst}} G(\theta_j, \Delta\theta_j) \quad (8.1)$$

$$\mathcal{L}(n|\mu, \theta) = \Pi_{i \in \text{bins}} P(n_i|\mu \cdot S_i(\theta) + \sum_s R^s B_i^s(\theta) + B'(\theta)) \times \Pi_{j \in \text{syst}} G(\theta_j, \Delta\theta_j) \quad (8.2)$$

where i represent bin number of histogram, n represent observed events, B represent dominant background, B' represent minor background and R represent the rateParam. Systematic uncertainty (j) is added as a gaussian distribution of nuisance parameter $NP(\theta)$. The rateParams are also different for each year dataset. Total four scale factors are used to control the normalisation of the major backgrounds. The rateParams estimated from the fit are given in the Table 8.2. All the systematic uncertainties discussed in the next section are added in the fit.

8.6 Systematic Uncertainty

As we know that systematic uncertainties can arise from a wide range of sources, such as detector calibrations, efficiency of particle identification, energy scale and resolution,

Control Region	Process	Normalisation Factor	Year
Top	$t\bar{t}$	1.08 ± 0.02	2017
	$t\bar{t}$	1.04 ± 0.02	2018
Z	Z+Jets	1.01 ± 0.05	2017
	Z+Jets	0.96 ± 0.04	2018

Table 8.2: Normalisation factor measured for $t\bar{t}$ and Z+Jets processes in Top and Z control region for 2017 and 2018.

luminosity determination, background modeling, and theoretical predictions. They are distinct from statistical uncertainties, which arise due to the limited number of events in the data sample.

Effect of systematic on shape is shown in appendix D. We have considered all the experimental and theoretical uncertainties in the fit. Most of the systematic uncertainties in resolved analysis are same as discussed in boosted analysis.

The list of systematic uncertainties along with average value has been shown in Table 8.3.

8.7 Results

Unblinded result of resolved analysis is not approved yet, therefore data is not shown in signal region, backgrounds are shown only, final results are interpreted in terms of upper limits with simulation only. Unrolled mass distribution is shown in Fig.8.12 where data is just sum of SM backgrounds. The upper limits on μ are calculated at 95% confidence level (CL) using a modified frequentist method [191, 195] computed with an asymptotic approximation [196].

8.7.1 Interpretations

In the resolved analysis, the same signal models are utilized for the interpretations. For the 2HDM+a model with $m_a = 150$ GeV, $\tan\beta = 1$, and $\sin\theta = 0.35$, the upper limits on the production cross-section at a 95% confidence level (CL) are presented as a function of m_A in Figure 8.13(a). The plot combines the data from 2017 and 2018. The black dotted line represents the expected limit, while the green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties, respectively. According to the expected limit, the mass range

Nuisance	Region	Uncertainty(%)	Type
CMSYEAR_PU	All	2-3	shape
CMSYEAR_eff_b	Signal & Top CR	4-5	shape
CMSYEAR_veto_tau	All	6	lnN
CMSYEAR_qcd_norm	All	50	lnN
lumi	All	2.5	lnN
JER	All	5	lnN
JECAbsolute	All	2	shape
JECAbsolute_YEAR	All	1	shape
JECBBEC1	All	1	shape
JECBBEC1_YEAR	All	0.5	shape
JECEC2	All	0.1	shape
JECEC2_YEAR	All	0.5	shape
JECFlavorQCD	All	2-3	shape
JECHF	All	0.1	shape
JECHF_YEAR	All	0.03	shape
JECRelativeBal	All	0.5	shape
JECRelativeSample_YEAR	All	0.5	shape
CMSYEAR_pdf	All	<1	shape
CMSYEAR_qcd_scale_dyjets	All	5	shape
CMSYEAR_qcd_scale_tt	All	<5	shape
CMSYEAR_qcd_scale_singlet	All	<5	shape
CMSYEAR_qcd_scale_smh	All	<5	shape
CMSYEAR_qcd_scale_qcd	All	<5	shape
CMSYEAR_qcd_scale_wjet	All	5	shape
CMSYEAR_qcd_scale_gjets	All	<5	shape
CMSYEAR_trig_met	Muon & Signal	0.5	shape
CMSYEAR_prefire	All	1	lnN
CMSYEAR_fake_b	All	4-5	lnN
CMSYEAR_EleTrig	Electron	1	shape
CMSYEAR_EleRECO	Electron	3	shape
CMSYEAR_EleID	Electron	0.5	shape
CMSYEAR_MuID	Muon	0.5	shape
CMSYEAR_MuISO	Muon	0.05	shape

Table 8.3: List of systematic Uncertainty. Some of the uncertainties denoted by "YAER" indicate that they are uncorrected between the 2017 and 2018 data periods.

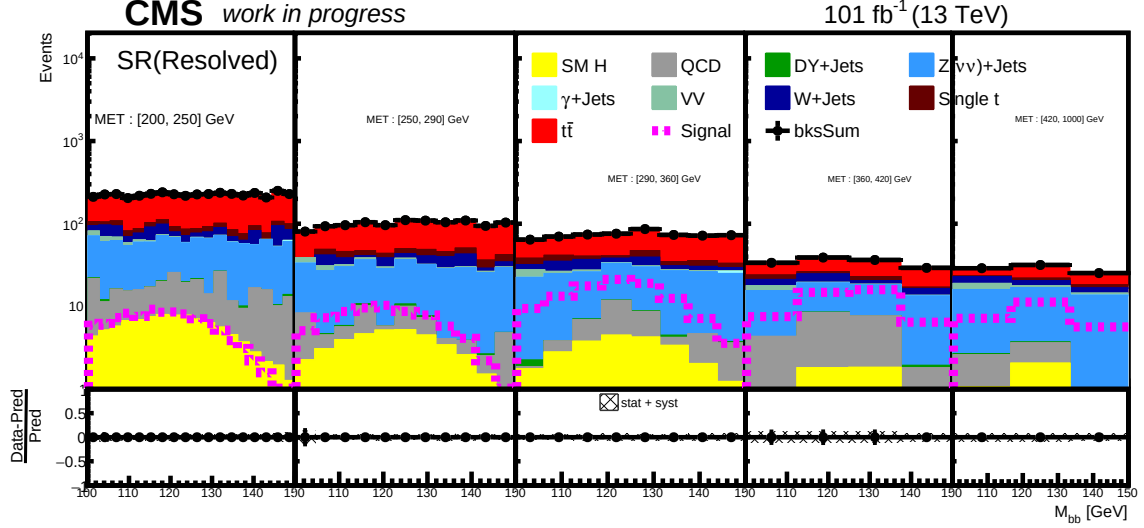
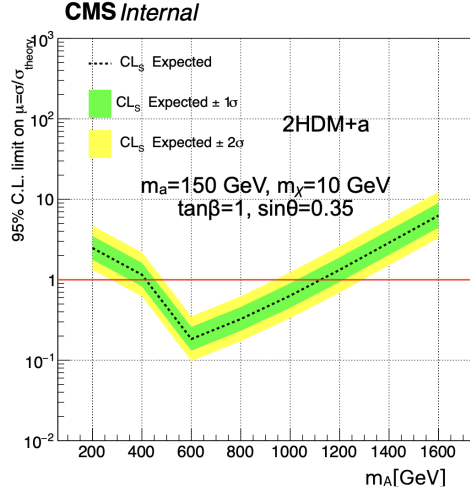


Figure 8.12: Mass distribution in five E_T^{miss} bins. The last MET bin includes all events with $E_T^{\text{miss}} > 420$ GeV. One signal hypothesis for 2HDM+a model is also shown overlaid where m_a is fixed 150 GeV, $\tan\beta = 1$, $\sin\theta = 0.35$. The lower panel shows a per-bin ratio of the data minus post-fit background yields and the background expectation.

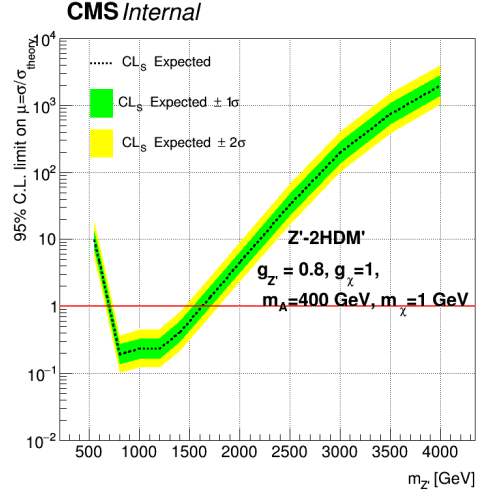
from 420 to 1100 GeV is excluded for this model.

Moving to Figure 8.13(b), it displays the expected limit as a function of the vector mediator Z' for the Z' -2HDM model, considering $m_A = 400$ GeV and $m_\chi = 1$ GeV. The expected limit in this model indicates that the mass range from 0.7 TeV to 1.6 TeV is excluded. Notably, the resolved analysis excludes a vector mediator mass of 0.7 TeV, which was not excluded in the boosted analysis.

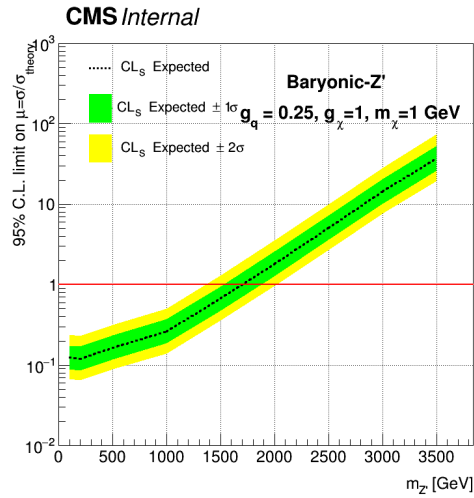
Lastly, Figure 8.13(c) showcases the expected limit as a function of the vector mediator Z' for the Baryonic model, considering $m_\chi = 1$ GeV. Here, vector mediator masses below 1.7 TeV are excluded according to the expected limit.



(a)



(b)



(c)

Figure 8.13: The 95% CL upper limit on signal strength for the resolved analysis as a function of: (a) heavier pseudoscalar mediator for 2HDM+a (b and c) vector mediator for Z'-2HDM and Baryonic-Z'.

COMBINED RESULTS OF BOOSTED AND RESOLVED ANALYSES

This analysis combines the resolved and boosted analyses to comprehensively search for dark matter produced in association with a Higgs boson decaying into a pair of bottom quarks. By combining the both analyses, we maximize the sensitivity of this search.

Since the resolved analysis is still blinded, we combined the boosted and resolved analyses using simulation data only. We present the expected upper limit on the production cross-section of Dark Matter.

The combination was carried out at the data card level, where we included signal and control regions from both analyses and performed a simultaneous fit. The resolved analysis is more sensitive to the low-mass region, while the boosted analysis is more sensitive to the high-mass region. Therefore, by combining the two, we obtained greater sensitivity over a large phase space of signal models.

We begin by discussing the impact and pull of nuisance parameters, which are crucial for accurately quantifying uncertainties in our analysis. We then proceed to interpret our results in the context of three theoretical models: 2HDM+a, Z' -2HDM, and Baryonic- Z' . Specifically, we present the expected limits on the production cross section of dark matter particles in each of these models.

9.1 Systematic Uncertainty

The combination analysis used the same systematic uncertainties as those used in the boosted and resolved analyses. Some of the uncertainties are correlated, while others are uncorrelated between the two analyses.

The following uncertainties are uncorrelated:

- The MET trigger

- QCD renormalisation and factorisation
- Parton distribution function (PDF)
- b-tagging
- Electron reconstruction and identification
- Muon reconstruction and identification
- JEC source (JECAbsolute_YEAR, JECBBEC1_YEAR, JECEC2_YEAR, JECHF_YEAR, JECRelativeSample_YEAR)

The following uncertainties are correlated:

- Luminosity
- JER
- JEC source (JECAbsolute, JECBBEC1, JECEC2, JECFlavorQCD, JECHF, JECRelative-Bal)

9.2 Asimov fit : Impacts and pulls

The impact of each source of uncertainty is studied. Fig. 9.1 shows the impact of nuisance parameters. Here, $\hat{\tau}$ denotes the best likelihood fit value of signal strength and error. The middle column represents the shift in the signal strength with respect to the best fit. It shows the difference between the best-fit nuisance and the pre-fit nuisance. The error bar denotes how much nuisance is constrained during the fit. θ_0 is the pre-fit nuisance parameter (NP), $\hat{\theta}$ is the best-fit nuisance, and $\Delta\theta$ is the uncertainty of NP. The last column shows the impact of each NP on $\hat{\tau}$ with its $\pm\sigma$ deviation, while other NPs are fixed to best-fit values. As the analysis is blinded until it is pre-approved, hence, fitting is performed using Asimov data.

Among the nuisance parameters, the most constrained one is mu_scale_dyjets, which corresponds to the QCD factorization and renormalization scale. This nuisance has a large uncertainty variation for DY + jets simulated samples. That's why it is constrained. In DY + jets samples, there was an issue in generating these samples. A parameter was mistakenly set at the generator level, causing the scale weights to be altered by a certain factor. As a result, the uncertainty for the QCD scale became significant. Due to large uncertainty, it has large impact on the parameter interest.

All other uncertainties look fine and do not show significant constrained or pull on the signal strength. A separate plot for pulls on each nuisance parameter value is shown in Fig 9.2.

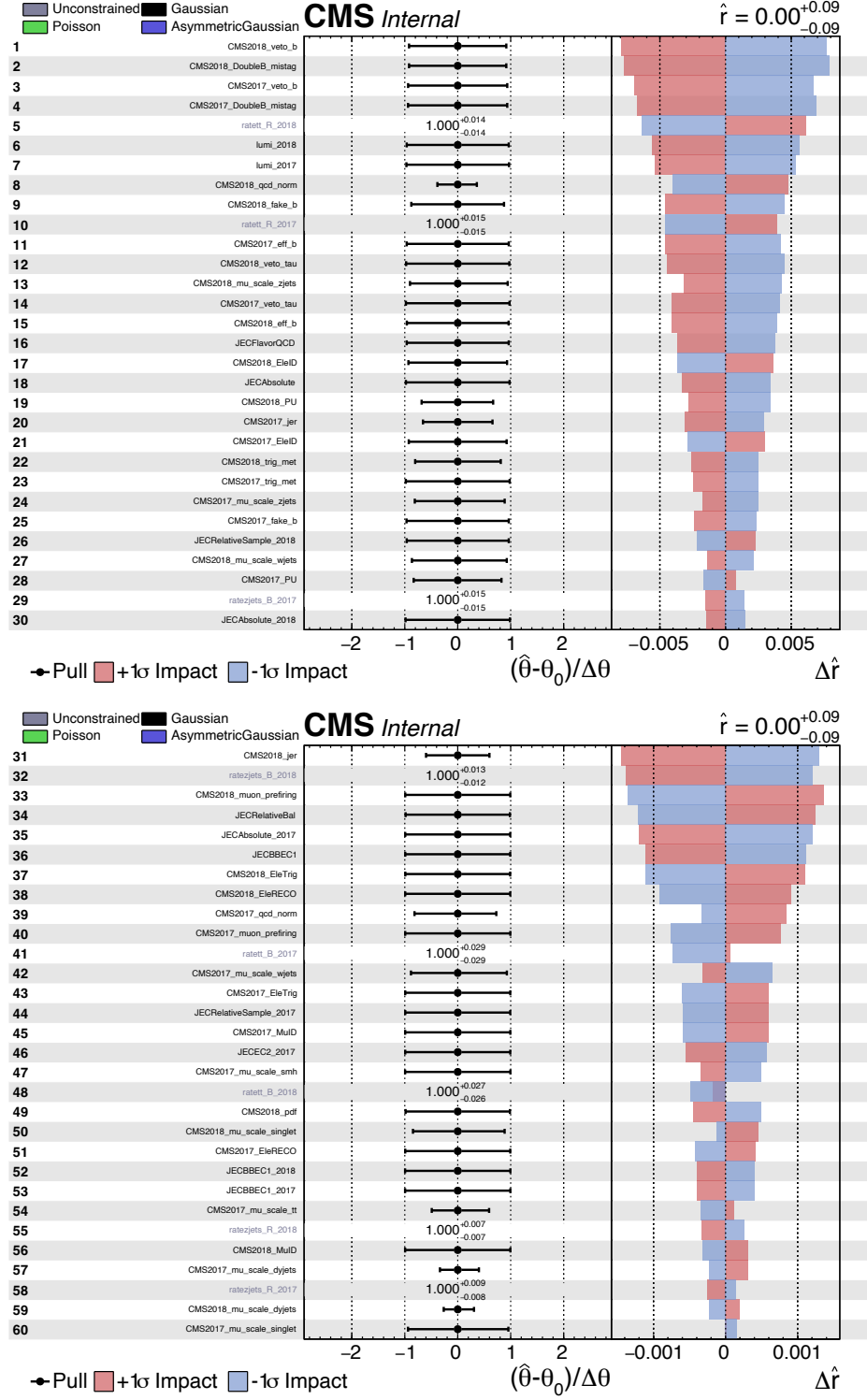


Figure 9.1: Impact of nuisances for combination of resolved and boosted with combined 2017 and 2018 data.

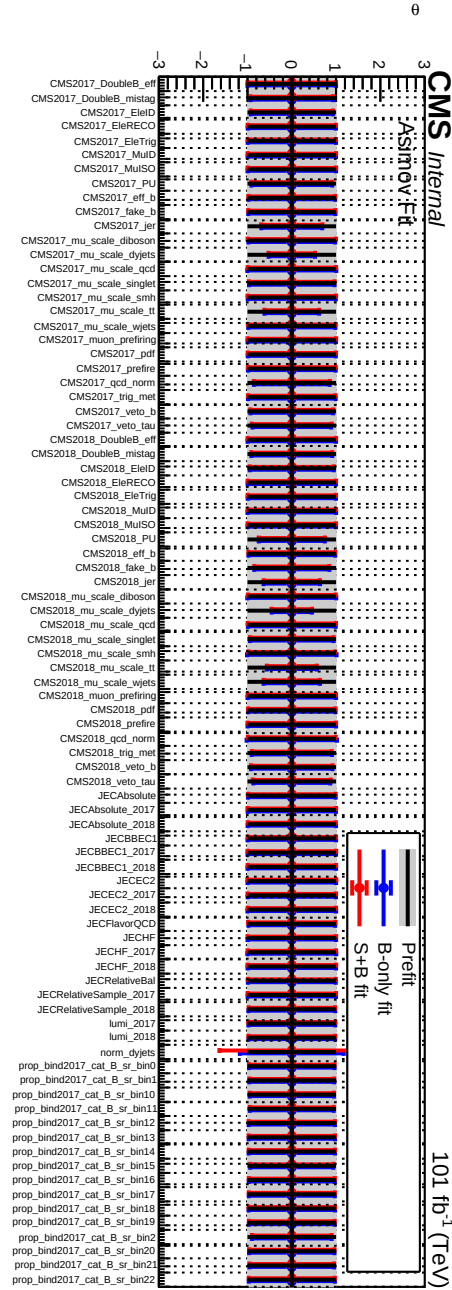


Figure 9.2: Pulls for Asimov fit.

9.3 Interpretations

The comparison of the limit reach between the resolved and boosted analyses is illustrated in Figure 9.3. It can be observed that the resolved analysis exhibits sensitivity in the low-mass region, while the boosted analysis is more sensitive in the high-mass region. By combining the two analyses, a larger phase space is covered, resulting in enhanced sensitivity. The interpretation of the results is based on the upper limit on the signal strength μ .

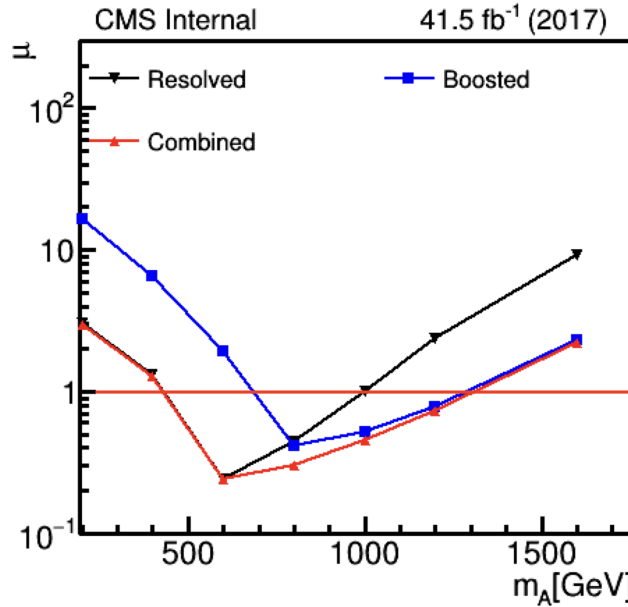


Figure 9.3: The comparison of expected upper limits at 95% CL on the production cross-section for resolved and boosted analysis.

For the Baryonic- Z' model, the combined expected limit is presented in Figure 9.4(a), showing the exclusion region in the $m_{Z'}$ and m_χ plane. The black line represents the expected limit, with the area below it indicating the excluded region. In this model, vector boson masses below 2.3 TeV are excluded (expected), while the coupling strengths g_z , $\tan\beta$, and dark matter are fixed at 0.8, 1, and 1, respectively.

In the Z' -2HDM model, the expected upper limit is shown in Figure 9.4(b) in the $m_{Z'}$ and m_A plane. At a low pseudoscalar mass region ($m_A = 400$ GeV), vector boson masses

ranging from 700 GeV to 2.5 TeV are excluded. The coupling strengths in this model are fixed with $g_\chi = 1$ (mediator-DM coupling) and $g_q = 0.25$ (mediator-quark coupling).

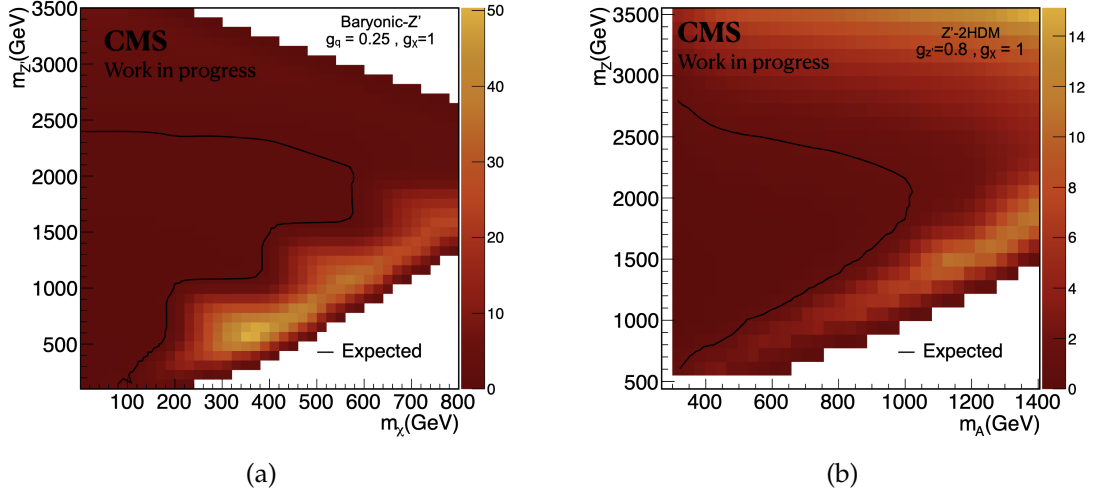


Figure 9.4: Exclusion limits at 95% CL on m_Z - m_χ plane in context of Baryonic- Z' model (a). The coupling to DM candidates is set to $g_\chi = 1$, the coupling to quarks is set to $g_q = 0.25$. The limit on m_Z - m_A plane in right plot is in context of Z' -2HDM(b). The mediator Z' coupling strength is fixed at 0.8, and $\tan\beta$ is fixed at 1.0. Color code represents the limit on the signal strength modifier.

For the 2HDM+a model, the results are presented in three scans: m_A , $\tan\beta$ and $\sin\theta$. In the m_A scan, pseudoscalar masses (m_A) from 400 to 1500 GeV are excluded, as shown in Figure 9.5(a). Similarly, in the $\tan\beta$ scan, $\tan\beta$ values below 3 are excluded (with $\sin\theta = 0.35$, $m_a = 150$ GeV, $m_A = 600$ GeV), as depicted in Figure 9.5(b). In the $\sin\theta$ scan, $\sin\theta$ values above 0.15 are excluded (with $\tan\beta = 1$, $m_a = 200$ GeV, $m_A = 600$ GeV), as shown in Figure 9.5(c).

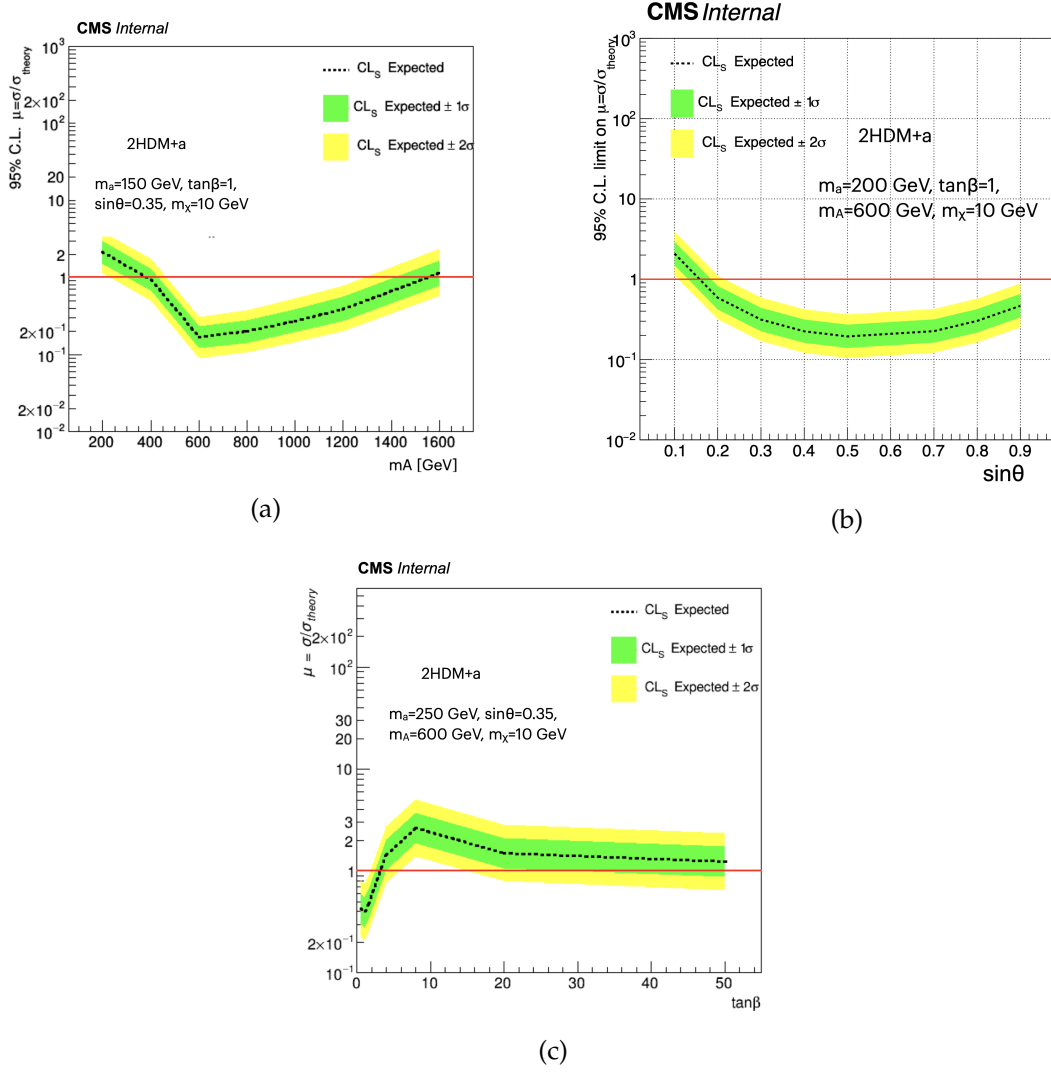


Figure 9.5: Exclusion limits at 95% CL on dark matter production as a function of heavier pseudoscalar mediator m_A (Fig. a), $\sin\theta$ (Fig. b) and $\tan\beta$ (Fig. c).

PROJECTION FOR RUN-3 AND HL-LHC

According to the plan for the LHC and its upgrade called HL-LHC (High Luminosity LHC), there are different operation periods (as shown in Fig.10.1). The current period is called Run 3, which started after a long shutdown called "LS2". During Run 3, the LHC is colliding protons with a center of mass energy of 13 TeV, and it is expected to collect an integrated luminosity of 250 fb^{-1} . After Run 3, there will be another long shutdown called "LS3", during which the CMS and ATLAS detectors will be upgraded, along with improvements to the trigger system to enhance overall performance.

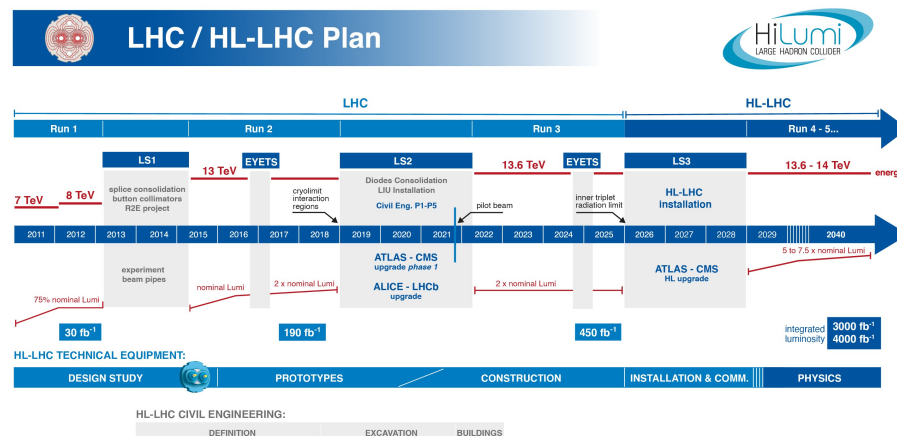


Figure 10.1: LHC future plan for HL-LHC [197]

Once the LS3 is completed, the next operation period will begin with an expected integrated luminosity of 3000 fb^{-1} at a center of mass energy of 14 TeV. This phase is known as the HL-LHC.

In this section, the analysis focuses on studying the sensitivity of the results for the Run 3 and HL-LHC periods. The obtained results are presented after scaling the integrated

luminosity to match Run 3 and HL-LHC. The systematic uncertainties considered are the same as those in 2018. However, the change in cross-section due to the change in center of mass energy from 13 to 13.5 TeV or 13 to 14 TeV has not been taken into account. The results are obtained using a binned maximum likelihood fit on the mass distribution, as described in Section 7.5.2.

For the specific case of 2HDM+a, Figure 10.2(a) displays the 95% confidence level upper limit on the signal strength as a function of the parameter m_A for the Run 2, Run 3, and HL-LHC data periods. The figure shows that the range of m_A values from 400 GeV to 1600 GeV is sensitive during Run 3, while for the HL-LHC, the full range of m_A values starting from $m_A \geq 200$ GeV is sensitive.

Figure 10.2(b) and (c) illustrate the sensitivity for scans of the parameters $\sin\theta$ and $\tan\beta$. From the $\sin\theta$ scan, it is observed that $\sin\theta = 0.1$ is not sensitive during Run 3 but becomes sensitive in the HL-LHC period. Regarding the $\tan\beta$ scan, $\tan\beta \leq 1.5$ and $\tan\beta = 50$ are sensitive in Run 3, while the full range of $\tan\beta$ values ($\tan\beta \leq 50$) is sensitive for the HL-LHC period.

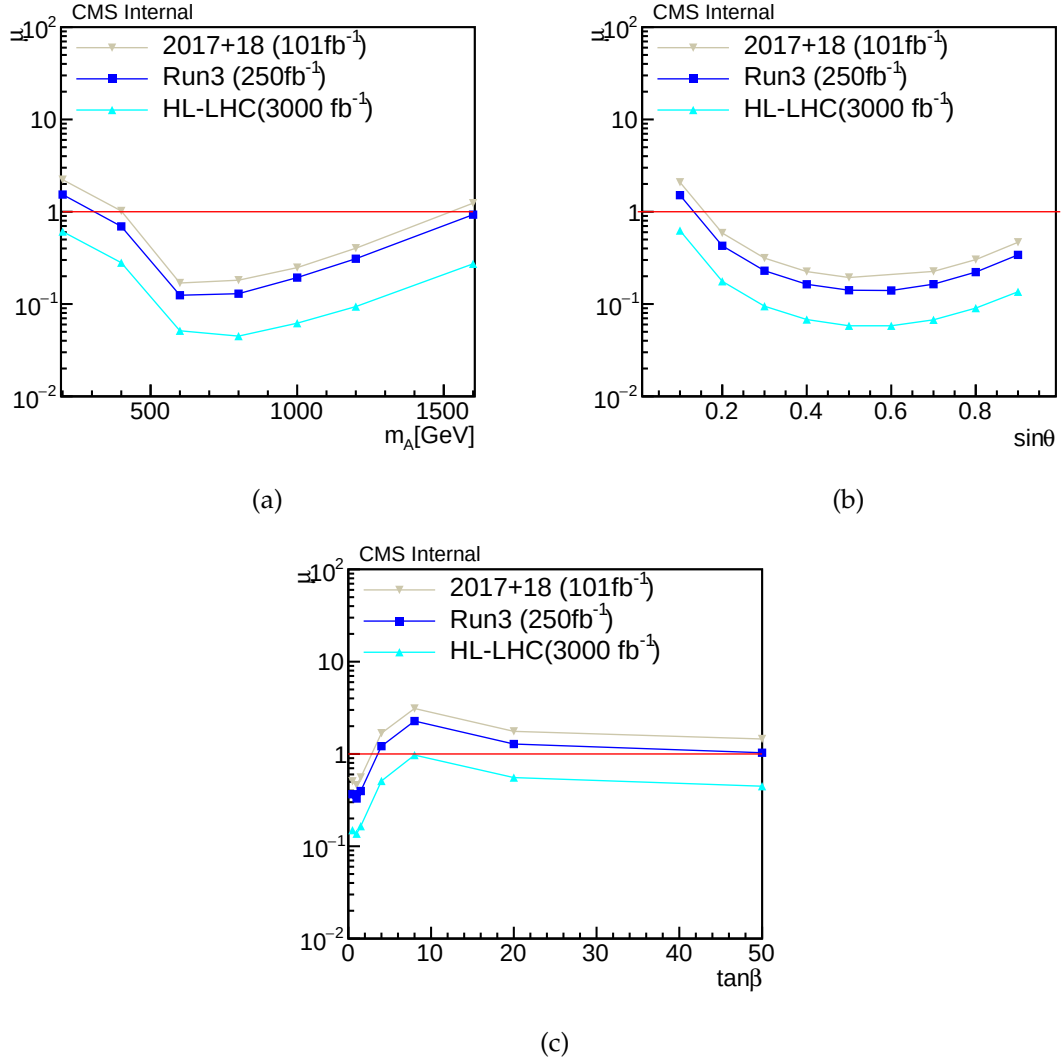


Figure 10.2: The expected upper limits at 95% CL on the DM production cross-section for Run3 and HL-LHC. (a) shows sensitivity for m_A and while (b) and (c) present sensitivity for $\sin\theta$ and $\tan\beta$

SUMMARY AND OUTLOOK

11.1 Summary

The existence of Dark Matter comes from cosmological observations[18], it turns out that 25% of the universe is made up of DM, the exact nature of DM particles is still unknown. All we know is that it is electrically neutral, participates only in gravitational interactions, and does not interact with ordinary baryonic matter. Due to these properties, the primary candidate for DM is the weakly interacting massive particle (WIMP)[52]

In this thesis, a search for dark matter produced in association with a Higgs boson decaying to a pair of b quarks has been performed. The analysis uses proton-proton collision data collected in 2017 and 2018 data taking period by the CMS experiment at $\sqrt{s}=13$ TeV. The analysis is performed in two categories: boosted and resolved categories. Both categories target different phase space of mass region. Resolved category aims for the low mass region where Higgs boson is low boosted or medium boosted while boosted category targets the high mediator mass region and highly boosted Higgs boson. For the first time the analysis is interpreted in 2HDM+a model in the resolved category. Using only 2016 data, boosted analysis was done and prior to that resolved analysis was also done. Combination of both categories improves the final sensitivity and able to exclude large phase of the signal models. There are five decay modes of Higgs boson: $H \rightarrow b\bar{b}$, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$, where $b\bar{b}$ is more sensitivity than other decay modes because it has highest branching ratio. The analysis focuses on three simplified models for interpretation of the results, namely, Z' -2HDM, baryonic- Z' and 2HDM+a models.

There are some standard model processes which can pose as signal like events. The major background are $t\bar{t}$ and irreducible $Z(\nu\nu) + \text{jets}$ background. In order to model the dominant background, control regions are defined (Top and Z control regions). These

two major backgrounds are estimated from the data and other minor backgrounds are directly taken from the simulation in signal region. In order to match simulation with data several correction factors are applied to the simulation. To extract the signal maximum profile likelihood fit is performed.

Final results are interpreted in terms of upper limits on the signal strength modifier $\mu = \sigma_{obs}/\sigma_{th}$, where σ_{th} is the predicted production cross-section of DM candidates in association with a Higgs boson, and σ_{obs} is observed cross-section. The upper limits on μ are calculated at 95% confidence level (CL) using a modified frequentist method [191, 195] computed with an asymptotic approximation [196]. For 2HDM+a, results are presented with three scans, m_A , $\tan\beta$, $\sin\theta$. From m_A scan plot as shown in Fig. 9.5(a), the mass from 400 to 1500 GeV is excluded. Fig 9.5(b) shows that the phase space below 3 is excluded and from $\sin\theta$ scan 9.5(c), the phase space for $\sin\theta$ above 1.5 is excluded. The results include combination of boosted and resolved categories, and combination of 2017 and 2018 data.

For Z' -2HDM, the CL95% upper limits on the production cross-section as a function of $m_{Z'}$ and m_A are shown in the Fig 9.4(right). The mass from 700 GeV to 2.5 TeV is excluded for $m_A=400$ GeV. For Baryonic- Z' , 2D CL95% upper limits on the production cross-section in m_χ - m'_Z plane are shown in Fig 9.4(left). The area under the curve represented by black line is excluded.

Additionally, a projection study examines the sensitivity of the analysis for future periods, namely Run 3 and HL-LHC, focusing on the 2HDM+a model only. This analysis performs the upper limits on the signal strength with respect to parameters such as m_A , $\sin\theta$, and $\tan\beta$. For the HL-LHC period, the phase space for all three parameters is sensitive. However, few points within the parameter ranges are not sensitive in the Run 3 period. These results are obtained through a maximum likelihood fit performed on the mass distribution.

11.2 Outlook

In the future, various refinements of monohbb analysis are possible. The following points can improve the sensitivity of the analysis:

- Various analysis selection and object reconstruction improvements can enhance the sensitivity of the analysis in the future.

- Low E_T^{miss} based triggers can help to catch low mediator mass and improve resolved category sensitivity.
- E_T^{miss} triggers are based on missing transverse energy and jet momentum sum, if jet is replaced by bjet then sensitivity will be improved.
- New b-tagging algorithm DeepJet [198] has better performance, it can improve sensitivity in resolved category.
- Resolved and boosted categories can benefit from the application of machine learning techniques, although the presented cut-based analysis seems to be well optimised for the given background modelling but still machine learning can improve sensitivity.

At the moment, the sensitivity of many analyses, e.g. monohbb search, is still statistically limited, indicating boosts in exclusion power to be expected with higher integrated luminosity. In the upcoming Run 3, the CMS detector will continue to collect pp collision data with an increased center-of-mass energy of 13.6 TeV and a higher collision rate, allowing for accesses to a large variety of exotic decay channels in search of DM.

APPENDIX 1

A.1 HEM15/16 Issue

During 2018 data taking, the power supply of two HCAL modules (HEM15 sector and HEM16 sector) were not functioning in middle of data taking (runs ≥ 319077 , i.e. last certified run of 2018B era, and all runs of 2018C+2018D) Due to this, HCAL deposits was not recorded for the region (η -3.0 to -1.3 and ϕ -1.57 to -0.87). Hence, reconstructed jets in this region will be affected and mis-measurement of jet energy will affect missing transverse energy.

For example, in electron region of resolved category, a bump of data observed in electron ϕ and E_T^{miss} ϕ distributions is presented in this section. Upper two Figs A.1 show that electron at negative η and ϕ is coming from HEM15/16. Since there is no HCAL energy deposit in HEM15/16 region, charge hadron can pass H/E and EM + Had isolation cut in HEM issue region. So there are more chances that affected jets are reconstructed as offline electron and these fake electrons pass analysis selection.

To deal with HEM 15/16 issue in all regions, we did many checks and finally we applied HEM veto based on jet η and ϕ . We removed event if any uncleaned jet is in the problematic $\eta - \phi$ region. Bottom two figures A.1 show that the after applying HEM veto based on jet, the problem is solved.

Finally, this analysis is performed after removing the event if any jet is in the region of $\eta < -1.3$ and $-1.57 > \phi > -0.87$.

This method effectively removes the problematic region but cuts $\approx 4\%$ into signal efficiency.

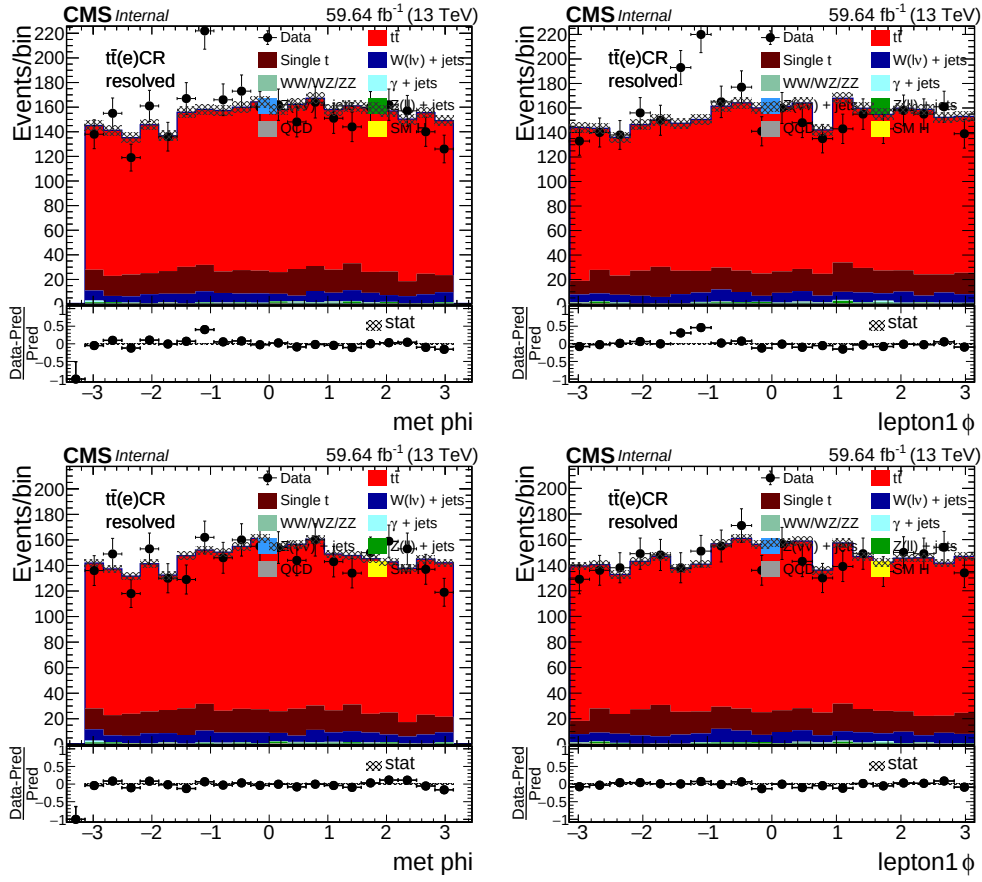


Figure A.1: Electron η and ϕ distribution in single electron region of resolved category. In top two plots HEM veto is not applied. In bottom two plots jet based HEM veto is applied

APPENDIX 2

B.1 Other contribution at CMS

I have performed the major part of the analysis presented in this thesis. I am the contact person for this analysis. I have also contributed to various service tasks in the physics object group (POG) and physics analysis group (PAG). Moreover, I have also worked on one more analysis related to Dark Matter searches. The following are the contributions:

- **Service tasks:**
 - Monte-Carlo generation contact for b-tagging vertex group (BTV): I worked on the generation of samples that are used for b-tagging scale factor measurement, mistag rate and other studies.
 - Calo based Jet/ E_T^{miss} for Run3: I performed pf and calo jet response and resolution studies. I also did pfMET and Calo E_T^{miss} response and resolution studies.
 - HBHENoise filter study at HLT for Run3: Removed HBHENoise filter in Run 3 because it was intended to reject HPD noise. With the switch to SiPM in Run3, this filter will not make sense to exist anymore.
 - Depth study at HLT: - L1 Trigger Expert Analyst (TEA): Worked as L1 TEA and performed the following tasks:
 - * CMS software release validation
 - * Select good runs to be used for physics analysis.
- **Search for dark matter produced in association with b-jets at CMS using full Run2 data:** I contributed in various tasks in this analysis. Details of work has been explained in the next appendix [C.1](#).

APPENDIX 3

C.1 Generator level study of 2HDM+a for the analysis "Search for dark matter produced in association with b-jets"

This analysis focuses on events with single or double b jets in the final state. The b-jets can arise from radiation or associated production processes. The analysis is divided into two categories, namely SR1 (with one b jet) and SR2 (with two b jets). Both categories allow for a maximum of one additional jet. To reduce background contributions, a lepton and photon veto is applied. Furthermore, events in both categories are required to have missing transverse energy (E_T^{miss}) greater than 250 GeV. Jet selection criteria include a minimum transverse momentum (p_T) of 30 GeV and a pseudorapidity ($|\eta|$) less than 2.4 for 2016 data and 2.5 for 2017 and 2018 data. The leading jet is required to have a p_T greater than 100 GeV. The dominant backgrounds in this analysis arise from $Z(\nu\nu) + \text{jets}$, $t\bar{t}$, and $W + \text{jets}$ processes. Estimation of these two backgrounds is performed using control regions.

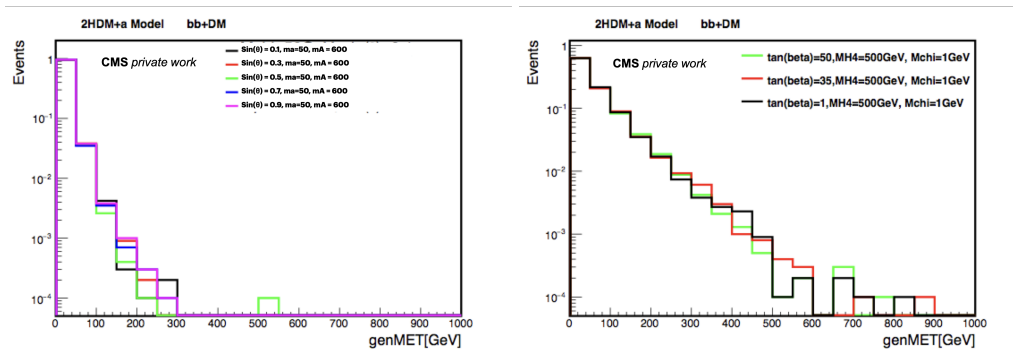


Figure C.1: Generator level plots for $\sin\theta$ (left) and $\tan\beta$ (right) scans.

In this analysis, a generator-level study was conducted to investigate the variation in the shape of missing transverse energy (E_T^{miss}) for different free parameters. The signal model used in this study is described in detail in Section 3.5.1. From this study, it was observed that the E_T^{miss} shape is dependent on parameters such as m_A , m_a , $\sin\theta$, and $\tan\beta$. Figure C.1 displays the generator-level E_T^{miss} shape for $\sin\theta$ and $\tan\beta$, while Figure C.2 shows the generator-level E_T^{miss} shape for the m_a scan. Similar variations in shape were also observed for the m_A scan.

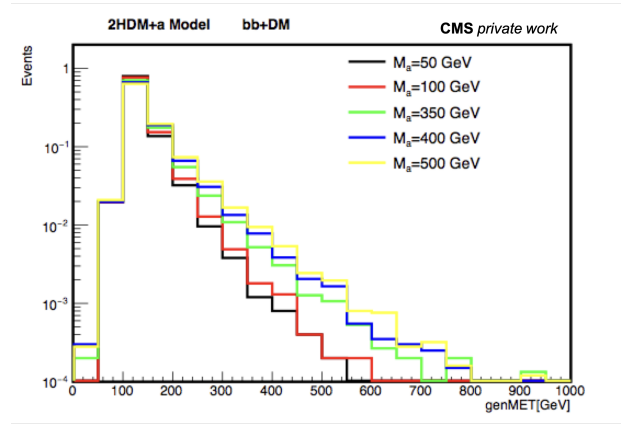


Figure C.2: Generator level plots for m_a scan.

C.2 E_T^{miss} trigger scale factor measurement

This analysis also uses same E_T^{miss} triggers as shown in Tab 6.6. I measured the E_T^{miss} trigger efficiency for this analysis. The trigger efficiency was evaluated separately for single muon events and double muon events. For single muon events, exact one tight muon is required passing muon trigger (HLT_IsoMu27 for 2017, and HLT_IsoMu24 for 2016 and 2018) while for double muon events, exact two muons are required and only of them should pass muon tight ID.

Fig C.3 shows the trigger efficiency for single muon and double muon events. Left plot is for single muon and right plot is for double muon events. The scale factor is calculated by taking ratio of trigger efficiency in Data and trigger efficiency in Monte-Carlo as shown in Fig C.4. The systematic uncertainty is calculated by taking difference in single muon events scale-factor and double muon events scale-factor.

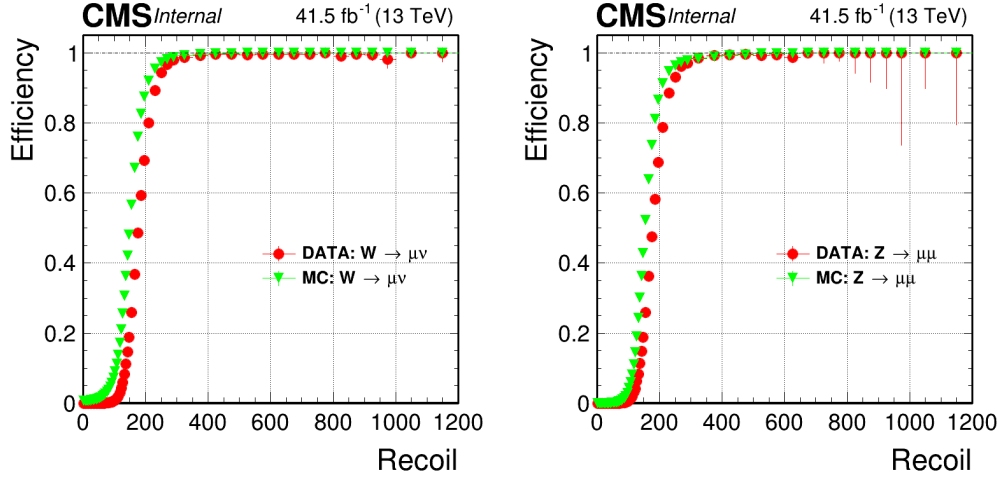


Figure C.3: Trigger efficiency for Monte-Carlo (left) and Data (right).

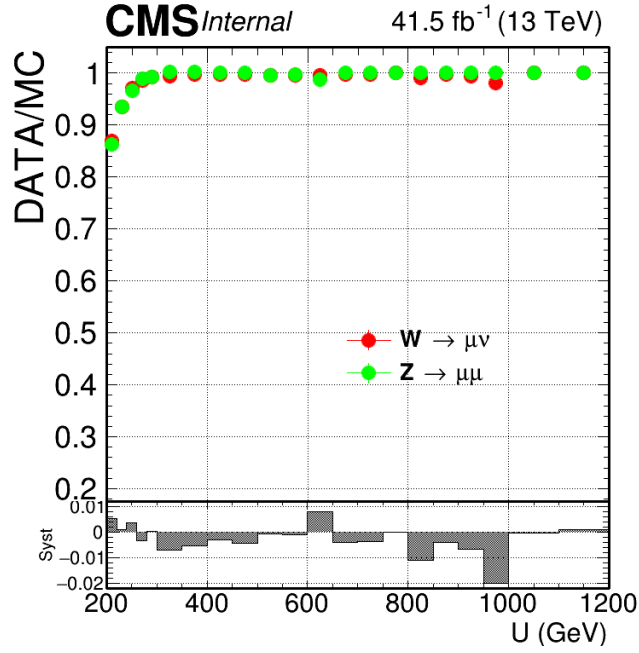


Figure C.4: Trigger scale-factor used to correct the simulation.

C.3 NLO QCD k-factor measurement for $W + \text{jets}$ LO samples

The $Z(\nu\nu) + \text{jets}$ and $W + \text{jets}$ processes play important role in this analysis. They form the key backgrounds and control regions of the analysis. The Monte-Carlo samples for

these electroweak processes produced at LO. The prediction for these processes gets significantly improved when the NLO corrections are applied.

To obtain QCD NLO corrections, I compared p_T distribution of vector boson(W/Z) at LO and NLO and then NLO/LO ratio was calculated. Figure C.5 shows the p_T distribution of vector boson at LO and NLO, bottom pad shows the ratio of NLO and LO. Vector boson (W/Z) is obtained using generator level particles and their PDG IDs.

However, later $Z(\nu\nu) + \text{jets}$ and $W + \text{jets}$ processes samples are replaced with NLO samples, therefore these corrections are not used in NLO samples.

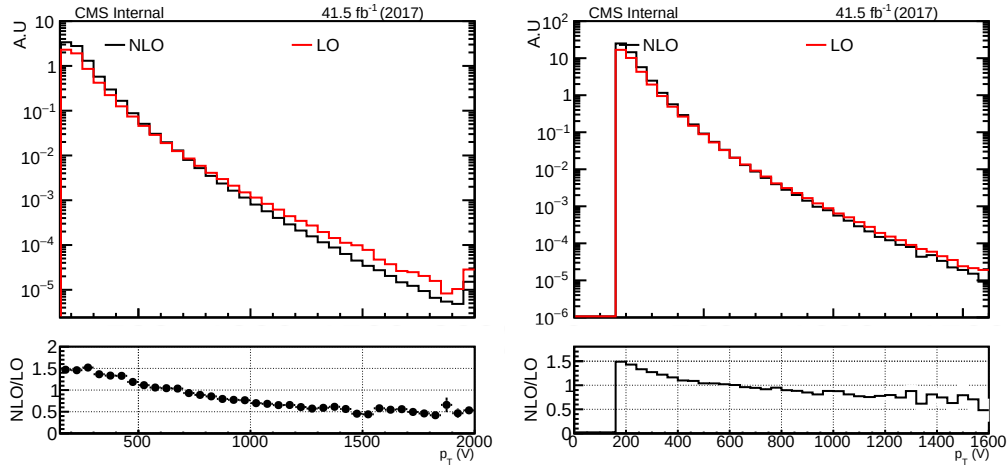


Figure C.5: Generator level vector boson p_T distribution for DY + jets (left) and W + jets (right) processes at LO and NLO. Bottom pad shows ratio of NLO and LO.

C.4 Optimizing b-tagging working point

This analysis requires single or double b jets in the final state. To identify b-jets deepCSV algorithm [182] has been used. BTV POG has provided three working points as mentioned in Sec 6.3.6. In order to optimize working point, I calculated significance for each working point. It is defined as:

$$\text{significance} = \frac{\text{signal efficiency}}{\sqrt{\text{background yield}}} \quad (\text{C.1})$$

Fig C.6 shows significance for loose and medium working points as a function of mediator mass. Figure shows that medium working point performs better than loose working point,

so medium working point has been used for b-tagging. Optimization is done for both categories: signal region 1 (SR1) and signal region 2 (SR2). Medium working point shows better performance in both categories.

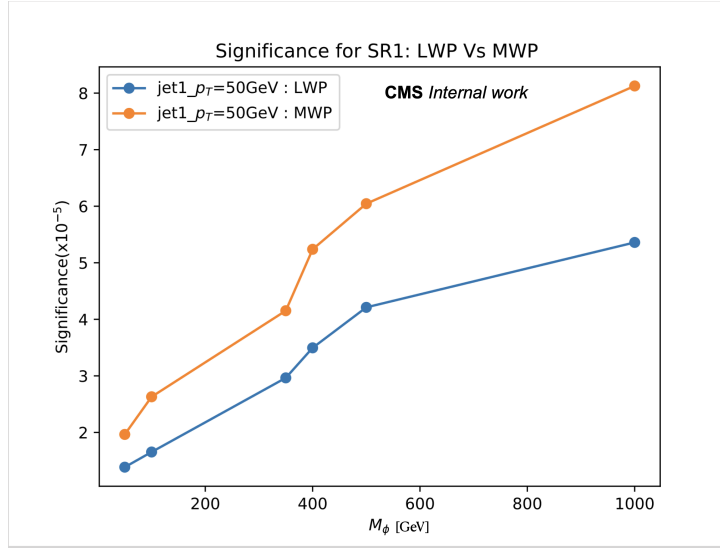


Figure C.6: b-tagging working point optimization.

APPENDIX 4

The following plots display the systematic uncertainties used in boosted and resolved analyses for the simultaneous fit. Each plot shows the variation of a specific systematic uncertainty with respect to the nominal value, both in the upward and downward directions. These uncertainties are incorporated into the fit to account for the systematic effects on the measured observables.

The figures in Appendix A are organized according to the different control and signal regions. Specifically, Figures [D.1](#) to [D.7](#) correspond to the signal region, Figures [D.8](#) to [D.17](#) correspond to the Top(e) control region, Figures [D.18](#) to [D.26](#) correspond to the Top(μ) control region, Figures [D.27](#) to [D.35](#) correspond to the Z(ee) control region, and Figures [D.36](#) to [D.44](#) correspond to the Z($\mu\mu$) control region.

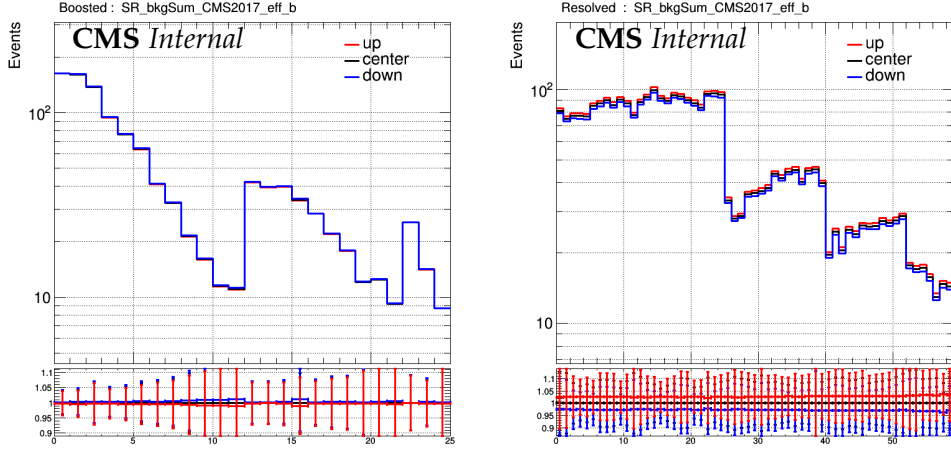


Figure D.1: The impact of b-tagging systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.

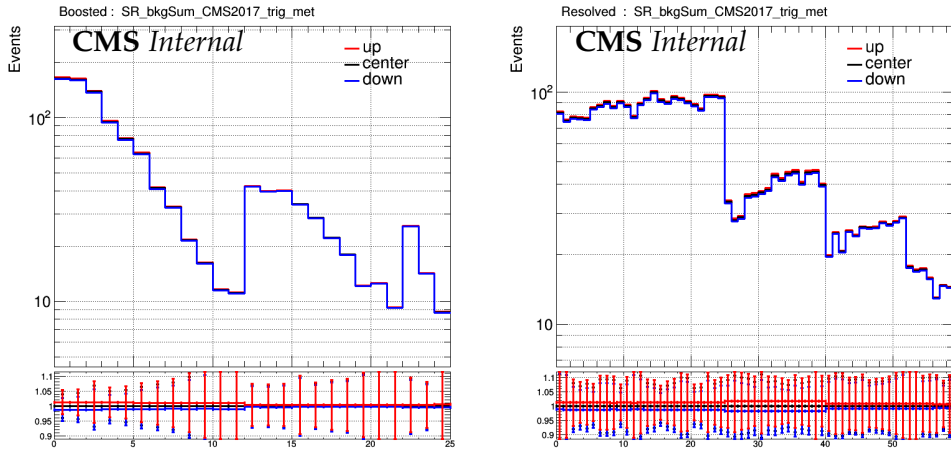


Figure D.2: The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers uncertainty is shifted up and down, respectively.

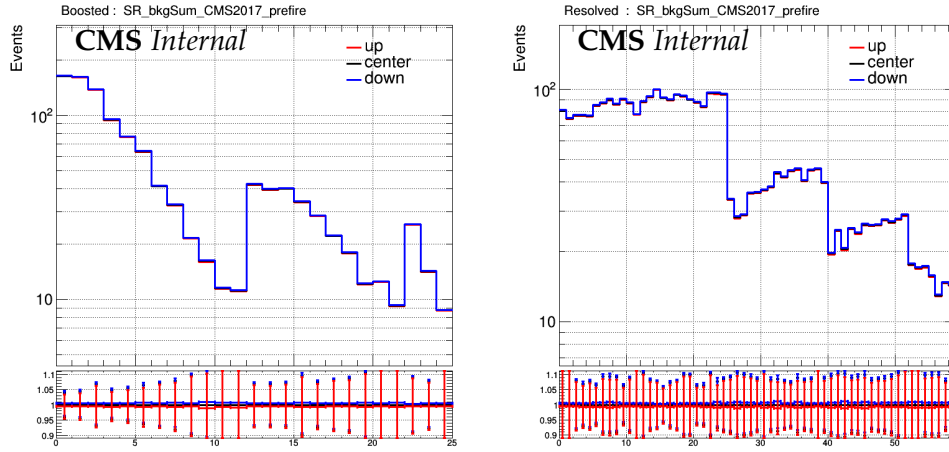


Figure D.3: The impact of L1-prefiring systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the L1-prefiring uncertainty is shifted up and down, respectively

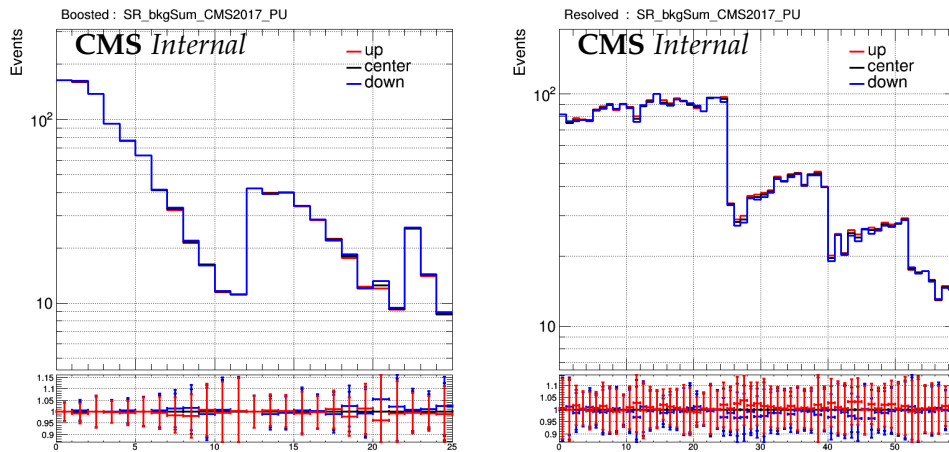


Figure D.4: The impact of pile-up reweighting systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting uncertainty is shifted up and down, respectively

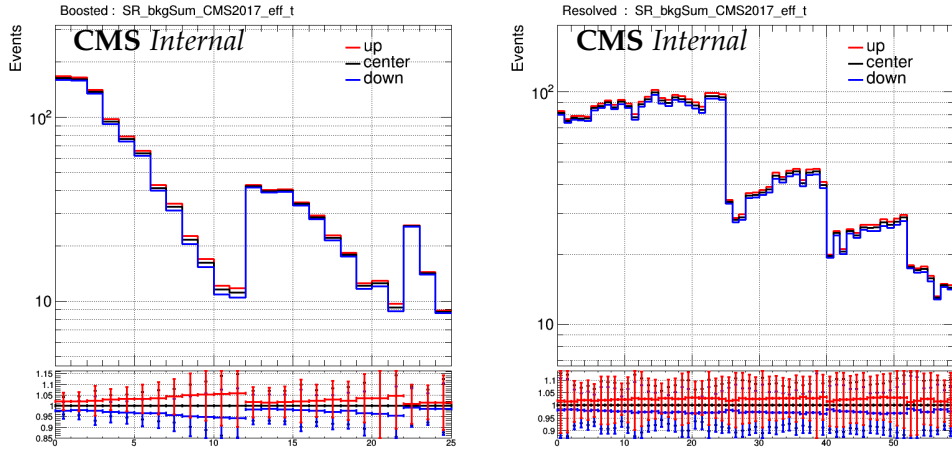


Figure D.5: The impact of top reweighting systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the top reweighting uncertainty is shifted up and down, respectively

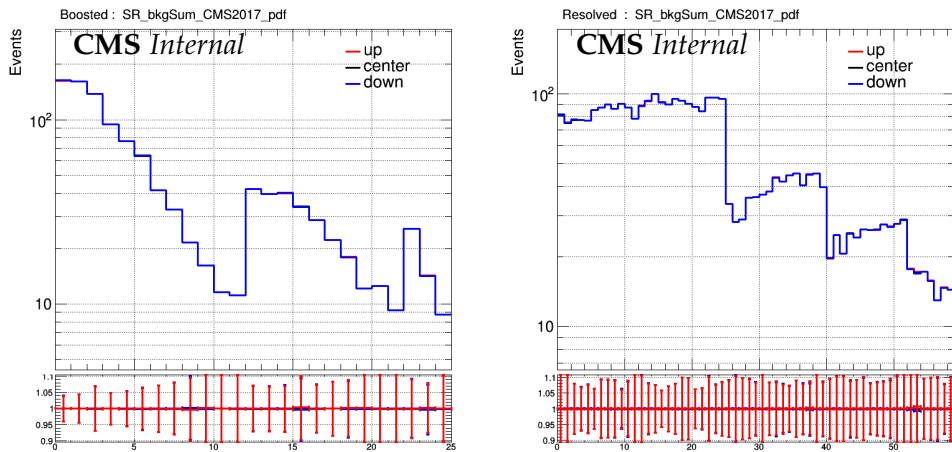


Figure D.6: The impact of pdf systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf uncertainty is shifted up and down, respectively

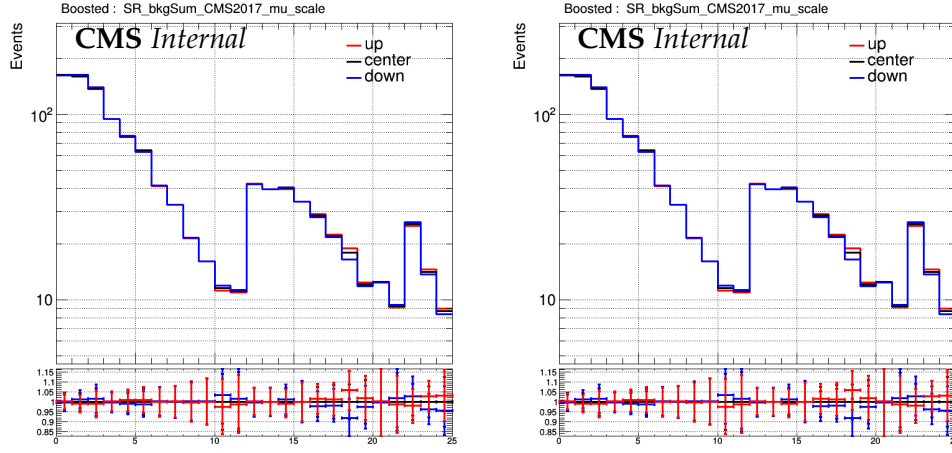


Figure D.7: The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the signal region. The center shape of the distribution represents the total expected background in the signal region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale uncertainty is shifted up and down, respectively

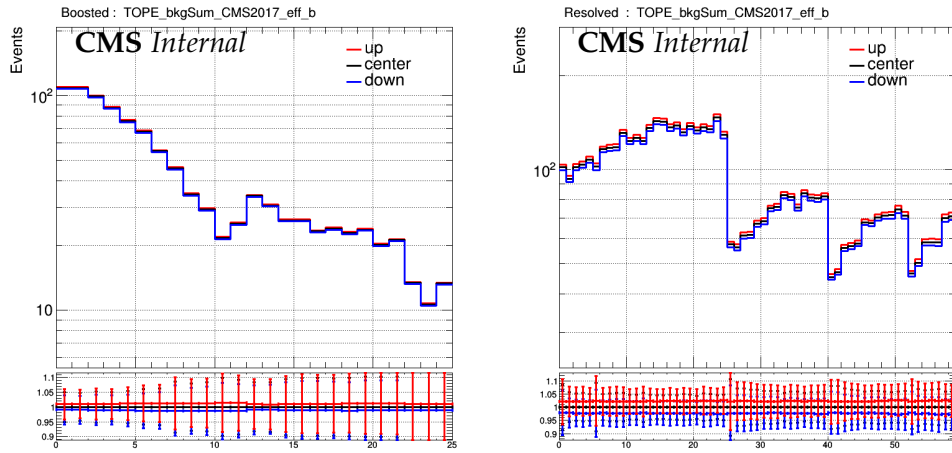


Figure D.8: The impact of b-tagging systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.

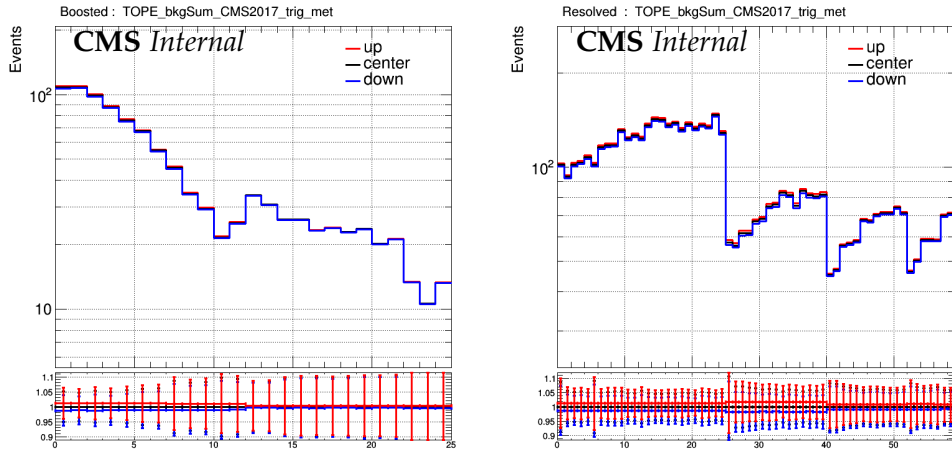


Figure D.9: The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers systematic uncertainty is shifted up and down, respectively.

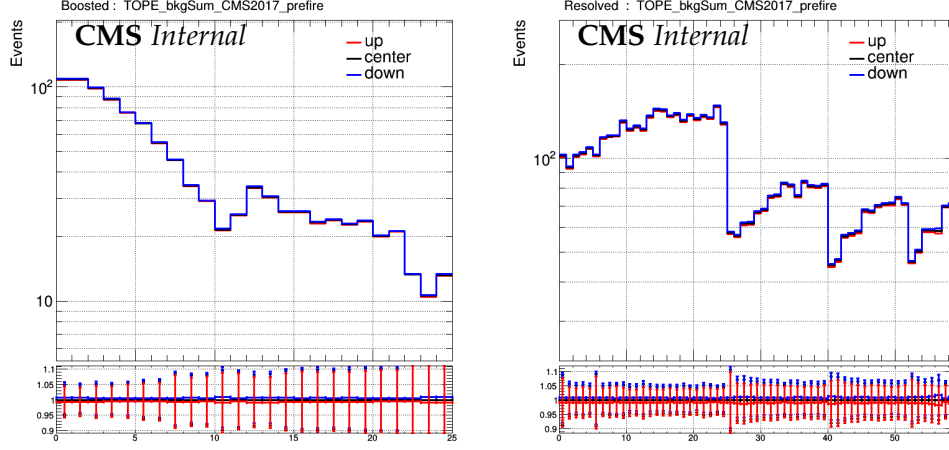


Figure D.10: The impact of prefiring systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the prefiring systematic uncertainty is shifted up and down, respectively.

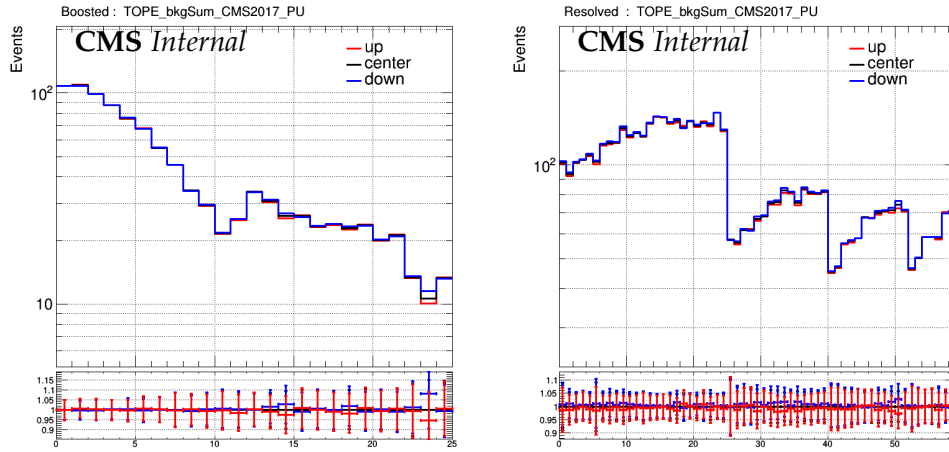


Figure D.11: The impact of pile-up reweighting systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting systematic uncertainty is shifted up and down, respectively.

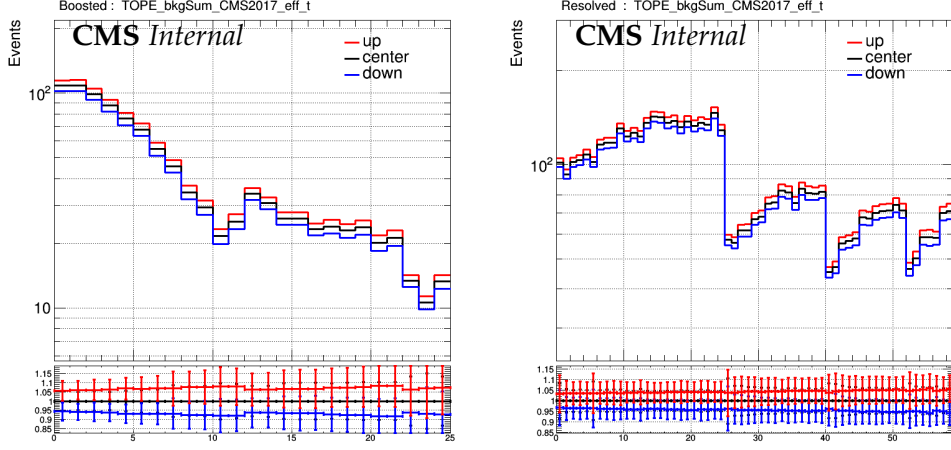


Figure D.12: The impact of top p_T reweighting systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the top p_T reweighting systematic uncertainty is shifted up and down, respectively.

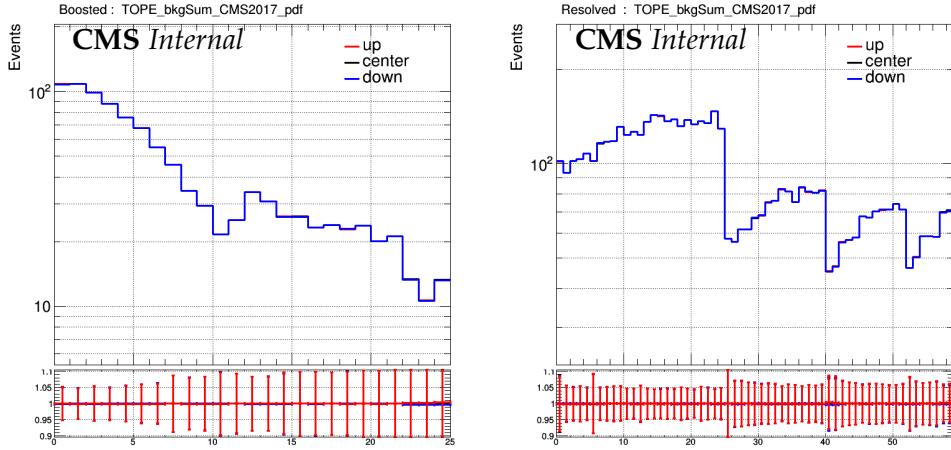


Figure D.13: The impact of pdf systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf systematic uncertainty is shifted up and down, respectively.

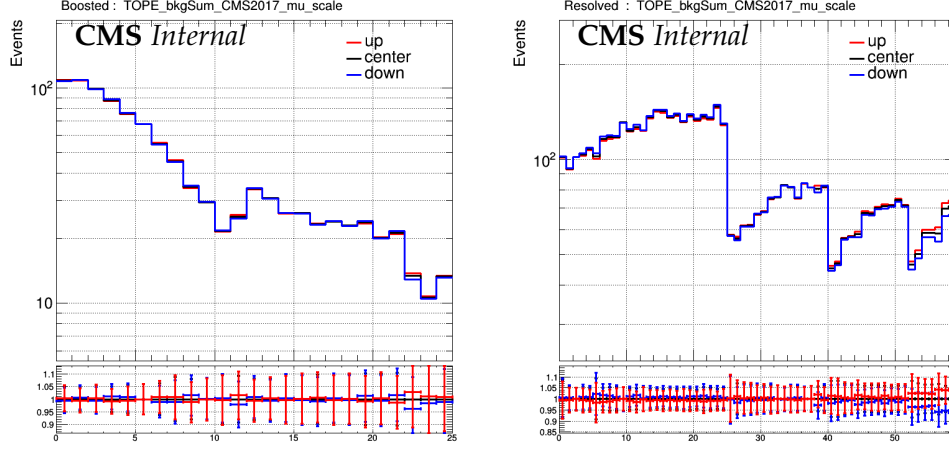


Figure D.14: The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale systematic uncertainty is shifted up and down, respectively.

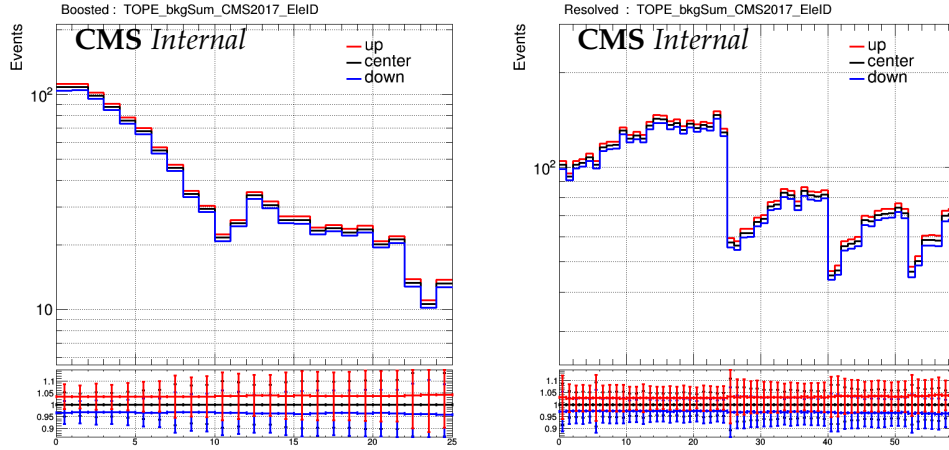


Figure D.15: The impact of electron identification scale systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron identification scale systematic uncertainty is shifted up and down, respectively.

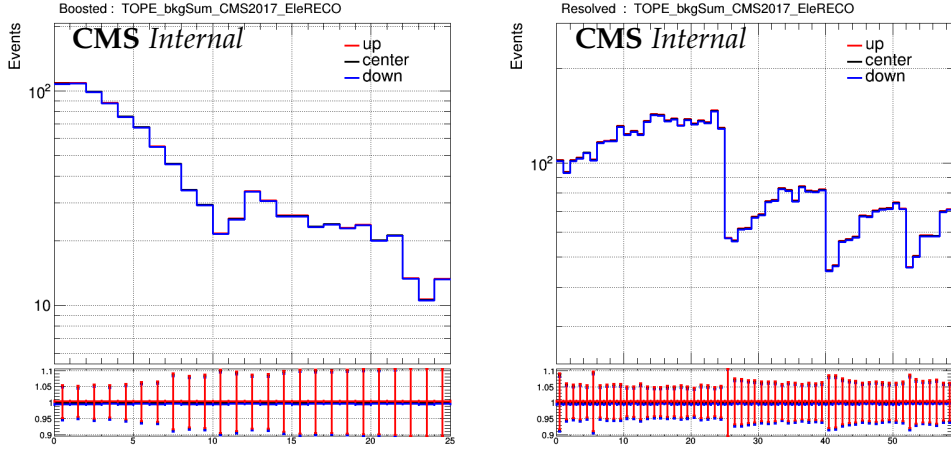


Figure D.16: The impact of electron reconstruction scale systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron reconstruction scale systematic uncertainty is shifted up and down, respectively.

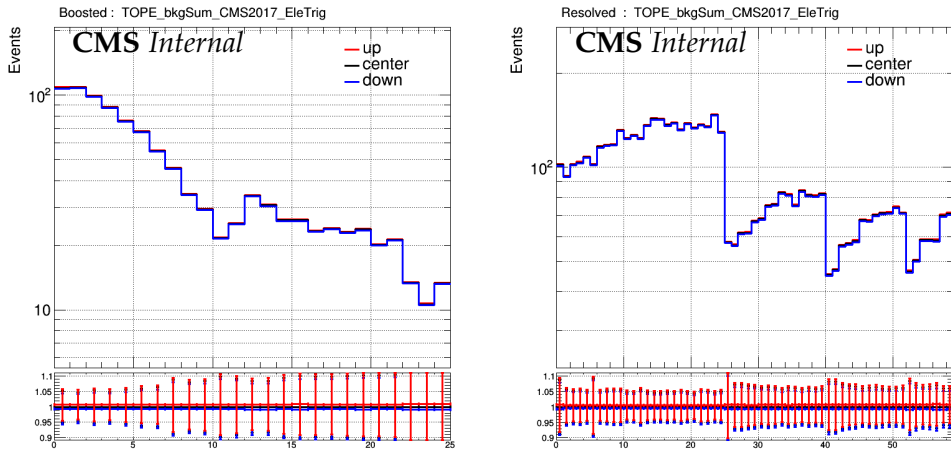


Figure D.17: The impact of electron trigger scale systematic uncertainty on the mass distribution in the Top(e) control region. The center shape of the distribution represents the total expected background in the Top(e) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron trigger scale systematic uncertainty is shifted up and down, respectively.

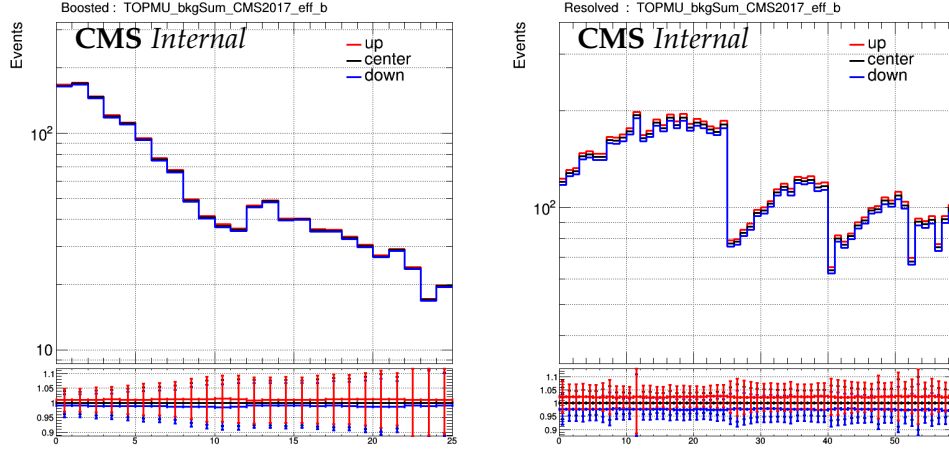


Figure D.18: The impact of b-tagging systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.

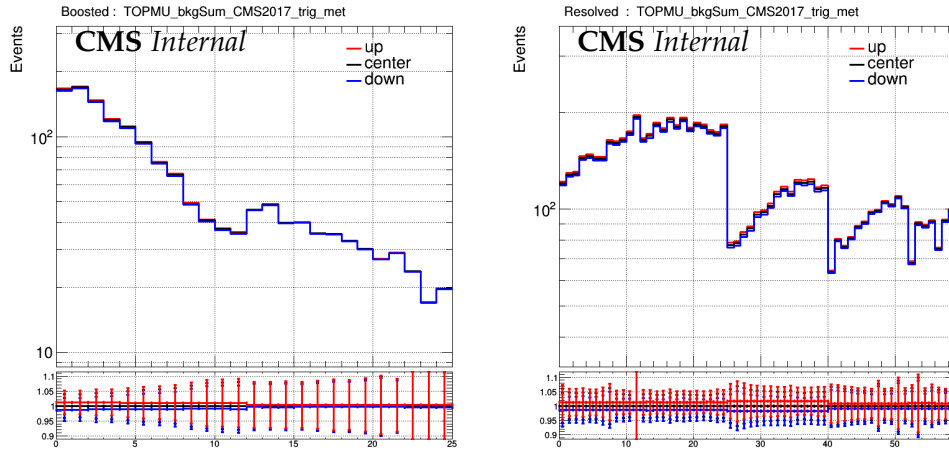


Figure D.19: The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers systematic uncertainty is shifted up and down, respectively.

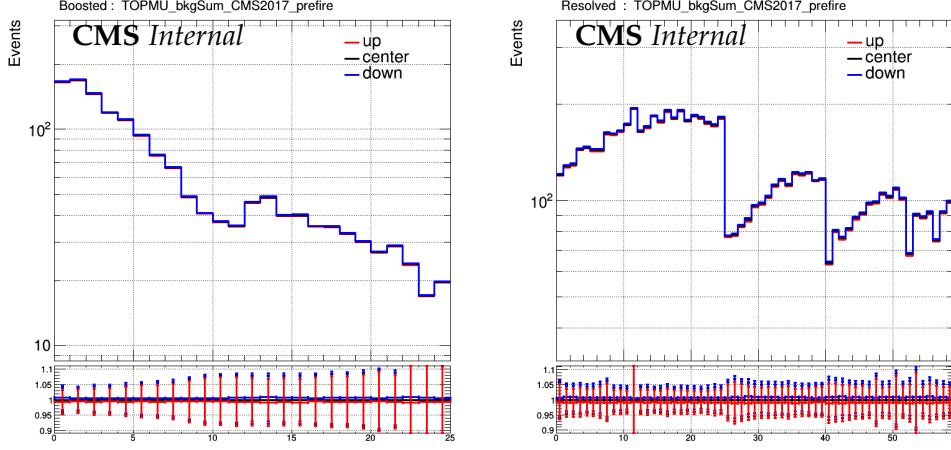


Figure D.20: The impact of prefiring systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the prefiring systematic uncertainty is shifted up and down, respectively.

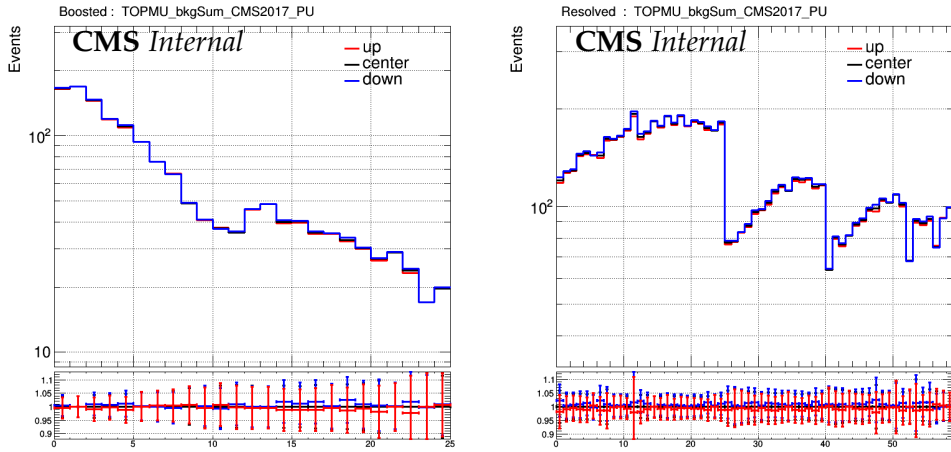


Figure D.21: The impact of pile-up reweighting systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting systematic uncertainty is shifted up and down, respectively.

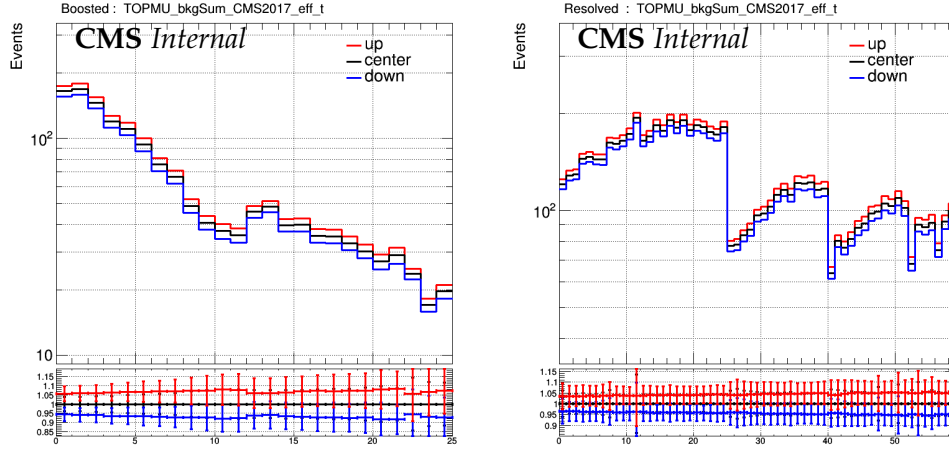


Figure D.22: The impact of p_T reweighting systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the p_T reweighting systematic uncertainty is shifted up and down, respectively.

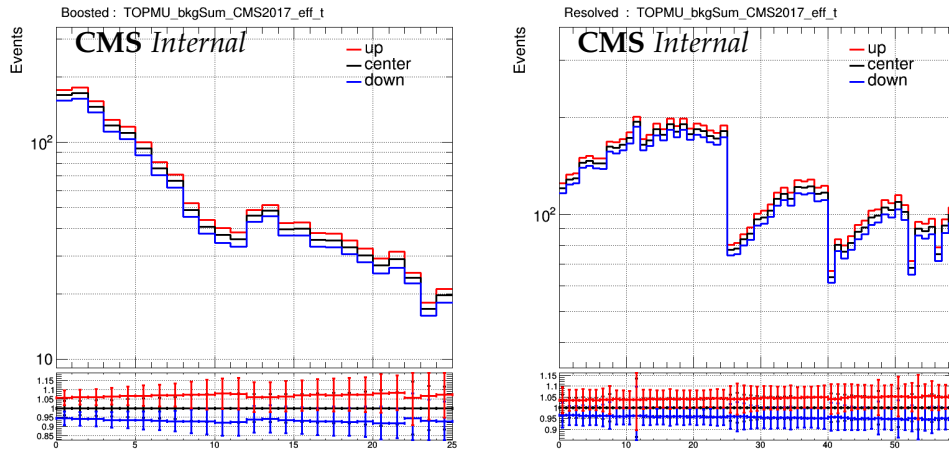


Figure D.23: The impact of pdf systematic uncertainty on the mass distribution in the $\text{Top}(\mu)$ control region. The center shape of the distribution represents the total expected background in the $\text{Top}(\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf systematic uncertainty is shifted up and down, respectively.

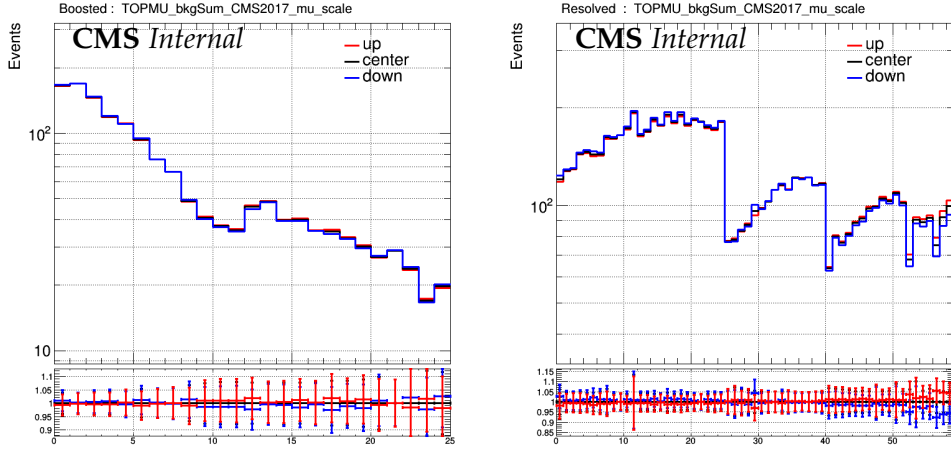


Figure D.24: The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the Top(μ) control region. The center shape of the distribution represents the total expected background in the Top(μ) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale systematic uncertainty is shifted up and down, respectively.

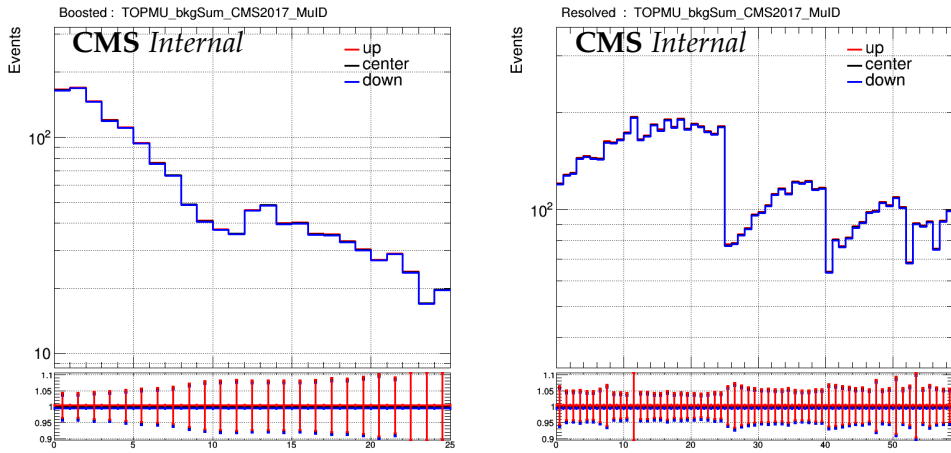


Figure D.25: The impact of muon identification scale systematic uncertainty on the mass distribution in the Top(μ) control region. The center shape of the distribution represents the total expected background in the Top(μ) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the muon identification systematic uncertainty is shifted up and down, respectively.

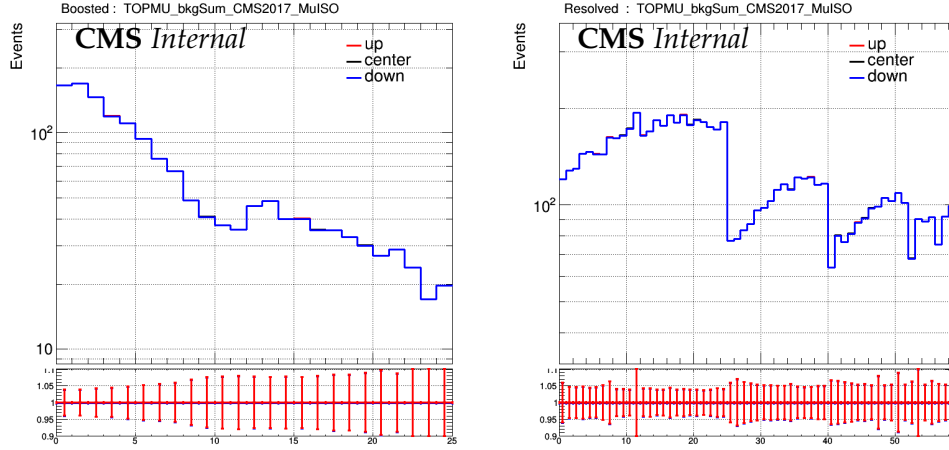


Figure D.26: The impact of muon isolation scale systematic uncertainty on the mass distribution in the Top(μ) control region. The center shape of the distribution represents the total expected background in the Top(μ) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the muon isolation systematic uncertainty is shifted up and down, respectively.

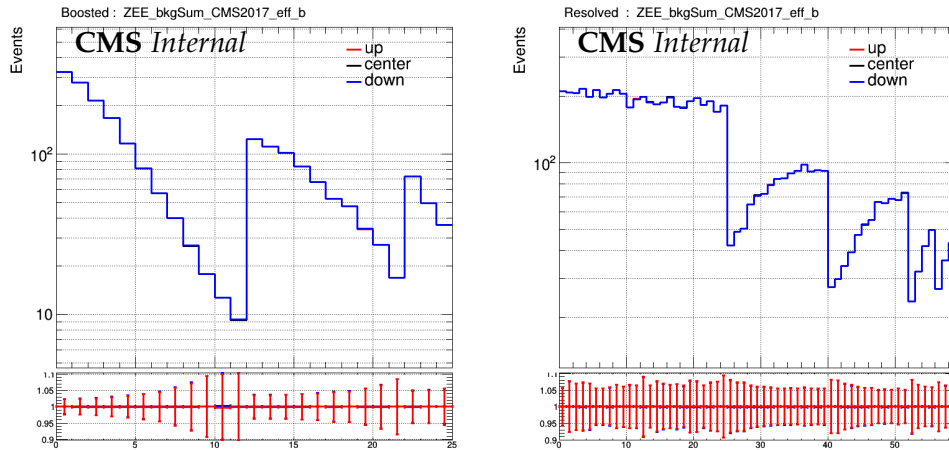


Figure D.27: The impact of b-tagging systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.

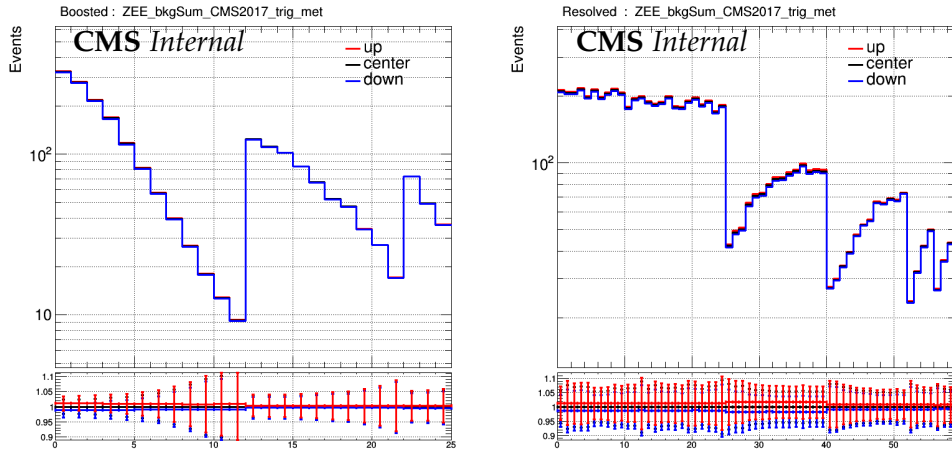


Figure D.28: The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the $Z(ee)$ control region. The center shape of the distribution represents the total expected background in the $Z(ee)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers systematic uncertainty is shifted up and down, respectively.

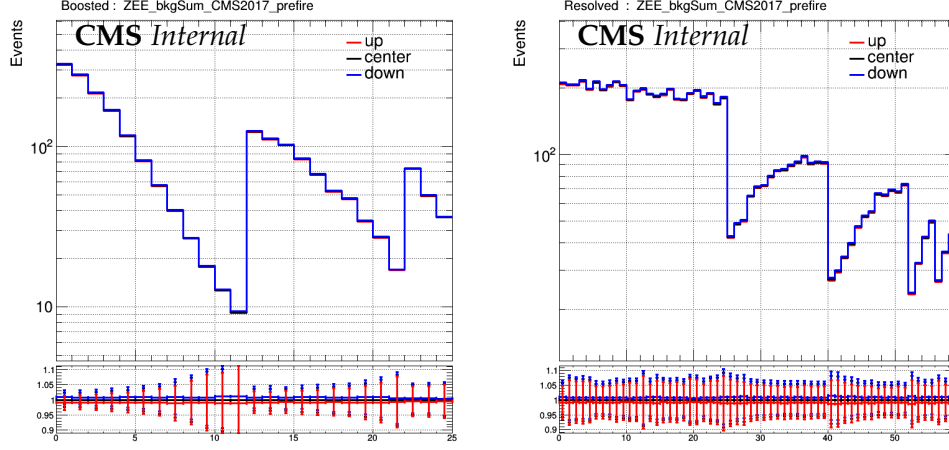


Figure D.29: The impact of prefiring systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the prefiring systematic uncertainty is shifted up and down, respectively.

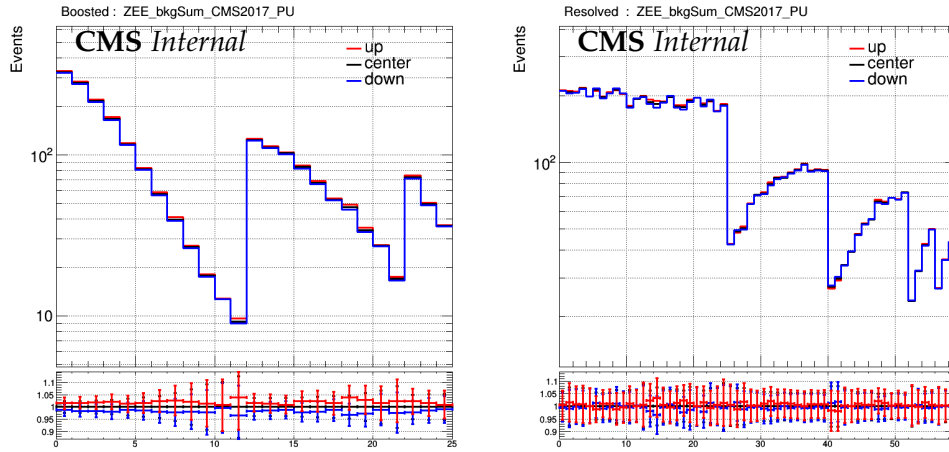


Figure D.30: The impact of pile-up reweighting systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting systematic uncertainty is shifted up and down, respectively.

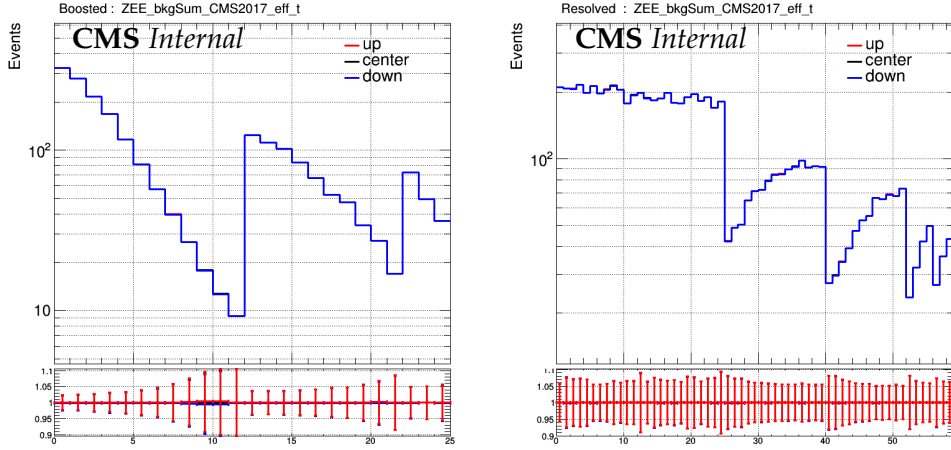


Figure D.31: The impact of p_T reweighting systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the p_T reweighting systematic uncertainty is shifted up and down, respectively.

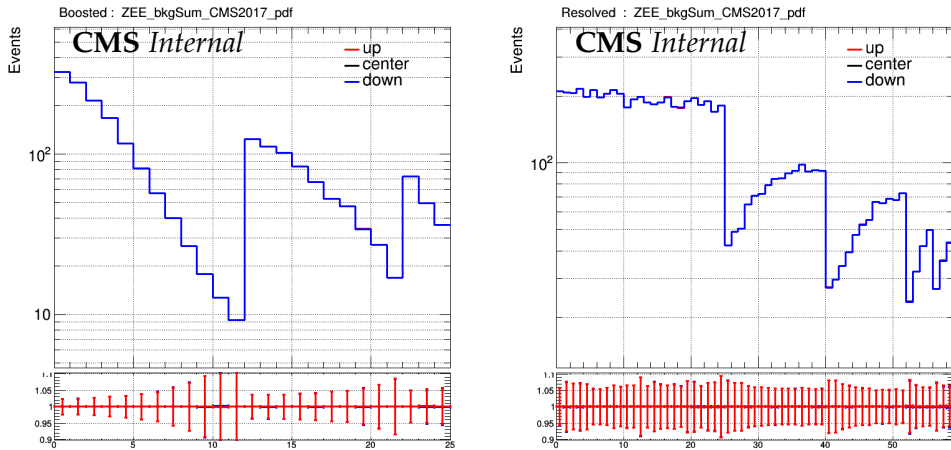


Figure D.32: The impact of pdf systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf systematic uncertainty is shifted up and down, respectively.

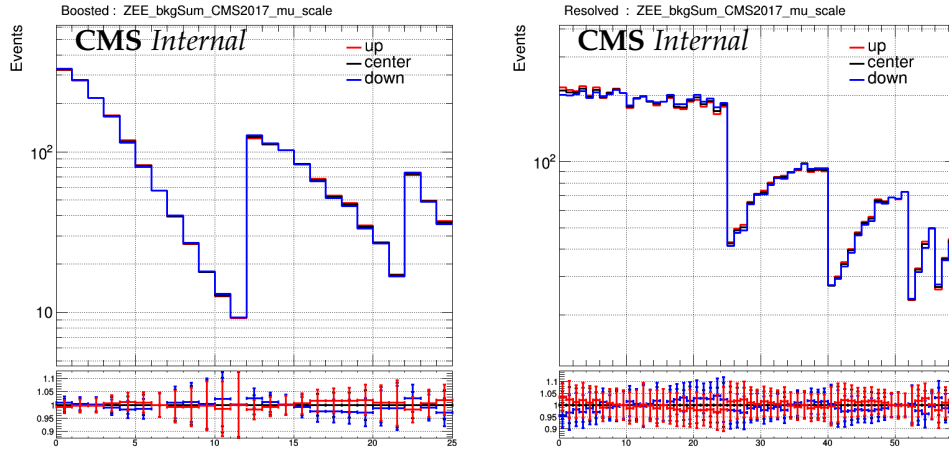


Figure D.33: The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale systematic uncertainty is shifted up and down, respectively.

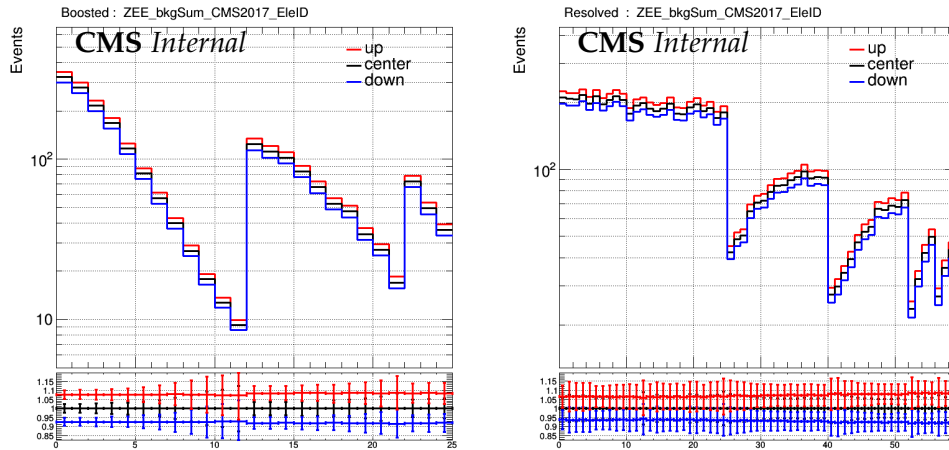


Figure D.34: The impact of electron identification scale systematic uncertainty on the mass distribution in the Z(ee) control region. The center shape of the distribution represents the total expected background in the Z(ee) control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron identification scale systematic uncertainty is shifted up and down, respectively.

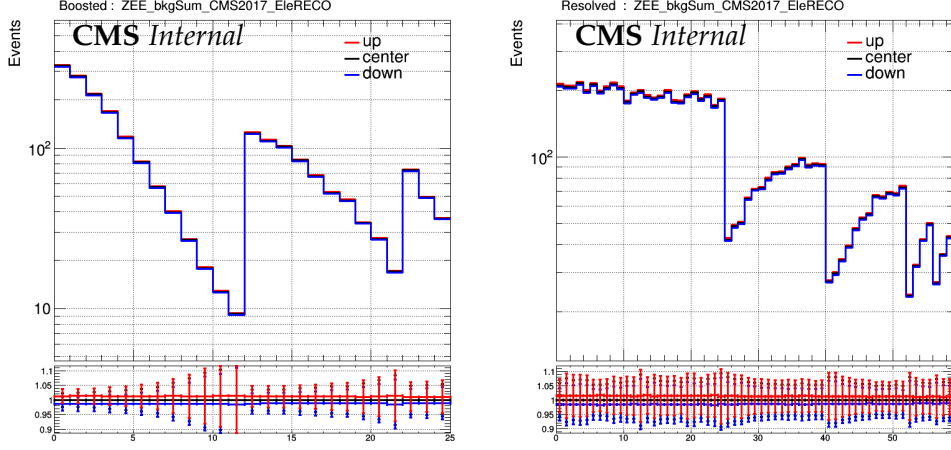


Figure D.35: The impact of electron reconstruction scale systematic uncertainty on the mass distribution in the $Z(ee)$ control region. The center shape of the distribution represents the total expected background in the $Z(ee)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the electron reconstruction scale systematic uncertainty is shifted up and down, respectively.

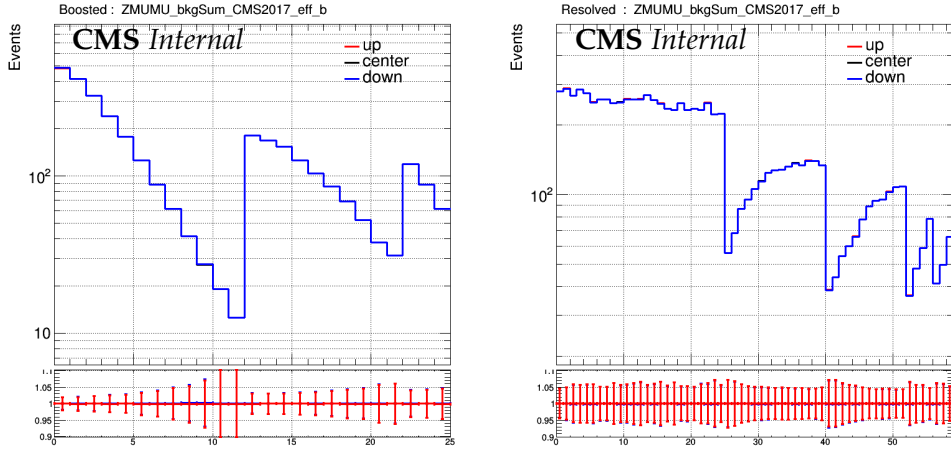


Figure D.36: The impact of b-tagging systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the b-tagging systematic uncertainty is shifted up and down, respectively.

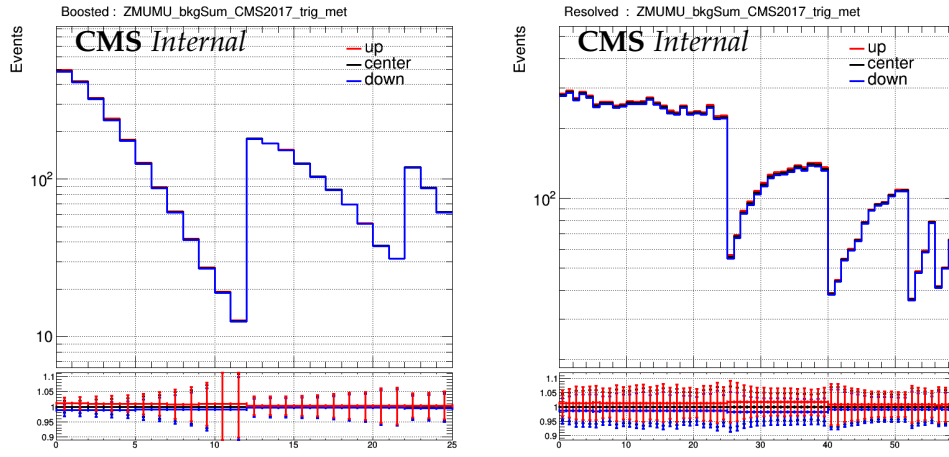


Figure D.37: The impact of E_T^{miss} triggers systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the E_T^{miss} triggers systematic uncertainty is shifted up and down, respectively.

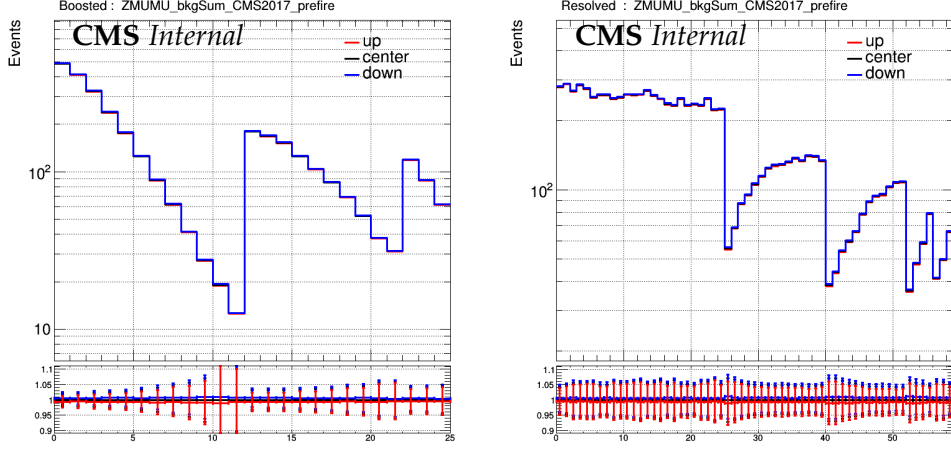


Figure D.38: The impact of prefiring systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the prefiring systematic uncertainty is shifted up and down, respectively.

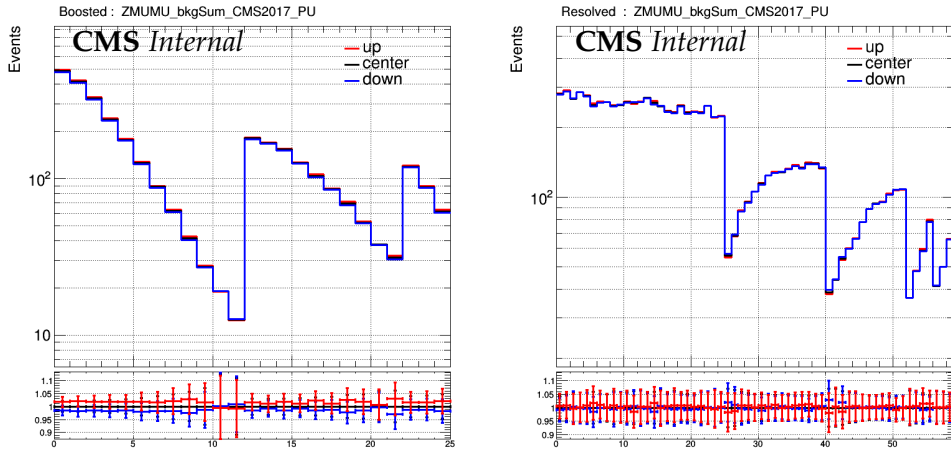


Figure D.39: The impact of pile-up reweighting systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pile-up reweighting systematic uncertainty is shifted up and down, respectively.

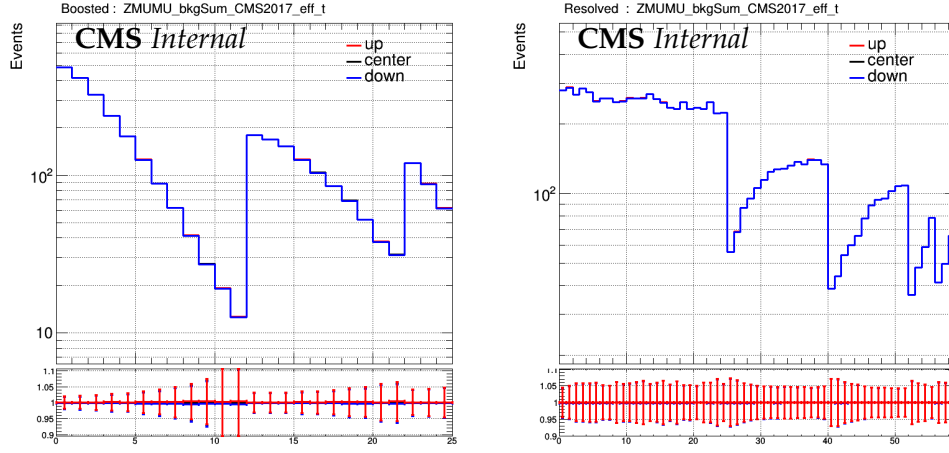


Figure D.40: The impact of top p_T reweighting systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the top p_T reweighting systematic uncertainty is shifted up and down, respectively.

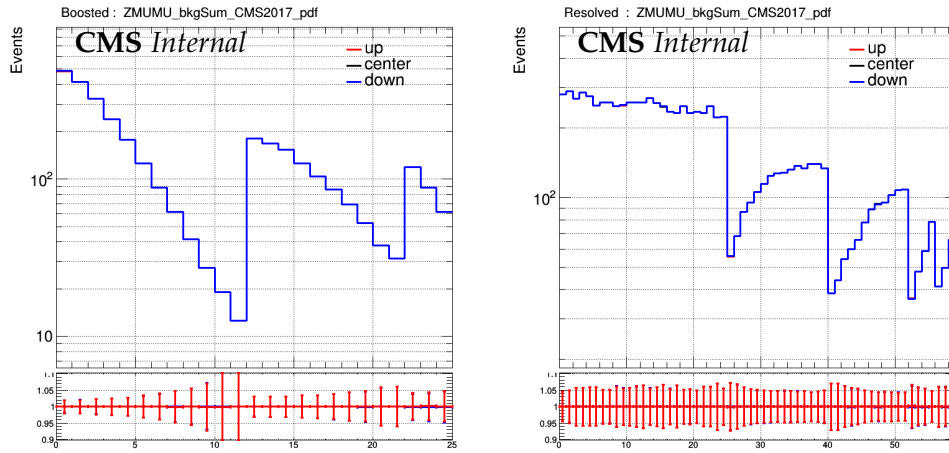


Figure D.41: The impact of pdf systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the pdf systematic uncertainty is shifted up and down, respectively.

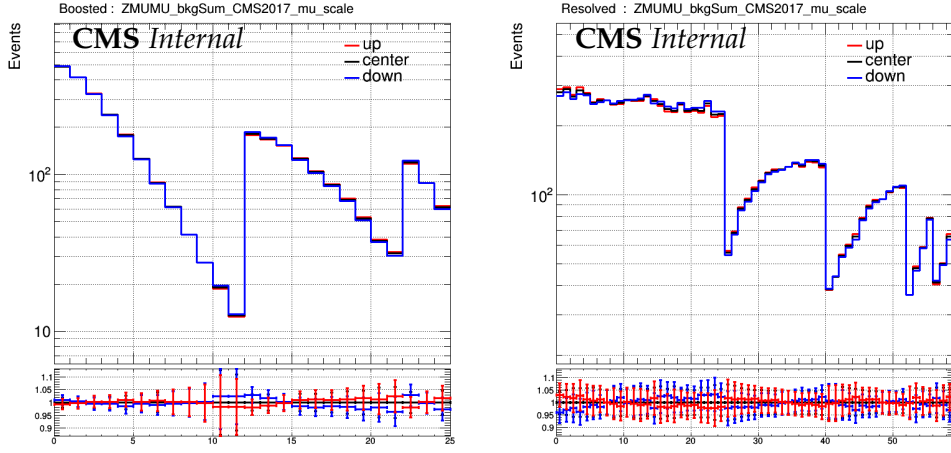


Figure D.42: The impact of qcd factorization and renormalization scale systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the qcd factorization and renormalization scale systematic uncertainty is shifted up and down, respectively.

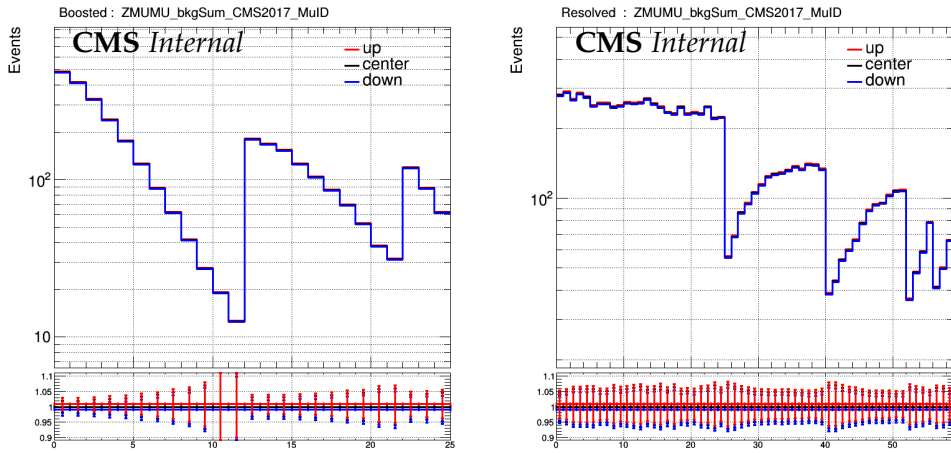


Figure D.43: The impact of muon identification systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the muon identification systematic uncertainty is shifted up and down, respectively.

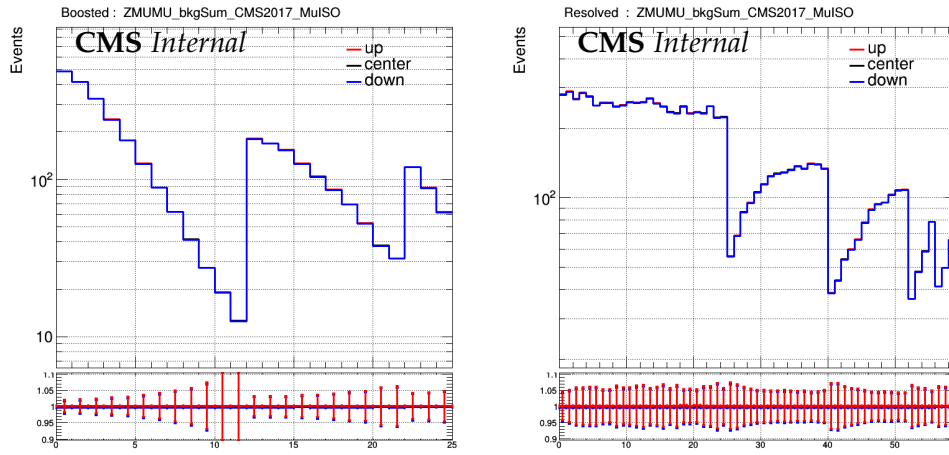


Figure D.44: The impact of muon isolation systematic uncertainty on the mass distribution in the $Z(\mu\mu)$ control region. The center shape of the distribution represents the total expected background in the $Z(\mu\mu)$ control region, while the up and down variations correspond to the systematic uncertainty. Specifically, these plots show the variation in the mass distribution that arises when the muon isolation systematic uncertainty is shifted up and down, respectively.

APPENDIX 5

We present the impact plot ([E.1](#)) for the boosted analysis. The plot illustrates the impacts of different nuisance parameters on the parameter of interest. Each nuisance parameter is represented by a bar, with the height of the bar indicating the magnitude of its impact. The larger the bar, the more significant the impact of the corresponding nuisance parameter. The plot includes first 60 nuisances. The impacts of all the nuisances are within 2%, which appears to be acceptable. Two nuisances (`btag_veto`, `tau_veto`) have largest impact because they have 5-6% uncertainty which is largest compared to other nuisances. Additionally, we present the pulls of the nuisances ([E.2](#)), which indicate the disparity between the pre-fit and post-fit uncertainties of each specific nuisance. The pulls of each nuisance are within 1σ , signifying that none of them exert a substantial influence.

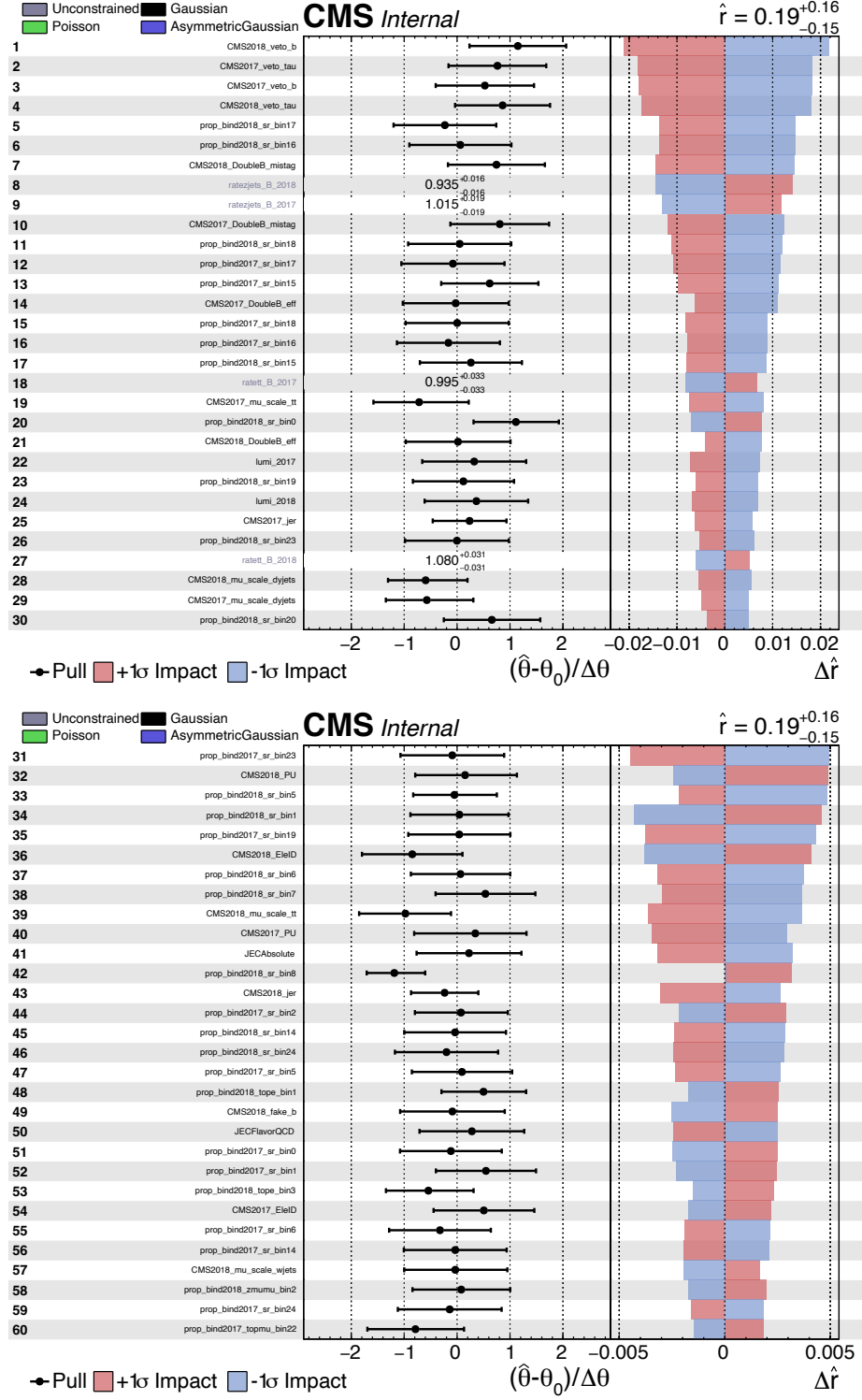


Figure E.1: Impact of nuisances for boosted analysis with combined 2017 and 2018 data.

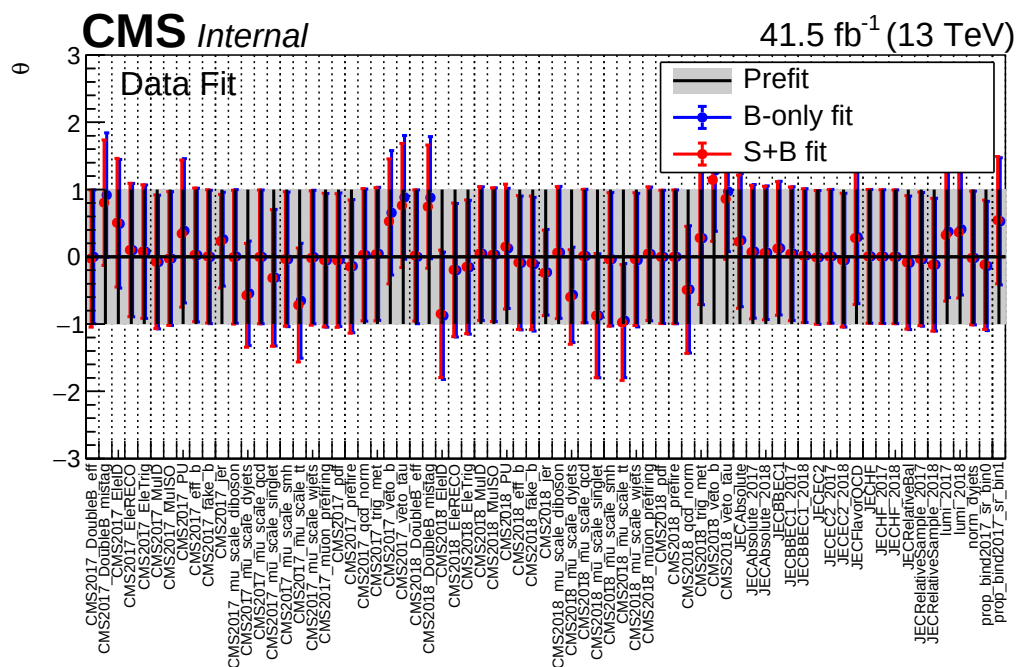


Figure E.2: Pulls of nuisances in boosted category with real data.

BIBLIOGRAPHY

- [1] F. Halzen and A. D. Martin, *QUARKS AND LEPTONS: AN INTRODUCTORY COURSE IN MODERN PARTICLE PHYSICS*. 1984, ISBN: 978-0-471-88741-6.
- [2] S. L. Glashow, "Partial Symmetries of Weak Interactions", *Nucl. Phys.*, vol. 22, pp. 579–588, 1961. doi: [10.1016/0029-5582\(61\)90469-2](https://doi.org/10.1016/0029-5582(61)90469-2).
- [3] A. Salam and J. C. Ward, "Electromagnetic and weak interactions", *Phys. Lett.*, vol. 13, pp. 168–171, 1964. doi: [10.1016/0031-9163\(64\)90711-5](https://doi.org/10.1016/0031-9163(64)90711-5).
- [4] S. Weinberg, "A Model of Leptons", *Phys. Rev. Lett.*, vol. 19, pp. 1264–1266, 1967. doi: [10.1103/PhysRevLett.19.1264](https://doi.org/10.1103/PhysRevLett.19.1264).
- [5] J. J. T. M. F.R.S., "Xl. cathode rays", *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 44, no. 269, pp. 293–316, 1897. doi: [10.1080/14786449708621070](https://doi.org/10.1080/14786449708621070). eprint: <https://doi.org/10.1080/14786449708621070>. [Online]. Available: <https://doi.org/10.1080/14786449708621070>.
- [6] E. Rutherford, "The scattering of alpha and beta particles by matter and the structure of the atom", *Phil. Mag. Ser. 6*, vol. 21, pp. 669–688, 1911. doi: [10.1080/14786440508637080](https://doi.org/10.1080/14786440508637080).
- [7] E. RUTHERFORD, "The structure of the atom", *Nature*, vol. 92, pp. 423–423, 1913. doi: [10.1038/092423a0](https://doi.org/10.1038/092423a0). [Online]. Available: <https://doi.org/10.1038/092423a0>.
- [8] J. Chadwick, "Possible Existence of a Neutron", *Nature*, vol. 129, p. 312, 1932. doi: [10.1038/129312a0](https://doi.org/10.1038/129312a0).
- [9] G. Arnison *et al.*, "Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at $\sqrt{s} = 540$ GeV", *Phys. Lett. B*, vol. 122, pp. 103–116, 1983. doi: [10.1016/0370-2693\(83\)91177-2](https://doi.org/10.1016/0370-2693(83)91177-2).
- [10] J. J. T. M. F.R.S., "Xl. cathode rays", *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 44, no. 269, pp. 293–316, 1897. doi: [10.1080/14786449708621070](https://doi.org/10.1080/14786449708621070). eprint: <https://doi.org/10.1080/14786449708621070>. [Online]. Available: <https://doi.org/10.1080/14786449708621070>.
- [11] G. Arnison *et al.*, "Experimental Observation of Lepton Pairs of Invariant Mass Around 95-GeV/c**2 at the CERN SPS Collider", *Phys. Lett. B*, vol. 126, pp. 398–410, 1983. doi: [10.1016/0370-2693\(83\)90188-0](https://doi.org/10.1016/0370-2693(83)90188-0).
- [12] G. Arnison, "Further Evidence for Charged Intermediate Vector Bosons at the SPS Collider", *Phys. Lett. B*, vol. 129, pp. 273–282, 1983. doi: [10.1016/0370-2693\(83\)90860-2](https://doi.org/10.1016/0370-2693(83)90860-2).
- [13] J. J. T. M. F.R.S., "Xl. cathode rays", *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 44, no. 269, pp. 293–316, 1897. doi: [10.1080/14786449708621070](https://doi.org/10.1080/14786449708621070). eprint: <https://doi.org/10.1080/14786449708621070>. [Online]. Available: <https://doi.org/10.1080/14786449708621070>.

- [14] P. W. Higgs, “Broken Symmetries and the Masses of Gauge Bosons”, *Phys. Rev. Lett.*, vol. 13, J. C. Taylor, Ed., pp. 508–509, 1964. doi: [10.1103/PhysRevLett.13.508](https://doi.org/10.1103/PhysRevLett.13.508).
- [15] F. Englert and R. Brout, “Broken Symmetry and the Mass of Gauge Vector Mesons”, *Phys. Rev. Lett.*, vol. 13, J. C. Taylor, Ed., pp. 321–323, 1964. doi: [10.1103/PhysRevLett.13.321](https://doi.org/10.1103/PhysRevLett.13.321).
- [16] G. Aad *et al.*, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B*, vol. 716, pp. 1–29, 2012. doi: [10.1016/j.physletb.2012.08.020](https://doi.org/10.1016/j.physletb.2012.08.020). arXiv: [1207.7214](https://arxiv.org/abs/1207.7214) [hep-ex].
- [17] S. Chatrchyan *et al.*, “Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC”, *Phys. Lett. B*, vol. 716, pp. 30–61, 2012. doi: [10.1016/j.physletb.2012.08.021](https://doi.org/10.1016/j.physletb.2012.08.021). arXiv: [1207.7235](https://arxiv.org/abs/1207.7235) [hep-ex].
- [18] N. Aghanim, Y. Akrami, F. Arroja, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini, A. J. Banday and R., “Planck 2018 results”, *Astronomy Astrophysics*, vol. 641, A1, 2020. doi: [10.1051/0004-6361/201833880](https://doi.org/10.1051/0004-6361/201833880). [Online]. Available: <https://doi.org/10.1051/0004-6361/201833880>.
- [19] G. Aad, “Search for Dark Matter in Events with Missing Transverse Momentum and a Higgs Boson Decaying to Two Photons in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector”, *Phys. Rev. Lett.*, vol. 115, no. 13, p. 131801, 2015. doi: [10.1103/PhysRevLett.115.131801](https://doi.org/10.1103/PhysRevLett.115.131801). arXiv: [1506.01081](https://arxiv.org/abs/1506.01081) [hep-ex].
- [20] G. Aad *et al.*, “Search for dark matter produced in association with a Higgs boson decaying to two bottom quarks in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *Phys. Rev. D*, vol. 93, no. 7, p. 072007, 2016. doi: [10.1103/PhysRevD.93.072007](https://doi.org/10.1103/PhysRevD.93.072007). arXiv: [1510.06218](https://arxiv.org/abs/1510.06218) [hep-ex].
- [21] M. Aaboud *et al.*, “Search for dark matter in association with a Higgs boson decaying to b -quarks in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Lett. B*, vol. 765, pp. 11–31, 2017. doi: [10.1016/j.physletb.2016.11.035](https://doi.org/10.1016/j.physletb.2016.11.035). arXiv: [1609.04572](https://arxiv.org/abs/1609.04572) [hep-ex].
- [22] S. Chatrchyan *et al.*, “Observation of a New Boson with Mass Near 125 GeV in pp Collisions at $\sqrt{s} = 7$ and 8 TeV”, *JHEP*, vol. 06, p. 081, 2013. doi: [10.1007/JHEP06\(2013\)081](https://doi.org/10.1007/JHEP06(2013)081). arXiv: [1303.4571](https://arxiv.org/abs/1303.4571) [hep-ex].
- [23] A. M. Sirunyan *et al.*, “Search for associated production of dark matter with a Higgs boson decaying to $b\bar{b}$ or $\gamma\gamma$ at $\sqrt{s} = 13$ TeV”, *JHEP*, vol. 10, p. 180, 2017. doi: [10.1007/JHEP10\(2017\)180](https://doi.org/10.1007/JHEP10(2017)180). arXiv: [1703.05236](https://arxiv.org/abs/1703.05236) [hep-ex].
- [24] M. Aaboud *et al.*, “Search for dark matter in association with a Higgs boson decaying to two photons at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Rev. D*, vol. 96, no. 11, p. 112004, 2017. doi: [10.1103/PhysRevD.96.112004](https://doi.org/10.1103/PhysRevD.96.112004). arXiv: [1706.03948](https://arxiv.org/abs/1706.03948) [hep-ex].
- [25] A. M. Sirunyan *et al.*, “Search for heavy resonances decaying into a vector boson and a Higgs boson in final states with charged leptons, neutrinos and b quarks at $\sqrt{s} = 13$ TeV”, *JHEP*, vol. 11, p. 172, 2018. doi: [10.1007/JHEP11\(2018\)172](https://doi.org/10.1007/JHEP11(2018)172). arXiv: [1807.02826](https://arxiv.org/abs/1807.02826) [hep-ex].
- [26] A. M. Sirunyan *et al.*, “Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks in proton–proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C*, vol. 79, no. 3, p. 280, 2019. doi: [10.1140/epjc/s10052-019-6730-7](https://doi.org/10.1140/epjc/s10052-019-6730-7). arXiv: [1811.06562](https://arxiv.org/abs/1811.06562) [hep-ex].
- [27] A. M. Sirunyan *et al.*, “Search for dark matter produced in association with a Higgs boson decaying to $\gamma\gamma$ or $\tau^+\tau^-$ at $\sqrt{s} = 13$ TeV”, *JHEP*, vol. 09, p. 046, 2018. doi: [10.1007/JHEP09\(2018\)046](https://doi.org/10.1007/JHEP09(2018)046). arXiv: [1806.04771](https://arxiv.org/abs/1806.04771) [hep-ex].

- [28] D. Abercrombie, N. Akchurin, E. Akilli *et al.*, “Dark matter benchmark models for early lhc run-2 searches: Report of the atlas/cms dark matter forum”, *Physics of the Dark Universe*, vol. 27, p. 100371, 2020, issn: 2212-6864. doi: [10.1016/j.dark.2019.100371](https://doi.org/10.1016/j.dark.2019.100371). [Online]. Available: <http://dx.doi.org/10.1016/j.dark.2019.100371>.
- [29] Wikipedia, *Elementary particle*. [Online]. Available: https://en.wikipedia.org/wiki/Elementary_particle.
- [30] M. Tanabashi, K. Hagiwara, K. Hikasa *et al.*, “Review of particle physics”, *Phys. Rev. D*, vol. 98, p. 030001, 3 2018. doi: [10.1103/PhysRevD.98.030001](https://doi.org/10.1103/PhysRevD.98.030001). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevD.98.030001>.
- [31] P. Bagnaia *et al.*, “Evidence for $Z^0 \rightarrow e^+e^-$ at the CERN $\bar{p}p$ Collider”, *Phys. Lett. B*, vol. 129, pp. 130–140, 1983. doi: [10.1016/0370-2693\(83\)90744-X](https://doi.org/10.1016/0370-2693(83)90744-X).
- [32] E. Torassa, “The standard model and higgs physics”, *Progress in Particle and Nuclear Physics*, vol. 100, pp. 69–106, 2018, issn: 0146-6410. doi: <https://doi.org/10.1016/j.pnpnp.2018.01.003>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0146641018300036>.
- [33] F. Englert and R. Brout, “Broken symmetry and the mass of gauge vector mesons”, *Phys. Rev. Lett.*, vol. 13, pp. 321–323, 9 1964. doi: [10.1103/PhysRevLett.13.321](https://doi.org/10.1103/PhysRevLett.13.321). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.13.321>.
- [34] G. S. Guralnik, C. R. Hagen and T. W. B. Kibble, “Global conservation laws and massless particles”, *Phys. Rev. Lett.*, vol. 13, pp. 585–587, 20 1964. doi: [10.1103/PhysRevLett.13.585](https://doi.org/10.1103/PhysRevLett.13.585). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.13.585>.
- [35] P. W. Higgs, “Broken symmetries and the masses of gauge bosons”, *Phys. Rev. Lett.*, vol. 13, pp. 508–509, 16 1964. doi: [10.1103/PhysRevLett.13.508](https://doi.org/10.1103/PhysRevLett.13.508). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.13.508>.
- [36] P. J. E. Peebles and B. Ratra, “The cosmological constant and dark energy”, *Reviews of Modern Physics*, vol. 75, no. 2, pp. 559–606, 2003. doi: [10.1103/revmodphys.75.559](https://doi.org/10.1103/revmodphys.75.559). [Online]. Available: <https://doi.org/10.1103/revmodphys.75.559>.
- [37] P. de Salas, D. Forero, C. Ternes, M. Trtola and J. Valle, “Status of neutrino oscillations 2018: 3sigma hint for normal mass ordering and improved CP sensitivity”, *Physics Letters B*, vol. 782, pp. 633–640, 2018. doi: [10.1016/j.physletb.2018.06.019](https://doi.org/10.1016/j.physletb.2018.06.019). [Online]. Available: <https://doi.org/10.1016/j.physletb.2018.06.019>.
- [38] Q. R. Ahmad, R. C. Allen, T. C. Andersen, J. D. V. Berg, R. G. V. de Water, C. J. Virtue, C. E. Waltham and J.-X., “Solar neutrinos at the sudbury neutrino observatory”, *Physical Review Letters*, vol. 87, no. 7, 2001. doi: [10.1103/physrevlett.87.071301](https://doi.org/10.1103/physrevlett.87.071301). [Online]. Available: <https://doi.org/10.1103/physrevlett.87.071301>.
- [39] P. Collaboration, “Planck 2015 results”, *Astronomy and Astrophysics*, vol. 594, A13, 2016. doi: [10.1051/0004-6361/201525830](https://doi.org/10.1051/0004-6361/201525830). [Online]. Available: <https://doi.org/10.1051/0004-6361/201525830>.
- [40] F. Zwicky, “Republication of: The redshift of extragalactic nebulae”, *General Relativity and Gravitation*, vol. 41, no. 1, pp. 207–224, 2009. doi: [10.1007/s10714-008-0707-4](https://doi.org/10.1007/s10714-008-0707-4). [Online]. Available: <https://doi.org/10.1007/s10714-008-0707-4>.

- [41] F. Zwicky, "On the Masses of Nebulae and of Clusters of Nebulae", *apj*, vol. 86, p. 217, Oct. 1937. doi: [10.1086/143864](https://doi.org/10.1086/143864).
- [42] V. C. Rubin and J. Ford W. Kent, "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions", *apj*, vol. 159, p. 379, Feb. 1970. doi: [10.1086/150317](https://doi.org/10.1086/150317).
- [43] V. Rubin, J. Ford W.K. and N. Thonnard, "Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 (R=4kpc) to UGC 2885 (R=122kpc).", *apj*, vol. 238, pp. 471–487, Jun. 1980. doi: [10.1086/158003](https://doi.org/10.1086/158003).
- [44] K. G. Begeman, A. H. Broeils and R. H. Sanders, "Extended rotation curves of spiral galaxies: dark haloes and modified dynamics", *Monthly Notices of the Royal Astronomical Society*, vol. 249, no. 3, pp. 523–537, Apr. 1991, ISSN: 0035-8711. doi: [10.1093/mnras/249.3.523](https://doi.org/10.1093/mnras/249.3.523). eprint: <https://academic.oup.com/mnras/article-pdf/249/3/523/18160929/mnras249-0523.pdf>. [Online]. Available: <https://doi.org/10.1093/mnras/249.3.523>.
- [45] A. Einstein, "Lens-like action of a star by the deviation of light in the gravitational field", English, *Science*, vol. 84, no. 2188, pp. 506–507, 1936, Cited By :490. [Online]. Available: www.scopus.com.
- [46] D. Clowe, M. Bradač, A. H. Gonzalez, M. Markevitch, S. W. Randall, C. Jones and D. Zaritsky, "A direct empirical proof of the existence of dark matter", *The Astrophysical Journal*, vol. 648, no. 2, L109–L113, 2006, ISSN: 1538-4357. doi: [10.1086/508162](https://doi.org/10.1086/508162). [Online]. Available: <http://dx.doi.org/10.1086/508162>.
- [47] A. Penzias and R. Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc per s.", *apj*, vol. 142, pp. 419–421, Jul. 1965. doi: [10.1086/148307](https://doi.org/10.1086/148307).
- [48] S. Colombi, S. Dodelson and L. M. Widrow, "Large-scale structure tests of warm dark matter", *The Astrophysical Journal*, vol. 458, p. 1, 1996. doi: [10.1086/176788](https://doi.org/10.1086/176788). [Online]. Available: <https://doi.org/10.1086/176788>.
- [49] S. White, "Simulations of sinking satellites", *apj*, vol. 274, pp. 53–61, Nov. 1983. doi: [10.1086/161425](https://doi.org/10.1086/161425).
- [50] F. Chadha-Day, J. Ellis and D. J. E. Marsh, *Axion dark matter: What is it and why now?*, 2021. doi: [10.48550/ARXIV.2105.01406](https://doi.org/10.48550/ARXIV.2105.01406). [Online]. Available: <https://arxiv.org/abs/2105.01406>.
- [51] L. D. Duffy and K. van Bibber, "Axions as dark matter particles", *New Journal of Physics*, vol. 11, no. 10, p. 105 008, 2009. doi: [10.1088/1367-2630/11/10/105008](https://doi.org/10.1088/1367-2630/11/10/105008). [Online]. Available: <https://doi.org/10.1088/1367-2630/11/10/105008>.
- [52] H. P. Nilles, "Supersymmetry, Supergravity and Particle Physics", *Phys. Rept.*, vol. 110, pp. 1–162, 1984. doi: [10.1016/0370-1573\(84\)90008-5](https://doi.org/10.1016/0370-1573(84)90008-5).
- [53] K. Griest and M. Kamionkowski, "Unitarity limits on the mass and radius of dark-matter particles", *Phys. Rev. Lett.*, vol. 64, pp. 615–618, 6 1990. doi: [10.1103/PhysRevLett.64.615](https://doi.org/10.1103/PhysRevLett.64.615). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.64.615>.
- [54] E. Aprile, K. Arisaka, F. Arneodo *et al.*, "First dark matter results from the xenon100 experiment", *Phys. Rev. Lett.*, vol. 105, p. 131 302, 13 2010. doi: [10.1103/PhysRevLett.105.131302](https://doi.org/10.1103/PhysRevLett.105.131302). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.105.131302>.
- [55] Y. Bai and T. M. P. Tait, "Inelastic Dark Matter at the LHC", *Phys. Lett. B*, vol. 710, pp. 335–338, 2012. doi: [10.1016/j.physletb.2012.03.011](https://doi.org/10.1016/j.physletb.2012.03.011). arXiv: [1109.4144](https://arxiv.org/abs/1109.4144) [hep-ph].

- [56] L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West, “Freeze-In Production of FIMP Dark Matter”, *JHEP*, vol. 03, p. 080, 2010. doi: [10.1007/JHEP03\(2010\)080](https://doi.org/10.1007/JHEP03(2010)080). arXiv: [0911.1120](https://arxiv.org/abs/0911.1120) [hep-ph].
- [57] N. Bernal, M. Heikinheimo, T. Tenkanen, K. Tuominen and V. Vaskonen, “The Dawn of FIMP Dark Matter: A Review of Models and Constraints”, *Int. J. Mod. Phys. A*, vol. 32, no. 27, p. 1730023, 2017. doi: [10.1142/S0217751X1730023X](https://doi.org/10.1142/S0217751X1730023X). arXiv: [1706.07442](https://arxiv.org/abs/1706.07442) [hep-ph].
- [58] J. H. Chang, R. Essig and A. Reinert, “Light(ly)-coupled Dark Matter in the keV Range: Freeze-In and Constraints”, *JHEP*, vol. 03, p. 141, 2021. doi: [10.1007/JHEP03\(2021\)141](https://doi.org/10.1007/JHEP03(2021)141). arXiv: [1911.03389](https://arxiv.org/abs/1911.03389) [hep-ph].
- [59] C. Dvorkin, T. Lin and K. Schutz, “Cosmology of Sub-MeV Dark Matter Freeze-In”, *Phys. Rev. Lett.*, vol. 127, no. 11, p. 111301, 2021. doi: [10.1103/PhysRevLett.127.111301](https://doi.org/10.1103/PhysRevLett.127.111301). arXiv: [2011.08186](https://arxiv.org/abs/2011.08186) [astro-ph.CO].
- [60] A. Coskuner, T. Trickle, Z. Zhang and K. M. Zurek, “Directional detectability of dark matter with single phonon excitations: Target comparison”, *Phys. Rev. D*, vol. 105, no. 1, p. 015010, 2022. doi: [10.1103/PhysRevD.105.015010](https://doi.org/10.1103/PhysRevD.105.015010). arXiv: [2102.09567](https://arxiv.org/abs/2102.09567) [hep-ph].
- [61] D. J. H. Chung, E. W. Kolb and A. Riotto, “Nonthermal supermassive dark matter”, *Phys. Rev. Lett.*, vol. 81, pp. 4048–4051, 19 1998. doi: [10.1103/PhysRevLett.81.4048](https://doi.org/10.1103/PhysRevLett.81.4048). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.81.4048>.
- [62] D. Carney *et al.*, “Snowmass2021 Cosmic Frontier White Paper: Ultraheavy particle dark matter”, Mar. 2022. arXiv: [2203.06508](https://arxiv.org/abs/2203.06508) [hep-ph].
- [63] H. Baer, K.-Y. Choi, J. E. Kim and L. Roszkowski, “Dark matter production in the early Universe: beyond the thermal WIMP paradigm”, *Phys. Rept.*, vol. 555, pp. 1–60, 2015. doi: [10.1016/j.physrep.2014.10.002](https://doi.org/10.1016/j.physrep.2014.10.002). arXiv: [1407.0017](https://arxiv.org/abs/1407.0017) [hep-ph].
- [64] S. Giagu, “Wimp dark matter searches with the atlas detector at the lhe”, *Frontiers in Physics*, vol. 7, May 2019. doi: [10.3389/fphy.2019.00075](https://doi.org/10.3389/fphy.2019.00075).
- [65] R. Bernabei, P. Belli, F. Cappella *et al.*, “First results from DAMA/LIBRA and the combined results with DAMA/NaI”, *The European Physical Journal C*, vol. 56, no. 3, pp. 333–355, 2008. doi: [10.1140/epjc/s10052-008-0662-y](https://doi.org/10.1140/epjc/s10052-008-0662-y). [Online]. Available: <https://doi.org/10.1140%2Fepjc%2Fs10052-008-0662-y>.
- [66] R Bernabei, P. Belli, F. Cappella *et al.*, “Dama/libra results and perspectives”, *Journal of Physics: Conference Series*, vol. 1056, p. 012005, Jul. 2018. doi: [10.1088/1742-6596/1056/1/012005](https://doi.org/10.1088/1742-6596/1056/1/012005).
- [67] D. S. Akerib *et al.*, “Results from a search for dark matter in the complete LUX exposure”, *Phys. Rev. Lett.*, vol. 118, no. 2, p. 021303, 2017. doi: [10.1103/PhysRevLett.118.021303](https://doi.org/10.1103/PhysRevLett.118.021303). arXiv: [1608.07648](https://arxiv.org/abs/1608.07648) [astro-ph.CO].
- [68] D. Woodward, “Latest results of the lux dark matter experiment”, *International Journal of Modern Physics: Conference Series*, vol. 50, p. 2060002, 2020. doi: [10.1142/S2010194520600022](https://doi.org/10.1142/S2010194520600022). eprint: <https://doi.org/10.1142/S2010194520600022>. [Online]. Available: <https://doi.org/10.1142/S2010194520600022>.
- [69] S. Archambault *et al.*, “Constraints on Low-Mass WIMP Interactions on ^{19}F from PICASSO”, *Phys. Lett. B*, vol. 711, pp. 153–161, 2012. doi: [10.1016/j.physletb.2012.03.078](https://doi.org/10.1016/j.physletb.2012.03.078). arXiv: [1202.1240](https://arxiv.org/abs/1202.1240) [hep-ex].

- [70] E. Behnke *et al.*, “Final Results of the PICASSO Dark Matter Search Experiment”, *Astropart. Phys.*, vol. 90, pp. 85–92, 2017. doi: [10.1016/j.astropartphys.2017.02.005](https://doi.org/10.1016/j.astropartphys.2017.02.005). arXiv: [1611.01499](https://arxiv.org/abs/1611.01499) [hep-ex].
- [71] E. Aprile, J. Aalbers, F. Agostini *et al.*, “First dark matter search results from the xenon1t experiment”, *Phys. Rev. Lett.*, vol. 119, p. 181 301, 18 2017. doi: [10.1103/PhysRevLett.119.181301](https://doi.org/10.1103/PhysRevLett.119.181301). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.119.181301>.
- [72] E. Aprile, J. Aalbers, F. Agostini *et al.*, “Dark matter search results from a one ton-year exposure of xenon1t”, *Phys. Rev. Lett.*, vol. 121, p. 111 302, 11 2018. doi: [10.1103/PhysRevLett.121.111302](https://doi.org/10.1103/PhysRevLett.121.111302). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.121.111302>.
- [73] D. S. Akerib *et al.*, “The LUX-ZEPLIN (LZ) Experiment”, *Nucl. Instrum. Meth. A*, vol. 953, p. 163 047, 2020. doi: [10.1016/j.nima.2019.163047](https://doi.org/10.1016/j.nima.2019.163047). arXiv: [1910.09124](https://arxiv.org/abs/1910.09124) [physics.ins-det].
- [74] E. Aprile *et al.*, “First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment”, Mar. 2023. arXiv: [2303.14729](https://arxiv.org/abs/2303.14729) [hep-ex].
- [75] J. Aalbers *et al.*, “First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment”, Jul. 2022. arXiv: [2207.03764](https://arxiv.org/abs/2207.03764) [hep-ex].
- [76] Y. Meng *et al.*, “Dark Matter Search Results from the PandaX-4T Commissioning Run”, *Phys. Rev. Lett.*, vol. 127, no. 26, p. 261 802, 2021. doi: [10.1103/PhysRevLett.127.261802](https://doi.org/10.1103/PhysRevLett.127.261802). arXiv: [2107.13438](https://arxiv.org/abs/2107.13438) [hep-ex].
- [77] E. Aprile *et al.*, “Dark Matter Search Results from a One Ton-Year Exposure of XENON1T”, *Phys. Rev. Lett.*, vol. 121, no. 11, p. 111 302, 2018. doi: [10.1103/PhysRevLett.121.111302](https://doi.org/10.1103/PhysRevLett.121.111302). arXiv: [1805.12562](https://arxiv.org/abs/1805.12562) [astro-ph.CO].
- [78] Collaboration, “Spectrum and variability of the galactic center VHE gamma-ray source HESS j1745290”, *Astronomy and Astrophysics*, vol. 503, no. 3, pp. 817–825, 2009. doi: [10.1051/0004-6361/200811569](https://doi.org/10.1051/0004-6361/200811569). [Online]. Available: <https://doi.org/10.1051/0004-6361/200811569>.
- [79] L. A. Antonelli, P. Antoranz and M. Backes, “MAGIC GAMMA-RAY TELESCOPE OBSERVATION OF THE PERSEUS CLUSTER OF GALAXIES: IMPLICATIONS FOR COSMIC RAYS, DARK MATTER, AND NGC 1275”, *The Astrophysical Journal*, vol. 710, no. 1, pp. 634–647, 2010. doi: [10.1088/0004-637x/710/1/634](https://doi.org/10.1088/0004-637x/710/1/634). [Online]. Available: <https://doi.org/10.1088/0004-637x/710/1/634>.
- [80] Collaboration, “Measurement of separate cosmic-ray electron and positron spectra with the fermi large area telescope”, *Physical Review Letters*, vol. 108, no. 1, 2012. doi: [10.1103/physrevlett.108.011103](https://doi.org/10.1103/physrevlett.108.011103). [Online]. Available: <https://doi.org/10.1103/physrevlett.108.011103>.
- [81] T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. K. N. Portillo, N. L. Rodd and T. R. Slatyer, “The characterization of the gamma-ray signal from the central Milky Way: A case for annihilating dark matter”, *Phys. Dark Univ.*, vol. 12, pp. 1–23, 2016. doi: [10.1016/j.dark.2015.12.005](https://doi.org/10.1016/j.dark.2015.12.005). arXiv: [1402.6703](https://arxiv.org/abs/1402.6703) [astro-ph.HE].
- [82] M. Ackermann *et al.*, “The Fermi Galactic Center GeV Excess and Implications for Dark Matter”, *Astrophys. J.*, vol. 840, no. 1, p. 43, 2017. doi: [10.3847/1538-4357/aa6cab](https://doi.org/10.3847/1538-4357/aa6cab). arXiv: [1704.03910](https://arxiv.org/abs/1704.03910) [astro-ph.HE].
- [83] ATIC collaboration, *Cosmic ray physics group*. [Online]. Available: <https://cosmicray.umd.edu/atic-home>.

- [84] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya *et al.*, “An anomalous positron abundance in cosmic rays with energies 1.5–100 gev”, *Nature*, vol. 458, no. 7238, pp. 607–609, 2009. doi: [10.1038/nature07942](https://doi.org/10.1038/nature07942). [Online]. Available: <https://doi.org/10.1038/nature07942>.
- [85] Collaboration, “Antiproton flux, antiproton-to-proton flux ratio, and properties of elementary particle fluxes in primary cosmic rays measured with the alpha magnetic spectrometer on the international space station”, *Phys. Rev. Lett.*, vol. 117, p. 091103, 9 2016. doi: [10.1103/PhysRevLett.117.091103](https://doi.org/10.1103/PhysRevLett.117.091103). [Online]. Available: <https://link.aps.org/doi/10.1103/PhysRevLett.117.091103>.
- [86] Auger Collaboration, *Auger*. [Online]. Available: <https://www.auger.org/>.
- [87] T. Tanaka *et al.*, “An Indirect Search for WIMPs in the Sun using 3109.6 days of upward-going muons in Super-Kamiokande”, *Astrophys. J.*, vol. 742, p. 78, 2011. doi: [10.1088/0004-637X/742/2/78](https://doi.org/10.1088/0004-637X/742/2/78). arXiv: [1108.3384](https://arxiv.org/abs/1108.3384) [astro-ph.HE].
- [88] D. Woodward, “Latest results of the lux dark matter experiment”, *International Journal of Modern Physics: Conference Series*, vol. 50, p. 2060002, 2020. doi: [10.1142/S2010194520600022](https://doi.org/10.1142/S2010194520600022). eprint: <https://doi.org/10.1142/S2010194520600022>. [Online]. Available: <https://doi.org/10.1142/S2010194520600022>.
- [89] M. G. Aartsen *et al.*, “Constraints on Ultrahigh-Energy Cosmic-Ray Sources from a Search for Neutrinos above 10 PeV with IceCube”, *Phys. Rev. Lett.*, vol. 117, no. 24, p. 241101, 2016, [Erratum: Phys.Rev.Lett. 119, 259902 (2017)]. doi: [10.1103/PhysRevLett.117.241101](https://doi.org/10.1103/PhysRevLett.117.241101). arXiv: [1607.05886](https://arxiv.org/abs/1607.05886) [astro-ph.HE].
- [90] A. Boveia *et al.*, “Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter”, *Phys. Dark Univ.*, vol. 27, O. Buchmueller, C. Doglioni, K. Hahn, U. Haisch, F. Kahlhoefer, M. Mangano, C. McCabe and T. M. P. Tait, Eds., p. 100365, 2020. doi: [10.1016/j.dark.2019.100365](https://doi.org/10.1016/j.dark.2019.100365). arXiv: [1603.04156](https://arxiv.org/abs/1603.04156) [hep-ex].
- [91] A. Albert *et al.*, “Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for dark matter mediators in visible and invisible decay channels and calculations of the thermal relic density”, *Phys. Dark Univ.*, vol. 26, p. 100377, 2019. doi: [10.1016/j.dark.2019.100377](https://doi.org/10.1016/j.dark.2019.100377). arXiv: [1703.05703](https://arxiv.org/abs/1703.05703) [hep-ex].
- [92] CMS EXO POG, *SummaryplotsEXO13TeV*. [Online]. Available: https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV#Moriond_2023.
- [93] M. Aaboud *et al.*, “Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector”, *Phys. Rev. D*, vol. 94, no. 3, p. 032005, 2016. doi: [10.1103/PhysRevD.94.032005](https://doi.org/10.1103/PhysRevD.94.032005). arXiv: [1604.07773](https://arxiv.org/abs/1604.07773) [hep-ex].
- [94] V. Khachatryan *et al.*, “Search for dark matter, extra dimensions, and unparticles in monojet events in proton–proton collisions at $\sqrt{s} = 8$ TeV”, *Eur. Phys. J. C*, vol. 75, no. 5, p. 235, 2015. doi: [10.1140/epjc/s10052-015-3451-4](https://doi.org/10.1140/epjc/s10052-015-3451-4). arXiv: [1408.3583](https://arxiv.org/abs/1408.3583) [hep-ex].
- [95] M. Aaboud *et al.*, “Search for dark matter at $\sqrt{s} = 13$ TeV in final states containing an energetic photon and large missing transverse momentum with the ATLAS detector”, *Eur. Phys. J. C*, vol. 77, no. 6, p. 393, 2017. doi: [10.1140/epjc/s10052-017-4965-8](https://doi.org/10.1140/epjc/s10052-017-4965-8). arXiv: [1704.03848](https://arxiv.org/abs/1704.03848) [hep-ex].
- [96] A. M. Sirunyan *et al.*, “Search for new physics in the monophoton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP*, vol. 10, p. 073, 2017. doi: [10.1007/JHEP10\(2017\)073](https://doi.org/10.1007/JHEP10(2017)073). arXiv: [1706.03794](https://arxiv.org/abs/1706.03794) [hep-ex].

- [97] M. Aaboud *et al.*, “Search for dark matter in events with a hadronically decaying vector boson and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP*, vol. 10, p. 180, 2018. doi: [10.1007/JHEP10\(2018\)180](https://doi.org/10.1007/JHEP10(2018)180). arXiv: [1807.11471](https://arxiv.org/abs/1807.11471) [hep-ex].
- [98] A. M. Sirunyan *et al.*, “Search for dark matter produced in association with a leptonically decaying Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Eur. Phys. J. C*, vol. 81, no. 1, p. 13, 2021, [Erratum: *Eur.Phys.J.C* 81, 333 (2021)]. doi: [10.1140/epjc/s10052-020-08739-5](https://doi.org/10.1140/epjc/s10052-020-08739-5). arXiv: [2008.04735](https://arxiv.org/abs/2008.04735) [hep-ex].
- [99] M. Aaboud *et al.*, “Search for new resonances in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Lett. B*, vol. 762, pp. 334–352, 2016. doi: [10.1016/j.physletb.2016.09.040](https://doi.org/10.1016/j.physletb.2016.09.040). arXiv: [1606.03977](https://arxiv.org/abs/1606.03977) [hep-ex].
- [100] V. Khachatryan *et al.*, “Search for heavy gauge W’ boson in events with an energetic lepton and large missing transverse momentum at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B*, vol. 770, pp. 278–301, 2017. doi: [10.1016/j.physletb.2017.04.043](https://doi.org/10.1016/j.physletb.2017.04.043). arXiv: [1612.09274](https://arxiv.org/abs/1612.09274) [hep-ex].
- [101] M. Aaboud *et al.*, “Search for dark matter produced in association with bottom or top quarks in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, *Eur. Phys. J. C*, vol. 78, no. 1, p. 18, 2018. doi: [10.1140/epjc/s10052-017-5486-1](https://doi.org/10.1140/epjc/s10052-017-5486-1). arXiv: [1710.11412](https://arxiv.org/abs/1710.11412) [hep-ex].
- [102] “Search for dark matter associated production with a single top quark in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, Aug. 2020.
- [103] V. Khachatryan *et al.*, “Search for the production of dark matter in association with top-quark pairs in the single-lepton final state in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP*, vol. 06, p. 121, 2015. doi: [10.1007/JHEP06\(2015\)121](https://doi.org/10.1007/JHEP06(2015)121). arXiv: [1504.03198](https://arxiv.org/abs/1504.03198) [hep-ex].
- [104] A. M. Sirunyan *et al.*, “Search for dark matter particles produced in association with a Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP*, vol. 03, p. 025, 2020. doi: [10.1007/JHEP03\(2020\)025](https://doi.org/10.1007/JHEP03(2020)025). arXiv: [1908.01713](https://arxiv.org/abs/1908.01713) [hep-ex].
- [105] T. Abe *et al.*, “LHC Dark Matter Working Group: Next-generation spin-0 dark matter models”, *Phys. Dark Univ.*, vol. 27, p. 100351, 2020. doi: [10.1016/j.dark.2019.100351](https://doi.org/10.1016/j.dark.2019.100351). arXiv: [1810.09420](https://arxiv.org/abs/1810.09420) [hep-ex].
- [106] M. Bauer, U. Haisch and F. Kahlhoefer, “Simplified dark matter models with two Higgs doublets: I. Pseudoscalar mediators”, *JHEP*, vol. 05, p. 138, 2017. doi: [10.1007/JHEP05\(2017\)138](https://doi.org/10.1007/JHEP05(2017)138). arXiv: [1701.07427](https://arxiv.org/abs/1701.07427) [hep-ph].
- [107] G. Aad *et al.*, “Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV”, *JHEP*, vol. 08, p. 045, 2016. doi: [10.1007/JHEP08\(2016\)045](https://doi.org/10.1007/JHEP08(2016)045). arXiv: [1606.02266](https://arxiv.org/abs/1606.02266) [hep-ex].
- [108] T. Abe, Y. Afik, A. Albert *et al.*, *Lhc dark matter working group: Next-generation spin-0 dark matter models*, 2018. arXiv: [1810.09420](https://arxiv.org/abs/1810.09420) [hep-ex].
- [109] L. Carpenter, A. DiFranzo, M. Mulhearn, C. Shimmin, S. Tulin and D. Whiteson, “Mono-higgs-boson: A new collider probe of dark matter”, *Physical Review D*, vol. 89, no. 7, 2014, issn: 1550-2368. doi: [10.1103/physrevd.89.075017](https://doi.org/10.1103/physrevd.89.075017). [Online]. Available: <http://dx.doi.org/10.1103/PhysRevD.89.075017>.
- [110] A. Berlin, T. Lin and L.-T. Wang, “Mono-higgs detection of dark matter at the lhc”, *Journal of High Energy Physics*, vol. 2014, no. 6, 2014, issn: 1029-8479. doi: [10.1007/jhep06\(2014\)078](https://doi.org/10.1007/jhep06(2014)078). [Online]. Available: [http://dx.doi.org/10.1007/JHEP06\(2014\)078](http://dx.doi.org/10.1007/JHEP06(2014)078).

- [111] L. Evans and P. Bryant, “LHC machine”, *Journal of Instrumentation*, vol. 3, no. 08, S08001–S08001, 2008. doi: [10.1088/1748-0221/3/08/S08001](https://doi.org/10.1088/1748-0221/3/08/S08001). [Online]. Available: <https://doi.org/10.1088/1748-0221/3/08/S08001>.
- [112] T. S. Pettersson and P. Lefèvre, “The Large Hadron Collider: conceptual design”, Tech. Rep., 1995. [Online]. Available: <https://cds.cern.ch/record/291782>.
- [113] E. Mobs, “The CERN accelerator complex - 2019. Complexe des accélérateurs du CERN - 2019”, 2019, General Photo. [Online]. Available: <https://cds.cern.ch/record/2684277>.
- [114] G. Aad *et al.*, “The ATLAS Experiment at the CERN Large Hadron Collider”, *JINST*, vol. 3, S08003, 2008. doi: [10.1088/1748-0221/3/08/S08003](https://doi.org/10.1088/1748-0221/3/08/S08003).
- [115] S. Chatrchyan *et al.*, “The CMS Experiment at the CERN LHC”, *JINST*, vol. 3, S08004, 2008. doi: [10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004).
- [116] K. Aamodt *et al.*, “The ALICE experiment at the CERN LHC”, *JINST*, vol. 3, S08002, 2008. doi: [10.1088/1748-0221/3/08/S08002](https://doi.org/10.1088/1748-0221/3/08/S08002).
- [117] A. A. Alves Jr. *et al.*, “The LHCb Detector at the LHC”, *JINST*, vol. 3, S08005, 2008. doi: [10.1088/1748-0221/3/08/S08005](https://doi.org/10.1088/1748-0221/3/08/S08005).
- [118] R. Aaij *et al.*, “Observation of CP Violation in Charm Decays”, *Phys. Rev. Lett.*, vol. 122, no. 21, p. 211 803, 2019. doi: [10.1103/PhysRevLett.122.211803](https://doi.org/10.1103/PhysRevLett.122.211803). arXiv: [1903.08726 \[hep-ex\]](https://arxiv.org/abs/1903.08726).
- [119] R. S. Bhalerao and R. V. Gavai, “Heavy Ions at LHC: A Quest for Quark-Gluon Plasma”, in *Physics at the Large Hadron Collider*, A. Datta, B. Mukhopadhyaya, A. Raychaudhuri, A. K. Gupta, C. L. Khetrapal, T. Padmanabhan and M. Vijayan, Eds. 2009, pp. 105–130. doi: [10.1007/978-81-8489-295-6_8](https://doi.org/10.1007/978-81-8489-295-6_8). arXiv: [0812.1619 \[hep-ph\]](https://arxiv.org/abs/0812.1619).
- [120] M. Albrow *et al.*, “CMS-TOTEM Precision Proton Spectrometer”, Sep. 2014.
- [121] O. Adriani *et al.*, “Technical design report of the LHCf experiment: Measurement of photons and neutral pions in the very forward region of LHC”, Feb. 2006.
- [122] A. Ariga *et al.*, “FASER: ForwArd Search ExpeRiment at the LHC”, Jan. 2019. arXiv: [1901.04468 \[hep-ex\]](https://arxiv.org/abs/1901.04468).
- [123] J. Pinfold *et al.*, “Technical Design Report of the MoEDAL Experiment”, Jun. 2009.
- [124] CMS Lumi, *Lumipublicresults*. [Online]. Available: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults>.
- [125] CMS, *Dataquality*. [Online]. Available: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/DataQuality>.
- [126] J. M. Campbell, J. W. Huston and W. J. Stirling, “Hard interactions of quarks and gluons: A primer for LHC physics”, *Reports on Progress in Physics*, vol. 70, no. 1, pp. 89–193, 2006. doi: [10.1088/0034-4885/70/1/r02](https://doi.org/10.1088/0034-4885/70/1/r02). [Online]. Available: <https://doi.org/10.1088/0034-4885/70/1/r02>.
- [127] T. Sakuma, “Cutaway diagrams of CMS detector”, 2019. [Online]. Available: <https://cds.cern.ch/record/2665537>.
- [128] Izaak Neutelings, *Cms coordinate system*. [Online]. Available: https://tikz.net/axis3d_cms/.

- [129] S. Chatrchyan *et al.*, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST*, vol. 9, no. 10, P10009, 2014. doi: [10.1088/1748-0221/9/10/P10009](https://doi.org/10.1088/1748-0221/9/10/P10009). arXiv: [1405.6569](https://arxiv.org/abs/1405.6569) [physics.ins-det].
- [130] “CMS Technical Design Report for the Pixel Detector Upgrade”, D. A. Matzner Dominguez *et al.*, Eds., Sep. 2012. doi: [10.2172/1151650](https://doi.org/10.2172/1151650).
- [131] A. Tricomi, “Upgrade of the cms tracker”, *Journal of Instrumentation*, vol. 9, no. 03, p. C03041, 2014. doi: [10.1088/1748-0221/9/03/C03041](https://doi.org/10.1088/1748-0221/9/03/C03041). [Online]. Available: <https://dx.doi.org/10.1088/1748-0221/9/03/C03041>.
- [132] V. Karimäki, “The CMS tracker system project: Technical Design Report”, M. Mannelli, P. Siegrist, H. Breuker, A. Caner, R. Castaldi, K. Freudenreich, G. Hall, R. Horisberger, M. Huhtinen and A. Cattai, Eds., 1997.
- [133] *The CMS electromagnetic calorimeter project: Technical Design Report*, ser. Technical design report. CMS. Geneva: CERN, 1997. [Online]. Available: <https://cds.cern.ch/record/349375>.
- [134] *CMS Physics: Technical Design Report Volume 1: Detector Performance and Software*, ser. Technical design report. CMS. Geneva: CERN, 2006, There is an error on cover due to a technical problem for some items. [Online]. Available: <http://cds.cern.ch/record/922757>.
- [135] Q. Ingram, “Energy resolution of the barrel of the CMS electromagnetic calorimeter”, *Journal of Instrumentation*, vol. 2, no. 04, P04004–P04004, 2007. doi: [10.1088/1748-0221/2/04/p04004](https://doi.org/10.1088/1748-0221/2/04/p04004). [Online]. Available: <https://doi.org/10.1088/1748-0221/2/04/p04004>.
- [136] A. M. Sirunyan *et al.*, “Calibration of the CMS hadron calorimeters using proton-proton collision data at $\sqrt{s} = 13$ TeV”, *JINST*, vol. 15, no. 05, P05002, 2020. doi: [10.1088/1748-0221/15/05/P05002](https://doi.org/10.1088/1748-0221/15/05/P05002). arXiv: [1910.00079](https://arxiv.org/abs/1910.00079) [physics.ins-det].
- [137] *The CMS hadron calorimeter project: Technical Design Report*, ser. Technical design report. CMS. Geneva: CERN, 1997, The following files are from http://uscms.fnal.gov/pub/hcal_tdr and may not be the version as printed, please check the printed version to be sure. [Online]. Available: <http://cds.cern.ch/record/357153>.
- [138] J. G. Layter, *The CMS muon project: Technical Design Report*, ser. Technical design report. CMS. Geneva: CERN, 1997. [Online]. Available: <https://cds.cern.ch/record/343814>.
- [139] V. Khachatryan *et al.*, “The CMS trigger system”, *JINST*, vol. 12, no. 01, P01020, 2017. doi: [10.1088/1748-0221/12/01/P01020](https://doi.org/10.1088/1748-0221/12/01/P01020). arXiv: [1609.02366](https://arxiv.org/abs/1609.02366) [physics.ins-det].
- [140] A. M. Sirunyan *et al.*, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST*, vol. 15, no. 10, P10017, 2020. doi: [10.1088/1748-0221/15/10/P10017](https://doi.org/10.1088/1748-0221/15/10/P10017). arXiv: [2006.10165](https://arxiv.org/abs/2006.10165) [hep-ex].
- [141] H. Sert, “CMS Run 2 High Level Trigger Performance”, *PoS*, vol. EPS-HEP2019, p. 165, 2020. doi: [10.22323/1.364.0165](https://doi.org/10.22323/1.364.0165).
- [142] V. Azzolini, B. van Besien, D. Bugelskis, T. Hreus, K. Maeshima, J. Fernandez Menendez, A. Norkus, J. F. Patrick, M. Rovere and M. A. Schneider, “The Data Quality Monitoring software for the CMS experiment at the LHC: past, present and future”, *EPJ Web Conf.*, vol. 214, p. 02003, 2019. doi: [10.1051/epjconf/201921402003](https://doi.org/10.1051/epjconf/201921402003). [Online]. Available: <https://cds.cern.ch/record/2701776>.

- [143] R. Brun and F. Rademakers, “Root — an object oriented data analysis framework”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 389, no. 1, pp. 81–86, 1997, New Computing Techniques in Physics Research V, issn: 0168-9002. doi: [https://doi.org/10.1016/S0168-9002\(97\)00048-X](https://doi.org/10.1016/S0168-9002(97)00048-X). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S016890029700048X>.
- [144] T. C. Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *Journal of Instrumentation*, vol. 12, no. 10, P10003–P10003, 2017. doi: [10.1088/1748-0221/12/10/p10003](https://doi.org/10.1088/1748-0221/12/10/p10003). [Online]. Available: <https://doi.org/10.1088/1748-0221/12/10/p10003>.
- [145] P. Billoir, “Progressive track recognition with a kalman-like fitting procedure”, *Computer Physics Communications*, vol. 57, no. 1, pp. 390–394, 1989, issn: 0010-4655. doi: [https://doi.org/10.1016/0010-4655\(89\)90249-X](https://doi.org/10.1016/0010-4655(89)90249-X). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/001046558990249X>.
- [146] P. Billoir and S. Qian, “Simultaneous pattern recognition and track fitting by the kalman filtering method”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 294, no. 1, pp. 219–228, 1990, issn: 0168-9002. doi: [https://doi.org/10.1016/0168-9002\(90\)91835-Y](https://doi.org/10.1016/0168-9002(90)91835-Y). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/016890029091835Y>.
- [147] R. Mankel, “A concurrent track evolution algorithm for pattern recognition in the hera-b main tracking system”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 395, no. 2, pp. 169–184, 1997, issn: 0168-9002. doi: [https://doi.org/10.1016/S0168-9002\(97\)00705-5](https://doi.org/10.1016/S0168-9002(97)00705-5). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168900297007055>.
- [148] R. Frühwirth, “Application of kalman filtering to track and vertex fitting”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 262, no. 2, pp. 444–450, 1987, issn: 0168-9002. doi: [https://doi.org/10.1016/0168-9002\(87\)90887-4](https://doi.org/10.1016/0168-9002(87)90887-4). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/0168900287908874>.
- [149] A. Strandlie and W. Wittek, “Propagation of Covariance Matrices of Track Parameters in Homogeneous Magnetic Fields in CMS”, CERN, Geneva, Tech. Rep., 2006. [Online]. Available: <http://cds.cern.ch/record/927379>.
- [150] J. R. Cash and A. H. Karp, “A variable order runge-kutta method for initial value problems with rapidly varying right-hand sides”, *ACM Trans. Math. Softw.*, vol. 16, no. 3, 201–222, 1990, issn: 0098-3500. doi: [10.1145/79505.79507](https://doi.org/10.1145/79505.79507). [Online]. Available: <https://doi.org/10.1145/79505.79507>.
- [151] T. C. Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *Journal of Instrumentation*, vol. 9, no. 10, P10009–P10009, 2014. doi: [10.1088/1748-0221/9/10/p10009](https://doi.org/10.1088/1748-0221/9/10/p10009). [Online]. Available: <https://doi.org/10.1088/1748-0221/9/10/p10009>.
- [152] M. Cacciari, G. P. Salam and G. Soyez, “The anti kt jet clustering algorithm”, *Journal of High Energy Physics*, vol. 2008, no. 04, pp. 063–063, 2008. doi: [10.1088/1126-6708/2008/04/063](https://doi.org/10.1088/1126-6708/2008/04/063). [Online]. Available: <https://doi.org/10.1088/1126-6708/2008/04/063>.

- [153] M. Cacciari, G. P. Salam and G. Soyez, “FastJet user manual”, *The European Physical Journal C*, vol. 72, no. 3, 2012. doi: [10.1140/epjc/s10052-012-1896-2](https://doi.org/10.1140/epjc/s10052-012-1896-2). [Online]. Available: [https://doi.org/10.1140%2Fepjc%2Fs10052-012-1896-2](https://doi.org/10.1140/2Fepjc%2Fs10052-012-1896-2).
- [154] M. S. and, “Performance of jets at CMS”, *Journal of Physics: Conference Series*, vol. 587, p. 012004, 2015. doi: [10.1088/1742-6596/587/1/012004](https://doi.org/10.1088/1742-6596/587/1/012004). [Online]. Available: <https://doi.org/10.1088/1742-6596/587/1/012004>.
- [155] T. C. collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *Journal of Instrumentation*, vol. 6, no. 11, P11002–P11002, 2011. doi: [10.1088/1748-0221/6/11/p11002](https://doi.org/10.1088/1748-0221/6/11/p11002). [Online]. Available: <https://doi.org/10.1088/1748-0221/6/11/p11002>.
- [156] “Jet energy scale and resolution measurement with Run 2 Legacy Data Collected by CMS at 13 TeV”, 2021. [Online]. Available: <http://cds.cern.ch/record/2792322>.
- [157] “Jet energy scale and resolution performance with 13 TeV data collected by CMS in 2016-2018”, 2020. [Online]. Available: <https://cds.cern.ch/record/2715872>.
- [158] B. Clerbaux, S. Elgammal, T. Mahmoud and P. E. Marage, “Saturation and Energy Corrections for TeV Electrons and Photons”, CERN, Geneva, Tech. Rep., 2006. [Online]. Available: <http://cds.cern.ch/record/1009074>.
- [159] V. Khachatryan *et al.*, “Performance of Electron Reconstruction and Selection with the CMS Detector in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV”, *JINST*, vol. 10, no. 06, P06005, 2015. doi: [10.1088/1748-0221/10/06/P06005](https://doi.org/10.1088/1748-0221/10/06/P06005). arXiv: [1502.02701](https://arxiv.org/abs/1502.02701) [physics.ins-det].
- [160] W. Adam, R. Fruhwirth, A. Strandlie and T. Todorov, “Reconstruction of electrons with the Gaussian sum filter in the CMS tracker at LHC”, *eConf*, vol. C0303241, TULT009, 2003. doi: [10.1088/0954-3899/31/9/N01](https://doi.org/10.1088/0954-3899/31/9/N01). arXiv: [physics/0306087](https://arxiv.org/abs/physics/0306087).
- [161] A. M. Sirunyan *et al.*, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST*, vol. 13, no. 06, P06015, 2018. doi: [10.1088/1748-0221/13/06/P06015](https://doi.org/10.1088/1748-0221/13/06/P06015). arXiv: [1804.04528](https://arxiv.org/abs/1804.04528) [physics.insdet].
- [162] T. C. collaboration, “Performance of cms muon reconstruction in pp collision events at $\sqrt{s} = 7$ tev”, *Journal of Instrumentation*, vol. 7, no. 10, P10002, 2012. doi: [10.1088/1748-0221/7/10/P10002](https://doi.org/10.1088/1748-0221/7/10/P10002). [Online]. Available: <https://dx.doi.org/10.1088/1748-0221/7/10/P10002>.
- [163] V. Khachatryan *et al.*, “Performance of Photon Reconstruction and Identification with the CMS Detector in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV”, *JINST*, vol. 10, no. 08, P08010, 2015. doi: [10.1088/1748-0221/10/08/P08010](https://doi.org/10.1088/1748-0221/10/08/P08010). arXiv: [1502.02702](https://arxiv.org/abs/1502.02702) [physics.ins-det].
- [164] “Performance of reconstruction and identification of tau leptons in their decays to hadrons and tau neutrino in LHC Run-2”, 2016.
- [165] S. Choudhury, “Tau Identification at the CMS Experiment in LHC Run-2”, *Int. J. Mod. Phys. Conf. Ser.*, vol. 46, p. 1860055, 2018. doi: [10.1142/S2010194518600558](https://doi.org/10.1142/S2010194518600558). [Online]. Available: <http://cds.cern.ch/record/2672956>.
- [166] C. Collaboration, “Performance of tau-lepton reconstruction and identification in cms”, *Journal of Instrumentation*, vol. 7, no. 01, P01001, 2012. doi: [10.1088/1748-0221/7/01/P01001](https://doi.org/10.1088/1748-0221/7/01/P01001). [Online]. Available: <https://dx.doi.org/10.1088/1748-0221/7/01/P01001>.

- [167] “Performance of missing energy reconstruction in 13 TeV pp collision data using the CMS detector”, CERN, Geneva, Tech. Rep., 2016. [Online]. Available: <https://cds.cern.ch/record/2205284>.
- [168] M. R. Whalley, D. Bourilkov and R. C. Group, “The Les Houches accord PDFs (LHAPDF) and LHA-GLUE”, in *HERA and the LHC: A Workshop on the Implications of HERA and LHC Physics (Startup Meeting, CERN, 26-27 March 2004; Midterm Meeting, CERN, 11-13 October 2004)*, Aug. 2005, pp. 575–581. arXiv: [hep-ph/0508110](https://arxiv.org/abs/hep-ph/0508110).
- [169] “Geant4—a simulation toolkit”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250–303, 2003, issn: 0168-9002. doi: [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- [170] S. Höche, “Introduction to parton-shower event generators”, in *Theoretical Advanced Study Institute in Elementary Particle Physics: Journeys Through the Precision Frontier: Amplitudes for Colliders*, 2015, pp. 235–295. doi: [10.1142/9789814678766_0005](https://doi.org/10.1142/9789814678766_0005). arXiv: [1411.4085](https://arxiv.org/abs/1411.4085) [hep-ph].
- [171] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli and M. Zaro, “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *Journal of High Energy Physics*, vol. 2014, no. 7, 2014. doi: [10.1007/jhep07\(2014\)079](https://doi.org/10.1007/jhep07(2014)079). [Online]. Available: [https://doi.org/10.1007/JHEP07\(2014\)079](https://doi.org/10.1007/JHEP07(2014)079).
- [172] C. Oleari, “The POWHEG-BOX”, *Nucl. Phys. B Proc. Suppl.*, vol. 205-206, J. Blümlein, S.-O. Moch and T. Riemann, Eds., pp. 36–41, 2010. doi: [10.1016/j.nuclphysbps.2010.08.016](https://doi.org/10.1016/j.nuclphysbps.2010.08.016). arXiv: [1007.3893](https://arxiv.org/abs/1007.3893) [hep-ph].
- [173] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen and P. Z. Skands, “An introduction to pythia 8.2”, *Computer Physics Communications*, vol. 191, 159–177, 2015, issn: 0010-4655. doi: [10.1016/j.cpc.2015.01.024](https://doi.org/10.1016/j.cpc.2015.01.024). [Online]. Available: <http://dx.doi.org/10.1016/j.cpc.2015.01.024>.
- [174] A. M. Sirunyan *et al.*, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C*, vol. 80, no. 1, p. 4, 2020. doi: [10.1140/epjc/s10052-019-7499-4](https://doi.org/10.1140/epjc/s10052-019-7499-4). arXiv: [1903.12179](https://arxiv.org/abs/1903.12179) [hep-ex].
- [175] R. D. Ball *et al.*, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C*, vol. 77, no. 10, p. 663, 2017. doi: [10.1140/epjc/s10052-017-5199-5](https://doi.org/10.1140/epjc/s10052-017-5199-5). arXiv: [1706.00428](https://arxiv.org/abs/1706.00428) [hep-ph].
- [176] A. Tumasyan *et al.*, “Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP*, vol. 11, p. 153, 2021. doi: [10.1007/JHEP11\(2021\)153](https://doi.org/10.1007/JHEP11(2021)153). arXiv: [2107.13021](https://arxiv.org/abs/2107.13021) [hep-ex].
- [177] A. M. Sirunyan *et al.*, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST*, vol. 16, no. 05, P05014, 2021. doi: [10.1088/1748-0221/16/05/P05014](https://doi.org/10.1088/1748-0221/16/05/P05014). arXiv: [2012.06888](https://arxiv.org/abs/2012.06888) [hep-ex].
- [178] M. Cacciari, G. P. Salam and G. Soyez, “The anti- k_t jet clustering algorithm”, *JHEP*, vol. 04, p. 063, 2008. doi: [10.1088/1126-6708/2008/04/063](https://doi.org/10.1088/1126-6708/2008/04/063). arXiv: [0802.1189](https://arxiv.org/abs/0802.1189) [hep-ph].
- [179] T. C. collaboration, “Determination of jet energy calibration and transverse momentum resolution in cms”, *Journal of Instrumentation*, vol. 6, no. 11, P11002–P11002, 2011, issn: 1748-0221. doi: [10.1088/1748-0221/6/11/p11002](https://doi.org/10.1088/1748-0221/6/11/p11002). [Online]. Available: <http://dx.doi.org/10.1088/1748-0221/6/11/P11002>.

- [180] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, *Physics Letters B*, vol. 659, no. 1-2, 119–126, 2008, ISSN: 0370-2693. DOI: [10.1016/j.physletb.2007.09.077](https://doi.org/10.1016/j.physletb.2007.09.077). [Online]. Available: <http://dx.doi.org/10.1016/j.physletb.2007.09.077>.
- [181] A. M. Sirunyan *et al.*, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST*, vol. 13, no. 05, P05011, 2018. DOI: [10.1088/1748-0221/13/05/P05011](https://doi.org/10.1088/1748-0221/13/05/P05011). arXiv: [1712.07158 \[physics.ins-det\]](https://arxiv.org/abs/1712.07158).
- [182] T. C. collaboration, “Identification of b-quark jets with the cms experiment”, *Journal of Instrumentation*, vol. 8, no. 04, P04013–P04013, 2013, ISSN: 1748-0221. DOI: [10.1088/1748-0221/8/04/p04013](https://doi.org/10.1088/1748-0221/8/04/p04013). [Online]. Available: <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>.
- [183] D. Bertolini, P. Harris, M. Low and N. Tran, “Pileup per particle identification”, *Journal of High Energy Physics*, vol. 2014, no. 10, 2014, ISSN: 1029-8479. DOI: [10.1007/jhep10\(2014\)059](https://doi.org/10.1007/jhep10(2014)059). [Online]. Available: [http://dx.doi.org/10.1007/JHEP10\(2014\)059](http://dx.doi.org/10.1007/JHEP10(2014)059).
- [184] J. Thaler and K. Van Tilburg, “Identifying boosted objects with n-subjettiness”, *Journal of High Energy Physics*, vol. 2011, no. 3, 2011, ISSN: 1029-8479. DOI: [10.1007/jhep03\(2011\)015](https://doi.org/10.1007/jhep03(2011)015). [Online]. Available: [http://dx.doi.org/10.1007/JHEP03\(2011\)015](http://dx.doi.org/10.1007/JHEP03(2011)015).
- [185] A. J. Larkoski, S. Marzani, G. Soyez and J. Thaler, “Soft Drop”, *JHEP*, vol. 05, p. 146, 2014. DOI: [10.1007/JHEP05\(2014\)146](https://doi.org/10.1007/JHEP05(2014)146). arXiv: [1402.2657 \[hep-ph\]](https://arxiv.org/abs/1402.2657).
- [186] “Performance of Deep Tagging Algorithms for Boosted Double Quark Jet Topology in Proton-Proton Collisions at 13 TeV with the Phase-0 CMS Detector”, 2018. [Online]. Available: <http://cds.cern.ch/record/2630438>.
- [187] M. Czakon, D. Heymes, A. Mitov, D. Pagani, I. Tsinikos and M. Zaro, “Top-pair production at the LHC through NNLO QCD and NLO EW”, *JHEP*, vol. 10, p. 186, 2017. DOI: [10.1007/JHEP10\(2017\)186](https://doi.org/10.1007/JHEP10(2017)186). arXiv: [1705.04105 \[hep-ph\]](https://arxiv.org/abs/1705.04105).
- [188] A. M. Sirunyan *et al.*, “A Deep Neural Network for Simultaneous Estimation of b Jet Energy and Resolution”, *Comput. Softw. Big Sci.*, vol. 4, no. 1, p. 10, 2020. DOI: [10.1007/s41781-020-00041-z](https://doi.org/10.1007/s41781-020-00041-z). arXiv: [1912.06046 \[hep-ex\]](https://arxiv.org/abs/1912.06046).
- [189] G. Cowan, K. Cranmer, E. Gross and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C*, vol. 71, p. 1554, 2011, [Erratum: *Eur.Phys.J.C* 73, 2501 (2013)]. DOI: [10.1140/epjc/s10052-011-1554-0](https://doi.org/10.1140/epjc/s10052-011-1554-0). arXiv: [1007.1727 \[physics.data-an\]](https://arxiv.org/abs/1007.1727).
- [190] S. S. Wilks, “The Large-Sample Distribution of the Likelihood Ratio for Testing Composite Hypotheses”, *Annals Math. Statist.*, vol. 9, no. 1, pp. 60–62, 1938. DOI: [10.1214/aoms/1177732360](https://doi.org/10.1214/aoms/1177732360).
- [191] A. L. Read, “Presentation of search results: The cls technique”, *Journal of Physics G: Nuclear and Particle Physics*, vol. 28, no. 10, pp. 2693–2704, 2002. DOI: [10.1088/0954-3899/28/10/313](https://doi.org/10.1088/0954-3899/28/10/313). [Online]. Available: <https://doi.org/10.1088/0954-3899/28/10/313>.
- [192] “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, 2018.
- [193] “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, 2019.
- [194] combine, *Higgsanalysis combinedlimit*. [Online]. Available: <http://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/part2/bin-wise-stats/>.

- [195] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 434, no. 2-3, pp. 435–443, 1999. doi: [10.1016/S0168-9002\(99\)00498-2](https://doi.org/10.1016/S0168-9002(99)00498-2). [Online]. Available: <https://doi.org/10.1016%2Fs0168-9002%2899%2900498-2>.
- [196] G. Cowan, K. Cranmer, E. Gross and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *The European Physical Journal C*, vol. 71, no. 2, 2011. doi: [10.1140/epjc/s10052-011-1554-0](https://doi.org/10.1140/epjc/s10052-011-1554-0). [Online]. Available: <https://doi.org/10.1140%2Fepjc%2Fs10052-011-1554-0>.
- [197] LHC team, *HL-LHC-project*. [Online]. Available: <https://hilumilhc.web.cern.ch/content/hl-lhc-project>.
- [198] E. Bols, J. Kieseler, M. Verzetti, M. Stoye and A. Stakia, “Jet Flavour Classification Using DeepJet”, *JINST*, vol. 15, no. 12, P12012, 2020. doi: [10.1088/1748-0221/15/12/P12012](https://doi.org/10.1088/1748-0221/15/12/P12012). arXiv: [2008.10519](https://arxiv.org/abs/2008.10519) [hep-ex].