

Search for disappearing tracks in proton-proton collisions at
 $\sqrt{s} = 13 \text{ TeV}$

Dissertation

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Abstract

A search is presented for long-lived charged particles that decay within the CMS detector and produce the signature of a disappearing track. A disappearing track is an isolated track with no associated hits in the muon detectors, small associated calorimeter energy deposits, and missing hits in the outer layers of the silicon tracker. The search uses 38.4 fb^{-1} of proton-proton collision data collected by the CMS detector in 2015 and 2016, at a center-of-mass energy of 13 TeV at the CERN LHC. The results of the search are interpreted in the context of anomaly-mediated supersymmetry breaking. The observation is consistent with the background-only hypothesis, and limits are set on the product of the cross section of direct chargino production and the branching fraction to a neutralino and a pion in terms of the chargino mass and lifetime. At 95% confidence level, charginos with masses less than 715 GeV are excluded for a lifetime of 3 ns.

This thesis is dedicated to my mother, Patricia.

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Vardan Khachatryan et al. Search for Displaced Supersymmetry in events with an electron and a muon with large impact parameters. *Phys. Rev. Lett.*, 114(6):061801, 2015.

Fields of Study

Major Field: Physics

Table of Contents

	Page
Abstract	ii
Dedication	iii
Vita	iv
List of Tables	viii
List of Figures	xiv
1. Introduction	1
1.1 Standard model	2
1.1.1 Electroweak symmetry breaking	4
1.1.2 Higgs mechanism	5
1.2 Hierarchy problem and supersymmetry	7
1.2.1 Hierarchy problem	7
1.2.2 Supersymmetry	8
1.2.3 Phenomenology of anomaly-mediated supersymmetry breaking	10
2. Large Hadron Collider and Compact Muon Solenoid detector	15
2.1 Large Hadron Collider	15
2.1.1 Injection chain	16
2.1.2 Magnets	19
2.1.3 Radiofrequency system	22
2.2 Compact Muon Solenoid detector	24
2.2.1 Coordinate system and common variables	27
2.2.2 Solenoid magnet	28
2.2.3 Tracker	31

2.2.4	Electromagnetic calorimeter	35
2.2.5	Hadron calorimeter	36
2.2.6	Muon system	40
2.2.7	Trigger system	47
2.2.8	Physics object reconstruction	48
3.	Search for disappearing tracks	54
3.1	Samples of experimental and simulated data	57
3.1.1	Experimental data	57
3.1.2	Simulated signal events	57
3.1.3	Simulated background events	61
3.2	Triggers	67
3.2.1	Use of p_T^{miss}	67
3.2.2	Triggers used in the search	71
3.3	Event selections	75
3.3.1	Fiducial track selections	75
3.3.2	Search region	83
3.4	Background estimation	99
3.4.1	Charged leptons	99
3.4.2	Fake tracks	123
3.5	Corrections to the simulated signal samples	132
3.5.1	Pileup scale factors	132
3.5.2	Missing hits corrections	133
3.5.3	Trigger efficiency scale factors	135
3.5.4	ISR scale factors	140
3.6	Systematic uncertainties	143
3.6.1	Uncertainties in background estimates	143
3.6.2	Uncertainties in signal selection efficiencies	148
3.7	Results	163
4.	Conclusion	168
Appendices		174
A.	Object identification criteria	174
B.	Initial unblinding of 2015 data	179

C.	Effect of $p_{\text{T}}^{\text{miss}}$ filters on signal acceptance	188
D.	Use of $p_{\text{T}}^{\text{miss, no } \mu}$	190
E.	Signal acceptance for $\text{pp} \rightarrow \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ vs. $\text{pp} \rightarrow \tilde{\chi}_1^{\pm} \tilde{\chi}_1^0$	192
F.	Trigger efficiencies of inclusive $p_{\text{T}}^{\text{miss}}$ paths	194
G.	Algorithms for finding missing hits corrections	200
	G.1 Algorithm for finding missing middle hits correction	200
	G.2 Algorithm for finding missing outer hits corrections	202
	Bibliography	204

List of Tables

Table		Page
3.1	Supersymmetry parameters used to generate simulated signal samples for each of the chargino masses we consider. The large mass scale of the squarks is indicated by $m(\tilde{d})$, the mass of the down squark. For each point, m_0 , $\tan\beta$, and $\text{sign}(\mu)$ are not varied and are set to 1 500 GeV, 5, and +1, respectively. These parameters are described in the text. .	58
3.2	Cross sections for chargino production calculated at NLO+NLL. The cross sections for $\text{pp} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\text{pp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ are listed separately, along with the total cross section, which is the sum of these two contributions.	58
3.3	Target chargino lifetimes achieved via lifetime reweighting and the original lifetime of the sample from which they are reweighted.	59
3.4	Names of the samples of simulated non-QCD multijet background processes used to study and validate the background estimation methods.	62
3.5	Names of the samples of simulated QCD multijet background processes used to study and validate the background estimation methods. . . .	63
3.6	Cross sections and equivalent integrated luminosities of the samples of simulated non-QCD multijet background processes used to study and validate the background estimation methods.	64
3.7	Cross sections and equivalent integrated luminosities of the samples of simulated QCD multijet background processes used to study and validate the background estimation methods.	65
3.8	Names of the samples of simulated background processes generated during the 2016 campaign.	65

3.9	Cross sections and equivalent integrated luminosities of the samples of simulated background processes generated during the 2016 campaign.	66
3.10	Triggers used in the search and for background estimation and systematic uncertainty evaluation for the data collected in 2015. The italicized trigger paths are those that were only available in the simulated samples but were not included in the menu during data-taking.	71
3.11	Triggers used in the search and for background estimation and systematic uncertainty evaluation for the data collected in 2016.	72
3.12	L1 seeds for our <code>HLT_MET75_IsoTrk50_v*</code> path for different run periods.	73
3.13	Selections used in the tag-and-probe study of electron reconstruction inefficiency. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria. The selected electron is the tag, while the selected track is the probe. . . .	80
3.14	Selections used in the tag-and-probe study of muon reconstruction inefficiency. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria. The selected muon is the tag, while the selected track is the probe.	81
3.15	The criteria defining the <i>basic selection</i> . The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	83
3.16	The criteria defining the <i>isolated track selection</i> . The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	86
3.17	Criteria used to reduce the contribution of fake tracks from the track-based isolation sum.	87
3.18	The criteria defining the <i>candidate track selection</i> . The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria. All reconstructed electrons and muons are used during this matching, in order to reject as many leptons as possible. Hadronic taus for this matching are identified using the criteria listed above in Table A.11, except that the isolation criterion.	93

3.19	The criteria defining the <i>disappearing track selection</i> . The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	93
3.20	Definitions of the lepton vetoes that are studied with the <i>tag-and-probe samples</i> in Section 3.4.1.	101
3.21	The criteria defining the <i>tau tag-and-probe sample</i> with an electron tag. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	102
3.22	The criteria defining the <i>tau tag-and-probe sample</i> with a muon tag. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	103
3.23	The criteria defining the <i>single-electron control sample</i> . The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	109
3.24	The criteria defining the <i>single-muon control sample</i> . The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	109
3.25	The criteria defining the <i>single-tau control sample</i> . The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	110
3.26	Electron background estimates for each run period considered in the search, along with the quantities used to calculate each estimate. The rightmost column is simply the product of the middle four columns. .	121
3.27	Muon background estimates for each run period considered in the search, along with the quantities used to calculate each estimate. The rightmost column is simply the product of the middle four columns. .	121
3.28	Tau background estimates for each run period considered in the search, along with the quantities used to calculate each estimate. The rightmost column is simply the product of the middle four columns. . . .	121

3.29	Results of lepton background closure test in simulated samples with relaxed selection criteria. The numbers of events are normalized to 2.7 fb^{-1} , the luminosity of the 2015 data set.	123
3.30	Results of lepton background closure test in simulated samples from the 2016 campaign. The numbers of events are normalized to 35.7 fb^{-1} , the luminosity of the 2016 data set.	124
3.31	The criteria defining the $Z \rightarrow \mu\mu$ <i>control sample</i> . The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.	125
3.32	Values of the raw fake track event probability and the sideband transfer factor for each run period.	126
3.33	Summary of estimated background event counts resulting from fake tracks. The uncertainties are statistical only.	126
3.34	Comparison of the fake track event probabilities, P_{fake} , and fake track background estimates, $N_{\text{est}}^{\text{fake}}$, obtained from the $Z \rightarrow \mu\mu$ control region and basic selection.	127
3.35	Fraction of tracks in the d_{xy} sideband that are identified as fake in simulated background events for various numbers of hits.	129
3.36	Sideband transfer factor calculated using only fake tracks from the simulated background samples as a function of the number of hits on the track. Both the transfer factor and the difference from the transfer factor for ≥ 7 hits is shown in the center and far-right columns, respectively.	131
3.37	Values for the hit removal probabilities obtained by fitting the missing middle and outer hit distributions from simulated background events to those distributions from experimental data. These values are used to randomly remove hits from the nominal hit patterns of tracks in simulated signal events.	135
3.38	<i>Base trigger selection</i> used to select events used to measure the efficiency of the HLT_MET75_IsoTrk50_v* trigger.	138

3.39	Summary of systematic uncertainties on the fake track background estimate.	145
3.40	P_{offline} and P_{trigger} calculated with the nominal and scaled down versions of the $ \vec{p}_T^{\text{miss, no } \mu} + \vec{p}_T^{\text{lepton}} $ distribution described in the text for events in the single electron control sample, as well as the resulting systematic uncertainty.	147
3.41	P_{offline} and P_{trigger} calculated with the nominal and scaled down versions of the $ \vec{p}_T^{\text{miss, no } \mu} + \vec{p}_T^{\text{lepton}} $ distribution described in the text for events in the single tau control sample, as well as the resulting systematic uncertainty.	147
3.42	Efficiency of the zero missing inner hits criterion for tracks in the muon control region in experimental data and simulation, as well as the resulting systematic uncertainty.	150
3.43	Efficiency of the zero missing middle hits criterion for tracks in the muon control region in experimental data and simulation, as well as the resulting systematic uncertainty.	150
3.44	Average value of the systematic uncertainty resulting from the uncertainty on the p_T^{miss} for each object type whose p_T is varied.	158
3.45	Efficiency of the $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$ criterion for tracks with at most 4 hits in the $Z \rightarrow \mu\mu$ control region in experimental data and simulation, as well as the resulting systematic uncertainty.	160
3.46	Typical values of the systematic uncertainties on the signal yields taken from simulation. The total listed on the last line is simply the sum in quadrature of each of the individual uncertainties.	162
3.47	Summary of numbers of events for the estimated backgrounds and the observed data. The uncertainties include those from statistical and systematic sources.	163
A.1	Standard criteria used to select primary vertices.	174
A.2	Tight jet ID with lepton veto defined by the Jet POG.	174

A.3	Tight electron ID defined by the Egamma POG for the 2015 data for electrons in the barrel ($ \eta < 0.1.479$).	175
A.4	Tight electron ID defined by the Egamma POG for the 2015 data for electrons in the endcaps ($0.1.479 < \eta < 2.5$).	175
A.5	Tight electron ID defined by the Egamma POG for the 2016 data for electrons in the barrel ($ \eta < 0.1.479$).	176
A.6	Tight electron ID defined by the Egamma POG for the 2016 data for electrons in the endcaps ($0.1.479 < \eta < 2.5$).	176
A.7	Loose electron ID defined by the Egamma POG for electrons in the barrel ($ \eta < 0.1.479$).	177
A.8	Loose electron ID defined by the Egamma POG for electrons in the endcaps ($0.1.479 < \eta < 2.5$).	177
A.9	Tight muon ID defined by the muon POG.	178
A.10	Loose muon ID defined by the muon POG.	178
A.11	Hadronic tau ID with light flavor rejection using tau ID sources defined by the tau POG.	178
B.1	Background estimates at the time of the initial unblinding compared to the observation in the 2015 data.	180

List of Figures

Figure	Page
1.1 Particle content of the standard model.	3
1.2 The scalar potential in the $\phi^+-\phi^0$ plane in the case of spontaneous symmetry breaking ($\mu^2 < 0$). The directions of the massless Goldstone bosons, $\vec{\phi}$, and the massive Higgs boson, H , are indicated by the arrows [59].	6
1.3 One-loop corrections to the Higgs boson mass via its interaction with a fermion (left) and with a scalar (right) [53].	8
1.4 Mass splitting between the lightest neutralino and lightest chargino as a function of M_2 for $\tan\beta = 2$ (left) and $\tan\beta = 10$ (right). The solid curves from top to bottom are for $\mu = 2M_2$, $\mu = 3M_2$, $\mu = 5M_2$, and $\mu = \infty$, where μ is the mass parameter for the superpartners of the Higgs fields. The dashed curves are the same but where μ has the opposite sign. The dot-dashed line shows the mass of the charged pion [34].	12
1.5 Lifetime, τ , of the lightest chargino as a function of the mass splitting, ΔM_χ , between the lightest chargino and lightest neutralino [16]. . . .	13
1.6 Event display of a simulated $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ event with an initial-state radiation (ISR) gluon jet.	14
2.1 Schematic of the LHC showing the approximate locations of the large detectors relative to one another [29].	17
2.2 The red bottle contains hydrogen gas that is used to supply protons to the Linac 2, and ultimately, the LHC.	18

2.3	Cross section of a superconducting dipole magnet used in the arcs of the LHC [29].	21
2.4	Schematic of the magnets to the right of the ATLAS detector. Each quadrupole and dipole magnet is labeled with a Q and D, respectively [29].	22
2.5	Illustration of protons from the LHC passing through a series of RF cavities [5].	23
2.6	Cryomodule containing four superconducting RF cavities [29].	25
2.7	Cutaway illustration of the CMS detector. Each subdetector is described in the following sections [63].	26
2.8	Artistic view showing the cold mass of the solenoid inside its cryostat (left), and photograph of the solenoid during initial construction of CMS (right) [19, 4].	29
2.9	Cross section of the cold mass of the solenoid magnet, showing the 4-layer winding [19].	29
2.10	Ratio of stored energy to cold mass versus stored energy for various solenoid magnets used in collider detectors. Gray indicates magnets that are no longer operational, and hollow markers indicate magnets for proposed experiments [58].	30
2.11	Schematic layout of the tracker in the r - z plane [19].	32
2.12	Basic layout of a pixel module [3].	33
2.13	Photographs of pixels in a disk (left) and barrel (right) sensor [19].	34
2.14	Fully assembled strip tracker module from the TEC [19].	35
2.15	Photographs of crystals from the ECAL barrel (left) and endcaps (right) coupled with their respective photodetectors [19].	37
2.16	Layout of the components of the HCAL in the r - z plane [19].	38

2.17	Partially assembled HE calorimeter before installation. Scintillator trays can be seen inserted in one of the azimuthal wedges [19].	39
2.18	Tile of plastic scintillator from the HO with embedded WLS fibers [19].	39
2.19	Cross section of an HPD [19].	40
2.20	Layout of one quarter of the CMS detector, with the muon system detailed. The DT stations are in beige, the CSC stations are in green, and the RPCs are blue.	41
2.21	Illustration of the cross section of a drift tube [19].	42
2.22	Photograph of one of the endcaps of CMS through two of the barrel sections of the flux return yoke during installation. The partially installed gray DT chambers, arranged in four concentric stations, can be seen interspersed in the red return yoke.	43
2.23	CSCs installed on one wheel of an endcap [19].	44
2.24	Schematic illustrating the principle of operation of a CSC [19].	45
2.25	An exploded view of one gas gap and the read-out strips in an RPC. Each RPC consists of two such gas gaps on either side of the strips [2].	46
2.26	RPCs installed on one wheel of an endcap [19].	46
2.27	Architecture of the L1 trigger [19].	49
2.28	Transverse slice of the CMS detector, with illustrations showing how each type of particle is reconstructed by particle flow, using information from all the subdetectors.	50
2.29	Display of an event in the y - z plane from the 2016 run illustrating the phenomenon of pileup. Each red dot is a reconstructed primary vertex, corresponding to an inelastic proton-proton interaction. The green lines are reconstructed tracks, the gray horizontal lines represent the first barrel layers of the pixel detector, and the scale on the border is in centimeters.	52

3.1	Associated calorimeter energy versus number of missing outer hits for selected tracks from a control region dominated by electrons, the largest background to the search. The data collected by CMS in 2016 is shown as colored bins, while a simulation of AMSB chargino production is shown as black boxes, with the size of each box indicating the relative size of the contents in that bin. The particular signal model shown here has a chargino with a mass of 700 GeV and a lifetime of $c\tau = 100$ cm. Associated calorimeter energy and number of missing outer hits are the primary variables used to distinguish signal from background in the search, as an obvious separation between the two is seen in this plane.	56
3.2	Distributions of actual chargino lifetime at generator level. Both plots come from a sample generated with a mean chargino lifetime of 100 cm/ c . The left plot is with no lifetime reweighting applied, while the right plot is reweighted to a target lifetime of 50 cm/ c . The red curve in both cases is the result of fitting the distribution with an exponential function.	60
3.3	Event displays of simulated signal events, one of $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ (top) and one of $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ (bottom). The PF $\vec{p}_T^{\text{miss}}$ vector is shown as a red arrow and the calorimeter-based $\vec{p}_T^{\text{miss}}$ vector is shown as a gold arrow.	68
3.4	Event display of a simulated $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ event with an ISR gluon jet. The PF $\vec{p}_T^{\text{miss}}$ vector is shown as a red arrow and the calorimeter-based $\vec{p}_T^{\text{miss}}$ vector is shown as a gold arrow.	69
3.5	Efficiency of the combination of p_T^{miss} triggers used in the search for simulated $W \rightarrow l\nu$ and experimental data from 2015 (top left), 2016B+C (top right), and 2016D–H (bottom).	74
3.6	Pseudorapidity of tracks with $p_T > 55$ GeV and within $\Delta R < 0.1$ of a generated chargino for various chargino masses.	76
3.7	Layout of one quarter of the CMS detector, with the muon system detailed.	77
3.8	Schematic of the silicon tracker in the ρ - z plane. Note that the TID and TEC are not shown here.	78

3.9	Channels identified as noisy or dead in the ECAL channel status record provided by a database of run conditions for run 260532 from 2015 (left) and for run 276811 from 2016 (right). Tracks within $\Delta R < 0.05$ of any of these channels are vetoed.	78
3.10	Electron reconstruction inefficiency as measured using the tag-and-probe study described in the text, for the 2015 data (left) and the 2016 data (right). Bins that are at least 2σ above the mean inefficiency are used to veto tracks in the search. These bins are marked by circles in the plots.	82
3.11	Muon reconstruction inefficiency as measured using the tag-and-probe study described in the text, for the 2015 data (left) and the 2016 data (right). Bins that are at least 2σ above the mean inefficiency are used to veto tracks in the search. These bins are marked by circles in the plots.	82
3.12	Distributions of the leading jet p_T vs. $p_T^{\text{miss, no } \mu}$ for events in the basic selection before any jet requirements are imposed. The distribution is shown for the 2016 experimental data (left) and for simulated signal events (right) with a 700 GeV chargino with a lifetime of 10 000 cm. The red dashed line indicates the chosen value for the jet p_T requirement.	84
3.13	Distributions of $\max \Delta\phi_{\text{jet, jet}} $ (left) and $ \Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu}) $ (right) for events in the basic selection before the angular requirements on the jets/ $p_T^{\text{miss, no } \mu}$ are imposed. The red dashed lines indicates the chosen value for the requirement on each variable.	85
3.14	Efficiency for the track-based isolation requirement used in the <i>isolated track selection</i> as a function of the number of primary vertices. The efficiency is shown with and without the pileup subtraction described in the text, showing that this subtraction effectively removes the pileup dependence from the isolation sum.	88
3.15	Kinematic distributions from the <i>isolated track selection</i> . The experimental data is from 2015 (2016) in the left (right) column. The right-most bin in each plot includes the overflow.	90

3.16	Plots of ΔR to nearest leptons for tracks selected in the <i>isolated track selection</i> . Minimum ΔR to a reconstructed electron, muon, and tau are shown in the top, middle, and bottom rows, respectively, and the experimental data is from 2015 (2016) in the left (right) column. The rightmost bin in each plot includes the overflow.	91
3.17	Plots of number of missing outer hits and $E_{\text{calo}}^{\Delta R < 0.5}$ for tracks selected in the <i>isolated track selection</i> . The experimental data is from 2015 (2016) in the left (right) column. The rightmost bin in each plot includes the overflow.	92
3.18	Distributions of $E_{\text{calo}}^{\Delta R < 0.5}$ (left) and number of missing outer hits (right) for tracks in simulation that pass the full <i>disappearing track selection</i> except for the requirement on the variable being plotted.	95
3.19	Cumulative selection efficiencies for each selection of the disappearing track selection for simulated signal events. The chargino mass in the simulated events is 700 GeV and three lifetime hypotheses are shown: 10 cm, 100 cm, and 1000 cm.	96
3.20	Event display of simulated signal event with a 700 GeV chargino with a lifetime of 10 cm/ c . The highlighted track is rejected by the track isolation requirement.	97
3.21	Event display of simulated signal event with a 700 GeV chargino with a lifetime of 10 cm/ c . The highlighted track is rejected by the track isolation requirement.	98
3.22	Tag-probe invariant mass spectra for events passing the electron (top) and muon (bottom) tag-and-probe selections from the 2015 and 2016 experimental data, before the corresponding lepton veto is applied to the probe track. The data are fit with the sum of a Breit-Wigner distribution convoluted with a crystal ball function and the so-called RooCMSShape function, representing the $Z \rightarrow \ell\ell$ signal and background, respectively.	105
3.23	Tag-probe invariant mass spectra for events passing the electron (left) and muon (right) tag-and-probe selections from the 2015 and 2016 experimental data, after the corresponding lepton veto is applied to the probe track.	106

3.24	Probe track p_T distributions before and after the application of the lepton veto for electrons (upper left), muons (upper right), and taus (bottom center). The p-value from a Kolmogorov-Smirnov (KS) test of the two distributions in each plot is also shown.	107
3.25	Distributions of $p_T^{\text{miss, no } \mu}$ vs. $ \Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu}) $ in single electron events. The left (right) column shows the $p_T^{\text{miss, no } \mu}$ distribution with the momentum of the electron counted as visible (invisible). The 2015, 2016B+C, and 2016D–H data are shown separately on the top, middle, and bottom rows, respectively.	111
3.26	Distributions of $p_T^{\text{miss, no } \mu}$ vs. $ \Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu}) $ in single tau events. The left (right) column shows the $p_T^{\text{miss, no } \mu}$ distribution with the momentum of the tau counted as visible (invisible). The 2015, 2016B+C, and 2016D–H data are shown separately on the top, middle, and bottom rows, respectively.	112
3.27	Distributions of $p_T^{\text{miss, no } \mu}$ vs. $ \Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu}) $ in single muon events. The 2015, 2016B+C, and 2016D–H data are shown separately on the top, middle, and bottom rows, respectively.	113
3.28	Illustration of how P_{offline} is calculated in the case of electrons in 2015. The fraction of events in the plot that fall within the red shaded region is P_{offline}	114
3.29	Trigger efficiency as a function of $p_T^{\text{miss, no } \mu}$ for events in the single-electron control region, using the calculation described in the text using trigger objects.	117
3.30	Trigger efficiency as a function of $p_T^{\text{miss, no } \mu}$ for events in the single-muon control region, using the calculation described in the text using trigger objects.	118
3.31	Trigger efficiency as a function of $p_T^{\text{miss, no } \mu}$ for events in the single-tau control region, using the calculation described in the text using trigger objects.	119

3.32	Distributions of d_{xy} for tracks from simulated background events passing the track criteria of the candidate track selection, but with the d_{xy} requirement removed. The selected track have various requirements on the number of hits: ≥ 7 (top left), 6 (top right), 5 (center), 4 (bottom left), or 3 (bottom right).	128
3.33	Fake track background estimate as a function of the choice of lower bound on the d_{xy} sideband region for the 2016B+C (left) and 2016D–H (right) run periods.	130
3.34	Distributions of the numbers of interactions for the 2015 (blue) and 2016 (red) data, both experimental (points) and simulated (lines). . .	132
3.35	Uncorrected distributions of missing middle (left) and outer (right) hits for tracks selected in the muon control region from both the 2015 experimental data and the simulation. In the case of the missing middle hits distribution, the usual criterion of zero missing middle hits in the muon control region is not applied.	133
3.36	Corrected distributions of missing middle (left) and outer (right) hits for tracks selected in the muon control region from both the 2015 experimental data and the simulation. In the case of the missing middle hits distribution, the usual criterion of zero missing middle hits in the muon control region is not applied.	136
3.37	Distribution of events in the plane of muon (left) or track (right) p_T vs. $p_T^{\text{miss, no } \mu}$ for simulated $W \rightarrow l\nu$ (left) or simulated signal (right) events. For the signal events, the chargino has a mass of 700 GeV and a lifetime of 1000 cm.	137
3.38	Efficiency of the combination of p_T^{miss} triggers used in the search for simulated $W \rightarrow l\nu$ and experimental data from 2015 (top left), 2016B+C (top right), and 2016D–H (bottom). The efficiency is plotted only with respect to $p_T^{\text{miss, no } \mu}$, with the dependence on the track p_T marginalized out, as described in the text.	139
3.39	Distributions of $p_T^{\text{miss, no } \mu}$ with and without the trigger efficiency scale factors for the 2016D–H period applied. Simulated signal events passing the triggers are plotted, with a 100 GeV chargino in the left plot and a 700 GeV chargino in the right plot.	140

3.40	Distributions of the p_T of $Z \rightarrow \mu\mu$ candidates in the $Z \rightarrow \mu\mu$ control region for simulated and experimental data from 2015 (left) and 2016 (right). The ratio plots shown below are the ISR scale factors applied to simulated signal events.	141
3.41	Generator-level distributions of Z boson p_T for $Z \rightarrow ll$ events generated in MADGRAPH5 (circles) and PYTHIA6 (filled histogram). The ratio plot below are the scale factors applied to simulated signal events. . .	142
3.42	Comparison of the nominal and scaled down versions of the $ \vec{p}_T^{\text{miss, no } \mu} + \vec{p}_T^{\text{lepton}} $ distribution described in the text for events in the single electron control sample (left) and the single tau control sample (right) from 2015 (top), 2016B+C (middle), and 2016D–H (bottom). The mean, μ of each distribution is listed in the legends.	146
3.43	Target pileup distributions used for evaluating the systematic uncertainty from the modeling of pileup in the simulated signal samples compared to the nominal distributions for the 2015 (left) and 2016 (right) data.	149
3.44	Number of missing inner (left) and middle (right) hits for tracks selected in the muon control region, but without the usual criteria requiring zero missing inner and middle hits.	151
3.45	Number of missing outer hits for tracks selected in the muon control region.	154
3.46	Systematic uncertainties on the signal acceptance from the modeling of missing outer hits for 2015 (top), 2016B+C (middle), and 2016D–H (bottom).	155
3.47	Comparison of $E_{\text{calo}}^{\Delta R < 0.5}$ in experimental data and simulation for tracks with at most 4 hits in the $Z \rightarrow \mu\mu$ control region.	159
3.48	Track reconstruction efficiency as measured in a muon tag-and-probe study by the tracking group within CMS as a function of muon $ \eta $. The performance in the data from 2015 (left) and from 2016 (right) is compared to that in simulation.	161

3.49	Ratio of track reconstruction efficiency in experimental and simulated data as measured in a muon tag-and-probe study by the tracking group within CMS as a function of muon $ \eta $. The ratio in the data from 2015 (left) and from 2016 (right) is compared to that in simulation.	161
3.50	The expected and observed 95% CL upper limits on the cross sections for direct chargino production as a function of chargino mass for various chargino lifetimes.	165
3.51	The expected and observed constraints on chargino lifetime and mass. The region to the left of the curve is excluded at 95% CL.	166
3.52	Upper limits at 95% CL on the cross section for direct chargino production as a function of chargino mass and lifetime. The left plot shows the expected limits, while the right plot shows the observed limits. . .	167
4.1	Expected mass exclusion with 300 fb^{-1} (left) or 500 fb^{-1} (right) of $\sqrt{s} = 14 \text{ TeV}$ data given the mass exclusion obtained with the 38.4 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ used in the present search. “System mass” here refers to the sum of the masses of the two ewkinos, which is always approximately $2m_{\tilde{\chi}_1^\pm}$, since the chargino and neutralino are nearly degenerate [1].	169
4.2	The expected and observed constraints on chargino lifetime and mass obtained by ATLAS using data taken during 2015 and 2016 at $\sqrt{s} = 13 \text{ TeV}$. The region to the left of the curve is excluded at 95% CL. Also shown are the previous constraints obtained by ATLAS at 8 TeV , the predicted relationship between chargino mass and lifetime within AMSB, and the constraints from the ALEPH experiment at the Large Electron-Positron (LEP) collider [25].	171
4.3	Event display of a simulated chargino-neutralino event where the chargino decays inside the muon system after leaving hits in the first two layers of the DTs.	172
B.1	Events observed in 2015 with tracks passing through the region of low hit efficiency in the TOB at $\eta = 0$. The highlighted track is the candidate signal track.	181
B.2	Pseudorapidity for candidate signal tracks from 2015 data.	182

B.3	Reconstruction inefficiency as a function of track η for electrons (left) and muons (right). These are identical to the left plots in Figures 3.10 and 3.11, just projected onto the horizontal axis.	182
B.4	Event display for event 308397944 from the initial unblinding of the 2015 data.	183
B.5	Event display for event 155190555 from the initial unblinding of the 2015 data.	184
B.6	Event display for event 264966793 from the initial unblinding of the 2015 data.	185
B.7	Event display for event 250962149 from the initial unblinding of the 2015 data.	186
B.8	Event display for event 287191840 from the initial unblinding of the 2015 data.	187
C.1	Efficiency of each of the recommended p_T^{miss} filters for simulated signal events generated with a 700 GeV chargino and that pass the full disappearing track search selection.	189
D.1	Comparison of $p_T^{\text{miss, no } \mu}$ vs. p_T^{miss} for simulated signal events with a 700 GeV chargino with a lifetime of 10 m. All generated events are used in the left plot, while only events passing the search triggers are used in the right plot.	191
D.2	Comparison of $p_T^{\text{miss, no } \mu}$ vs. p_T^{miss} for simulated signal events with a 700 GeV chargino with a lifetime of 10 m and that pass the full disappearing track selection.	191
E.1	Signal acceptance for each of the generated chargino masses and lifetimes for $\text{pp} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ events (top) and $\text{pp} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ events (bottom). The uncertainties shown are simply the statistical uncertainties resulting from the sizes of the generated samples.	193
F.1	Efficiencies of the p_T^{miss} leg (left column) and track leg (right column) of <code>HLT_MET75_IsoTrk50_v*</code> as a function of $p_T^{\text{miss, no } \mu}$ and track p_T , respectively.	195

F.2	Efficiencies of individual $p_{\text{T}}^{\text{miss}}$ paths used in the combined signal trigger for 2015 data, compared to $W \rightarrow l\nu$ Monte Carlo.	196
F.3	Efficiencies of individual $p_{\text{T}}^{\text{miss}}$ paths used in the combined signal trigger for 2015 data (continued), compared to $W \rightarrow l\nu$ Monte Carlo.	197
F.4	Efficiencies of individual $p_{\text{T}}^{\text{miss}}$ paths used in the combined signal trigger for 2016 B+C data, compared to $W \rightarrow l\nu$ Monte Carlo.	198
F.5	Efficiencies of individual $p_{\text{T}}^{\text{miss}}$ paths used in the combined signal trigger for 2016 D–H data, compared to $W \rightarrow l\nu$ Monte Carlo.	199

Chapter 1: Introduction

The standard model (SM) of particle physics [37, 70, 64] is a quantum field theory concerning the electroweak and strong interactions that, together with the general theory of relativity describing gravitational interactions, represents the most fundamental picture of nature that humanity has achieved. However, there are several reasons to believe the standard model is not a complete theory of the electroweak and strong interactions. Thus, there is a wide variety of candidate theories for beyond-the-standard-model (BSM) physics that have been proposed.

In this chapter, we will give a brief overview of the content of the SM, followed by a description of some of its known shortcomings. This will be followed by an introduction to supersymmetry, including the phenomenology of anomaly-mediated supersymmetry breaking (AMSB), which will be used to interpret the results of the search presented later. The experimental testing of BSM theories such as AMSB is one of the primary purposes of building and running high-energy particle colliders like the Large Hadron Collider (LHC). In Chapter 2, we will describe the LHC and the Compact Muon Solenoid (CMS) detector, one of the general purpose detectors at the LHC. Data from the CMS detector is then used in Chapter 3, in a search for one particularly striking experimental signature of BSM physics, “disappearing tracks”. Finally, our conclusions will be presented in Chapter 4.

1.1 Standard model

The SM is a gauge theory based on the symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$. Under $SU(3)_c$, (anti-)quarks transform as (anti-)triplets, while all leptons transform as singlets. All left-handed fermions transform as doublets under $SU(2)_L$, whereas the right-handed quarks and charged leptons transform as singlets. There are no right-handed neutrinos in the SM. Finally, weak hypercharge (Y) is defined via the Gell-Mann–Nishijima formula:

$$Q = T_3 + \frac{1}{2}Y, \quad (1.1)$$

where Q is the electric charge and T_3 is the third component of weak isospin.

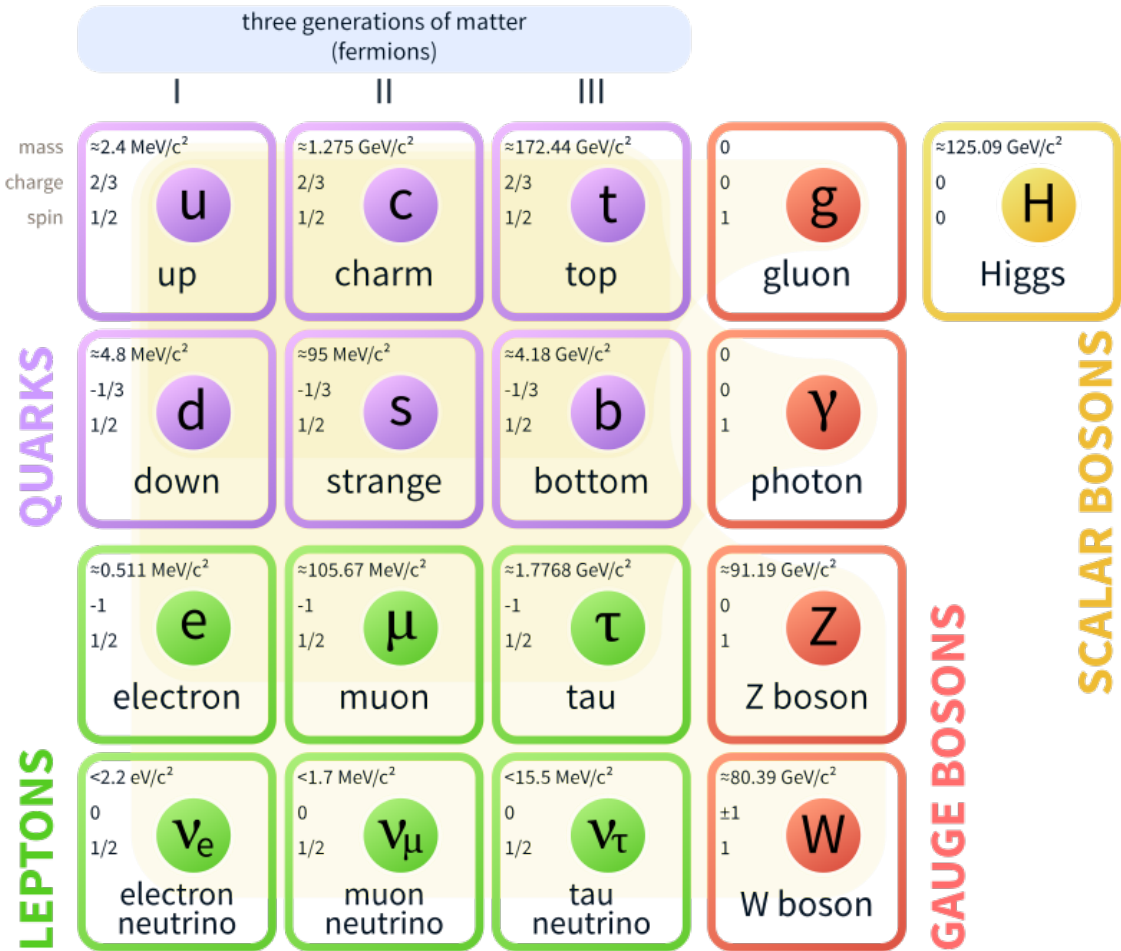
For each of the twelve generators of $SU(3)_c \times SU(2)_L \times U(1)_Y$, there is a gauge field, corresponding to twelve physical gauge bosons. There are eight gluons, which, due to the non-abelian nature of $SU(3)_c$, carry color charge and interact with themselves as well as with the quarks. Since $SU(3)_c$ is an unbroken symmetry, these eight gluons are indistinguishable from one another. There are W^+ and W^- bosons, which are the electrically charged components of the four electroweak gauge fields. After electroweak symmetry is spontaneously broken down to $U(1)_{\text{em}}$ (see Section 1.1.1), the neutral electroweak gauge fields, W^3 and B are rotated, yielding the physical photon (γ) and Z boson:

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B \\ W^3 \end{pmatrix}, \quad (1.2)$$

where θ_W is the Weinberg, or weak mixing, angle. The photon is the gauge boson of the $U(1)_{\text{em}}$ symmetry group. A summary of the particle content of the SM, along with each of their observed masses, electric charges, and spins, is shown in Figure 1.1.

Figure 1.1: Particle content of the standard model.

Standard Model of Elementary Particles



1.1.1 Electroweak symmetry breaking

A general feature of gauge theories such as the SM is that explicit mass terms for the gauge fields are forbidden. The reason for this is that such terms would not be gauge invariant, since when we introduce the gauge fields in order to impose the gauge symmetry, we require them to transform as

$$W_\mu^a \rightarrow W_\mu^a - \frac{1}{g} \partial_\mu \alpha^a + f^{abc} \alpha_b W_{c\mu} \quad (1.3)$$

under an infinitesimal transformation, where W_μ^a are gauge fields with group index a and coupling g , $\alpha^a = \alpha^a(x)$ are the group transformation parameters, and f^{abc} are the structure constants of the group. Thus, mass terms of the form $W_\mu^a W^{a\mu}$ are not invariant. This is a problem because explicitly breaking a gauge symmetry with such terms leads to a theory that is not renormalizable [69].

Worse still, since the symmetry group of the SM is chiral, i.e., left-handed and right-handed fermions transform differently, explicit masses for Dirac fermions are also forbidden. Consider a mass term for a Dirac fermion in the Lagrangian such as

$$\bar{f}f = \bar{f}_L f_R + \bar{f}_R f_L, \quad (1.4)$$

where f is some Dirac field, $\bar{f} = f^\dagger \gamma^0$ is its Dirac adjoint, and the L and R subscripts denote its left-handed and right-handed projections, respectively. Such a term mixes left-handed and right-handed fields and cannot be gauge invariant in the case of a chiral symmetry group. Since we observe the $W^\pm$ and Z bosons to have nonzero mass, we can therefore conclude that $SU(2)_L \times U(1)_Y$ is a broken symmetry. Since breaking this symmetry explicitly would leave the SM nonrenormalizable, it must be broken spontaneously.

1.1.2 Higgs mechanism

One possibility for spontaneous electroweak symmetry breaking is the Higgs mechanism [28, 40, 43, 42, 44, 51]. With the Higgs mechanism, two complex scalar fields that transform as a doublet under $SU(2)_L$ are added to the theory,

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}. \quad (1.5)$$

The potential for the scalar doublet is given by

$$V(\Phi^\dagger\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2, \quad (1.6)$$

with $\lambda > 0$ to ensure that it is bounded from below.

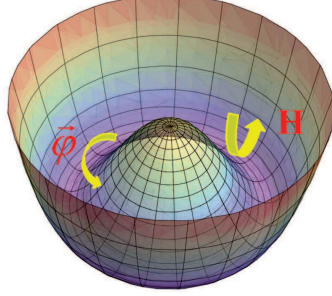
The potential $V(\Phi^\dagger\Phi)$ is responsible for breaking electroweak symmetry. This can be seen by analyzing the classical vacuum expectation value (VEV) of the theory. The classical VEV is obtained by minimizing the potential with respect to Φ . For $\mu^2 > 0$, there is a unique minimum located at $\phi^+ = \phi^0 = 0$. This vacuum is invariant under $SU(2)_L$ so the symmetry is unbroken. But for $\mu^2 < 0$, the potential has a circle of minima in the $\phi^+-\phi^0$ plane (see Fig. 1.2) at

$$\Phi^\dagger\Phi = \frac{v^2}{2} = -\frac{\mu^2}{2\lambda}. \quad (1.7)$$

The classical VEV will lie at a single point along this circle. Since the vacuum in this case is not invariant under $SU(2)_L$, even though the Lagrangian still is, we say that the symmetry is spontaneously broken.

Now, as discovered by Nambu in the context of the Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity and subsequently generalized by Goldstone, the spontaneous breaking of continuous global symmetries is associated with massless bosonic states, one for each generator that is broken [56, 38, 39]. These are called

Figure 1.2: The scalar potential in the $\phi^+-\phi^0$ plane in the case of spontaneous symmetry breaking ($\mu^2 < 0$). The directions of the massless Goldstone bosons, $\vec{\phi}$, and the massive Higgs boson, H , are indicated by the arrows [59].



Goldstone bosons. It turns out that essentially the same thing happens when a gauge symmetry is broken. In this case however, instead of the Goldstone bosons remaining in the physical spectrum, the associated degrees of freedom are absorbed by the gauge bosons, becoming the degrees of freedom corresponding to the longitudinally polarized states of the now-massive gauge bosons. This is often described as the gauge bosons “eating” the Goldstone bosons.

In the case of electroweak symmetry breaking, the gauge group $SU(2)_L \times U(1)_Y$ has four generators. Three of the generators are broken when the scalar doublet, with four degrees of freedom, acquires a nonzero VEV. Thus, three of the gauge bosons, the W^+ , W^- , and Z bosons, become massive with one real scalar from the doublet remaining as a massive physical particle, the Higgs boson. The remaining gauge boson, γ , stays massless. The same Higgs mechanism can also be used to give mass to fermions in a gauge invariant way by introducing Yukawa interactions between the fermions and the scalar doublet.

1.2 Hierarchy problem and supersymmetry

Although the SM has been incredibly successful at explaining the results of hundreds of experimental analyses over the past half century, several problems with the theory have been identified. These problems fall into three categories:

- phenomena not explained in the SM, such as gravity and dark matter
- experimental results that contradict the SM, such as the anomalous magnetic dipole moment of the muon [58]
- theoretical issues that, although not technically problems with the theory, likely indicate a lack of understanding

Of particular relevance to us is the hierarchy problem, which falls into the third category. Although it is entirely possible that the hierarchy problem is simply a feature of nature with no resolution, the history of science shows that it most likely indicates a presently unknown underlying symmetry that would at least partially mitigate the problem. The hierarchy problem and one such underlying symmetry known as supersymmetry are briefly described in the following sections.

1.2.1 Hierarchy problem

The introduction of a scalar Higgs boson to spontaneously break electroweak symmetry turns out to be problematic [71, 35, 67, 68]. Like other massive particles in the SM, the square of the bare Higgs boson mass, m_H^2 , receives quantum corrections from each particle with which it interacts, including the Higgs boson itself. Examples of the lowest order of such corrections are shown in Figure 1.3.

Figure 1.3: One-loop corrections to the Higgs boson mass via its interaction with a fermion (left) and with a scalar (right) [53].



The problem comes from the fact that in a generic quantum field theory, such corrections to the mass of a scalar field are roughly proportional to the square of an ultraviolet cutoff scale, Λ_{UV}^2 , which is introduced to regularize the loop integrals. This cutoff scale can be thought of as the scale at which some form of BSM physics would become relevant. Thus, naïvely, one would expect $m_{\text{H}} \sim \Lambda_{\text{UV}}$.

However, we know that the mass of the Higgs boson is $\sim 125 \text{ GeV}$ [8, 21, 15, 9], while experiments at particle colliders such as the LHC have discovered no sign of BSM physics up to $\sim 1 \text{ TeV}$. At the very least, we expect BSM physics to exist at the Planck scale, $M_{\text{P}} = (8\pi G)^{-1/2} \approx 2.4 \times 10^{18} \text{ GeV}$, where the quantum effects of gravity become important, and it becomes difficult to explain why the Higgs boson is so much less massive compared to M_{P} without some sort of cancellation of the large quantum corrections to m_{H}^2 .

1.2.2 Supersymmetry

In order to achieve this cancellation of the quantum corrections to m_{H}^2 , first note that fermion loop diagrams and boson loop diagrams, such as the two in Figure 1.3, correct m_{H}^2 with opposite signs, suggesting that some sort of symmetry between

fermions and bosons could provide the necessary cancellations. This is exactly what supersymmetry provides in a systematic fashion, to all orders in perturbation theory [53]. A supersymmetry transformation turns fermionic fields into bosonic fields and bosonic fields into fermionic fields. Thus, any theory that posits that supersymmetry is a symmetry of nature predicts spin-0 bosonic partners for every SM fermion and spin-1/2 fermionic partners for every SM boson. These partners are called superpartners or sparticles. In this way, every quantum correction to m_H^2 coming from loop diagrams with SM particles is canceled by a correction coming from loop diagrams with the corresponding sparticles.

Supersymmetry is only an exact symmetry if each sparticle has the same mass as the corresponding SM particle. Since we have not observed sparticles at the same masses as the SM particles, we can conclude that supersymmetry, if a symmetry of nature, is broken. Unfortunately, if we include soft supersymmetry-breaking terms in the Lagrangian for even the minimal extension of the SM that includes supersymmetry, known as the minimal supersymmetric standard model (MSSM), this leads to the introduction of over 100 new parameters, including masses, phases, and mixing angles. Without any further assumptions, these parameters are all independent and would, in principle, each have to be measured in experiments, in the event that supersymmetry were discovered.

This enormous level of arbitrariness can be mitigated by assuming a high-energy mechanism for supersymmetry breaking. There are several such possible mechanisms that have been proposed, but for our purposes, we will focus on AMSB [36, 61], which yields a particularly striking experimental signature, a “disappearing track”, which is described in the next section and which will be the target of the search presented

in Chapter 3. We note now that AMSB is not the only theory that could yield this experimental signature [47, 41, 14, 13, 23], and indeed the search presented in Chapter 3 is designed to target this signature, as opposed to being heavily optimized with respect to AMSB in particular. Nonetheless, the results of the search will be interpreted within the context of AMSB, so we discuss some of the salient phenomenology here.

1.2.3 Phenomenology of anomaly-mediated supersymmetry breaking

The most important consequence of AMSB with respect to particle collider phenomenology is the mass spectrum that results for the gauginos, the superpartners of the SM gauge bosons. Within AMSB, the masses of the gauginos are, at leading order, proportional to the beta functions of the corresponding gauge couplings [34, 30, 45, 31]:

$$M_i = \frac{\beta_i}{g_i} m_{3/2}, \quad (1.8)$$

where $i = 1, 2, 3$ corresponds to the $U(1)_Y$, $SU(2)_L$, and $SU(3)_c$ gauge groups, respectively; g_i are the gauge couplings; β_i are the beta functions, defined as

$$\beta_i(g_i) = \frac{\partial g_i}{\partial \log Q}, \quad (1.9)$$

which give the dependence of the coupling constants on an energy scale Q ; and $m_{3/2}$ is the mass of the gravitino, the superpartner of the graviton, the supposed gauge boson that mediates gravity. Plugging in the beta functions calculated to one-loop, we get [34]

$$\begin{aligned}
M_1 &= \frac{11\alpha}{4\pi \cos^2 \theta_W} m_{3/2} \\
M_2 &= \frac{\alpha}{4\pi \sin^2 \theta_W} m_{3/2} \\
M_3 &= -\frac{3\alpha_s}{4\pi} m_{3/2},
\end{aligned} \tag{1.10}$$

where $\alpha = \sqrt{4\pi e}$ and $\alpha_s = \sqrt{4\pi g_s}$ are defined in terms of the elementary electric charge e and strong coupling constant g_s and tacitly depend on the energy scale at which they are measured. Thus, the mass ratios of the gauginos are

$$|M_1| : |M_2| : |M_3| = (11 \tan^2 \theta_W) : 1 : \left(\frac{3\alpha_s \sin^2 \theta_W}{\alpha} \right), \tag{1.11}$$

or, using the approximate values near the Z mass of $\alpha \approx 1/128$, $\alpha_s \approx 0.12$, and $\sin^2 \theta_W \approx 0.22$ [27, 58], we get

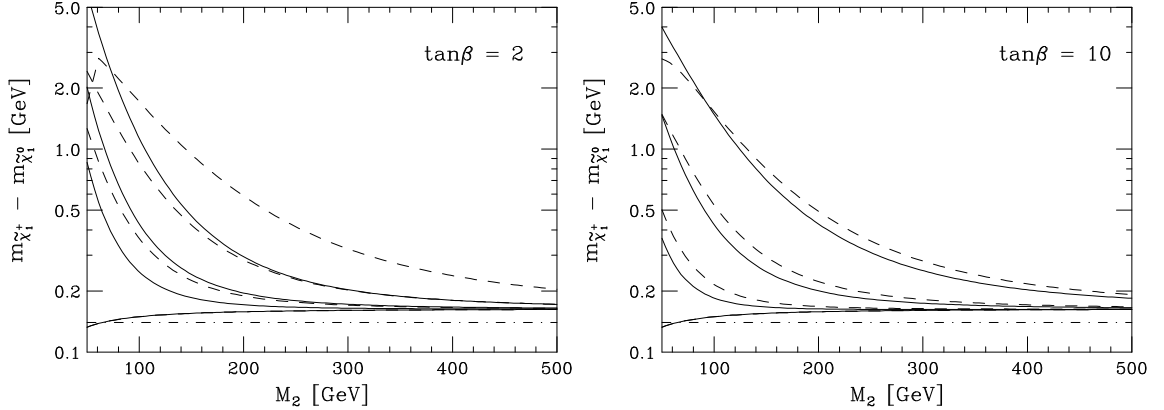
$$|M_1| : |M_2| : |M_3| \approx 3.1 : 1 : 10. \tag{1.12}$$

What this means is that the triplet of winos, the superpartners of the $SU(2)_L$ gauge fields, are the lightest sparticles (LSP), as opposed to the more conventional bino, the superpartner of the $U(1)_Y$ gauge field, which is often the LSP in other forms of gravity-mediated supersymmetry breaking such as mSUGRA [16, 53]. The mass eigenstates that would be observed in an experiment are superpositions of the neutral wino or bino, in the case of the neutral state, or of the charged winos, in the case of the charged states. The lightest of the neutral states, referred to as neutralinos, is therefore wino-like in AMSB, and is nearly mass-degenerate with the lightest of the charged states, referred to as charginos.

Indeed, detailed studies of the mass splitting, $\Delta M_\chi = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$, between the lightest neutralino, $\tilde{\chi}_1^0$, and lightest chargino, $\tilde{\chi}_1^\pm$, show that typically $\Delta M_\chi \sim m_{\pi^\pm}$,

where $m_{\pi^\pm} \approx 140 \text{ MeV}$ is the mass of the charged pion [34]. This can be seen in Figure 1.4 for a variety of choices of parameters. With this near degeneracy, and assuming R -parity, $\tilde{\chi}_1^\pm$ can only decay into final states with $\tilde{\chi}_1^0$, which, being the LSP, is stable.

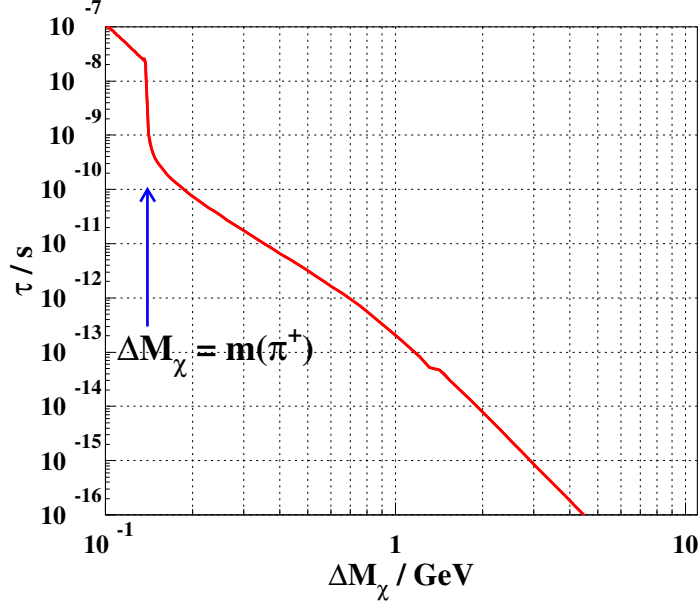
Figure 1.4: Mass splitting between the lightest neutralino and lightest chargino as a function of M_2 for $\tan\beta = 2$ (left) and $\tan\beta = 10$ (right). The solid curves from top to bottom are for $\mu = 2M_2$, $\mu = 3M_2$, $\mu = 5M_2$, and $\mu = \infty$, where μ is the mass parameter for the superpartners of the Higgs fields. The dashed curves are the same but where μ has the opposite sign. The dot-dashed line shows the mass of the charged pion [34].



The limited phase space available for the decay of $\tilde{\chi}_1^\pm$ implies two features that result in a particularly striking experimental signature [16]. First, the chargino acquires a relatively long lifetime, such that it may have a macroscopic decay length, as seen in Figure 1.5. For $\Delta M_\chi \sim m_{\pi^\pm}$, the decay length can be on the order of $\sim 1 \text{ m}$. Second, the charged particles produced in the $\tilde{\chi}_1^\pm$ decay will be very soft, i.e., they will have very little momentum. Inside the strong magnetic fields used in collider detectors, such soft charged particles will follow very tightly curved trajectories. Combined with

their origin being displaced from the usual point of production by ~ 1 m, this means that the charged particles from the $\tilde{\chi}_1^\pm$ decay are not reconstructed by the standard tracking algorithms used in such experiments.

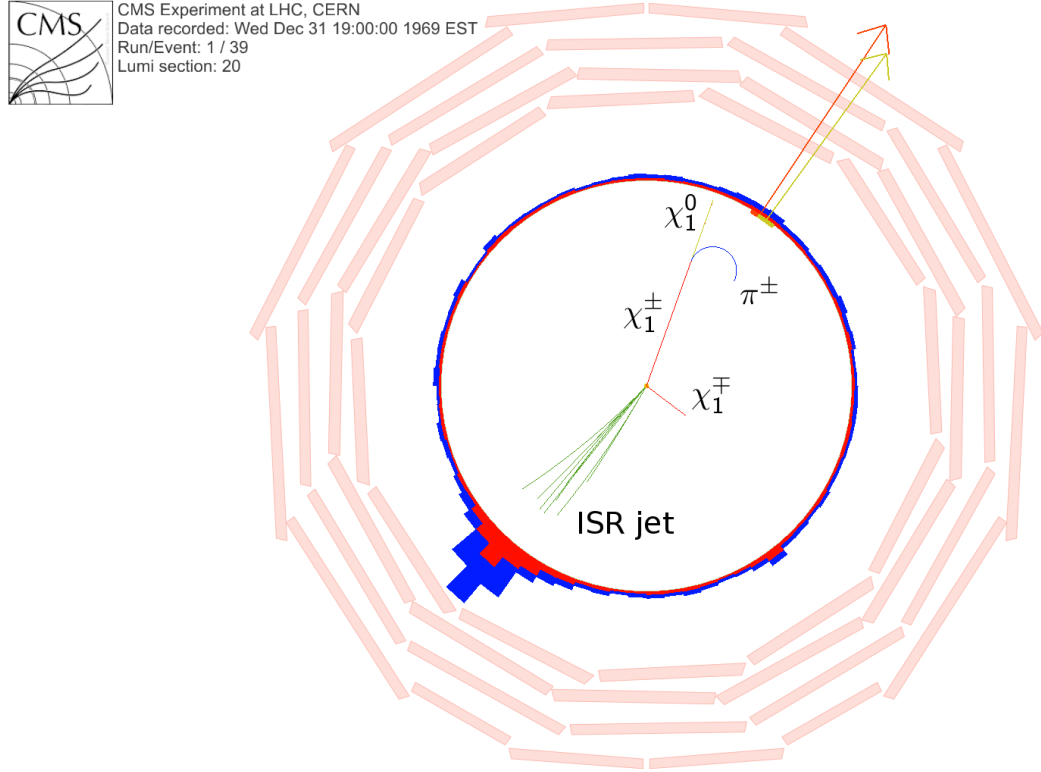
Figure 1.5: Lifetime, τ , of the lightest chargino as a function of the mass splitting, ΔM_χ , between the lightest chargino and lightest neutralino [16].



The decay mode that dominates for $m_{\pi^\pm} \lesssim \Delta M_\chi \lesssim 700$ MeV is $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$ [16]. The $\tilde{\chi}_1^0$, being neutral and not carrying color charge, will escape a collider detector undetected. Therefore, if a $\tilde{\chi}_1^\pm$ is produced and decays within the inner tracker after traveling for ~ 1 m, neither the $\tilde{\chi}_1^0$ nor the $\pi^\pm$ will be detected, and the resulting track will appear to disappear as illustrated in Figure 1.6: a “disappearing track”. This unusual signature is very rare within the SM, except via detector inefficiencies, mistakes of the reconstruction algorithms, or certain inelastic interactions of charged

particles with detector material such as charge exchange interactions like $\pi^\pm n \rightarrow \pi^0 p$. It thus makes a promising, although challenging, target for a search for BSM physics.

Figure 1.6: Event display of a simulated $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ event with an initial-state radiation (ISR) gluon jet.



Chapter 2: Large Hadron Collider and Compact Muon Solenoid detector

The search for BSM physics has led physicists to construct enormous particle accelerators capable of colliding particles at high energies. By analyzing the products of high energy particle collisions, we are able to explore ever higher energy scales, and hopefully glimpse signs of new physics. In this chapter, we briefly describe the LHC, currently the most powerful particle collider in the world, and give a thorough overview of the CMS detector, one of the detectors at the LHC. Data from CMS is used in the analysis described in Chapter 3. Full details on the LHC and CMS detector can be found in [29] and [19], respectively.

2.1 Large Hadron Collider

The LHC is currently the largest and most powerful particle collider in the world. It occupies a circular tunnel spanning the French-Swiss border near Geneva that is 27 km in circumference and up to 175 m below the surface. The LHC is designed to collide beams of either protons, with energy up to 7 TeV, or lead ions, with energy up to 2.76 TeV per nucleon. The LHC was run with a beam energy of 3.5 TeV in 2010 and 2011, followed by a run at 4 TeV in 2012. From 2013–2014, the LHC was shutdown to allow for upgrades and maintenance to the machine and detectors. It

was restarted in 2015 with a beam energy of 6.5 TeV, and was run at this energy during 2016 and 2017.

The beams are made to collide at four interaction points, which are instrumented with seven detectors:

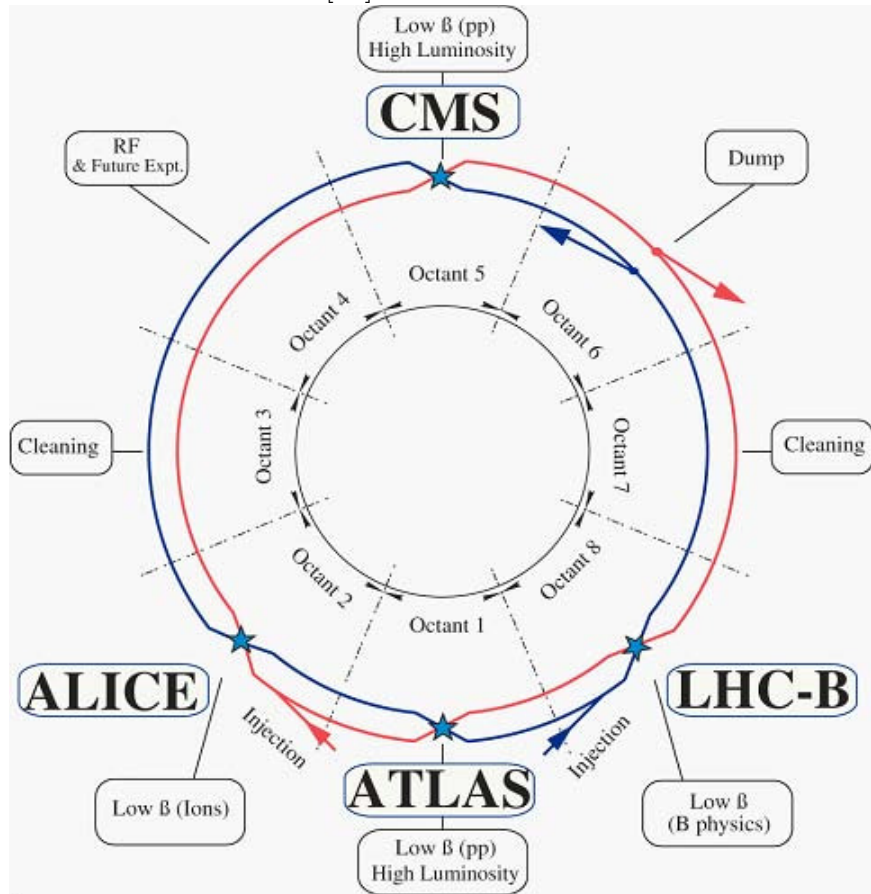
- CMS and ATLAS are general purpose collider detectors
- LHCb specializes in flavor physics
- ALICE specializes in heavy ion physics
- TOTEM shares an interaction point with CMS and is designed to measure the total proton-proton cross section, as well as elastic and diffractive scattering
- LHCf shares an interaction point with ATLAS and measures neutral pions in an effort to understand the origin of cosmic rays
- MoEDAL shares an interaction point with LHCb and is designed to search for magnetic monopoles and other highly ionizing particles

Figure 2.1 shows a schematic of the LHC showing the approximate locations of the large detectors relative to one another. In this brief description of the LHC, we will focus exclusively on the proton-proton operation, especially as it relates to the high-luminosity interaction points of CMS and ATLAS.

2.1.1 Injection chain

A series of accelerators are used to take protons from a bottle of hydrogen gas (see Figure 2.2) gradually up to an energy of 450 GeV before being injected into the LHC. The first step in the chain is the Linear accelerator 2 (Linac 2), which began operation

Figure 2.1: Schematic of the LHC showing the approximate locations of the large detectors relative to one another [29].



in 1978, replacing Linac 1. Protons are extracted from the hydrogen bottle in pulses of up to $100\ \mu\text{s}$. After being ionized by an electric field, the resulting protons enter the accelerator, where radiofrequency (RF) cavities accelerate them to 50 MeV. Linac 2 is planned to be replaced by Linac 4 in 2020, in preparation for the high-luminosity upgrade of the LHC [12].

Figure 2.2: The red bottle contains hydrogen gas that is used to supply protons to the Linac 2, and ultimately, the LHC.



The next step in the injection chain is the Proton Synchrotron Booster (PSB). Prior to the startup of the PSB in 1972, protons were injected directly from the linac into the Proton Synchrotron (PS) at 50 MeV. However, the low injection energy greatly limited the number of protons the PS could accept. Thus, the PSB, composed of four superimposed synchrotron rings, was built to accelerate protons from the linac

to 1.4 GeV before they are received by the PS, allowing 100 times as many protons to be accepted.

The PS began accelerating protons in 1959 as CERN's flagship accelerator and first synchrotron. At the time, it was the highest energy accelerator in the world. Over its nearly six decades of operation, it has undergone many upgrades, with the intensity of its proton beam increasing a thousandfold. As well as protons, it has accelerated antiprotons, electrons, positrons, and helium, oxygen, and sulfur nuclei. As part of the LHC injection chain, protons from the PSB are received in the 628 m synchrotron, and accelerated up to 25 GeV.

Protons from the PS are injected into the Super Proton Synchrotron (SPS), where they are accelerated up to 450 GeV in the nearly 7 km circumference synchrotron, which is CERN's second largest accelerator and the last stop for protons destined for the LHC. After beginning operation in 1976, the SPS has provided beams for a wide variety of experiments. Most notably, operating as a proton-antiproton collider (called Sp $\bar{p}$ S), its beams provided data for the discovery of the $W^\pm$ and Z^0 bosons by the UA1 and UA2 experiments in 1983. Currently, the SPS provides protons for the NA61/SHINE and NA62 experiments, and the COMPASS experiment, as well as the LHC.

2.1.2 Magnets

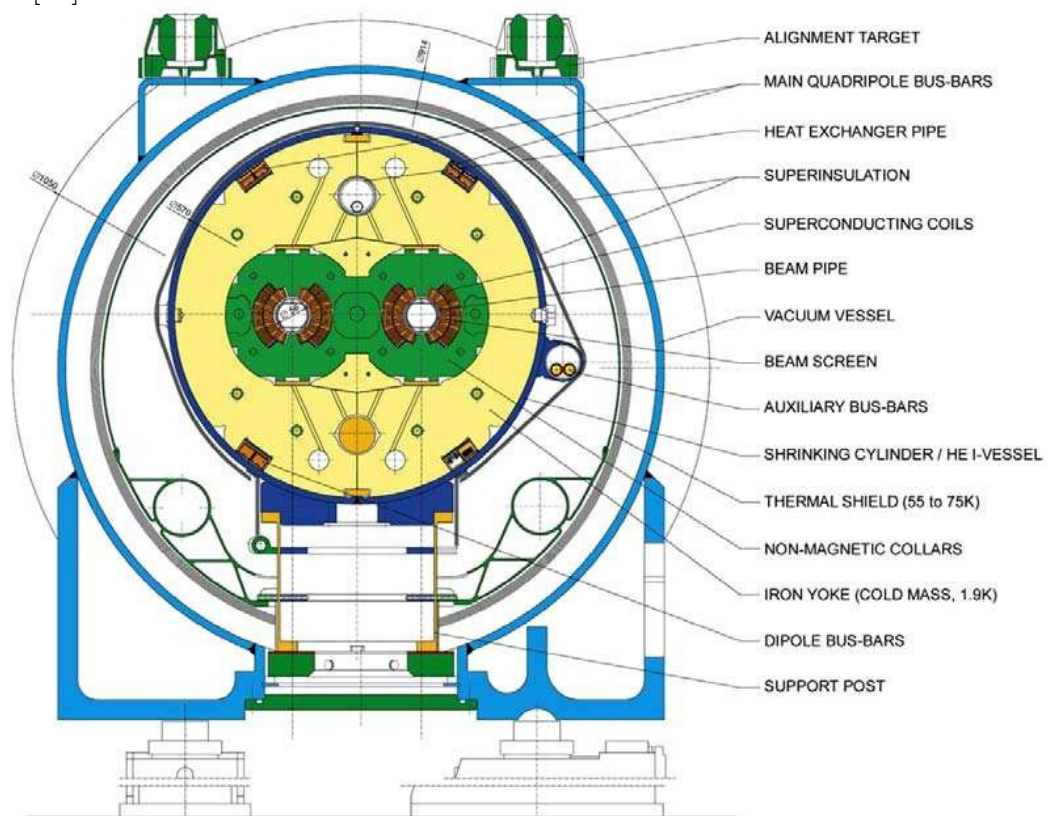
The LHC itself is composed of eight arcs in which the trajectories of the beams are curved by superconducting dipole magnets. Each arc is made up of 23-106.9 m long arc cells, each of which consists of six 15 m-long dipole magnets, along with the associated cryostat and higher-order magnets. The higher-order magnets include

quadrupoles, used to keep the beams focused, as well as sextupole, octupole, and decapole magnets used to correct the magnetic field at the extremities of the dipoles. There are 1104 dipole magnets within the arcs, comprising most of the length of the LHC.

Because the LHC collides two proton beams, separate magnetic fields, pointing in opposite directions, are required for the two counter-rotating beams. Due to space limitations in the tunnel housing the collider and cost considerations, a so-called two-in-one design was chosen, where the two beam pipes, separated by 194 mm, and associated superconductor windings are contained in a common cold mass with a common cryostat. This design is illustrated in the cross section of one of the dipole magnets in Figure 2.3.

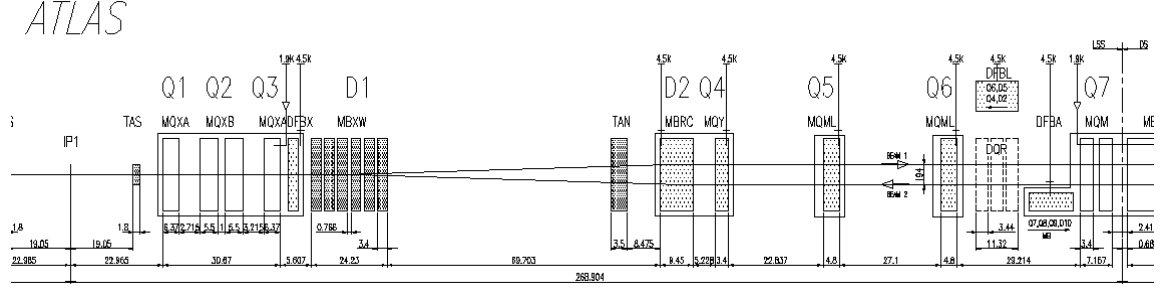
Between each arc are eight straight sections, each approximately 528 m long, corresponding to the four interaction points, two collimation systems, the RF system, and a beam dump insertion. The two high-luminosity interaction points corresponding to the locations of CMS and ATLAS are identical except that the beams cross in the horizontal plane in CMS and in the vertical plane in ATLAS. The high-luminosity at each point is generated by a so-called inner triplet assembly, consisting of three superconducting quadrupole magnets that squeeze the incoming beams from $200\text{ }\mu\text{m}$ to $16\text{ }\mu\text{m}$ in diameter. The beams share a common beam pipe within the inner triplet, which can be seen as magnets Q1–3 in the schematic of the magnets to the right of the ATLAS detector in Figure 2.4. Outside of the inner triplet are a pair of dipole magnets, one superconducting and one conventional, that separate/recombine the beams from the single beam pipe of the inner triplet assembly to the two used in the

Figure 2.3: Cross section of a superconducting dipole magnet used in the arcs of the LHC [29].



arcs. Finally, there is a series of quadrupole magnets that match the straight sections to the arcs.

Figure 2.4: Schematic of the magnets to the right of the ATLAS detector. Each quadrupole and dipole magnet is labeled with a Q and D, respectively [29].



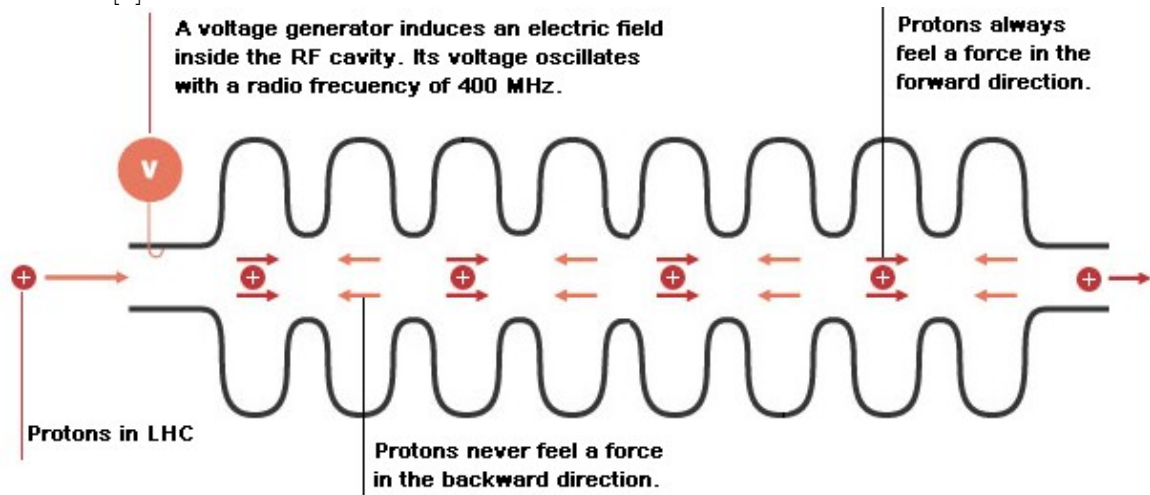
All of the superconducting magnets in the LHC are made using NbTi cables. In total, approximately 600 t of superconducting cables are used. At the design beam energy of 7 TeV, the dipole magnets must operate at 8.33 T, which necessitates cooling the superconducting cables to 1.9 K with liquid helium, with only a ~ 1.5 K margin between the operating and critical temperatures, above which the magnets would cease being superconducting and would quench. A current of 11 850 A is required to generate this high magnetic field.

2.1.3 Radiofrequency system

The LHC uses superconducting RF cavities to accelerate the proton beams from the injection energy of 450 GeV to a design energy of 7 TeV. Klystrons, which are vacuum tubes that use linear beams of electrons to amplify radio waves, are used to deliver high-power, oscillating electric fields to superconducting RF cavities. As

illustrated in Figure 2.5, the cavities are arranged in series such that the direction of the electric field alternates from cavity to cavity, and the field direction in each cavity oscillates forward and backward at a frequency of 400 MHz. This has two effects on the protons passing through the cavities. First, protons passing through at very specific times that match the frequency of the cavities will experience a net acceleration in the beam direction. Second, protons that are out of sync with the frequency of the cavities will be accelerated or decelerated such that the protons accumulate in tightly packed groups referred to as bunches.

Figure 2.5: Illustration of protons from the LHC passing through a series of RF cavities [5].



With an RF frequency of 400 MHz, the time window in which each bunch fits, referred to as a bucket, is 2.5 ns. Since the protons in the LHC, even at the injection energy of 450 GeV, are traveling at very nearly the speed of light, each bucket occupies

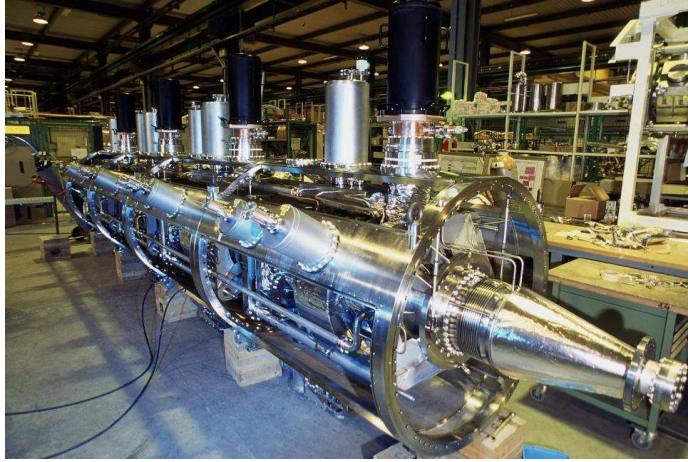
~ 75 cm in space, resulting in $\sim 37\,000$ buckets around the entire circumference of the LHC. However, not every bucket is filled with a proton bunch. There is a 25 ns separation between bunches, meaning only one in ten buckets is filled with a bunch and that the bunch crossing frequency inside the detectors is 40 MHz, as well as a nearly $3\,\mu\text{s}$ abort gap in each beam that allows for the requisite magnets to switch on when the beams are dumped. The maximum number of buckets filled with bunches is 2808.

On each orbit of the LHC, each beam is accelerated by eight RF cavities, each with a voltage of 2 MV at the design beam energy of 7 TeV. These cavities are grouped into so-called cryomodules, each housing four cavities cooled to 4.5 K using liquid helium. One such cryomodule is shown in Figure 2.6. The cavities are composed of copper sputtered with a thin layer of superconducting niobium. This superconducting layer minimizes RF power losses in the cavity walls so that nearly all the power is delivered to the beams. The four cryomodules, two per beam, and associated sixteen klystrons, one for each cavity, are located in the straight section just counterclockwise of the CMS interaction point.

2.2 Compact Muon Solenoid detector

The CMS detector is one of the large general-purpose collider detectors at the LHC, and collected the data used in the analysis presented in Chapter 3. CMS is composed of subdetectors that fall in two general categories: tracking detectors and calorimeters. Tracking detectors are designed to record the trajectories of charged particles while minimally interacting with them. On the other hand, calorimeters are

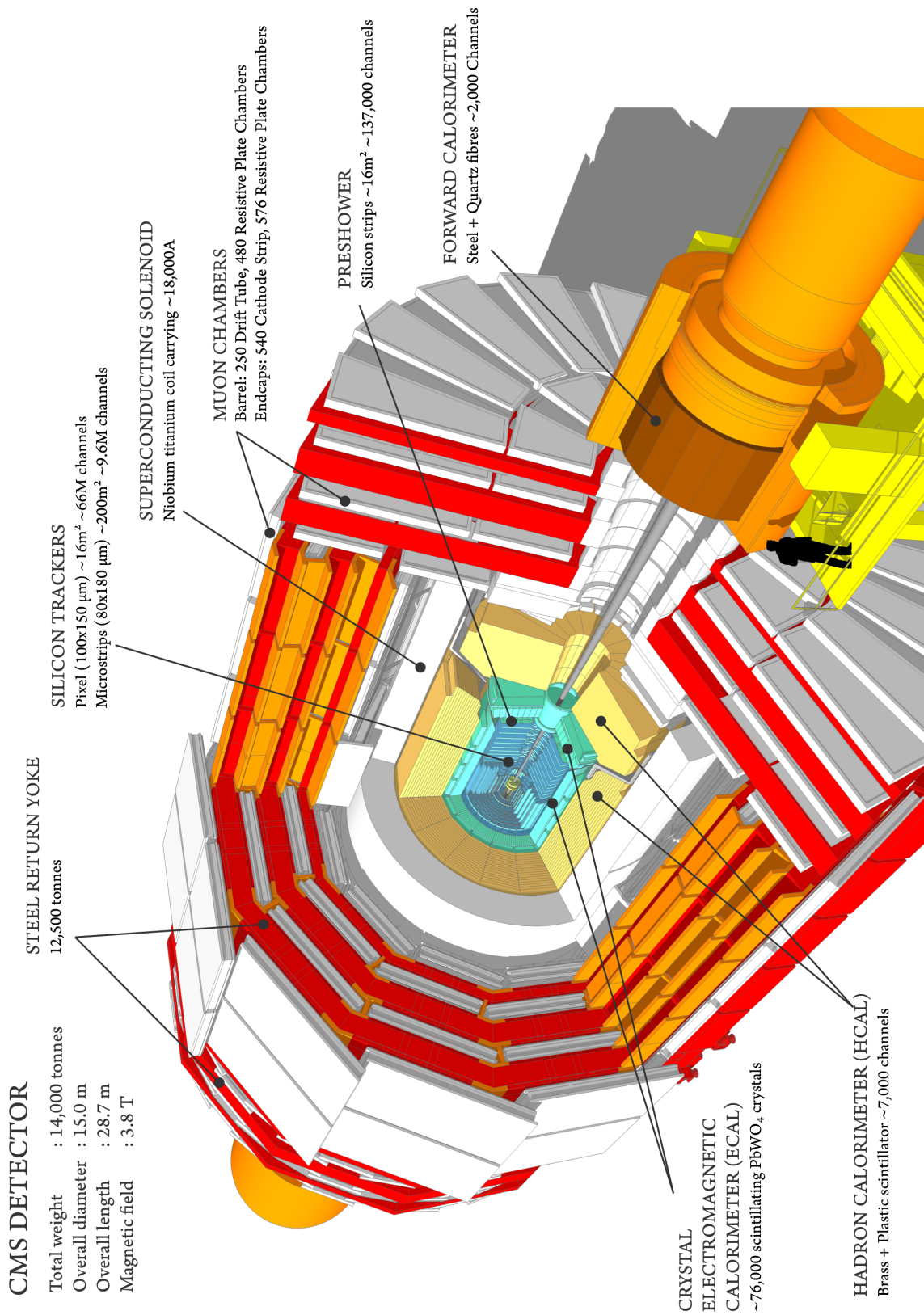
Figure 2.6: Cryomodule containing four superconducting RF cavities [29].



designed to measure the energy of charged and neutral particles by stopping them and measuring the energy of the resulting particle shower.

Typical of modern collider detectors, CMS has an inner tracker, simply referred to as the tracker in the following sections, closest to the interaction point of the colliding beams and a muon tracking system, typically referred to as the muon system, on the outermost part of the detector. Between the two is the calorimeter, composed of an electromagnetic (ECAL) and hadron (HCAL) calorimeter, as well as the large solenoid magnet, the magnetic field of which provides the curvature of the trajectories of charged particles necessary to measure their momenta. A cutaway illustration of the CMS detector is shown in Figure 2.7. Each of these subdetectors, as well as the magnet, is described in the following sections after an introduction of the coordinate system of CMS and several variables that will be used throughout subsequent chapters.

Figure 2.7: Cutaway illustration of the CMS detector. Each subdetector is described in the following sections [63].



2.2.1 Coordinate system and common variables

CMS uses a right-handed coordinate system with the origin at the nominal interaction point inside the detector. The x -axis points horizontally toward the center of the LHC, and the y -axis points vertically upward. Thus, the z -axis points in the direction of the counterclockwise rotating beam. Along the z -axis is the longitudinal direction, and in the x - y plane is the transverse direction. The polar angle θ is measured from the positive z -axis, and the azimuthal angle ϕ is measured from the positive x -axis in the x - y plane. The radial coordinate in the x - y plane is $r = \sqrt{x^2 + y^2}$. Occasionally, we will also use the pitch angle $\lambda \equiv \pi/2 - \theta$, which is the angle from the x - y plane.

Momentum, energy, and mass will generally be denoted by $\vec{p}$, E , and m , respectively. The components of momentum along the x -, y -, and z -axis will be called p_x , p_y , and p_z , respectively, and the magnitude of momentum will be denoted by p . Since, in a given proton-proton collision, the longitudinal momenta of the initial state partons is unknown, we often make use of the transverse momentum $\vec{p}_T \equiv p_x \hat{x} + p_y \hat{y}$ with magnitude p_T . And since the transverse momenta of the initial state partons is always very nearly zero, we also define, for a given event, the missing transverse momentum as

$$\vec{p}_T^{\text{miss}} \equiv - \sum_i \vec{p}_{T,i}, \quad (2.1)$$

where the sum is over all the visible final state particles in an event. For an event with no invisible particles, such as neutrinos, the magnitude of this vector, p_T^{miss} , should vanish. We will make extensive use of p_T^{miss} in Chapter 3.

In collider physics, it is common to use the pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ instead of the polar angle θ . This is useful because, for massless particles, η for a given particle is equal to the rapidity, y , needed to boost an observer in the lab frame

to a frame in which the particle moves only in the x - y plane. This can be seen by rewriting η in the following way:

$$\eta \equiv -\ln \left[\tan \left(\frac{\theta}{2} \right) \right] = -\ln \sqrt{\frac{1 - \cos \theta}{1 + \cos \theta}} = -\ln \sqrt{\frac{1 - p_z/p}{1 + p_z/p}} = \frac{1}{2} \ln \frac{p + p_z}{p - p_z}. \quad (2.2)$$

Then if $m = 0$, $p = E$, and

$$\eta = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \equiv y. \quad (2.3)$$

Therefore, in the limit of massless particles, differences in η are Lorentz invariant under boosts along the z -axis. Distances between objects in the η - ϕ plane,

$$\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}, \quad (2.4)$$

will frequently be used to discuss the separation between objects produced in the collisions.

2.2.2 Solenoid magnet

The solenoid magnet is the central feature of CMS, around which the rest of the detector was designed. It is the largest superconducting magnet ever constructed, with a diameter of 6 m and length of 12.5 m (see Figure 2.8). This is large enough to fit the entire tracker and calorimeters inside the bore of the magnet. Designed to reach a magnetic field of up to 4 T, this equates to a stored energy of 2.6 GJ at the full current of 19.14 kA. This current is provided through cables of NbTi superconductor, which is cooled with liquid helium. In order to provide the number of ampere-turns required for a 4 T field, the winding is made up of 4 layers, a cross section of which can be seen in Figure 2.9.

The solenoid magnet in CMS is also one of the thinnest magnets in a collider detector relative to the large energy stored in its magnetic field (see Figure 2.10).

Figure 2.8: Artistic view showing the cold mass of the solenoid inside its cryostat (left), and photograph of the solenoid during initial construction of CMS (right) [19, 4].

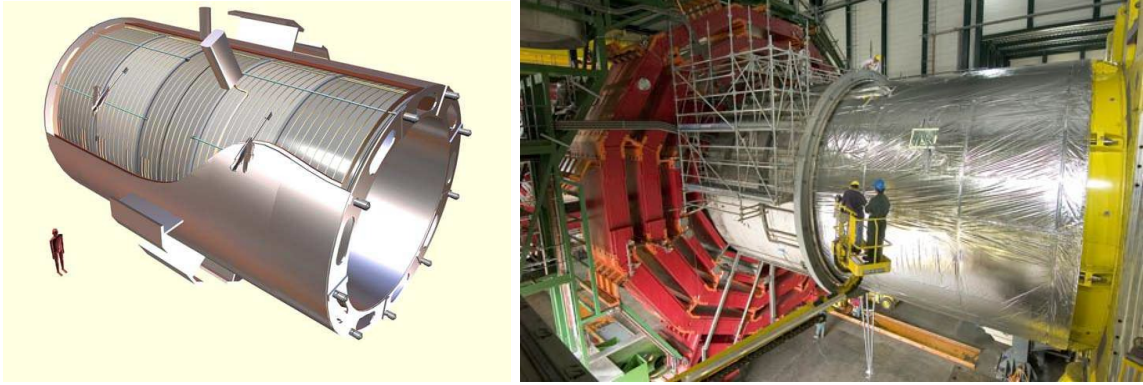
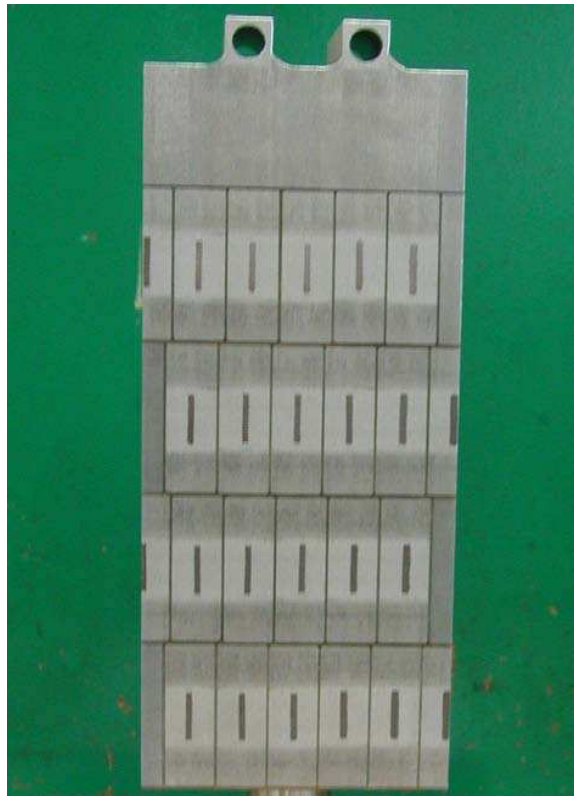
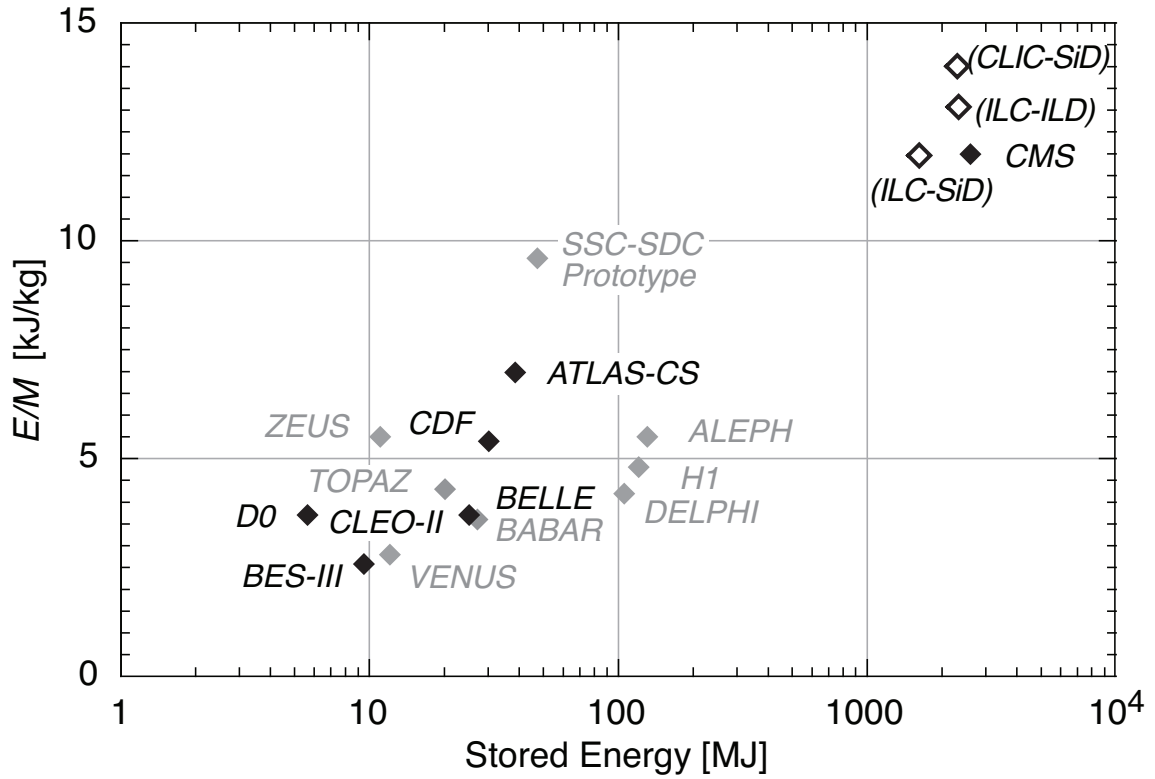


Figure 2.9: Cross section of the cold mass of the solenoid magnet, showing the 4-layer winding [19].



This is important for physics reasons, as the magnet is dead material, and could cause excessive particle scattering and absorption if it were too thick. However, this poses an obvious mechanical dilemma, as the powerful magnetic field exerts a large hoop stress (130 MPa) on the magnet. To deal with this stress, the magnet winding is reinforced with aluminum, as can be seen above in Figure 2.9, so that it serves a mechanical function in addition to carrying current.

Figure 2.10: Ratio of stored energy to cold mass versus stored energy for various solenoid magnets used in collider detectors. Gray indicates magnets that are no longer operational, and hollow markers indicate magnets for proposed experiments [58].



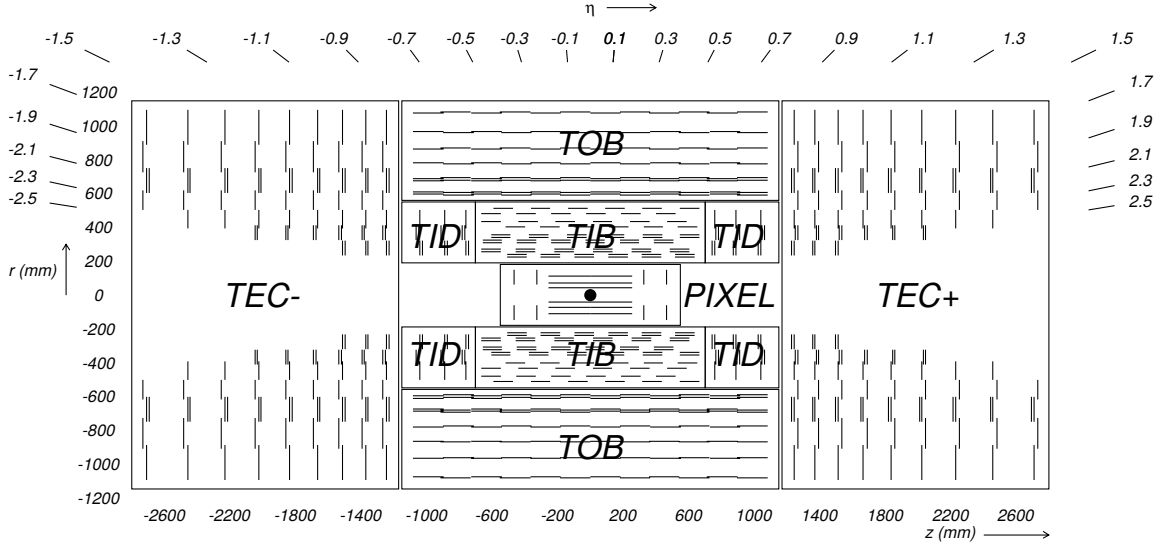
2.2.3 Tracker

CMS is the first collider experiment to use silicon technologies throughout its entire tracker. With a length of 5.8 m, diameter of 2.5 m, and a total active area of $\sim 200 \text{ m}^2$, it is the largest silicon tracker ever built. Closest to the interaction point, where the particle fluence is highest, silicon pixel modules are used in order to keep the occupancy at reasonable levels. These are arranged in three cylindrical barrel layers and two forward disks at either end. Farther out from the interaction point, where the particle flux is lower, silicon microstrips are used, organized into three subsystems: the Tracker Inner Barrel and Disks (TIB/TID), composed of four barrel layers and three forward disks at either end; the Tracker Outer Barrel (TOB), made up of six barrel layers; and the Tracker Endcaps (TEC), which have nine disks on either end. A schematic of the tracker layout is shown in Figure 2.11. The individual modules of the tracker are supported on various carbon fiber composite structures and cooled to -10°C with C_6F_{14} . The next two sections contain a more detailed description of each of the pixel and strip subdetectors.

Pixel tracker

The basic layout of a pixel module is shown in Figure 2.12. There is a silicon sensor that traversing charged particles ionize. This sensor is bump bonded to a readout chip (ROC), which amplifies and transmits the resulting charge collected from the sensor. The pixel pitch is $100 \times 150 \mu\text{m}^2$ in the r - ϕ and z directions, respectively, with each pixel attached to a pixel unit cell on the ROC via an indium bump. Each ROC is connected to 52×80 pixels in this way, and each module consists of several ROCs (as many as 16 in the barrel, and as few as 2 in the forward disks). A total of 768

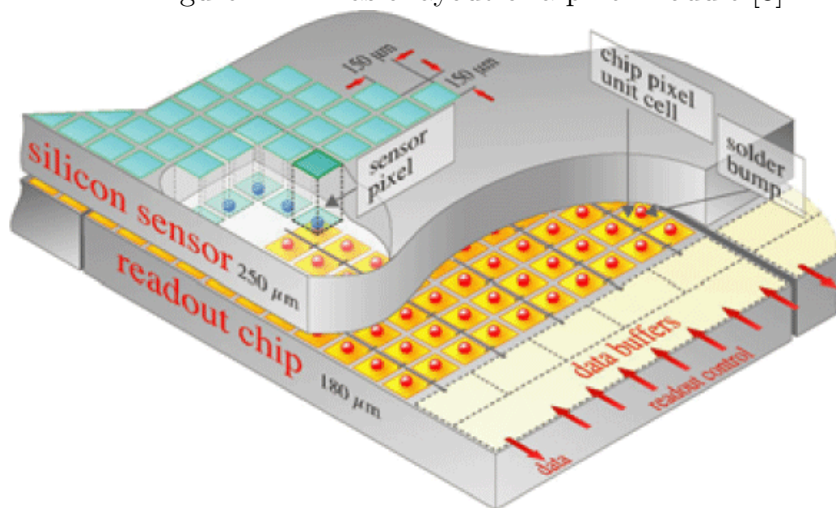
Figure 2.11: Schematic layout of the tracker in the r - z plane [19].



modules are mounted in the barrel layers, and 672 are mounted in the forward disks.

The silicon sensors of the pixel tracker utilize the so-called n-on-n concept. Each pixel consists of a highly doped n^+ -type implant in a high-resistance n-type substrate. The p-n junction is then placed on the backside of the sensor. Photographs of the pixels in disk and barrel sensors are shown in Figure 2.13. Although this type of sensor is significantly more expensive to produce because of the double-sided processing required, it was chosen because it can continue to be operated at moderate bias voltages even after high doses of radiation. One of the effects of such radiation in a silicon sensor is damage to the silicon crystal lattice caused by non-ionizing energy loss, which causes the substrate to change from n-type to p-type over time. But after

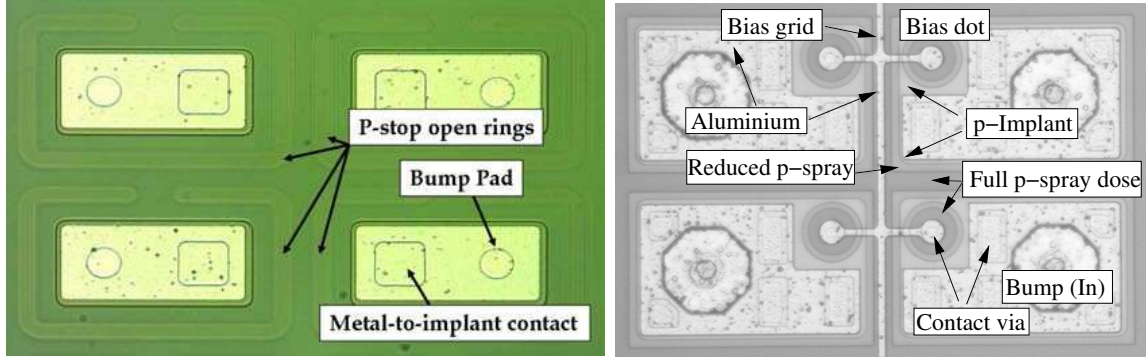
Figure 2.12: Basic layout of a pixel module [3].



this type inversion, an n-on-n sensor can still be operated partially depleted without excessively high bias voltages.

The ROC is a custom ASIC that is fabricated using a commercial 250 nm CMOS process. Its main purpose is to amplify and transmit the charge collected after a charged particle traverses the sensor. The encoded address of each pixel that receives a signal above a certain configurable threshold and the pulse height of the signal is transmitted via an analog link. This analog pulse height enables an improvement of the hit position resolution via charge sharing. The pixel modules are oriented in such a way as to enhance the Lorentz drift of the charge carriers in the sensors, so that the signal from a traversing charged particle is typically collected by more than one pixel in a module. By interpolating the signals collected, a hit position resolution as good as 15 μm can be achieved.

Figure 2.13: Photographs of pixels in a disk (left) and barrel (right) sensor [19].



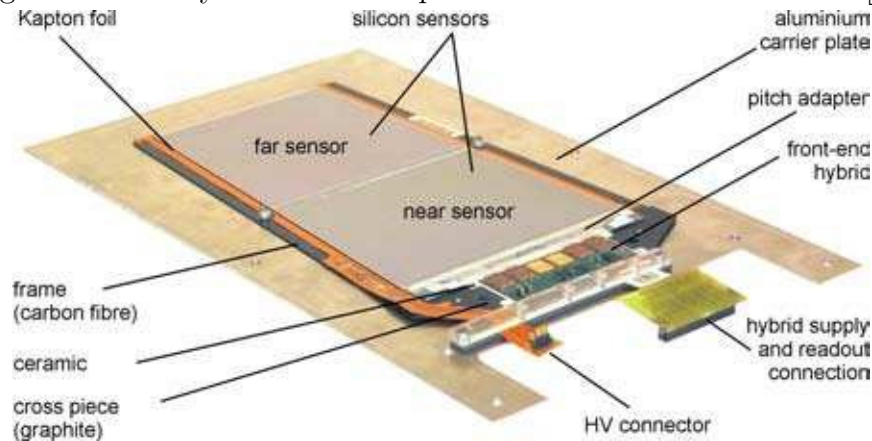
Strip tracker

The strip tracker relies on the same basic principles of operation as the pixel tracker. Instead of pixels, the silicon sensors here are based on microstrips with a typical length of 10 cm and pitch ranging from $80\text{ }\mu\text{m}$ in the TIB, up to $184\text{ }\mu\text{m}$ in the TEC. Due to the less intense radiation environment compared to that of the pixel detector, the sensors are of the more typical, and less expensive, p-on-n type. During irradiation tests, the full depletion voltage of these sensors was observed to increase with fluence, as expected from type inversion of the n-type substrate, but stayed below the maximum tolerable voltage for the sensors of 500 V. In the first two layers of the TIB, TID, and TOB, and in certain sections of the TEC, each module is mounted back-to-back with a second module at a stereo angle of 100 mrad. This allows for a two-dimensional measurement of the position of charged particles traversing these modules, similar to the measurements in the pixel detector.

Each p⁺-type implant is covered with an aluminum strip with an insulating layer of silicon oxide and nitride between. The aluminum strips are then wire bonded to

the ROC. Thus, the sensor is capacitatively coupled to the ROC, which helps protect it from the high leakage currents expected after irradiation. A fully assembled module can be seen in Figure 2.14. As in the case of the pixel detector, the ROC is a custom ASIC fabricated with a 250 nm CMOS process. To optimize the spatial resolution using charge sharing, the full analog signal from the sensors is read out.

Figure 2.14: Fully assembled strip tracker module from the TEC [19].



2.2.4 Electromagnetic calorimeter

The ECAL is a hermetic homogeneous calorimeter composed of lead tungstate (PbWO_4) crystals with 61 200 mounted in the barrel and 7 324 mounted in each endcap. Lead tungstate has several features that make it ideal for use in the ECAL of CMS. The scintillation in the crystals is fast with 80% of the light emitted within the LHC bunch crossing time of 25 ns. The Moliere radius is small (2.2 cm) and the radiation length is short (0.89 cm), resulting in a fine granularity and compact calorimeter. The crystals are also sufficiently radiation hard to survive the particle

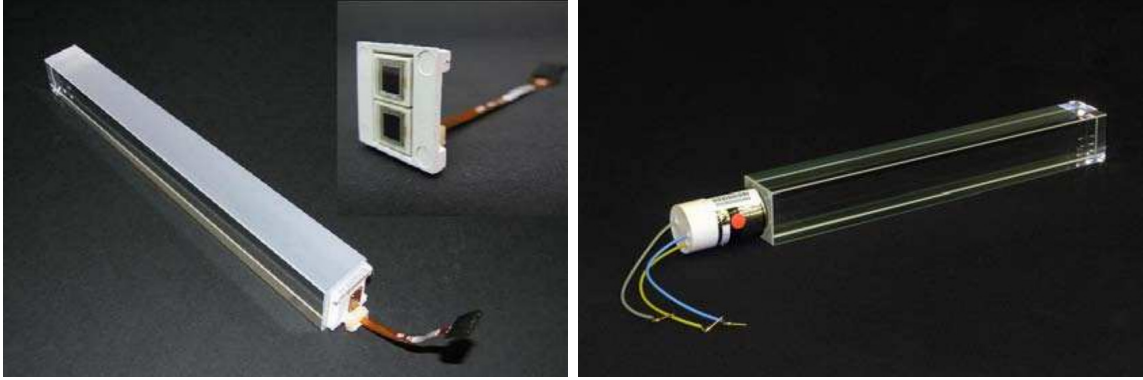
fluxes expected from the LHC. Ionizing radiation tends to decrease light transmission via the formation of color centers in the crystals. However, even with the maximum radiation damage expected during the lifetime of the detector, the induced light attenuation length will remain greater than three times the length of the crystals. Photographs of crystals from the barrel and endcaps are shown in Figure 2.15 coupled with their respective photodetectors.

Each crystal in the barrel is coupled to two avalanche photodiodes (APD), each with an active area of $5 \times 5 \text{ mm}^2$ and quantum efficiency of 75% at 430 nm (approximately the peak wavelength of scintillation light emitted by PbWO_4). Each APD consists of a silicon p-n diode operated with a reverse bias close to the breakdown voltage, leading to an intrinsic gain. The APDs are operated at a gain of 50 and the pair on each crystal is read out in parallel. In the endcaps, where the more intense radiation environment makes the use of APDs untenable, vacuum phototriodes (VPT) are used instead. VPTs are essentially photomultipliers with a single gain stage. The bialkali photocathode has a quantum efficiency of 22% at 430 nm and is operated at a gain of 10. The lower quantum efficiency and gain compared to the APDs in the barrel are compensated by the much larger active area of 280 mm^2 .

2.2.5 Hadron calorimeter

The HCAL is a hermetic sampling calorimeter composed of brass and steel absorber plates interspersed with plastic scintillator tiles or quartz fibers. As with the ECAL, there is a cylindrical barrel part (HB) and two endcaps (HE), covering the pseudorapidity ranges $|\eta| < 1.3$ and $1.3 < |\eta| < 3$, respectively. In addition, there are 1–2 layers of scintillator outside of the solenoid in the barrel (the outer calorimeter

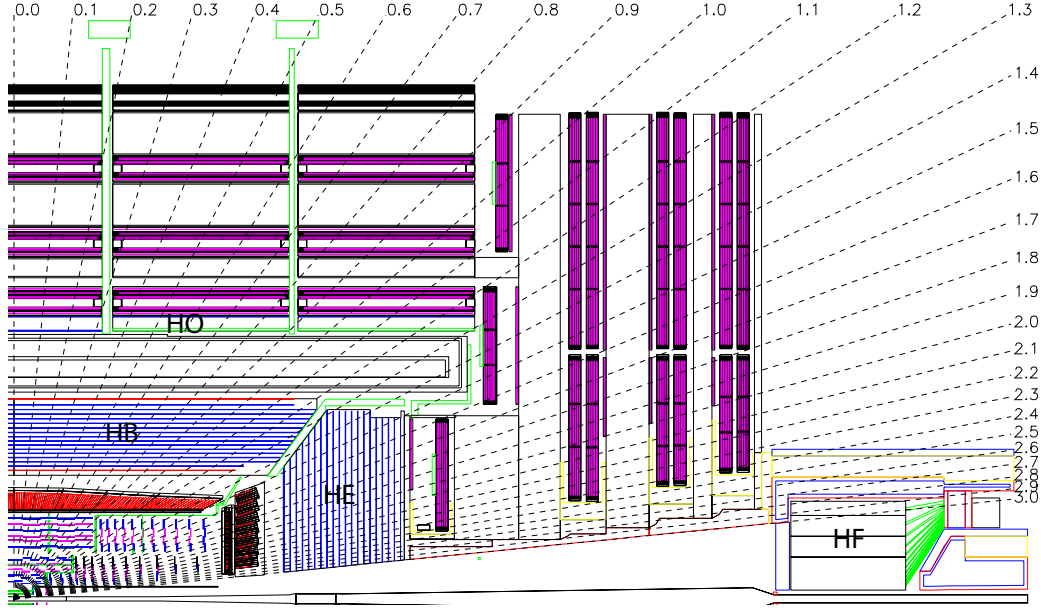
Figure 2.15: Photographs of crystals from the ECAL barrel (left) and endcaps (right) coupled with their respective photodetectors [19].



or HO), which help to improve the containment of the HB and measure late-starting hadronic showers. There are also additional calorimeters at $|z| = 11.2\text{ m}$ (the forward calorimeters or HF), which extend the pseudorapidity coverage to $|\eta| = 5.2$. Figure 2.16 shows the layout of the different components of the HCAL.

Within the HB, HE, and HO, the absorber plates are composed mostly of brass, some of which was recycled from over a million World War II artillery shells from the Russian Navy, with stainless steel plates used in certain locations for structural support. A photograph of one of the partially assembled HE calorimeters is shown in Figure 2.17. The plates range in thickness from 50.5 mm in the HB to 79 mm in the HE, with a total calorimeter thickness, including the ECAL, of $10 \lambda_l$ in the HE but only $6.92 \lambda_l$ at $\eta = 0$ in the HB. This is the motivation for the HO, which consists of a single layer of scintillator just outside the solenoid magnet except in the region closest to $\eta = 0$ where two layers on either side of a 19.5 cm thick piece of iron are

Figure 2.16: Layout of the components of the HCAL in the r - z plane [19].



used. The HO increases the minimum thickness of the total barrel calorimeter to $11.8 \lambda_I$.

Interspersed in the layers of absorber of the HB, HE, and HO are tiles of plastic scintillator. Most of these tiles are 3.7 mm thick with thicker tiles of 9 mm used in a few places of the HB and HE and throughout the HO. The scintillation light is collected with wavelength-shifting (WLS) fibers embedded in grooves in the tiles (see Figure 2.18). These WLS fibers have a diameter of 0.94 mm and shift the blue-violet scintillation light to a green light that is carried by clear optic fibers to hybrid photodiodes (HPD). These consist of a photocathode held approximately 3.3 mm from a pixelated silicon photodiode. Photoelectrons from the photocathode are accelerated by a strong electric field into the photodiode, resulting in a gain of approximately 2000. Figure 2.19 shows a photograph of a cross section of an HPD.

Figure 2.17: Partially assembled HE calorimeter before installation. Scintillator trays can be seen inserted in one of the azimuthal wedges [19].

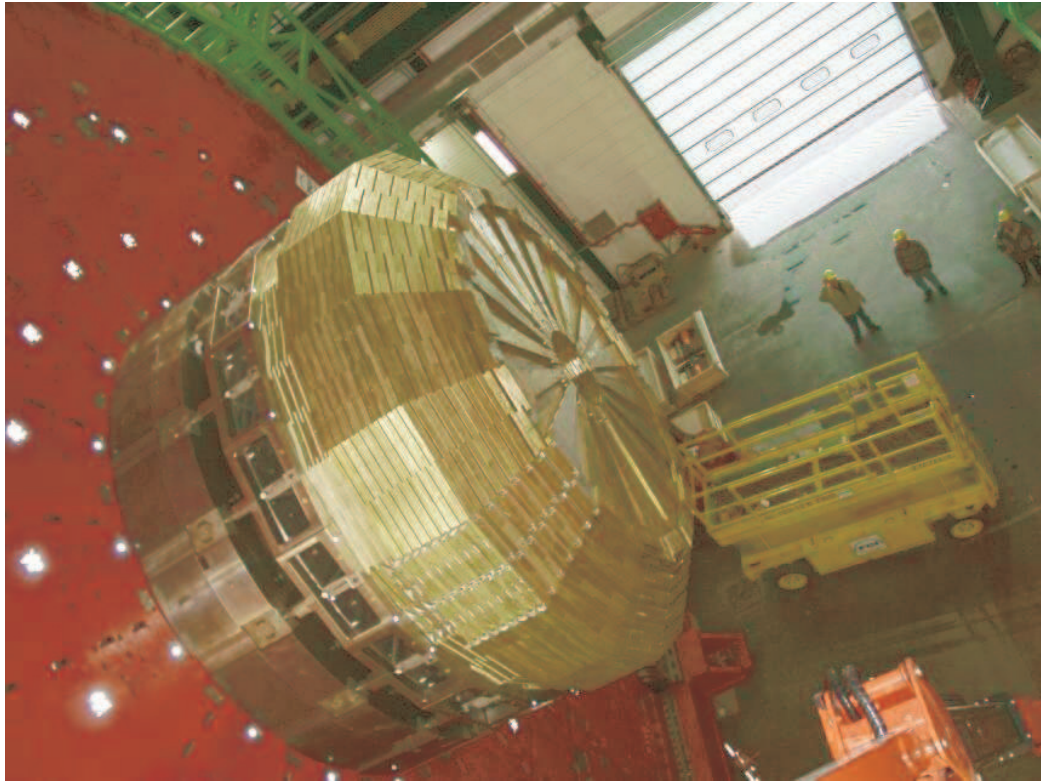


Figure 2.18: Tile of plastic scintillator from the HO with embedded WLS fibers [19].

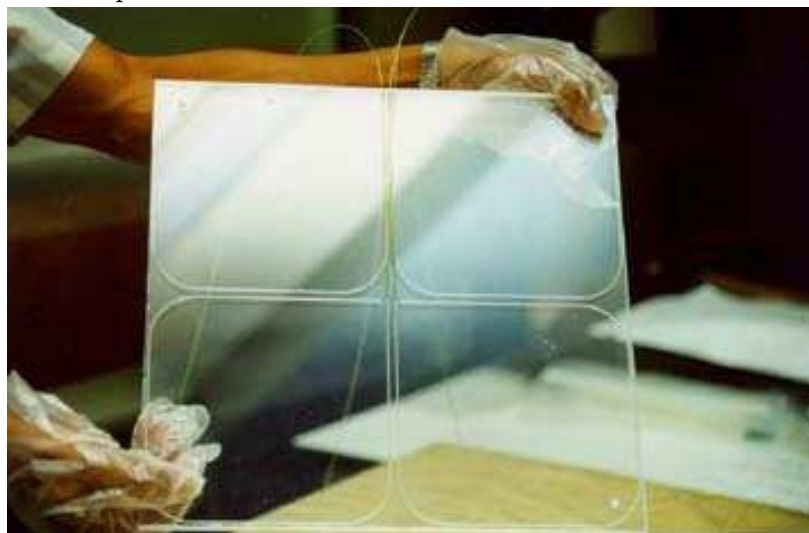
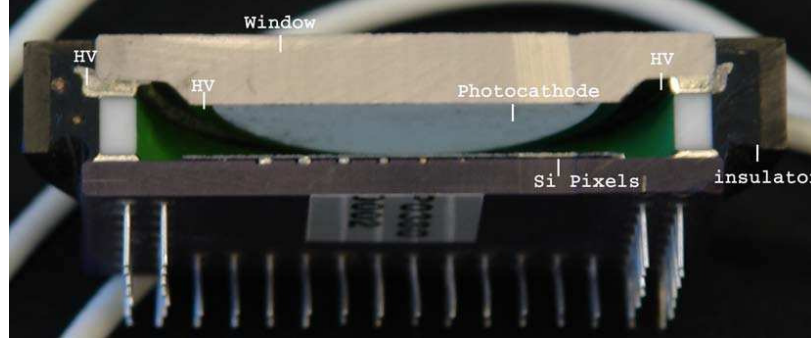


Figure 2.19: Cross section of an HPD [19].



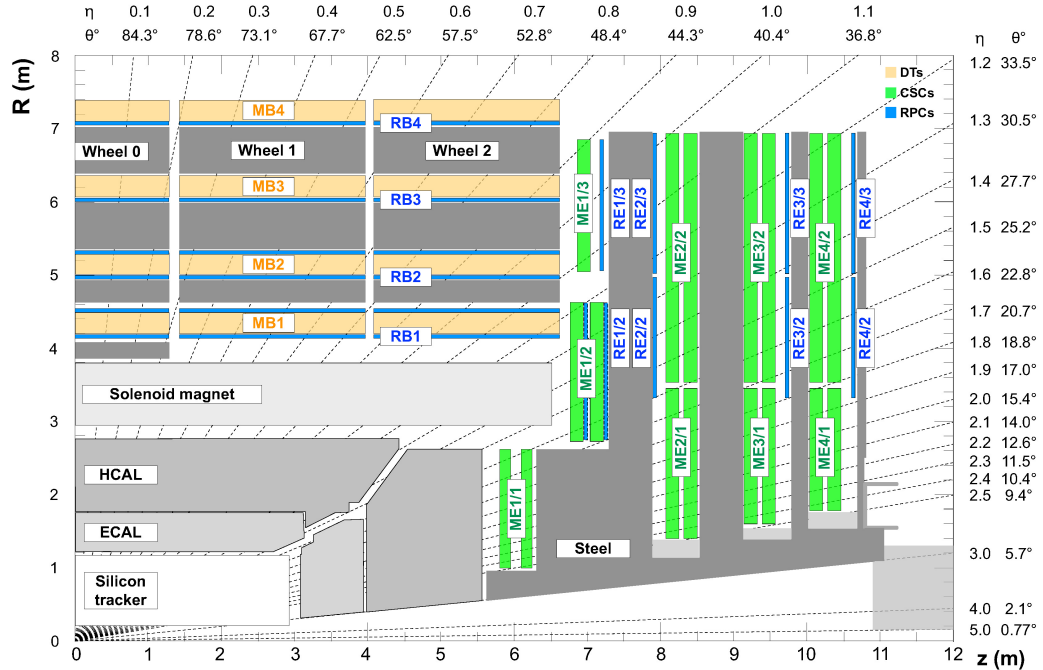
Because of the extreme radiation environment to which the HF is exposed, different technologies are required. The absorber of the HF is entirely composed of steel plates that are 5 mm thick and arranged in a cylindrical structure of radius 130 cm. Quartz fibers are inserted into grooves within these plates. These fibers are $800\text{ }\mu\text{m}$ in diameter and were chosen over plastic scintillator due to their superior radiation hardness. These fibers are coupled to more conventional 8-stage photomultiplier tubes (PMT), which can be used here instead of HPDs due to the smaller magnetic field. Charged particles within hadronic particle showers generate Cherenkov light as they traverse the quartz fibers. This signal is then read out by the PMTs.

2.2.6 Muon system

The muon system constitutes another tracking detector that is mounted in the steel flux return yoke, outside of the calorimeters and magnet. As the name implies, the muon system is designed to identify and measure the momenta of muons, since they are the only standard model particles that can reliably penetrate the calorimeters and magnet and traverse through the flux return yoke. The muon system consists

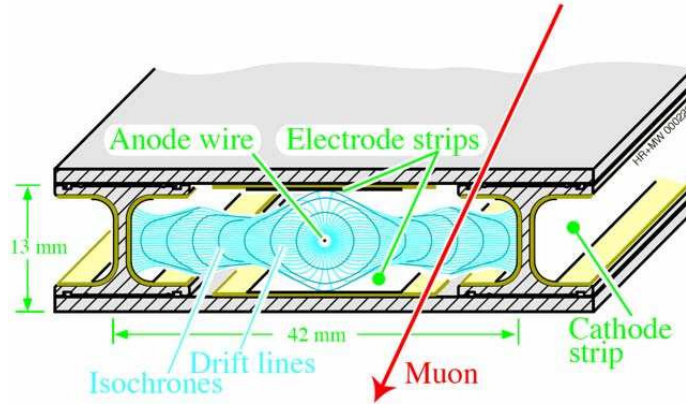
of three types of gas chamber. Drift tubes (DT) are used to provide precise muon tracking in the barrel, covering $|\eta| < 1.2$. In the endcaps, where the muon and background rates are much higher and the magnetic field is large and less uniform, cathode strip chambers (CSC) are used, with coverage between $0.9 < |\eta| < 2.4$. Resistive plate chambers (RPC) are used in both the barrel and endcaps, out to $|\eta| < 1.6$, to provide fast, unambiguous bunch crossing assignments to muon candidates for the purposes of triggering. The layout of the muon chambers in one quarter of CMS is shown in Figure 2.20. Altogether, the muon system contains approximately 25000 m^2 of detectors.

Figure 2.20: Layout of one quarter of the CMS detector, with the muon system detailed. The DT stations are in beige, the CSC stations are in green, and the RPCs are blue.



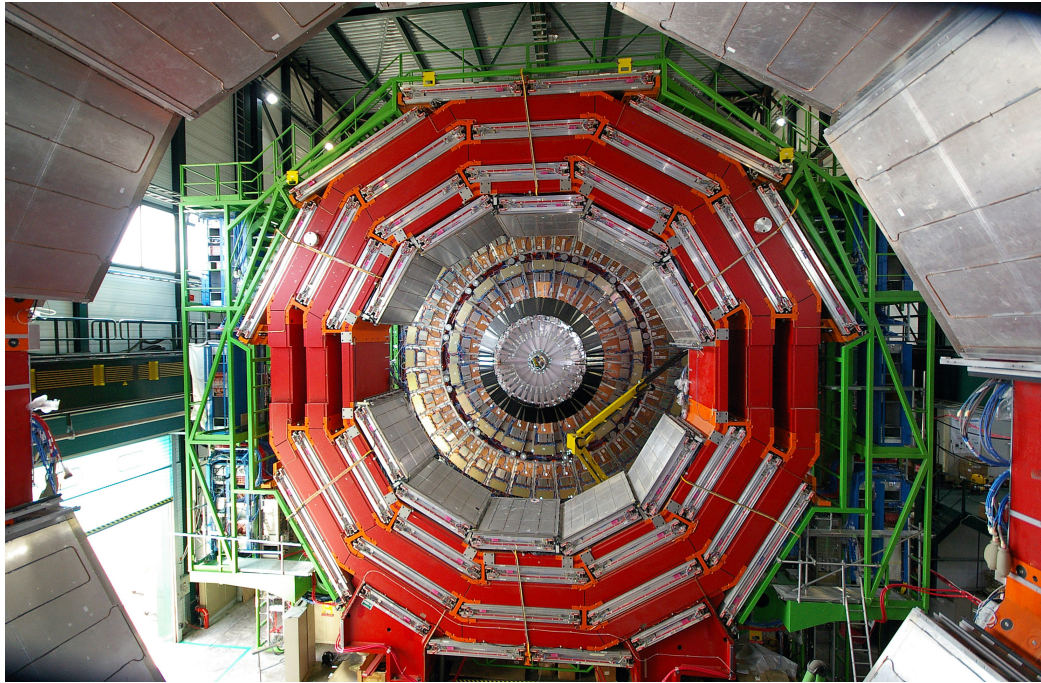
The drift tubes consist of aluminum tubes with a cross sectional area of $13 \times 42 \text{ mm}^2$ with a $50 \mu\text{m}$ diameter gold-plated stainless steel anode wire running down the middle of each tube, as illustrated in Figure 2.21. The field electrodes and cathode strips consist of aluminum tape insulated from the grounded aluminum walls of the tube by a layer of mylar tape. Charged particles traversing a tube ionize the Ar/CO₂ gas mixture inside, with the liberated charges collected and read out on the electrodes. Each DT chamber consists of two superlayers (SL) of four layers of tubes each, arranged parallel to the beam axis, with an additional SL arranged perpendicular to the beam axis in all but the outer DT station. Thus, most of the chambers can provide orthogonal position measurements in the r - ϕ and z directions. There are four DT stations, each consisting of 60–70 chambers arranged in concentric cylinders (see Figure 2.22).

Figure 2.21: Illustration of the cross section of a drift tube [19].



Each CSC is trapezoidal, with those in the inner rings covering 10° in ϕ and those in the outer rings covering 20° in ϕ (see Figure 2.23). Within each chamber are

Figure 2.22: Photograph of one of the endcaps of CMS through two of the barrel sections of the flux return yoke during installation. The partially installed gray DT chambers, arranged in four concentric stations, can be seen interspersed in the red return yoke.



seven panels onto which cathodes strips are milled such that they lie along the radial direction. Gold-plated tungsten anode wires are wound azimuthally around three of the panels, except in the innermost ME1/1 chambers. Since ME1/1 sits just inside the solenoid magnet and is exposed to a strong and uniform magnetic field, its anode wires are tilted to compensate for the Lorentz drift of the electrons. When a charged particle ionizes the Ar/CO₂/CF₄ gas mixture inside the chamber, the r coordinate of the particle is read out by the nearest anode wire, while the ϕ coordinate is given by interpolating the induced mirror charges read out on nearby cathode strips. This principle of operation is illustrated in Figure 2.24.

Figure 2.23: CSCs installed on one wheel of an endcap [19].

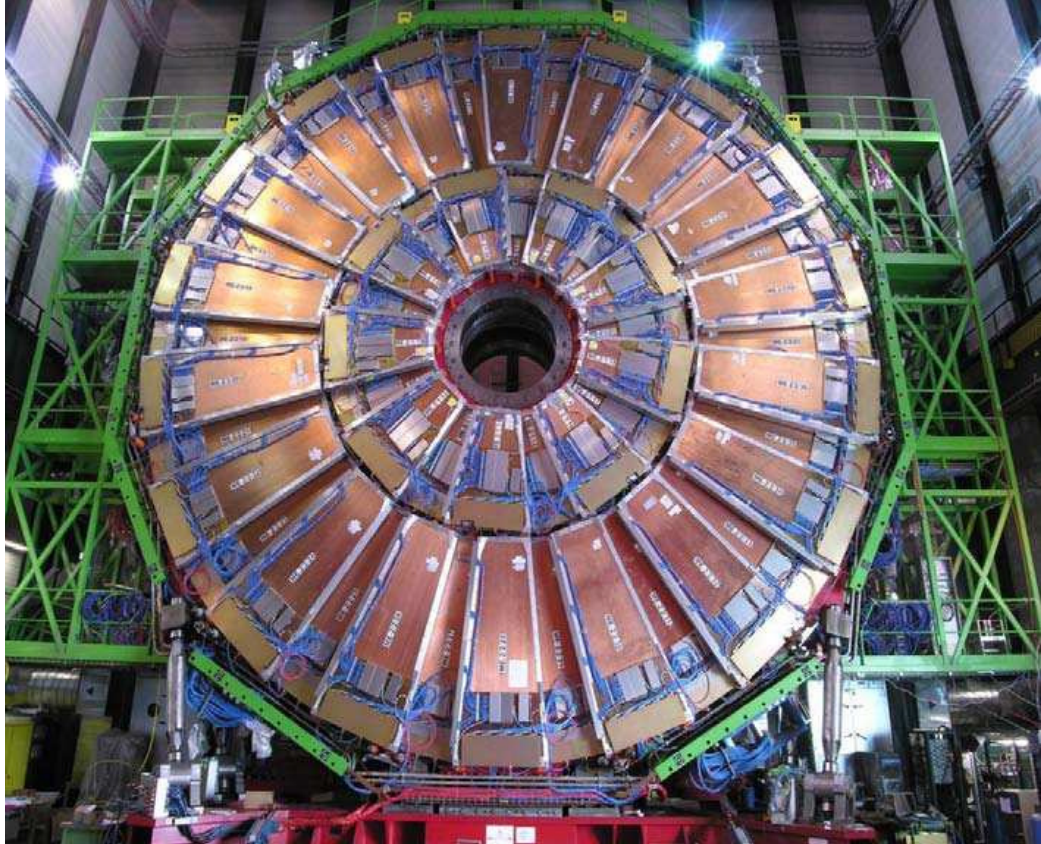
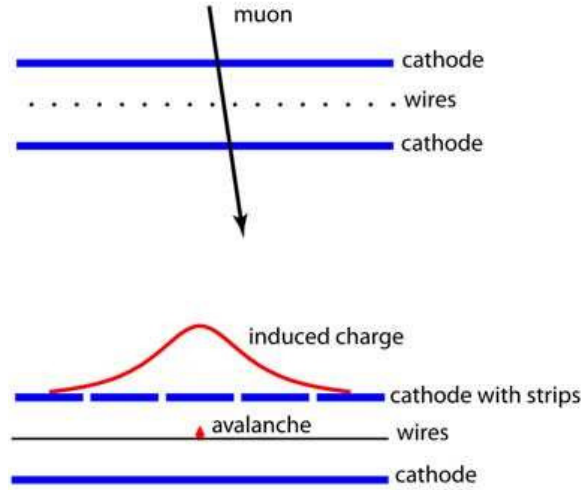


Figure 2.24: Schematic illustrating the principle of operation of a CSC [19].



The RPCs consist of two pairs of parallel bakelite electrode plates, with each pair separated by a 2 mm gas gap. The plates are operated in avalanche mode, such that when a charged particle traverses the gas gaps, the electrons from the ionized gas are accelerated sufficiently to produce an avalanche. This charge is then read out by strips between the two pairs of plates. An exploded view of one of these gas gaps and the read-out strips can be seen in Figure 2.25. This double-gap structure allows the chambers to be operated at a lower gas gain and with higher efficiency than would be possible with a single gap. These double-gap modules are rectangular in the barrel region, with four layers of chambers accompanying the DT chambers, with the readout strips aligned parallel to the beam axis. In the endcaps, the modules are trapezoidal, with four layers of chambers interspersed among the CSCs (see Figure 2.26). The strips in these chambers are aligned radially. Except for the mechanical differences, the RPCs in the barrel and endcap are identical.

Figure 2.25: An exploded view of one gas gap and the read-out strips in an RPC. Each RPC consists of two such gas gaps on either side of the strips [2].

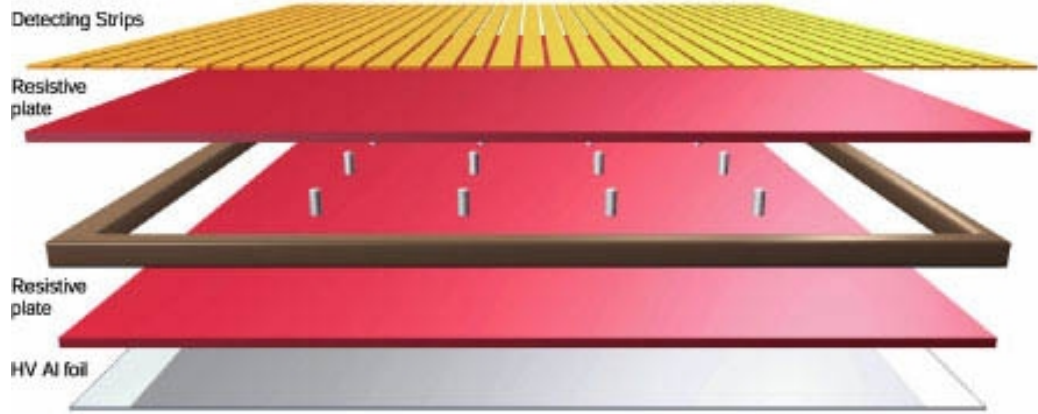
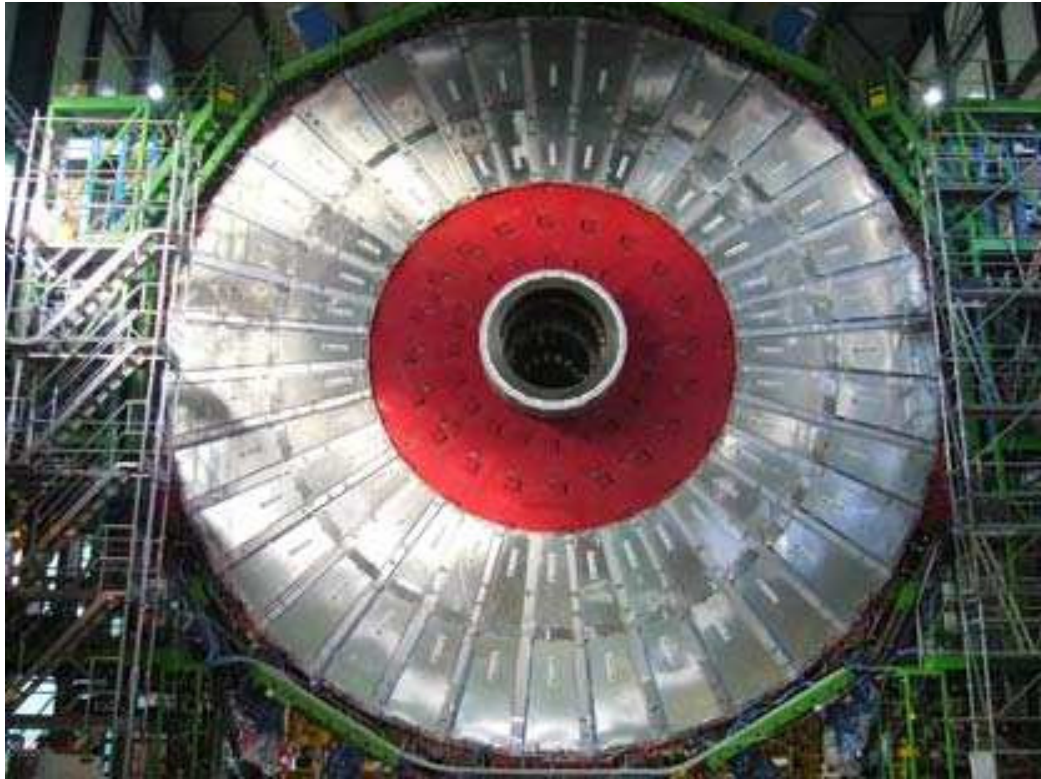


Figure 2.26: RPCs installed on one wheel of an endcap [19].



2.2.7 Trigger system

The LHC collides proton bunches every 25 ns, corresponding to a bunch crossing rate of 40 MHz. At design luminosity, each bunch crossing yields an average of 20 inelastic proton-proton interactions, leading to an interaction rate of 800 MHz. This exceeds, by several orders of magnitude, the rate and amount of data that is possible to read out, store, and process. Furthermore, the majority of these interactions involve well-understood physics that is not relevant to the understanding of the Higgs boson and the search for BSM physics, the primary physics goals of CMS. Thus, a system for quickly selecting events that are relevant to these goals for permanent storage has been developed. This system is called the trigger.

The trigger in CMS was developed as a two-tiered system. The level 1 (L1) trigger is implemented in custom hardware and reduces the event rate from 40 MHz to 100 kHz. The high level trigger (HLT) is implemented in software that runs on a computing farm consisting of over 10 000 commodity processors. Only events accepted by the L1 trigger are further processed by the HLT, which reduces the event rate to 1 kHz. The reconstruction algorithms used in the HLT are generally very similar to those used for offline physics analysis. We will discuss the HLT paths used in the search presented in Chapter 3 and will not discuss the HLT further here.

L1 trigger

For the purposes of flexibility, the L1 trigger is implemented using field-programmable gate arrays (FPGA) where possible, but custom ASICs and programmable memory lookup tables (LUT) are also used where speed and radiation hardness demand it. The system comprises both on-detector electronics, as well as electronics located in

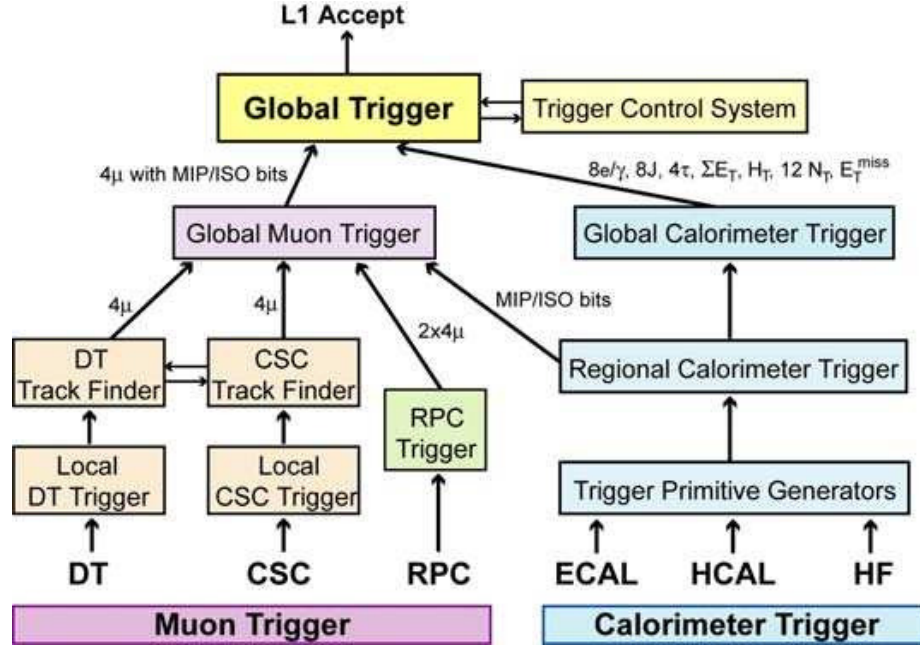
the underground control room, approximately 90 m from the experimental cavern. The maximum allowed latency for the L1 trigger is $3.2\,\mu\text{s}$. Since this is greater than the 25 ns time between bunch crossings, the data from multiple bunch crossings is stored in a pipeline and processed in parallel to avoid deadtime.

The architecture of the L1 trigger system is illustrated in Figure 2.27. Only information from the calorimeters and muon system is used and each system works using three stages. At the lowest level are trigger primitive generators (TPG), which produce local calorimeter trigger towers and track segments, in the case of the calorimeters and muon system, respectively. At the next level are regional triggers that combine the trigger primitives into trigger objects in limited spatial regions. These trigger objects represent physics objects such as electrons and muons. The global calorimeter and muon triggers then determine the highest-rank objects across the entire detector, where the rank is based on energy or momentum as well as the level of confidence in the measurements. Finally, the global trigger (GT) determines whether to issue an L1 accept (L1A) based on algorithms using the highest-rank objects, as well as the readiness of the subdetectors and data acquisition (DAQ) as determined by the trigger control system (TCS). This L1A causes the event to be processed further by the HLT and is passed to the subdetectors by the timing, trigger, and control (TTC) system.

2.2.8 Physics object reconstruction

CMS uses a so-called particle flow (PF) algorithm to reconstruct the physics objects produced in the collisions [65]. The idea of particle flow is to combine information

Figure 2.27: Architecture of the L1 trigger [19].

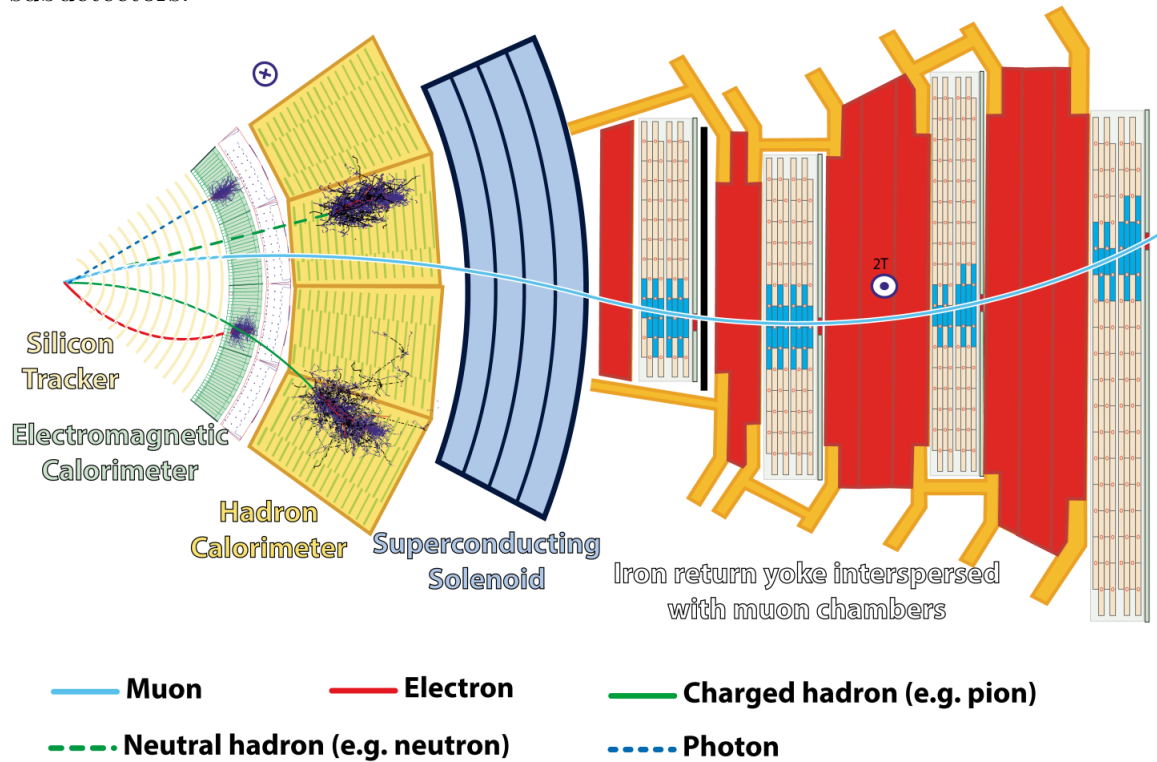


from all of the subdetectors in a consistent way in an effort to reconstruct every particle in the final state of every event. This list of particles, or PF candidates, is then used as input to reconstruct composite objects, such as hadronic jets and missing transverse momentum.

Each PF candidate is identified as one of five types: muon, electron, photon, charged hadron, or neutral hadron. Muons are identified by linking tracks in the silicon tracker with compatible hits in the muon system. The track is then refit, including the muon system hits, to produce what is known as a “global muon”. Electrons are reconstructed by matching tracks in the silicon tracker with compatible deposits of energy in the ECAL. In order to correctly reconstruct the energy of the electron, energy deposits consistent with bremsstrahlung from the track are added to

the main deposit produced when the electron itself encounters the ECAL. Photons are reconstructed from similar deposits of energy in the ECAL, but where no associated track is found to be compatible. Likewise, charged (neutral) hadrons are reconstructed from energy deposits in the HCAL, with (without) a compatible track in the silicon tracker. A summary of the basic ideas of how each type of particle is reconstructed is shown in the transverse slice of CMS in Figure 2.28.

Figure 2.28: Transverse slice of the CMS detector, with illustrations showing how each type of particle is reconstructed by particle flow, using information from all the subdetectors.



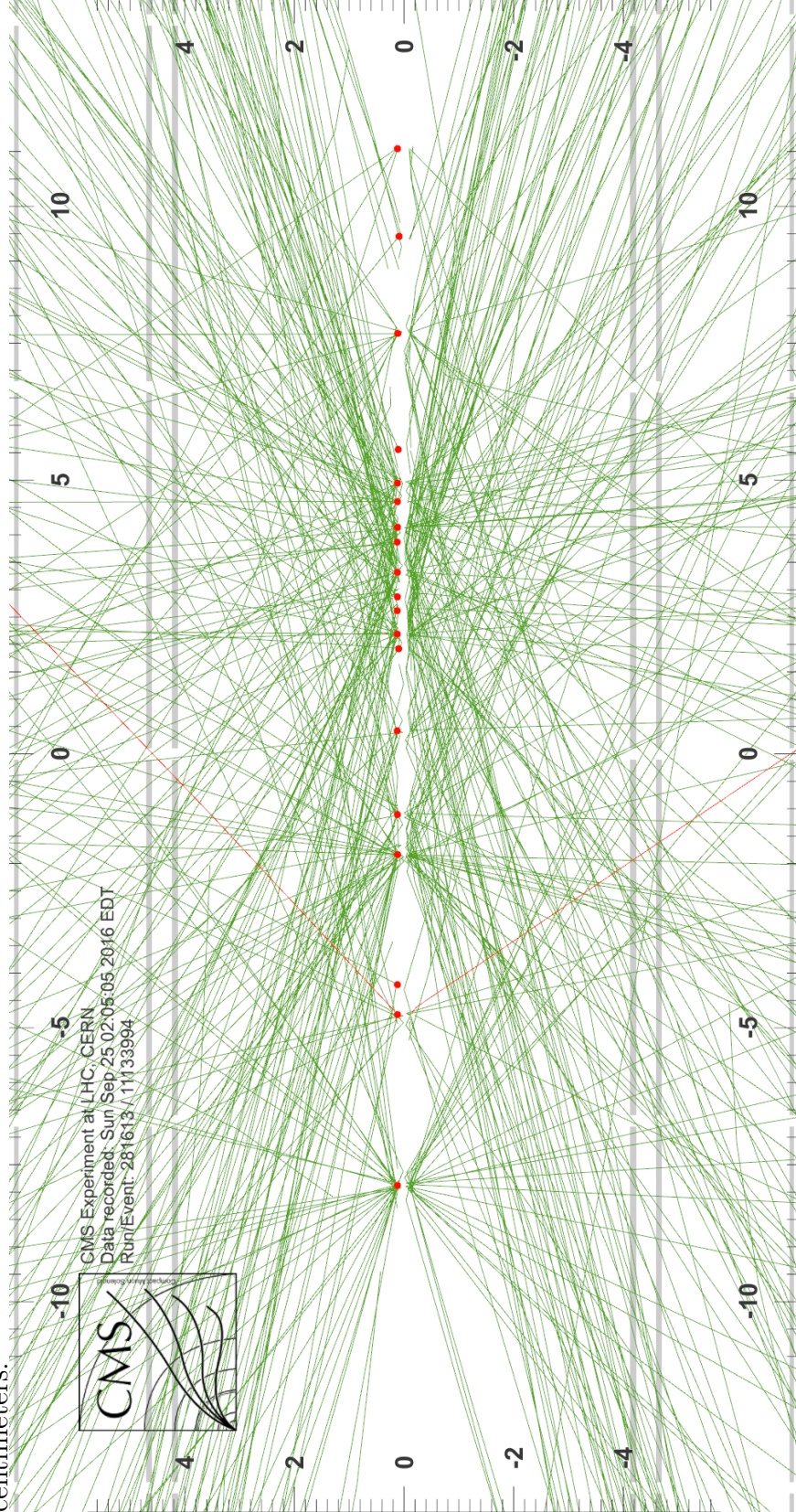
Reconstructed tracks are also clustered into primary vertices, meant to represent the locations of each inelastic pp interaction in a bunch crossing, using a sophisticated deterministic annealing algorithm [22]. In a hadron collider like the LHC, it is common for multiple inelastic interactions to occur within a single bunch crossing, resulting in multiple primary vertices per event, as can be seen in the event display in Figure 2.29. This phenomenon is known as pileup. Whenever a single primary vertex needs to be selected within an event, the reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex, where the physics objects are the objects returned by a jet finding algorithm applied to all tracks associated with the vertex, plus the corresponding associated missing transverse momentum. The transverse and longitudinal impact parameters of a track with respect to this primary interaction vertex are defined as

$$d_{xy} \equiv \frac{-(v_x - x)p_y + (v_y - y)p_x}{p_T} \quad \text{and} \quad d_z \equiv (v_z - z) - \frac{(v_x - x)p_x + (v_y - y)p_y}{p_T} \cdot \frac{p_z}{p_T}, \quad (2.5)$$

respectively, where (v_x, v_y, v_z) is the point of closest approach on the track to the CMS origin, and (x, y, z) are the coordinates of the primary interaction vertex. We will occasionally also make use of the longitudinal impact parameter of a track with respect to the CMS origin, z_0 , which is defined as d_z above, but with $(x, y, z) = (0, 0, 0)$.

Hadronic jets are reconstructed by running the anti- k_T clustering algorithm with a distance parameter of $R = 0.4$ [17], implemented in FASTJET [18], on the list of PF candidates for each event with charged hadron subtraction applied. Charged hadron subtraction is a technique used to reduce the likelihood of reconstructing jets coming from pileup, and consists of removing any charged PF candidates that are not consistent with originating from the primary vertex from the list of PF candidates that

Figure 2.29: Display of an event in the y - z plane from the 2016 run illustrating the phenomenon of pileup. Each red dot is a reconstructed primary vertex, corresponding to an inelastic proton-proton interaction. The green lines are reconstructed tracks, the gray horizontal lines represent the first barrel layers of the pixel detector, and the scale on the border is in centimeters.



is used as input to the jet clustering algorithm. Several levels of jet energy corrections (JEC) are also applied to the resulting jets. These corrections are designed to remove the energy from pileup interactions, make the jet response uniform over p_T and η , and to correct for any remaining small differences in the jet response in data and simulation [50].

Missing transverse momentum is calculated as

$$\vec{p}_T^{\text{miss}} = - \sum_i \vec{p}_{T,i}, \quad (2.6)$$

where the sum is over all PF candidates. As with jets, this p_T^{miss} is corrected, this time using so-called type-1 corrections. Type-1-corrected p_T^{miss} replaces the $\vec{p}_T$ of all the particles that can be clustered into jets with the $\vec{p}_T$ of the jets with the standard JECs applied. In the analysis presented in Chapter 3, we will also typically use p_T^{miss} with the p_T of all reconstructed muons counted as invisible, which we denote as $p_T^{\text{miss, no } \mu}$. This is done so that the offline p_T^{miss} is consistent with the calorimeter-based p_T^{miss} used in the triggers, both at L1 and HLT.¹ In addition to the type-1 corrections, we apply a set of p_T^{miss} filters designed to remove events with badly reconstructed p_T^{miss} . The effect of these filters on the acceptance of simulated signal events was found to be negligible.²

¹See Appendix D for more details on this issue.

²See Appendix C.

Chapter 3: Search for disappearing tracks

This chapter presents a search for long-lived charged BSM particles that decay within the volume of the silicon tracker and produce the signature of a disappearing track. As discussed in Chapter 1, such a signature could be produced in AMSB, and we benchmark the search in terms of the chargino mass and lifetime in AMSB, although as noted before, there are many other BSM scenarios that produce the disappearing track signature.

Because no tracking is currently done in the L1 trigger of CMS, events are collected with triggers based on L1 p_T^{miss} seeds, where the p_T^{miss} is produced by the recoil of the BSM particles against initial-state radiation (ISR). To select candidate disappearing tracks, we first require events to contain an isolated, high- p_T track. Next, this track is required to not be consistent with a charged lepton. Finally, candidate tracks are required to have small associated energy deposits in the calorimeter, and to have several missing outer hits in the silicon tracker, the distinctive features of disappearing tracks from signal processes. By contrast, tracks from background standard model processes typically have few missing outer tracker hits or have large associated calorimeter energy deposits, as illustrated in Figure 3.1. Standard model processes only produce the disappearing track signature if some aspect of the reconstruction fails, e.g., if

the electromagnetic calorimeter does not reconstruct all of the energy of an electron. These background contributions are estimated with data-driven techniques.

A previous CMS analysis [49] searched for disappearing tracks in 19.5 fb^{-1} of 8 TeV pp collisions. It excluded at 95% confidence level direct electroweak production of charginos with a mass less than 505 GeV for a mean proper lifetime of 7 ns. Two main improvements with respect to the 8 TeV search have been implemented for the 13 TeV search. A new dedicated trigger has been added, which accepts events that pass a minimal $p_{\text{T}}^{\text{miss}}$ requirement and contain an isolated high- p_{T} track. Also, the method used to estimate the backgrounds from standard model leptons has been modified to be fully data-driven, which makes the search more robust against changes in the reconstruction software and the detector performance and simulation.

The rest of the chapter is organized as follows. Section 3.1 lists all data samples used for this search. The triggers used to collect events are described in Section 3.2, and Section 3.3 details the offline selection requirements used to identify candidate signal tracks. Section 3.4 describes the methods used to estimate the backgrounds. Corrections made to the simulated signal samples are described in Section 3.5. In Section 3.6, the systematic uncertainties are evaluated, and finally, Section 3.7 presents the results of the search and their interpretation.

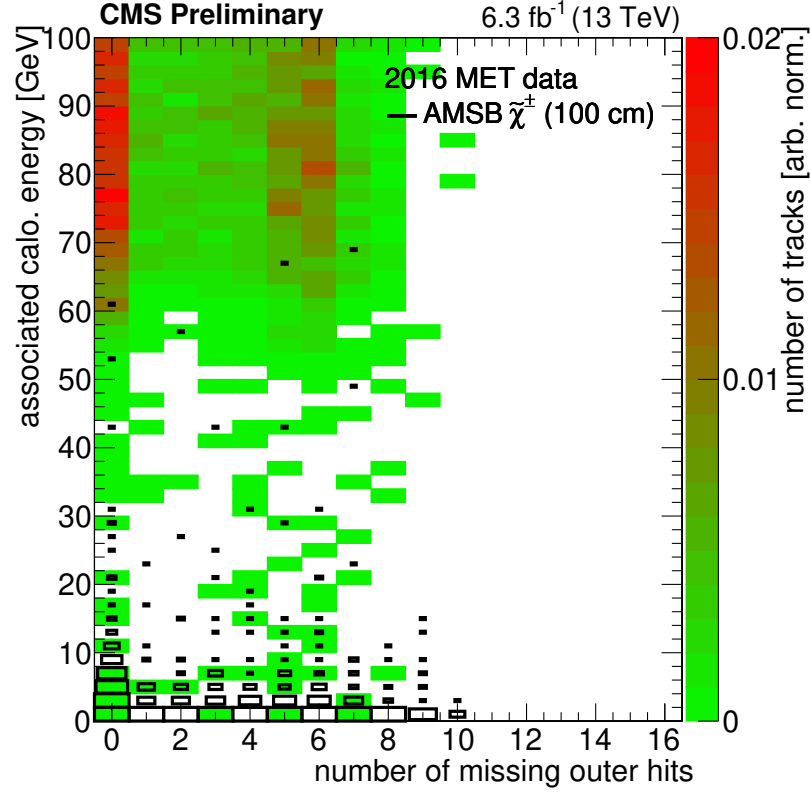


Figure 3.1: Associated calorimeter energy versus number of missing outer hits for selected tracks from a control region dominated by electrons, the largest background to the search. The data collected by CMS in 2016 is shown as colored bins, while a simulation of AMSB chargino production is shown as black boxes, with the size of each box indicating the relative size of the contents in that bin. The particular signal model shown here has a chargino with a mass of 700 GeV and a lifetime of $c\tau = 100$ cm. Associated calorimeter energy and number of missing outer hits are the primary variables used to distinguish signal from background in the search, as an obvious separation between the two is seen in this plane.

3.1 Samples of experimental and simulated data

3.1.1 Experimental data

The search is performed with data collected by the CMS detector in 2015 and 2016 from pp collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 38.4 fb^{-1} . All of the data used was certified to be of sufficient quality for physics analysis.

3.1.2 Simulated signal events

As mentioned previously, we use AMSB as a benchmark for evaluating the sensitivity of the search. We simulate direct chargino production via the processes $\text{pp} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\text{pp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$. The mass spectrum of the sparticles in AMSB is determined by four parameters: the gravitino mass $m_{3/2}$, the universal scalar mass m_0 , the ratio of the VEVs of the Higgs fields $\tan \beta$, and the sign of the higgsino mass term $\text{sign}(\mu)$. Of these, only $m_{3/2}$ has an appreciable impact on the mass of the chargino. Thus, by varying this parameter, we calculate the sparticle mass spectrum using ISAJET 7.80 [57] for chargino masses between 100 and 900 GeV in intervals of 100 GeV. The supersymmetry parameters for each mass point are listed in Table 3.1. The cross sections for chargino production are calculated as a function of chargino mass and are listed in Table 3.2. They are calculated at NLO+NLL using the RESUMMINO code from [32, 33] with CTEQ6.6 [55] and MSTW2008NLO90CL [52] parton distribution function (PDF) sets.

For each mass point, we generate samples corresponding to lifetimes of $10 \text{ cm}/c$, $100 \text{ cm}/c$, $1000 \text{ cm}/c$, and $10\,000 \text{ cm}/c$. Although in AMSB, the mass spectrum, specifically the mass splitting between the chargino and neutralino, determines the

Table 3.1: Supersymmetry parameters used to generate simulated signal samples for each of the chargino masses we consider. The large mass scale of the squarks is indicated by $m(\tilde{d})$, the mass of the down squark. For each point, m_0 , $\tan\beta$, and $\text{sign}(\mu)$ are not varied and are set to 1500 GeV, 5, and +1, respectively. These parameters are described in the text.

$m_{3/2}$ [TeV]	$m(\tilde{\chi}_1^\pm)$ [GeV]	Δm [GeV]	$m(\tilde{d})$ [GeV]
35.1	100.0	0.189	1649
68.9	200.0	0.174	2019
103.7	300.0	0.172	2494
139.0	400.0	0.173	3018
174.4	500.0	0.173	3561
210.3	600.0	0.173	4121
246.4	700.0	0.173	4686
282.9	800.0	0.174	5261
320.2	900.0	0.174	5845

Table 3.2: Cross sections for chargino production calculated at NLO+NLL. The cross sections for $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ are listed separately, along with the total cross section, which is the sum of these two contributions.

$m(\tilde{\chi}_1^\pm)$ [GeV]	$\sigma(pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp)$ [pb]	$\sigma(pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm)$ [pb]	total σ [pb]
100	11.61 ± 0.52	22.67 ± 0.97	34.3 ± 1.1
200	0.903 ± 0.054	1.81 ± 0.1	2.71 ± 0.11
300	0.19 ± 0.013	0.387 ± 0.026	0.577 ± 0.03
400	0.0586 ± 0.0047	0.121 ± 0.0096	0.18 ± 0.011
500	0.0221 ± 0.0019	0.0464 ± 0.0042	0.0685 ± 0.0046
600	0.0095 ± 0.00091	0.0201 ± 0.002	0.0296 ± 0.0022
700	0.00444 ± 0.00046	0.0095 ± 0.001	0.0139 ± 0.0011
800	0.00221 ± 0.00025	0.00476 ± 0.00056	0.00697 ± 0.00062
900	0.00115 ± 0.00014	0.0025 ± 0.00031	0.00365 ± 0.00034

chargino lifetime, by treating the lifetime as a free parameter, we are able to evaluate the sensitivity of the search to a broader range of models.

With just this selection of lifetimes, we are also able to study intermediate chargino lifetimes via lifetime reweighting. If we wish to reweight a sample generated with mean lifetime τ_{src} to a target mean lifetime of τ_{dst} , then we define a weight,

$$w_{\tau} = \prod_i \frac{\left(\frac{1}{\tau_{\text{dst}}} e^{-\tau_i/\tau_{\text{dst}}} \right)}{\left(\frac{1}{\tau_{\text{src}}} e^{-\tau_i/\tau_{\text{src}}} \right)}, \quad (3.1)$$

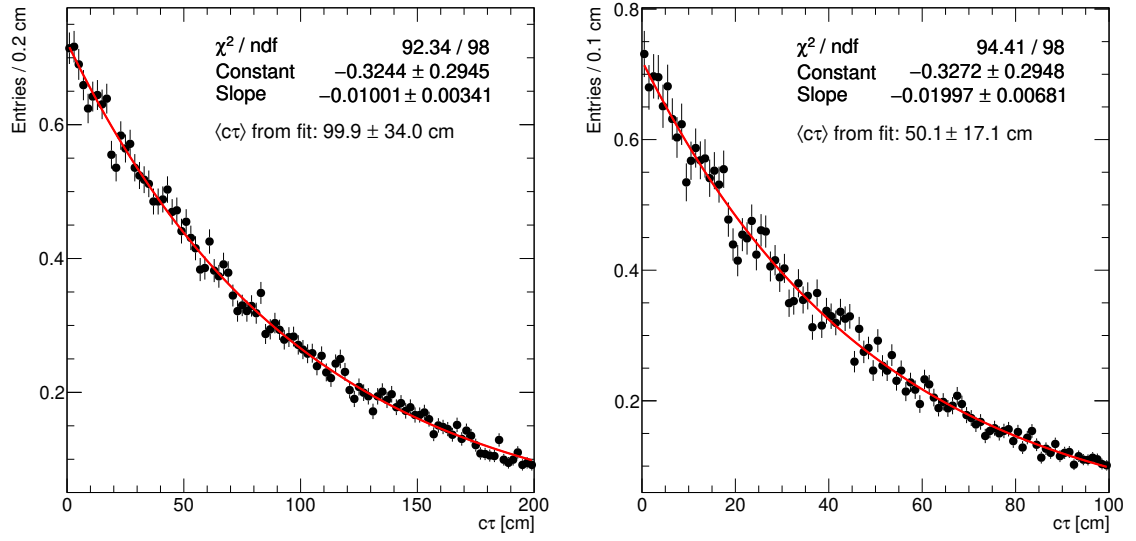
where τ_i is the actual lifetime of the i -th chargino in the given event ($i = 1, 2$ for a $\text{pp} \rightarrow \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ event and $i = 1$ for a $\text{pp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^{\pm}$ event). This weight is calculated and applied to each event, reshaping the distribution of actual chargino lifetimes with mean τ_{src} to that expected for a lifetime of τ_{dst} , as shown in Figure 3.2. The target lifetimes used and the original lifetimes of the samples from which they are reweighted are listed in Table 3.3.³

Table 3.3: Target chargino lifetimes achieved via lifetime reweighting and the original lifetime of the sample from which they are reweighted.

original lifetime [cm/c]	target lifetimes [cm/c]
10	2, 3, 4, 5, 6, 7, 8, 9, 10
100	20, 30, 40, 50, 60, 70, 80, 90, 100
1 000	200, 300, 400, 500, 600, 700, 800, 900, 1 000
10 000	2 000, 3 000, 4 000, 5 000, 6 000, 7 000, 8 000, 9 000, 10 000

³The reweighting is always applied such that $\tau_{\text{dst}} < \tau_{\text{src}}$ so that events on the tail of the distribution of actual chargino lifetimes are never weighted up.

Figure 3.2: Distributions of actual chargino lifetime at generator level. Both plots come from a sample generated with a mean chargino lifetime of $100 \text{ cm}/c$. The left plot is with no lifetime reweighting applied, while the right plot is reweighted to a target lifetime of $50 \text{ cm}/c$. The red curve in both cases is the result of fitting the distribution with an exponential function.



The events are generated with PYTHIA 6.4.26 [66], using the CTEQ6L1 [60] PDF sets. Interactions with the detector and decays of long-lived particles, including the decays of the charginos, are simulated with GEANT4 10.0 patch-02 [10, 11]. The effects of pileup are simulated by mixing in random events from samples of simulated minimum bias events during the subsequent digitization and reconstruction of the simulated signal samples. This is done twice, resulting in two separate sets of samples, one with simulated pileup conditions matching the conditions observed during the 2015 run, and one matching the conditions observed during the 2016 run.

3.1.3 Simulated background events

The methods used to estimate the backgrounds for the search use only experimental data. However, samples of simulated background events are used to study and validate these methods. These samples are also used to assign systematic uncertainties to the expected signal yields. The names of these samples are listed in Tables 3.4 and 3.5 and their cross sections and equivalent integrated luminosities are given in Tables 3.6 and 3.7.

The above samples were produced using conditions designed to match the data taken during 2015 and using the software used to reconstruct the data taken during 2015. Unless otherwise stated, the samples of simulated background events used in any study are from the above lists. In order to verify that the different conditions present during the 2016 run do not affect the conclusions drawn from the above samples, we also occasionally utilize samples produced to match the conditions of the 2016 run. These samples are listed in Table 3.8 and their cross sections and equivalent integrated luminosities are given in Table 3.9.

Table 3.4: Names of the samples of simulated non-QCD multijet background processes used to study and validate the background estimation methods.

composite sample	constituent sample	name of the sample
$Z \rightarrow ll$	$M_{ll} \in [10, 50) \text{ GeV}$	DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8
	$M_{ll} \in [50, \infty)$	DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
single top	s-channel	ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1
	t-channel	ST_t-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1
	tW	ST_tW_top_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1
	$\bar{t}W$	ST_tW_antitop_5f_NoFullyHadronicDecays_13TeV-powheg_TuneCUETP8M1
$t\bar{t}$	$t\bar{t}$	TT_TuneCUETP8M1_13TeV-powheg-pythia8
diboson	$W\gamma$	WGToLNuG_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
	$Z\gamma$	ZGTo2LG_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8
	$WW \rightarrow l\nu q\bar{q}$	WWToLNuQQ_13TeV-powheg
	$WW \rightarrow l\nu l\nu$	WWTo2L2Nu_13TeV-powheg
	WZ	WZ_TuneCUETP8M1_13TeV-pythia8
	ZZ	ZZ_TuneCUETP8M1_13TeV-pythia8
$W \rightarrow l\nu$	inclusive	WJetsToLNu_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
	$H_T \in [100, 200) \text{ GeV}$	WJetsToLNu_HT-100To200_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
	$H_T \in [200, 400) \text{ GeV}$	WJetsToLNu_HT-200To400_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
	$H_T \in [400, 600) \text{ GeV}$	WJetsToLNu_HT-400To600_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
	$H_T \in [600, \infty) \text{ GeV}$	WJetsToLNu_HT-600ToInf_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
$Z \rightarrow \nu\bar{\nu}$	$H_T \in [100, 200) \text{ GeV}$	ZJetsToNuNu_HT-100To200_13TeV-madgraph
	$H_T \in [200, 400) \text{ GeV}$	ZJetsToNuNu_HT-200To400_13TeV-madgraph
	$H_T \in [400, 600) \text{ GeV}$	ZJetsToNuNu_HT-400To600_13TeV-madgraph
	$H_T \in [600, \infty) \text{ GeV}$	ZJetsToNuNu_HT-600ToInf_13TeV-madgraph

Table 3.5: Names of the samples of simulated QCD multijet background processes used to study and validate the background estimation methods.

composite sample	constituent sample	name of the sample
QCD	$\hat{p}_T \in [5, 10)$ GeV	QCD_Pt_5to10_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [10, 15)$ GeV	QCD_Pt_10to15_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [15, 30)$ GeV	QCD_Pt_15to30_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [30, 50)$ GeV	QCD_Pt_30to50_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [50, 80)$ GeV	QCD_Pt_50to80_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [80, 120)$ GeV	QCD_Pt_80to120_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [120, 170)$ GeV	QCD_Pt_120to170_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [170, 300)$ GeV	QCD_Pt_170to300_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [300, 470)$ GeV	QCD_Pt_300to470_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [470, 600)$ GeV	QCD_Pt_470to600_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [600, 800)$ GeV	QCD_Pt_600to800_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [800, 1000)$ GeV	QCD_Pt_800to1000_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [1000, 1400)$ GeV	QCD_Pt_1000to1400_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [1400, 1800)$ GeV	QCD_Pt_1400to1800_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [1800, 2400)$ GeV	QCD_Pt_1800to2400_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [2400, 3200)$ GeV	QCD_Pt_2400to3200_TuneCUETP8M1_13TeV_pythia8
	$\hat{p}_T \in [3200, \infty)$ GeV	QCD_Pt_3200toInf_TuneCUETP8M1_13TeV_pythia8

Table 3.6: Cross sections and equivalent integrated luminosities of the samples of simulated non-QCD multijet background processes used to study and validate the background estimation methods.

composite sample	constituent sample	cross section $\times$ BR [pb]	equiv. int. lumi. [pb ⁻¹]
$Z \rightarrow \ell\ell$	$M_{\ell\ell} \in [10, 50) \text{ GeV}$	18 610	3 398
	$M_{\ell\ell} \in [50, \infty)$	6 025.2	1 481
single top	s-channel	3.36	183 245
	t-channel	70.69	104 514
	tW	19.418	278 205
	$\bar{t}W$	19.418	274 340
$t\bar{t}$	$t\bar{t}$	831.76	104 184
diboson	$W\gamma$	489	9811
	$Z\gamma$	117.864	14 437
	$WW \rightarrow l\nu q\bar{q}$	49.997	125 488
	$WW \rightarrow l\nu l\nu$	12.178	137 111
	WZ	47.13	16 091
	ZZ	16.523	56 001
$W \rightarrow l\nu$	inclusive	61 526.7	607
	$H_T \in [100, 200) \text{ GeV}$	1 345	6 656
	$H_T \in [200, 400) \text{ GeV}$	359.7	12 434
	$H_T \in [400, 600) \text{ GeV}$	48.91	33 531
	$H_T \in [600, \infty) \text{ GeV}$	18.77	54 572
$Z \rightarrow \nu\bar{\nu}$	$H_T \in [100, 200) \text{ GeV}$	280.35	14 909
	$H_T \in [200, 400) \text{ GeV}$	77.67	65 399
	$H_T \in [400, 600) \text{ GeV}$	10.73	64 367
	$H_T \in [600, \infty) \text{ GeV}$	4.116	230 939

Table 3.7: Cross sections and equivalent integrated luminosities of the samples of simulated QCD multijet background processes used to study and validate the background estimation methods.

composite sample	constituent sample	cross section $\times$ BR [pb]	equiv. int. lumi. [pb ⁻¹]
QCD	$\hat{p}_T \in [5, 10)$ GeV	$6.101\,83 \times 10^{10}$	9.282×10^{-5}
	$\hat{p}_T \in [10, 15)$ GeV	$5.887\,58 \times 10^9$	1.059×10^{-3}
	$\hat{p}_T \in [15, 30)$ GeV	$1.837\,41 \times 10^9$	2.040×10^{-2}
	$\hat{p}_T \in [30, 50)$ GeV	$1.409\,32 \times 10^8$	4.901×10^{-2}
	$\hat{p}_T \in [50, 80)$ GeV	$1.920\,43 \times 10^7$	2.661×10^{-1}
	$\hat{p}_T \in [80, 120)$ GeV	$2.762\,53 \times 10^6$	1.983
	$\hat{p}_T \in [120, 170)$ GeV	471 100	12.37
	$\hat{p}_T \in [170, 300)$ GeV	117 276	39.84
	$\hat{p}_T \in [300, 470)$ GeV	7 823	266.1
	$\hat{p}_T \in [470, 600)$ GeV	648.2	4 158
	$\hat{p}_T \in [600, 800)$ GeV	186.9	16 667
	$\hat{p}_T \in [800, 1000)$ GeV	32.293	88 767
	$\hat{p}_T \in [1000, 1400)$ GeV	9.418 3	247 704
	$\hat{p}_T \in [1400, 1800)$ GeV	0.842 65	295 265
	$\hat{p}_T \in [1800, 2400)$ GeV	0.114 943	1 841 173
	$\hat{p}_T \in [2400, 3200)$ GeV	0.006 829 81	50 978 138
	$\hat{p}_T \in [3200, \infty)$ GeV	0.000 165 445	1 747 275 530

Table 3.8: Names of the samples of simulated background processes generated during the 2016 campaign.

composite sample	constituent sample	name of the sample
Z $\rightarrow$ ll	$M_{ll} \in [50, \infty)$ GeV	DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
diboson	WZ $\rightarrow$ l ν ν ν	WZTo1L3Nu_13TeV_amcatnloFXFX_madspin_pythia8

Table 3.9: Cross sections and equivalent integrated luminosities of the samples of simulated background processes generated during the 2016 campaign.

composite sample	constituent sample	cross section $\times$ BR [pb]	equiv. int. lumi. [pb^{-1}]
Z $\rightarrow$ ll	$M_{\text{ll}} \in [50, \infty) \text{ GeV}$	6 025.2	23 976
diboson	WZ $\rightarrow$ l ν $\nu\nu$	3.05	307 406

3.2 Triggers

3.2.1 Use of p_T^{miss}

Because CMS currently has no tracking at Level 1 (L1), it is impossible to trigger on tracks alone. Hence, we need to use another object, and we employ the same strategy as collider searches for dark matter: we trigger on p_T^{miss} . Now, our chosen signal can generate p_T^{miss} in one of three ways:

- a $\tilde{\chi}_1^\pm$ can be produced with a $\tilde{\chi}_1^0$ with the $\tilde{\chi}_1^\pm$ reaching the muon chambers (see Figure 3.3, top)
- two $\tilde{\chi}_1^\pm$ can be produced with only one reaching the muon chambers (see Figure 3.3, bottom)⁴
- the ewkino pair can be accompanied by ISR (see Figure 3.4)

In the first two cases, the $\tilde{\chi}_1^\pm$ that reaches the muon chambers is reconstructed as a muon, and therefore contributes visible momentum to PF p_T^{miss} , but not to calorimeter-based p_T^{miss} . On the other hand, the $\tilde{\chi}_1^0$ contributes no visible momentum since it interacts only weakly. The $\tilde{\chi}_1^\pm$ that fails to reach the muon chambers also contributes no visible momentum because, being a track with no calorimeter energy nor muon chamber hits, it is considered a fake track by particle flow and ignored. Finally, in the third case, if the ISR is a gluon and has sufficient p_T , then it can contribute substantially to both PF p_T^{miss} and to calorimeter-based p_T^{miss} .

⁴This type of event could be selected using a single-muon trigger. This muon + disappearing track topology is not pursued in the current search, but is being investigated for future iterations of this search.

Figure 3.3: Event displays of simulated signal events, one of $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ (top) and one of $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ (bottom). The PF $\vec{p}_T^{\text{miss}}$ vector is shown as a red arrow and the calorimeter-based $\vec{p}_T^{\text{miss}}$ vector is shown as a gold arrow.

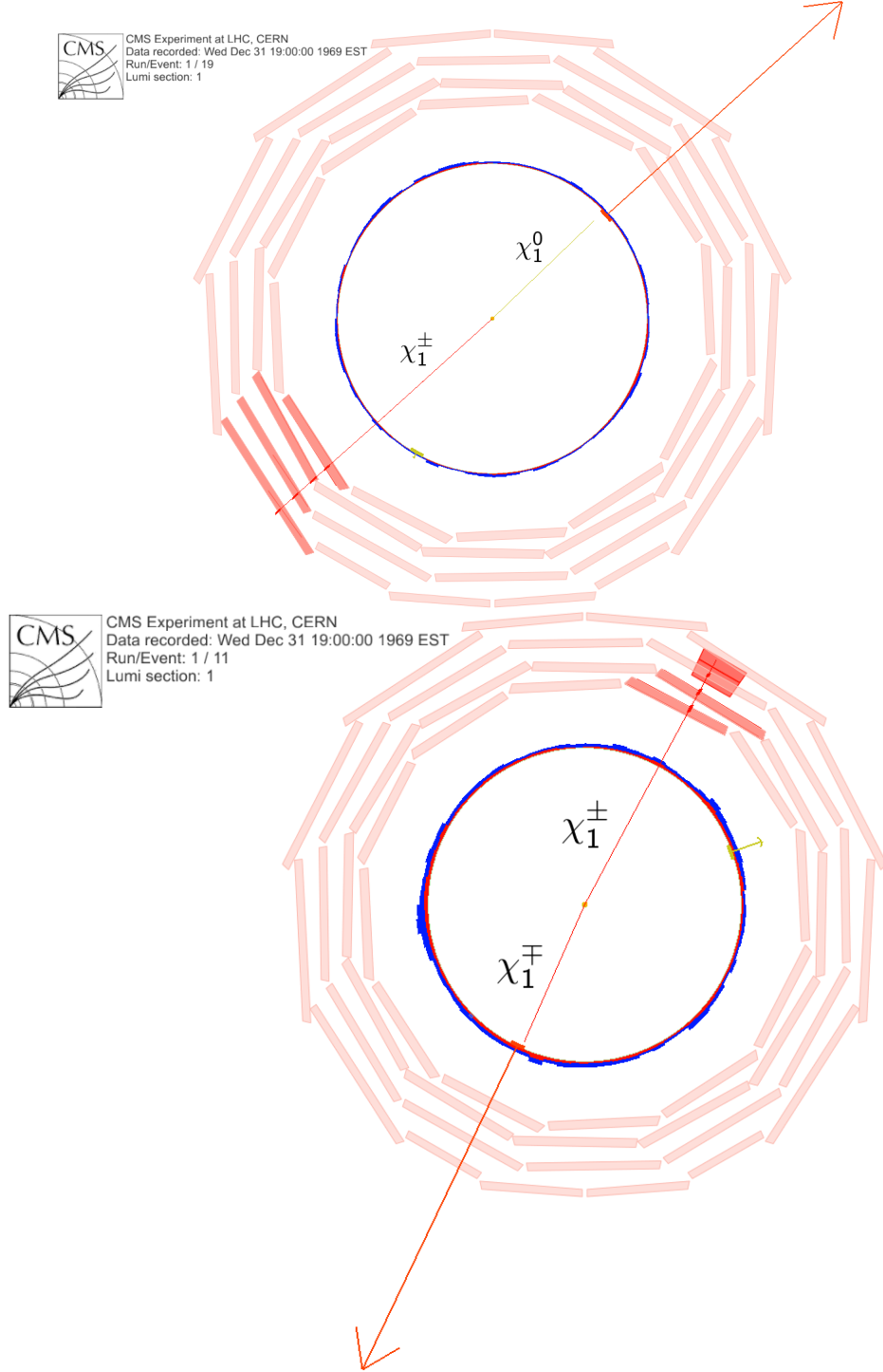
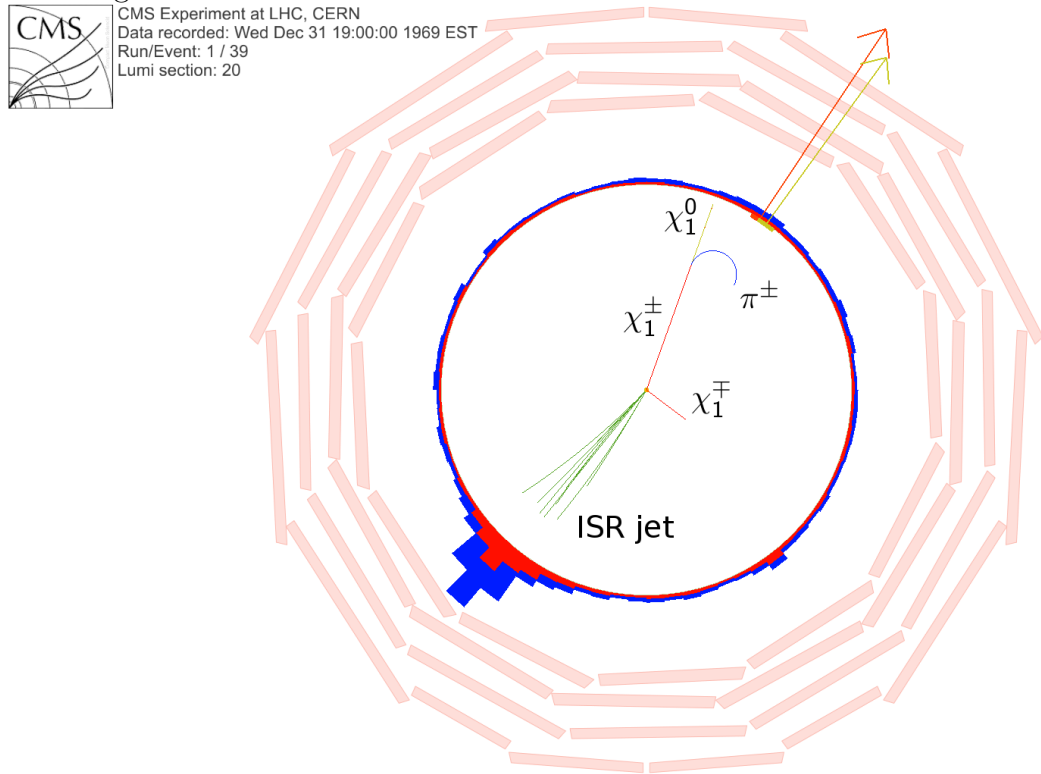


Figure 3.4: Event display of a simulated $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ event with an ISR gluon jet. The PF $\vec{p}_T^{\text{miss}}$ vector is shown as a red arrow and the calorimeter-based $\vec{p}_T^{\text{miss}}$ vector is shown as a gold arrow.



Again because there is no tracking at L1, the only type of p_T^{miss} that can be used at L1 is calorimeter-based p_T^{miss} . Therefore, the signal event with p_T^{miss} generated by a high- p_T ISR gluon jet is exactly the category of event that we target.

3.2.2 Triggers used in the search

This search uses data collected with the disjunction of several p_T^{miss} triggers. Various single lepton triggers are also used for the estimation of backgrounds and for studies of systematic uncertainties. The complete list of triggers used for the data collected in 2015 is shown in Table 3.10, while that for the data collected in 2016 is shown in Table 3.11. The single tau trigger used was prescaled during 2015 and 2016, while all other trigger paths were unprescaled during the entire data-taking period considered here.

Table 3.10: Triggers used in the search and for background estimation and systematic uncertainty evaluation for the data collected in 2015. The italicized trigger paths are those that were only available in the simulated samples but were not included in the menu during data-taking.

primary data set	trigger path
MET	HLT_MET75_IsoTrk50_v*
	HLT_PFMET90_PFMHT90_IDTight_v*
	HLT_PFMETNoMu90_JetIdCleaned_PFMHTNoMu90_IDTight_v*
	<i>HLT_PFMETNoMu90_NoiseCleaned_PFMHTNoMu90_IDTight_v*</i>
SingleElectron	HLT_Ele22_eta2p1_WPLoose_Gsf_v*
	<i>HLT_Ele22_eta2p1_WP75_Gsf_v*</i>
SingleMuon	HLT_IsoMu20_v*
	HLT_IsoTkMu20_v*
Tau	HLT_LooseIsoPFTau50_Trk30_eta2p1_v*

The HLT_MET75_IsoTrk50_v* path was developed specifically for this search, and was monitored throughout the 2015 and 2016 runs. This path consists of three steps:

1. disjunction of L1 p_T^{miss} seeds (see Table 3.12 below)

Table 3.11: Triggers used in the search and for background estimation and systematic uncertainty evaluation for the data collected in 2016.

primary data set	trigger path
MET	HLT_MET75_IsoTrk50_v*
	HLT_PFMET100_PFMHT100_IDTight_BeamHaloCleaned_v*
	HLT_PFMET120_PFMHT120_IDTight_v*
	HLT_PFMETNoMu120_PFMHTNoMu120_IDTight_v*
	HLT_PFMET170_HBHECleaned_v*
	HLT_MET200_v*
	HLT_PFMET300_v*
SingleElectron	HLT_Ele25_eta2p1_WPTight_Gsf_v*
SingleMuon	HLT_IsoMu24_v*
	HLT_IsoTkMu24_v*
Tau	HLT_LooseIsoPFTau50_Trk30_eta2p1_v*

2. high-level trigger (HLT) p_T^{miss} filter, `hltMET75`

3. HLT track filter, `hltTrk50Filter`

As mentioned in Section 3.2.1, the L1 seeds use calorimeter-based p_T^{miss} . As the LHC met and exceeded its design luminosity during 2016, some of these seeds had to be prescaled or disabled due to high rates. Thus, additional, higher threshold seeds were included in the `HLT_MET75_IsoTrk50_v*` path starting with run 2016D, as shown in Table 3.12. For this reason, when we discuss the methods for estimating the backgrounds in Section 3.4, we will consider the 2016B+C and 2016D–H data separately.

At HLT, the p_T^{miss} filter requires `hltMET` > 75 GeV, where `hltMET` is the calorimeter-based p_T^{miss} calculated in the HLT. The track filter is only processed for events passing `hltMET75` and requires at least one HLT track to pass the following criteria:

Table 3.12: L1 seeds for our HLT_MET75_IsoTrk50_v* path for different run periods.

run period	L1 seeds for HLT_MET75_IsoTrk50_v*
2015	L1_ETM60 $\vee$ L1_ETM70
2016B+C	L1_ETM60 $\vee$ L1_ETM70
2016D–H	L1_ETM50 $\vee$ L1_ETM60 $\vee$ L1_ETM70 $\vee$ L1_ETM80 $\vee$ L1_ETM90 $\vee$ L1_ETM100

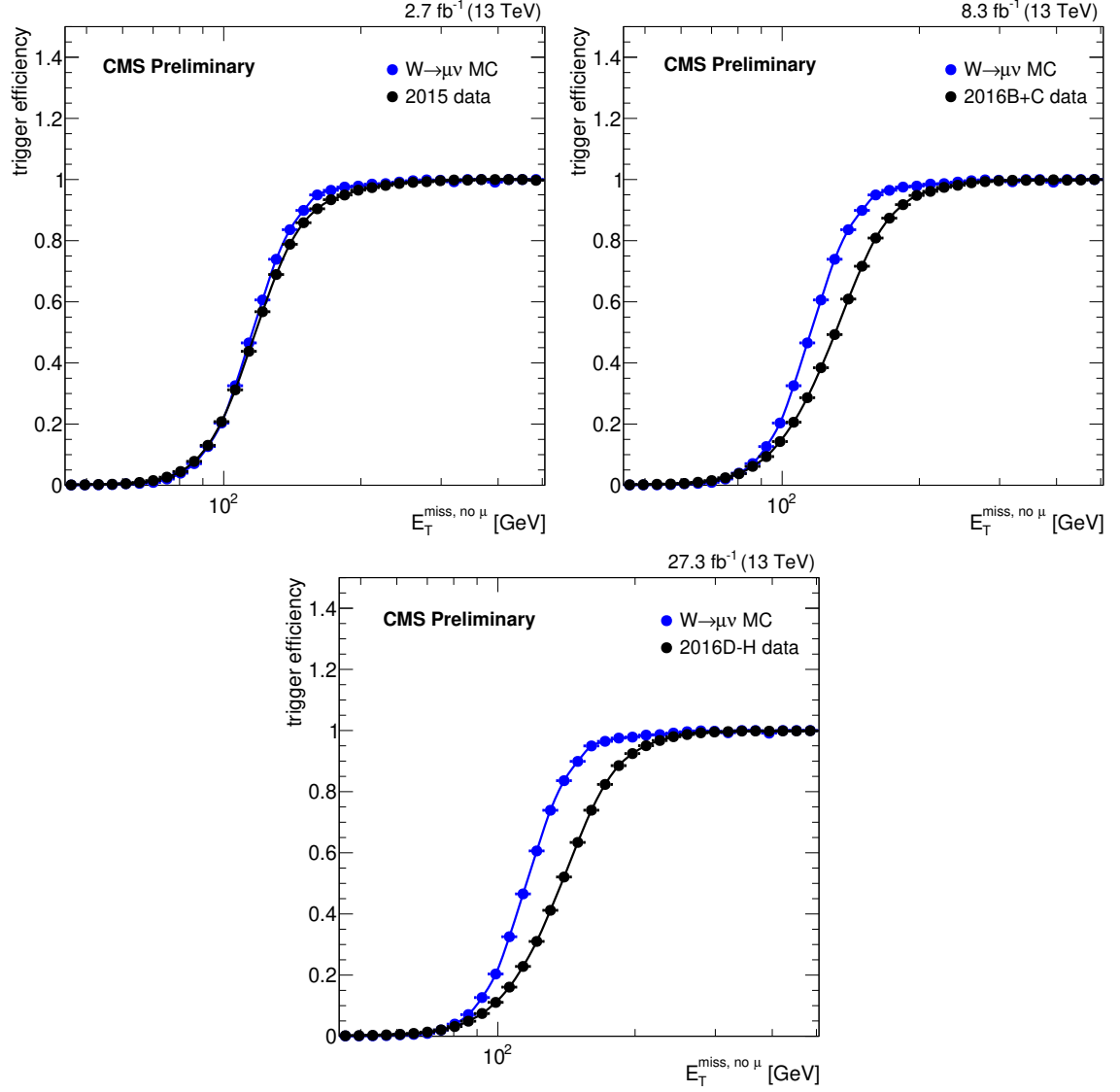
- $p_T > 50 \text{ GeV}$
- track-based isolation $< 0.05 p_T$
- ≥ 5 silicon hits
- no missing inner hits
- no missing middle hits

Inner hits are defined as those closest to the interaction point, and middle hits are those between the innermost and outermost hit on the track. In other words, the hits on the HLT track are required to be consecutive, starting in the innermost layer of the tracker that the track traversed. The track-based isolation is calculated simply as the scalar sum of the p_T of all tracks reconstructed in the HLT down to $p_T = 50 \text{ MeV}$ within $\Delta R < 0.3$ of the track in question.⁵

The details of the calculation of the efficiencies of the triggers listed above are given in Section 3.5.3; however, for reference when discussing the event selections below, these efficiencies are plotted as a function of $p_T^{\text{miss, no } \mu}$, which is p_T^{miss} calculated offline with the p_T of all reconstructed muons counted as invisible, in Figure 3.5.

⁵No accounting for pileup was present in the isolation calculation for the 2015 and 2016 runs.

Figure 3.5: Efficiency of the combination of p_T^{miss} triggers used in the search for simulated $W \rightarrow l\nu$ and experimental data from 2015 (top left), 2016B+C (top right), and 2016D–H (bottom).



3.3 Event selections

The search is performed by selecting events passing certain requirements on the physics objects within each event. These objects were introduced in Section 2.2.8, and in order to ensure that only reliably reconstructed objects are selected, sets of standard identification criteria, defined in Appendix A, are further imposed. Objects passing these identification criteria are then used in the selections defined in the following sections, which are designed to select events with a disappearing track.

3.3.1 Fiducial track selections

As most signal tracks are produced centrally, especially for higher mass charginos (see Figure 3.6), we only select tracks with $|\eta| < 2.1$. Then in order to avoid selecting tracks that are missing muon chamber hits and associated calorimeter energy due to detector inefficiencies, we veto tracks that fall into any of several known regions of high inefficiency. First, there are three regions in $|\eta|$ that are vetoed:

- $0.15 < |\eta| < 0.35$: there is a gap here between wheels 0 and 1 of the DT stations
- $1.42 < |\eta| < 1.65$: this is the region where the barrel and endcap sections of the ECAL overlap
- $1.55 < |\eta| < 1.85$: this is the transition region between the outermost rings and innermost ring of the CSCs

A schematic layout of one quarter of the CMS detector, in which these three regions can be identified, is shown in Figure 3.7.

There is also a region of low hit efficiency in the middle of the TOB region of the strip tracker. In Figure 3.8, one can see that if a track originates from very close to

Figure 3.6: Pseudorapidity of tracks with $p_T > 55$ GeV and within $\Delta R < 0.1$ of a generated chargino for various chargino masses.

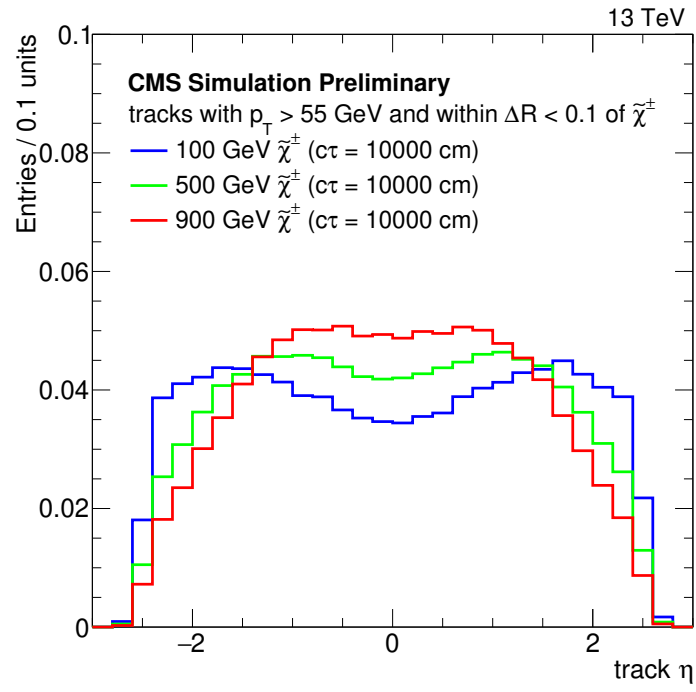
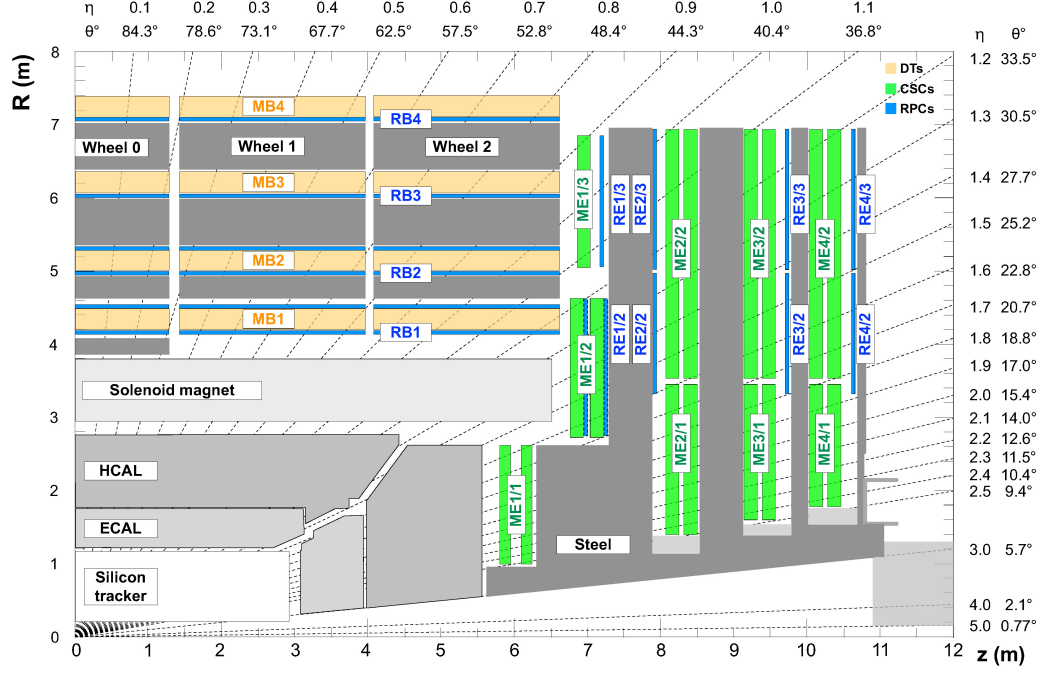


Figure 3.7: Layout of one quarter of the CMS detector, with the muon system detailed.



$z = 0$ and has a pseudorapidity very close to $\eta = 0$, then it will pass through only the edges of all the modules in the TOB, and potentially have missing hits in all six layers. Two such tracks were found in the 2015 data before implementing a veto of this region.⁶ We now veto tracks that have $|z_0| < 0.5$ cm and $|\lambda| < 10^{-3}$, where $\lambda = \frac{\pi}{2} - \theta$ is the pitch angle of the track, to avoid this poorly instrumented region of the TOB.

In addition to these fixed fiducial selections, the ECAL channel statuses provided via a database of run conditions are checked for each run, and tracks that are within $\Delta R < 0.05$ of any noisy or dead channels are vetoed. Maps of the noisy or dead ECAL channels for one run from 2015 and one run from 2016 are shown in Figure 3.9.

⁶See Appendix B for further details.

Figure 3.8: Schematic of the silicon tracker in the ρ - z plane. Note that the TID and TEC are not shown here.

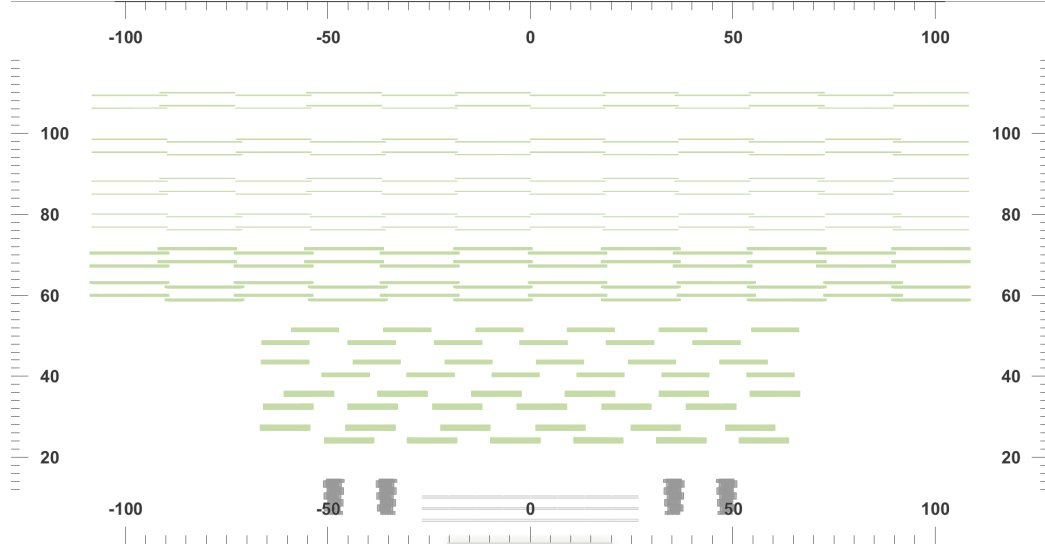
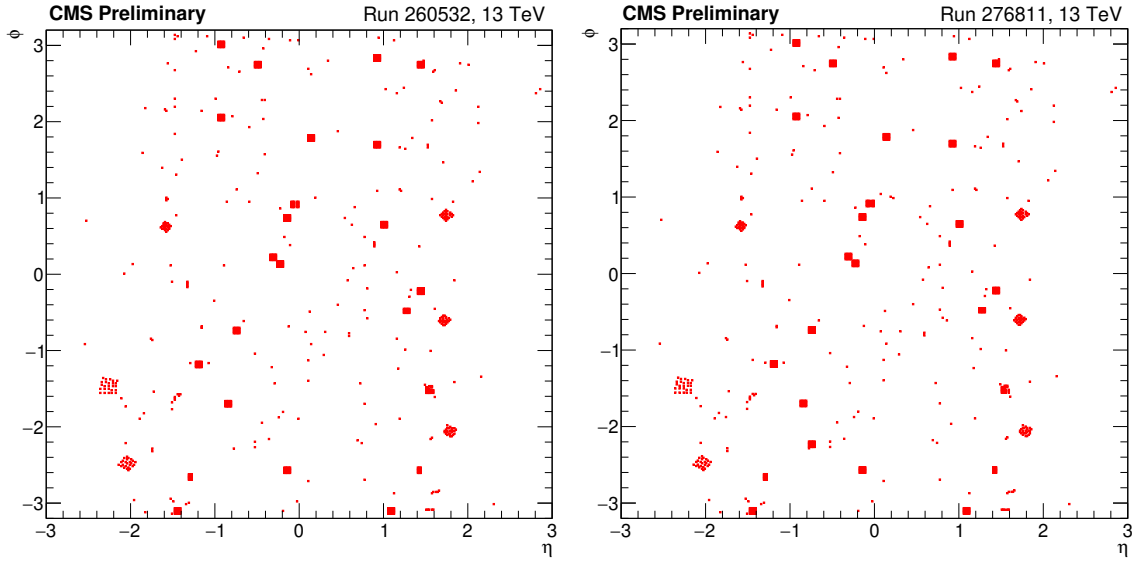


Figure 3.9: Channels identified as noisy or dead in the ECAL channel status record provided by a database of run conditions for run 260532 from 2015 (left) and for run 276811 from 2016 (right). Tracks within $\Delta R < 0.05$ of any of these channels are vetoed.



Additional regions of detector inefficiency are identified in the η - ϕ plane using a tag-and-probe study. For the electron reconstruction inefficiency, events are selected using the requirements in Table 3.13.⁷ The reconstructed electron serves as the tag and the track is the probe. For this study, if there are more than one possible tags or more than one possible probes in a given event, only one unique pair is chosen at random.⁸ Then the electron reconstruction inefficiency is defined as the fraction of selected tracks for which

$$\min \Delta R_{\text{track, loose electron}} > 0.15 \quad (3.2)$$

is true; i.e., the fraction of selected tracks that are not matched to an electron passing loose ID.⁹ The muon reconstruction inefficiency is defined similarly, using the selections in Table 3.14. Again, only one unique tag-probe pair per event is selected.

The reconstruction inefficiency is calculated in bins of size 0.1×0.1 in the probe track η - ϕ plane (see Figures 3.10 and 3.11). We then use any bins that are at least 2σ above the mean inefficiency to veto tracks in the search. Any tracks within the radius¹⁰ of such a bin is rejected. This is done separately for the 2015 and 2016 data.

⁷Except for the p_T criterion, the selections on the track come from the *isolated track selection*, which is defined below in Section 3.3.2.

⁸Although we choose one probe track at random from those passing the track selections, only $\sim(4.65^{+0.29}_{-0.27} \times 10^{-3})\%$ of events in experimental data have more than one possible track to choose from, so this choice of arbitration method should have a negligible effect on the results.

⁹No fit to the tag-probe invariant mass spectrum in order to separate true $Z \rightarrow \ell\ell$ events from background is done as the purpose of this study is to identify regions of abnormally high reconstruction inefficiency, not to measure the actual value of the inefficiency.

¹⁰ $\sqrt{0.05^2 + 0.05^2} = \sqrt{0.005} \approx 0.071$

Table 3.13: Selections used in the tag-and-probe study of electron reconstruction inefficiency. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria. The selected electron is the tag, while the selected track is the probe.

quantity	object	selection
event passes SingleElectron triggers		
≥ 1	electrons	$p_T > 25 \text{ GeV}$
≥ 1	electrons	$ \eta < 2.1$
≥ 1	electrons	passing tight electron ID
	exactly one passing electron chosen randomly	
≥ 1	tracks	$p_T > 30 \text{ GeV}$
≥ 1	tracks	$ \eta < 2.1$
≥ 1	tracks	$ \eta < 0.15 \text{ OR } \eta > 0.35$
≥ 1	tracks	$ \eta < 1.42 \text{ OR } \eta > 1.65$
≥ 1	tracks	$ \eta < 1.55 \text{ OR } \eta > 1.85$
≥ 1	tracks	$\min \Delta R_{\text{track, noisy/dead ECAL ch.}} > 0.05$
≥ 1	tracks	$ d_z > 0.5 \text{ cm OR } \lambda > 10^{-3}$
≥ 1	tracks	number of pixel hits ≥ 3
≥ 1	tracks	number of valid hits ≥ 7
≥ 1	tracks	missing inner hits = 0
≥ 1	tracks	missing middle hits = 0
≥ 1	tracks	rel. track-based iso. < 0.05
≥ 1	tracks	$ d_{xy} < 0.02 \text{ cm}$
≥ 1	tracks	$ d_z < 0.5 \text{ cm}$
≥ 1	track-jet pairs	$\Delta R_{\text{track, jet}} > 0.5$
≥ 1	track-electron pairs	$M_{\text{track, electron}} > 10 \text{ GeV}$
≥ 1	tracks	$\min \Delta R_{\text{track, muon}} > 0.15$
≥ 1	tracks	$\min \Delta R_{\text{track, had. tau}} > 0.15$
	exactly one passing track chosen randomly	
= 1	track-electron pairs	$ M_{\text{track, electron}} - M_Z < 10 \text{ GeV}$
= 1	track-electron pairs	$q_{\text{track}} \cdot q_{\text{electron}} < 0$

Table 3.14: Selections used in the tag-and-probe study of muon reconstruction inefficiency. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria. The selected muon is the tag, while the selected track is the probe.

quantity	object	selection
event passes SingleMuon triggers		
≥ 1	muons	$p_T > 25 \text{ GeV}$
≥ 1	muons	$ \eta < 2.1$
≥ 1	muons	passing tight muon ID
	exactly one passing muon chosen randomly	
≥ 1	tracks	$p_T > 30 \text{ GeV}$
≥ 1	tracks	$ \eta < 2.1$
≥ 1	tracks	$ \eta < 0.15 \text{ OR } \eta > 0.35$
≥ 1	tracks	$ \eta < 1.42 \text{ OR } \eta > 1.65$
≥ 1	tracks	$ \eta < 1.55 \text{ OR } \eta > 1.85$
≥ 1	tracks	$\min \Delta R_{\text{track,noisy/dead ECAL ch.}} > 0.05$
≥ 1	tracks	$ d_z > 0.5 \text{ cm OR } \lambda > 10^{-3}$
≥ 1	tracks	number of pixel hits ≥ 3
≥ 1	tracks	number of valid hits ≥ 7
≥ 1	tracks	missing inner hits = 0
≥ 1	tracks	missing middle hits = 0
≥ 1	tracks	rel. track-based iso. < 0.05
≥ 1	tracks	$ d_{xy} < 0.02 \text{ cm}$
≥ 1	tracks	$ d_z < 0.5 \text{ cm}$
≥ 1	track-jet pairs	$\Delta R_{\text{track,jet}} > 0.5$
≥ 1	track-muon pairs	$M_{\text{track,muon}} > 10 \text{ GeV}$
≥ 1	tracks	$\min \Delta R_{\text{track,electron}} > 0.15$
≥ 1	tracks	$\min \Delta R_{\text{track,had. tau}} > 0.15$
≥ 1	tracks	$E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$
	exactly one passing track chosen randomly	
= 1	track-muon pairs	$ M_{\text{track,muon}} - M_Z < 10 \text{ GeV}$
= 1	track-muon pairs	$q_{\text{track}} \cdot q_{\text{muon}} < 0$

Figure 3.10: Electron reconstruction inefficiency as measured using the tag-and-probe study described in the text, for the 2015 data (left) and the 2016 data (right). Bins that are at least 2σ above the mean inefficiency are used to veto tracks in the search. These bins are marked by circles in the plots.

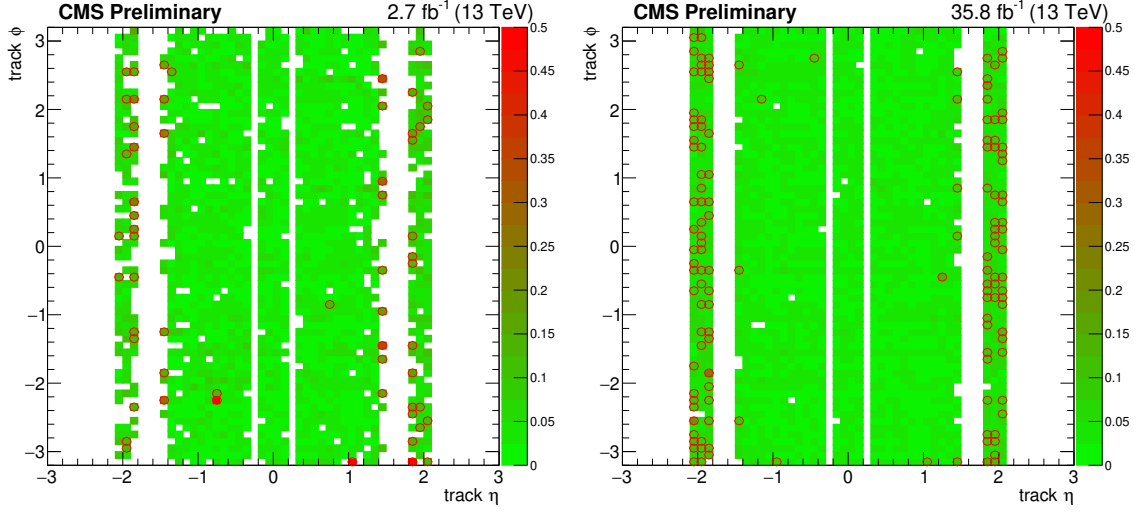
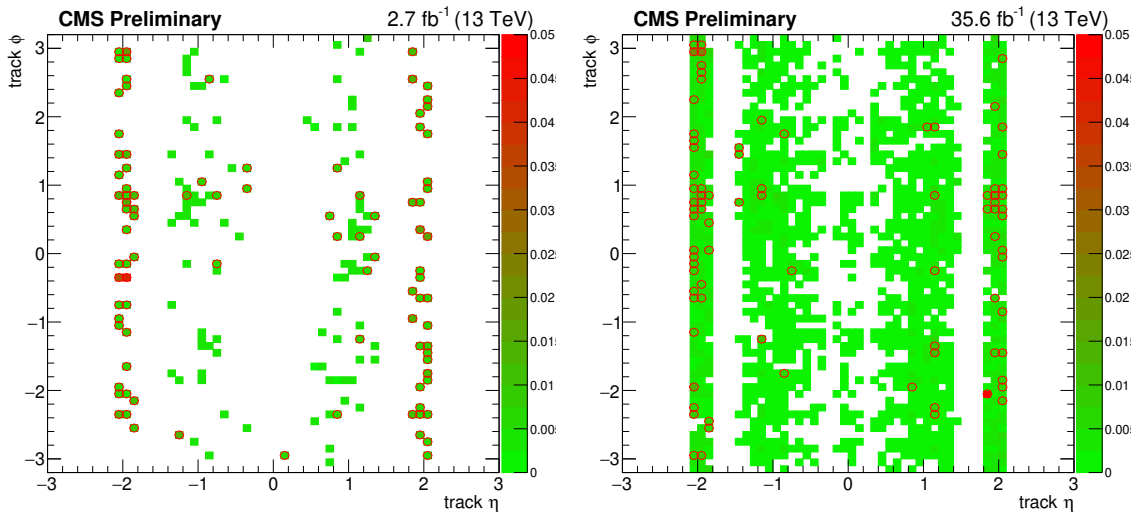


Figure 3.11: Muon reconstruction inefficiency as measured using the tag-and-probe study described in the text, for the 2015 data (left) and the 2016 data (right). Bins that are at least 2σ above the mean inefficiency are used to veto tracks in the search. These bins are marked by circles in the plots.



3.3.2 Search region

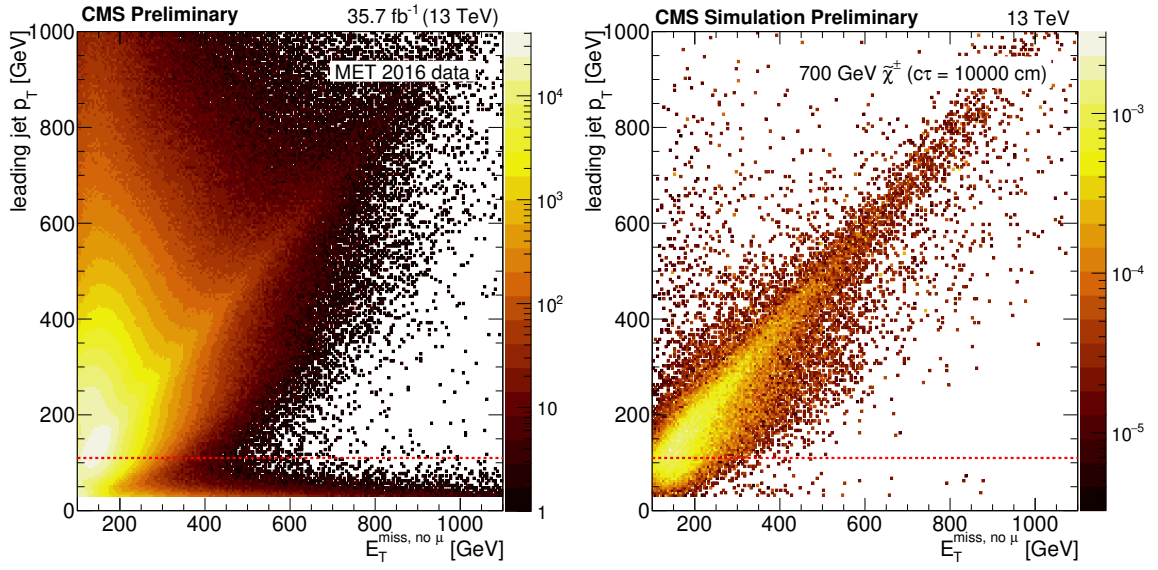
The selections for the search begin with the *basic selection*, which defines an event topology consistent with having a high- p_T jet from ISR and a subsequently large $p_T^{\text{miss, no } \mu}$. The criteria of the *basic selection* are listed in Table 3.15. As seen from the trigger efficiencies in Section 3.2.2, the criteria of $p_T^{\text{miss, no } \mu} > 100 \text{ GeV}$ is well below the point at which the triggers become fully efficient. This is chosen to maximize the number of potential signal events that are selected. Although the leading jet p_T is largely correlated with $p_T^{\text{miss, no } \mu}$ for signal events, in experimental data, there are a significant number of high- $p_T^{\text{miss, no } \mu}$ events in which the p_T of the leading jet is low, as seen in Figure 3.12. These are removed by requiring at least one jet with $p_T > 110 \text{ GeV}$.

Table 3.15: The criteria defining the *basic selection*. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
event passes MET triggers		
≥ 1	primary vertices	passing good primary vertex requirements
	$p_T^{\text{miss, no } \mu}$	$p_T > 100 \text{ GeV}$
≥ 1	jets	$p_T > 110 \text{ GeV}$
≥ 1	jets	$ \eta < 2.4$
≥ 1	jets	passing tight ID with lepton veto requirements
	jet pairs	$\max \Delta\phi_{\text{jet, jet}} < 2.5$
	$p_T^{\text{miss, no } \mu}$	$ \Delta\Phi(\text{leading jet}, p_T^{\text{miss, no } \mu}) > 0.5$

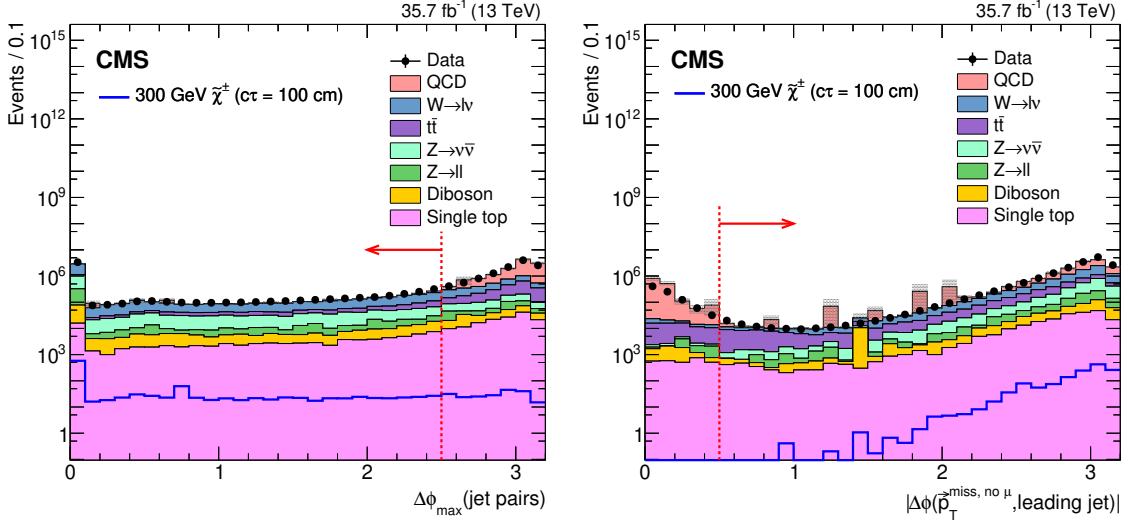
The angular requirements of the basic selection are designed to remove the large, very reducible background from QCD multijet events. These enter the selection

Figure 3.12: Distributions of the leading jet p_T vs. $p_T^{\text{miss, no } \mu}$ for events in the basic selection before any jet requirements are imposed. The distribution is shown for the 2016 experimental data (left) and for simulated signal events (right) with a 700 GeV chargino with a lifetime of 10 000 cm. The red dashed line indicates the chosen value for the jet p_T requirement.



largely in the form of back-to-back dijet events where a mismeasurement of the jet energy conspires to produce a large value for $p_T^{\text{miss, no } \mu}$. The $\max |\Delta\phi_{\text{jet, jet}}| < 2.5$ requirement targets the dijet topology, while the requirement of $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})| > 0.5$ targets events with badly mismeasured jet energy. Signal events are essentially flat in the former variable, while being strongly peaked at π in the latter, as seen in Figure 3.13.

Figure 3.13: Distributions of $\max |\Delta\phi_{\text{jet, jet}}|$ (left) and $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})|$ (right) for events in the basic selection before the angular requirements on the jets/ $p_T^{\text{miss, no } \mu}$ are imposed. The red dashed lines indicates the chosen value for the requirement on each variable.



Events passing the *basic selection* are then required to pass the *isolated track selection*. As the name suggests, this selection defines an event topology consistent with having a high- p_T isolated track. The requirements of the *isolated track selection*

are listed in Table 3.16. This is where the fiducial selections described in the previous section are applied.

Table 3.16: The criteria defining the *isolated track selection*. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
event passes <i>basic selection</i>		
≥ 1	tracks	$p_T > 55 \text{ GeV}$
≥ 1	tracks	passing fiducial selections (see Section 3.3.1)
≥ 1	tracks	number of pixel hits ≥ 3
≥ 1	tracks	number of valid hits ≥ 7
≥ 1	tracks	missing inner hits = 0
≥ 1	tracks	missing middle hits = 0
≥ 1	tracks	rel. track-based iso. < 0.05
≥ 1	tracks	$ d_{xy} < 0.02 \text{ cm}$
≥ 1	tracks	$ d_z < 0.5 \text{ cm}$
≥ 1	track-jet pairs	$\Delta R_{\text{track,jet}} > 0.5$

The track p_T requirement is chosen to be approximately at the point at which the track leg of `HLT_MET75_IsoTrk50_v*` becomes fully efficient.¹¹ The fiducial track selections, as well as the requirements on the number of hits and number of missing hits, are designed so that we are selecting the highest quality tracks possible.

The track-based isolation used in the *isolated track selection* is calculated as the scalar sum of the p_T of the tracks within a cone of $\Delta R < 0.3$. This cone size, as well as the value of the isolation requirement, are chosen to match the requirements made in `HLT_MET75_IsoTrk50_v*`. To reduce the contribution to the isolation sum of fake

¹¹The efficiency of the track leg of `HLT_MET75_IsoTrk50_v*` can be seen in Figure F.1 of Appendix F.

tracks, i.e., tracks that represent pattern recognition errors instead of actual charged particles, only tracks passing the requirements in Table 3.17 are considered. And to reduce the contribution to the isolation sum of tracks from pileup, only tracks within $\Delta d_z < 3 \sigma_{d_z}$ of the track whose isolation is being calculated are considered, where

$$\sigma_{d_z} \equiv \sqrt{\sigma_{z_0}^2 + \sigma_z^2}, \quad (3.3)$$

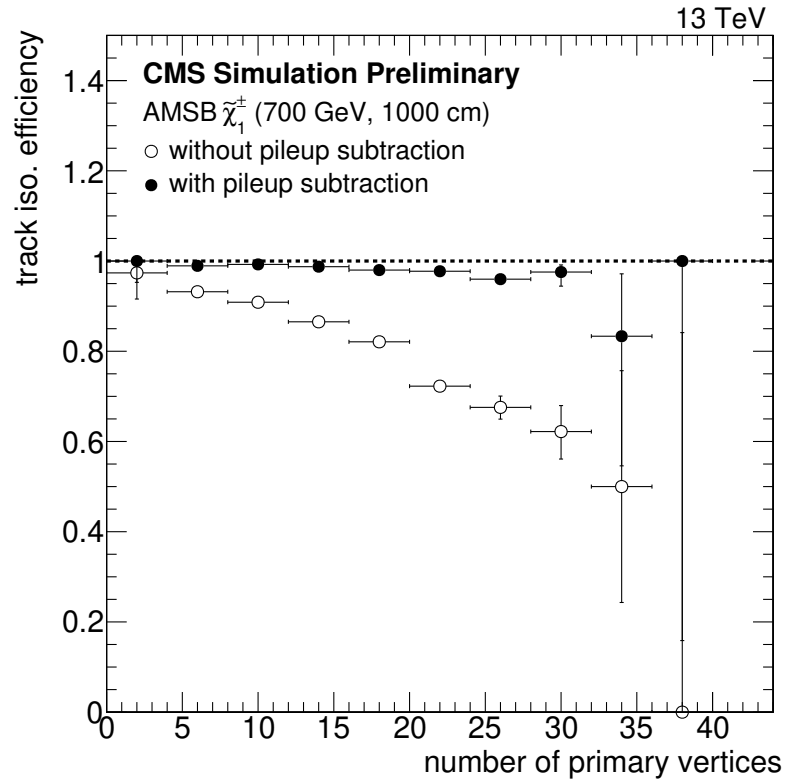
σ_{z_0} is the uncertainty on z_0 resulting from the track fit, and σ_z is the uncertainty on the position of the primary vertex in z resulting from the vertex fit. This is similar to the charged hadron subtraction applied during jet reconstruction, and has the expected effect of removing the pileup dependence from the isolation sum (see Figure 3.14). Note that the overall offline selection efficiency for the *isolated track selection* increases by only $(0.8 \pm 0.4)\%$ for the 2016 data with respect to the 2015 data, showing that neither the increasing pileup nor any other difference between the two data sets has a strong influence on the search at this stage of the selection.

Table 3.17: Criteria used to reduce the contribution of fake tracks from the track-based isolation sum.

variable	selection
χ^2/ndf	< 20
pixel layers with hits	≥ 2
silicon layers (both pixels and strips) with hits	≥ 5
$ d_{xy} $	$< 5 \sigma$

We show several plots comparing simulated background events to experimental data below after applying the *isolated track selection*. This is to indicate the relative contributions of the different standard model processes at this point in the selection.

Figure 3.14: Efficiency for the track-based isolation requirement used in the *isolated track selection* as a function of the number of primary vertices. The efficiency is shown with and without the pileup subtraction described in the text, showing that this subtraction effectively removes the pileup dependence from the isolation sum.



Since our methods for estimating the backgrounds in the search region rely solely on experimental data, perfect agreement with the simulation is not required. Kinematic plots of $p_T^{\text{miss, no } \mu}$ and track p_T are shown in Figure 3.15, and plots of ΔR to the nearest lepton for selected tracks are shown in Figure 3.16. Finally, the number of missing outer hits and $E_{\text{calo}}^{\Delta R < 0.5}$ for selected tracks are shown in Figure 3.17. As discussed below, these last two variables define the criteria for a track to disappear. Note that the poor modeling of the number of missing outer hits is due in part to the so-called HIP effect, which is not simulated, and we correct for this as described in Section 3.5.

The vast majority of events selected by the *isolated track selection* are events with leptons from the decays of gauge bosons. Most of these are removed in the next phase of the selection, called the *candidate track selection*, where events with tracks matched to leptons are rejected. The requirements of the *candidate track selection* are listed in Table 3.18. All reconstructed electrons and muons are used during this matching, in order to reject as many leptons as possible. Hadronic taus for this matching are identified using the criteria listed above in Table A.11, except that the isolation criterion.¹² The particular choice of $\Delta R > 0.15$ was motivated by the plots in Figure 3.16, as this value removes the vast majority of the events in the peaks near $\min \Delta R_{\text{track, lepton}} = 0$ resulting from successfully reconstructed leptons.

Finally, we require the tracks passing the *candidate track selection* to “disappear” in the *disappearing track selection*, which defines the search region. The *disappearing track selection* is defined in Table 3.19. The calorimeter energy sum, $E_{\text{calo}}^{\Delta R < 0.5}$, is calculated as the sum of all calorimeter towers (from both the ECAL and HCAL)

¹²The isolation criterion is that where `byTightCombinedIsolationDeltaBetaCorr3Hits > 0.5` is required.

Figure 3.15: Kinematic distributions from the *isolated track selection*. The experimental data is from 2015 (2016) in the left (right) column. The rightmost bin in each plot includes the overflow.

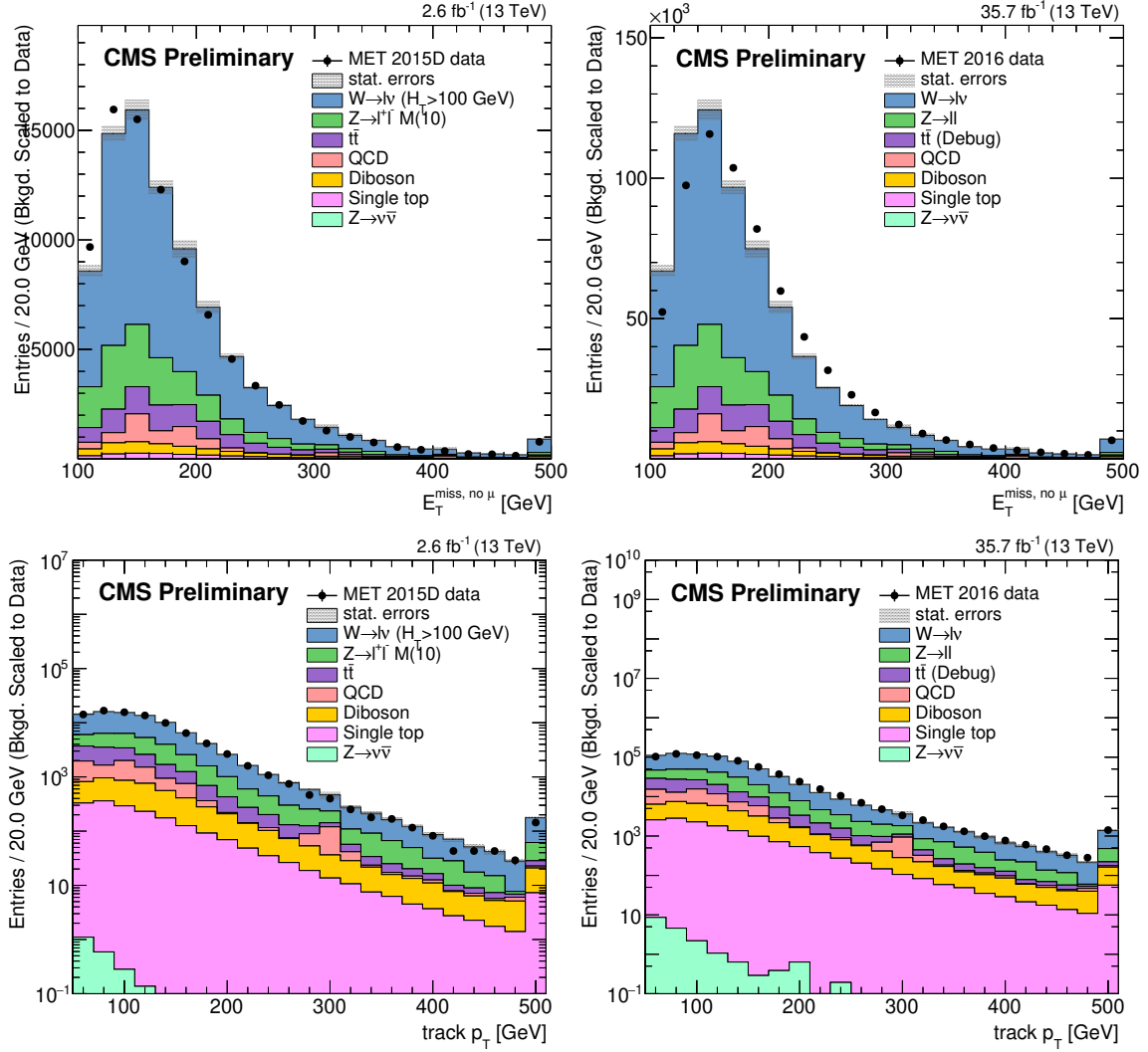


Figure 3.16: Plots of ΔR to nearest leptons for tracks selected in the *isolated track selection*. Minimum ΔR to a reconstructed electron, muon, and tau are shown in the top, middle, and bottom rows, respectively, and the experimental data is from 2015 (2016) in the left (right) column. The rightmost bin in each plot includes the overflow.

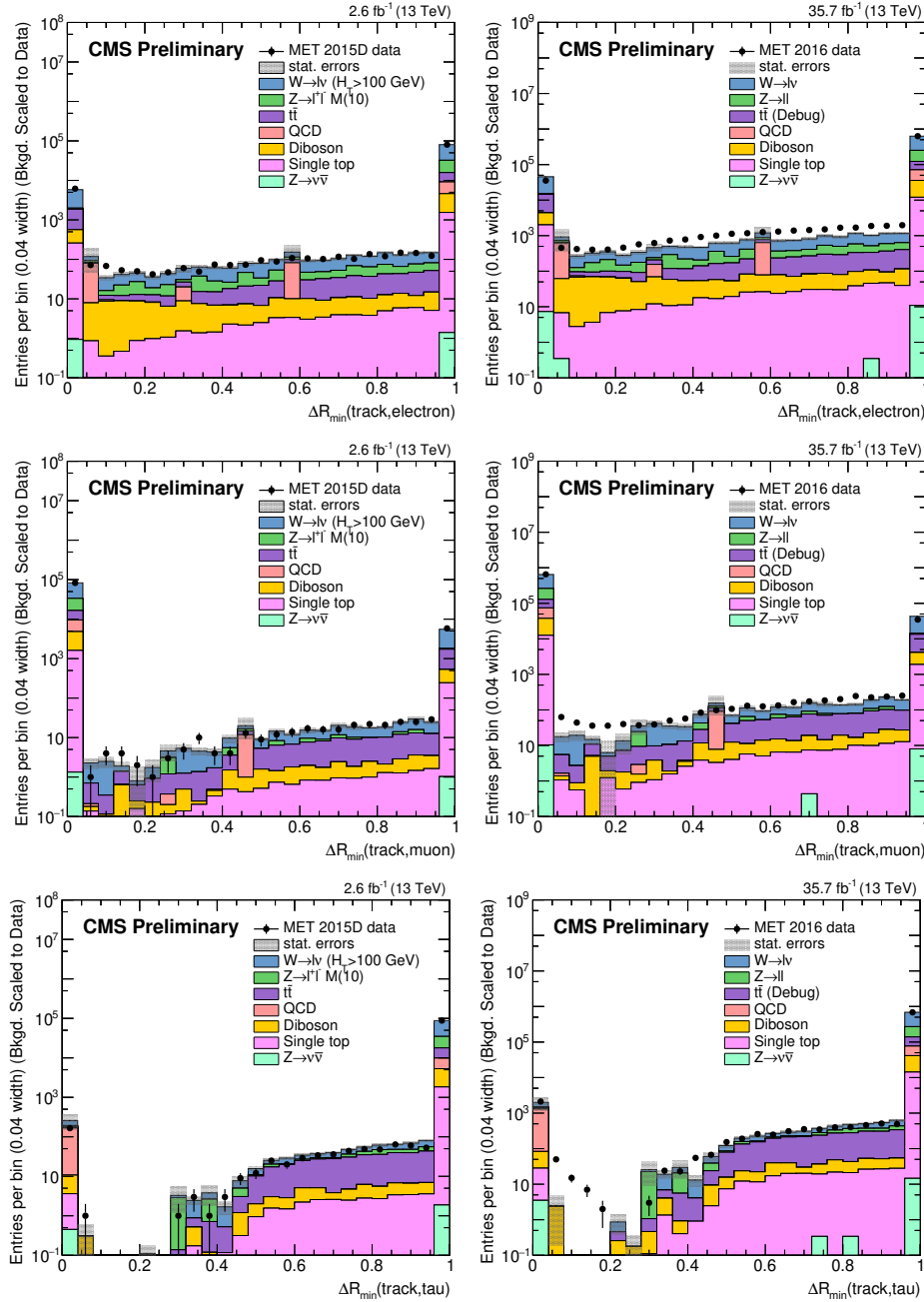


Figure 3.17: Plots of number of missing outer hits and $E_{\text{calo}}^{\Delta R < 0.5}$ for tracks selected in the *isolated track selection*. The experimental data is from 2015 (2016) in the left (right) column. The rightmost bin in each plot includes the overflow.

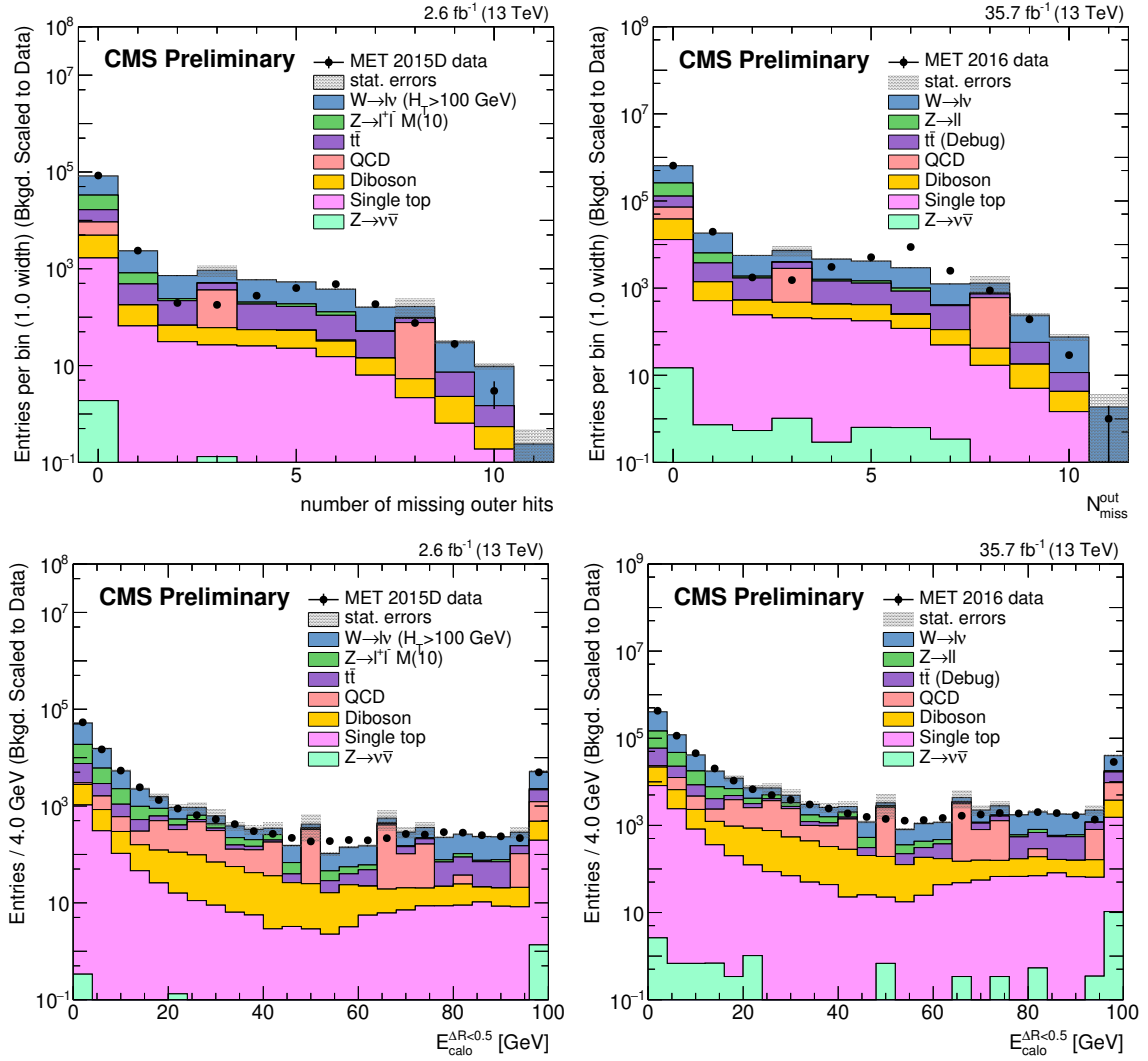


Table 3.18: The criteria defining the *candidate track selection*. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria. All reconstructed electrons and muons are used during this matching, in order to reject as many leptons as possible. Hadronic taus for this matching are identified using the criteria listed above in Table A.11, except that the isolation criterion.

quantity	object	selection
event passes <i>isolated track selection</i>		
≥ 1	tracks	$\min \Delta R_{\text{track,electron}} > 0.15$
≥ 1	tracks	$\min \Delta R_{\text{track,muon}} > 0.15$
≥ 1	tracks	$\min \Delta R_{\text{track,had. tau}} > 0.15$

within a cone of $\Delta R < 0.5$ of the selected track. The sum is then corrected for contamination from pileup using ρ , the median calorimeter energy density of the event, which is simply multiplied by the cone size of 0.5.

Table 3.19: The criteria defining the *disappearing track selection*. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
event passes <i>candidate track selection</i>		
≥ 1	tracks	$E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$
≥ 1	tracks	missing outer hits ≥ 3

The distributions of $E_{\text{calo}}^{\Delta R < 0.5}$ and number of missing outer hits are shown in Figure 3.18 for tracks in simulation that pass the full *disappearing track selection* except for the requirement on the variable being plotted. Very good separation

between signal and background is seen for both of these variables, and requiring $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$ and at least three missing outer hits is sufficient to remove all background within the albeit limited statistical precision of the simulation.

Finally, the cumulative selection efficiency of each selection is shown in Figure 3.19 for simulated signal events with various lifetime hypotheses. Several features of this plot are worth noting. For the shortest lifetimes, large drops in efficiency are seen for the requirements on p_T , number of pixel hits, number of valid hits, and track isolation. This is because when the chargino passes through very few layers of the inner tracker, the resulting track is unlikely to be reconstructed. Thus, the tracks we select are mostly either fake tracks, and mostly rejected by the requirements on p_T , number of pixel hits, and number of valid hits, or are constituents of the ISR jet, and mostly rejected by the isolation requirement. Event displays demonstrating the latter case are seen in Figures 3.20 and 3.21.

For the longest lifetimes, large drops in efficiency are seen for the requirement of $\min \Delta R_{\text{track, muon}} > 0.15$, which is designed to reject reconstructed muons. This is because if the chargino is very long-lived, it may pass through a few muon chambers before decaying, and be reconstructed as a muon. A large drop for the efficiency of the final requirement on number of missing outer hits is also seen for a similar reason: longer lived charginos are more likely to pass through all, or nearly all, layers of the inner tracker before decaying, and so will be more likely to have fewer than three missing outer hits.

Figure 3.18: Distributions of $E_{\text{calo}}^{\Delta R < 0.5}$ (left) and number of missing outer hits (right) for tracks in simulation that pass the full *disappearing track selection* except for the requirement on the variable being plotted.

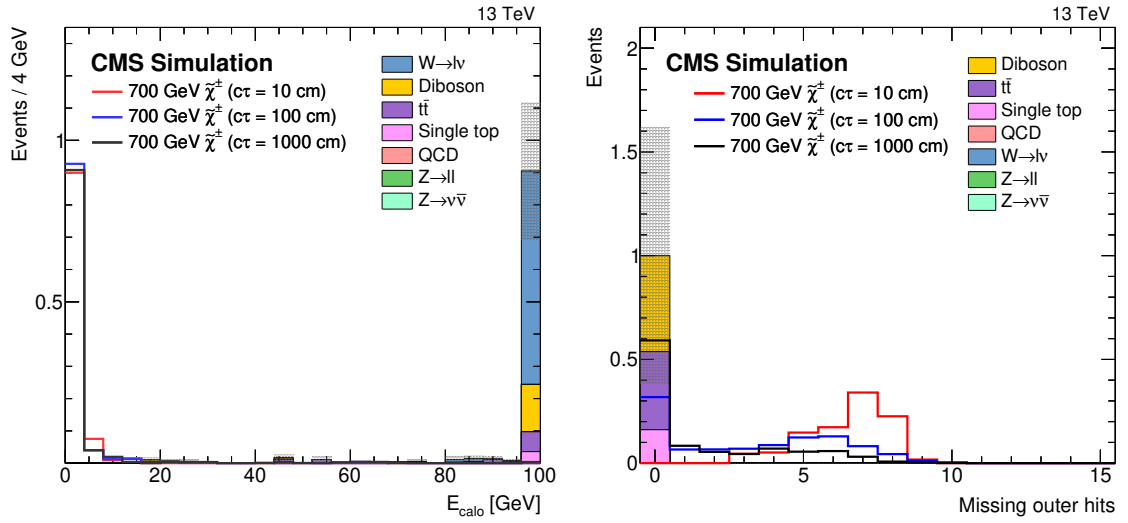


Figure 3.19: Cumulative selection efficiencies for each selection of the disappearing track selection for simulated signal events. The chargino mass in the simulated events is 700 GeV and three lifetime hypotheses are shown: 10 cm, 100 cm, and 1000 cm.

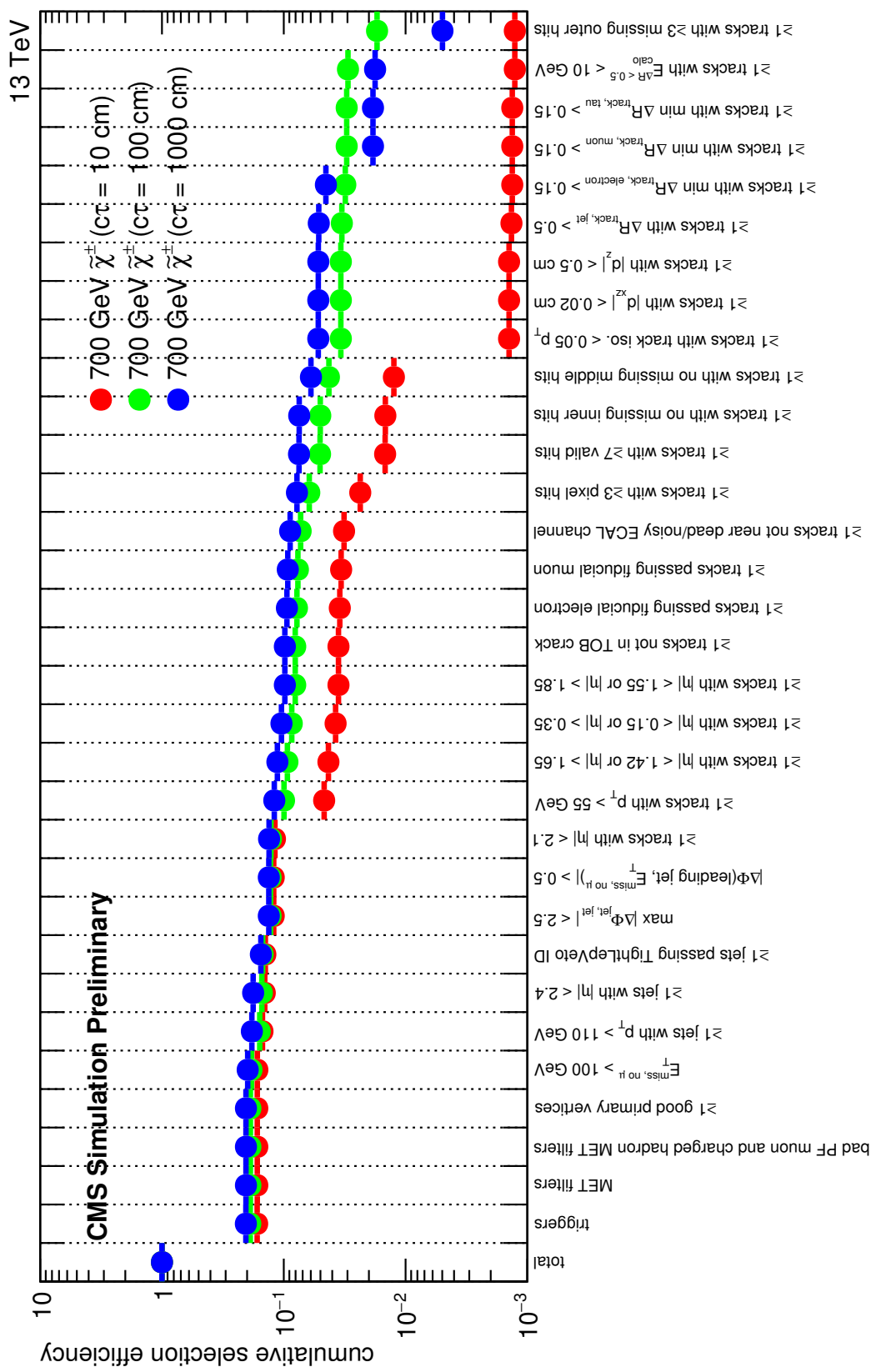


Figure 3.20: Event display of simulated signal event with a 700 GeV chargino with a lifetime of 10 cm/ c . The highlighted track is rejected by the track isolation requirement.

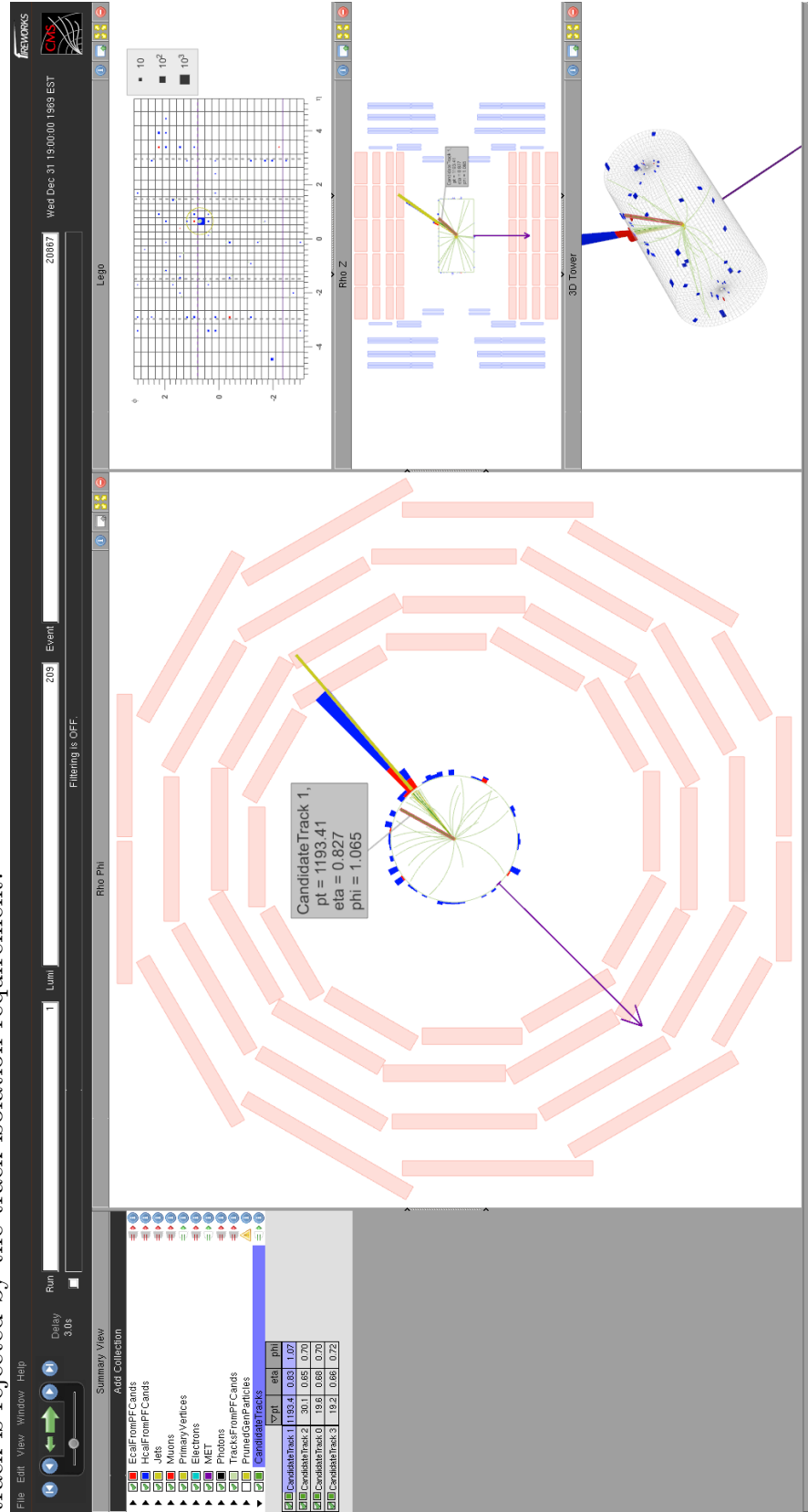
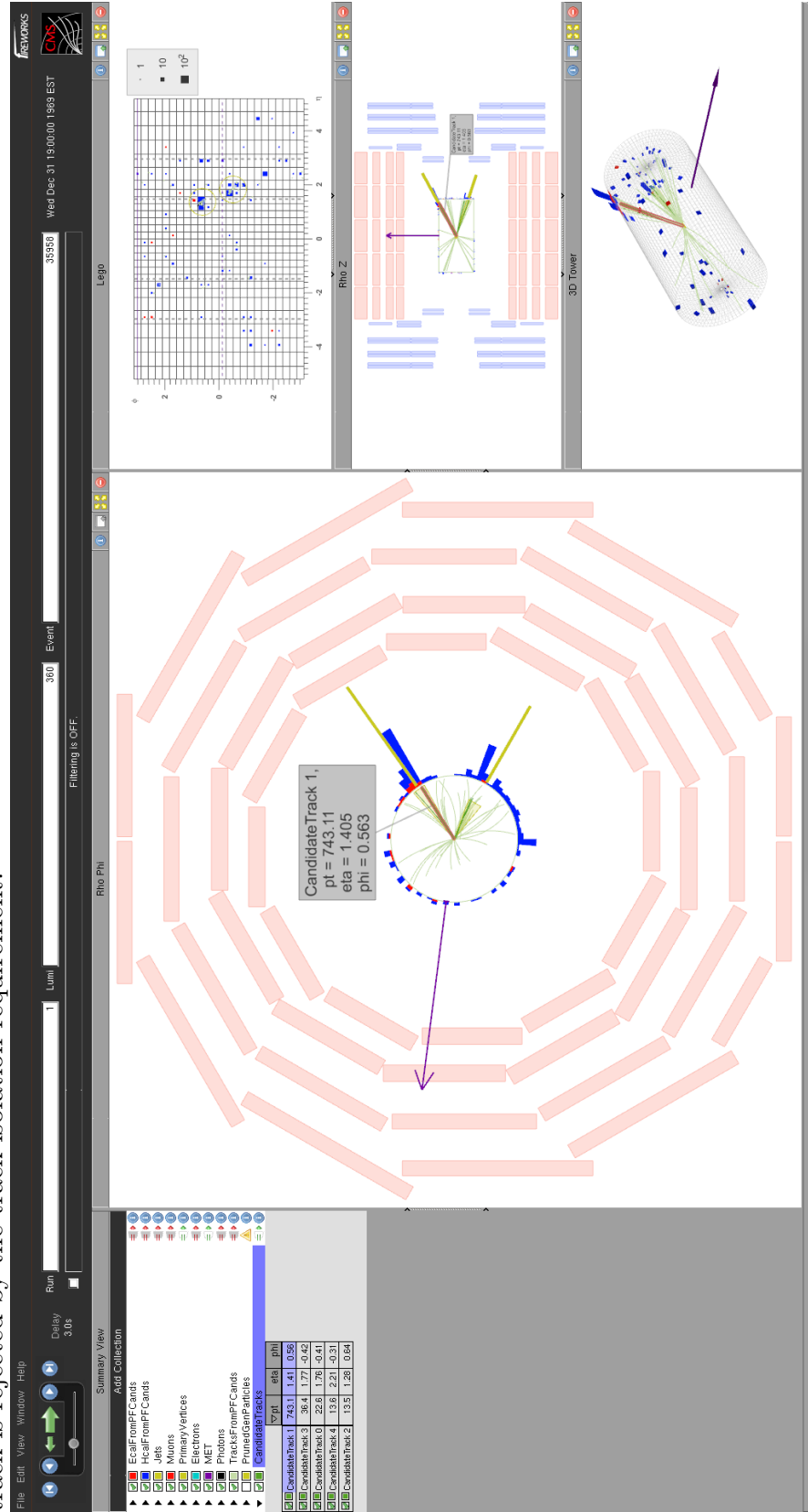


Figure 3.21: Event display of simulated signal event with a 700 GeV chargino with a lifetime of 10 cm/ c . The highlighted track is rejected by the track isolation requirement.



3.4 Background estimation

3.4.1 Charged leptons

The dominant source of high- p_T , isolated tracks from standard model processes is charged leptons from the decay of gauge bosons. In order for events with such tracks to enter our search region, three things must happen:

- the lepton must fail to be reconstructed as such, while still leaving a track in the silicon tracker
- the resulting $p_T^{\text{miss, no } \mu}$ must be large enough for the event to pass our offline $p_T^{\text{miss, no } \mu}$ requirement
- the resulting $p_T^{\text{miss, no } \mu}$ must be large enough for the event to pass our triggers

The key point here is that the $p_T^{\text{miss, no } \mu}$ is correlated with whether the lepton is reconstructed as a lepton or not. A successfully reconstructed lepton will be present in the list of candidates produced by particle flow, and thus, in the case of an electron or a tau, its p_T will count as visible momentum when $p_T^{\text{miss, no } \mu}$ is calculated. Conversely, a lepton that is not successfully reconstructed as such, but which still leaves a track that passes the selections of our search region, will not be present in the list of candidates produced by particle flow, and its p_T will count as invisible momentum when $p_T^{\text{miss, no } \mu}$ is calculated.¹³ The method used to estimate the background from charged leptons is based on calculating the probability of the three events listed above, with each lepton flavor treated independently.

¹³In principle, the lepton could be misreconstructed as a charged hadron and contribute visible momentum in that way. However, this is highly unlikely given the requirement that $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$: particle flow would have to match a track with $p_T > 55 \text{ GeV}$ to an energy deposit of less than 10 GeV.

Probability to pass the lepton veto

The first probability we consider is P_{veto} , the probability that the lepton in a single lepton event is not reconstructed as such:

$$P_{\text{veto}} = P(\text{pass lepton veto}). \quad (3.4)$$

The lepton vetoes are defined in Table 3.20. There is a separate veto for each lepton flavor, and each veto starts with the $\min \Delta R_{\text{track,lepton}} > 0.15$ criterion used in the candidate track selection. Recall from the definition of the candidate track selection in Section 3.3.2, that the definitions of $\min \Delta R_{\text{track,lepton}}$ include all reconstructed electrons and muons, while hadronic taus passing the selections in Table A.11 with the exception of the isolation criterion are used. Depending on the lepton flavor, the $\min \Delta R_{\text{track,lepton}}$ requirement is highly correlated with certain other criteria from the search region; e.g., the electron and tau vetoes are highly correlated with the selection on $E_{\text{calo}}^{\Delta R < 0.5}$. For this reason, other selections are included in the lepton vetoes, including that of missing outer hits ≥ 3 , to account for any possible correlations between lepton reconstruction and our track selections. Thus, P_{veto} implicitly includes the probability for a track to have missing outer hits.

To estimate P_{veto} , we use tag-and-probe studies. We defined electron and muon tag-and-probe selections in Section 3.3.1 in Tables 3.13 and 3.14, respectively, when discussing the method for identifying residual areas of electron and muon reconstruction inefficiency. The tag-and-probe samples we use here are identical except for the additional rejection of tracks near the identified areas of reconstruction inefficiency from that study. We also do not choose only one tag-probe pair per event, but rather

Table 3.20: Definitions of the lepton vetoes that are studied with the *tag-and-probe samples* in Section 3.4.1.

flavor	quantity	object	selection
electron	≥ 1	tracks	$\min \Delta R_{\text{track,electron}} > 0.15$
	≥ 1	tracks	$E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$
	≥ 1	tracks	missing outer hits ≥ 3
muon	≥ 1	tracks	$\min \Delta R_{\text{track,muon}} > 0.15$
	≥ 1	tracks	missing outer hits ≥ 3
tau	≥ 1	tracks	$\min \Delta R_{\text{track,had. tau}} > 0.15$
	≥ 1	track-jet pairs	$\Delta R_{\text{track,jet}} > 0.5$
	≥ 1	tracks	$E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$
	≥ 1	tracks	missing outer hits ≥ 3

use all unique pairs passing the selections. In addition, there are two *tau tag-and-probe samples*: one that attempts to tag the electron from a $\tau \rightarrow e\nu\nu$ decay, and one that attempts to tag the muon from a $\tau \rightarrow \mu\nu\nu$ decay. The selections of these two samples are listed in Tables 3.21 and 3.22, respectively.

We require $M_T(p_T^{\text{miss}}, \text{lepton}) < 40 \text{ GeV}$ to reduce the contamination from W+jets where the W decays to an electron or muon and a parton fragments into a single high- p_T hadron. This is the same strategy used to reduce this background in the measurement of the $Z \rightarrow \tau\tau$ cross section at 7 TeV [20]. Although there is still significant contamination from hadrons not from tau decays, this is acceptable since isolated hadrons are indistinguishable from hadrons from $\tau \rightarrow \pi^\pm \nu$ decays.

Because of the very few numbers of events that pass the lepton vetoes, no fit to the tag-probe invariant mass spectrum is attempted in order to extract the $Z \rightarrow ll$ signal from the background of continuum Drell–Yan events, non-Drell–Yan events,

Table 3.21: The criteria defining the *tau tag-and-probe sample* with an electron tag. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
event passes SingleElectron triggers		
≥ 1	electrons	$p_T > 25 \text{ GeV}$
≥ 1	electrons	$ \eta < 2.1$
≥ 1	electrons	passing tight electron ID
≥ 1	electrons	$M_T(p_T^{\text{miss}}, \text{electron}) < 40 \text{ GeV}$
≥ 1	tracks	$p_T > 30 \text{ GeV}$
≥ 1	tracks	passing fiducial selections (see Section 3.3.1)
≥ 1	tracks	number of pixel hits ≥ 3
≥ 1	tracks	number of valid hits ≥ 7
≥ 1	tracks	missing inner hits = 0
≥ 1	tracks	missing middle hits = 0
≥ 1	tracks	rel. track-based iso. < 0.05
≥ 1	tracks	$ d_{xy} < 0.02 \text{ cm}$
≥ 1	tracks	$ d_z < 0.5 \text{ cm}$
≥ 1	tracks	$\min \Delta R_{\text{track,electron}} > 0.15$
≥ 1	tracks	$\min \Delta R_{\text{track,muon}} > 0.15$
$= 1$	track-electron pairs	$15 \text{ GeV} < M_Z - M_{\text{track,electron}} < 50 \text{ GeV}$
$= 1$	track-electron pairs	$q_{\text{track}} \cdot q_{\text{electron}} < 0$

Table 3.22: The criteria defining the *tau tag-and-probe sample* with a muon tag. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
event passes SingleMuon triggers		
≥ 1	muons	$p_T > 25 \text{ GeV}$
≥ 1	muons	$ \eta < 2.1$
≥ 1	muons	passing tight muon ID
≥ 1	muons	$M_T(p_T^{\text{miss}}, \text{muon}) < 40 \text{ GeV}$
≥ 1	tracks	$p_T > 30 \text{ GeV}$
≥ 1	tracks	passing fiducial selections (see Section 3.3.1)
≥ 1	tracks	number of pixel hits ≥ 3
≥ 1	tracks	number of valid hits ≥ 7
≥ 1	tracks	missing inner hits = 0
≥ 1	tracks	missing middle hits = 0
≥ 1	tracks	rel. track-based iso. < 0.05
≥ 1	tracks	$ d_{xy} < 0.02 \text{ cm}$
≥ 1	tracks	$ d_z < 0.5 \text{ cm}$
≥ 1	tracks	$\min \Delta R_{\text{track,electron}} > 0.15$
≥ 1	tracks	$\min \Delta R_{\text{track,muon}} > 0.15$
$= 1$	track-muon pairs	$15 \text{ GeV} < M_Z - M_{\text{track,muon}} < 50 \text{ GeV}$
$= 1$	track-muon pairs	$q_{\text{track}} \cdot q_{\text{muon}} < 0$

and events with fake tracks. Certainly, there is such background in these tag-and-probe selections, as seen by the fits to the electron and muon tag-probe invariant mass spectra shown in Figure 3.22, before the final lepton veto is applied to the probe track. However, after applying the lepton veto, the Z peak is still clearly visible, as seen in Figure 3.23. Thus, the values we measure for $P_{\text{veto}}^{\text{raw}}$ are fair estimates of the probability of true leptons to pass the lepton vetoes and are not dominated by this background contamination.

Nonetheless, in a very simple way, we can subtract the contamination from events with fake tracks by inverting the requirement in the tag-and-probe selections that the tag and probe be oppositely-charged. With these *same-sign tag-and-probe selections*, one for each of the four nominal tag-and-probe selections, we remove all $Z \rightarrow l\bar{l}$ events and are left with an estimate of the charge-symmetric component of the background contamination in the nominal tag-and-probe selections; i.e., an estimate of the contamination from fake tracks in the tag-and-probe selections. This applies both before and after the lepton veto is applied to the probe track, so that P_{veto} is defined as

$$P_{\text{veto}} = \frac{N_{\text{T\&P}}^{\text{veto}} - N_{\text{SST\&P}}^{\text{veto}}}{N_{\text{T\&P}} - N_{\text{SST\&P}}}, \quad (3.5)$$

where $N_{\text{T\&P}}$ ($N_{\text{T\&P}}^{\text{veto}}$) and $N_{\text{SST\&P}}$ ($N_{\text{SST\&P}}^{\text{veto}}$) are the numbers of passing tag-probe pairs from the events in the nominal and same-sign tag-and-probe selections, respectively, before (after) the final vetoes are applied to the probe track. The values we calculate for P_{veto} in experimental data are shown below in Tables 3.26, 3.27, and 3.28.

Note that although the typical p_T of the probe tracks in the tag-and-probe samples is less than that of the candidate tracks in the search region, there is no significant change in P_{veto} for tracks with larger p_T . This can be seen by performing a Kolmogorov-Smirnov (KS) test to compare the distributions of probe track p_T for

Figure 3.22: Tag-probe invariant mass spectra for events passing the electron (top) and muon (bottom) tag-and-probe selections from the 2015 and 2016 experimental data, before the corresponding lepton veto is applied to the probe track. The data are fit with the sum of a Breit-Wigner distribution convoluted with a crystal ball function and the so-called RooCMSShape function, representing the $Z \rightarrow l\bar{l}$ signal and background, respectively.

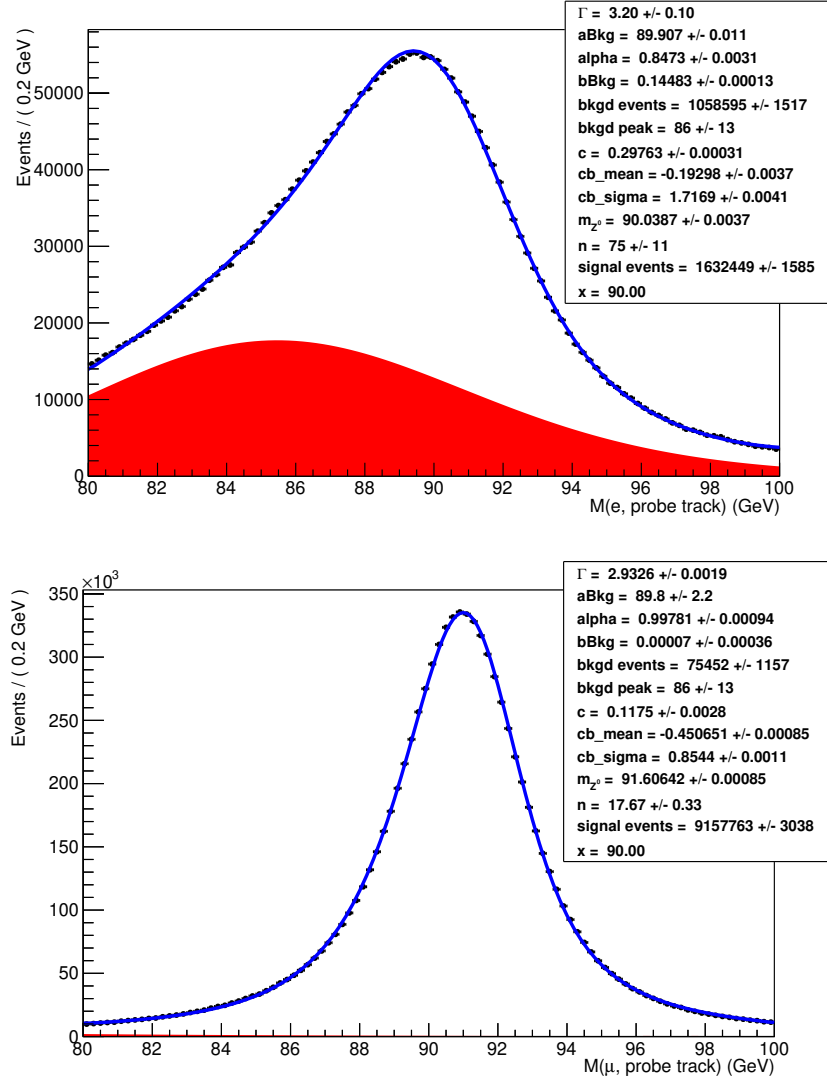
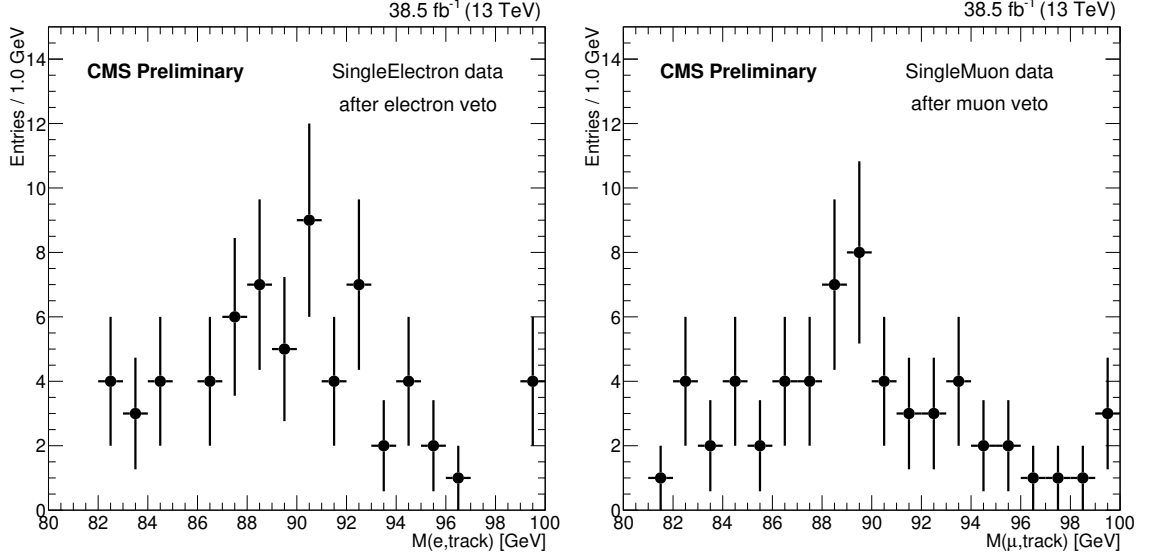
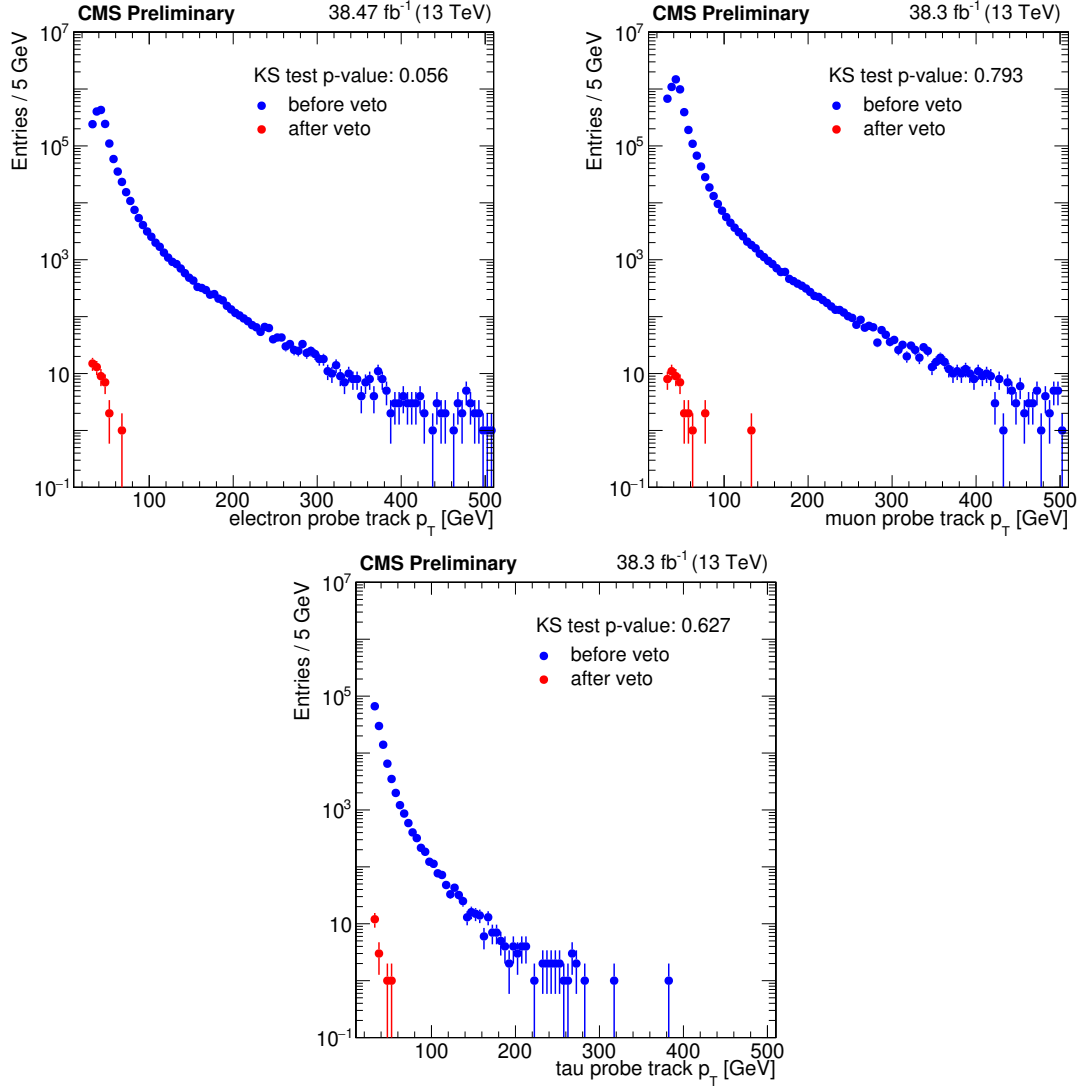


Figure 3.23: Tag-probe invariant mass spectra for events passing the electron (left) and muon (right) tag-and-probe selections from the 2015 and 2016 experimental data, after the corresponding lepton veto is applied to the probe track.



the events comprising $N_{T\&P}$ and $N_{T\&P}^{\text{veto}}$. These distributions, as well as the p-value from the test, are shown in Figure 3.24. Although there is some tension between the probe track p_T distributions before and after the veto in the case of electrons, in all cases, $p > 0.05$, meaning the null hypothesis that the events are drawn from the same distribution cannot be rejected at 95%.

Figure 3.24: Probe track p_T distributions before and after the application of the lepton veto for electrons (upper left), muons (upper right), and taus (bottom center). The p-value from a Kolmogorov-Smirnov (KS) test of the two distributions in each plot is also shown.



Probability to pass the offline p_T^{miss} requirements

We define P_{offline} as the probability of a single lepton event to pass our offline requirements of $p_T^{\text{miss, no } \mu} > 100 \text{ GeV}$ and $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})| > 0.5$ given that the lepton is not reconstructed as such; i.e.,

$$P_{\text{offline}} = P(\text{pass offline } p_T^{\text{miss}} \text{ cuts} | \text{pass lepton veto}). \quad (3.6)$$

To estimate this probability, we use *single-lepton control regions* that are designed to count the leptons that could enter the search region, were they to fail to be reconstructed. Each involves selecting a reconstructed lepton matched to a track passing the selections of the *isolated track selection* in an event passing the jet criteria of the *basic selection*. The selections of the *single-electron control sample*, *single-muon control sample*, and *single-tau control sample* are listed in Tables 3.23, 3.24, and 3.25, respectively.¹⁴¹⁵

Now, to estimate P_{offline} , the main assumption we make is that if a lepton is not reconstructed, then it contributes no visible momentum to the event.¹⁶ Thus, for electrons and taus, we introduce modified p_T^{miss} distributions that represent what $p_T^{\text{miss, no } \mu}$ would look like if the lepton in these events were not reconstructed:

$$\vec{p}_T^{\text{miss, no } \mu} \longrightarrow \vec{p}_T^{\text{miss, no } \mu} + \vec{p}_T^{\text{lepton}} \quad \text{for electrons and taus.} \quad (3.7)$$

¹⁴The *isolated track selection* includes the requirement $p_T > 55 \text{ GeV}$. So although we include a selection on the lepton p_T in these control regions, we later impose a tighter requirement on the track p_T .

¹⁵Although the *single-tau control sample* is defined using the hadronic tau ID, this sample also includes isolated hadrons from other sources that are mistaken for single-prong hadronic tau decays. This is because the pion from a $\tau \rightarrow \pi^\pm \nu$ decay is indistinguishable from an isolated hadron from any other source.

¹⁶In practice, an unreconstructed lepton cannot contribute more than 10 GeV in the search region because we explicitly require the associated calorimeter energy of selected tracks to be under this threshold. A systematic uncertainty associated with this assumption is calculated in Section 3.6.1.

Table 3.23: The criteria defining the *single-electron control sample*. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
		event passes SingleElectron triggers
		Ele22_eta2p1_WPLoose_Gsf (2015)
		Ele25_eta2p1_WPTight_Gsf (2016)
≥ 1	electrons	$p_T > 35 \text{ GeV}$
≥ 1	electrons	$ \eta < 2.1$
≥ 1	electrons	passes tight electron ID
		exactly one passing electron chosen randomly
		event passes jet criteria of <i>basic selection</i>
		event passes track criteria of <i>isolated track selection</i>
		track matched to selected electron within $\Delta R < 0.1$

Table 3.24: The criteria defining the *single-muon control sample*. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
		event passes SingleMuon triggers
		IsoMu20 OR IsoTkMu20 (2015)
		IsoMu24 OR IsoTkMu24 (2016)
≥ 1	muons	$p_T > 35 \text{ GeV}$
≥ 1	muons	$ \eta < 2.1$
≥ 1	muons	passes tight muon ID
		exactly one passing muon chosen randomly
		event passes jet criteria of <i>basic selection</i>
		event passes track criteria of <i>isolated track selection</i>
		track matched to selected muon within $\Delta R < 0.1$

Table 3.25: The criteria defining the *single-tau control sample*. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
event passes Tau triggers		
LooseIsoPFTau50_Trk30_eta2p1		
≥ 1	taus	$p_T > 50 \text{ GeV}$
≥ 1	taus	$ \eta < 2.1$
≥ 1	taus	passes hadronic tau ID
exactly one passing tau chosen randomly		
event passes jet criteria of <i>basic selection</i>		
event passes track criteria of <i>isolated track selection</i>		
track matched to selected tau within $\Delta R < 0.1$		

No such modification is necessary in the case of muons since we always count the p_T of muons as invisible. Then, using the events in the single-lepton control regions defined above, we create two-dimensional distributions of $p_T^{\text{miss, no } \mu}$ vs. $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})|$ with these modifications to $p_T^{\text{miss, no } \mu}$. These distributions, before and after the modification to $p_T^{\text{miss, no } \mu}$, are shown in Figures 3.25 and 3.26 for electrons and taus, respectively. The distributions for muons, which receive no such modification to $p_T^{\text{miss, no } \mu}$, are shown in Figure 3.27.

Finally, we estimate P_{offline} by counting the fraction of events with $p_T^{\text{miss, no } \mu} > 100 \text{ GeV}$ and $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})| > 0.5$ in these modified $p_T^{\text{miss, no } \mu}$ distributions. This is illustrated in Figure 3.28, where P_{offline} is the fraction of events in the plot that fall within the red shaded region. The values we calculate for P_{offline} in experimental data are shown below in Table 3.26, 3.27, and 3.28.

Figure 3.25: Distributions of $p_T^{\text{miss, no } \mu}$ vs. $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})|$ in single electron events. The left (right) column shows the $p_T^{\text{miss, no } \mu}$ distribution with the momentum of the electron counted as visible (invisible). The 2015, 2016B+C, and 2016D–H data are shown separately on the top, middle, and bottom rows, respectively.

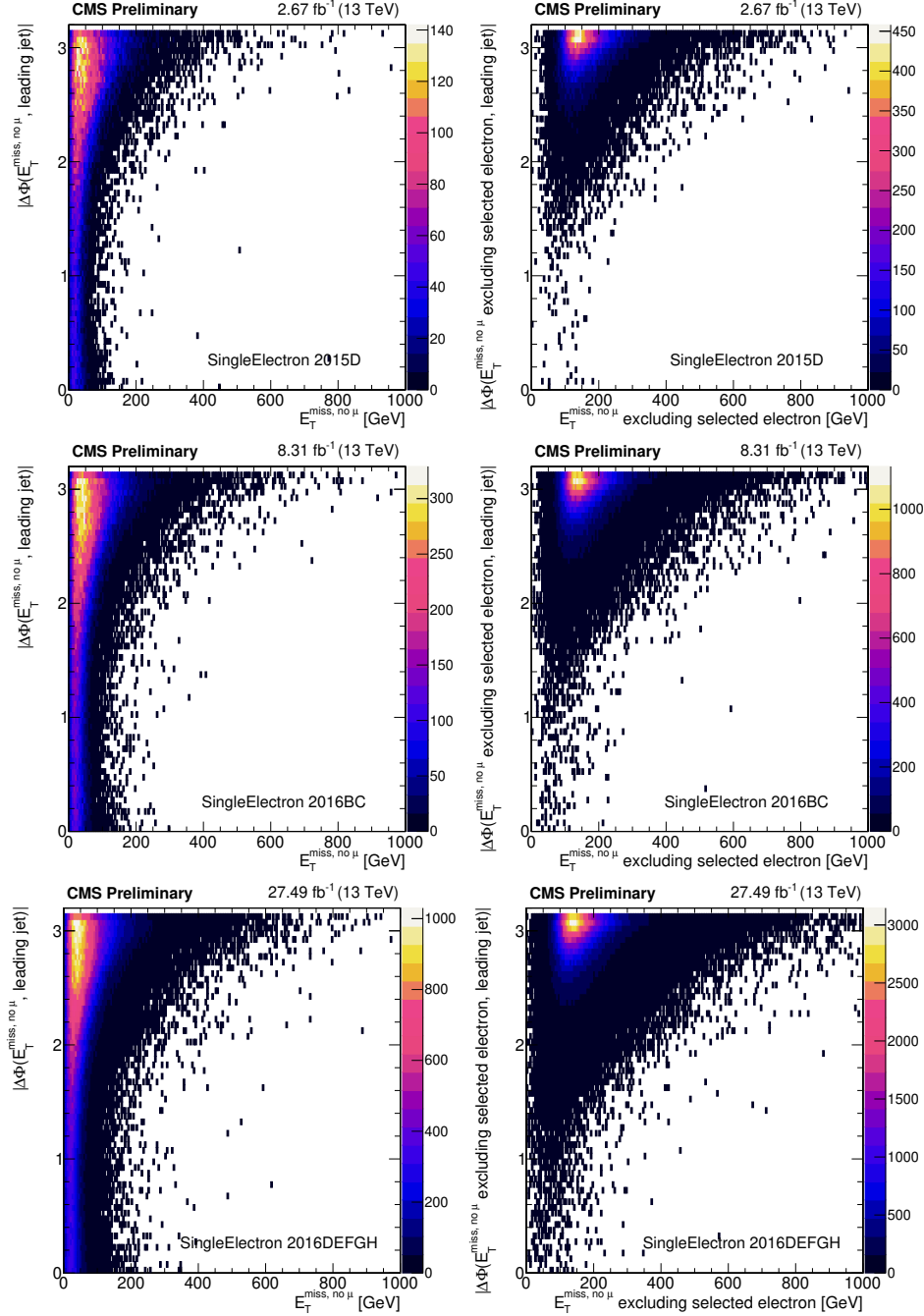


Figure 3.26: Distributions of $p_T^{\text{miss, no } \mu}$ vs. $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})|$ in single tau events. The left (right) column shows the $p_T^{\text{miss, no } \mu}$ distribution with the momentum of the tau counted as visible (invisible). The 2015, 2016B+C, and 2016D–H data are shown separately on the top, middle, and bottom rows, respectively.

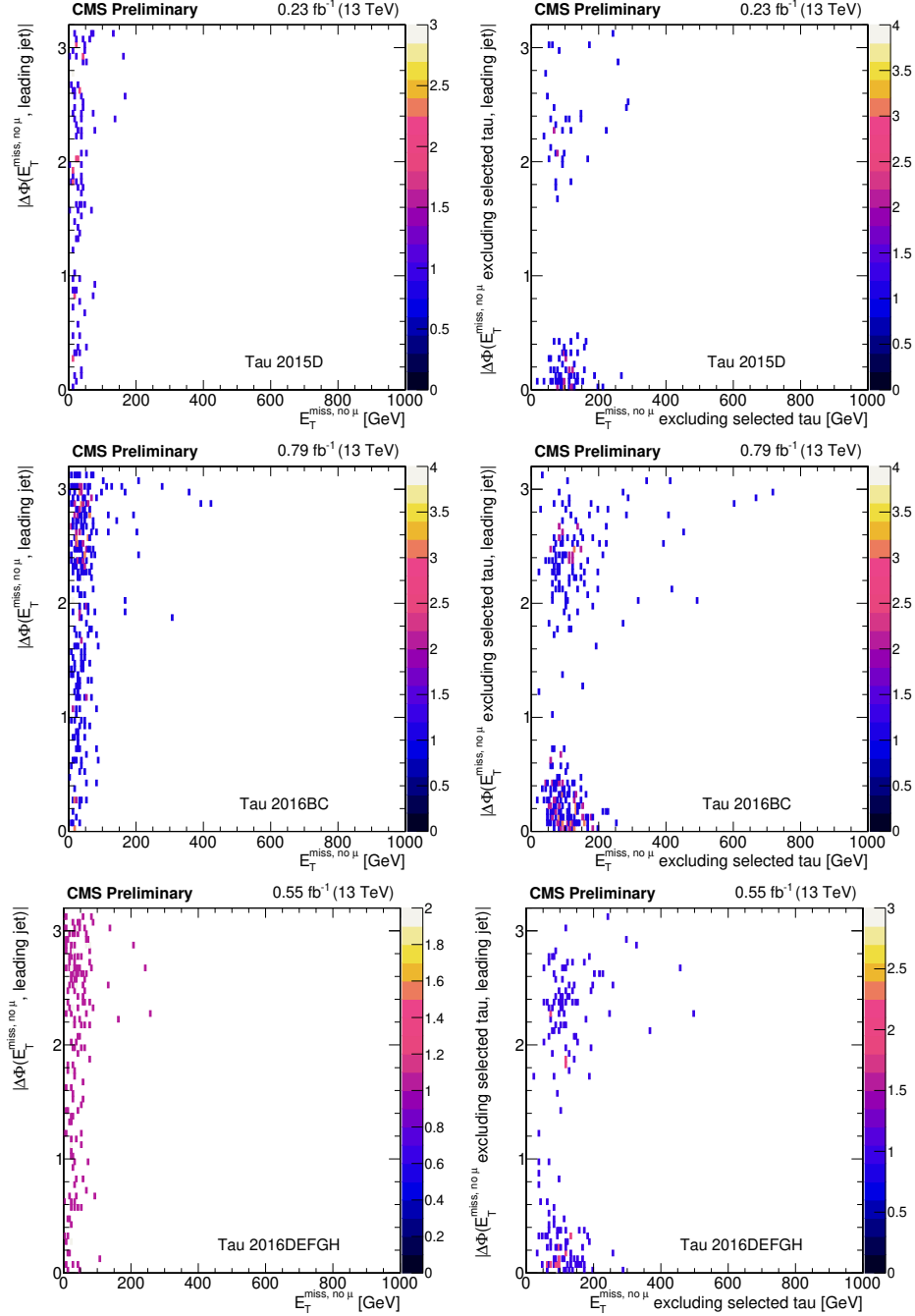


Figure 3.27: Distributions of $p_T^{\text{miss, no } \mu}$ vs. $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})|$ in single muon events. The 2015, 2016B+C, and 2016D–H data are shown separately on the top, middle, and bottom rows, respectively.

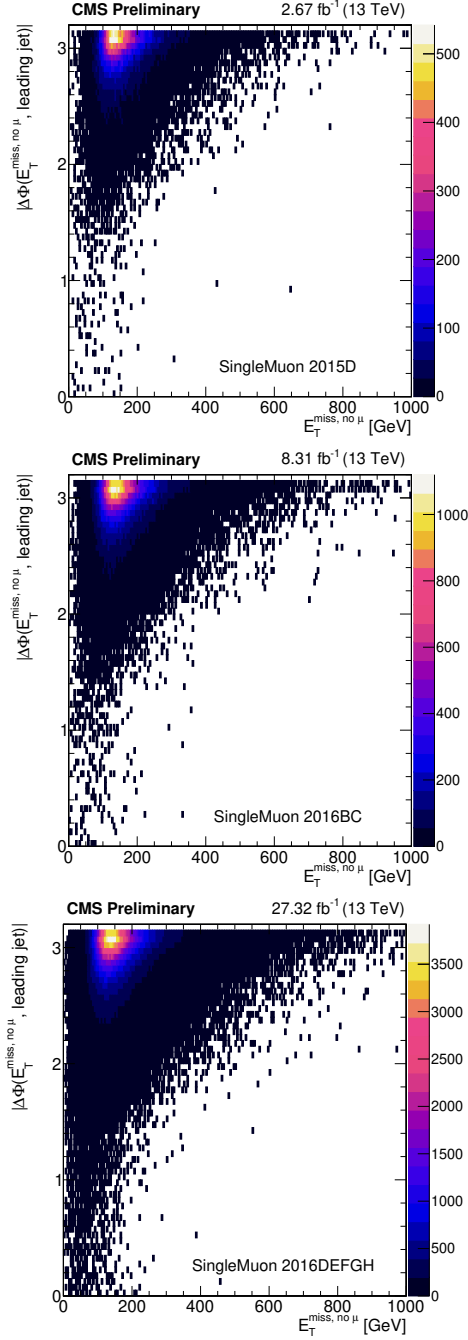
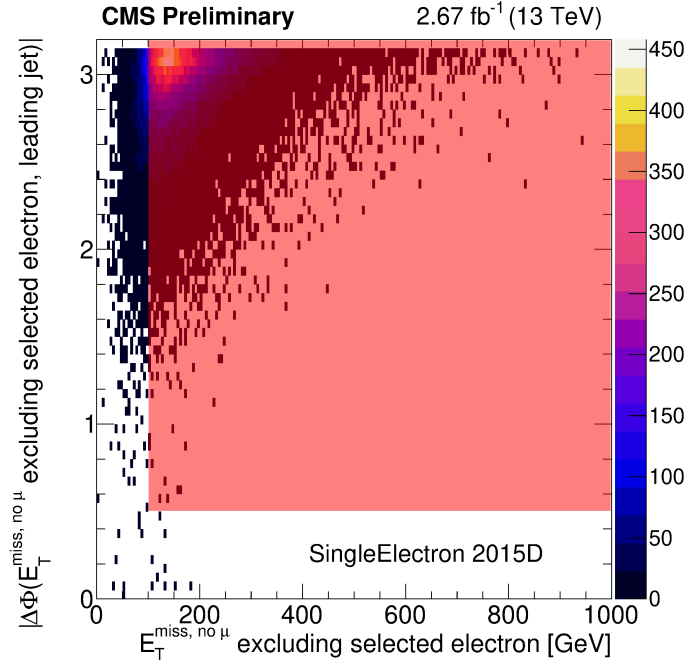


Figure 3.28: Illustration of how P_{offline} is calculated in the case of electrons in 2015. The fraction of events in the plot that fall within the red shaded region is P_{offline} .



Probability to pass the p_T^{miss} triggers

We define P_{trigger} as the probability of a single lepton event to pass the p_T^{miss} triggers used in the search given that the lepton is not reconstructed as such and the event passes our offline requirements of $p_T^{\text{miss, no } \mu} > 100 \text{ GeV}$ and $|\Delta\phi(\text{leading jet}, p_T^{\text{miss, no } \mu})| > 0.5$; i.e.,

$$P_{\text{trigger}} = P(\text{pass } p_T^{\text{miss}} \text{ triggers} | \text{pass lepton veto} \cap \text{pass } p_T^{\text{miss}} \text{ cuts}). \quad (3.8)$$

To estimate P_{trigger} , we estimate, event-by-event, what the online MET and MHT used in the HLT would be if the selected lepton were not reconstructed in each of the single-lepton control regions. This is done by first matching the selected lepton to a lepton trigger object and a jet trigger object (nearest ones within $\Delta R < 0.1$) and adding the $\vec{p}_T$ vector of the trigger object to the $\vec{p}_T$ vector of the nominal online MET and nominal online MHT, respectively. This is done for each variety of online MET (calorimeter-based MET, PFMET, and PFMETNoMu) and each variety of online MHT (nominal PFMHT and PFMETNoMu) used in our search triggers, being careful in the case of muons to add nothing to the varieties from which muons were already excluded.

Likewise, we estimate what the ETM object used in the L1 trigger would be if the selected lepton were not reconstructed by matching the selected lepton to a lepton L1 object (nearest one within $\Delta R < 0.1$) and add its $\vec{p}_T$ vector to the $\vec{p}_T$ of the nominal L1 ETM. This is done in the case of electrons and taus, but not muons, since the L1 ETM is calculated using only information from the calorimeters.

With these estimates of what the online MET and MHT used in the HLT and the ETM used in the L1 trigger would be if the selected lepton were not reconstructed, we then determine if any of our search triggers would have fired. In

the case of `HLT_MET75_IsoTrk50_v*`, we also require the event to have passed the `hltTrk50Filter` filter. This properly accounts for the efficiency of the track leg of `HLT_MET75_IsoTrk50_v*` since we are interested in the behavior of the triggers when the selected lepton is not reconstructed, but still leaves a track that passes our isolated track selection.

The efficiency to pass the MET triggers using the above method with modified trigger objects is shown as a function of $|\vec{p}_T^{\text{miss, no } \mu} + \vec{p}_T^{\text{lepton}}|$ in Figures 3.29, 3.30, and 3.31, for the single-electron, muon, and tau control regions, respectively. As expected from the prescaling and disabling of the lower-threshold L1 ETM seeds as the instantaneous luminosity of the LHC increased throughout the run, the turn-on for the MET triggers moves up in the latter data.

Finally, P_{trigger} is simply the fraction of events in each single-lepton control region passing the online p_T^{miss} requirements that also fire one of the search triggers according to the above calculation:

$$P_{\text{trigger}} = \frac{N_{\text{ctrl}}^l(\text{passes } p_T^{\text{miss}} \text{ cuts} \cap \text{passes MET trigs. with modified trig. objs.})}{N_{\text{ctrl}}^l(\text{passes } p_T^{\text{miss}} \text{ cuts})}, \quad (3.9)$$

where $N_{\text{ctrl}}^l(p)$ is the number of events in the single-lepton control region for which p is true. The values we calculate for P_{trigger} in experimental data are shown below in Table 3.26, 3.27, and 3.28.

Figure 3.29: Trigger efficiency as a function of $p_T^{\text{miss, no } \mu}$ for events in the single-electron control region, using the calculation described in the text using trigger objects.

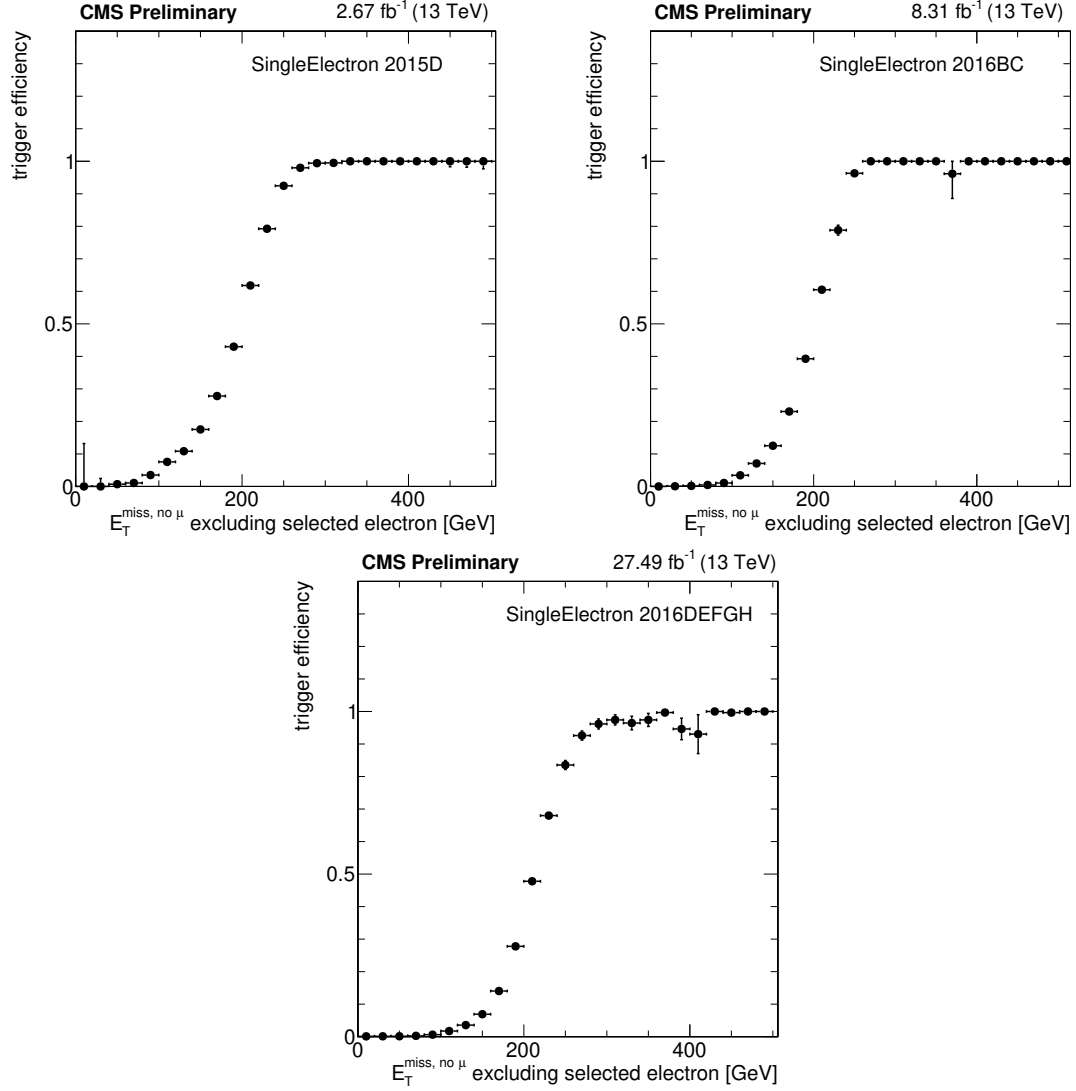


Figure 3.30: Trigger efficiency as a function of $p_T^{\text{miss, no } \mu}$ for events in the single-muon control region, using the calculation described in the text using trigger objects.

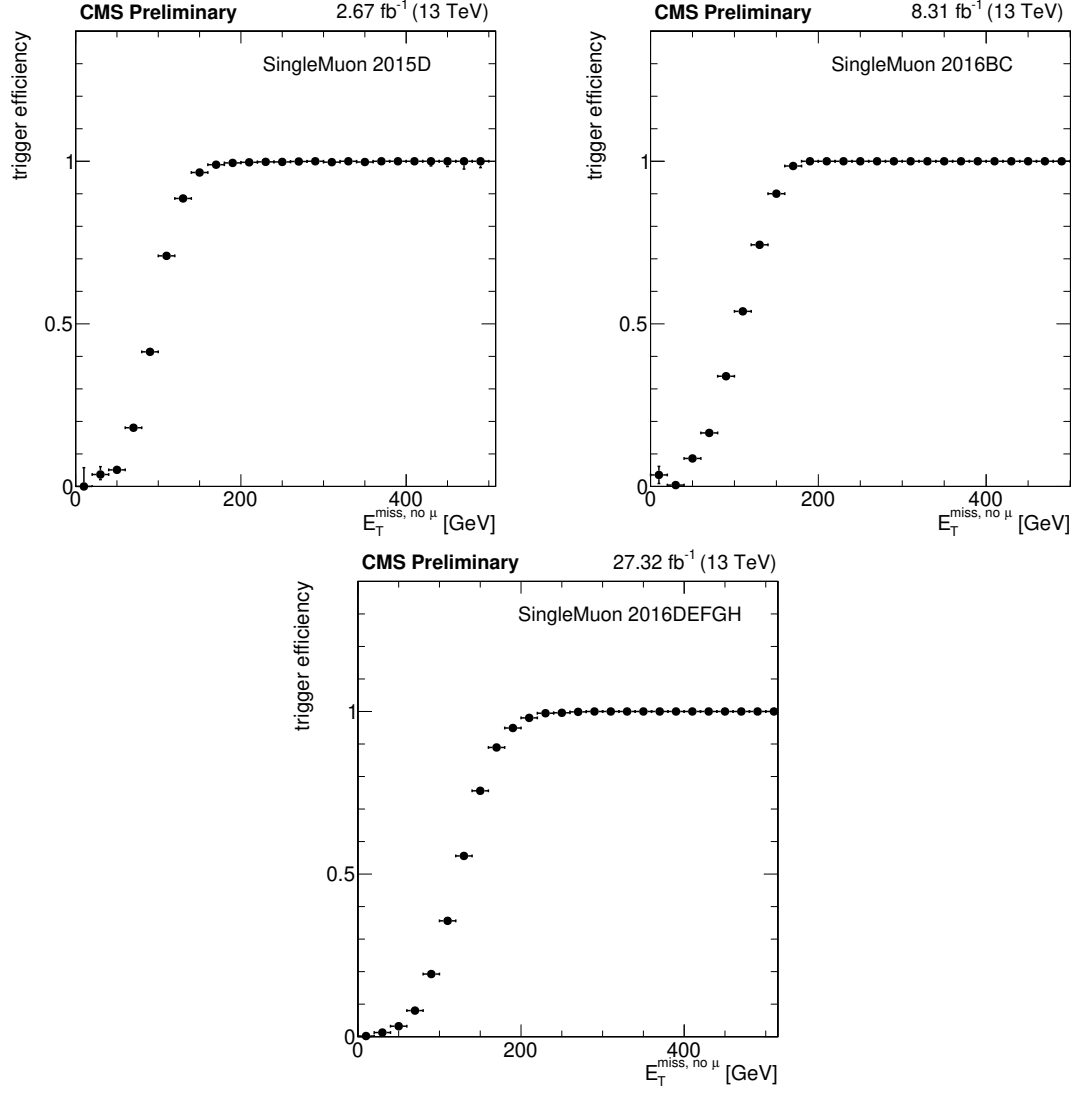
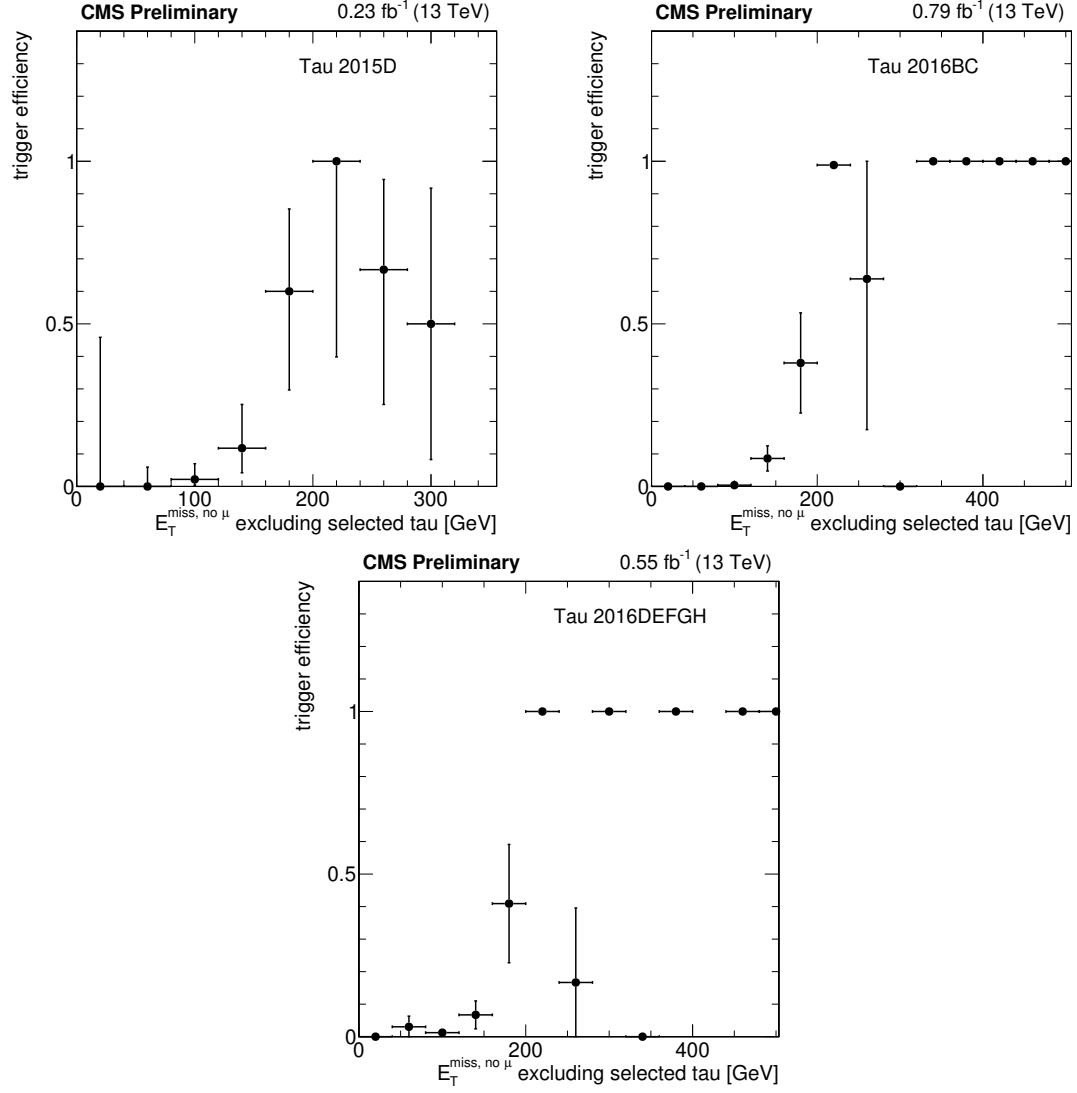


Figure 3.31: Trigger efficiency as a function of $p_T^{\text{miss, no } \mu}$ for events in the single-tau control region, using the calculation described in the text using trigger objects.



Background estimates

With the probabilities defined above, we can then define the probability of an event with a charged lepton to enter our search region:

$$\begin{aligned}
& P(\text{enter search region}) \\
&= P(\text{pass lepton veto} \cap \text{pass offline } p_{\text{T}}^{\text{miss}} \text{ cut} \cap \text{pass } p_{\text{T}}^{\text{miss}} \text{ triggers}) \\
&= P_{\text{veto}} P_{\text{offline}} P_{\text{trigger}},
\end{aligned}$$

where we use the chain rule of probability to factor the probabilities in the last line. Finally, we use the single lepton control regions defined above in Section 3.4.1 to estimate the total numbers of events containing each flavor of lepton, $N_{\text{ctrl}}^{\text{l}}$. Recall that we require the track associated with the lepton in these control regions to have $p_{\text{T}} > 55 \text{ GeV}$, the same requirement that we make in our disappearing track selection. All that remains is to multiply this number by the probabilities calculated above to get the background expected from charged leptons:

$$N_{\text{est}}^{\text{l}} = N_{\text{ctrl}}^{\text{l}} P_{\text{veto}} P_{\text{offline}} P_{\text{trigger}}. \quad (3.10)$$

The resulting electron, muon, and tau background estimates are summarized in Tables 3.26, 3.27, and 3.28, respectively, along with each of the quantities used to calculate the estimates.

Table 3.26: Electron background estimates for each run period considered in the search, along with the quantities used to calculate each estimate. The rightmost column is simply the product of the middle four columns.

run period	electron background				estimate
	N_{ctrl}^1	P_{veto}	P_{offline}	P_{trigger}	
2015	58820 ± 240	$(6.1 \pm 4.3) \times 10^{-6}$	0.9024 ± 0.0054	0.369 ± 0.0043	0.119 ± 0.084
2016B+C	156120 ± 400	$(1.95 \pm 0.61) \times 10^{-5}$	0.8987 ± 0.0033	0.3475 ± 0.0034	0.95 ± 0.30
2016D-H	470140 ± 690	$(1.59 \pm 0.42) \times 10^{-5}$	0.9004 ± 0.0019	0.2841 ± 0.0020	1.91 ± 0.50

Table 3.27: Muon background estimates for each run period considered in the search, along with the quantities used to calculate each estimate. The rightmost column is simply the product of the middle four columns.

run period	muon background				estimate
	N_{ctrl}^1	P_{veto}	P_{offline}	P_{trigger}	
2015	64200 ± 250	$(0_{-0}^{+1.3}) \times 10^{-6}$	0.9057 ± 0.0052	0.9257 ± 0.0078	$0_{-0}^{+0.072}$
2016B+C	145930 ± 380	$(8.8 \pm 2.6) \times 10^{-6}$	0.8969 ± 0.0034	0.8736 ± 0.0063	1.01 ± 0.30
2016D-H	555420 ± 750	$(2.89 \pm 0.98) \times 10^{-6}$	0.8932 ± 0.0017	0.7588 ± 0.0032	1.09 ± 0.37

Table 3.28: Tau background estimates for each run period considered in the search, along with the quantities used to calculate each estimate. The rightmost column is simply the product of the middle four columns.

run period	tau background				estimate
	N_{ctrl}^1	P_{veto}	P_{offline}	P_{trigger}	
2015	1280 ± 120	$(8_{-8}^{+12}) \times 10^{-5}$	0.12 ± 0.035	0.31 ± 0.28	$0.0037_{-0.0037}^{+0.0066}$
2016B+C	3230 ± 180	$(1.41 \pm 0.70) \times 10^{-4}$	0.26 ± 0.033	0.27 ± 0.12	0.032 ± 0.022
2016D-H	8910 ± 670	$(1.04 \pm 0.35) \times 10^{-4}$	0.318 ± 0.048	0.21 ± 0.13	0.063 ± 0.045

Closure tests in simulated events

We perform a closure test of our lepton background estimation method in samples of simulated events. Because of the limited event counts afforded by our full search selection, the test is performed using slightly relaxed selection criteria. These criteria start with the full disappearing track selection, but with the following modifications:

- all jet-related selections are removed from the basic selection (see Table 3.15)
- for the electron and muon background estimates, the track p_T requirement is lowered from 55 GeV to 35 GeV (see Table 3.16)
- the final selection on missing outer hits for tracks is removed (see Table 3.19)

For the background estimation procedure, the first two modifications are made to the single lepton control regions used to determine N_{ctrl}^l , and the missing outer hits requirement is removed from the vetoes of the lepton tag-and-probe samples (see Table 3.20). The background estimates thus obtained are then compared to the results of running the modified search selection on the simulated samples with the truth information allowing for a comparison of each flavor separately.

The results of this closure test are shown in Table 3.29 for the simulated samples of $W \rightarrow l\nu$ and $t\bar{t}$ events, which represent the largest sources of events with p_T^{miss} and high- p_T isolated tracks from standard model processes.¹⁷ The sample of $t\bar{t}$ events is also particularly large, allowing for a more precise test.

¹⁷This closure test was performed before the full set of fiducial track selections was finalized. This is why the estimated and observed numbers of events may seem rather large compared to the current estimates from experimental data.

Table 3.29: Results of lepton background closure test in simulated samples with relaxed selection criteria. The numbers of events are normalized to 2.7fb^{-1} , the luminosity of the 2015 data set.

sample	flavor	N_{est}^1	N_{obs}^1	$ N_{\text{est}}^1 - N_{\text{obs}}^1 $
$W \rightarrow l\nu$	electron	2.6 ± 0.9	1.9 ± 0.8	0.44σ
	muon	0.24 ± 0.17	$0_{-0}^{+0.39}$	0.57σ
	tau	insufficient statistics		
$t\bar{t}$	electron	0.88 ± 0.33	0.48 ± 0.10	1.2σ
	muon	0.057 ± 0.022	0.066 ± 0.038	0.20σ
	tau	0.068 ± 0.030	0.022 ± 0.022	1.2σ

Updated closure test with 2016 simulation

The above closure test was also performed using the samples of simulated background events produced in 2016, which are listed above in Table 3.8, in order to verify that the different conditions of the 2016 run do not somehow invalidate the background estimation method described above. Closure is again achieved, as seen in Table 3.30, within the albeit limited statistical precision afforded by the available samples.

3.4.2 Fake tracks

Fake tracks, i.e., tracks that do not correspond to actual charged particles but rather to errors in the pattern recognition of the tracking software, are an obvious source of background. Because they do not correspond to actual particles, they are generally missing associated calorimeter energy and hits in the muon chambers. They would also be expected to have missing hits in the inner tracker in a random pattern. Although this contribution to the background should be largely suppressed by our

Table 3.30: Results of lepton background closure test in simulated samples from the 2016 campaign. The numbers of events are normalized to 35.7 fb^{-1} , the luminosity of the 2016 data set.

sample	flavor	N_{est}^l	N_{obs}^l	$ N_{\text{est}}^l - N_{\text{obs}}^l $
Z $\rightarrow$ ll	electron	0.049 ± 0.019	$0_{-0}^{+0.20}$	0.24σ
	muon	0.038 ± 0.015	$0_{-0}^{+0.20}$	0.19σ
	tau	0.111 ± 0.051	$0_{-0}^{+0.20}$	0.53σ
WZ $\rightarrow$ l $\nu\nu\nu$	electron	$(3.6 \pm 1.6) \times 10^{-4}$	$0_{-0}^{+0.032}$	0.011σ
	muon	$(1.64 \pm 0.67) \times 10^{-4}$	0.014 ± 0.014	0.99σ
	tau	$(9._{-9.}^{+11.}) \times 10^{-5}$	$0_{-0}^{+0.032}$	0.0029σ

requirements on the impact parameters of the tracks and that the tracks be missing no inner or middle hits in the inner tracker, we estimate this background to verify that this is the case.

We use the Z $\rightarrow\mu\mu$ control selection defined in Table 3.31 as a representative sample of standard model events.¹⁸ Since we can obtain a very pure sample of Z $\rightarrow\mu\mu$ events with this selection, we can be confident that any additional tracks that satisfy our disappearing track requirements must be fake tracks. In addition, we replace the usual transverse impact requirement with a sideband selection, designed to further enhance the likelihood that the tracks we select are fake, since all of the charged particles in a Z $\rightarrow\mu\mu$ event should be prompt. In particular, we make the following substitution:

$$|d_{xy}| < 0.02 \text{ cm} \quad \longrightarrow \quad 0.02 \text{ cm} < |d_{xy}| < 0.1 \text{ cm}. \quad (3.11)$$

¹⁸In principle, we could use a different control region, e.g., of Z $\rightarrow$ ee events. As we will see below in Section 3.4.2, we do use the basic selection to evaluate the dependence of the fake track background estimate on the choice of control region. However, as we will see in Section 3.6.1, the fake track background estimate is dominated by its systematic uncertainty, so that adding more events to the control region would have little effect on the final results.

Then assuming this sideband is composed entirely of fake tracks¹⁹, the raw fake track event probability is defined as

$$P_{\text{fake}}^{\text{raw}} = \frac{\text{events from denom. with a dis. trk. with } 0.02 \text{ cm} < |d_{xy}| < 0.1 \text{ cm}}{\text{events passing } Z \rightarrow \mu\mu}. \quad (3.12)$$

Table 3.31: The criteria defining the $Z \rightarrow \mu\mu$ *control sample*. The requirements are cumulative, with only the objects passing a given criterion being considered in subsequent criteria.

quantity	object	selection
	event passes SingleMuon triggers	
= 2	muons	$p_{\text{T}} > 25 \text{ GeV}$
= 2	muons	$ \eta < 2.1$
= 2	muons	passes tight muon ID
= 1	muon pairs	$q_{\text{muon}} \cdot q_{\text{muon}} < 0$
= 1	muon pairs	$ M_{\text{muon,muon}} - M_{\text{Z}} < 10 \text{ GeV}$

To this raw probability, we apply a transfer factor from the d_{xy} sideband in which $P_{\text{fake}}^{\text{raw}}$ is measured, to the nominal d_{xy} region of the disappearing track selection. This transfer factor is the ratio of the number of events passing the nominal d_{xy} selection to the number in the sideband²⁰; i.e.,

$$P_{\text{fake}} = \left(\frac{N_{|d_{xy}| < 0.02 \text{ cm}}}{N_{\text{sideband}}} \right)_{n_{\text{hits}}=3} P_{\text{fake}}^{\text{raw}}. \quad (3.13)$$

The transfer factor is measured using events with tracks with exactly three hits to ensure we do not suffer from contamination from real tracks, which would highly bias

¹⁹The validity of this assumption is explored in Section 3.4.2.

²⁰We assume that each event has only one selected track. Only $(0.07 \pm 0.01)\%$ of events with a 3-hit track have two such tracks. When more than 3 hits are required, no events have more than one selected track in the entire 2015 and 2016 data set.

the shape of d_{xy} . This transfer factor, as well as the raw fake track event probabilities, is listed in Table 3.32 for each run period.

Table 3.32: Values of the raw fake track event probability and the sideband transfer factor for each run period.

run period	$P_{\text{fake}}^{\text{raw}}$	sideband transfer factor
2015	$(0_{-0}^{+3.8}) \times 10^{-7}$	0.132 ± 0.022
2016B+C	$(4.4 \pm 2.2) \times 10^{-7}$	0.1474 ± 0.0099
2016D–H	$(2.17 \pm 0.82) \times 10^{-8}$	0.198 ± 0.0054

With this definition of the fake track event probability, our fake track background is then

$$N_{\text{est}}^{\text{fake}} = P_{\text{fake}} N_{\text{ctrl}}^{\text{basic}}, \quad (3.14)$$

where $N_{\text{ctrl}}^{\text{basic}}$ is the number of events in the basic selection. Table 3.33 shows the resulting estimate for the fake track background.

Table 3.33: Summary of estimated background event counts resulting from fake tracks. The uncertainties are statistical only.

run period	P_{fake}	estimate $N_{\text{ctrl}}^{\text{basic}}$	$N_{\text{est}}^{\text{fake}}$
2015	$(0_{-0}^{+5.05}) \times 10^{-8}$	$(1.566 \pm 0.001) \times 10^6$	$0_{-0}^{+0.0791}$
2016B+C	$(6.50 \pm 3.25) \times 10^{-8}$	$(5.890 \pm 0.002) \times 10^6$	0.383 ± 0.193
2016D–H	$(4.30 \pm 1.63) \times 10^{-8}$	$(2.1230 \pm 0.0005) \times 10^7$	0.913 ± 0.346
total			1.30 ± 0.40

Validation of fake track background estimate

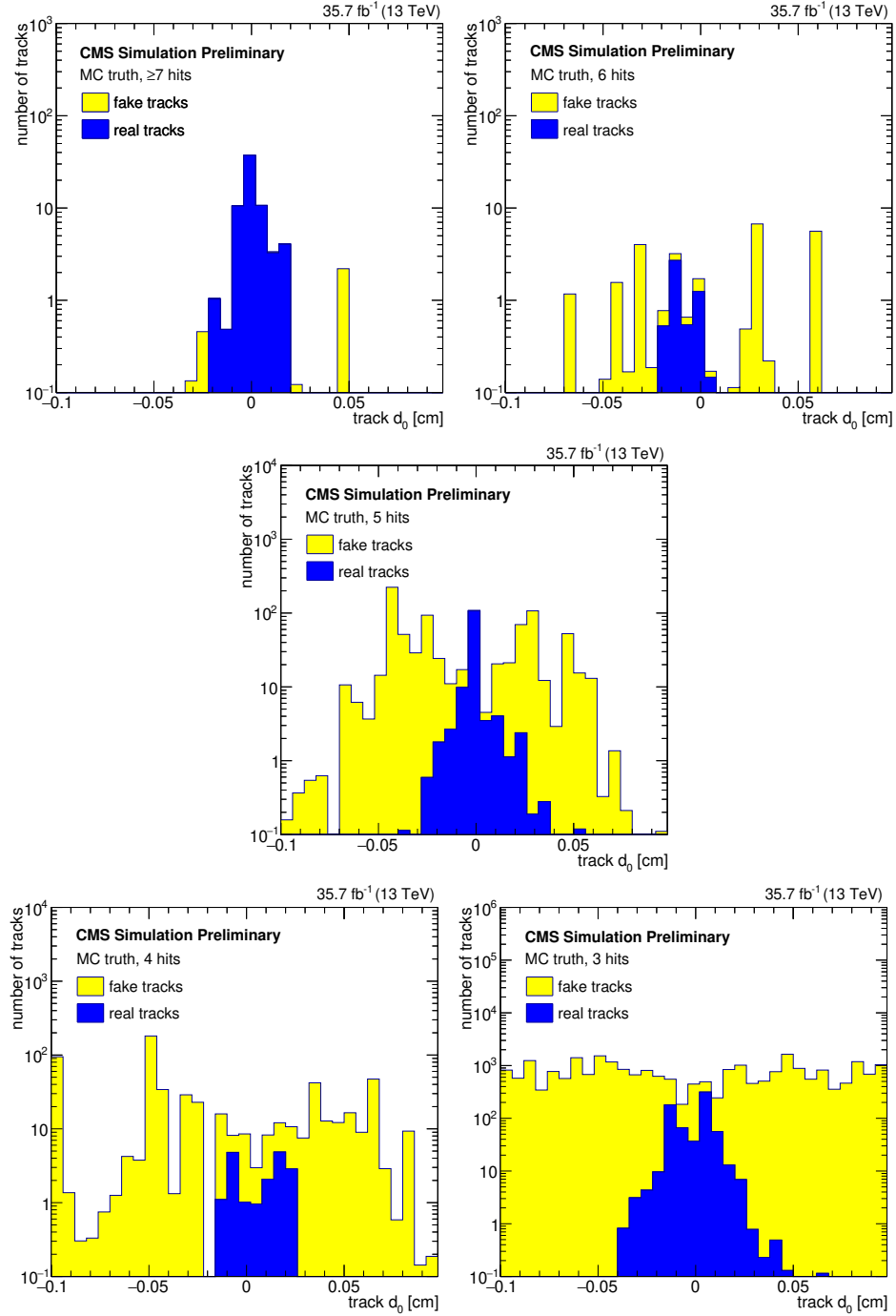
The fake track background estimate rests on several assumptions. One is that the fake track event probability can be taken from the $Z \rightarrow \mu\mu$ control region, or indeed any control region, and applied to get a background estimate for the signal region. This assumption is tested by instead calculating P_{fake} and the fake track background estimate in the basic selection. The results are compared in Table 3.34. Excellent agreement is seen between the two regions, and we have chosen to take the estimate from the region resulting in the smaller statistical uncertainty, which is the $Z \rightarrow \mu\mu$ control region.

Table 3.34: Comparison of the fake track event probabilities, P_{fake} , and fake track background estimates, $N_{\text{est}}^{\text{fake}}$, obtained from the $Z \rightarrow \mu\mu$ control region and basic selection.

run period	$Z \rightarrow \mu\mu$	P_{fake} basic	$Z \rightarrow \mu\mu$	$N_{\text{est}}^{\text{fake}}$ basic
2015	$(0_{-0}^{5.05}) \times 10^{-8}$	$(0_{-0}^{+1.05}) \times 10^{-7}$	$0_{-0}^{+0.0791}$	$0_{-0}^{+0.164}$
2016B+C	$(6.50 \pm 3.25) \times 10^{-8}$	$(6.04 \pm 4.27) \times 10^{-8}$	0.383 ± 0.193	0.356 ± 0.254
2016D-H	$(4.30 \pm 1.63) \times 10^{-8}$	$(3.93 \pm 1.97) \times 10^{-8}$	0.913 ± 0.346	0.835 ± 0.419

A second assumption is that the d_{xy} sideband region is dominated by fake tracks. To verify this, we look at the d_{xy} distributions of tracks in simulated background events with a track that passes the track criteria of our candidate track selection, but with the usual d_{xy} selection removed and with various requirements on the number of hits. Since this is simulation, we also separate real tracks (matched to a generator particle with $\Delta R < 0.1$) and fake tracks ($\Delta R > 0.1$ from any generator particle). Thus, we get the plots in Figure 3.32.

Figure 3.32: Distributions of d_{xy} for tracks from simulated background events passing the track criteria of the candidate track selection, but with the d_{xy} requirement removed. The selected track have various requirements on the number of hits: ≥ 7 (top left), 6 (top right), 5 (center), 4 (bottom left), or 3 (bottom right).



In each plot, we see that the sideband region is dominated by fake tracks. Numerically, the fraction of tracks in the sideband that are identified as fake is shown in Table 3.35. The relatively low fraction for ≥ 7 hits is likely the result of several of the individual simulated samples having zero tracks pass the selections.

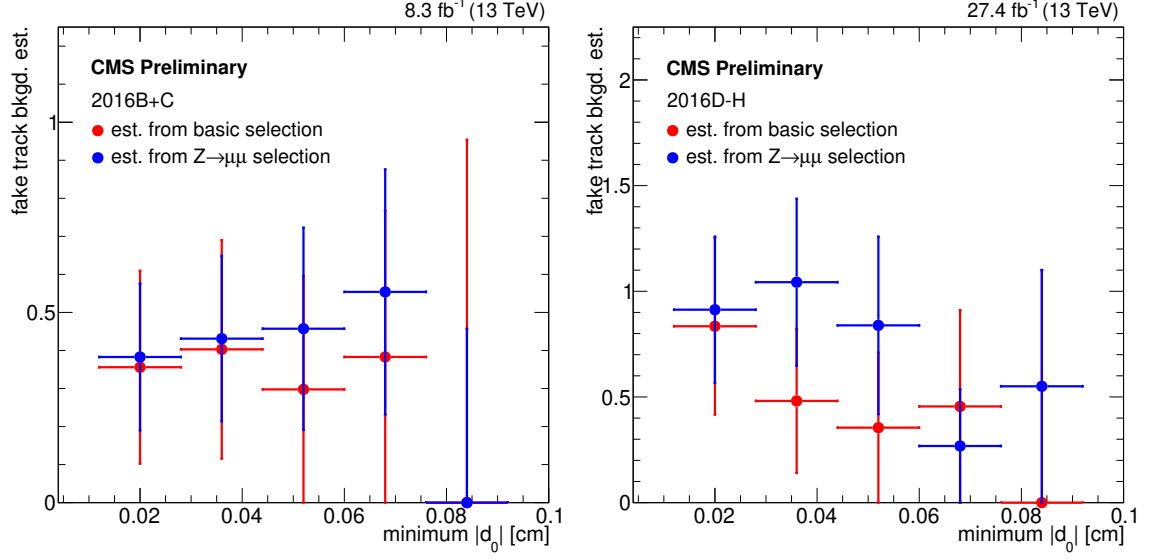
Table 3.35: Fraction of tracks in the d_{xy} sideband that are identified as fake in simulated background events for various numbers of hits.

number of hits	fraction of tracks in sideband that are fake
≥ 7	$(69.9 \pm 18.5)\%$
6	$(97.7 \pm 1.9)\%$
5	$(99.7 \pm 0.2)\%$
4	$(98.8 \pm 0.9)\%$
3	$(99.952 \pm 0.009)\%$

Even if there is some slight contamination from real tracks in the sideband region for ≥ 7 hits, it is clear from the above distributions that this contamination would disappear by increasing the lower bound on the sideband. However, we see in Figure 3.33 that the fake track background estimate is quite insensitive to the choice of this lower bound.

Finally, a third assumption made in the estimation of the fake track background is that it is valid to evaluate the sideband transfer factor using tracks with 3 hits. From the d_{xy} distributions in Figure 3.32, it is clear that when we require 3 hits, we select mostly fake tracks. Then, in Table 3.36 we see that the transfer factor calculated using only fake tracks from the simulated background samples does not change significantly going from 3 hits to ≥ 7 hits. Therefore, by evaluating the transfer factor using tracks

Figure 3.33: Fake track background estimate as a function of the choice of lower bound on the d_{xy} sideband region for the 2016B+C (left) and 2016D–H (right) run periods.



with 3 hits, we indeed are sampling the d_{xy} distribution of predominantly fake tracks, and this distribution does not change significantly going from 3 hits to ≥ 7 hits.

Table 3.36: Sideband transfer factor calculated using only fake tracks from the simulated background samples as a function of the number of hits on the track. Both the transfer factor and the difference from the transfer factor for ≥ 7 hits is shown in the center and far-right columns, respectively.

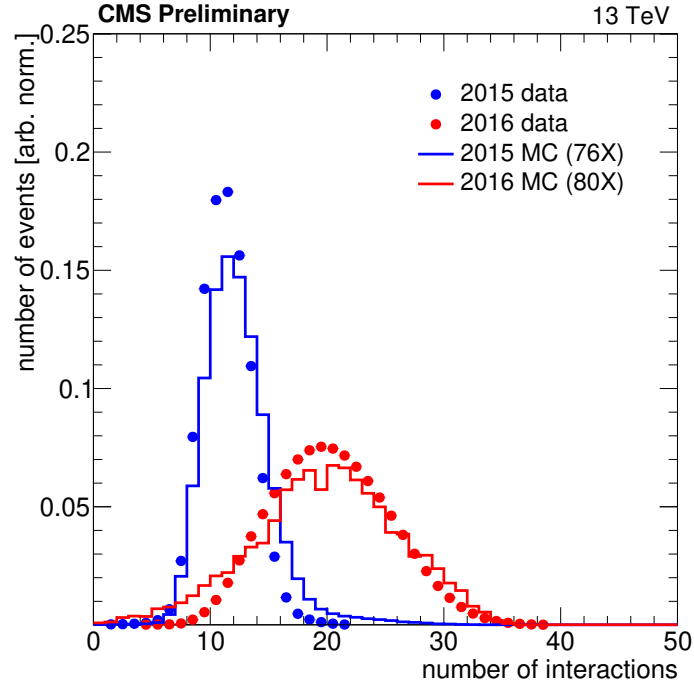
num. of hits	trans. fact. using fake trks.	diff. from trans. fact. with ≥ 7 hits
≥ 7	0.15 ± 0.12	0
6	0.056 ± 0.032	0.77σ
5	0.054 ± 0.022	0.80σ
4	0.068 ± 0.029	0.67σ
3	0.049 ± 0.012	0.85σ

3.5 Corrections to the simulated signal samples

3.5.1 Pileup scale factors

Pileup scale factors are applied to simulated signal events to correct for differences in the number of pileup interactions between the simulated and experimental data. These scale factors are calculated by dividing the PDF for the actual number of pileup interactions by that used during the production of the simulated events. These PDFs are shown in Figure 3.34 for the 2015 and 2016 experimental data and the corresponding simulated data.

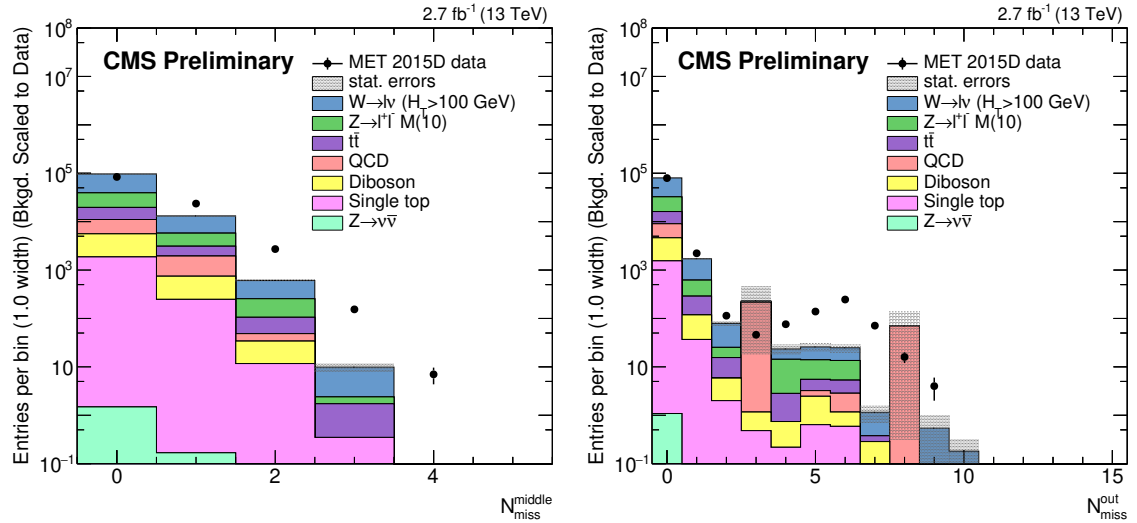
Figure 3.34: Distributions of the numbers of interactions for the 2015 (blue) and 2016 (red) data, both experimental (points) and simulated (lines).



3.5.2 Missing hits corrections

As was discussed in Section 3.3, the selections used in the search utilize the number of missing middle and outer hits on candidate tracks to discriminate against tracks from background sources. However, as can be seen in Figure 3.35, taken from the *muon control region* of the 2015 data, defined as the candidate track selection without the muon veto, these variables are not well-modeled in the simulation. The most obvious feature that is not modeled is a large peak near 6 missing outer hits, which is caused by a mismodeling of the extrapolation of tracks from the TIB to the TOB, where tracks in the experimental data are more likely to be missing all of their TOB hits (the TOB has 6 layers). Additional random missing middle and outer hits are also more likely in the experimental data, which is related to the HIP effect.

Figure 3.35: Uncorrected distributions of missing middle (left) and outer (right) hits for tracks selected in the muon control region from both the 2015 experimental data and the simulation. In the case of the missing middle hits distribution, the usual criterion of zero missing middle hits in the muon control region is not applied.



This mismodeling does not affect the background estimates since they are taken exclusively from experimental data, but it does affect the estimated signal selection efficiencies, which are taken directly from simulation. Thus, we attempt to correct the simulation in order to get more realistic estimates of the signal efficiencies. This is done by randomly removing hits from the nominal hit pattern at a rate that is determined by fitting the resulting missing middle and outer hits distributions to those from experimental data.

Because nothing as sophisticated as refitting tracks is done, there are four hit removal probabilities that must be determined:

- $P_0 \equiv P(\text{missing extra middle hit})$
- $P_{\text{pre-TOB}} \equiv P(\text{missing extra outer hits})$
- $P_{\text{TOB}} \equiv P(\text{missing all TOB hits})$
- $P_{\text{post-TOB}} \equiv P(\text{missing extra outer hits} | \text{missing all TOB hits})$

The first is determined by fitting the missing middle hits distribution obtained from the samples of simulated background events to the distribution from experimental data in the muon control region where the criterion on missing middle hits has been omitted. This fit is done by correcting the missing middle hits distribution in simulated events for each point in a grid of values for P_0 . At each point, the χ^2 difference between the corrected distribution and the distribution in experimental data is calculated, and the value of P_0 that minimizes the χ^2 test statistic is chosen.²¹

The other three parameters listed above are determined simultaneously by fitting the missing outer hits distribution in the muon control region where the criterion on

²¹See Appendix G.1 for details on how the corrected distribution is calculated.

missing middle hits has been applied. Similar to the procedure used to determine P_0 , the fit is performed by correcting the missing outer hits distribution in simulated events for each point in a grid of values for $(P_{\text{pre-TOB}}, P_{\text{TOB}}, P_{\text{post-TOB}})$ and determining the values that minimize the χ^2 difference with the distribution in experimental data.²² The values for these four probabilities are listed in Table 3.37 for the run periods considered in the search.

Table 3.37: Values for the hit removal probabilities obtained by fitting the missing middle and outer hit distributions from simulated background events to those distributions from experimental data. These values are used to randomly remove hits from the nominal hit patterns of tracks in simulated signal events.

run period	P_0	P_{TOB}	$P_{\text{pre-TOB}}$	$P_{\text{post-TOB}}$
2015	0.018	0.0083	0.0052	0.27
2016B+C	0.039	0.039	0.0066	0.25
2016D–H	0.025	0.030	0.0046	0.28

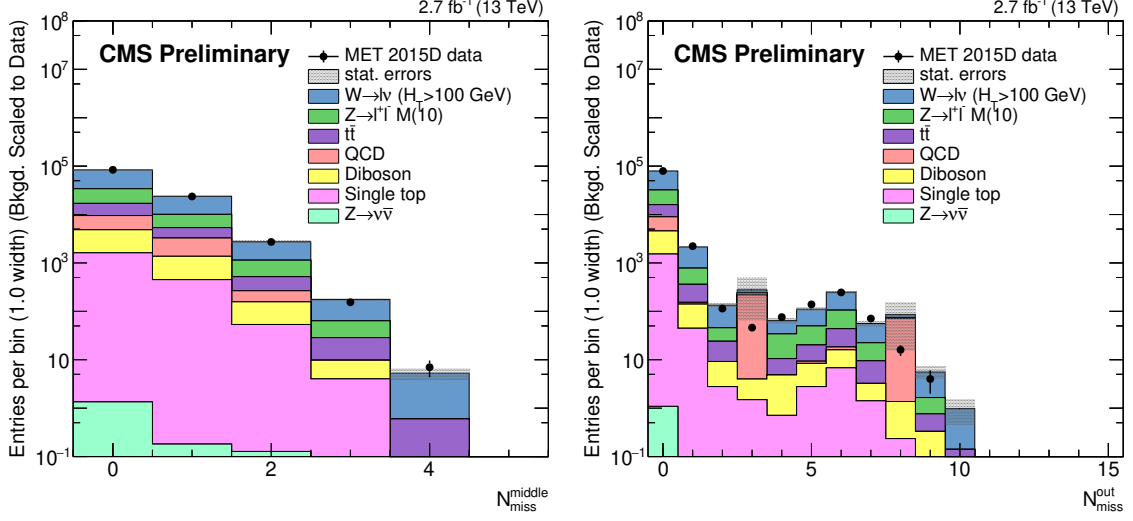
After correcting the missing middle and outer hits distributions, excellent agreement between the simulated and experimental data is achieved, as can be seen in Figure 3.36. A systematic uncertainty on the signal selection efficiencies is calculated to account for any residual disagreement, as discussed in Section 3.6.2.

3.5.3 Trigger efficiency scale factors

Trigger efficiency scale factors are applied to simulated signal events to correct for differences in the trigger efficiency between simulated and experimental data. One of the primary sources of difference is the increasing $p_{\text{T}}^{\text{miss}}$ threshold in the L1 trigger

²²See Appendix G.2 for details on how the corrected missing outer hits distribution is calculated.

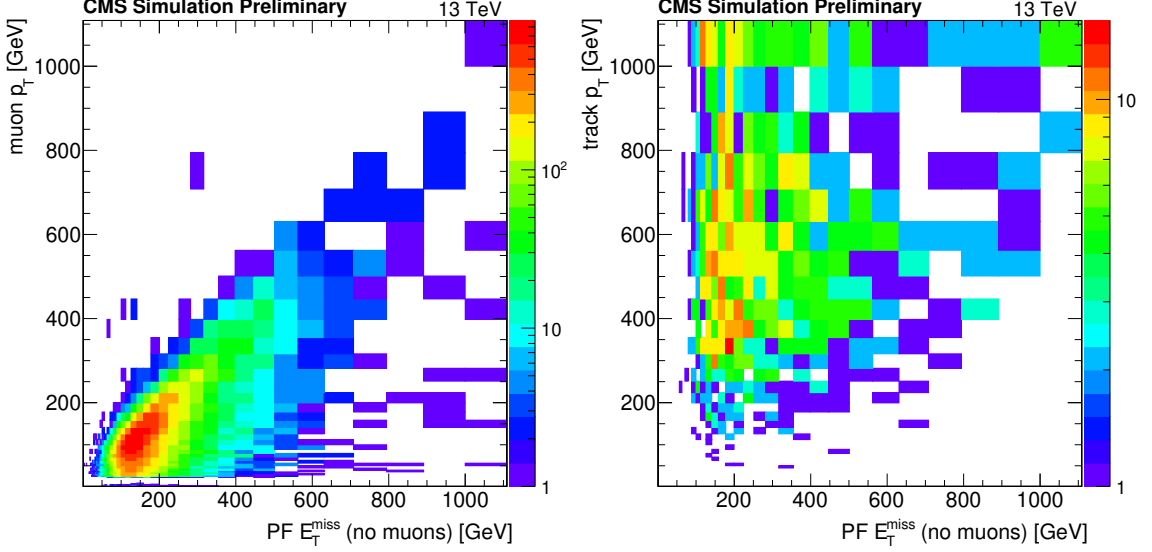
Figure 3.36: Corrected distributions of missing middle (left) and outer (right) hits for tracks selected in the muon control region from both the 2015 experimental data and the simulation. In the case of the missing middle hits distribution, the usual criterion of zero missing middle hits in the muon control region is not applied.



throughout 2015 and 2016. The lower-threshold L1 p_T^{miss} seeds were dynamically prescaled during each run as the luminosity changed, and this prescaling became more aggressive over time as the luminosity increased. This results in a rather large discrepancy in the trigger efficiency between the experimental and simulated data for the latter part of the 2016 run, since of course, the L1 menu in the simulated samples did not change.

In principle, since the triggers used in the search select events based on p_T^{miss} and isolated track p_T , it would be logical to bin the trigger efficiencies in p_T^{miss} and track p_T . But, as can be seen in Figure 3.37, signal and standard model events populate very different regions of this plane, and it is not possible to get trigger efficiencies in the region relevant to the signal.

Figure 3.37: Distribution of events in the plane of muon (left) or track (right) p_T vs. $p_T^{\text{miss, no } \mu}$ for simulated $W \rightarrow l\nu$ (left) or simulated signal (right) events. For the signal events, the chargino has a mass of 700 GeV and a lifetime of 1000 cm.



However, we are really only interested in the trigger efficiency on the plateau of the track leg of `HLT MET75_IsoTrk50_v*` since in the search region, we require track $p_T > 55$ GeV, which is just on the plateau (see the plots on the right of Figure F.1 in Appendix F). And because we see that the difference between experimental and simulated data does not change dramatically as a function of track p_T on this plateau, we can marginalize out the track p_T from the trigger efficiency:

$$\varepsilon(p_T^{\text{miss, no } \mu}) = \int_{55 \text{ GeV}}^{\infty} \varepsilon(p_T^{\text{miss, no } \mu}, p_T) dp_T. \quad (3.15)$$

Now, the largest source of events from standard model processes with significant p_T^{miss} and a high- p_T , isolated track is $W \rightarrow l\nu$. For this reason, when evaluating the trigger efficiency, we target $W \rightarrow \mu\nu$ and use events collected with the `SingleMuon` triggers listed in Tables 3.10 and 3.11. Offline, we require the events to have a

well-reconstructed, isolated muon with no missing inner or middle hits in the silicon tracker. The marginalization of the track p_T discussed above is achieved by requiring this muon to have $p_T > 55$ GeV. This *base trigger selection* is detailed in Table 3.38.

Table 3.38: *Base trigger selection* used to select events used to measure the efficiency of the `HLT_MET75_IsoTrk50_v*` trigger.

quantity	object	selection
event passes SingleMuon triggers		
≥ 1	muons	$p_T > 55$ GeV
≥ 1	muons	$ \eta < 2.1$
≥ 1	muons	passing tight muon ID (see Table A.9 below)
≥ 1	muons	missing inner hits = 0
≥ 1	muons	missing middle hits = 0

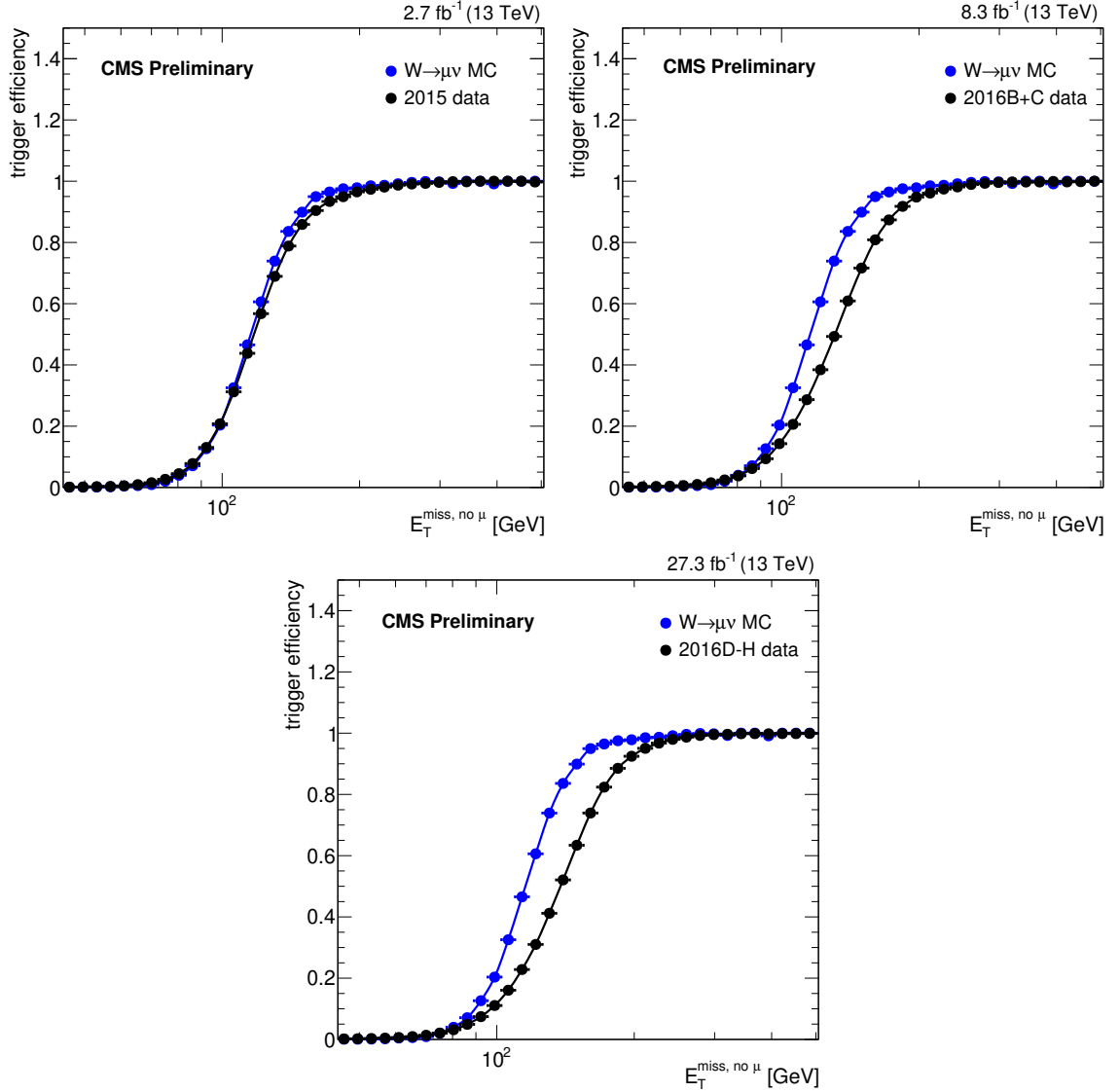
The trigger efficiency is then defined as

$$\varepsilon(p_T^{\text{miss, no } \mu}) = \frac{\text{events from denom. passing combination of } p_T^{\text{miss}} \text{ triggers}}{\text{events passing base trigger selection}}, \quad (3.16)$$

where the combination of p_T^{miss} triggers is that listed in Tables 3.10 or 3.11. The resulting efficiencies for experimental and simulated data are shown in Figure 3.38. Finally, the ratio of the trigger efficiencies for experimental and simulated data define the trigger efficiency scale factors that are used to correct the simulated signal events. As mentioned above, the p_T^{miss} threshold in the L1 trigger increased especially in the latter part of 2016, which can be clearly seen in Figure 3.38.

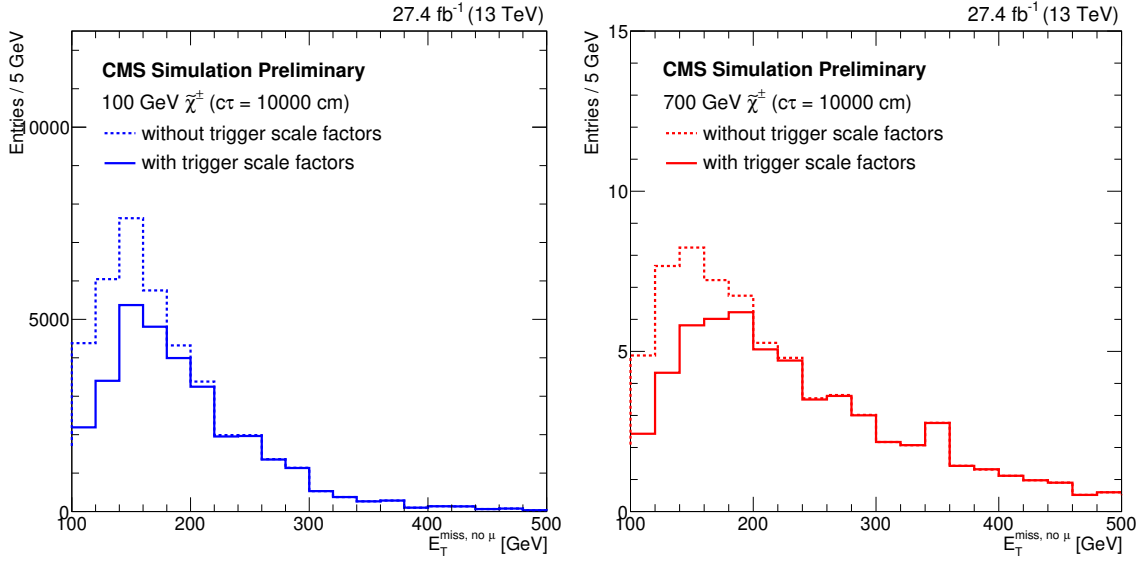
The effect of the trigger efficiency scale factors for the 2016D–H period on the simulated signal is shown in Figure 3.39. Only the trigger decision is applied to the

Figure 3.38: Efficiency of the combination of p_T^{miss} triggers used in the search for simulated $W \rightarrow l\nu$ and experimental data from 2015 (top left), 2016B+C (top right), and 2016D–H (bottom). The efficiency is plotted only with respect to $p_T^{\text{miss, no } \mu}$, with the dependence on the track p_T marginalized out, as described in the text.



data in the plots, and the $p_T^{\text{miss, no } \mu}$ distributions are compared with and without the scale factors applied. The signal yield passing the triggers is reduced by $\sim 21\%$ in the case of the 100 GeV chargino and by $\sim 14\%$ for the 700 GeV chargino.

Figure 3.39: Distributions of $p_T^{\text{miss, no } \mu}$ with and without the trigger efficiency scale factors for the 2016D–H period applied. Simulated signal events passing the triggers are plotted, with a 100 GeV chargino in the left plot and a 700 GeV chargino in the right plot.

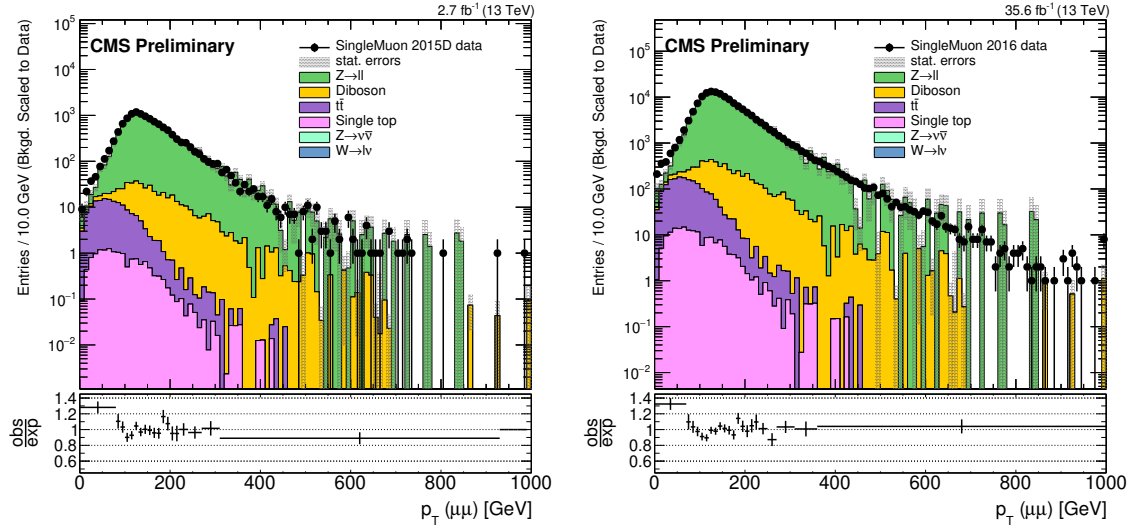


3.5.4 ISR scale factors

Because the search depends on jets from ISR for triggering and the initial basic selection, we correct for any mismodeling of this feature in the simulation. This is done by comparing the p_T distribution of $Z \rightarrow \mu\mu$ candidates in the $Z \rightarrow \mu\mu$ control region in simulated data to those in experimental data. The ratio of these distributions provides scale factors that are used to correct the simulated signal events. Since the

p_T of $Z \rightarrow \mu\mu$ candidates is usually generated by the recoil of the Z off an ISR jet, this is a way of correcting the modeling of ISR jets that is independent of the uncertainties on jet energy scale and resolution. The p_T distribution of $Z \rightarrow \mu\mu$ candidates is shown in Figure 3.40 along with the resulting ISR scale factors.

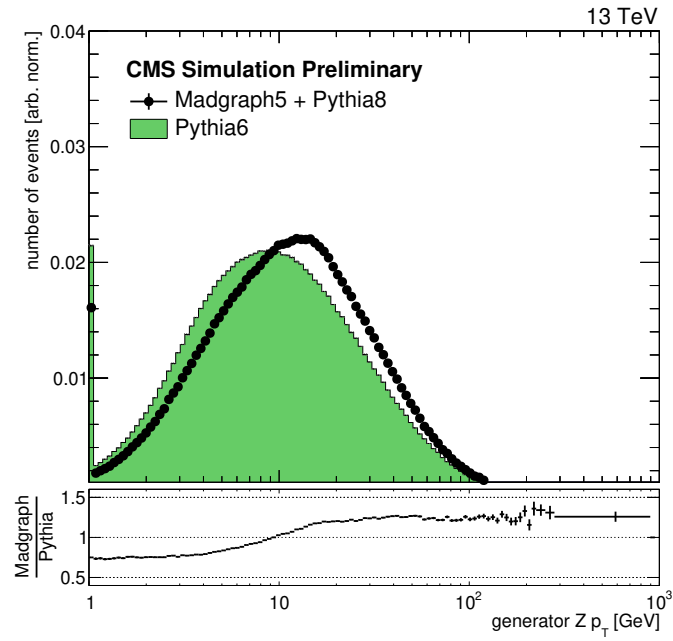
Figure 3.40: Distributions of the p_T of $Z \rightarrow \mu\mu$ candidates in the $Z \rightarrow \mu\mu$ control region for simulated and experimental data from 2015 (left) and 2016 (right). The ratio plots shown below are the ISR scale factors applied to simulated signal events.



Now, the sample of simulated $Z \rightarrow ll$ events that we use was generated in MADGRAPH5 with hadronization performed in PYTHIA8 with the MLM jet-parton matching scheme. However, we wish to apply the above scale factors to our samples of simulated signal events, which were generated in PYTHIA6. Thus, we generate a large sample of $Z \rightarrow ll$ events in PYTHIA6 and compare the generator-level distribution of Z boson p_T between this sample and the nominal $Z \rightarrow ll$ sample generated in MADGRAPH5. These

distributions and the ratio of the MADGRAPH5 distribution to the PYTHIA6 distribution, which defines the scale factors, are shown in Figure 3.41. The product of these scale factors and the scale factors derived above using experimental data is applied to the simulated signal samples.

Figure 3.41: Generator-level distributions of Z boson p_T for $Z \rightarrow ll$ events generated in MADGRAPH5 (circles) and PYTHIA6 (filled histogram). The ratio plot below are the scale factors applied to simulated signal events.



3.6 Systematic uncertainties

The results of this analysis are subject to systematic uncertainties in the integrated luminosity, the estimated background contributions, and in the efficiency of the signal. The uncertainty on the integrated luminosity of the 2015 data is 2.3% [24]. The uncertainty on the integrated luminosity of the 2016 data is estimated to be 2.5%. The uncertainties in the background estimates and in the signal selection efficiency are described in the sections below.

3.6.1 Uncertainties in background estimates

In the following sections, we detail the systematic uncertainties in the fake track and charged lepton background estimates. Since the background estimates are fully data-driven, these uncertainties result only from testing the assumptions on which each background estimation method relies. The assumptions made to estimate the fake track background were already discussed in detail in Section 3.4.2, in relation to validating that method, and will be translated into uncertainties on the estimates below. The assumption that an unreconstructed lepton deposits exactly zero energy in the calorimeters, used to calculate P_{offline} and P_{trigger} in the charged lepton background estimation method, will be discussed and quantified as uncertainties on the estimates below in Section 3.6.1.

Systematic uncertainty in fake track background estimate

We assign a systematic uncertainty corresponding to each of the three assumptions of the fake track background estimation method discussed in Section 3.4.2. First, we assign the difference between the estimates obtained from the $Z \rightarrow \mu\mu$ control region

and basic selection (see Table 3.34), relative to the nominal estimate from the $Z \rightarrow \mu\mu$ control region, as an uncertainty resulting from potential dependence of P_{fake} on the control region in which it is calculated. This yields a 7.01% (8.58%) uncertainty for 2016B+C (2016D–H). In the case of the 2015 data, where both estimates are zero, we assign a very conservative 20% uncertainty.

For the potential dependence on the choice of range for our d_{xy} sideband region, we assign the maximum up and down variations, relative to the central value of the nominal fake track background estimate, from the plots of the estimate versus minimum d_{xy} in Figure 3.35 as systematic uncertainties. This gives us uncertainties of $\left(\begin{smallmatrix} +44.7 \\ -100 \end{smallmatrix}\right)\%$ for 2016B+C and $\left(\begin{smallmatrix} +14.2 \\ -100 \end{smallmatrix}\right)\%$ for 2016D–H. Again, since the estimate for the 2015 data is zero, we assign a conservative uncertainty of 50%.

Finally, for the potential variation in the transfer factor going from 3 to ≥ 7 hits, we use the maximum up and down one-sigma variations of the transfer factor, relative to the central value of the transfer factor for 3 hits, using MC truth fake tracks, as presented in Table 3.36. This yields an uncertainty of $\left(\begin{smallmatrix} +97.9 \\ -51.4 \end{smallmatrix}\right)\%$, which we apply to the estimate for each run period we consider.

The systematic uncertainties on the fake track background estimate are summarized in Table 3.39.

Systematic uncertainty in lepton background estimates

The lepton background estimates rely on the assumption that when a lepton is not reconstructed as such that it contributes exactly zero visible momentum to the event. We test the impact of this assumption by replacing the nominal $|\vec{p}_{\text{T}}^{\text{miss, no } \mu} + \vec{p}_{\text{T}}^{\text{lepton}}|$

Table 3.39: Summary of systematic uncertainties on the fake track background estimate.

run period	uncertainty source			total
	control region	sideband region	transfer factor	
2015	20%	50%	$\begin{pmatrix} +97.9 \\ -51.4 \end{pmatrix} \%$	$\begin{pmatrix} +112 \\ -0 \end{pmatrix} \%$
2016B+C	7.01%	$\begin{pmatrix} +44.7 \\ -100 \end{pmatrix} \%$	$\begin{pmatrix} +97.9 \\ -51.4 \end{pmatrix} \%$	$\begin{pmatrix} +108 \\ -100 \end{pmatrix} \%$
2016D–H	8.58%	$\begin{pmatrix} +14.2 \\ -100 \end{pmatrix} \%$	$\begin{pmatrix} +97.9 \\ -51.4 \end{pmatrix} \%$	$\begin{pmatrix} +99.3 \\ -100 \end{pmatrix} \%$

distribution used to calculate P_{offline} and P_{trigger} with a “scaled down” version,

$$\left| \vec{p}_{\text{T}}^{\text{miss, no } \mu} + \frac{p_{\text{T}}^{\text{lepton}} - 10 \text{ GeV}}{p_{\text{T}}^{\text{lepton}}} \vec{p}_{\text{T}}^{\text{lepton}} \right|, \quad (3.17)$$

and recalculating P_{offline} and P_{trigger} . In other words, we assume that unreconstructed leptons contribute 10 GeV of visible momentum to the event. The value of 10 GeV is chosen because candidate tracks are required to have $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$ in the disappearing tracks search region. A comparison of the nominal and scaled down distributions is shown in Figure 3.42.²³

Finally, the difference from unity of the ratio

$$\frac{(P_{\text{offline}} P_{\text{trigger}})_{\text{scaled down}}}{(P_{\text{offline}} P_{\text{trigger}})_{\text{nominal}}} \quad (3.18)$$

is taken as the systematic uncertainty. The nominal and scaled down values of the constituent probabilities, as well as the resulting systematic uncertainties, are listed in Table 3.40 for electrons and in Table 3.41 for taus.

This uncertainty is not evaluated for muons, since even successfully reconstructed muons are not expected to contribute substantial visible calorimeter energy to an

²³The data in the single-tau control sample were collected with a prescaled trigger as mentioned in Section 3.1.1, and the effective integrated luminosities reported on the plots include this prescale.

Figure 3.42: Comparison of the nominal and scaled down versions of the $|\vec{p}_T^{\text{miss, no } \mu} + \vec{p}_T^{\text{lepton}}|$ distribution described in the text for events in the single electron control sample (left) and the single tau control sample (right) from 2015 (top), 2016B+C (middle), and 2016D–H (bottom). The mean, μ of each distribution is listed in the legends.

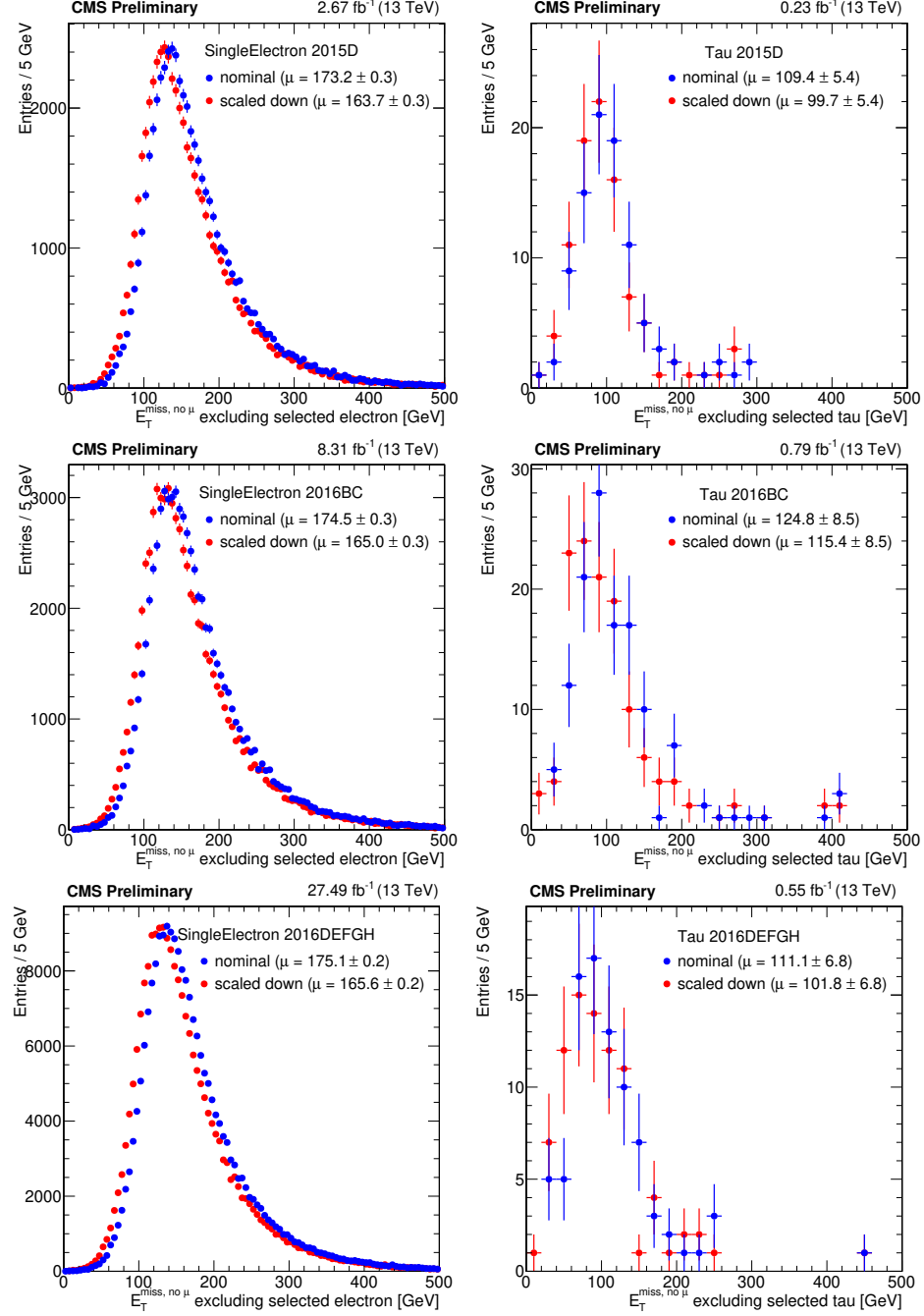


Table 3.40: P_{offline} and P_{trigger} calculated with the nominal and scaled down versions of the $|\vec{p}_T^{\text{miss, no } \mu} + \vec{p}_T^{\text{lepton}}|$ distribution described in the text for events in the single electron control sample, as well as the resulting systematic uncertainty.

run period	nominal		scaled down		sys. unc.
	P_{offline}	P_{trigger}	P_{offline}	P_{trigger}	
2015	0.904 ± 0.005	0.655 ± 0.013	0.851 ± 0.005	0.622 ± 0.013	10.6%
2016B+C	0.916 ± 0.005	0.479 ± 0.011	0.869 ± 0.005	0.446 ± 0.010	11.7%
2016D-H	0.917 ± 0.003	0.461 ± 0.006	0.870 ± 0.003	0.429 ± 0.006	11.7%

Table 3.41: P_{offline} and P_{trigger} calculated with the nominal and scaled down versions of the $|\vec{p}_T^{\text{miss, no } \mu} + \vec{p}_T^{\text{lepton}}|$ distribution described in the text for events in the single tau control sample, as well as the resulting systematic uncertainty.

run period	nominal		scaled down		sys. unc.
	P_{offline}	P_{trigger}	P_{offline}	P_{trigger}	
2015	0.508 ± 0.017	0.476 ± 0.022	0.420 ± 0.015	0.467 ± 0.024	18.7%
2016B+C	0.492 ± 0.075	0.347 ± 0.079	0.423 ± 0.068	0.331 ± 0.081	18.0%
2016D-H	0.488 ± 0.093	0.295 ± 0.081	0.417 ± 0.084	0.287 ± 0.088	16.9%

event. Furthermore, being the lepton background with the smallest expected contribution to the search region, and with fairly large statistical uncertainties, we do not assign a systematic uncertainty to the muon background estimate.

3.6.2 Uncertainties in signal selection efficiencies

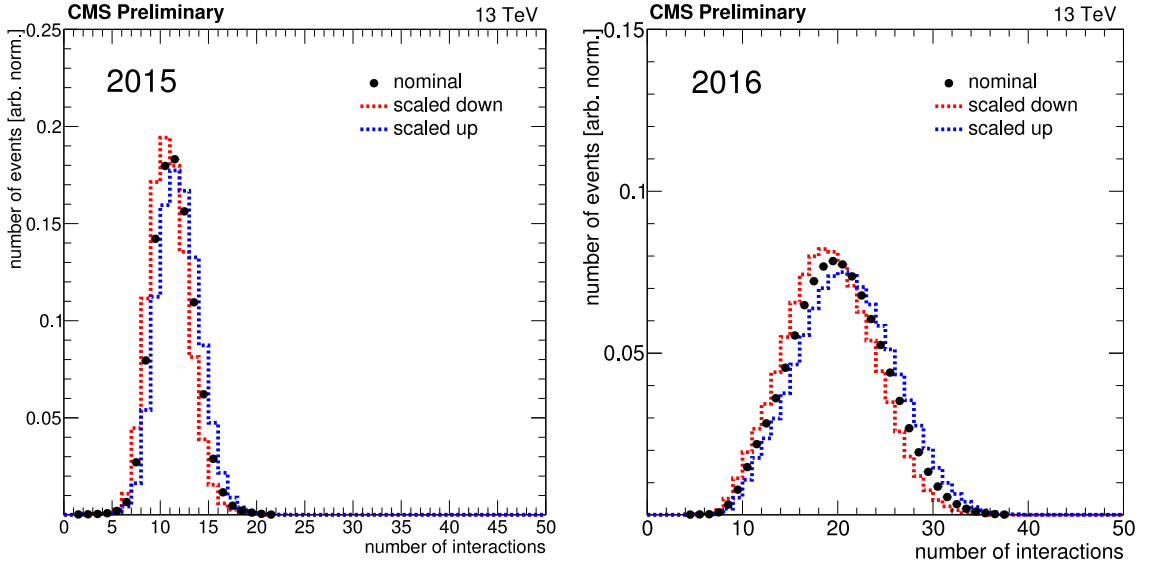
In the following sections, we detail the systematic uncertainties in the expected signal yields, which are derived from simulation. The uncertainties related to the modeling of pileup, ISR, jet energy, and trigger efficiency are derived by varying the relevant simulated quantities, or scale factors applied to the simulation, within the appropriate uncertainties or resolutions. These systematic uncertainties have values that depend on the specific chargino mass and lifetime hypothesis. On the other hand, the uncertainties related to the modeling of missing inner, middle, and outer hits, and track reconstruction efficiency are derived by comparing simulated and experimental data in appropriate control regions. These systematic uncertainties have values that depend on the run period in question.

Pileup

There is an uncertainty associated with the modeling of pileup interactions in the samples of simulated signal events, the distribution of which may differ from that present in the experimental data. We evaluate this uncertainty by using different target distributions for pileup reweighting, produced using different assumptions for the minimum bias cross section. The best-fit value for this cross section was determined to be 69 mb (69.2 mb) with an uncertainty of 4.6% in 2015 (2016). The difference in signal efficiency when using the distributions produced with the best-fit value plus or minus its uncertainty is taken as the systematic uncertainty from the modeling

of pileup. These distributions are compared to the nominal target distributions in Figure 3.43 for the 2015 and 2016 data, and the resulting uncertainty is 2–3% on average.

Figure 3.43: Target pileup distributions used for evaluating the systematic uncertainty from the modeling of pileup in the simulated signal samples compared to the nominal distributions for the 2015 (left) and 2016 (right) data.



Missing inner and middle hits

The uncertainty associated with the modeling of missing inner and middle hits in simulation is evaluated using the muon control region.²⁴ This selection is run on samples of experimental and simulated standard model processes without including the track criteria requiring zero missing inner and middle hits. The distributions of the number of missing inner hits and number of missing middle hits in this selection

²⁴The muon control region is defined in Section 3.5.2 as the candidate track selection with the muon veto removed.

are shown in Figure 3.44. Then the efficiencies for these criteria are evaluated, and the systematic uncertainty is assigned as the relative difference between the efficiency in experimental data and the efficiency in simulated data. These efficiencies and the resulting systematic uncertainties are shown in Tables 3.42 and 3.43.

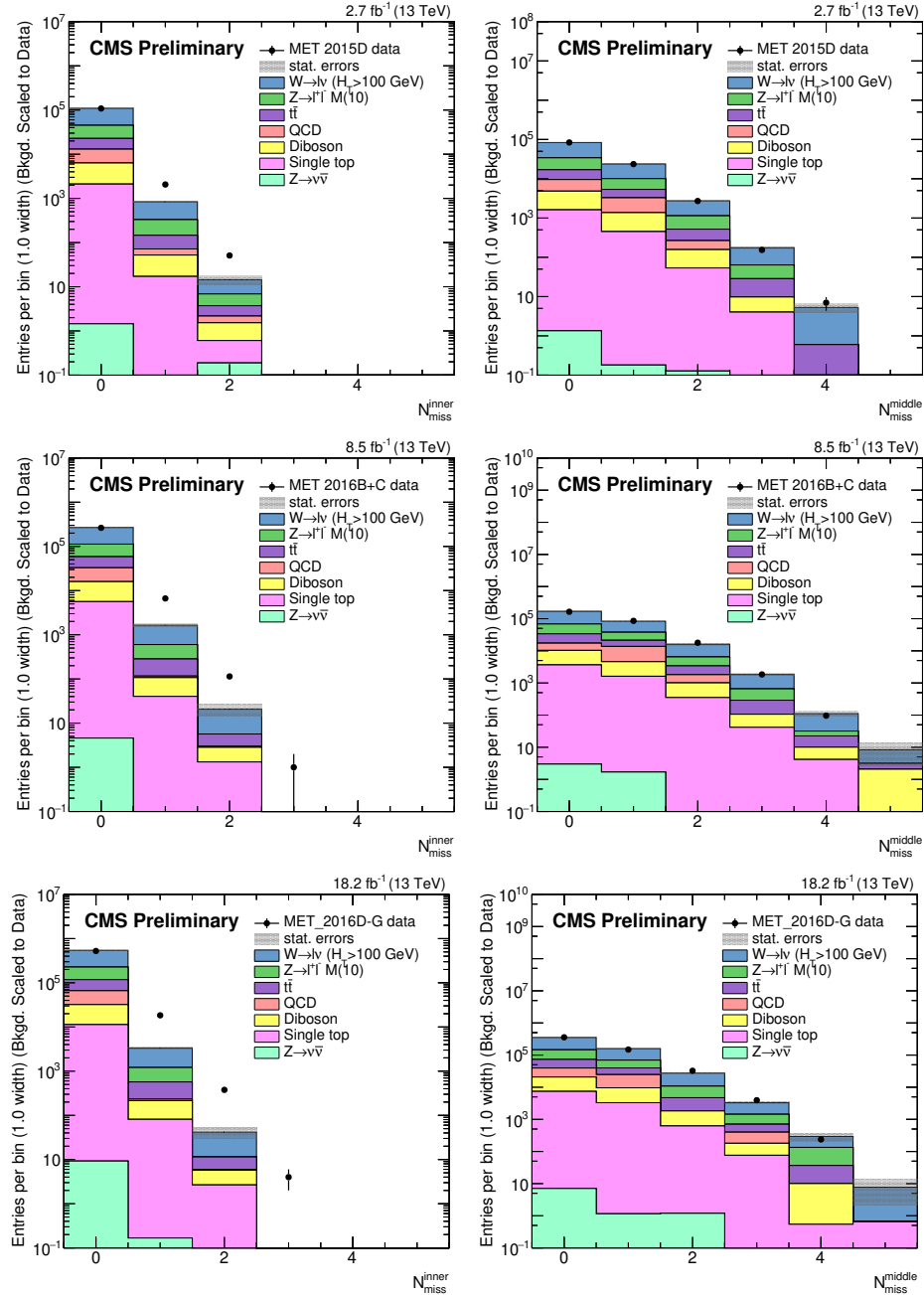
Table 3.42: Efficiency of the zero missing inner hits criterion for tracks in the muon control region in experimental data and simulation, as well as the resulting systematic uncertainty.

run period	eff. of missing inner hits = 0		
	exp. data	simulation	sys. unc.
2015	0.9809 ± 0.0004	0.9923 ± 0.0003	1.16%
2016B+C	0.9750 ± 0.0003	0.9938 ± 0.0004	1.93%
2016D-H	0.9655 ± 0.0002	0.9938 ± 0.0004	2.93%

Table 3.43: Efficiency of the zero missing middle hits criterion for tracks in the muon control region in experimental data and simulation, as well as the resulting systematic uncertainty.

run period	eff. of missing middle hits = 0		
	exp. data	simulation	sys. unc.
2015	0.760 ± 0.001	0.758 ± 0.005	0.269%
2016B+C	0.6089 ± 0.0009	0.627 ± 0.012	2.95%
2016D-H	0.6587 ± 0.0006	0.651 ± 0.011	1.23%

Figure 3.44: Number of missing inner (left) and middle (right) hits for tracks selected in the muon control region, but without the usual criteria requiring zero missing inner and middle hits.



Missing outer hits

The uncertainty associated with the modeling of missing outer hits in simulation is also evaluated using the muon control region.²⁵ First, we must distinguish between *true* and *accidental* missing outer hits:

- *True* missing outer hits result from a charged particle not traversing the outermost tracker layers. This is the type of missing outer hit expected to be present on tracks in signal events.
- *Accidental* missing outer hits result from detector inefficiencies or mistakes of the tracking software. For muons especially, this type is expected to account for most missing outer hits.

We assign no systematic uncertainty on the modeling of true missing outer hits. This is because we trust that GEANT4 knows where to decay the charginos in simulated signal events, and because the uncertainties in the positions of the tracker layers in the GEANT4 model of CMS should have a negligible effect on the number of true missing outer hits. More pragmatically, there is no reliable control region of disappearing tracks in the experimental data to which we could compare. We do, however, assign a systematic on the modeling of accidental missing outer hits, as described below.

Since the vast majority of the tracks in the muon control region come from muons, we assume none of these tracks have any true missing outer hits in the inner tracker, and indeed this is true for over 96% of these tracks, as can be seen in Figure 3.45.

²⁵The muon control region is defined in Section 3.5.2 as the candidate track selection with the muon veto removed.

Thus, these distributions represent the number of accidental missing outer hits we can expect for tracks in experimental and simulated data.

Now, the signal yield is proportional to the efficiency for a track to have at least three missing outer hits, which can be written as

$$\varepsilon^{\geq 3} = \varepsilon_{\text{true}}^{\geq 3} + \varepsilon_{\text{true}}^{\geq 2} \cdot \varepsilon_{\text{acc.}}^{\geq 1} + \varepsilon_{\text{true}}^{\geq 1} \cdot \varepsilon_{\text{acc.}}^{\geq 2} + \varepsilon_{\text{true}}^{\geq 0} \cdot \varepsilon_{\text{acc.}}^{\geq 3}, \quad (3.19)$$

where $\varepsilon_{\text{true}}^p$ ($\varepsilon_{\text{acc.}}^p$) are the efficiencies for selected tracks to have p true (accidental) missing outer hits. The efficiencies $\varepsilon_{\text{true}}^p$ depend on the signal point in question and can be estimated directly from the missing outer hits distribution for selected tracks in simulated signal events passing the disappearing track selection except the criterion on number of missing outer hits.²⁶ Per the discussion above, the efficiencies $\varepsilon_{\text{acc.}}^p$ can be estimated from the missing outer hits distributions from the muon control region, and can apply either to the simulation or to the experimental data, depending on the source of the distribution.

Thus, we assign the relative difference between $\varepsilon^{\geq 3}$ for experimental and simulated data as a systematic on the signal acceptance. The values of the uncertainties are shown in Figure 3.46.

Trigger efficiency

The uncertainty associated with the modeling of the trigger efficiency is assessed by shifting the trigger efficiencies used to generate the trigger efficiency scale factors discussed in Section 3.5.3 up and down by 1σ . This is done independently for the $p_{\text{T}}^{\text{miss}}$ and track legs and for experimental and simulated data, resulting in four variations

²⁶This distribution includes accidental missing outer hits, but should be dominated by true missing outer hits since the former only occur at a rate of $\sim 3\%$. Thus, this distribution is a good approximation of the distribution of true missing outer hits.

Figure 3.45: Number of missing outer hits for tracks selected in the muon control region.

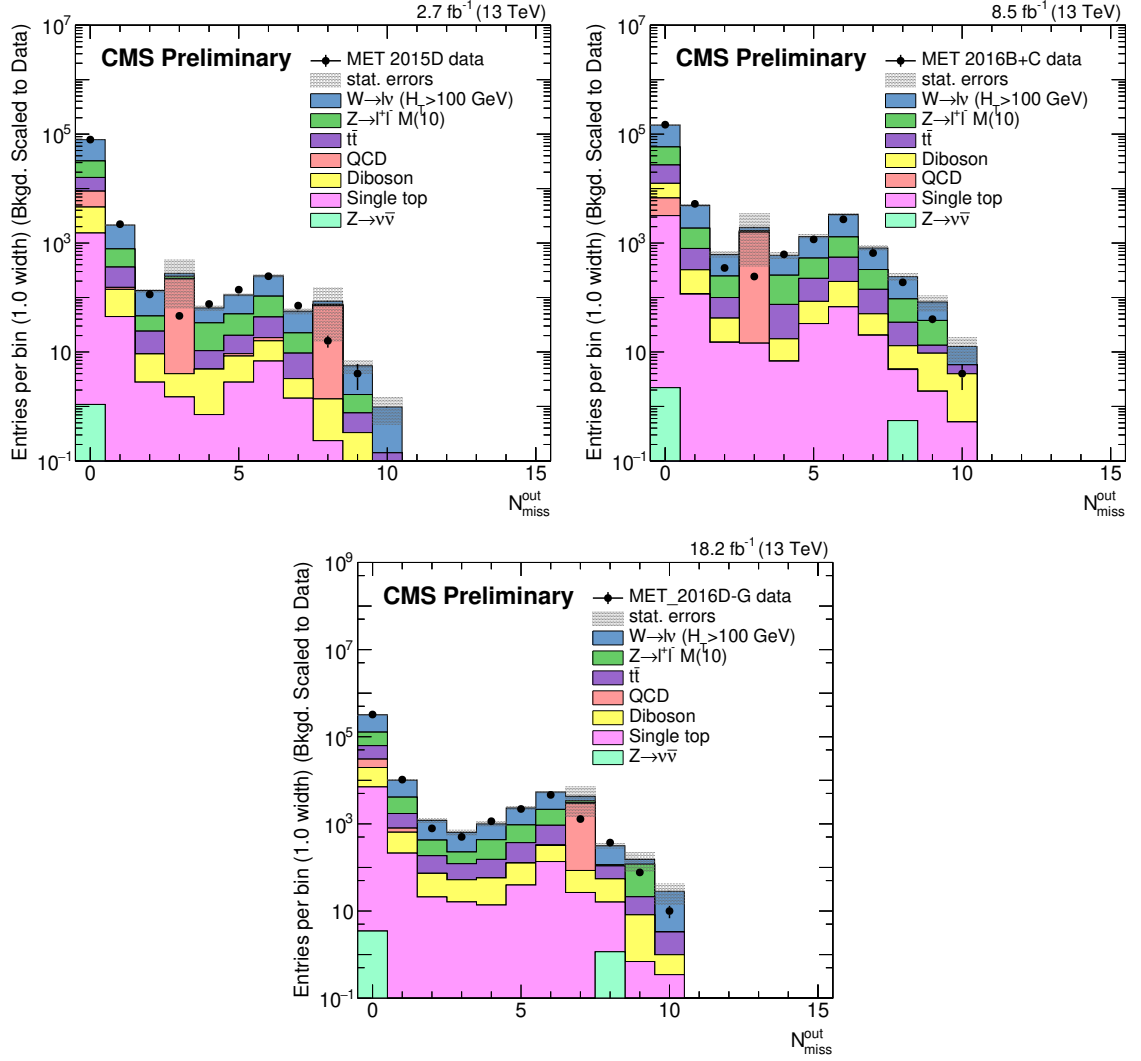
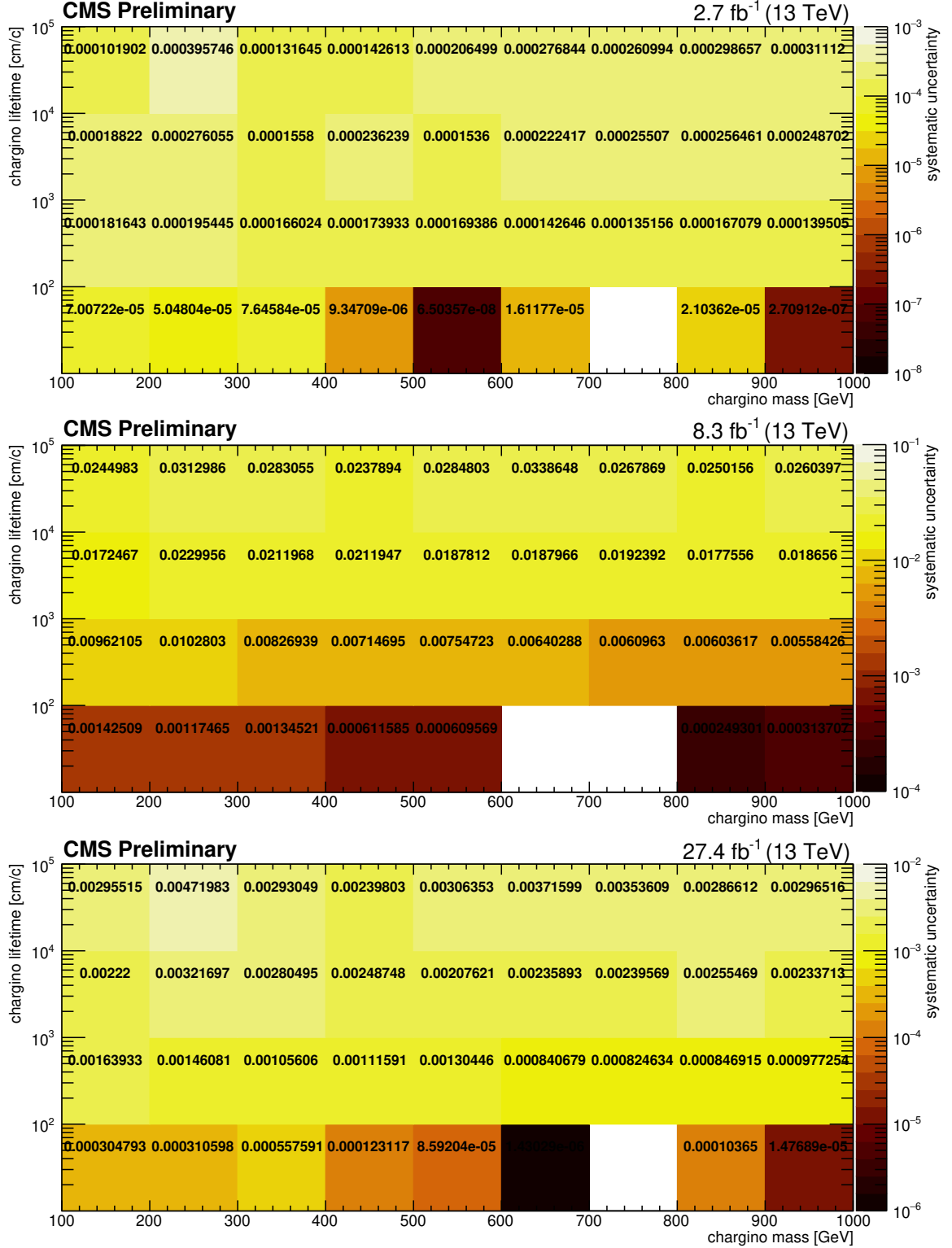


Figure 3.46: Systematic uncertainties on the signal acceptance from the modeling of missing outer hits for 2015 (top), 2016B+C (middle), and 2016D–H (bottom).



of the trigger efficiency scale factors. Each of these sets of scale factors is applied to the simulated events in the disappearing track selection, and each of the resulting changes to the signal yield relative to the nominal signal yield is taken as a systematic uncertainty. For the $p_{\text{T}}^{\text{miss}}$ leg, the average uncertainty is $0.09 - 0.2\%$, while that for the track leg is $4-6\%$.

ISR

The uncertainty associated with the simulation of ISR jets is evaluated by comparing the signal yields in the disappearing track selection with and without the ISR scale factors discussed in Section 3.5.4 applied. The relative change in signal yield is taken as a systematic uncertainty. The average value of this uncertainty is $8-9\%$.

Jet energy scale and resolution

The jets used in the search have the standard set of jet energy corrections applied, as described in Section 2.2.8. The effect of the uncertainty on the jet energy scale is evaluated by shifting the p_{T} of the jets up and down by the 1σ uncertainty on the cumulative jet energy corrections. The resulting relative change in signal yield is taken as a systematic uncertainty. This uncertainty is $2-6\%$ on average.

The effect of the uncertainty on the jet energy resolution is evaluated according to the scaling and smearing methods recommended by the Jet and Missing Energy group within CMS:

- *scaling*: reconstructed jet p_{T} is scaled based on the difference in p_{T} between the reconstructed jet and a well-matched generator jet, i.e.:

$$p_{\text{T}} = \max [p_{\text{T,gen}} + \varepsilon(p_{\text{T,reco}} - p_{\text{T,gen}})], \quad (3.20)$$

where ε is the ratio of jet p_T resolutions measured by the Jet and Missing Energy group in experimental and simulated data

- *smearing*: reconstructed jet p_T is randomly smeared using a Gaussian of width $\sigma_{\text{MC},p_T}\sqrt{\varepsilon^2 - 1}$, where again ε is the ratio of jet energy resolutions measured by the Jet and Missing Energy group in experimental and simulated data, and σ_{MC,p_T} is the jet p_T resolution measured in simulation

Reconstructed jets are considered well-matched to generator jets according to the criteria

$$\Delta R < R/2 \quad \text{and} \quad |\Delta p_T| < 3\sigma_{\text{MC},p_T}, \quad (3.21)$$

where $R = 0.4$ is the anti- k_T cone parameter of the jets. We apply scaling to the p_T of well-matched jets and smearing to the p_T of all others. The resulting relative change in signal yield after applying the hybrid method is taken as a systematic uncertainty. This uncertainty is 3–6% on average.

p_T^{miss}

The effect of the uncertainty on the p_T^{miss} is determined by varying the p_T of each object that contributes visible momentum to the event according to the uncertainty in the energy scale of the object, as prescribed by the Jet and Missing Energy group. The resulting relative change in signal yield is taken as a systematic uncertainty. The average values of this uncertainty for each object type whose p_T is varied are listed in Table 3.44. The average value across all object types is 0.4%.

Table 3.44: Average value of the systematic uncertainty resulting from the uncertainty on the p_T^{miss} for each object type whose p_T is varied.

object	average sys. unc.
jets	0.1%
taus	0.2%
photons	2%
unclustered energy	0.1–0.2%

$$E_{\text{calo}}^{\Delta R < 0.5}$$

The uncertainty associated with the modeling of the $E_{\text{calo}}^{\Delta R < 0.5}$ distribution in simulation is assessed by comparing the efficiency of the $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$ selection for a sample of fake tracks in experimental data and simulation. For this, disappearing tracks with at most 4 hits are selected from the $Z \rightarrow \mu\mu$ control region, which provides a sample overrun with fake tracks, the idea being to provide a uniform random sampling of the calorimeter for comparison. The $E_{\text{calo}}^{\Delta R < 0.5}$ distribution in experimental data and simulation is shown in Figure 3.47. The efficiency of the $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$ selection is shown in Table 3.45 along with the resulting systematic uncertainty, which is taken as the relative difference between the efficiencies. The efficiency of this selection for tracks selected by the candidate track selection in simulated signal events is similar at 95–98%, which supports the idea that we are indeed randomly sampling the calorimeter.

Figure 3.47: Comparison of $E_{\text{calo}}^{\Delta R < 0.5}$ in experimental data and simulation for tracks with at most 4 hits in the $Z \rightarrow \mu\mu$ control region.

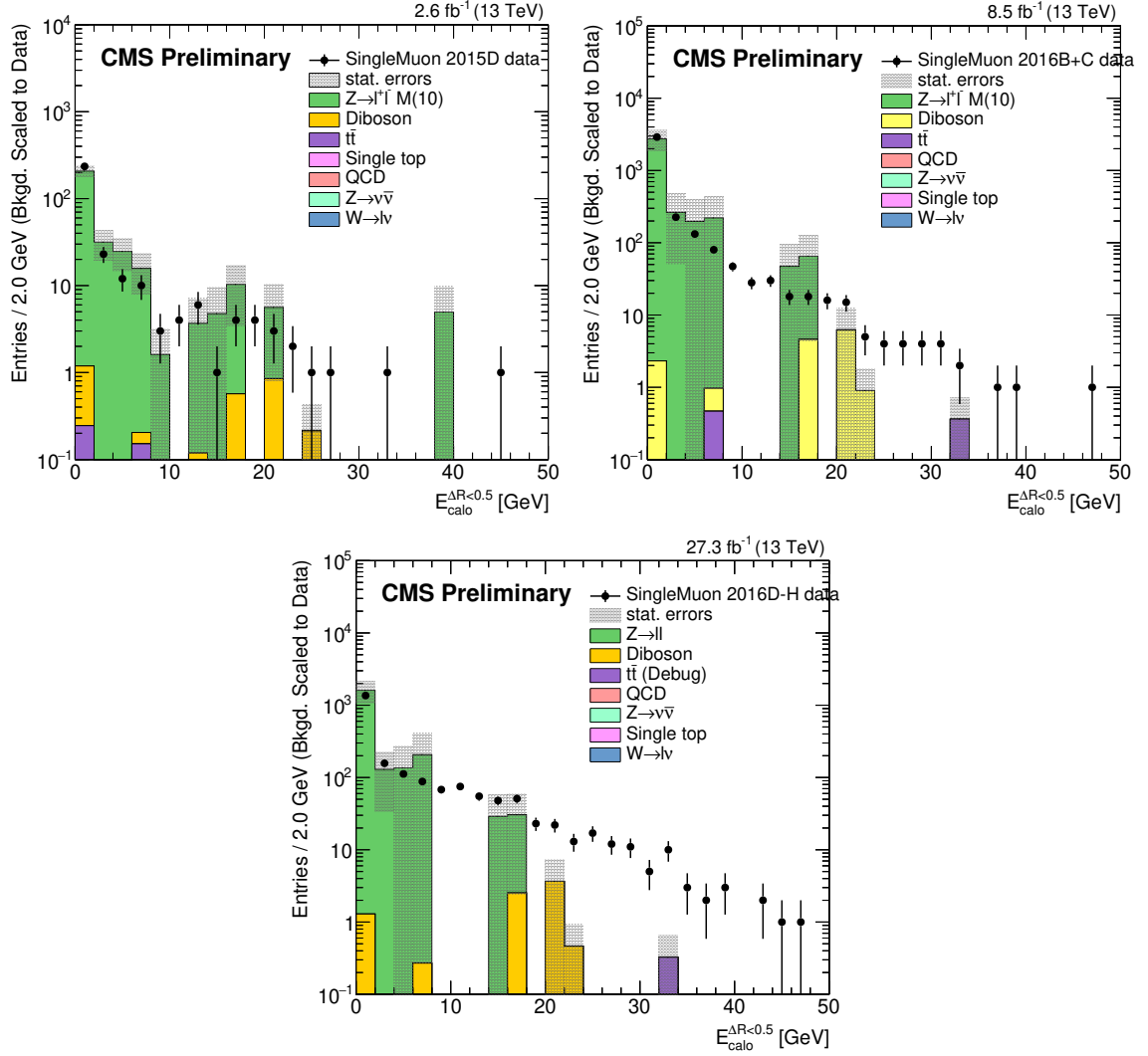


Table 3.45: Efficiency of the $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$ criterion for tracks with at most 4 hits in the $Z \rightarrow \mu\mu$ control region in experimental data and simulation, as well as the resulting systematic uncertainty.

run period	eff. of $E_{\text{calo}}^{\Delta R < 0.5} < 10 \text{ GeV}$		
	exp. data	simulation	sys. unc.
2015	$0.910^{+0.016}_{-0.019}$	0.904 ± 0.035	0.627%
2016B+C	$0.957^{+0.003}_{-0.004}$	0.966 ± 0.023	0.979%
2016D–H	0.960 ± 0.002	0.970 ± 0.020	1.02%

Track reconstruction efficiency

The uncertainty in the track reconstruction efficiency is assessed by the tracking group within CMS using a tag-and-probe study [6]. The track reconstruction efficiency is measured for probe muons, which are identified using only information from the muon system and matched to tracks in the inner tracker that are reconstructed without the benefit of muon seeds. The resulting track reconstruction efficiencies for 2015 and 2016 experimental and simulated data are shown in Figure 3.48, and the ratios of the efficiencies in experimental and simulated data are shown in Figure 3.49. We assign a systematic uncertainty to cover the largest difference between the efficiencies in experimental and simulated data: 1.5% for 2015 and 4.5% for 2016.²⁷

²⁷The efficiencies for 2016 represent only the first 9.2 fb^{-1} of data, before the HIP effect was solved. Thus, they should represent a worst case scenario in terms of agreement between experimental and simulated data, resulting in a conservative systematic uncertainty when applied to the data taken later in the year.

Figure 3.48: Track reconstruction efficiency as measured in a muon tag-and-probe study by the tracking group within CMS as a function of muon $|\eta|$. The performance in the data from 2015 (left) and from 2016 (right) is compared to that in simulation.

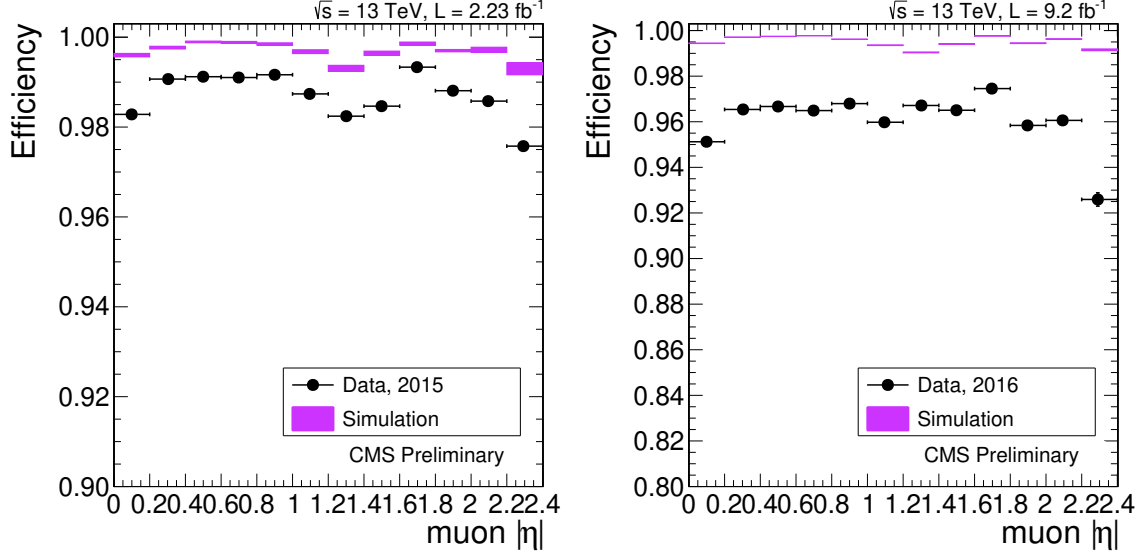
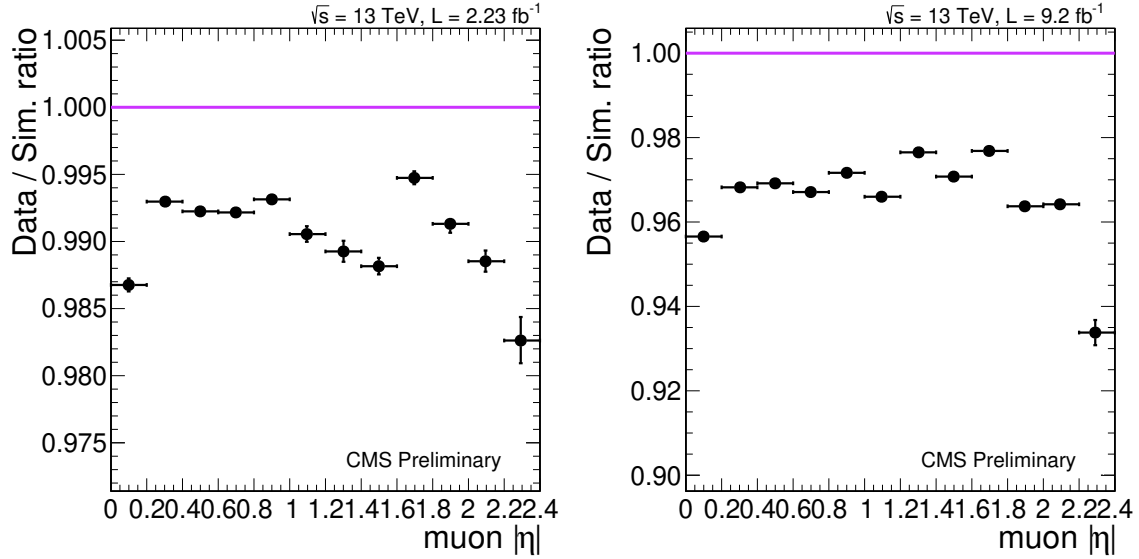


Figure 3.49: Ratio of track reconstruction efficiency in experimental and simulated data as measured in a muon tag-and-probe study by the tracking group within CMS as a function of muon $|\eta|$. The ratio in the data from 2015 (left) and from 2016 (right) is compared to that in simulation.



Summary

A summary of the systematic uncertainties described above in the signal efficiency for simulated samples of charginos with masses in the range 100–900 GeV and lifetimes of 10–10 000 cm/ c is given in Table 3.46.

Table 3.46: Typical values of the systematic uncertainties on the signal yields taken from simulation. The total listed on the last line is simply the sum in quadrature of each of the individual uncertainties.

source of uncertainty	typical value
pileup	2–3%
ISR	8–9%
trigger efficiency ($p_{\text{T}}^{\text{miss}}$ leg)	0.09–0.2%
trigger efficiency (track leg)	4–6%
jet energy scale	2–6%
jet energy resolution	3–6%
$p_{\text{T}}^{\text{miss}}$	0.4%
$E_{\text{calo}}^{\Delta R < 0.5}$	0.6–1%
missing inner hits	1–3%
missing middle hits	0.3–3%
missing outer hits	0.03–3%
track reconstruction efficiency	1.5–4.5%
total	10–16%

3.7 Results

The numbers of expected events from background sources compared with the observed numbers of events in the search sample are shown in Table 3.47. The observation agrees well with the expected background, and we proceed to set 95% CL upper limits on the production cross section of direct electroweak chargino production within the context of AMSB. Recall from Section 3.1.2 that this production occurs via the processes $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ in a ratio of approximately 1 : 2.²⁸ The upper limits on the total production cross section are calculated in a grid of chargino masses and lifetimes.

Table 3.47: Summary of numbers of events for the estimated backgrounds and the observed data. The uncertainties include those from statistical and systematic sources.

run period	leptons	est. event count		obs.
		fake tracks	total	
2015	$0.12^{+0.11}_{-0.08} \pm 0.01$	$0^{+0.079+0.025}_{-0 \quad -0}$	$0.12^{+0.14+0.03}_{-0.08-0.01}$	1
2016B+C	$1.99 \pm 0.42 \pm 0.11$	$0.38 \pm 0.19^{+0.41}_{-0.38}$	$2.38 \pm 0.46^{+0.43}_{-0.40}$	2
2016D–H	$3.07 \pm 0.63 \pm 0.22$	$0.91 \pm 0.35 \pm 0.91$	$3.98 \pm 0.71^{+0.93}_{-0.94}$	4
total	$5.18 \pm 0.76 \pm 0.25$	$1.3 \pm 0.4 \pm 1.0$	$6.48 \pm 0.86 \pm 1.03$	7

The limits are calculated with the modified frequentist method often referred to as CL_s [62, 48], using the LHC-type CL_s method [7]. This method uses a test statistic based on a profile likelihood ratio [26] and treats nuisance parameters in a frequentist context. Nuisance parameters for the systematic uncertainties in the

²⁸See Appendix E for a comparison of the acceptances for $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ events.

integrated luminosity and in the signal selection efficiency are constrained with log-normal distributions. There are two types of nuisance parameters for the uncertainties in the background estimates, and they are specified separately for each of the four background contributions. Those that result from the limited size of the control samples are constrained with gamma distributions, while those that are associated with statistical uncertainties in multiplicative factors and the systematic uncertainties discussed in Section 3.6.1 are constrained with log-normal distributions.

The expected and observed limits on the cross section are shown in Figure 3.50 as a function of chargino mass for several different chargino lifetimes. The intersection of the theory prediction and the upper limit on the cross section is used to set a constraint on the mass of the chargino, for a given chargino lifetime. This procedure is repeated for a large number of chargino lifetimes, in order to produce a two-dimensional constraint on the chargino mass and mean proper lifetime, which is shown in Figure 3.51. Charginos up to a mass of 715 GeV are excluded for a lifetime of 3 ns. The expected and observed upper limits on the cross section are also shown in the plane of chargino mass and mean proper lifetime in Figure 3.52.

Figure 3.50: The expected and observed 95% CL upper limits on the cross sections for direct chargino production as a function of chargino mass for various chargino lifetimes.

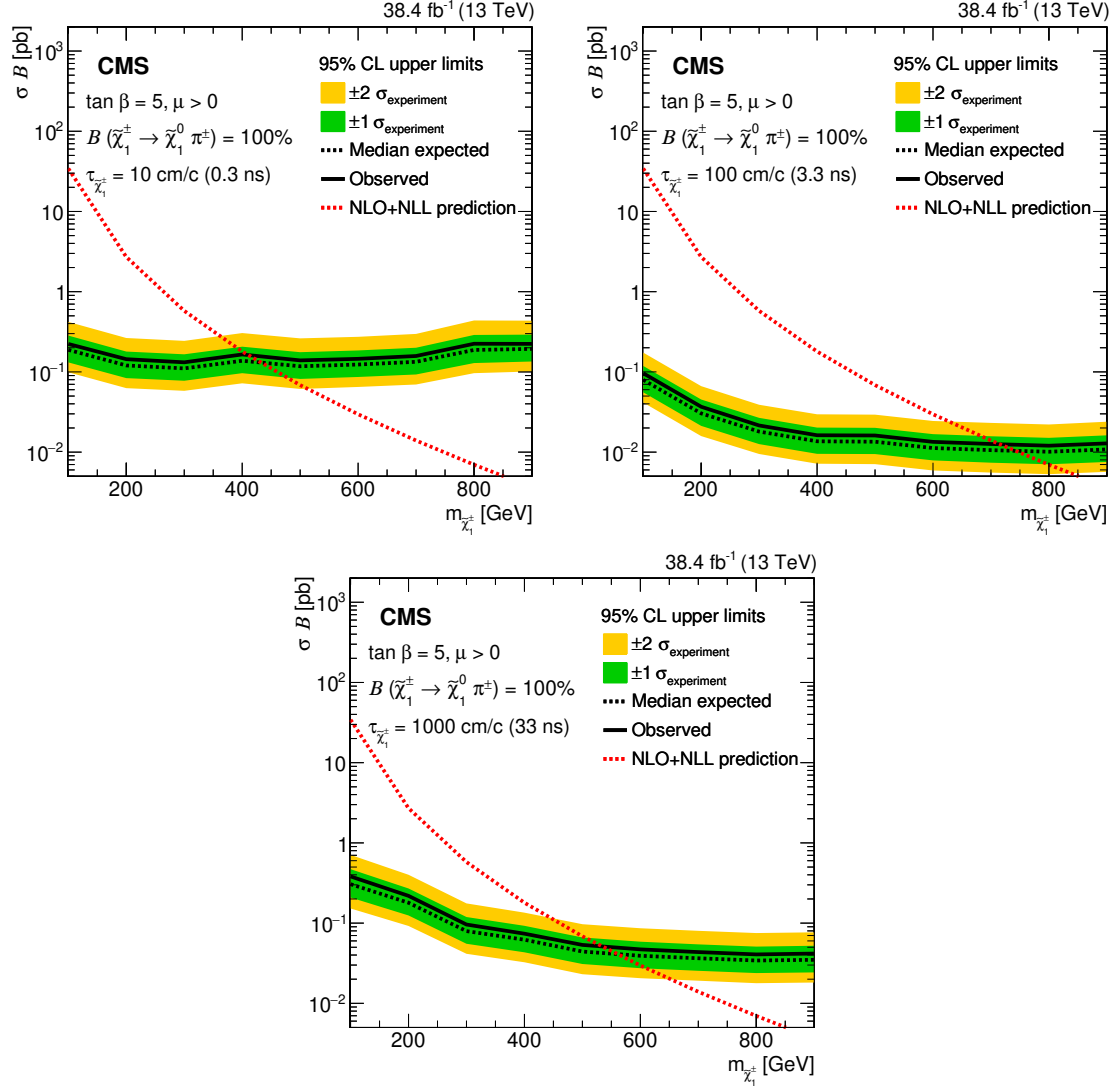


Figure 3.51: The expected and observed constraints on chargino lifetime and mass. The region to the left of the curve is excluded at 95% CL.

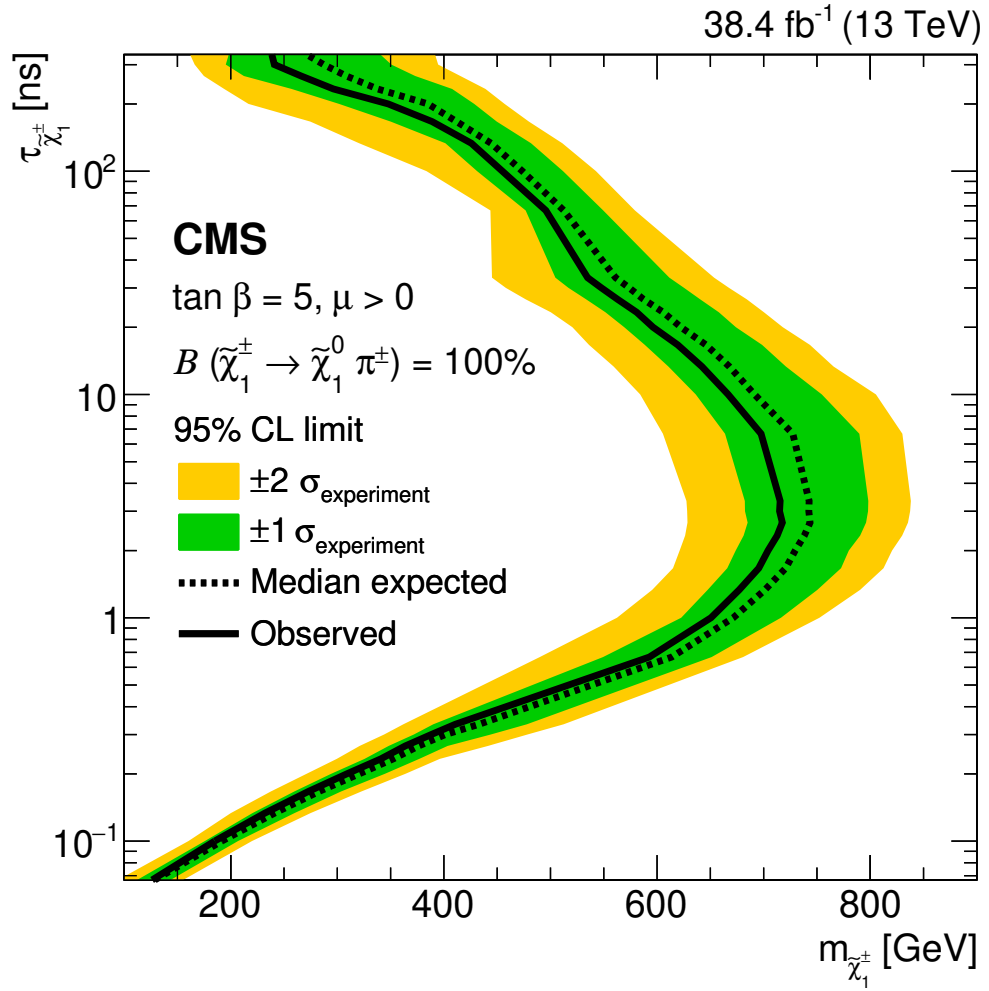
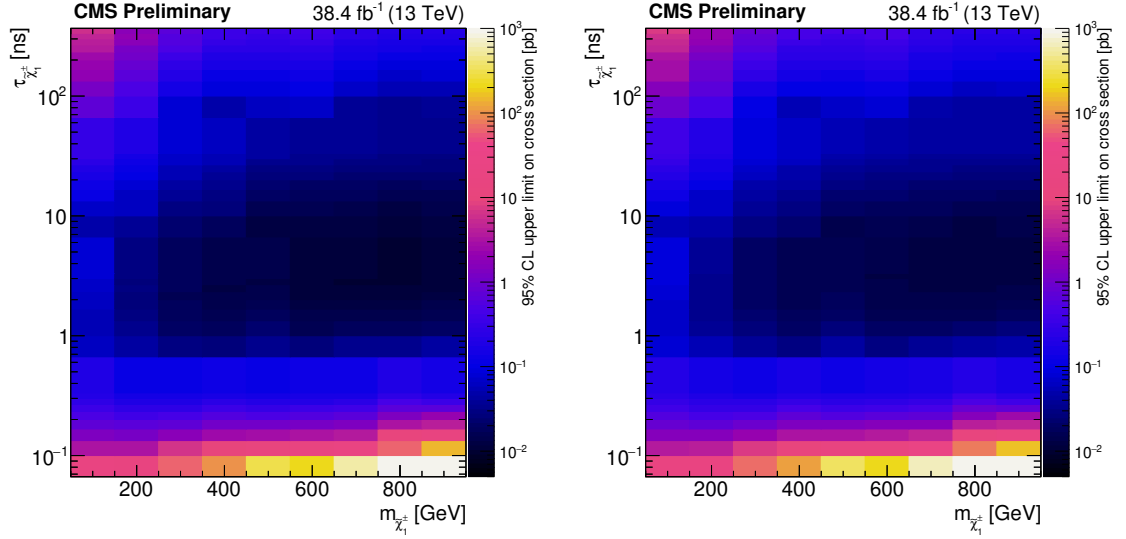


Figure 3.52: Upper limits at 95% CL on the cross section for direct chargino production as a function of chargino mass and lifetime. The left plot shows the expected limits, while the right plot shows the observed limits.



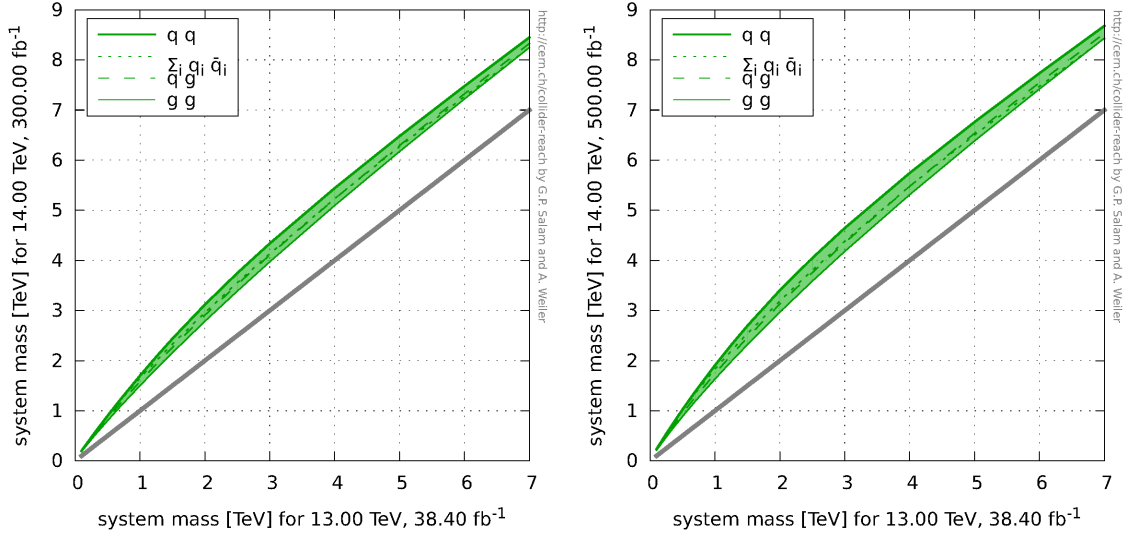
Chapter 4: Conclusion

A search has been presented for long-lived charged particles that decay within the CMS detector and produce the signature of a disappearing track. In a sample of proton-proton data recorded at a collision energy of $\sqrt{s} = 13 \text{ TeV}$ and corresponding to an integrated luminosity of 38.4 fb^{-1} , seven events are observed in the search sample, compared with the estimated background from Standard Model processes of $6.48 \pm 0.86 \text{ (stat)} \pm 1.03 \text{ (syst)}$ events. The observation is consistent with the background-only hypothesis, and we place constraints on the mass of charginos from direct electroweak production, for chargino mean proper lifetimes between 0.1 and 100 ns. Charginos with a mass up to 715 GeV for a lifetime of 3 ns are excluded at 95% CL. These constraints extend the limits set by a previous search performed by CMS [49]. For chargino lifetimes $\gtrsim 0.7 \text{ ns}$, these are currently the world's most stringent limits on direct chargino production using a disappearing track signature.

Before approximately 2023, when the LHC will shutdown to be upgraded to the High-Luminosity LHC (HL-LHC), CMS is projected to collect around $300\text{--}500 \text{ fb}^{-1}$ of data. Based on the results of the present search, and assuming most of the data collected before 2023 is collected at $\sqrt{s} = 14 \text{ TeV}$, we should have sensitivity to charginos up to 1 100–1 200 GeV for a lifetime of 3 ns with a repeat of this search (see Figure 4.1), if the selection efficiencies for signal and background events do not change

significantly from the present search. The selection efficiencies will almost certainly change over the next few years, in particular, at the trigger level as thresholds are raised in response to the increasing instantaneous luminosity and pileup. The p_T^{miss} threshold for our HLT_MET75_IsoTrk50_v* trigger was already raised from 75 GeV to 105 GeV for the 2017 run. Nonetheless, it should be possible to discover or exclude 1 TeV charginos at a lifetime of 3 ns with this search before the HL-LHC starts.

Figure 4.1: Expected mass exclusion with 300 fb^{-1} (left) or 500 fb^{-1} (right) of $\sqrt{s} = 14 \text{ TeV}$ data given the mass exclusion obtained with the 38.4 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ used in the present search. “System mass” here refers to the sum of the masses of the two ewkinos, which is always approximately $2m_{\tilde{\chi}_1^\pm}$, since the chargino and neutralino are nearly degenerate [1].



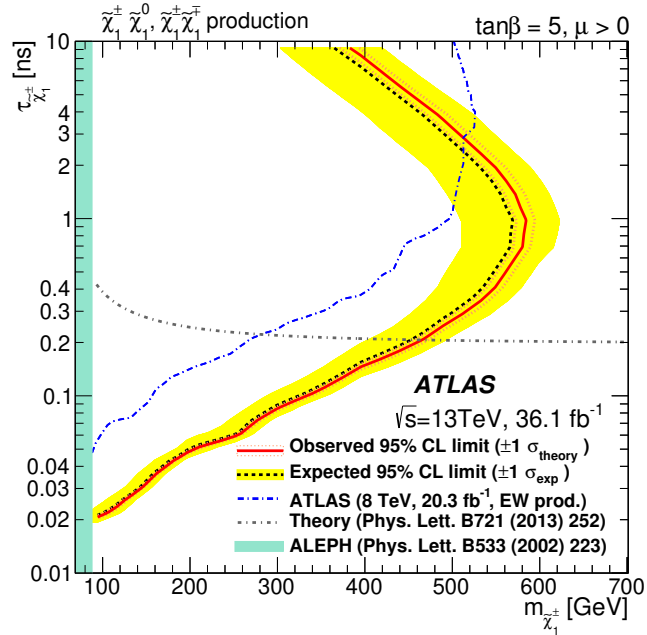
As noted previously, we calculate limits without assuming a particular relation between the chargino mass and lifetime. However, in AMSB, a certain choice of supersymmetry parameters determines the sparticle mass spectrum, which determines

both the chargino mass and lifetime. Within AMSB, the lifetime is ~ 0.2 ns at high chargino masses, with little variation with mass [46]. At this lifetime, the present search excludes charginos with masses up to 310 GeV, and the above projections indicate that we should have sensitivity to charginos up to 520 GeV (580 GeV) with 300 fb^{-1} (500 fb^{-1}) of data at 14 TeV.

Several extensions of the present search are possible however, which would enhance the sensitivity to models such as AMSB. For example, the pixel detector in CMS was upgraded after the 2016 run, with an extra layer being added in both the barrel and each endcap [54]. These extra layers should enable us to relax the requirement on the number of hits used in the present search, which is used primarily to mitigate the background from fake tracks, without increasing that background significantly. This would enhance sensitivity to shorter-lived particles. In fact, ATLAS has already used this strategy to perform a search for short disappearing tracks using data taken at $\sqrt{s} = 13 \text{ TeV}$, taking advantage of the fourth pixel barrel layer that they installed during the long shutdown before 2015 [25]. As can be seen in Figure 4.2, they exclude higher mass charginos than the present search for lifetimes $\lesssim 0.7$ ns. For a chargino lifetime of 0.2 ns, they already exclude charginos up to a mass of ~ 460 GeV.

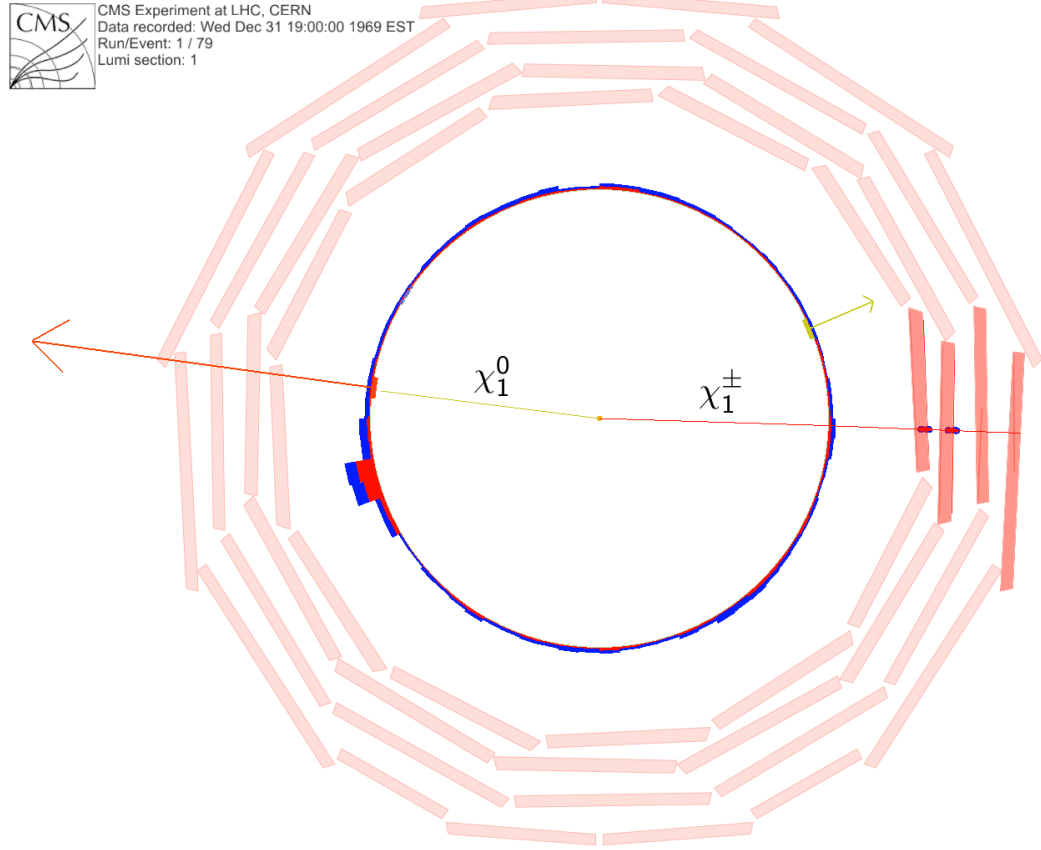
It is also possible to extend the sensitivity to longer-lived particles. As already noted in Section 3.2.1, in addition to targeting events with a disappearing track and ISR jet, we can target events where the disappearing track is accompanied by a muon, produced, e.g., by the second chargino in a chargino-chargino event. Since the second chargino must pass through enough muon chambers to yield a reconstructed muon, this would enhance sensitivity to longer-lived particles. We can even take this one step further. Recognizing that the muon system is a tracking detector, we can search

Figure 4.2: The expected and observed constraints on chargino lifetime and mass obtained by ATLAS using data taken during 2015 and 2016 at $\sqrt{s} = 13$ TeV. The region to the left of the curve is excluded at 95% CL. Also shown are the previous constraints obtained by ATLAS at 8 TeV, the predicted relationship between chargino mass and lifetime within AMSB, and the constraints from the ALEPH experiment at the Large Electron-Positron (LEP) collider [25].



for tracks that disappear *inside the muon system* to further increase the signal yield at higher lifetimes. This type of signature is illustrated with a chargino-neutralino event in Figure 4.3.

Figure 4.3: Event display of a simulated chargino-neutralino event where the chargino decays inside the muon system after leaving hits in the first two layers of the DTs.



Extending the present search in these ways will be important for maximizing our chances of observing BSM physics with various disappearing track signatures that would be overlooked by other, more conventional, searches for supersymmetry and other BSM models. These extensions, along with the ever-growing data set collected

by CMS, will be capable of putting serious pressure on models like AMSB over the next several years. That being said, if no evidence for new physics is observed, and as a realization of AMSB with a disappearing track signature becomes less and less likely, it will be ever more important to interpret the results of disappearing track searches in terms of potentially more viable models, such as those referenced in Chapter 1. This will help keep the results as relevant as possible to the high energy physics theory community as the search for disappearing tracks continues into the future.

Appendix A: Object identification criteria

Table A.1: Standard criteria used to select primary vertices.

selection name	variable	selection
good primary vertex	isValid	= true
	ndof	≥ 4
	$ z $	$< 24 \text{ cm}$
	ρ	$< 2 \text{ cm}$

Table A.2: Tight jet ID with lepton veto defined by the Jet POG.

selection name	variable	selection
tight jet ID with lepton veto	neutral hadron fraction	< 0.9
	charged hadron fraction	> 0
	neutral EM fraction	< 0.9
	charged EM fraction	< 0.9
	number of constituents	> 1
	charged multiplicity	> 0
	muon fraction	< 0.8

Table A.3: Tight electron ID defined by the Egamma POG for the 2015 data for electrons in the barrel ($|\eta| < 0.1.479$).

selection name	variable	selection ($ \eta < 1.479$)
tight electron ID	full 5×5 $\sigma_{i\eta i\eta}$	< 0.0101
	$ \Delta\eta_{\text{in}} $	< 0.00926
	$ \Delta\phi_{\text{in}} $	< 0.0336
	h/E	< 0.0597
	rel. iso. with ρ -corr.	< 0.0591
	$ 1/E - 1/p $	$< 0.012 \text{ GeV}^{-1}$
	$ d_{xy} $	$< 0.0111 \text{ cm}$
	$ d_z $	$< 0.0466 \text{ cm}$
	missing inner hits	≤ 2
	has matched conversion	$= \text{false}$

Table A.4: Tight electron ID defined by the Egamma POG for the 2015 data for electrons in the endcaps ($0.1.479 < |\eta| < 2.5$).

selection name	variable	selection ($1.479 < \eta < 2.5$)
tight electron ID	full 5×5 $\sigma_{i\eta i\eta}$	< 0.0279
	$ \Delta\eta_{\text{in}} $	< 0.00724
	$ \Delta\phi_{\text{in}} $	< 0.0918
	h/E	< 0.0615
	rel. iso. with ρ -corr.	< 0.0759
	$ 1/E - 1/p $	$< 0.00999 \text{ GeV}^{-1}$
	$ d_{xy} $	$< 0.0351 \text{ cm}$
	$ d_z $	$< 0.417 \text{ cm}$
	missing inner hits	≤ 1
	has matched conversion	$= \text{false}$

Table A.5: Tight electron ID defined by the Egamma POG for the 2016 data for electrons in the barrel ($|\eta| < 0.1.479$).

selection name	variable	selection ($ \eta < 1.479$)
tight electron ID	full 5×5 $\sigma_{i\eta i\eta}$	< 0.00998
	$ \Delta\eta_{\text{in}} $	< 0.00308
	$ \Delta\phi_{\text{in}} $	< 0.0816
	h/E	< 0.0414
	rel. iso. with ρ -corr.	< 0.0588
	$ 1/E - 1/p $	$< 0.0129 \text{ GeV}^{-1}$
	$ d_{xy} $	$< 0.05 \text{ cm}$
	$ d_z $	$< 0.10 \text{ cm}$
	missing inner hits	≤ 1
	has matched conversion	$= \text{false}$

Table A.6: Tight electron ID defined by the Egamma POG for the 2016 data for electrons in the endcaps ($0.1.479 < |\eta| < 2.5$).

selection name	variable	selection ($1.479 < \eta < 2.5$)
tight electron ID	full 5×5 $\sigma_{i\eta i\eta}$	< 0.0292
	$ \Delta\eta_{\text{in}} $	< 0.00605
	$ \Delta\phi_{\text{in}} $	< 0.0394
	h/E	< 0.0641
	rel. iso. with ρ -corr.	< 0.0571
	$ 1/E - 1/p $	$< 0.0129 \text{ GeV}^{-1}$
	$ d_{xy} $	$< 0.10 \text{ cm}$
	$ d_z $	$< 0.20 \text{ cm}$
	missing inner hits	≤ 1
	has matched conversion	$= \text{false}$

Table A.7: Loose electron ID defined by the Egamma POG for electrons in the barrel ($|\eta| < 0.1.479$).

selection name	variable	selection ($ \eta < 1.479$)
loose electron ID	full $5 \times 5 \sigma_{i\eta i\eta}$	< 0.0103
	$ \Delta\eta_{\text{in}} $	< 0.0105
	$ \Delta\phi_{\text{in}} $	< 0.115
	h/E	< 0.104
	$ 1/E - 1/p $	$< 0.102 \text{ GeV}^{-1}$
	$ d_{xy} $	$< 0.0261 \text{ cm}$
	$ d_z $	$< 0.41 \text{ cm}$
	missing inner hits	≤ 2
	has matched conversion	$= \text{false}$

Table A.8: Loose electron ID defined by the Egamma POG for electrons in the endcaps ($0.1.479 < |\eta| < 2.5$).

selection name	variable	selection ($1.479 < \eta < 2.5$)
loose electron ID	full $5 \times 5 \sigma_{i\eta i\eta}$	< 0.0301
	$ \Delta\eta_{\text{in}} $	< 0.00814
	$ \Delta\phi_{\text{in}} $	< 0.182
	h/E	< 0.0897
	$ 1/E - 1/p $	$< 0.126 \text{ GeV}^{-1}$
	$ d_{xy} $	$< 0.118 \text{ cm}$
	$ d_z $	$< 0.822 \text{ cm}$
	missing inner hits	≤ 1
	has matched conversion	$= \text{false}$

Table A.9: Tight muon ID defined by the muon POG.

selection name	variable	selection
tight muon ID	isGlobalMuon	= true
	isPFMuon	= true
	χ^2/ndof	< 10
	valid muon hits	> 0
	matched muon stations	> 1
	$ d_{xy} $	< 0.2 cm
	$ d_z $	< 0.5 cm
	valid pixel hits	> 0
	tracker layers with hits	> 5
	rel. iso. with $\Delta\beta$ -corr.	< 0.15

Table A.10: Loose muon ID defined by the muon POG.

selection name	variable	selection
loose muon ID	isGlobalMuon OR isTrackerMuon	= true
	isPFMuon	= true

Table A.11: Hadronic tau ID with light flavor rejection using tau ID sources defined by the tau POG.

selection name	variable	selection
hadronic tau ID	decayModeFinding (old DM finding)	> 0.5
	byTightCombinedIsolationDeltaBetaCorr3Hits	> 0.5
	againstElectronLooseMVA5/6	> 0.5
	againstMuonLoose3	> 0.5

Appendix B: Initial unblinding of 2015 data

In order to validate the background estimation methods in experimental data, it was decided to perform a preliminary unblinding of just the 2015 data. Based on the null results from Run 1, this data set of 2.59 fb^{-1} is not large enough to yield a discovery of the chosen signal model, thus we expect the observation to be consistent with the estimated background. Whether this is the case or not is then a test of the validity of the background estimation methods.

The fiducial track selections were not finalized when the 2015 data was unblinded, thus the background estimates were larger than they currently are. Table B.1 compares the background estimates with the observation of 5 events. The observation agrees with the background estimate within 0.7σ , confirming the validity of the estimates.

Upon examining the observed events, several features were noted:

- two events have tracks with pseudorapidities extremely close to $\eta = 0$ (see Figure B.1)
- the other three events are also near $\eta = 0$, and all are at $\eta > 0$ (see Figure B.2)
- all candidate tracks have corresponding GSF tracks: four with zero missing outer hits, one with one missing outer hit

Table B.1: Background estimates at the time of the initial unblinding compared to the observation in the 2015 data.

bkgd. source	2015 estimate	observation
e	4.3 ± 0.6	
μ	0.40 ± 0.15	
τ	1.4 ± 0.8	
fake tracks	0.69 ± 0.69	
total	6.8 ± 1.3	5

Regarding the first feature, the two candidate tracks have pseudorapidities of $\eta = 2.81 \times 10^{-4}$ and $\eta = 5.16 \times 10^{-5}$ and have no missing silicon hits except in the TOB, in which they have no hits. After examining the geometry of the strip tracker, it was found that tracks with such small values of η will pass through only the edges of modules in the TOB if they originate near $z = 0$. This can be seen clearly in Figure B.1. This region of low hit efficiency in the TOB is now vetoed as described in Section 3.3.1.

The cause of the second feature mentioned above is less clear. The electron and muon reconstruction inefficiencies have no corresponding jumps near $\eta = 0$ that would potentially explain this clustering of observed tracks (see Figure B.3). This feature is potentially just a coincidence, and was not investigated further, as the final set of selections rejects all of these events.

For reference, the event displays for all 5 events are shown in Figures B.4, B.5, B.6, B.7, and B.8.

Figure B.1: Events observed in 2015 with tracks passing through the region of low hit efficiency in the TOB at $\eta = 0$. The highlighted track is the candidate signal track.

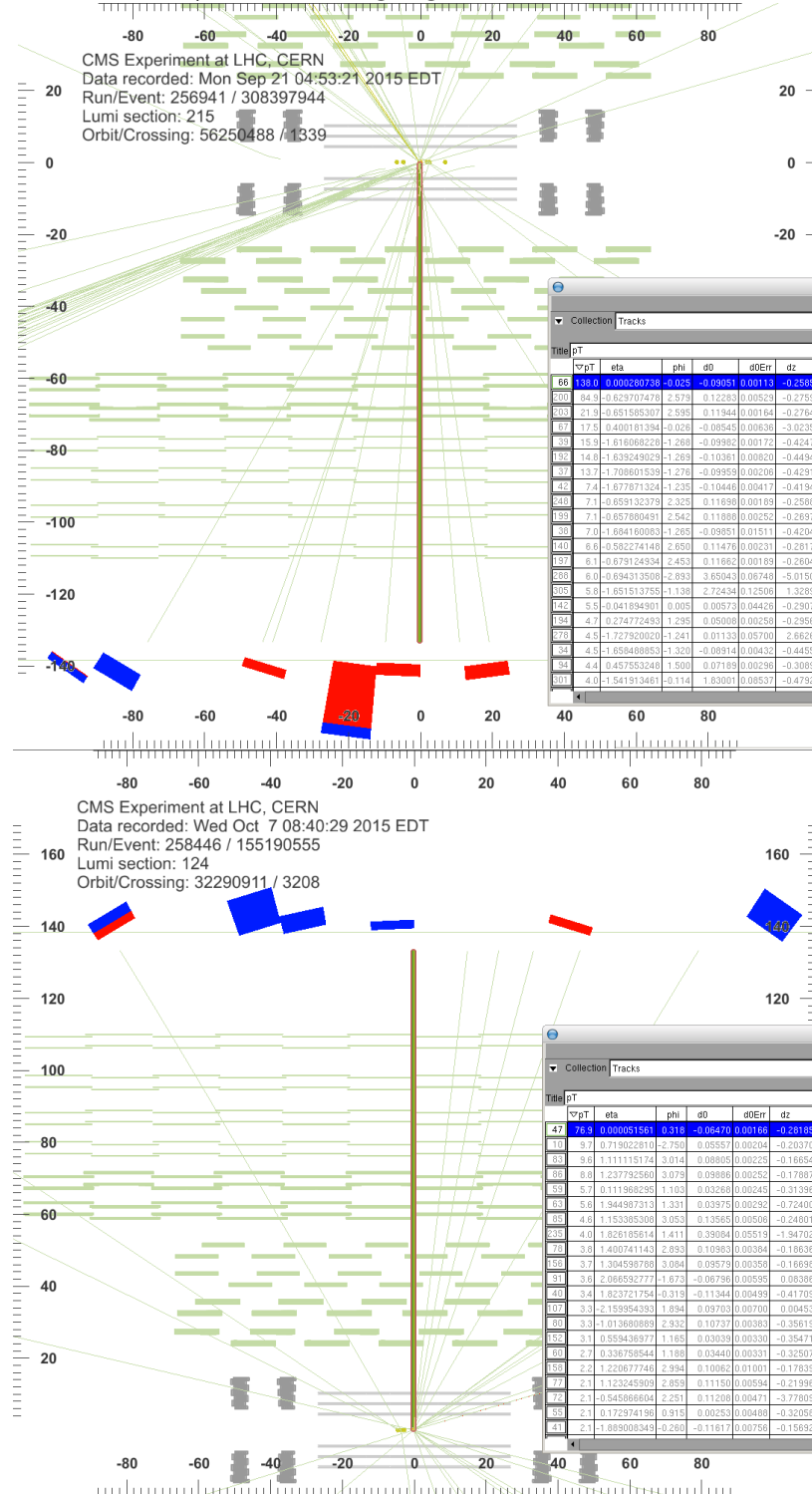


Figure B.2: Pseudorapidity for candidate signal tracks from 2015 data.

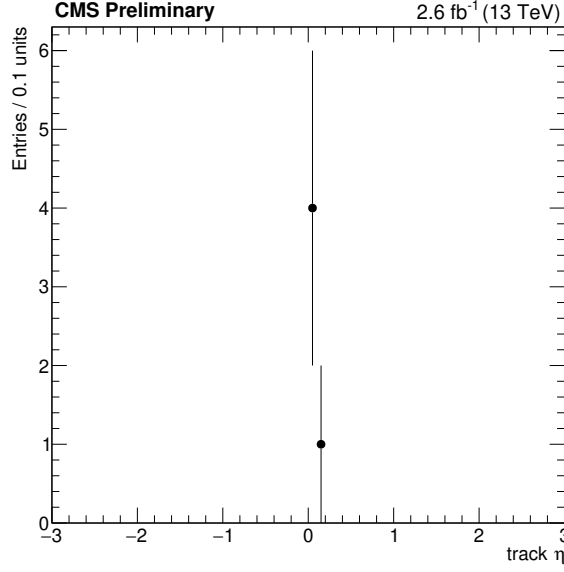


Figure B.3: Reconstruction inefficiency as a function of track η for electrons (left) and muons (right). These are identical to the left plots in Figures 3.10 and 3.11, just projected onto the horizontal axis.

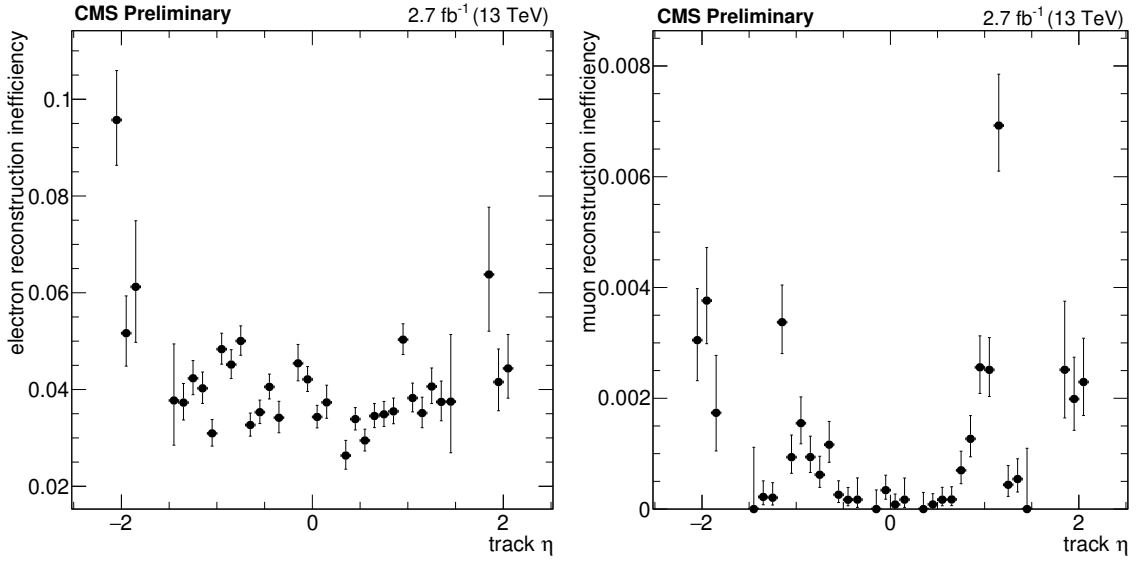


Figure B.4: Event display for event 308397944 from the initial unblinding of the 2015 data.

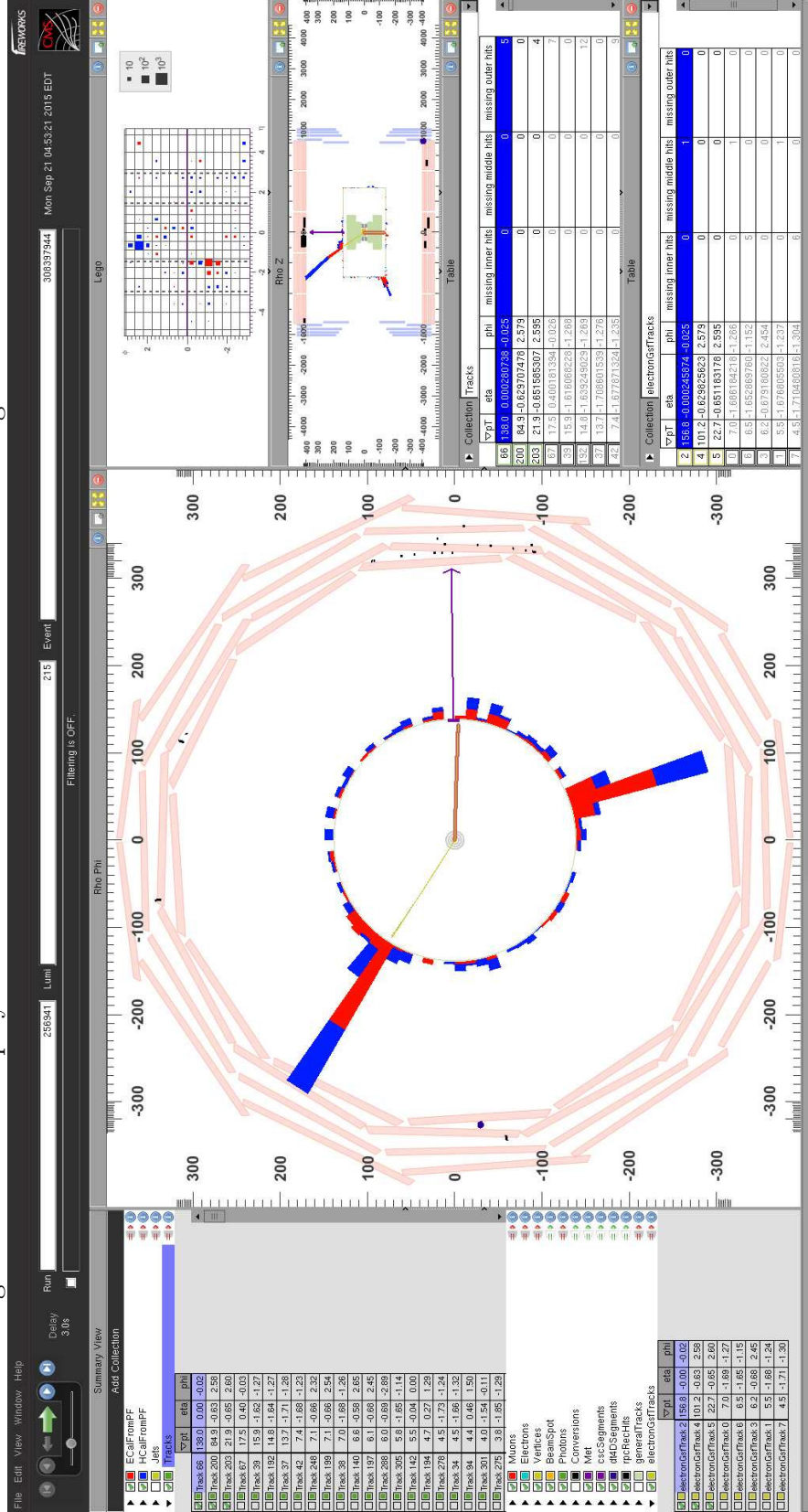


Figure B.5: Event display for event 155190555 from the initial unblinding of the 2015 data.

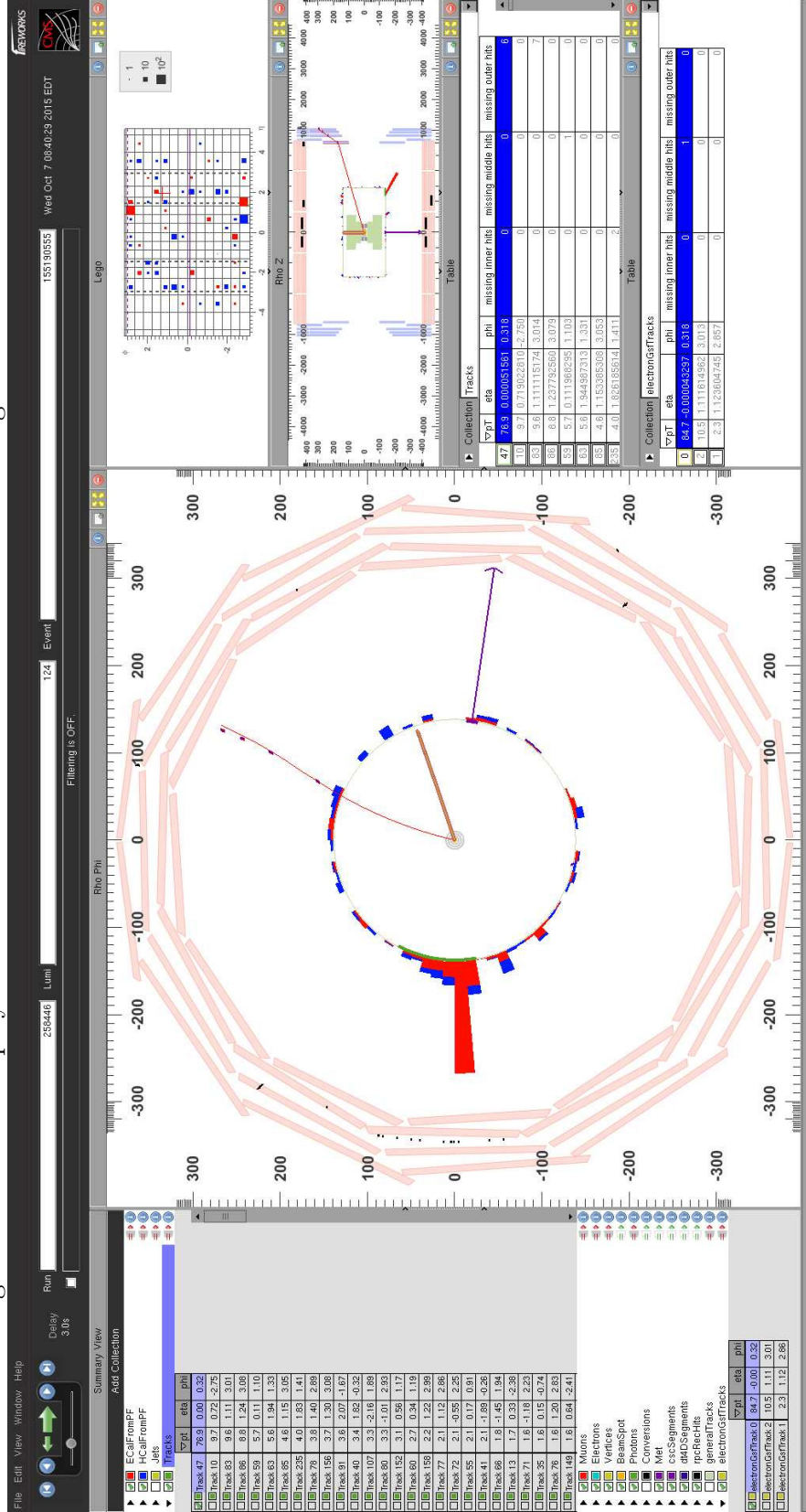


Figure B.6: Event display for event 264966793 from the initial unblinding of the 2015 data.

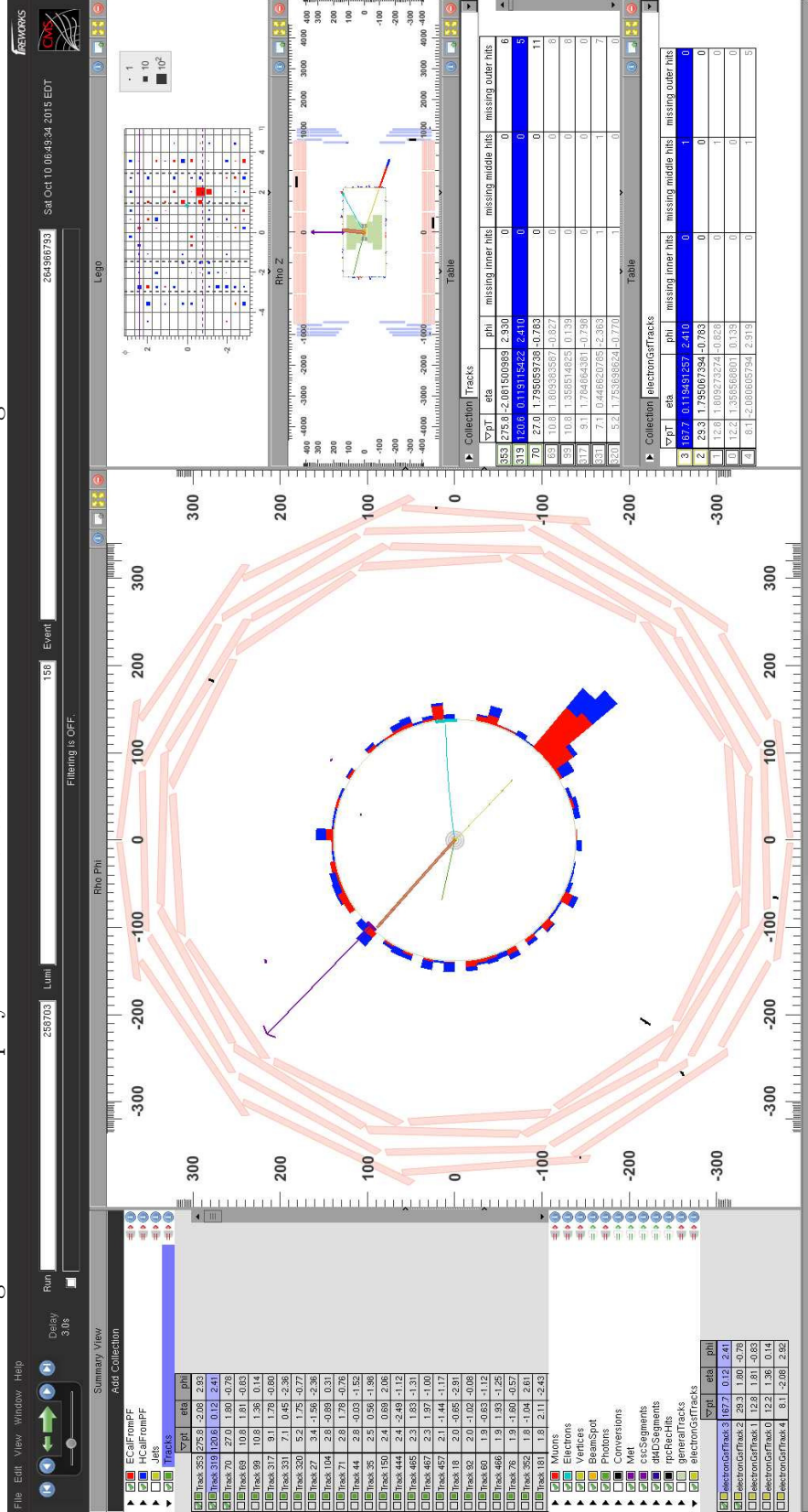
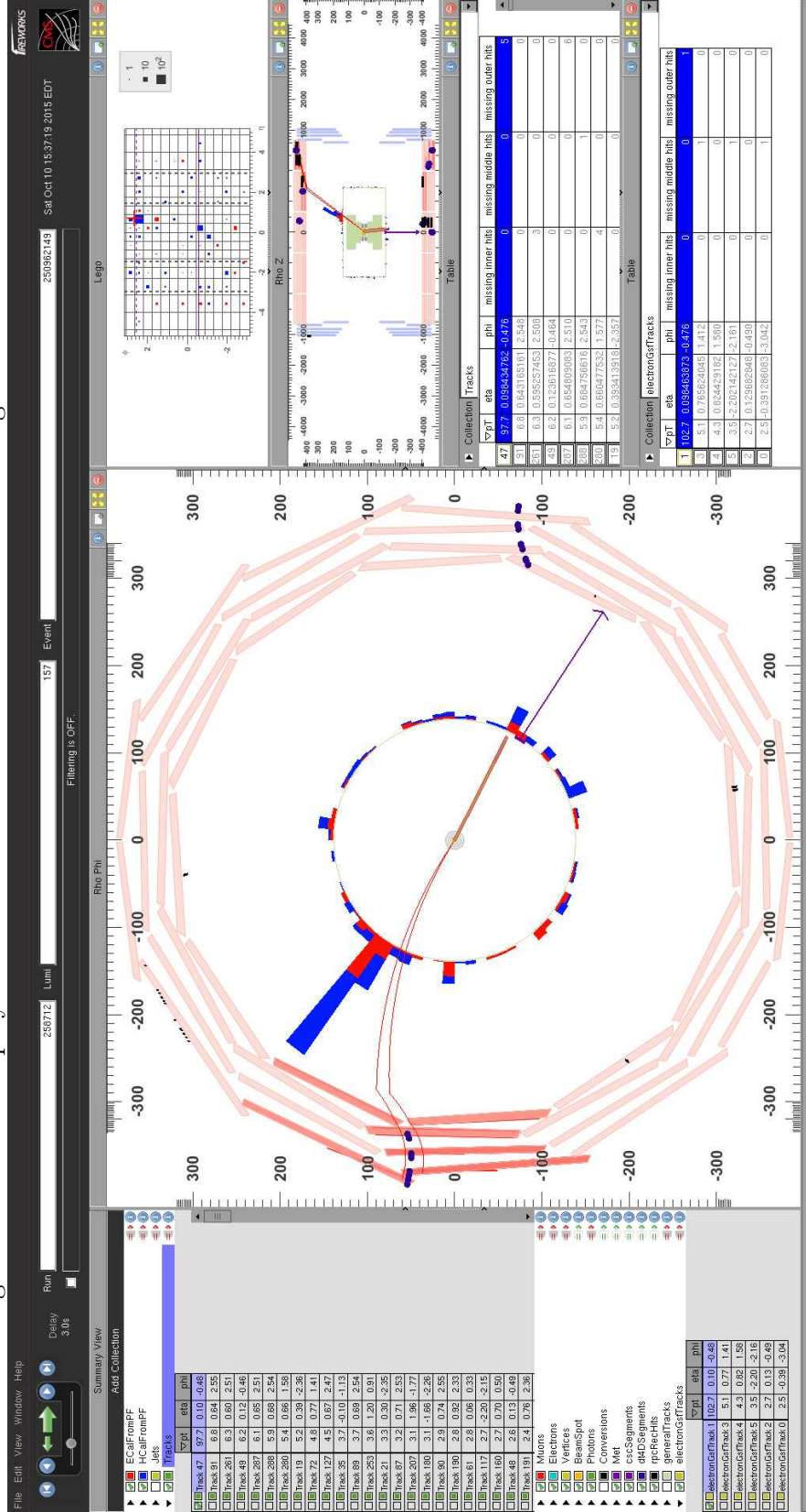


Figure B.7: Event display for event 250962149 from the initial unblinding of the 2015 data.



The screenshot displays the ROOT software interface for event analysis. The main 3D plot shows particle tracks in a cylindrical detector. A red track is highlighted, and a green track is also visible. The top panel shows a 2D projection of the tracks in the Rho-Z plane. The bottom panel shows a 2D projection of the tracks in the Rho-Phi plane. The right side of the interface contains a 'Collection' table with columns for track ID, eta, phi, and hit status. The bottom status bar shows the event number 103 and the date 20191040.

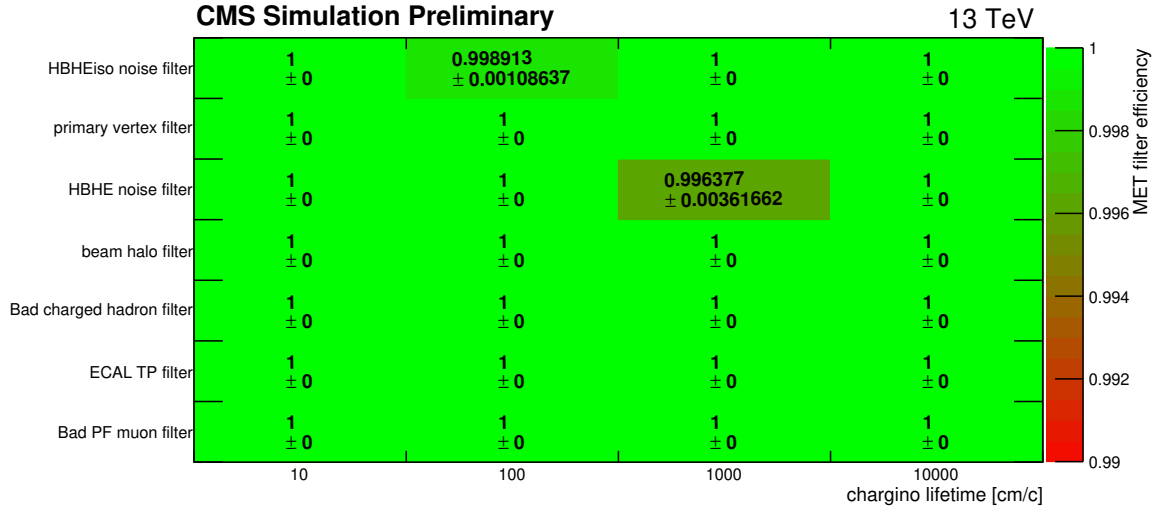
Collection	Tracks	Tracks	Tracks	Tracks
Track ID	eta	phi	missing inner hits	missing middle hits
72	123.3	0.095151466	1.801	0
40	42.51	0.362002072	0.840	0
43	37.61	0.820375114	-0.820	0
148	32.81	0.963129193	0.738	1
139	27.11	0.371359605	0.851	0
41	18.61	0.365837952	0.932	0
159	14.51	0.002661619	2.133	0
45	12.3	0.047217503	0.732	0

Collection	electronTracks	electronTracks	electronTracks	electronTracks
Track ID	eta	phi	missing inner hits	missing middle hits
1	146.7	0.082137548	1.801	1
0	13.4	0.915161776	-0.759	0

Appendix C: Effect of $p_{\text{T}}^{\text{miss}}$ filters on signal acceptance

We test the effect of the $p_{\text{T}}^{\text{miss}}$ filters recommended by the Jet and Missing Energy group within CMS on our signal acceptance by calculating the efficiency of each of these filters on simulated signal events passing our full disappearing track search selection. We perform this test with the samples generated with a 700 GeV chargino, and we compare the results for all of the generated lifetimes. As can be seen from the results in Figure C.1, the filters have a negligible effect on the signal acceptance.

Figure C.1: Efficiency of each of the recommended p_T^{miss} filters for simulated signal events generated with a 700 GeV chargino and that pass the full disappearing track search selection.



Appendix D: Use of $p_T^{\text{miss, no } \mu}$

For this search, we utilize selections on $p_T^{\text{miss, no } \mu}$, i.e., p_T^{miss} where the p_T of all reconstructed muons has been added as invisible momentum. Although signal events are free of high- p_T muons, a chargino can be reconstructed as such if it lives long enough to leave hits in the muon chambers. Thus, for the case of $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$, where one chargino decays in the inner tracker, yielding a disappearing track, and the other is reconstructed as a muon, there can be a significant discrepancy between p_T^{miss} and $p_T^{\text{miss, no } \mu}$. This discrepancy increases with increasing chargino lifetime, as more and more charginos are reconstructed as muons.

However, as seen in the left plot of Figure D.1, this discrepancy can go either way; i.e., $p_T^{\text{miss, no } \mu}$ can be larger or smaller than p_T^{miss} . Furthermore, since we use triggers based on L1 calorimeter-based p_T^{miss} seeds, the triggers have the effect of removing events with low $p_T^{\text{miss, no } \mu}$, regardless of their p_T^{miss} (see the right plot of Figure D.1). Thus, an offline selection on $p_T^{\text{miss, no } \mu}$, as opposed to p_T^{miss} , removes fewer signal events after the trigger decisions are applied. The correlation between $p_T^{\text{miss, no } \mu}$ and p_T^{miss} is shown in Figure D.2 for events passing the full disappearing track selection.

Figure D.1: Comparison of $p_T^{\text{miss, no } \mu}$ vs. p_T^{miss} for simulated signal events with a 700 GeV chargino with a lifetime of 10 m. All generated events are used in the left plot, while only events passing the search triggers are used in the right plot.

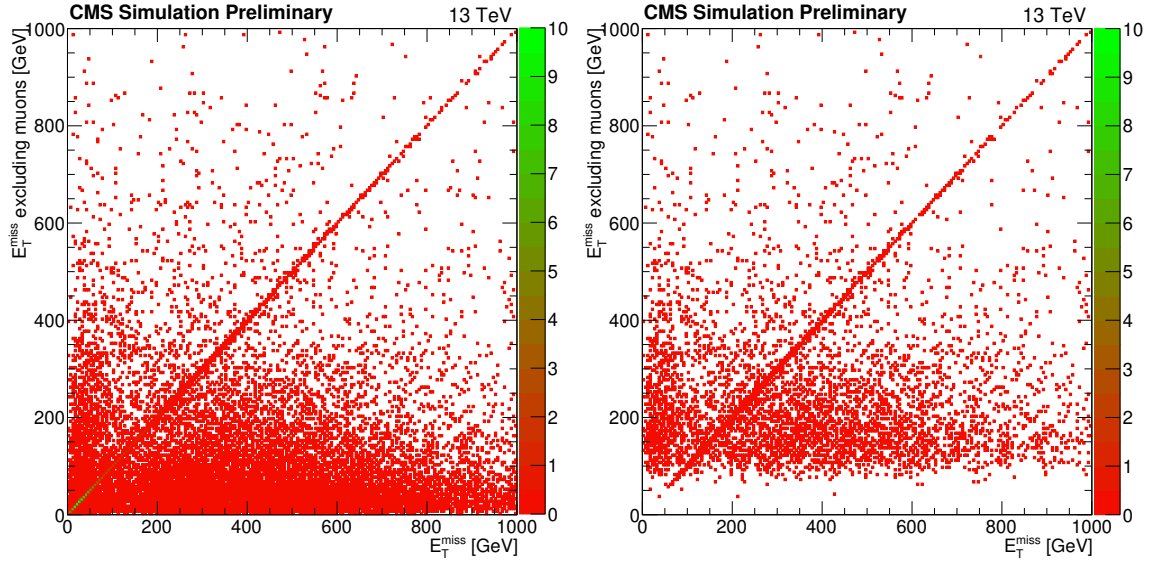
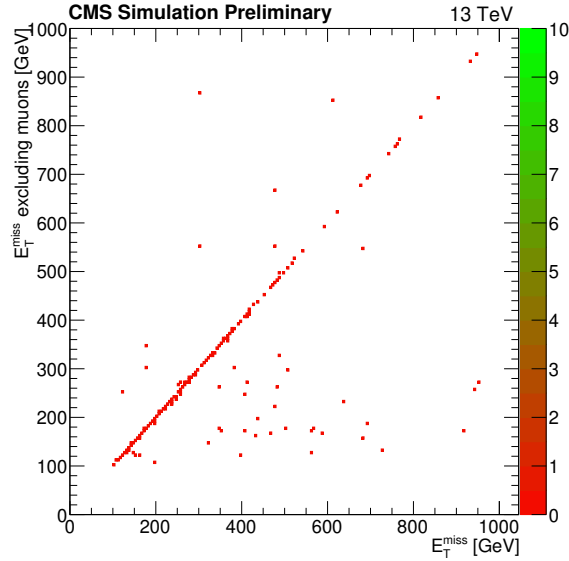


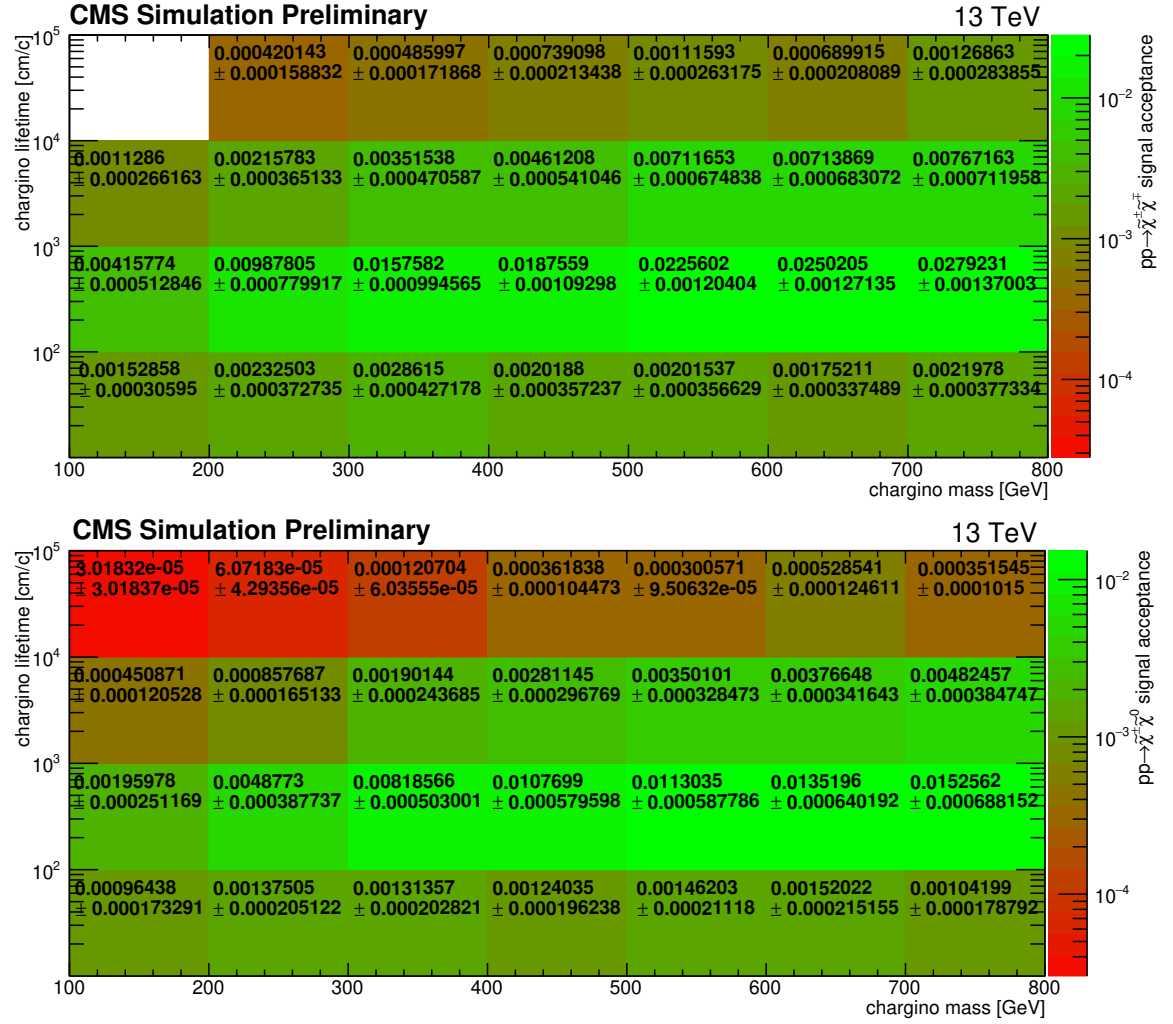
Figure D.2: Comparison of $p_T^{\text{miss, no } \mu}$ vs. p_T^{miss} for simulated signal events with a 700 GeV chargino with a lifetime of 10 m and that pass the full disappearing track selection.



Appendix E: Signal acceptance for $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ vs. $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$

Figure E.1 shows the signal acceptances for $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$. As expected, the acceptance is higher for the former, which accounts for $\sim 1/3$ of chargino production, since each event has two charginos that can potentially yield a disappearing track.

Figure E.1: Signal acceptance for each of the generated chargino masses and lifetimes for $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ events (top) and $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^0$ events (bottom). The uncertainties shown are simply the statistical uncertainties resulting from the sizes of the generated samples.



Appendix F: Trigger efficiencies of inclusive p_T^{miss} paths

The efficiency of the disjunction of all signal paths is shown in Figure 3.38. Below, the efficiencies of each leg of the `HLT_MET75_IsoTrk50_v*` path are shown in Figure F.1 and the efficiencies of each individual p_T^{miss} path are shown in Figures F.2, F.3, F.4, and F.5.

Figure F.1: Efficiencies of the p_T^{miss} leg (left column) and track leg (right column) of HLT_MET75_IsoTrk50_v* as a function of $p_T^{\text{miss, no } \mu}$ and track p_T , respectively.

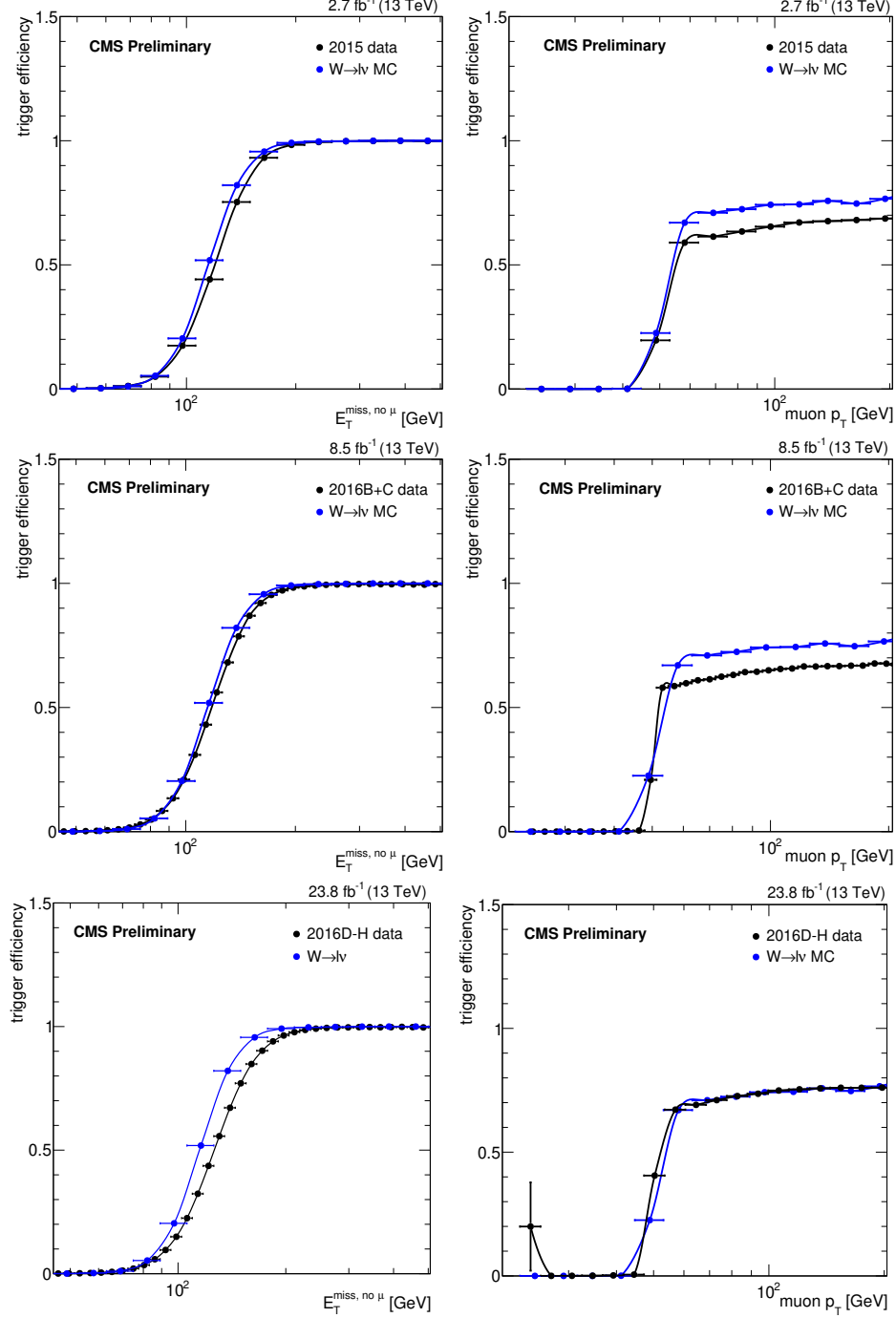


Figure F.2: Efficiencies of individual p_T^{miss} paths used in the combined signal trigger for 2015 data, compared to $W \rightarrow l\nu$ Monte Carlo.

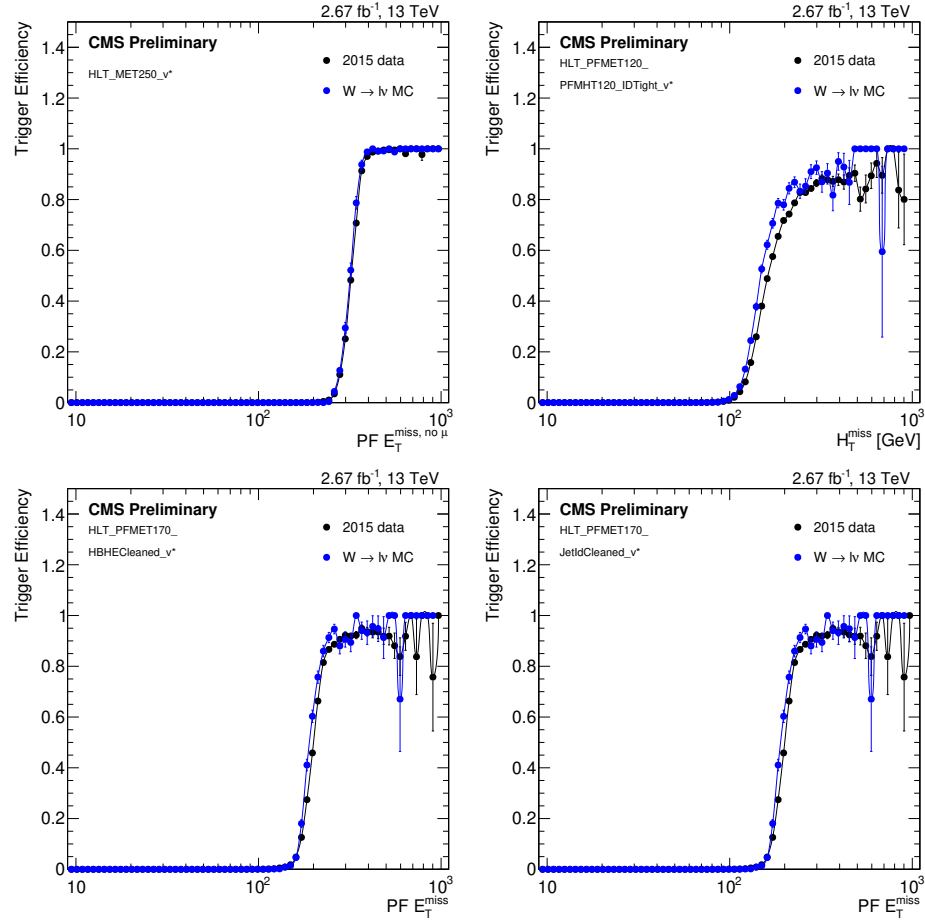


Figure F.3: Efficiencies of individual p_T^{miss} paths used in the combined signal trigger for 2015 data (continued), compared to $W \rightarrow l\nu$ Monte Carlo.

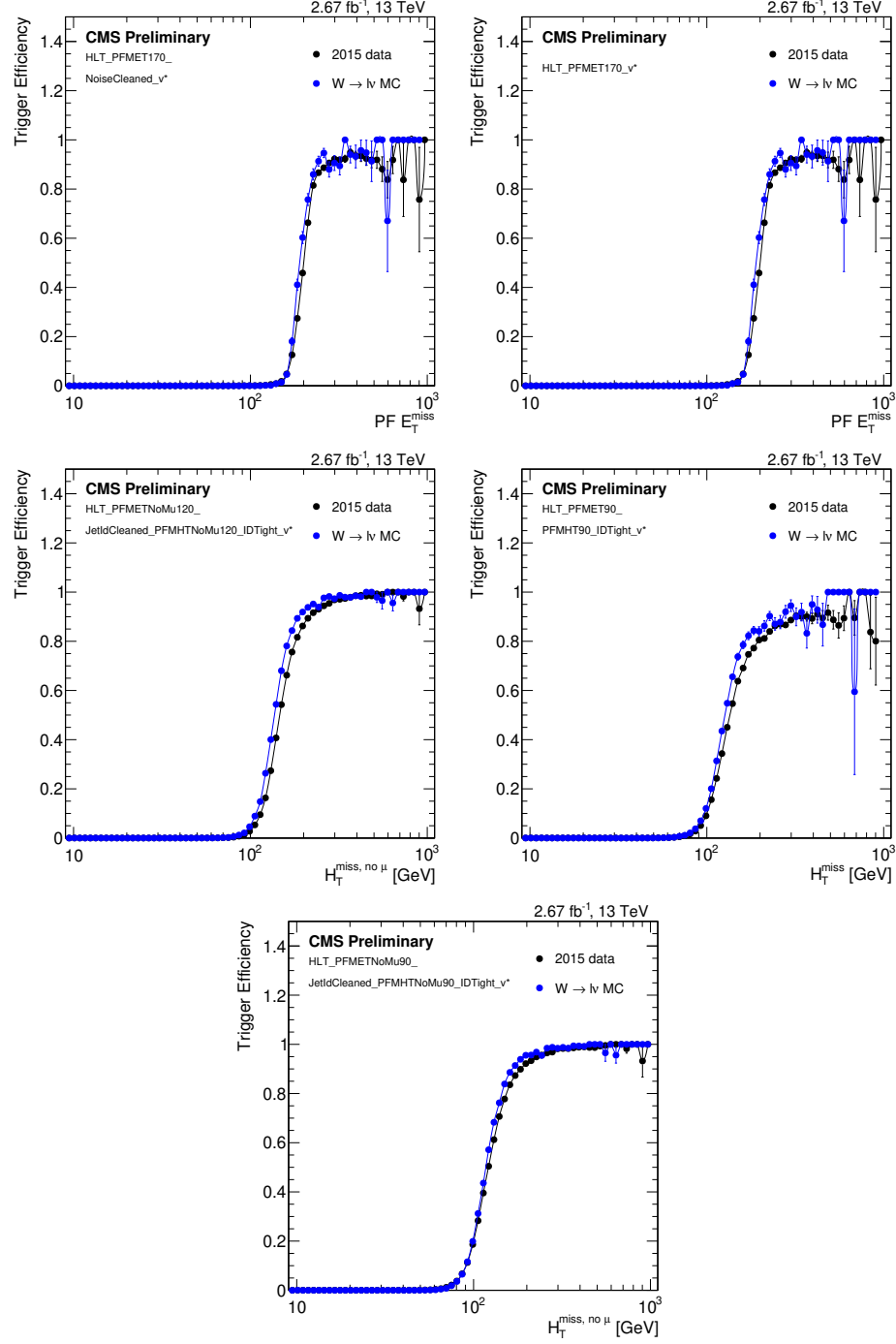


Figure F.4: Efficiencies of individual p_T^{miss} paths used in the combined signal trigger for 2016 B+C data, compared to $W \rightarrow l\nu$ Monte Carlo.

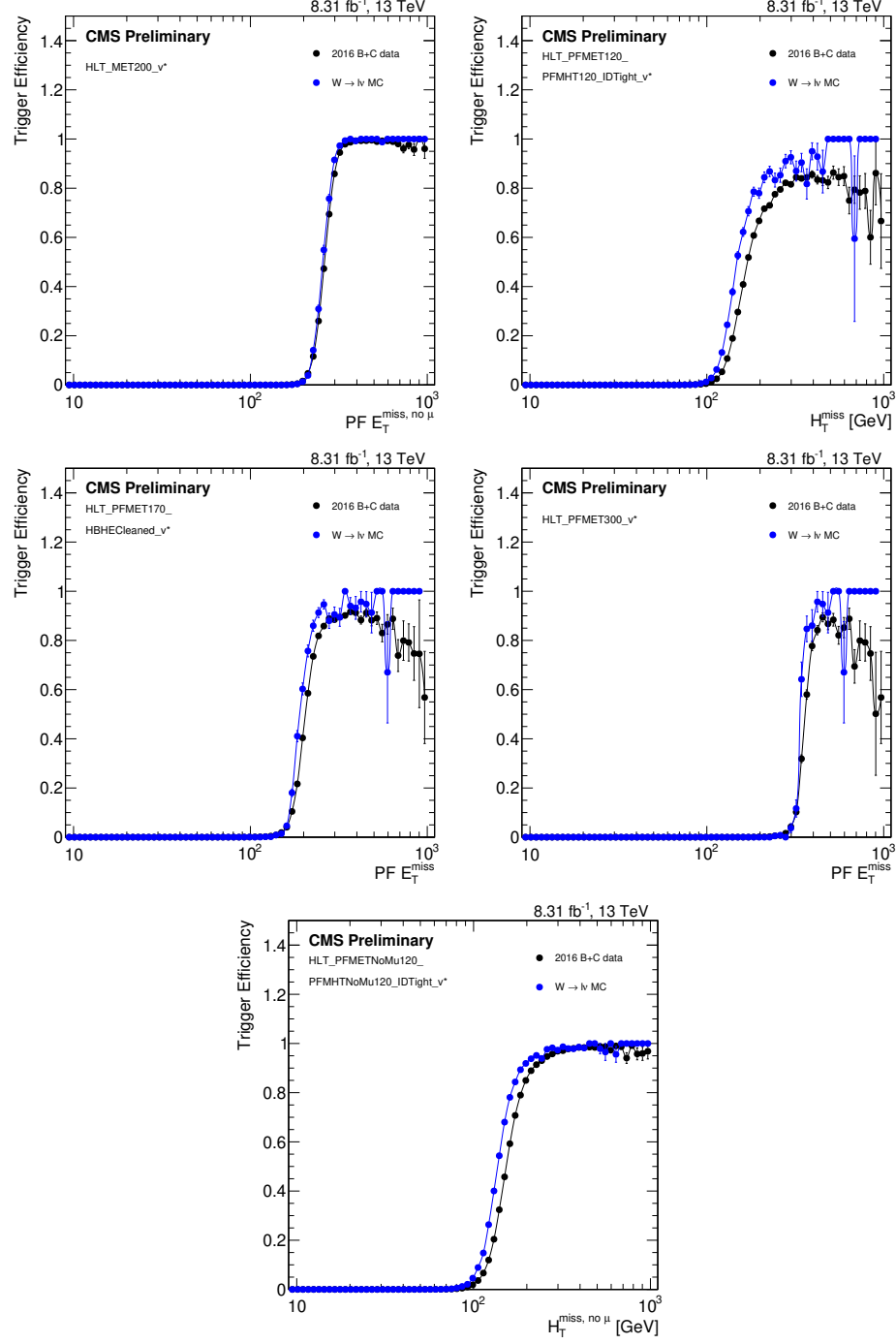
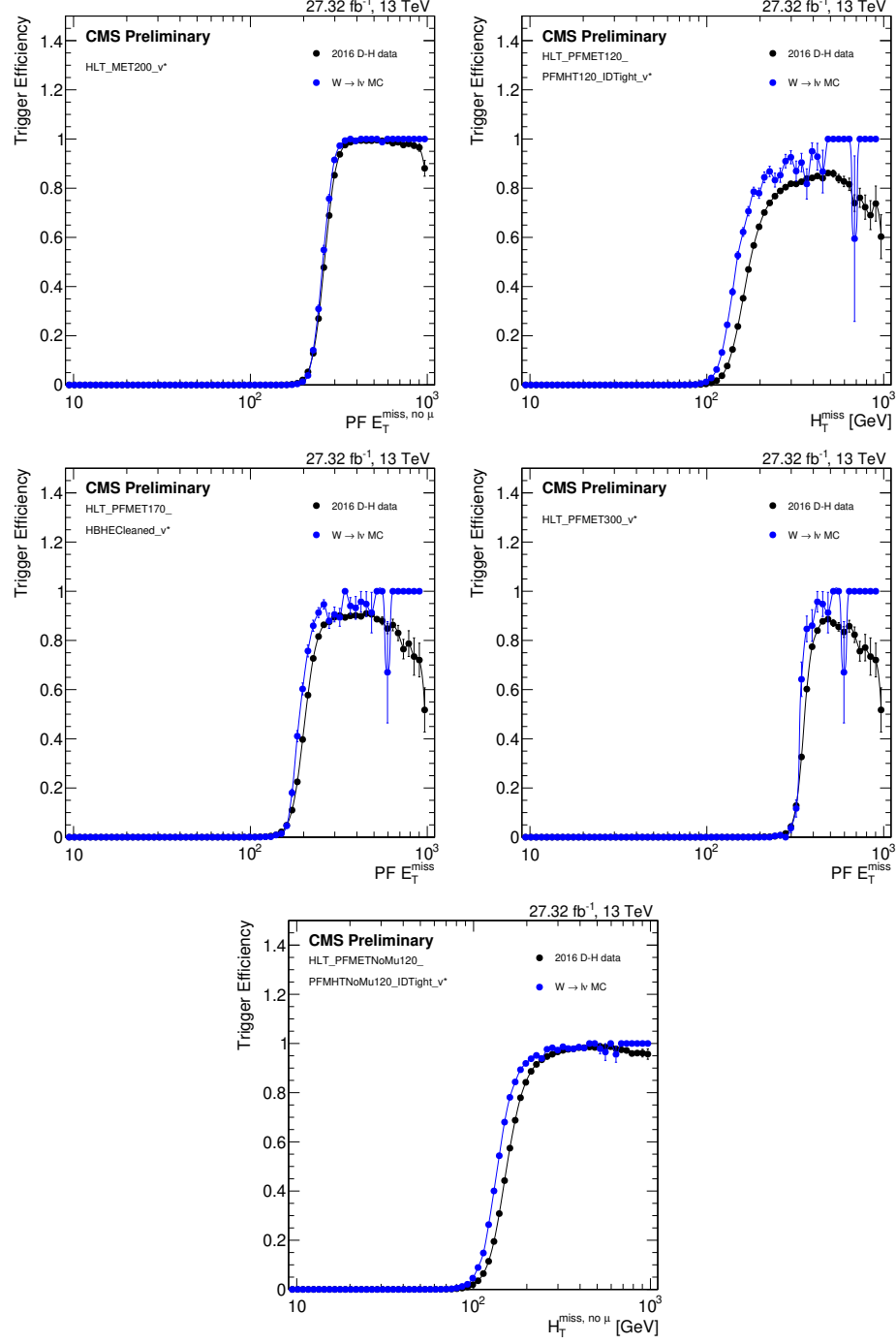


Figure F.5: Efficiencies of individual p_T^{miss} paths used in the combined signal trigger for 2016 D-H data, compared to $W \rightarrow l\nu$ Monte Carlo.



Appendix G: Algorithms for finding missing hits corrections

G.1 Algorithm for finding missing middle hits correction

Given a two-dimensional histogram, `uncorrectedMC`, of the number of hits in the strip detector vs. the number of missing middle hits filled using simulated background events and a probability to drop a single hit, `hitDropProbability`, the following procedure, `getCorrectedMC`, returns the expected distribution of missing middle hits.

```
Sub getExtraMissingMiddleHitsPDF (nHits, hitDropProbability)
  Book 1D histogram pdf
  For iToy = 0 to 10000
    missingMiddleHits = 0
    countMissingMiddleHits = False

    For iHit = 0 to nHits
      x = Random number in [0, 1)
      hit = x > hitDropProbability

      If not hit and countMissingMiddleHits Then
        missingMiddleHits = missingMiddleHits + 1
      Else If hit Then
        countMissingMiddleHits = True
      End If

    Next iHit
    pdf.Fill (missingMiddleHits)
  Next iToy

  Normalize histogram pdf

  Return pdf
End Sub

Sub getCorrectedMC (uncorrectedMC, hitDropProbability)
  Book 1D histogram correctedMC
  For nHits = 1 to 20
    extraMissingMiddleHitsPDF = getExtraMissingMiddleHitsPDF (nHits, hitDropProbability)

    For originalMissingMiddleHits = 0 to 6
      bin = uncorrectedMC.FindBin (originalMissingMiddleHits, nHits)
      nTracks = uncorrectedMC.GetBinContent (bin)
```

```

For extraMissingMiddleHits = 0 to 6
    bin = extraMissingMiddleHitsPDF.FindBin (extraMissingMiddleHits)
    extraMissingMiddleHitProbability = extraMissingMiddleHitsPDF.GetBinContent (bin)

    missingMiddleHits = originalMissingMiddleHits + extraMissingMiddleHits
    bin = correctedMC.FindBin (missingMiddleHits)
    currentNTracks = correctedMC.GetBinContent (bin)

    correctedMC.SetBinContent (bin, currentNTracks + nTracks * extraMissingMiddleHitProbability)

Next extraMissingMiddleHits
Next originalMissingMiddleHits
Next nHits

Return correctedMC
End Sub

```

G.2 Algorithm for finding missing outer hits corrections

Given a three-dimensional histogram, `uncorrectedMC`, of the number of hits in the strip detector vs. the number of hits in the TOB vs. the number of missing outer hits filled using simulated background events, a probability to drop a single hit, `hitDropProbability`, and a probability to drop every hit in the TOB, `tobDropProbability`, the following procedure, `getCorrectedMC`, returns the expected distribution of missing outer hits.

```
Sub getExtraMissingOuterHitsPDF (nHits, hitDropProbability)
  Book 1D histogram pdf
  For iToy = 0 to nToys
    missingOuterHits = 0
    For iHit = 0 to nHits
      x = Random number in [0, 1)
      hit = x > hitDropProbability

      If not hit Then
        missingOuterHits = missingOuterHits + 1
      Else
        Break
      End If
    Next iHit
    pdf.Fill (missingOuterHits)
  Next iToy

  Normalize histogram pdf

  Return pdf
End Sub

Sub getCorrectedMC (uncorrectedMC, hitDropProbability, tobDropProbability, preOrPostTOB)
  Book 1D histogram correctedMC
  For nHits = 1 to 20
    extraMissingOuterHitsPDF = getExtraMissingOuterHitsPDF (nHits, hitDropProbability)
    For originalMissingOuterHits = 1 to 16
      For tobHits = 1 to 16
        bin = uncorrectedMC.FindBin (originalMissingOuterHits, tobHits, nHits)
        nTracks = uncorrectedMC.GetBinContent (bin)

        For extraMissingOuterHits = 0 to 16
          bin = extraMissingOuterHitsPDF.FindBin (extraMissingOuterHits)
          extraMissingOuterHitsProbability = extraMissingOuterHitsPDF.GetBinContent (bin)

          If preOrPostTOB = "PRE_TOB" Then
            missingOuterHits = originalMissingOuterHits + extraMissingOuterHits
            missingOuterHitsWithTOBDrop = originalMissingOuterHits + tobHits
          Else If preOrPostTOB = "POST_TOB" Then
            missingOuterHits = originalMissingOuterHits
            missingOuterHitsWithTOBDrop = originalMissingOuterHits + extraMissingOuterHits + tobHits
          End If

          bin = correctedMC.FindBin (missingOuterHits)
          currentNTracks = correctedMC.GetBinContent (bin)
        Next extraMissingOuterHits
      Next tobHits
    Next originalMissingOuterHits
  Next nHits
End Sub
```



```

        correctedMC.SetBinContent (bin, currentNTracks + nTracks \
                                * extraMissingOuterHitsProbability * (1 - tobDropProbability))

        bin = correctedMC.FinDBin (missingOuterHitsWithTOBDrop)
        currentNTracks = correctedMC.GetBinContent (bin)
        correctedMC.SetBinContent (bin, currentNTracks + nTracks \
                                * extraMissingOuterHitsProbability * tobDropProbability)

    Next extraMissingOuterHits
  Next tobHits
  Next originalMissingOuterHits
Next nHits

Return correctedMC
End Sub

```

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