

FLORIDA STATE UNIVERSITY
COLLEGE OF ARTS AND SCIENCES

SEARCH FOR A LIGHT PSEUDOSCALAR HIGGS BOSON IN THE TWO HIGGS
DOUBLET MODEL AND OPERATIONS, COMMISSIONING OF THE CMS PHASE-1
PIXEL DETECTOR

By

REDWAN MD HABIBULLAH

A Dissertation submitted to the
Department of Physics
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

2022

Copyright © 2022 Redwan Md Habibullah. All Rights Reserved.



Redwan Md Habibullah defended this dissertation on June 30, 2022.
The members of the supervisory committee were:

Rachel Yohay
Professor Directing Dissertation

Jonathan Dennis
University Representative

Andrew Warren Askew
Committee Member

Volker Crede
Committee Member

Takemichi Okui
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the dissertation has been approved in accordance with university requirements.

TABLE OF CONTENTS

List of Tables	vii
List of Figures	viii
Abstract	xx
1 Introduction	1
2 Theoretical Background	7
2.1 The Standard Model and Its Shortcomings	7
2.1.1 The matter and gauge content of the Standard Model	7
2.1.2 The Higgs mechanism	9
2.1.3 Limitations of the Standard Model	13
2.2 Supersymmetry	15
2.3 MSSM	15
2.4 NMSSM	16
2.5 Phenomenological Models	17
2.6 $h \rightarrow 2\mu 2\tau$ Final State	20
2.7 Related Work and Other Motivations	21
3 The Large Hadron Collider (LHC)	23
3.1 Structural Attributes and Performance Constraints	25
3.1.1 Structural layout	25
3.1.2 Performance constraints	30
3.2 Magnets	31
3.3 Cryogenics	33
3.4 Injection Chain	35
3.5 The Radio Frequency Cavities	36
4 CMS Detector	38
4.1 Electromagnetic Calorimeter	39
4.1.1 Lead tungstate crystals	39
4.1.2 The structure of the ECAL	40
4.1.3 Readout of the ECAL	43
4.1.4 Performance of the ECAL	45
4.1.5 Impact of radiation on ECAL response	46
4.2 CMS Tracker	47
4.2.1 Status of the strip tracker	47
4.3 Performance of the Strips Tracker	49
4.4 Hadronic Calorimeter	52
4.4.1 HB	52

4.4.2	HE	54
4.4.3	HO	55
4.4.4	HF	58
4.5	Muon Chambers	59
4.5.1	Drift tube system	60
4.5.2	Cathode strip chambers	61
4.5.3	Resistive plate chambers	62
5	The Pixel Detector	64
5.1	Pixel Detector and Its Upgrade	64
5.2	Phase-1 Pixel DAQ and Control System	68
5.2.1	Front-end ASICS	69
5.2.2	Back-end	74
5.2.3	Portcards	78
5.3	Operational Challenges of the Pixel Detector	79
5.4	Performance of the Pixel Detector	80
5.5	Refurbishment, Re-installation and Commissioning	84
6	Pixel Projects	86
6.1	Radiation Damage Correction Studies	86
6.1.1	The readback mechanism	86
6.1.2	Radiation damage correction studies	88
6.1.3	Formulation for radiation damage correction	94
6.1.4	Results	103
6.1.5	Conclusion	104
6.2	The Automatic Timing Scan	105
6.2.1	Pixel timing scan	105
6.2.2	Timing scan procedure for Run 2	107
6.2.3	Motivation for the automatic timing scan	109
6.2.4	Procedure of the automatic timing scan	109
6.2.5	Status	111
6.3	Pixel Monitoring	111
6.3.1	ROC monitoring project	111
7	Analysis	113
7.1	Analysis Strategy	113
7.1.1	Tau decay channels and Run 2 final states	114
7.1.2	$\mu\mu\tau_e\tau_h$ final state	115
7.2	Objects	117
7.2.1	Electrons	117
7.2.2	Muons	118
7.2.3	Taus	119
7.2.4	DiTau pair $\tau_h\tau_h$	120

7.3	Signal Selection and Background Rejection	121
7.4	Event Selections	121
7.4.1	Semi leptonic decay channels	122
7.4.2	Full leptonic decay channels	124
7.4.3	Full hadronic decay channel	125
7.5	Tau Scale Factor Measurement	126
7.6	Datasets and Trigger	134
7.6.1	Monte Carlo samples	135
7.7	Background Estimation	135
7.7.1	Fully-leptonic final states	135
7.7.2	Semi-leptonic final states	144
7.7.3	Fully hadronic final state	151
7.8	Fitting Strategy	154
7.8.1	Fit for the fully leptonic final states	155
7.8.2	Fit for semi-leptonic and fully hadronic final states	156
7.8.3	Signal modelling	165
7.9	Systematic Uncertainties	165
7.9.1	Sources of systematic uncertainties	170
7.10	Discovery and Limit Setting	171
7.11	Results and Interpretation	172
7.12	Conclusion	172

Appendix

A	Jet to Tau Fake Rate	183
B	Tau Efficiency	186
B.1	Hadronic Tau Reconstruction Efficiency	187
B.2	Di-Tau Reconstruction Efficiency	188
C	Auxiliary Electronics and Optical Components - Details	192
C.1	POH	193
C.2	DOH	193
C.3	DC-DC Converters	193
C.4	Portcards	194
D	Deep Neural Network Application for Fully Hadronic Final State	196
D.1	Training Information	196
D.2	Network Architecture	196
D.2.1	Performance	197

E Observed Data	200
Bibliography	213
Biographical Sketch	219

LIST OF TABLES

2.1	Field content of the MSSM and their corresponding quantum numbers. Just one generation of quarks and leptons is shown here. Reprinted from [1].	16
2.2	The couplings of pseudoscalar mass eigenstates to fermions and gauge fields in the type-II and type-III models.	18
5.1	The different types of TBMs and their various properties. partially reprinted from [55].	70
6.1	The readback types and their corresponding values.	87
6.2	The delivered luminosity for various modules by the end of 2018 and the estimated fluence using the per fb^{-1} values from Ref. [73]. The values were only given for the BPix layers.	97
6.3	Radiation dose estimate for each (BPix) layer by the end of 2018 calculated using the Fluka estimates. The dose estimate for each (FPix) ring is determined using an unofficial estimate which depends on the ring radius [75].	99
6.4	Percentage (average) shift in V_{bg} for each layer at the end of 2018.	101
7.1	Various cuts of the loose working point of the cut based electron ID.	117
7.2	The list of the nuisance parameters with their initial systematic uncertainties.	131
7.3	The list of the tau ID scale factors and their uncertainties measured using the full runII data. The numbers in the brackets stand for the measured results for $p_T(\tau_h) > 20 \text{ GeV}$ (not elaborated here).	131
7.4	Collision datasets and integrated luminosity	134
7.5	Background MC samples for the 2016,2017 and 2018.	136
7.6	Systematic uncertainties.	170
E.1	Table showing in detail the Background MC samples for the 2016,2017 and 2018. Era, pythia tune, campaign and version information included.	212

LIST OF FIGURES

1.1	Summary plot of the fit to the per-production mode (left) and per-decay mode (right) signal strength modifiers. The last point in the per-production mode summary plot is taken from a separate fit and indicates the result of the combined overall signal strength μ . Reprinted from [4].	2
1.2	Results with the generic κ -framework, taking into account effective loops with the constraint $ \kappa_W , \kappa_Z \leq 1$ and $B_{inv} > 0$ and $B_{undet} > 0$ as free parameters. 68% and 95% CL regions for B_{inv} vs B_{undet} are shown here [6].	4
2.1	The Standard Model of particle physics [7].	7
2.2	The interactions in the Standard Model. Reprinted from [10].	9
2.3	The Higgs potential on a plane defined by the real and imaginary parts of the complex scalar field [10].	11
2.4	(top) The $\gamma\gamma$ invariant mass distribution where each event is weighted by the ratio of signal over signal plus background, for each sub-category of events . (bottom) Distribution of the four-lepton reconstructed mass for the sum of the $4e$, 4μ , and $2e2\mu$ channels. Reprinted from [3].	14
2.5	Decay of Higgs to a pair of pseudoscalars. One decays to a pair of τ 's while the other decays to a pair of μ 's.	18
2.6	Pseudoscalar branching ratios to various final states for Type-II Yukawa couplings at two different values of $\tan \beta$. Reprinted from Ref[2].	19
2.7	Branching ratios for various final states for Type III Yukawa couplings at two different values of $\tan \beta$. Reprinted from Ref[2].	19
3.1	A representation of the Large Hadron Collider (LHC) along with the positioning of other experiments. Reprinted from Reference [36].	24
3.2	A schematic layout of the Large Hadron Collider (LHC) . Reprinted from Reference [37].	26
3.3	Overview of the beam dump system at IR6. Reprinted from reference [38].	28
3.4	The magnet assembly of a single arc cell following the FODO structure, reprinted from [38].	29
3.5	The cross-section of the LHC dipole . Reprinted from reference [37].	32

3.6	A schematic view of the cryogenic system, showing the 'Islands' and the location of the refrigeration plants. Reprinted from reference [37].	34
3.7	The injector complex of the LHC. Reprinted from Reference [37].	35
3.8	Cryomodule containing the RF cavities. Reprinted from Reference [37]. . . .	36
4.1	A transverse slice through the CMS detector showing the various sub-detectors and the path of various particles through the detector.	38
4.2	ECAL crystal with the photo-detector [40].	40
4.3	The structural layout of the CMS ECAL. This shows the module and super-modules of the ECAL barrel as well as the endcap and pre-shower. Reprinted from Reference [41].	41
4.4	Half-Disk (Dee) of the ECAL endcap [42].	42
4.5	A schematic view of the readout of the ECAL [41].	44
4.6	Relative electron (ECAL) energy resolution unfolded in bins of pseudorapidity η for the ECAL Barrel and the ECAL Endcaps. The resolution is showed separately for low bremsstrahlung electrons (left) and for all electrons (right). Reprinted from Reference [44].	45
4.7	ECAL response to laser light [45].	46
4.8	The fraction of inactive components for the CMS silicon strip detector as a function of the delivered LHC integrated luminosity [46].	48
4.9	The signal-to-noise ratio for modules in the TIB(left) and TOB(right), corrected for path length inside the silicon sensors. The position of the Most Probable Value (MPV) is estimated using a fit to a Landau convoluted to a Gaussian and represents the signal-to-noise ratio [48].	49
4.10	The hit efficiency of s silicon strip detectors for four TIB (left) and five TOB (right) layers as a function of instantaneous luminosity [48].	50
4.11	The muon momentum resolution as a function of transverse momentum, using muon system and only, inner tracker only and both. Reprinted from Reference [41].	51
4.12	Muon reconstruction efficiency as a fuction of pseudorapidity for the tracker.	51
4.13	Schematic view of the CMS detector showing parts of the HCAL. The locations of the Hdaron barrel (HB), endcap (HE), outer (HO) and forward (HF) calorimeters. [41].	53

4.14	Schematic diagram showing the HE absorber. [41].	55
4.15	Diagram showing the HE scintillator tray. [41].	55
4.16	Schematic diagram showing the layout of the HO trays.[41].	56
4.17	Schematic view of an HO tray shown with individual tiles and the corresponding grooves for WLS fibres.Each optically independent (four WLS fibres) tile is mapped to an HB tower. Optical fibres from the tray are routed to the decoder box, which contains the photodetector and read-out electronics.[41].	57
4.18	The cross sectional view of the HF calorimeter [41].	58
4.19	A schematic diagram of the Muon system geometry.[50].	59
4.20	Layout of the DT chambers in one of the 5 wheels[41].	60
4.21	Sketch of a cell showing drift lines and isochrones[41].	61
4.22	Layout of a CSC[41].	62
4.23	The operational principle of the CSC[41].	63
5.1	A conceptual layout comparing the different layers and disks in previous and the current pixel detector [51].	64
5.2	A transverse view comparing the pixel barrel layers in the previous and the current pixel detector [51].	65
5.3	Pixel modules for BPix layer 1 (left), BPix layer 2-4 (middle), and the FPix (right). [52].	66
5.4	Phase-1 BPix and FPix detectors together with the service half-cylinders that hold the readout and control circuits as well as power and cooling lines [52]. .	67
5.5	Overview of the Phase-1 pixel DAQ [55]. It shows the communication between the DAQ components. The hit data from the modules go to the FED through the POH, and from there to the Central DAQ. Configuration data for the modules comes from the computer to the Pixel Front-End Controller (PixFEC) and then are forwarded through the modified Digital OptoHybrid (mDOH) to the modules. Configuration data for the auxiliary electronics are sent from the Tracker Front-end Controller (TkFEC) to the Command and Control Unit (CCU) and then to the portcard (through the Digital OptoHybrid (DOH)). Advanced Mezzanine Card 13 (AMC13) distributes clock and triggers to all the components.	68

5.6	Readout scheme for readout chips showing the passing of the token and the double column readout [56].	69
5.7	Schematic diagram of the TBM chip that shows the path that readout data follow, as well as the different components taking part in the procedure. The data from the ROCs are transmitted to the TBM at the speed of 160 Mbit/s. For each TBM core they are then multiplexed into streams of 320 Mbit/s and then encoded (400 Mbit/s), before they are sent out to the FED. [55].	71
5.8	The parts of a pixel unit cell [57].	72
5.9	PSI46dig chip[58]. On the top part of the chip the pixels are organized in 26 double columns of 2x80 pixels each. Below the pixels are the 80 data buffers, and after that the 24 timestamp buffers.	73
5.10	The Pixel FED card consists of an FC7 board and the Rx-FMC mezzanine card. BPix uses 80 FEDS while FPix uses 28 FEDs [59].	75
5.11	The different states of FED [59].	76
5.12	FEC (Pix and TK) cards have the same FC7 board as the FEDs but a different mezzanine card. TkFEC and PixFEC have the same hardware and differs only in firmware. BPix uses 80 FEDs, 8 Px FECs and 2 TkFECs. FPix uses 28 FEDs, 8 Px FECs and 1 TkFEC [59].	77
5.13	Distribution of the ROC thresholds in terms of number of electrons for all four layers of the BPix [63].	81
5.14	Hit efficiency of various layers and disks of the Phase-1 pixel detector.	82
5.15	Hit residuals for layer 2 (top left), layer 3 (top right) and disk 2 (bottom) using the triplet reconstruction method [64].	83
5.16	Part of FPix detector undergoing cooling repairs (left) and a part of BPix being craned over from the clean room to the CMS underground tunnel prior to installation (right).	84
6.1	Average value of V_d in ADC units (top) and after conversion to volts (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.	89
6.2	Average value of V_a in ADC units (top) and after conversion to volts (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.	90

6.3	Average value of V_{ana} in ADC units (top) and after conversion to volts (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.	91
6.4	Average value of V_{bg} in ADC units (top) and after conversion to volts (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.	92
6.5	Average value of I_{ana} in ADC units (top) and after conversion to mA (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.	93
6.6	The change in bandgap voltage (left) and percentage shift in bandgap voltage (right) with irradiation dose. The values were taken for PROC600 chips [68].	95
6.7	Total delivered luminosity for the year 2018 from CMS public plots (left) [70] and LHC performance plots (right) [71]	96
6.8	Total delivered luminosity for 2018 (left) and the total delivered luminosity with 2017 included (right).	97
6.9	Radiation dose for a layer 1 ROC (BPix_BmO_SEC1_LYR1_LDR1F_MOD3_ROC12) in Mrad (left) and MGy (right) as a function of time in 2018.	98
6.10	Radiation dose for a layer 2 ROC (BPix_BpO_SEC6_LYR2_LDR10F_MOD2_ROC5) in Mrad (left) and MGy (right) as a function of time in 2018.	99
6.11	Radiation dose for a layer 3 ROC (BPix_BmO_SEC8_LYR3_LDR22F_MOD1_ROC14) in Mrad (left) and MGy (right) as a function of time in 2018.	100
6.12	Radiation dose for a layer 4 ROC (BPix_BpI_SEC1_LYR4_LDR1F_MOD2_ROC0) in Mrad (left) and MGy (right) as a function of time in 2018.	100
6.13	Radiation dose for ROCs in different layers, in Mrad (left) and MGy (right) as a function of time in 2018.	101
6.14	Fit to the graph in order to obtain the percentage shift in bandgap voltage at any value of the dose.	102
6.15	The $V_a[V]$ uncorrected value (green), the value multiplied by ratios of V_{bg} (blue), and the corrected value (red) as a function of time.	103
6.16	Radiation damage correction results for ROCs in layer 3 (left) and layer 1 (right). Both plots show the $V_a[V]$ uncorrected (green), the values multiplied by ratios of V_{bg} (blue), and the corrected values (red) as a function of time. . .	104

6.17	Radiation damage correction results for ROCs in layer 2. The quantities shown are the uncorrected (green) and corrected (red) values for $V_{\text{ana}}[\text{V}]$ (left) and $V_{\text{d}}[\text{V}]$ (right) as a function of time.	105
6.18	WBC and clock/trigger delay to correctly time the signal/hit.	107
6.19	The Timing scan for (left) several layers of the BPix and (right) various disks of the FPix.	108
6.20	LHC and Pixel Status for a Timing scan performed during Run 2 (2018). . .	108
6.21	LHC, pixel and global status during Soft Error Recovery	110
6.22	Procedure of the automatic timing scan	110
7.1	The masses of Higgs boson and of pseudoscalars (a) that are searched in this analysis.	114
7.2	Tau decay channels considered in the analysis.	116
7.3	Schematic diagram of jet cleaning, reprinted from [80].	120
7.4	Graphic depicting ABCD method for $\mu\mu\tau_\mu\tau_h$. Region definitions for $\mu\mu\tau_e\tau_h$ and $\mu\mu\tau_h\tau_h$ are similar.	123
7.5	Comparison between data and simulation for $10 < p_T(\tau_h) < 20$ GeV in the distribution of $M_T(\tau_\mu, E_T^{\text{miss}})$ in different years, regardless of the requirement in $M_T(\tau_\mu, E_T^{\text{miss}})$. These are pre-fit results. The error bars stand for statistical uncertainties.	128
7.6	Comparison between data and simulation for $10 < p_T(\tau_h) < 20$ GeV in the distribution of $p_T(\tau_h)$ in different years, regardless of the requirement in $p_T(\tau_h)$. These are pre-fit results. The error bars stand for statistical uncertainties. . .	129
7.7	The re-scaling factor of the QCD background as a function of $M^{\text{vis}}(\mu\tau_h)$ for $10 < p_T(\tau_h) < 20$ GeV, using the data taken in different years. The error bars stand for statistical uncertainties from a data-driven approach.	130
7.8	The re-scaling factor of the W+jets background as a function of $M^{\text{vis}}(\mu\tau_h)$ for $10 < p_T(\tau_h) < 20$ GeV, using the data taken in different years. The error bars stand for the quadrature summation of the statistical uncertainties of the data and MCs.	130
7.9	The shape varied distribution of the QCD background as a function of $M^{\text{vis}}(\mu\tau_h)$ for $10 < p_T(\tau_h) < 20$ GeV, using the data taken in different years.	132

7.10	The shape varied distribution of the W+jets background as a function of $M^{vis}(\mu\tau_h)$ for $10 < p_T(\tau_h) < 20$ GeV, using the data taken in different years. .	132
7.11	Comparison between data and simulation for $10 < p_T(\tau_h) < 20$ GeV in the distribution of $M^{vis}(\mu\tau_h)$ in different years. These are pre-fit results. The error bars stand for statistical uncertainties, while the systematic uncertainties are amounted as the fence bands.	133
7.12	Comparison between data and simulation for $10 < p_T(\tau_h) < 20$ GeV in the distribution of $M^{vis}(\mu\tau_h)$ in different years. These are post-fit results. The error bars stand for statistical uncertainties, while the systematic uncertainties are amounted as the fence bands.	133
7.13	Comparison between 2017 data and simulation with the tight requirement $ M_{inv}(\mu_1, \mu_2) - M_Z < 10$ GeV, and additional μ_3 with isolation < 0.15 (left) and with isolation < 0.4 (right).	138
7.14	Comparison between 2017 data and simulation with the tight requirement $ M_{inv}(\mu_1, \mu_2) - M_Z < 10$ GeV, and additional electron with loose electron ID (left) and with veto electron ID while isolation < 0.6 (right).	138
7.15	Fake rates as a function of the probe p_T for muons which satisfy the loose selection criteria, measured in a $Z(\ell\ell) + \ell$ sample in the 2016 (left), 2017 (middle), 2018 (right) data at 13 TeV. Comparison of data with tight requirement $ M_{inv}(\mu_1, \mu_2) - M_Z < 10$ GeV, and an additional μ_3 with different isolation requirements.	139
7.16	Fake rates as a function of the probe p_T for electrons which satisfy the loose selection criteria, measured in a $Z(\ell\ell) + \ell$ sample in the 2016 (left), 2017 (middle), 2018 (right) data at 13 TeV. Comparison of data with tight requirement $ M_{inv}(\mu_1, \mu_2) - M_Z < 10$ GeV, and an additional electron with different electron IDs.	140
7.17	Dimuon invariant mass distribution of the events selected in the 2P+2F control sample in the 2017 dataset for the $\mu\mu\tau_\mu\tau_e$ channel.	141
7.18	Four-lepton invariant mass distribution of the events selected in the 2P+2F control sample in the 2017 dataset for the $\mu\mu\tau_{mu}\tau_e$ channel.	141
7.19	Dimuon invariant mass distribution of the events selected in the 3P+1F control sample in the 2017 dataset for all the considered channels: 4μ (left), $2\mu 2e$ (middle) and $3\mu e$ (right).	142
7.20	Four-lepton invariant mass distribution of the events selected in the 3P+1F control sample in the 2017 dataset for the $\mu\mu\tau_\mu\tau_e$ channel.	143

7.21	Dimuon invariant mass distribution of the events extrapolated in the signal region in the 2017 dataset for the $\mu\mu\tau_\mu\tau_e$ channel.	144
7.22	Four-lepton invariant mass distribution of the events extrapolated in the signal region in the 2017 dataset for the $\mu\mu\tau_\mu\tau_e$ channel.	145
7.23	The tau fake rates used in estimating the signal region for $\tau_\mu\tau_h$ pair, using 2016 (left), 2017 (middle), and 2018 (right) data. The denominator consists of "jets" selected as a muon cleaned tau from the HPS algorithm passing "decayModeFinding". The numerator are the "jets" that pass the medium MVA isolation. Rates are separated by decay mode: DM0 (one prong), DM1 (one prong + π^0), and DM10 (3 prongs + π^0 s).	147
7.24	The tau fake rates used in estimating the signal region for $\tau_e\tau_h$ pair, using 2016 (left), 2017 (middle), and 2018 (right) data. The denominator consists of "jets" selected as a electron cleaned tau from the HPS algorithm passing "decayModeFinding". The numerator are the "jets" that pass the medium MVA isolation. Rates are separated by decay mode: DM0 (one prong), DM1 (one prong + π^0), and DM10 (3 prongs + π^0 s).	147
7.25	Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_\mu\tau_h$ channel, using 2016 data. Additionally, total events are split by decay mode.	148
7.26	Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_\mu\tau_h$ channel, using 2017 data. Additionally, total events are split by decay mode.	149
7.27	Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_\mu\tau_h$ channel, using 2018 data. Additionally, total events are split by decay mode.	149
7.28	Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_e\tau_h$ channel, using 2016 data. Additionally, total events are split by decay mode.	150
7.29	Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_e\tau_h$ channel, using 2017 data. Additionally, total events are split by decay mode.	150
7.30	Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_e\tau_h$ channel, using 2018 data. Additionally, total events are split by decay mode.	151
7.31	Fake rate uncertainty estimation for in $\tau_\mu\tau_h$ channel, using 2016, 2017, and 2018 data. All decay modes are added and discrepancy compared in low p_T regions.	152

7.32	Fake rate uncertainty estimation for in $\tau_e\tau_h$ channel, using 2016, 2017, and 2018 data. All decay modes are added and discrepancy compared in low p_T regions.	152
7.33	The fake rates used in estimating the signal region for $\tau_h\tau_h$ pair, using 2016 (left), 2017 (middle), and 2018 (right) data. The denominator consists of a reconstructed jet selected with very loose working point (0.2) of “DeepDiTau” discriminator. The numerator are having a ”jet” that pass the different customized working points of “DeepDiTau” discriminator.	153
7.34	Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_h\tau_h$ channel, using 2016 (left), 2017 (middle), and 2018 (right) data.	154
7.35	Prefit dimuon mass distributions for the signal region in the $\tau_\mu\tau_e$ final state.	157
7.36	Prefit $m_{\mu\mu}$ distributions for the control region.	158
7.37	Schematic of the fit regions in the semi-leptonic final states. Events with two isolated muons enter the control region (blue). Events which additionally have a ditau candidate are further divided on the isolation of the ditau object with isolated ditau candidates forming the signal region (green) and anti-isolated ditau candidates forming the sideband (red). Additionally, anti-isolating the dimuon candidates forms two analogous regions for the misidentification efficiency validation (gray).	160
7.38	Prefit dimuon (left) and 4-body (right) visible mass distributions for the sideband region in the $\tau_e\tau_h$ final state.	162
7.39	Prefit dimuon (left) and 4-body (right) visible mass distributions for the sideband region in the $\tau_\mu\tau_h$ final state.	163
7.40	Prefit dimuon (left) and 4-body (right) visible mass distributions for the sideband region in the $\tau_h\tau_h$ final state.	164
7.41	Modelling of the signal dimuon (left) and 4-body (right) visible mass distributions for various pseudoscalar masses, $H = 125$ GeV.	166
7.42	Modelling of the signal dimuon (left) and 4-body (right) visible mass distributions.	167
7.43	Spline interpolation of the signal integral and dimuon mass modelling.	168
7.44	Spline interpolation of the signal 4-body mass modelling.	169
7.45	Full Run 2 expected limits for channels $\mu\mu\tau_\mu\tau_h$ (a), $\mu\mu\tau_e\tau_h$ (b), $\mu\mu\tau_h\tau_h$ (c), $\mu\mu\tau_\mu\tau_e$ (d). $H=125$ GeV.	173

7.46	Full Run 2 expected limits for channels $\mu\mu\tau_\mu\tau_h$ (a), $\mu\mu\tau_e\tau_h$ (b), $\mu\mu\tau_h\tau_h$ (c), $\mu\mu\tau_\mu\tau_e$ (d) . $H = 250$ GeV.	174
7.47	Observed Limit for channel $\mu\mu\tau_\mu\tau_h$	175
7.48	Observed data in 2018 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots are in the (dimuon) low mass region (2.5 GeV to 8.5 GeV).	176
7.49	Observed data in 2018 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The plots are in the low mass region.	177
7.50	Observed data in 2018 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots are in the (dimuon) upsilon region (6 GeV to 14 GeV).	178
7.51	Observed data in 2018 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The plots are in the upsilon region.	179
7.52	Observed data in 2018 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots are in the (dimuon) high mass region (11.5 GeV to 24.5 GeV).	180
7.53	Observed data in 2018 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The plots are in the high mass region.	181
A.1	Jet $\rightarrow$ tau fake rate for μ cleaned taus and standard taus for various years as a function of Jet Pt.	184
A.2	Jet $\rightarrow$ tau fake rate for e cleaned taus and standard taus for various years as a function of Jet Pt.	185
B.1	The reconstruction efficiency of the standard tau HPS (dashed line) and μ cleaned HPS (solid line) reconstruction as a function of pseudoscalar masses for different years and for $m_H = 125, 250, 500, 750$ and 1000	188
B.2	The reconstruction efficiency of the standard tau HPS (dashed line) and e cleaned HPS (solid line) reconstruction as a function of pseudoscalar masses for different years and for $m_H = 125, 250, 500, 750$ and 1000	189
B.3	The Di-Tau reconstruction efficiency of the standard tau HPS (dashed line) and μ cleaned HPS (solid line) reconstruction as a function of pseudoscalar mass for different years and for $m_H = 125, 250, 500, 750$ and 1000	191

B.4	The Di-Tau reconstruction efficiency of the standard tau HPS (dashed line) and e cleaned HPS (solid line) reconstruction as a function of pseudoscalar mass for different years and for $m_H = 125, 250, 500, 750$ and 1000	191
C.1	POH4 (left) and POH7 (right). The POH's are named based on the number of output optical fibres. POH4 is used in BPix while POH7 is used in FPix [55].	192
C.2	Four DC-DC converters on the a bus board. A pair of the converters are analog while the other pair is digital [52].	194
C.3	Picture of a portcard used in an FPix test setup. [90].	195
D.1	The light-jet and b-jet distributions in p_T and eta are re-weighted to match those of the τ_h, τ_h	197
D.2	Accuracy and loss plots of DeepDiTau.	198
D.3	The confusion matrix for DeepDiTau.	198
D.4	The performance of DeepDiTau in p_T ranges of $20 - 50 GeV$, $50 - 100 GeV$, $100 - 1000 GeV$	199
D.5	The performance of DeepDiTau in η ranges of $0 - 0.5$, $0.5 - 1.0$, $1.0 - 1.5$, $1.5 - 2.0$, $2.0 - 2.5$	199
E.1	Observed data in 2016 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. The data are in the low mass region.	200
E.2	Observed data in 2016 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The data are in the low mass region.	201
E.3	Observed data in 2016 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. The data are in the upilon region.	202
E.4	Observed data in 2016 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The data are in the upilon region.	203
E.5	Observed data in 2016 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. The data are in the high mass region.	204

E.6	Observed data in 2016 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The data are in the high mass region. . . .	205
E.7	Observed data in 2017 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots show the low mass region.	206
E.8	Observed data in 2017 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. These plots show the low mass region. . . .	207
E.9	Observed data in 2017 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots show the upsilin region.	208
E.10	Observed data in 2017 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. These plots show the upsilin region.	209
E.11	Observed data in 2017 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots show the high mass region.	210
E.12	Observed data in 2017 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. These plots show the high mass region. . . .	211

ABSTRACT

A search is presented for a light pseudoscalar Higgs boson using full Run 2 data (2016-2018) collected by the CMS (Compact Muon Solenoid) experiment at the LHC (Large Hadron Collider), corresponding to an integrated luminosity of 137.60 fb^{-1} and at a $\sqrt{s} = 13 \text{ TeV}$. The study looks into the decay Higgs boson (H) via the $H \rightarrow aa \rightarrow \mu\mu\tau\tau$ channel. The Higgs boson can be both standard-model-like (125 GeV) or heavier. The pseudoscalar mass falls within the range $m_a \in [2m_\tau, m_H/2]$. The large mass difference between the Higgs and the pseudoscalar means that the final tau lepton decay products are highly boosted in the decay direction and collimated. A modified version of tau reconstruction is used to account for the highly overlapping decay products. The modified reconstruction technique gives higher reconstruction efficiency over the standard tau reconstruction and hence better signal significance and background rejection. In the absence of a significant signal, model-independent limits are set at 95% C.L. on the branching fraction for $H \rightarrow aa \rightarrow \mu\mu\tau\tau$ as a function of m_a . The document also discusses the operations and commissioning of the CMS Phase-1 pixel detector.

CHAPTER 1

INTRODUCTION

The discovery of the 125 GeV Higgs boson at the Compact Muon Solenoid (CMS) and ATLAS detectors of the Large Hadron Collider (LHC) has been one of the most significant achievements of experimental and theoretical high energy physics. Although the Standard Model of particle physics (SM) successfully describes most phenomena, there are still a lot of unconquered territories to explore. The Higgs boson appears to complete the Standard Model by providing a mass generation mechanism for all the particles, but it also suggests that there may be physics beyond the Standard Model (BSM). For instance, the Higgs mechanism cannot explain *why* there is a hierarchy of mass scales among the particles. This hierarchy exists between the scale at which the electromagnetic and the weak forces unify ($\sim 10^2$ GeV) and the largest energy scale imaginable (the Planck scale $M_{pl} \sim 10^{19}$ GeV). The 17 orders of magnitude that exists between the well explored electroweak scale and the Planck scale may be explained by new physics[1]. One way to look for new physics is to search to for “exotic” decays of the Higgs; i.e., the decay of Higgs to new light states beyond the Standard Model[2].

The Higgs boson was discovered in 2012 [3]. However, the mass of the Higgs was not known particularly well. In addition, the couplings of the SM bosons and fermions to the Higgs boson also needed further studying for better understanding.

As experiments like CMS and ATLAS collected more data, scientists undertook further studies to determine the mass more precisely and better understand the nature of the couplings. The coupling measurements using partial or full Run 2 (2016-2018) data improved remarkably. Figure 1.1 shows a quick summary of the signal strength (μ) values for different decay modes and production modes of the Higgs. This diagram gives a sense of the precision with which the couplings are known at present. While these coupling are better known, they do not constraint every single extension to the standard model.

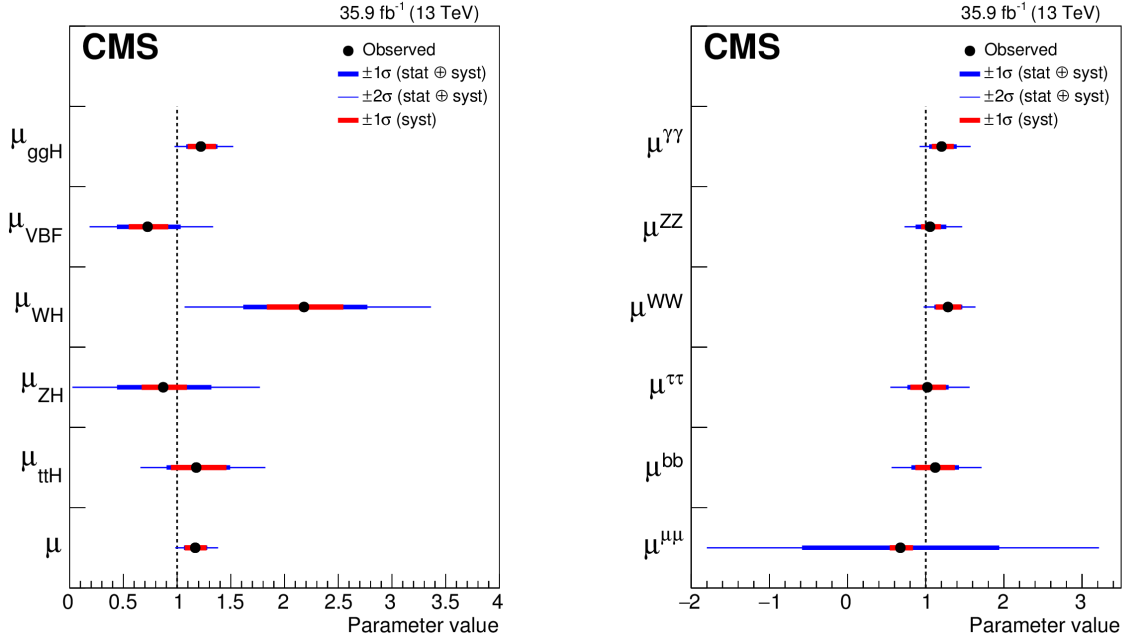


Figure 1.1: Summary plot of the fit to the per-production mode (left) and per-decay mode (right) signal strength modifiers. The last point in the per-production mode summary plot is taken from a separate fit and indicates the result of the combined overall signal strength μ . Reprinted from [4].

Recent studies into the Higgs boson’s properties as we accumulate more data have significantly constrained some beyond standard model theories. However, the present studies do not cover all the theoretically possible Higgs decay modes, and some undetermined decay modes may not have been observed and included in the combined analysis.

We had indications from Run I CMS and ATLAS combined results that there was much to explore in terms of undetected (“undet”) and invisible (“inv”) decays of the Higgs into beyond standard model particles. The results showed that $\text{BR}_{\text{undet}} + \text{BR}_{\text{inv}} < 0.34$ at 95% CL [5]. Undetected means decay to BSM particles that evade detection due to producing unsearched decay topologies or modifications of the decay branching fractions into SM particles in the case of channels not directly measured. Invisible refers to decays into BSM particles that do not interact appreciably with ordinary matter and thus are invisible to the detector.

In Run 2, the results were obtained from the κ -framework model where ggH and $H \rightarrow \gamma\gamma$ loops were scaled using coupling modifiers, κ . The coupling modifiers represent deviations in fermionic or bosonic Higgs boson couplings from the SM predictions. For a given production process or decay mode i , a coupling modifier κ_i is given by:

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$

Here σ represent cross-section and Γ represent the decay width. In one of the parametrizations the constraint $|\kappa_W|, |\kappa_Z| < 1$ and $\text{BR}_{\text{undet}}, \text{BR}_{\text{inv}}$ are allowed to vary freely as the parameters of interest (POI). This results in a 2D likelihood scan of the BR_{undet} vs BR_{inv} as shown in Figure 1.2. It is seen that $\text{BR}_{\text{undet}} < 0.28$ (0.47) at 68% (95%) CL in the 2D $\text{BR}_{\text{undet}} - \text{BR}_{\text{inv}}$ plane. **Thus, allowed branching ratio is as yet unseen exotic decay at 68% and 95% is < 30% and < 50% respectively.** Thus, this unconstrained branching ratio of undetected or exotics decay of the Higgs motivates direct searches for Higgs decay to exotics beyond the standard model.

The inability of the Higgs couplings to constrain the standard model extensions and the unconstrained branching ratio of Higgs decays to exotics provides the motivation for looking

into new physics couplings of the Higgs. And indeed, there is good reason to believe, based on theoretical ideas about extensions to the standard model, that there could be multiple Higgs doublets. The extensions to the standard model are also motivated by the fact that the extensions address some existing shortcomings of the standard model.

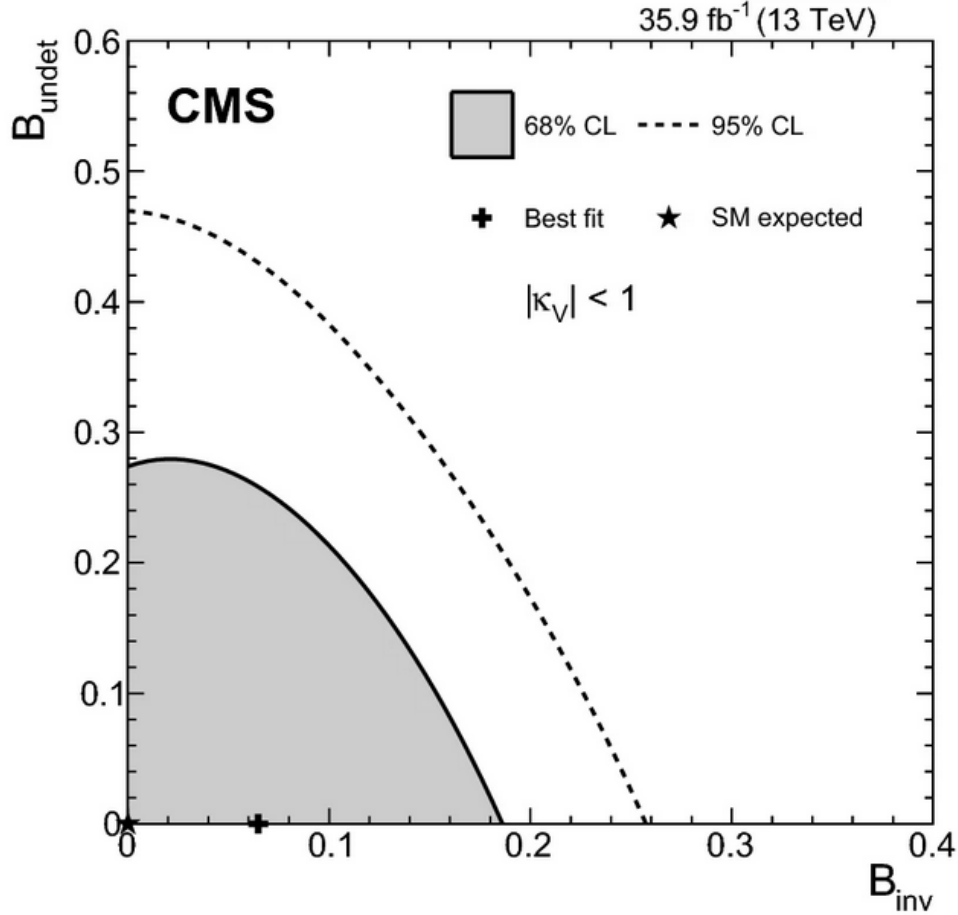


Figure 1.2: Results with the generic κ -framework, taking into account effective loops with the constraint $|\kappa_W|, |\kappa_Z| \leq 1$ and $B_{inv} > 0$ and $B_{undet} > 0$ as free parameters. 68% and 95% CL regions for B_{inv} vs B_{undet} are shown here [6].

In the sections that follow I will talk in more details about particular problems of the standard model and the solutions to these problems and additionally how they relate to the extended Higgs sectors.

In section 2.1.3 I will talk about the problems with the standard model. Next, I will talk about how supersymmetry addresses one of the problems with the standard model, particularly the Higgs hierarchy problem in section 2.2. Like many other models of physics beyond the SM, supersymmetry naturally predicts two Higgs doublets. The Higgs doublets are a part of the minimal particle content that is required to realize supersymmetry. In section 2.3, I talk about the minimal supersymmetric extension to the standard model (MSSM), which features the minimal particle content for supersymmetry. While the MSSM is powerful, it has its own theoretical problem called the μ **parameter problem**. The solution to the problem with MSSM is addressed in a further extension called the Next-to-Minimal supersymmetric extension to the standard model (NMSSM), which I will discuss in section 2.4. The NMSSM solves the problem of MSSM, addresses a problem with the standard model, and predicts a (light) pseudoscalar particle. This pseudoscalar particle which arises in solving problems with the standard model and MSSM is what I look for in my search.

In section 2.5 I will talk about the phenomenological models that motivate my specific search I pursue beyond the standard model. The phenomenological models parametrize the different possible couplings of the light pseudoscalar to SM fermions. One particular case of these models is NMSSM which solves the Higgs hierarchy problem in the standard model and the μ parameter problem in MSSM. In this and other models, multiple Higgs doublets lead to multiple physical Higgs scalar particles with Yukawa-like couplings. In the Yukawa type couplings, the Higgs scalars couple strongest to the heaviest particles (τ among the standard model leptons). The Yukawa coupling is an essential factor in determining the specific final state for my search.

My research focuses on the decay of the 125 GeV Higgs boson to two lighter BSM pseudoscalar particles. The dataset used is the Run 2 dataset from CMS and the total integrated luminosity for Run 2 is 137.60 fb^{-1} . I look for the decay of scalar Higgs boson (H) to a pair of (light) pseudoscalar bosons (a), one of which decays to a pair of taus while the other decays to a couple of muons ($H \rightarrow aa \rightarrow \mu\mu\tau\tau$). The search is essentially a search for two peaks as the characteristic signature of a pseudoscalar is a peak in the dimuon mass

spectrum ($m_{\mu\mu}$) and a broader peak in the four-body mass spectrum ($m_{\mu\mu\tau\tau}$). The specifics of the signature are also talked about in sections 2.6 and 7.1.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 The Standard Model and Its Shortcomings

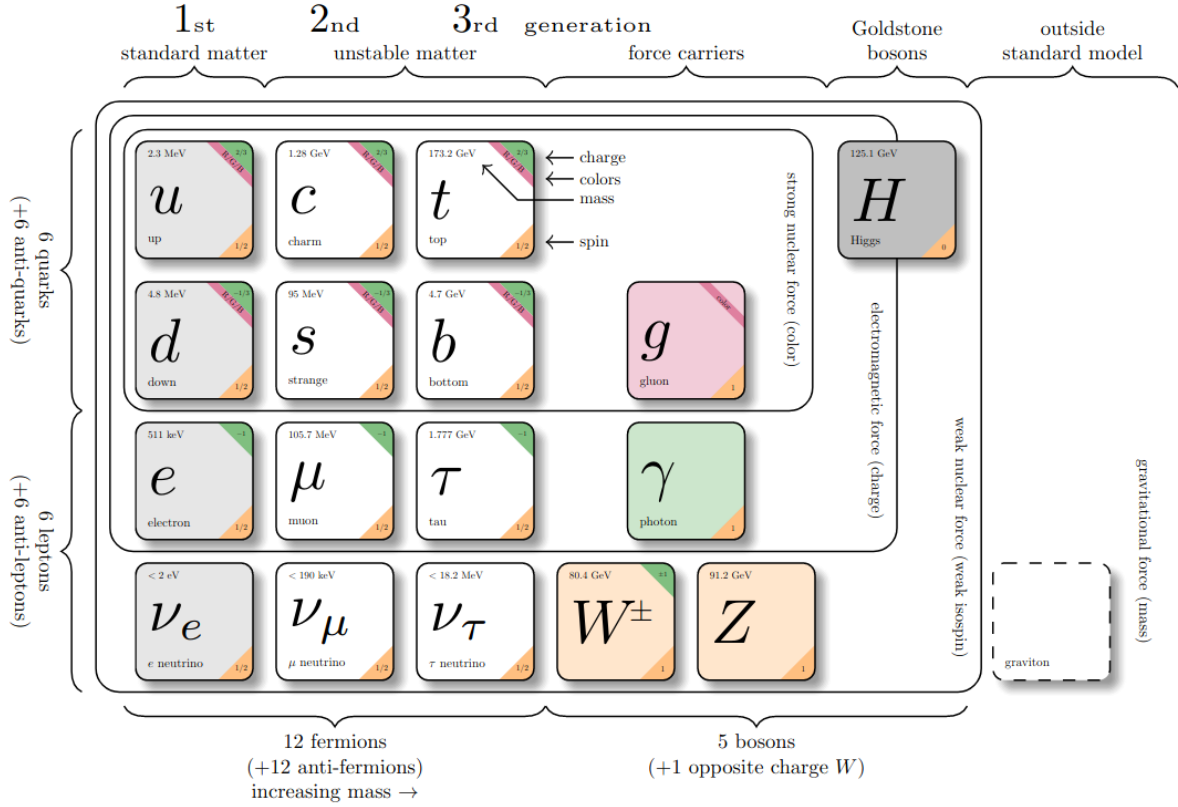


Figure 2.1: The Standard Model of particle physics [7].

2.1.1 The matter and gauge content of the Standard Model

The Standard Model is the most recent theory of high energy physics that can describe the fundamental particles around us and their interactions. It has become established as a well-verified physics theory over time through many tests and experiments [8].

The particles of the Standard Model is shown in the Figure 2.1.

The matter content of the Standard Model consists of the elementary particles, which are essentially the building blocks of matter [9]. The elementary particles can be divided into two groups, the quarks and the leptons. Each of the groups has six particles. The leptons have the electron, electron neutrino, muon, muon neutrino, tau and the tau neutrino. The leptons are categorized into different “generations” based on their mass. The first generation contains the electron and the associated neutrino; the second generation is the muon and the corresponding neutrino; the tau and the tau neutrino form the third generation. The quarks similarly have the up and down quarks creating the first generation, the charm and the strange quarks constitute the second generation, and the third generation contains the top and bottom quarks. It is understood that in both cases, the lightest and the most stable particles will form the first generation. In contrast, the heavier and less stable particles form the second and third generations. Consequently, the first generation of the quarks (up and down quarks) form the proton and the neutron that constitute the nucleus of an atom, while the first generation leptons (electron) orbit the nucleus as part of orbitals, thus making up all known matter around us.

Four fundamental forces describe the interaction between the fundamental particles. They are the strong force, the weak force, electromagnetic force, and the gravitational force. The Standard Model was successful in describing three out of the four fundamental forces as the gravitational force is still not incorporated into the Standard Model. The interaction between the particles in the standard model is mediated through the gauge bosons. The gauge bosons act as the force carriers, and the particles experience the fundamental forces through the exchange of the gauge bosons.

The gauge bosons form the gauge part of the Standard Model and consist of the photon, Z bosons, $W^\pm$ bosons, gluons, and gravitons. The Z bosons and the $W^\pm$ bosons act as the force carriers of the weak force; both quarks and leptons feel the weak force. The photons are the force carriers for the electromagnetic force, affecting all the charged particles. The strong force is experienced only by the quarks, and the gluons act as the force carriers. Though not

experimentally observed yet, the graviton is posited to serve as the exchange boson for the gravitational force.

The figure 2.2 shows the properties of the various fundamental forces, their carriers, the particles they act on, and their effective ranges.

Properties of the Interactions				
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.				
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at $\begin{cases} 10^{-18} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{cases}$	10^{-41}	0.8	1	25
	10^{-41}	10^{-4}	1	60

© 2016 Contemporary Physics Education Project
CPEPhysics.org

Figure 2.2: The interactions in the Standard Model. Reprinted from [10].

The discovery of the Higgs boson provided a mass generation mechanism for the exchange bosons ($W^\pm$ and Z), quarks, and charged leptons. The mass generation of the exchange bosons happens through a process called the (Brout-Englert) Higgs mechanism.

2.1.2 The Higgs mechanism

The Higgs mechanism is a process by which $W^\pm$ and Z bosons gain mass. The mass generation happens through a process of electro-weak Symmetry Breaking (EWSB), where the introduction of a scalar field (the Higgs field) retains the structure of the gauge interactions at high energies but still generates the observed masses of the $W^\pm$ and Z bosons [11].

In the Standard Model the electroweak interactions are described by a gauge field theory. The gauge field theory in this case is invariant under the $SU(2)_L \times U(1)_Y$ symmetry group. Here Y represents the weak hypercharge and L signifies left handed weak isospin.

The process of symmetry breaking starts through the introduction of a self-interacting $SU(2)_L$ complex doublet scalar field, the Higgs field (Φ). The Standard Model scalar potential in this case is given by:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad (2.1)$$

The Higgs field is represented:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ \phi^0 + ia^0 \end{pmatrix} \quad (2.2)$$

ϕ^+ is the charged component of the Higgs doublet and ϕ^0 and a^0 are the Charge Parity(CP)-even and CP-odd neutral components, respectively. The Higgs field, being a $SU(2)$ complex doublet, has four real degrees of freedom, and only one survives after the process of EWSB. It is furthermore a color singlet and has a weak hypercharge of $Y=1$. When $\mu^2 < 0$, that is the quadratic term is negative, the CP-even neutral component of the Higgs doublet attains a non-zero vacuum expectation value (VEV).

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.3)$$

The attainment of the non-zero VEV leads to **spontaneous symmetry breaking** of Standard Model gauge symmetry. The gauge symmetry of $SU(3)_C \times SU(2)_L \times U(1)_Y$ is broken down into $SU(3)_C \times U(1)_{em}$. As a result, the Higgs field is no longer invariant under the whole electroweak group gauge transformation but just invariant under $U(1)_{em}$ transformation, retaining the invariance of the electric charge. This can also be seen as shifting of the global minimum or the ground state of the theory. With the unbroken symmetry, the Higgs potential would be parabolic, and the ground state/ minimum potential would follow the system's symmetry, residing at $\Phi = 0$. In the case of the broken symmetry, the ground state moves from $\Phi = 0$ to $\Phi = v$ and can spontaneously choose from an arbitrary number of minimum potential points on the real Φ - imaginary Φ plane.

The SM gauge group $SU(2)_L \times U(1)_Y$ has four generators, each representing one degree of freedom. As a result of the spontaneous symmetry breaking, three of the four generators are

broken and the corresponding degrees of freedom removed, leaving only one. This results in the generation of three massless Goldstone bosons, which are later absorbed to give masses to the $W^\pm$ and Z gauge bosons.

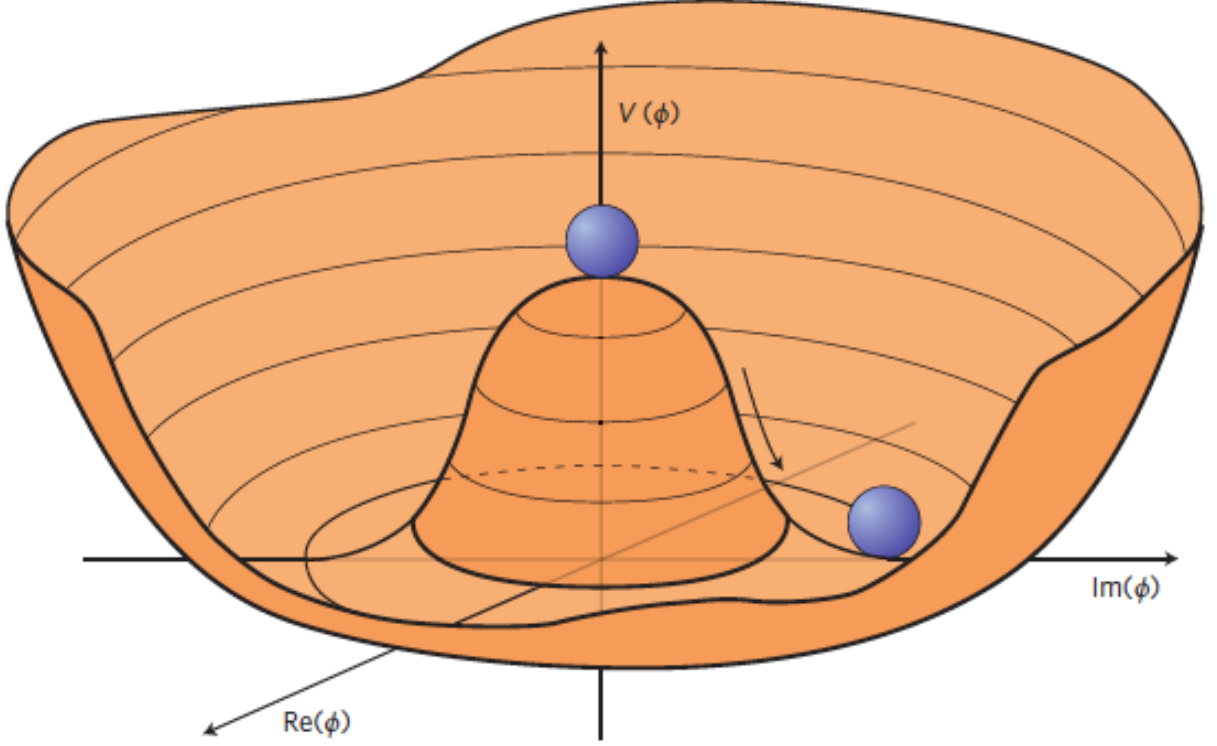


Figure 2.3: The Higgs potential on a plane defined by the real and imaginary parts of the complex scalar field [10].

The Higgs field couples with the $SU(2)_L \times U(1)$ gauge bosons per the covariant derivative in the kinetic part of the Higgs Lagrangian.

$$\mathcal{L}_{Higgs} = |D_\mu \Phi|^2 - V(\Phi) = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) \quad (2.4)$$

Here the $D_\mu \Phi$ is given by:

$$D_\mu \Phi = (\partial_\mu + ig\sigma^a W_\mu^a/2 + ig'Y B_\mu/2)\Phi \quad (2.5)$$

Here g and g' are the gauge coupling constants of $SU(2)_L$ and $U(1)_Y$ respectively. $SU(2)_L$ and $U(1)_Y$ factors of the gauge group commute and therefore are assigned different coupling constants [12]. σ^a are the Pauli matrices with $a = 1, 2$ and 3 . $W_\mu^1, W_\mu^2, W_\mu^3$, are gauge bosons of $SU(2)$, B_μ is the gauge boson of $U(1)$ and finally $Y = 1$.

The coupling of the Higgs field with the gauge bosons in the above manner results in the neutral and two charged massless Goldstone degrees of freedom to mix with the (3) broken generators of $SU(2)_L \times U(1)_Y$ and become the longitudinal components of the Z and $W^\pm$ gauge bosons respectively. The fourth unbroken generator corresponding to the conserved $U(1)_{em}$ gauge symmetry, and the corresponding gauge field, the photon, remains massless after the EWSB process.

The gauge boson mass terms come from the square of the covariant derivative in 2.5 evaluated at the VEV from 2.3. The most relevant terms are :

$$\Delta\mathcal{L} = \frac{1}{2} \begin{pmatrix} 0 & v \end{pmatrix} \left(\frac{1}{2}gW_\mu^a\sigma^a + \frac{1}{2}g'B_\mu \right) \left(\frac{1}{2}gW^{b\mu}\sigma^b + \frac{1}{2}g'B^\mu \right) \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.6)$$

Now plugging in the values of the Pauli matrices we get:

$$\Delta\mathcal{L} = \frac{v^2}{8} [g^2(W_\mu^1)^2 + g^2(W_\mu^2)^2 + (-gW_\mu^3 + g'B_\mu)^2] \quad (2.7)$$

Thus the three massive vector bosons are:

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

$$Z_\mu^0 = \frac{1}{\sqrt{g^2 + (g')^2}}(gW_\mu^3 - g'B_\mu)$$

With masses $m_{W^\pm} = g\frac{v}{2}$ and $m_Z = \sqrt{g^2 + g'^2}\frac{v}{2}$. To summarise, in the Higgs mechanism after the EWSB, from the initial four degrees of freedom of the complex Higgs doublet field, two are used up by the $W^\pm$ bosons to gain mass, and the Z boson takes one to obtain its mass while the remaining degree of freedom becomes the physical Higgs boson. And finally, since the Higgs doublet is postulated to couple to the fermions through the Yukawa interactions, the fermions also gain mass due to the Higgs mechanism.

The experimental evidence of the existence of the Higgs boson and the confirmation of the Higgs mechanism was obtained in 2012 when both ATLAS and CMS announced an excess of events at 125 GeV with 5σ statistical significance (discovery significance) [3, 13]. The Figure 2.4 shows the diphoton invariant mass distribution and four lepton invariant mass distribution reported by CMS.

2.1.3 Limitations of the Standard Model

There are numerous notable limitations of the standard model. First, the complete theory of gravitation is still not incorporated into the standard model. The standard model can still not supply a viable candidate for dark matter. The standard model cannot explain the matter/antimatter asymmetry in the universe or baryogenesis. Furthermore, the standard model cannot account for dark energy and the universe’s accelerating expansion. In direct contradiction to the standard model predictions, recent observations showed that the neutrinos could oscillate between different generations and have masses [14]. And last but not least, it cannot address the **Higgs hierarchy problem**.

The inability of the Standard Model to explain the hierarchy of mass scales has been an important motivator towards looking for a new framework as we move to higher energies.

The Standard Model Higgs field has an electrically neutral part, in the form of a complex scalar H with a classical potential

$$V = m_H^2 |H|^2 + \lambda |H|^4 \quad (2.8)$$

Here λ is the coupling constant and m_H is the mass of the Higgs boson. At the minimum value of the potential V , the Standard Model requires a vacuum expectation value (VEV) for H . With $\lambda > 0$ and $m_H^2 < 0$, the VEV is $\langle H \rangle = \sqrt{\frac{-m_H^2}{2\lambda}}$. Experimentally, $\langle H \rangle$ is known to be 174 GeV. The discovery of the Higgs boson with a mass around 125 GeV during 2012 would imply that the value of m_H is of similar order of magnitude as the VEV [1]. In quantum field theory, m_H^2 is calculated as a perturbative expansion in which each term is proportional to Λ_{UV}^2 , where Λ_{UV} is the high energy “cutoff” scale of the SM. If the SM is to be valid to scales significantly higher than the electroweak scale, very precisely chosen

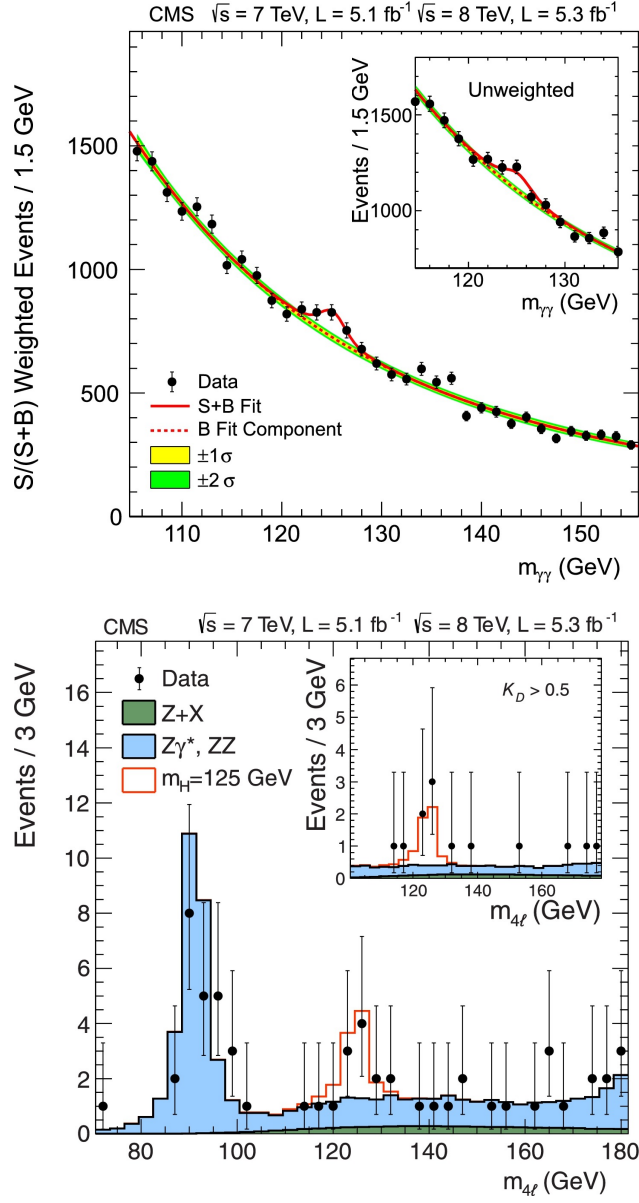


Figure 2.4: (top) The $\gamma\gamma$ invariant mass distribution where each event is weighted by the ratio of signal over signal plus background, for each sub-category of events. (bottom) Distribution of the four-lepton reconstructed mass for the sum of the $4e$, 4μ , and $2e2\mu$ channels. Reprinted from [3].

counterterms proportional to Λ_{UV}^2 would need to be added to the calculation of m_H^2 to yield the measured value, unless there is some phenomenon that naturally leads to the cancellation of the quantum corrections.

2.2 Supersymmetry

Supersymmetry (SUSY) leads to the necessary cancellation of the quantum corrections. Supersymmetry is the transformation that turns a fermionic state into a bosonic one and vice versa. It can be considered as an extended version of space-time symmetries in quantum field theory [11]. There is a relative minus sign between the contribution to quantum correction Δm_H^2 for the fermion and boson loops. Therefore, if every fermion has a corresponding boson and vice versa, cancellation of quantum corrections is possible.

2.3 MSSM

The Minimal Supersymmetric extension to the Standard Model (MSSM) involves addition of the minimal amount of particles to the Standard Model to realize supersymmetry. The MSSM extends the Standard Model by an additional Higgs doublet along with the supersymmetric partners involved. Table 2.1 tabulates the field content of some members of the MSSM and their gauge quantum numbers.

A supermultiplet is a term used to describe a particle and its corresponding superpartner. For example, the gluons have gluino fermionic superpartners, and the gauge bosons have gaugino fermionic superpartners. These supermultiplets together are termed as the gauge supermultiplets. In addition, the leptons and the quarks have their scalar superpartners, and the supermultiplets they form are termed as the matter supermultiplets. The scalar superpartners of the quarks are the squarks, and the sleptons are the scalar superpartners of the leptons. And for all the cases mentioned above, each superpartner has its corresponding antiparticle. The Higgs supermultiplets consist of the Higgs doublets and the Higgsino fermionic superpartners, along with the associated antiparticles.

Table 2.1: Field content of the MSSM and their corresponding quantum numbers. Just one generation of quarks and leptons is shown here. Reprinted from [1].

Field Content of the MSSM						
Super-multiplets	Super-field	Bosonic fields	Fermionic partners	$SU(3)$	$SU(2)$	$U(1)$
gluon/gluino	$\hat{V}_S$	g	$\tilde{g}$	8	1	0
gauge	$\hat{V}$	$W^\pm, W^0$	$\tilde{W}^\pm, \tilde{W}^0$	1	3	0
boson/gaugino	$\hat{V}'$	B	$\tilde{B}$	1	1	0
slepton/lepton	$\hat{L}$	$(\tilde{\nu}_L, \tilde{e}_L^-)$	$(\nu, e^-)_L$	1	2	-1
	$\hat{E}^c$	e_R^+	e_R^c	1	1	2
squark/quark	$\hat{Q}$	$(\tilde{u}_L, \tilde{d}_L)$	$(u, d)_L$	3	2	$\frac{1}{3}$
	$\hat{U}^c$	$\tilde{u}_R^*$	u_L^c	$\bar{3}$	1	$-\frac{4}{3}$
	$\hat{D}^c$	$\tilde{d}_R^*$	d_L^c	$\bar{3}$	1	$\frac{2}{3}$
Higgs/higgsino	$\hat{H}_d$	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	1	2	-1
	$\hat{H}_u$	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	1	2	1

However, there are some drawbacks of the MSSM, the most important being the presence of a dimensionful term in the superpotential known as the “ μ term”. Prior to spontaneous symmetry breaking the μ -term has to be adjusted manually to the electroweak scale but there is no dynamical explanation for the adjustment [15].

2.4 NMSSM

The Next-to-Minimal supersymmetric extension to Standard Model (NMSSM) solves the problem of adjustment of the μ -term by hand. The NMSSM involves the addition of an additional gauge singlet which leads to the dynamic generation of the μ -term. It also predicts an additional light pseudoscalar boson a that couples to the Higgs and to fermions.

The MSSM potential in terms of the scalar fields is given by:

$$W_{MSSM} = \tilde{u}_R^* y_u (\tilde{Q}^T \epsilon H_u) - \tilde{d}_R^* y_d (\tilde{Q}^T \epsilon H_d) - \tilde{e}_R^* y_e (\tilde{L}^T \epsilon H_d) + \mu (H_u^T \epsilon H_d). \quad (2.9)$$

With the dimensionless couplings given by y_u, y_d , and y_e . The term proportional to $\mu (H_u^T \epsilon H_d)$ is required to give mass to the up and down type fermions. H_u and H_d are the

two Higgs doublets. The μ term here is dimensionful, as mentioned before, and there is no explanation for why it is at the electroweak scale.

The introduction of a new scalar field S solves this problem. The μ parameter gets replaced with coupling to the scalar field, causing it to have an explanation as a vacuum of the scalar field, and this yields the μ near the electroweak scale [15].

In the NMSSM, the superpotential becomes:

$$W_{NMSSM} = \tilde{u}_R^* y_u (\tilde{Q}^T \epsilon H_u) - \tilde{d}_R^* y_d (\tilde{Q}^T \epsilon H_d) - \tilde{e}_R^* y_e (\tilde{L}^T \epsilon H_d) + \lambda (H_u^T \epsilon H_d) S + \frac{1}{3} \kappa S^3. \quad (2.10)$$

where λ and κ are also dimensionless couplings. The scalar field S obtains a vacuum expectation value to generate the parameter μ . The μ -term is replaced by $\lambda S (H_u^T \epsilon H_d)$, and through the spontaneous symmetry breaking the μ -term is generated near the electroweak scale with $\mu = \lambda \langle S \rangle$.

Final states from the exotic Higgs decays we are searching for will be interpreted in terms of a broad class of phenomenological models that include the NMSSM.

2.5 Phenomenological Models

The beyond standard model scenario considered here is the decay of the Higgs to a pair of pseudoscalar bosons a with masses between twice the mass of taus and half the mass of the Higgs ($2m_\tau < m_a < \frac{m_h}{2}$). One pseudoscalar decays to a pair of muons, while the other decays to a pair of taus. Figure 2.5 shows a possible Feynmann diagram of the process.

A phenomenological model of this decay is the Two Higgs Doublet Model along with a Singlet scalar field S (2HDM+S). The specific 2HDM+S models are differentiated based on the types of pseudoscalar-fermion couplings that occur in them. The models that predict the $2\mu 2\tau$ final state are the NMSSM-like Type-II models and type-III 2HDM(lepton specific)[2].

An important parameter in both these models is the tangent of the rotation angle which diagonalizes the pseudoscalar mass matrices. It is quantitatively defined as $\tan\beta = \frac{v_1}{v_2}$ where v_1 and v_2 are the vacuum expectation values of the scalar doublets in the models.

- Type II: In this model all the fermions couple to one of the Higgs doublets and the branching ratios are similar to NMSSM models. The models have a $\tan\beta$ dependence

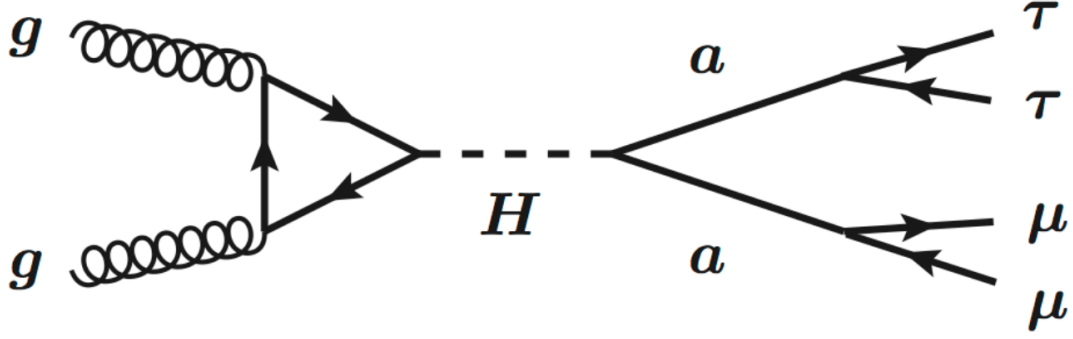


Figure 2.5: Decay of Higgs to a pair of pseudoscalars. One decays to a pair of τ 's while the other decays to a pair of μ 's.

Table 2.2: The couplings of pseudoscalar mass eigenstates to fermions and gauge fields in the type-II and type-III models.

	couplings	Type II	Type III
a	g_{aVV}	0	0
	$g_{at\bar{t}}$	$\cot \beta$	$\cot \beta$
	$g_{ab\bar{b}}$	$-\cot \beta$	$-\cot \beta$
	$g_{a\tau\bar{\tau}}$	$-\cot \beta$	$\tan \beta$

with possibility of enhancement or suppression for down-type fermions based on the value of $\tan \beta$.

- Type III: This is a lepton specific model where leptons couple to one of the doublets while the quarks couple to the other. These models too have a $\tan \beta$ dependence. Depending on the value of $\tan \beta$, decay of pseudoscalars to leptons can be enhanced compared to quarks.

The $\tan \beta$ dependency of the models are listed in Table 2.2. It can be clearly seen that the couplings of pseudoscalars to $b\bar{b}$ and $\tau^+\tau^-$ are similar in type-II models, but in type-III (lepton specific) models they are different. The effects of the different couplings can be clearly seen in the branching ratio plots for the two models (Figure 2.6 and Figure 2.7).

It is seen that for the type-II model above the b -quark pair (10 GeV) threshold and for a higher value of $\tan \beta$ the branching ratio to $b\bar{b}$, $\tau^+\tau^-$ and $\mu^+\mu^-$ (somewhat) is enhanced.

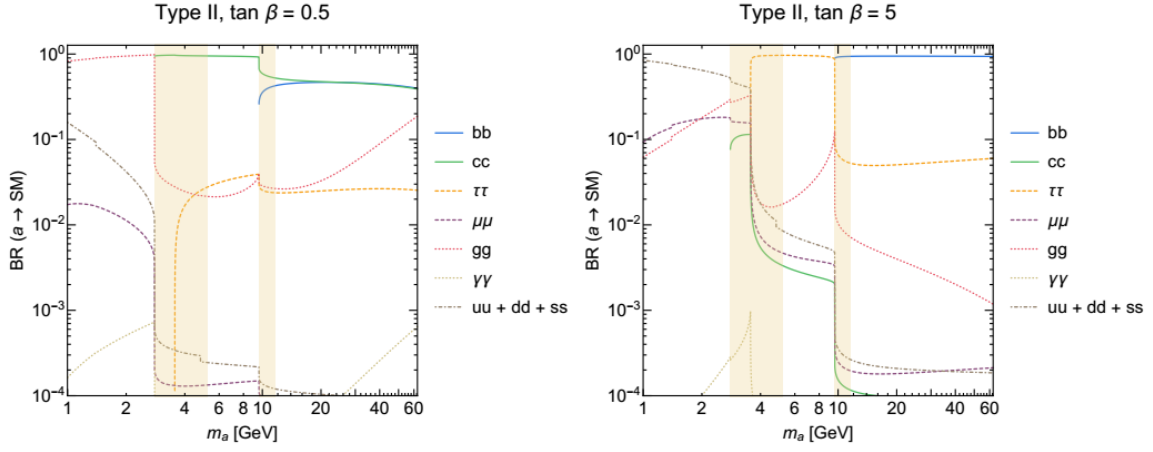


Figure 2.6: Pseudoscalar branching ratios to various final states for Type-II Yukawa couplings at two different values of $\tan \beta$. Reprinted from Ref[2].

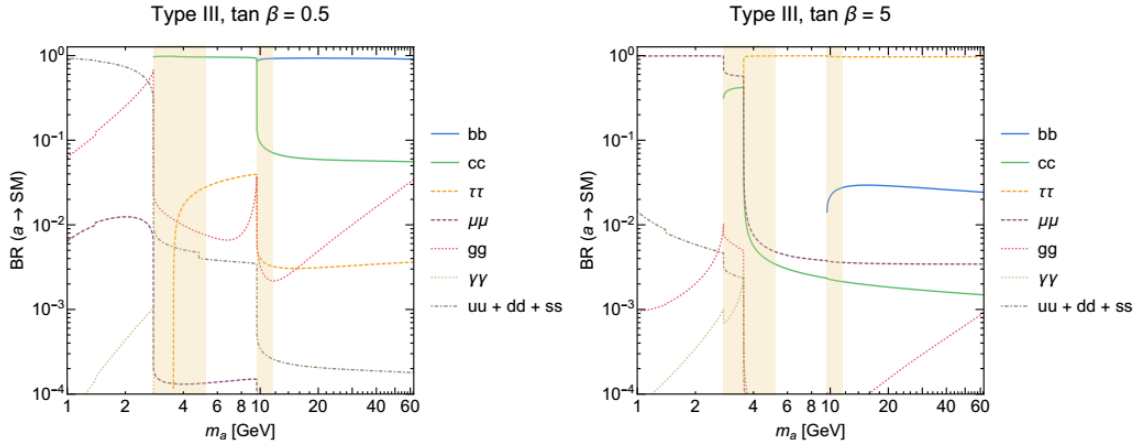


Figure 2.7: Branching ratios for various final states for Type III Yukawa couplings at two different values of $\tan \beta$. Reprinted from Ref[2].

For the type-III in similar conditions, the branching ratio to $\tau^+\tau^-$ and $\mu^+\mu^-$ is enhanced while that to $b\bar{b}$ is actually suppressed.

2.6 $h \rightarrow 2\mu 2\tau$ Final State

We study the mass range of $m_a \in [2m_\tau, m_h/2]$ and assume that the pseudoscalar-lepton couplings are in direct proportion to the mass of the lepton (m_τ, m_μ, m_e). Therefore, the most dominant $2 \rightarrow 4$ fully leptonic branching fraction is 4τ and the next most prominent branching ratio is $2\mu 2\tau$ [2]. The taus in the 4τ or the $2\mu 2\tau$ final state have either leptonic(35%) or hadronic(65%) decays.

There are several reasons to prefer $2\mu 2\tau$ final state over the 4τ final state. Considering the 4-body decay of the Higgs, the Higgs mass-energy is bound to be distributed among an enormous number of final-state particles. By rough estimation each tau in the 4τ decay mode should have $p_T(\tau) \lesssim 30$ GeV. The subsequent decay of such a tau, however, causes the energy of the final state particles to potentially be so low that the visible p_T (excluding the neutrinos) is insufficient for reconstruction. The leptonic decays of the tau result in two neutrinos, often causing the leptons to have too low energy (or p_T) for triggering or reconstruction. The presence of neutrinos in the 4τ final state leads to poor mass resolution in the reconstruction of the pseudoscalar (2-body) or Higgs (4-body) mass. Moreover, the leptons in the leptonic decay can be also non-isolated from each other and the neighbouring hadronically decaying tau, which makes reconstruction even more challenging[2].

The $2\mu 2\tau$ final state has fewer neutrinos per event than the 4τ , which means that there is less missing energy and better mass resolution. The most important advantage of the $2\mu 2\tau$ final state is the fully reconstructable di-muon system, $m(\mu^+\mu^-)$. The muons from $a \rightarrow \mu\mu$ are much more energetic than the leptons from tau decay and they easily pass the reconstruction and triggering threshold. This results in a sharp resonant peak in the di-muon invariant mass spectrum occurring at the pseudoscalar mass m_a . Experimentally speaking, the $2\mu 2\tau$ final state gives us a better opportunity for background rejection and signal selection, as the mass of pseudoscalar m_a may be used as a discriminating variable against background.

2.7 Related Work and Other Motivations

There have been a lot of theoretical studies related to the exotic decay of the SM-like Higgs to a pair of lighter bosons. The scenario we consider in this study is the decay of Higgs to a couple of light pseudoscalar bosons[2]. There were studies of LHC constraints on 2HDM [16]. Some studies looked into the possible parameter space of the type II 2HDM based on information from LHC Higgs searches [17, 18]. There were also phenomenological studies looking into the second Higgs doublet [19]. Some studies looked into aligned 2HDM where both doublets couple to down-type quarks and charged leptons with aligned Yukawa coupling [20]. Finally, some studies also consider the future prospects of the 2HDM [21].

There were also theoretical studies in the NMSSM or NMSSM-like context. There are studies concerning the natural NMSSM Higgs bosons [22]. Some specifically look into the light Higgs scalar in the NMSSM[23]. In contrast, others look into NMSSM scenarios with low-mass pseudoscalars [24]. Furthermore, some studies investigate adding a singlet field to the 2HDM [25].

Many experimental searches have looked for light scalars and pseudoscalar Higgs bosons, both in the CMS and the ATLAS data. One such search in the CMS experiment looked into light Higgs bosons in the 30-100 GeV mass range[26]. The data collected corresponded to an integrated luminosity of 19.7 fb^{-1} at a center-of-mass energy of 8 TeV. Another search looked into the mass range 0.25-8.5 GeV for a light pseudoscalar Higgs boson [27]. Another search for a light pseudoscalar Higgs boson at the center-of-mass energy of 7 TeV placed stringent limits in the mass range 5-14 GeV and excluded the upsilon resonance region [28]. There were also results from the LHCb experiment at a center-of-mass energy 7-8 TeV looking for a dimuon resonance in the upsilon region ($pp \rightarrow aX$, $a \rightarrow \mu\mu$), in the mass range 5 GeV to 15 GeV [29]. The limits set by this search were pretty comparable to [28]. Direct constraints on $\text{BR}(H \rightarrow aa, hh)$ in the $\mu\mu\tau\tau$ and 4τ final states are obtained from a CMS search performed at 8 TeV [30].

There have also been numerous searches for light pseudoscalar Higgs bosons using Run 2 LHC data. One search from the CMS experiment used data collected at 13 TeV [31]. The search looks into the $\mu\mu\tau\tau$ final state and covers the mass range from $15 < m_a < 62.5 \text{ GeV}$.

This study improved the previous limits significantly. Another search from data collected by the ATLAS experiment at 13 TeV looks into four lepton final states and sets limits in the mass range $1 < m_a < 2.5\text{GeV}$ and $4.5 < m_a < 8\text{ GeV}$ [32]. One of the more recent searches from the CMS experiment uses Run 2 data collected at 13 TeV and focuses on the $\mu\mu\tau\tau$ final state [33]. To date, it sets the most competitive limits in the mass range $3.6 < m_a < 21\text{ GeV}$.

CHAPTER 3

THE LARGE HADRON COLLIDER (LHC)

The Large Hadron Collider (LHC) is the world's largest particle accelerator which collides particles with the highest (center-of-mass) energy [34]. Since its inception on September 10, 2008, it has remained the most powerful machine of its kind and played an integral part in significant advances in particle physics. LHC is situated at the France-Swiss Border and housed inside an underground tunnel initially created to contain a previous particle collider, the Large Electron-Positron collider (LEP). The LEP tunnel is 26.7 *km* in length and is built at a slight gradient of 1.4 % varying from 175 *m* (under Jura) to 50 *m* towards Lake Geneva with an average depth of 100 *m* [35].

The LHC is, in principle, a hadron accelerator and collider consisting of two roughly circular rings. Equal and opposite particle (hadron) beams traverse these rings and collide at specific pre-determined points. The beams travel in two tubes kept at ultra high vacuum, the beam pipes. Two beams colliding in this manner has an advantage over beams colliding a fixed target in that the energy of the collision is the sum of the energy of the two beams. Moreover as massive hadrons (protons for instance) are collided the energy loss per turn from synchrotron radiation is expected to be minimal when compared to light particles like electrons.

The beams need to be kept on the rings while being accelerated to obtain enough energy for the final collision. Superconducting magnets line the LHC rings and generate strong magnetic fields. The magnetic fields provide the necessary centripetal force to keep the beams within the rings. Dipole magnets bend the beam, quadropole magnets focus the beam while some other magnets actually "squeeze" the particles on the beam just before the collision.

The superconducting magnets used in the LHC are electromagnets and are constructed from coils of niobium-titanium (Nb-Ti) wires. These wires can operate in a superconducting state and pass current with little or no resistance and minimal resistive energy loss. The wires can only reach superconducting states at low temperatures; this is achieved in the LHC using superfluid helium, which can reach -271°C . All four experimental insertions involve the crossing of the two beams from one magnet bore to the other. The beams circulating the rings collide at four locations, which correspond to the positions of the particle detectors ALICE (A Large Ion Collider Experiment), ATLAS (A Toroidal LHC ApparatuS), CMS (Compact Muon Solenoid), and LHCb (studies physics of B-meson decays in the LHC).

The figure 3.1 shows the LHC along with all with the experiments along the LHC tunnel.

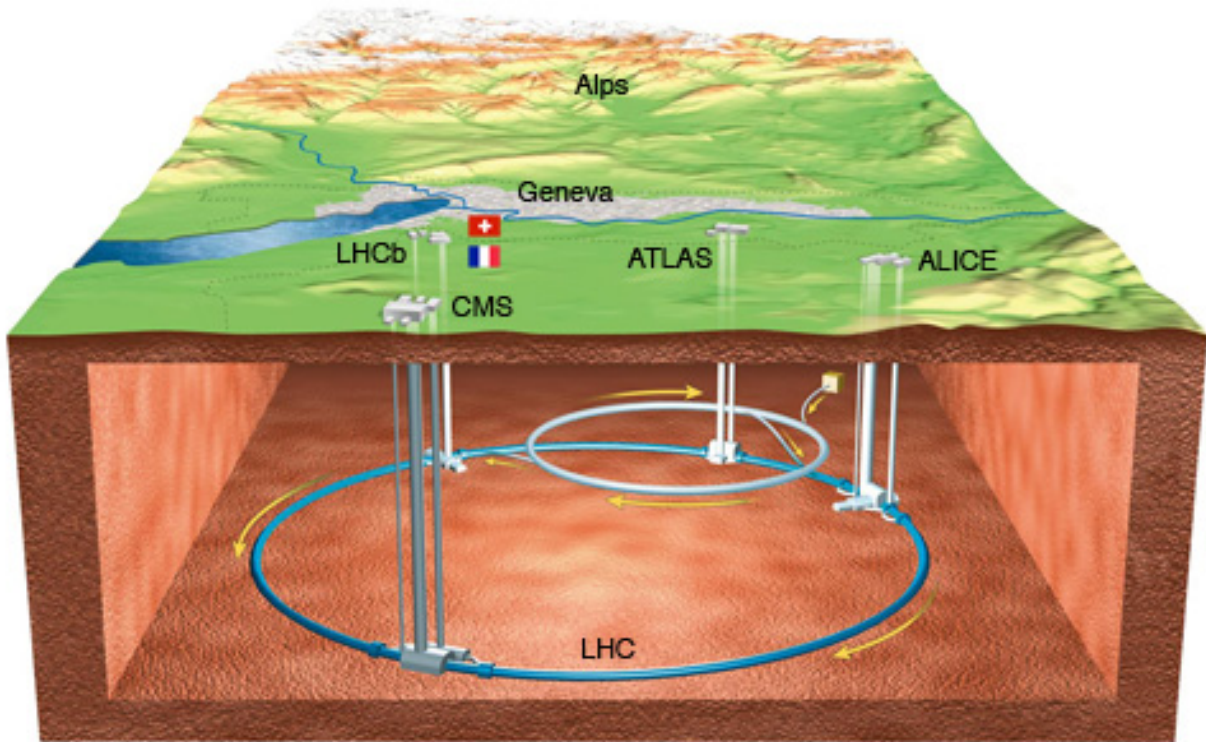


Figure 3.1: A representation of the Large Hadron Collider (LHC) along with the positioning of other experiments. Reprinted from Reference [36].

The main goals of the LHC is the address several unanswered questions that remain within and beyond the Standard Model. For instance, the theory of gravitation is still not

incorporated into the Standard Model. The matter/ antimatter asymmetry, **Baryogenesis**, still needs to be explained. There is still ongoing search for particles and phenomena responsible for **dark matter** and **dark energy**. Dark matter makes up roughly 27% of the universe and dark energy accounts for 68% of the universe but still a viable candidate of dark matter has not been found.

The remaining part of the chapter gives a brief overview of the various parts of LHC . We talk about the design considerations and performance limitations in Section 3.1. We talk about the magnets in section 3.2, the cryogenics in Section 3.3, the Radio Frequency Cavities in Section 3.5 and the Beam injection Chain 3.4. The materials in the next section are mainly taken from references [37], [35] and [38].

3.1 Structural Attributes and Performance Constraints

3.1.1 Structural layout

The LHC would seem like a perfect circle to the uninitiated eye, but LHC is not exactly circular. It has eight curved **arcs** and eight straight sections called the '**insertions**'. An Insertion consists of long straight sections (**LSS**) with two transition regions on two sides, called the '**dispersion suppressors**'. The insertions are 545 *m* long, and their structural layout can vary depending on their specific use. Insertions can be used as **experimental insertions** where beams collide within an experiment. They can also be used as **utility insertions** for beam dumping, beam cleaning and beam injection. The figure 3.2 shows the rough layout of the LHC.

The interaction Region 1 (IR1) and interaction Region 5 (IR5) are experimental insertions on diametrically opposite sides of the LHC. These insertions host the high luminosity experiments, ATLAS at Point 1 (at IR1) and CMS at Point 5 (at IR5). There are two further experimental insertions at Point 2 (IR2) and Point 8 (IR8), and they host the experiments ALICE and LHCb. These insertions also include the beam injection systems; Point 2 has the beam injection system for one beam while point 8 has the beam injection system

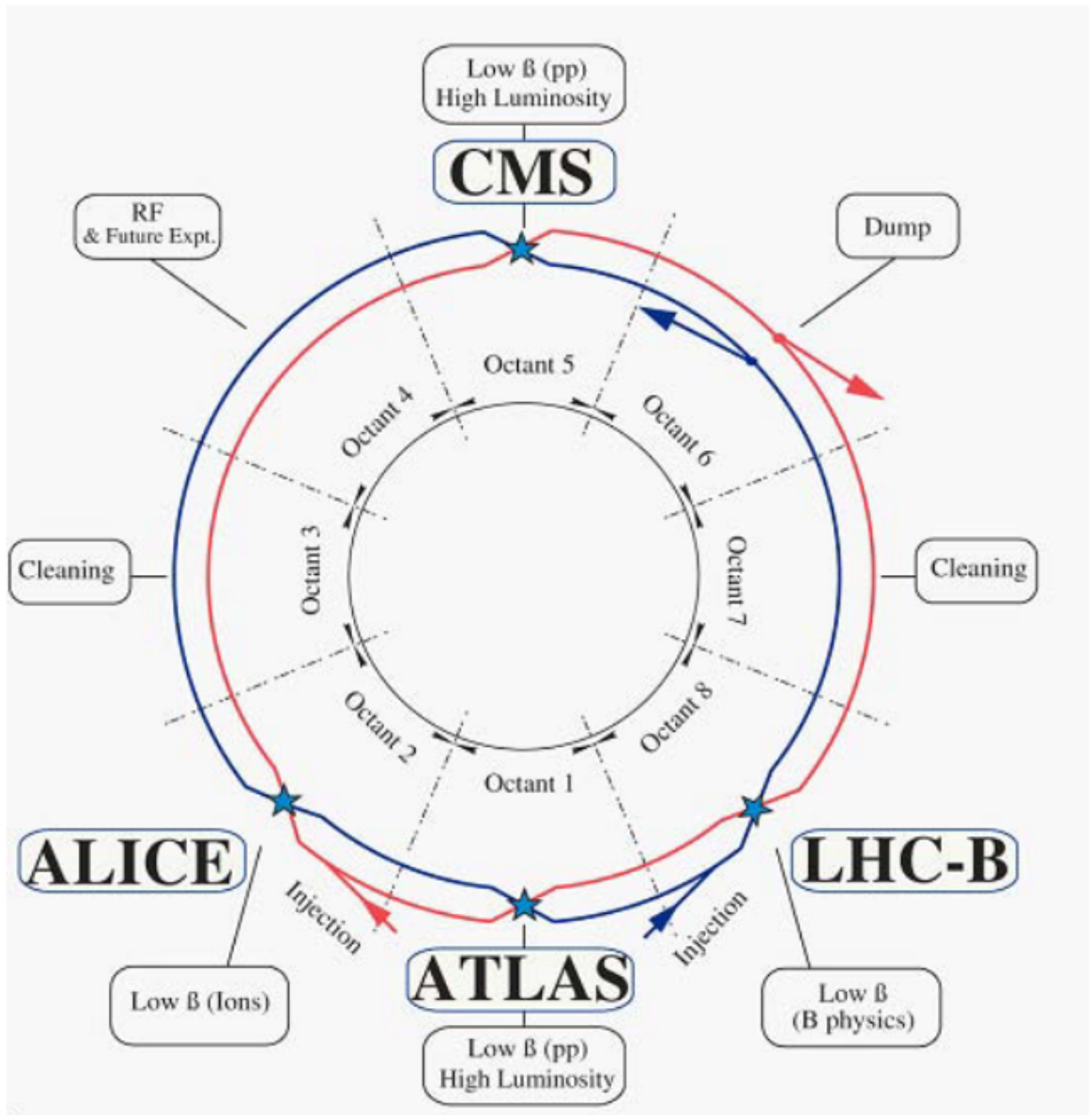


Figure 3.2: A schematic layout of the Large Hadron Collider (LHC) . Reprinted from Reference [37].

for the other. The beams arrive at the LHC slightly below the LHC reference plane, and the injection system provides the kick to bring the beams back up. All four experimental insertions involve the crossing of the two beams from one magnet bore to the other.

The straight sections at Point 3 (IR3) and Point 7 (IR7) contain the beam collimation systems dedicated to beam cleaning. The LHC collides beams at intensities never achieved in the past, and the energy density of the beams in the transverse plane is roughly 1000 times higher than similar machines in the past. The magnets are at high risk of getting quenched, and accelerator parts are prone to severe damage if the beams are not sufficiently collimated. The beam collimation system protects the accelerator against planned and unplanned beam loss.

The insertion at Point 6 (IR6) involves the beam dumping system. The primary goal of the beam dumping system is the efficient extraction of the beams from the two rings with minimal beam losses. A combination of 'kicker' and septum magnets perform the beam extraction. First, the fast-pulsed ('kicker') magnets deflect the beams in a horizontal plane away from their initial path and towards the double steel septum magnets. The septum magnets then vertically deflect the beams to another set of kicker magnets that dilute the beams' intensity. The beams then hit the beam dump blocks, which is the final step of the beam dump. The beam dump blocks are cylinders of graphite composite encased in concrete and can absorb the beam energy and spread out the hadronic showers without disintegrating in the process.

The figure 3.3 shows the schematic diagram of the beam dump system of the LHC, situated at Point 6.

The insertion at Point 4 (IR4) has the Radio Frequency (RF) systems, one independent system for each beam.

The dispersion suppressors are present in the transition region between the arcs and the straight sections. There are 16 dispersion suppressors in total in the LHC. The dispersion suppressors mainly offset the horizontal dispersion in the arc due to the combination and separation of dipole magnets and bumps in the crossing angle. The presence of the dispersion suppressors also helps to fit the LHC in the LEP tunnel.

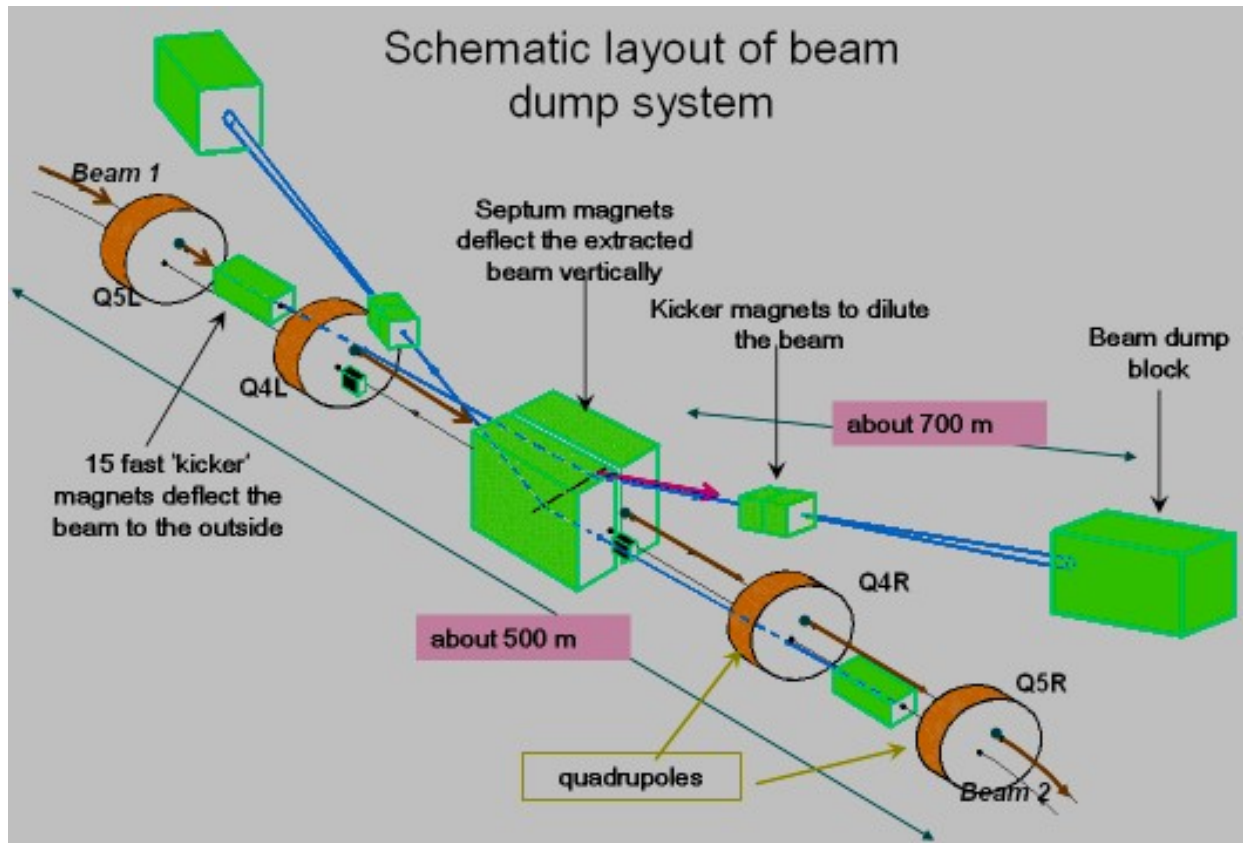


Figure 3.3: Overview of the beam dump system at IR6. Reprinted from reference [38].

The LHC arcs are 2.45 km long and consist of 23 arc cells containing 154 dipole magnets. The arc cells are 106.9 m in length and contain 2 half-cells which are 53.45 m in length. The half-cells contain three long dipole magnets, a short straight section (**SSS**), and a long cold mass(long cryostat). The magnet assembly in each arc cell contains the main dipole magnets, the quadrupole magnets, and the multipole magnets and is said to follow the **FODO** structure.

In the FODO structure, F represents quadrupoles that focus the beam vertically and defocus horizontally, D represents the quadrupoles that focus horizontally and defocus vertically and finally, O represents free space or deflecting magnets.

The figure 3.4 shows the schematic diagram for the arrangement magnets in an arc cell.

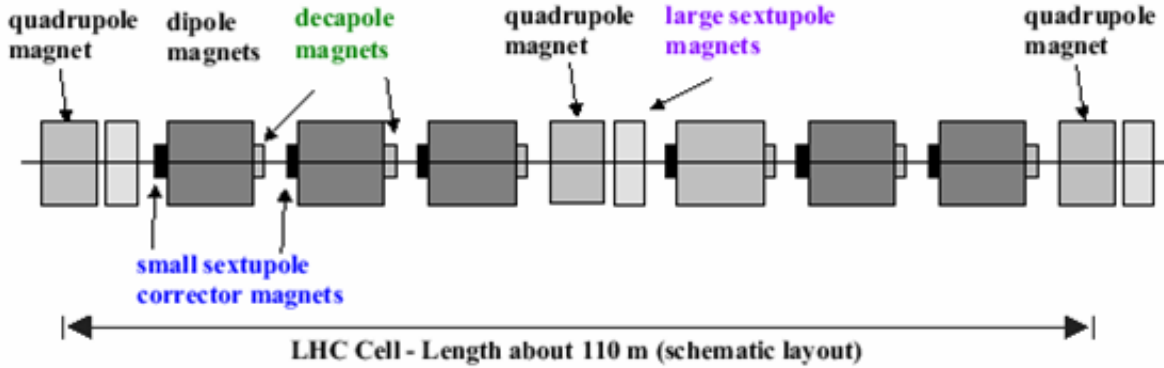


Figure 3.4: The magnet assembly of a single arc cell following the FODO structure, reprinted from [38].

A **sector** is the functional unit of the LHC. The sections are regions of the machine in between two insertion points. The magnet installation, hardware commissioning is done sector by sector, and the sectors are also powered independently.

An **octant** is the part of the machine from the middle of one arc to the middle of the adjacent arc. The octant covers a full insertion, so it is a better functional unit to describe the various uses of the insertions.

3.1.2 Performance constraints

In order to explore newer and rarer particle signatures, the LHC needs to collide particles with enormous energy and at an unprecedented rate. However, various limiting factors constrain the maximum attainable beam energy and beam energy.

In the LHC, the number of events generated depends on the machine luminosity and the event cross-section. The machine luminosity is dependant on various beam related parameters and is described as :

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (3.1)$$

Here N_b is the number of particles per LHC bunch , n_b is the number of particles per LHC beam, f_{rev} is the revolution frequency of the bunches, γ_r is the relativistic gamma factor, ϵ_n is the normalized transverse beam emittance, β^* is the beta (amplitude) function at the collision point and F represent the luminosity reduction factor which depends on the crossing angle value at the interaction point (IP). The beam emittance quantifies the average spread of particles of the beam in position-momentum phase space. A lower emittance value leads to a greater probability of particle interactions and thus leads to greater luminosity. The β function is related to linearly to the square of the transverse beam size σ and inversely to the emittance. A low value of β would lead to a "squeezed" beam and maximize luminosity. The value of β at the interaction point, β^* is designed to be the lowest in order to achieve high luminosity. In addition to **low** values of emittance and β function, one also needs **high** particle occupancy per bunch.

When the bunches of both the LHC beams collide, nonlinear **beam-beam interactions** experienced by the beam particles limit the maximum particle occupancy per bunch. The linear tune shift (ξ) describes these interactions and scales as N_b/ϵ_n . The value of ξ across all IPs should be less than 0.015 and for each IP (given there are three IPs requiring head-on collisions) less than 0.005.

The beam collimation system determines the minimum **mechanical aperture** of the LHC arcs, and it is roughly 10 times the RMS beam size. The mechanical aperture, in

conjunction with the highest value of β function of 180 and a maximum obtainable value of ϵ_n , limits the bunch occupancy value to $N_b = 1.15 \times 10^{15}$. The mechanical aperture also limits the minimum value of β at the IP (β^*) and thus the peak luminosity value at the LHC. The peak dipole field inside the storage ring depends on the beam losses that occur during operation and, in turn, limits the maximum beam energy inside the LHC. The synchrotron radiation inside the storage rings is absorbed by the cryogenic system, resulting in radiative heating. The resulting heat load imposes a limit on the maximum attainable beam intensity by the LHC. The LHC beams consist of positively charged protons, and protons in one beam interact with the protons of the other beam and the conducting boundaries of the LHC vacuum system. These interactions lead to beam instabilities which are proportional to the beam current. The beam instabilities impose a limit on the beam intensities inside the LHC. The beam losses that occur during the collisions affect the beam intensities and the emittances, and eventually, the Luminosity of the LHC. The luminosity, therefore, decays over time and is characterized by the luminosity lifetime.

3.2 Magnets

The magnets in the LHC carry out the essential job of bending and focussing the two beams. The **dipole** magnets are essential for bending the beams; the **quadrupoles** focus the beams. Then, additional correction magnets are attached to the body of the dipoles and the quadrupoles. As already mentioned above, the dipoles of the LHC are superconducting electromagnets and made of winding of Niobium-Titanium (Nb-Ti) wires. The dipole magnets must provide a high magnetic field of 8.33 T to bend two 7 TeV beams around the LHC ring, 27 Km in length. The superconducting electromagnets require cryogenic temperature for their operation. A temperature of 1.9 K is achieved by supplying superfluid helium to the magnet system. The cryogenic ($\sim 2\text{ K}$) temperature reduces the heat capacity of the cable. So a tiny deposition of energy can trigger a magnet quench for a temperature higher than the critical temperature (T_c).

The LHC has 1232 dipoles for bending beams. They are 15 m in length and weigh around 35 tonnes . The core of the dipole magnet is the dipole textbf"cold mass", named based on

the fact that all the components are in thermal contact with the helium superfluid. The cold dipole mass has a twin-bore design that provides apertures for two bore tubes (tubes for circulating beams). The twin-bore design also allows the winding of superconducting cables of two-beam channels on the same cold mass, with magnetic flux circulating opposite direction through the two channels.

The LHC dipole is shown in figure 3.5.

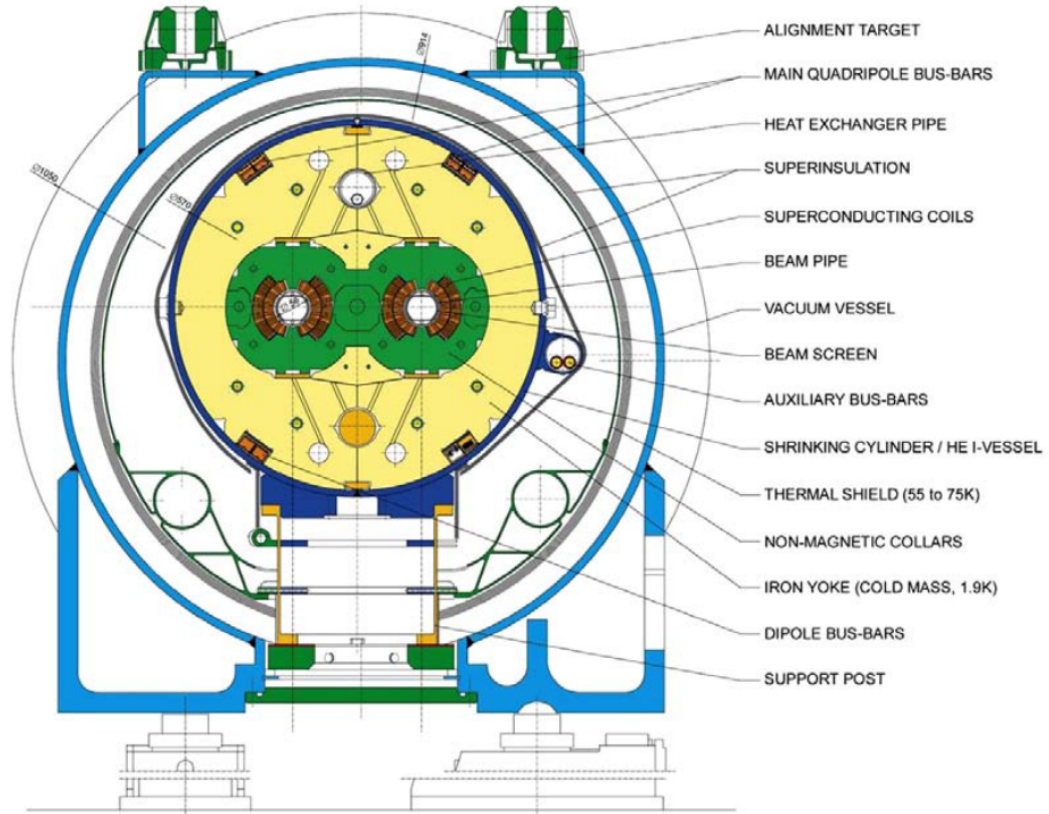


Figure 3.5: The cross-section of the LHC dipole . Reprinted from reference [37].

The whole cryo-dipole assembly fits inside the **vacuum vessel**. The vacuum vessel is a cylindrical tube made of alloyed low-carbon steel, with an outer diameter of 914 mm and a wall thickness of 12 mm . The vacuum vessels also allow vacuum and cryo-tight connections to adjacent units using stainless steel end flanges and elastomer seals.

The LHC has 392 quadrupoles, 5-7 *m* long, for focussing the beams. The main quadrupole magnets, **MQ**, are present on the SSS of the arcs, along with various connector magnets. The SSS also has some additional magnets. Octupoles, **MO**, tuning quadrupoles, **MQT**, or skew quadrupole correctors, **MQS**, populate the end upstream. The combined sextupole-dipole correctors, MSCB, are present on the downstream end.

The **insertion magnets** are the magnets in the eight insertion regions. They can be both superconducting or conventionally conducting. Four of the insertion regions are experimental insertion regions, while the rest are for RF(1), beam cleaning (2), and beam dumping(1). Individually powered quadrupoles, present at the matching and dispersion suppressor section, are responsible for tuning the LHC beam at the insertions. These are the **matching section quadrupoles**.

In the dispersion suppressors, the main dipoles have the same structural attributes as the main dipoles of the arcs. The main dipoles also share the same cryostats, with the only thing different being the cryostat circuit.

The beams on the LHC arc have a separation of 194 *mm*, and the separation dipoles at several insertions work to change beam separation for collision, beam cleaning or RF cavities insertion. These are the **matching section separator dipoles**.

There are four single-aperture quadrupoles close to the collision points called the **low- β triplet**. The low-beta signifies that they work to effectively "squeeze" the beams to get maximum luminosity.

3.3 Cryogenics

The whole 27 *Km* of the LHC ring is cooled and maintained at the superconducting temperature due to the cryogenic system. A temperature of 1.9 *K* (-271.3 °C), which is even colder than outer space, is the target temperature and is essential to increase the field strength of the superconducting NbTi wires to a maximum. A multi-step cooling process takes superfluid helium to the 1.9 *K*. The LHC magnetic components are immersed in a superfluid helium bath to reach the same temperature.

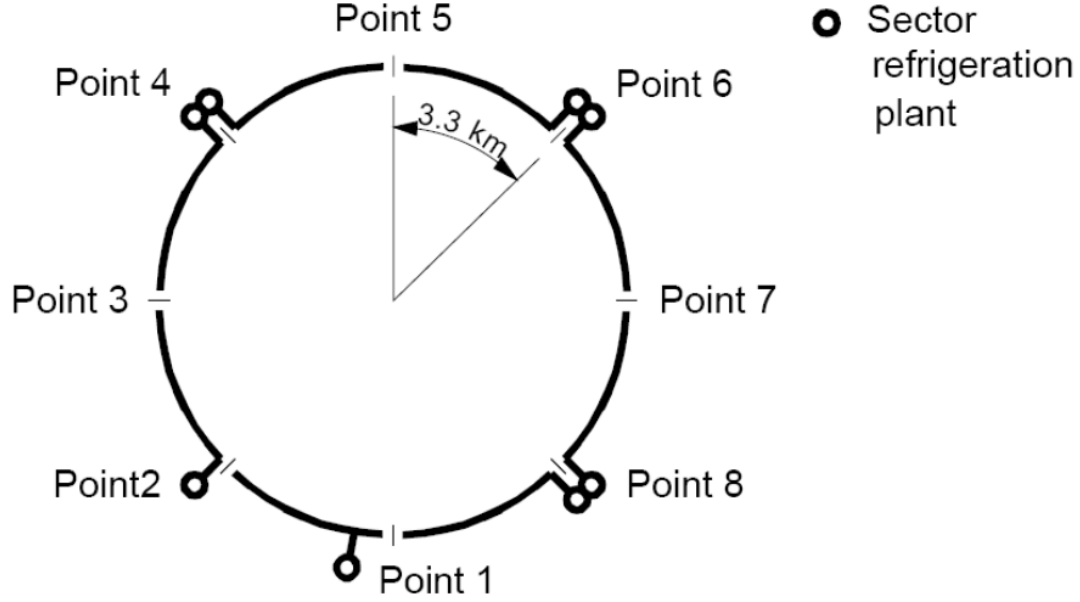


Figure 3.6: A schematic view of the cryogenic system, showing the 'Islands' and the location of the refrigeration plants. Reprinted from reference [37].

Superfluid helium has high thermal conductivity and a large specific heat capacity. These properties make superfluid helium an ideal coolant for refrigeration of a superconducting system and stabilizing any thermal disturbances. The low bulk viscosity of superfluid helium also allows it to reach all the magnetic windings easily.

The figure 3.6 shows the layout of the cryogenic system. There are 5 'cryogenic islands' at access points 1, 2, 4, 6, 8. Each island has refrigeration equipment and auxiliary services arranged to distribute superfluid helium and carry refrigeration power to the order of $\sim KW$. An island can support one or two corresponding tunnel sectors and comprises one or two refrigeration plants. The refrigeration plants inside an island have one $4.5 K$ refrigerator unit and one $1.8 K$ refrigerator unit. The refrigeration capacity required by the $4.5 K$ unit is $150 kW$, and that required by the $1.8 K$ unit is $20 kW$.

First, the helium gas is cooled to $80 K$ using 10,000 tonnes of liquid nitrogen in the process. The refrigeration turbines then bring helium to a temperature of $4.5 K$. The helium is then injected into the magnet cold masses and cooled to $1.9 K$ by the $1.8 K$

refrigeration units. At a pressure of 1 *atm*, helium first liquifies at 4.2 *K*, followed by an additional phase change to reach the superfluid state at a temperature of 2.17 *K*.

3.4 Injection Chain

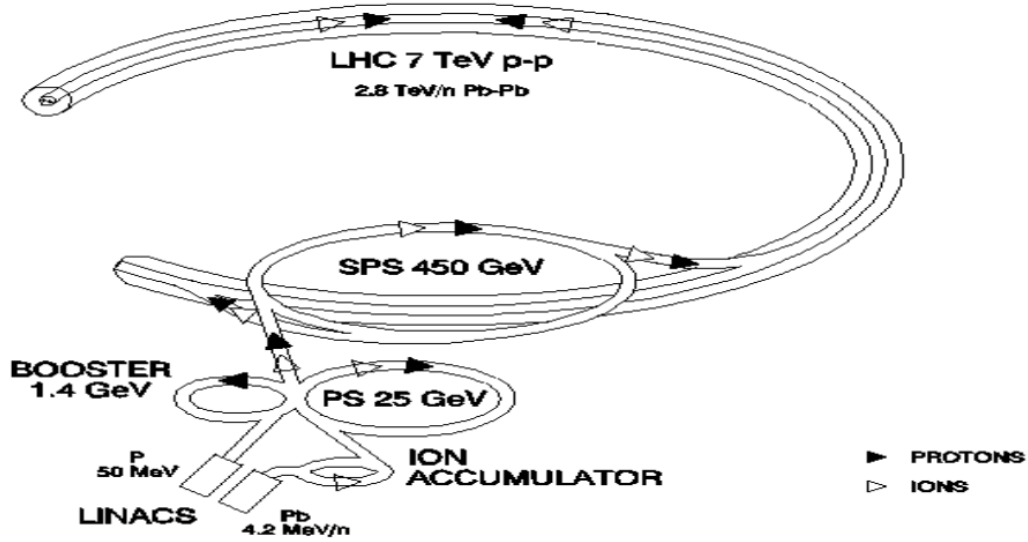


Figure 3.7: The injector complex of the LHC. Reprinted from Reference [37].

The whole Injection chain starts with a single bottle of hydrogen. First, hydrogen gas goes from the bottle into a metal tube **Duoplasmatron** where an electric field surrounds it. The hydrogen atoms turn to protons due to bombardment by free electrons in the electric field. The protons are then injected into the Proton Synchrotron Booster (**PSB**); this used to happen at an energy of 50 *MeV* from **Linac 2**. **Linac 4**, at an energy of 160 *MeV*, has replaced Linac2 in the 2019-2020 shutdown. The PSB accelerates the protons to an energy of 1.4 *GeV* and then feeds the proton beam to the Proton Synchrotron (**PS**). In the PS, the protons are accelerated to 25 *GeV* and then sent into the Super Proton Synchrotron (**SPS**). The SPS accelerates the protons to 450 *GeV*. The SPS finally transfers the protons to the LHC simultaneously in both clockwise and anticlockwise directions. The two proton beams

are accelerated for 20 minutes inside the LHC until they reach an energy of 6.5 TeV . The two 6.5 TeV collide at the experimental insertions with center-of mass energy of 13 TeV .

The injection chain is showed in figure 3.7.

3.5 The Radio Frequency Cavities

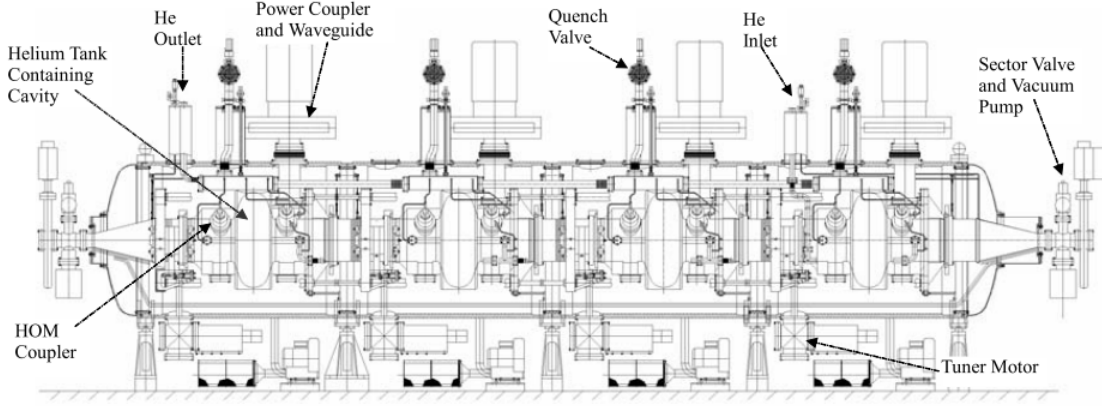


Figure 3.8: Cryomodule containing the RF cavities. Reprinted from Reference [37].

The Radio Frequency cavities are responsible for the acceleration of the beams and tightly packing the protons into bunches, which ensures high luminosity and a maximum number of collisions at the collision point. The acceleration scheme causes the energy of the proton beams to rise from 450 GeV to a maximum energy of 6.5 TeV per beam and 13 TeV center-of-mass energy. The acceleration happens for a total of 20 minutes, and the proton beams gain more and more energy through acceleration every turn. This continued acceleration is possible because Radio Frequency fields are always programmed to be the correct polarity/orientation every time the protons pass through.

A 400 MHz superconducting cavity system accelerates the injected beam. The same system also dampens the errors or discrepancies that may occur in a longitudinal direction during the injection. The acceleration occurs using an 8 single-cell cavities, each with an accelerating voltage of 2 MV , which corresponds to a field strength of 5.5 MV/m . Each of

the cavities has an individual RF system with klystron, circulator, and load. Four cavities, each equipped with helium tank, tuner, Higher-Order Modules (HOM) couplers, and power couplers, are grouped into a single cryo-module. Figure 3.8 shows part of a cryo-module.

CHAPTER 4

CMS DETECTOR

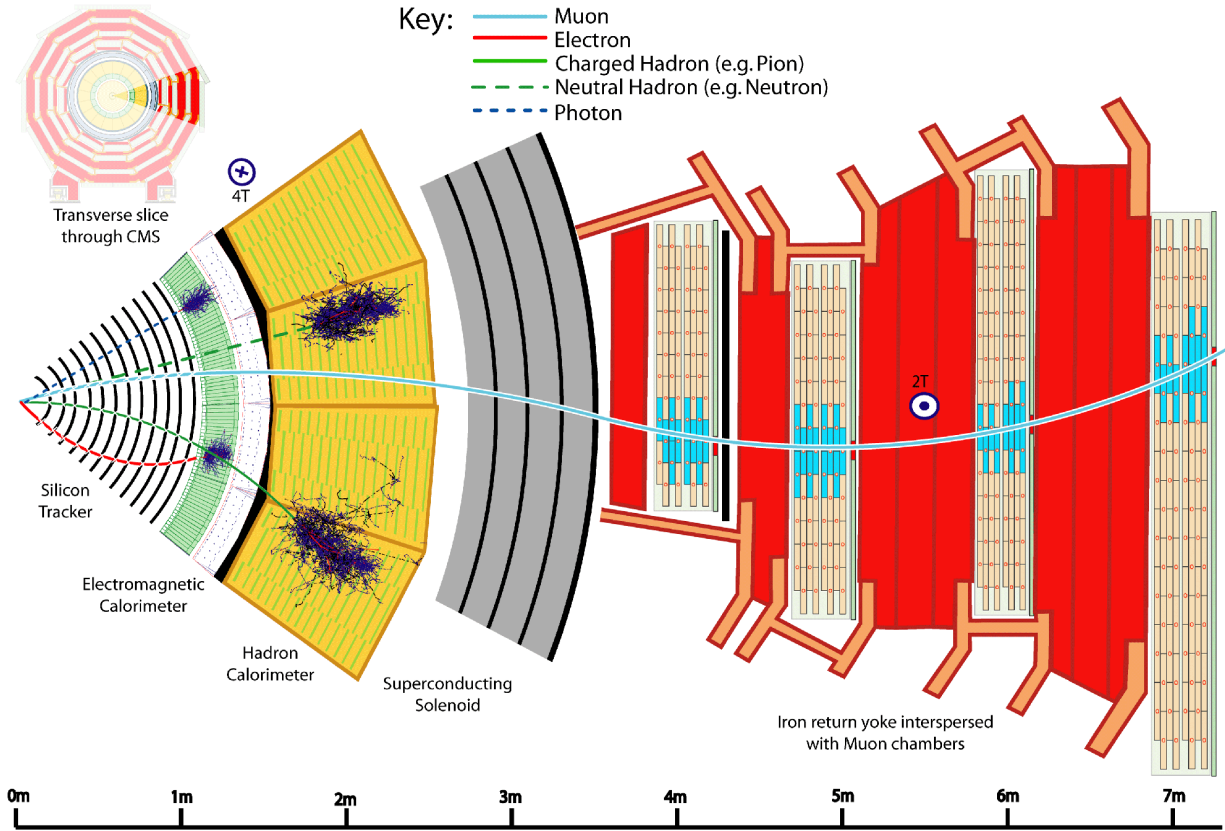


Figure 4.1: A transverse slice through the CMS detector showing the various sub-detectors and the path of various particles through the detector.

The CMS is a multi-purpose detector at the LHC, at CERN. It is roughly cylindrical in shape with a length of 21m, a diameter of 16m, weighing around 12500t. An essential feature of CMS is a 13m long and 6m inner diameter superconducting solenoid magnet that produces a magnetic field of 3.8T. The detector is composed of sub-detectors with different

functionality. The Figure 4.1 represents a transverse slice through the CMS detector showing the various sub-deectors.

4.1 Electormagnetic Calorimeter

The electromagnetic calorimeter (ECAL) is just outside the CMS tracker and is made of lead tungstate crystals (PbWO_4). The crystals are scintillating and the scintillation light is detected by photodetectors. The ECAL measures energy deposits from electromagnetically interacting particles (electrons,photons).

The ECAL is a Homogeneous calorimeter which means that it acts as a single medium absorber and detector. It is also able to enclose the whole electromagnetic shower, so it is termed as Hermetic. ECAL is reputed to have a high energy resolution resulting from its homogeneity.

The CMS ECAL has a barrel part (EB), an endcap part (EE), and a Pre-shower part (ES) in front of the EE.

4.1.1 Lead tungstate crystals

The Lead Tungstate crystals are dense crystals ideal for use in the ECAL. The crystals have a density of about 8.28 g/cm^3 and a radiation length of 0.89 cm . The high density and the small radiation length results in compact electromagnetic showers, which can be fully contained within the crystals. The crystals have a small Moliere radius of 2.2 cm which means that there is not much lateral shower development inside the crystals, and the showers are well contained. The total volume of the ECAL crystals is 11 m^3 with a total weight of 91.4 tonnes [39].

Right after the crystals are grown and machined into shape, they are polished. The polishing ensures that there are total internal reflections on the crystal surfaces, ensuring optimal light collection.



Figure 4.2: ECAL crystal with the photo-detector [40].

4.1.2 The structure of the ECAL

The ECAL barrel has 61200 lead tungstate crystals and covers a pseudorapidity range of $|\eta| < 1.479$. The crystals are shaped like truncated trapezoids, and their structure varies slightly with their position in η . The crystals have an off-point geometry, 1.7° off the vertex, to prevent particles from going in between the crystals. Thin-walled structures called **submodules** contain crystals. Each submodule contains a pair of crystals; the crystals are left and right-hand reflections of the same shape. In the whole ECAL barrel, 17 such shapes are used, so using a pair in each submodule reduces the different types of crystal required.

The submodules are arranged in larger structures called the **modules**. Inside each module, the supermodules are held in place using an aluminum grid that supports the weight from the back. Depending on the position in eta, the modules can store different numbers of crystals. The modules can have either 400 or 500 crystals. 4 modules together create a supermodule. A supermodule has 1700 crystals (400+400+400+500). 36 Such supermodules cover the whole azimuthal range and form the whole ECAL barrel. Figure 4.3 shows

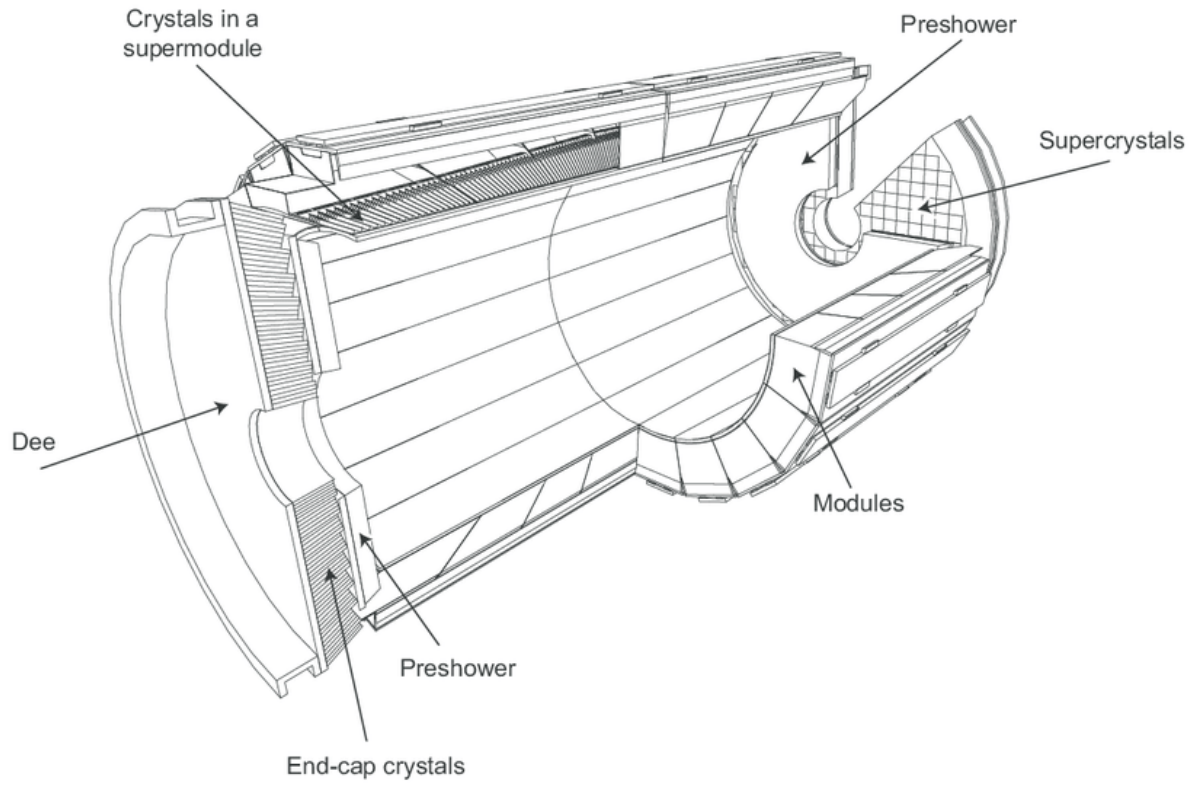


Figure 4.3: The structural layout of the CMS ECAL. This shows the module and supermodules of the ECAL barrel as well as the endcap and pre-shower. Reprinted from Reference [41].

the various parts of the ECAL barrel.

The photodetectors used in EB are the avalanche photodiodes (APDs). The APDs have an active area of 25 mm^2 . Each crystal has a pair of APDs.

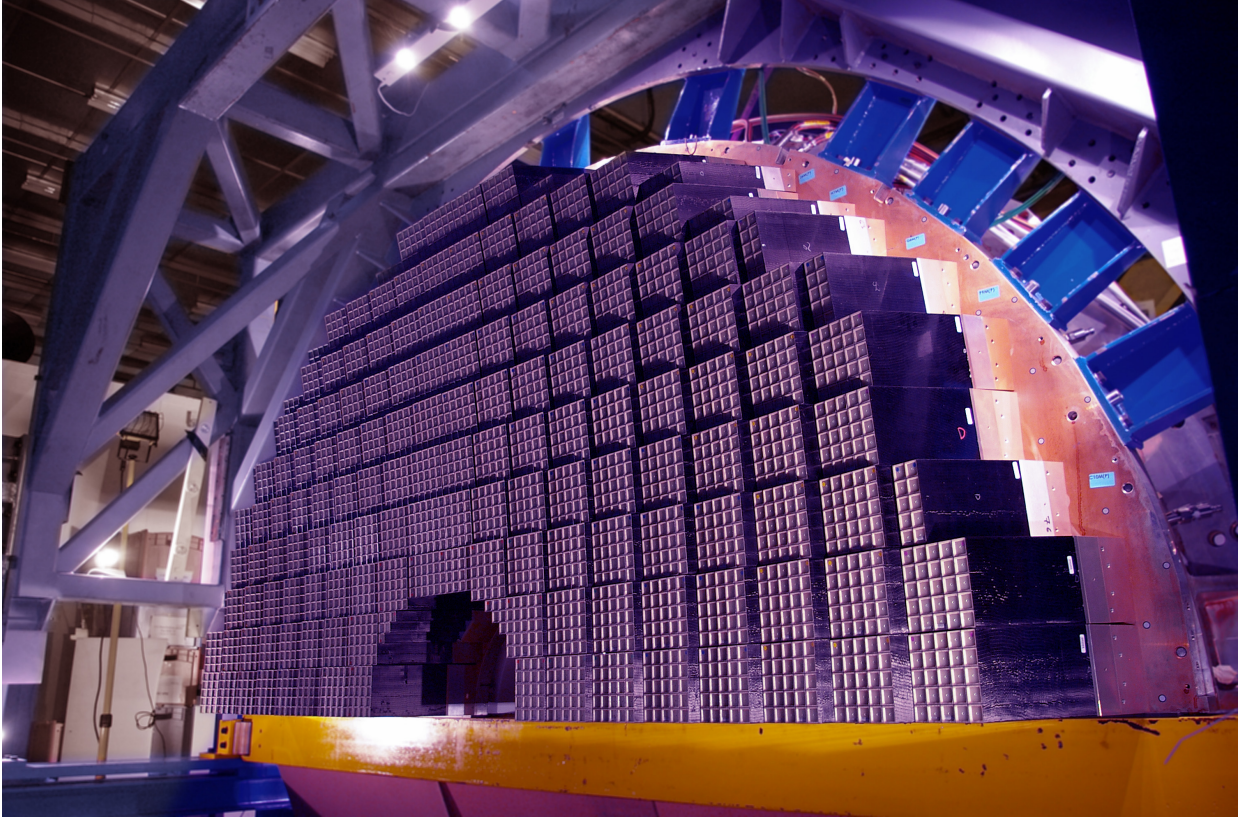


Figure 4.4: Half-Disk (Dee) of the ECAL endcap [42].

The ECAL endcap consists of 14648 lead tungstate crystals. This has coverage over pseudorapidity range of $1.479 < |\eta| < 3.0$. Each endcap consists of two half-disks called the **Dees**, each containing 3662 crystals. The crystals in the endcap are all similarly shaped and are arranged in 5×5 units called the SuperCrystals (SC). The crystals are arranged in 138 standard SCs and 18 fractional ones present on the inner and outer circumference. The Figure 4.4 shows a part of the ECAL endcap.

The photodiodes used in the EE are the vacuum phototriodes (VPTs). The VPT is 12.5 mm in radius, and a single one is glued to each crystal. These are photomultipliers with

a single gain stage. The gain of VPTs is smaller compared to that of the APDs, but they compensate through the larger active area of about 280 mm^2 .

The ECAL Preshower is situated in front of the EE. It is the first large-area silicon detector and was the driving factor behind the design and construction of the CMS Tracker. The detector covers the pseudorapidity range of $1.653 < |\eta| < 2.60$. It is a sampling calorimeter with layers of lead and silicon. The lead radiators are the active materials causing the electromagnetic showers. The silicon strip sensors after each lead radiator act as the energy absorber and measure the energy deposited. There are 4 half-disk Dees with Lead/Silicon planes. There are a total of 137216 silicon strips.

4.1.3 Readout of the ECAL

The readout of the ECAL occurs using the on-detector electronics. The readout system is designed to readout 5×5 crystals (in $\eta \times \phi$) rather than a single crystal at a time. The group of 25 crystals is called a **trigger tower**. Attached to such a trigger tower or super-crystal are the main components of the readout: five Very Front End (**VFE**) boards, one Front End (**FE**) board, Gigabit Optical Hybrid (**GOH**, 2 in EB, and 6 in EE), and Low Voltage Regulator Card (**LVR**) [43].

There are about 2448 trigger towers, 12240 VFE cards, and 2448 FE cards. VFE cards are primarily involved in signal amplification, shaping, and digitization. On the other hand, the FE cards are concerned with data pipeline to off detector electronics and trigger primitive generation (TPG).

The data is not sent to the off-detector electronics at each bunch crossing; a digital sum of trigger tower energy deposits is generated and sent to the trigger system. The digitized data is sent out after the Level-1 trigger latency $3.2 \mu\text{s}$, when the L1 accept (L1A) signal is issued.

Figure 4.5 shows the steps of the readout with the on-detector electronics. First, the scintillation light is collected by the photo-detectors (VPT or APD). The signal reaches the Multi-Gain Pre-Amplifier (MGPA) inside VFE card. Inside the MPGA, the signal is pre-amplified shaped and then again amplified by three amplifiers. The three amplifiers

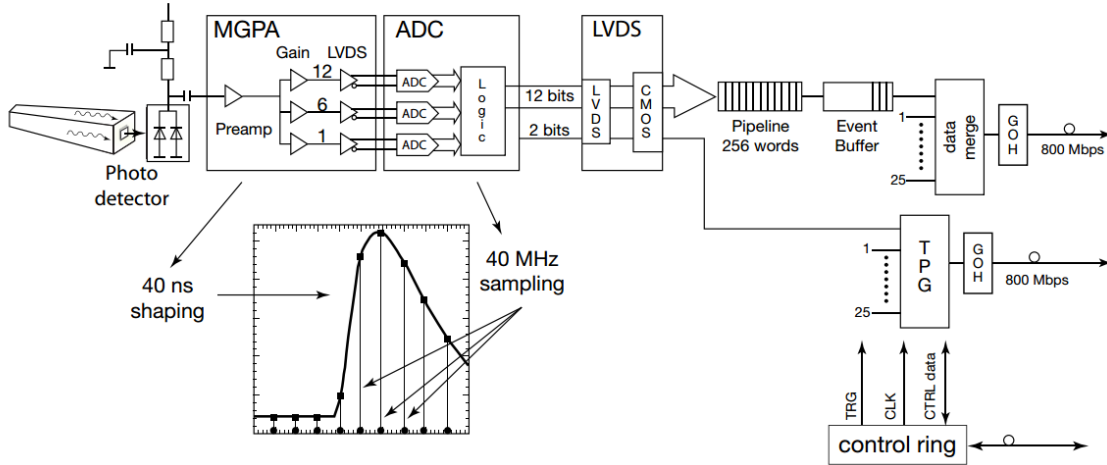


Figure 4.5: A schematic view of the readout of the ECAL [41].

have gains of 12, 6 and 1. The high gain value 12, is used for low energy, while for high energy ~ 1 TeV, we use the lower gain value 1. A multi-channel, 40 MHz, 12-bit ADC, the AD41240, digitizes in parallel the three analog output signals coming out from the three amplifiers. The baseline to the ADC inputs is adjusted using three programmable 8-bit DACs of the MGPA. AD41240 has four channels, but only three are used in the digitization process. After digitization, the output reaches an integrated logic that selects the highest non-saturated signal as the output. A radiation-hard buffer adapts the output of the ADC (low voltage differential signals) to single ended CMOS input of the FE cards.

The FE card has the functionality of storing the digitized data until the L1A signal is received. The data is stored in 256-word long dual-ported memories called data **pipelines**. During each bunch crossing, the FE cards also calculate the energy sum of the trigger towers and send it to the off-detector electronics, Trigger Concentrator Card (TCC). An ASIC, the FENIX chip, coordinates the summation. In the case of the EE, strips of five crystals in ϕ are summed by the FENIX chip, and 5 GOHs transmit five such sums. On the other hand, an additional FENIX chip takes the five strip sums and calculates a “fine-grain” bit for the EB. The bit represents the electromagnetic shower candidates inferred from the energy distribution of the trigger towers. One GOH transmits the trigger tower energy sum as well

as the fine grain bit to the TCC, at a rate of 800 *Mbps*. After the receipt of the L1A signal, the corresponding data is transmitted to the Data Concentrator Cards (**DCC**).

The TCC receives trigger primitive data from the FE cards and sends trigger tower energy sums to the Calorimeter Trigger at a rate of 40 *MHz*. The DCC receives crystal and trigger data on receipt of an L1A signal. It also applies a data reduction algorithm before transferring data to DAQ.

4.1.4 Performance of the ECAL

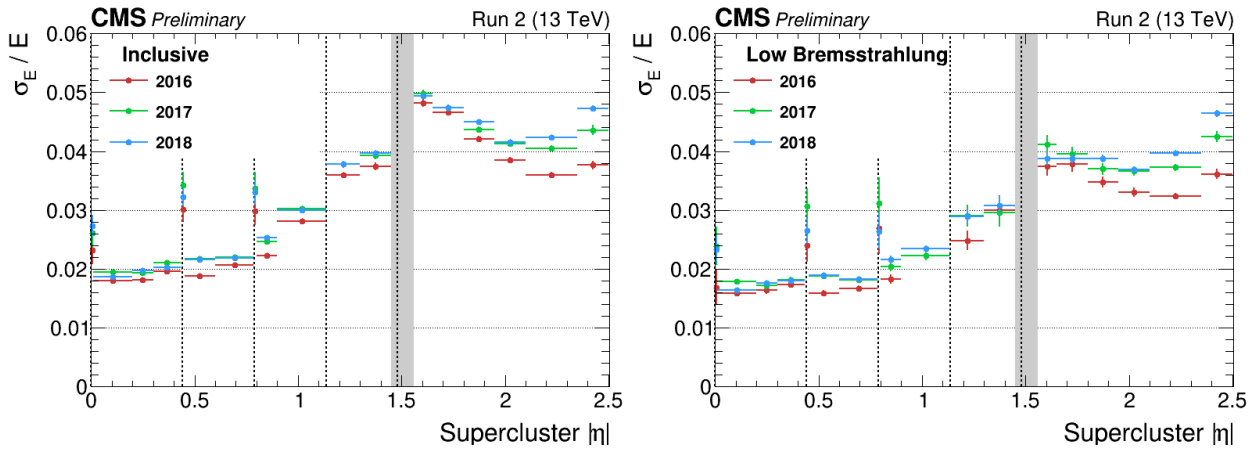


Figure 4.6: Relative electron (ECAL) energy resolution unfolded in bins of pseudorapidity η for the ECAL Barrel and the ECAL Endcaps. The resolution is showed separately for low bremsstrahlung electrons (left) and for all electrons (right). Reprinted from Reference [44].

The performance of the ECAL can be evaluated in terms of the single electron fractional energy resolution. The energy resolution is a measure of the precision with which the ECAL can measure energy. Figure 4.6 shows the single electron fractional energy resolution unfolded in bins of η for both EB and EE during different years of Run 2. It can be concluded that the resolution is affected by the amount of material in front of the ECAL and is degraded in the regions of η cracks between the ECAL modules [44].

Given all these factors, the resolution of ECAL is still excellent, and the performance is consistent. A stable ECAL energy resolution is observed throughout Run 2 despite the increased LHC luminosity and the aging of the detector.

4.1.5 Impact of radiation on ECAL response

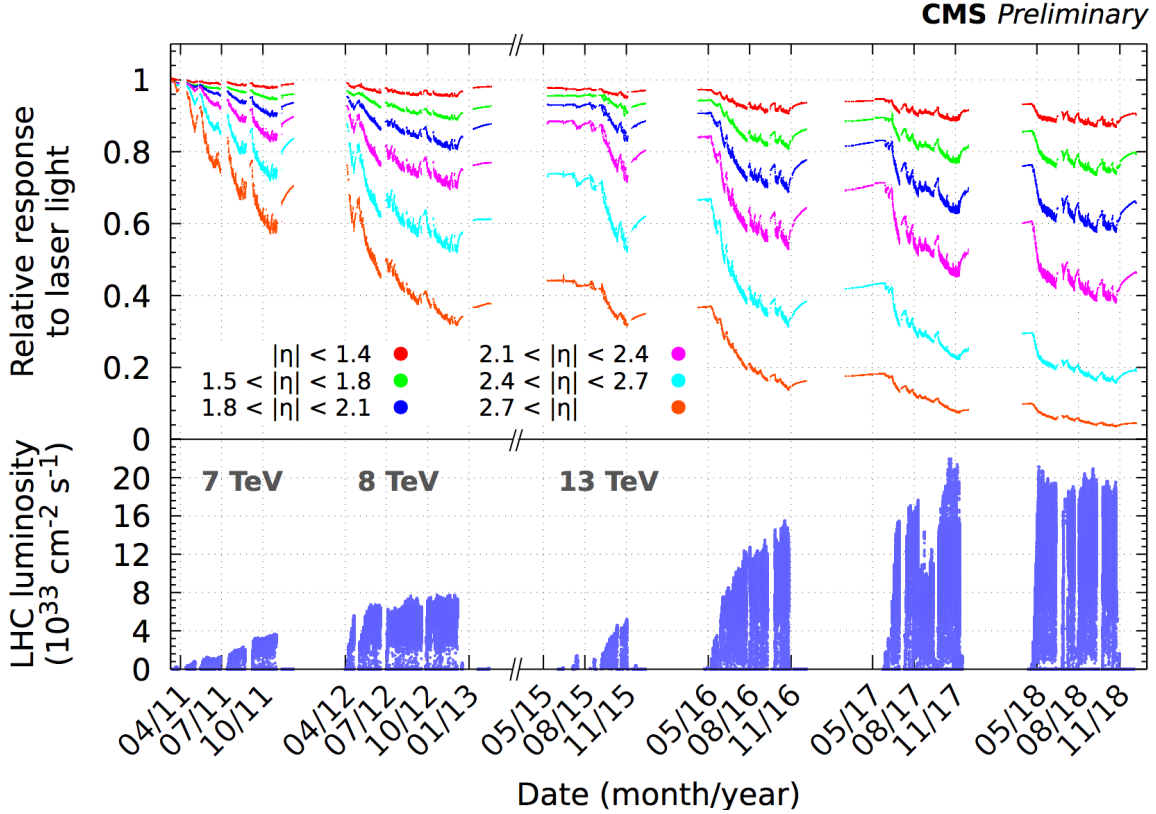


Figure 4.7: ECAL response to laser light [45].

The response of the ECAL changes significantly with radiation damage. The crystal degrades with time, and there is a gradual decrease in light output.

The luminosity spikes during runtime lead to loss of signal due to radiation damage. The radiation damage manifests through the formation of **color centers**.

The color centers appear after radiation due to the oxygen vacancies and impurities in the lattice. In addition, the color centers create absorption bands that absorb scintillation light produced by the crystals. The consequence of this is the wavelength-dependant loss of light transmission without changes to the scintillation mechanism. Thus, as the number of color centers increases, the light reaching the photodetectors decreases over time. The

damage can be tracked and corrected by monitoring the optical transparency with injected laser light.

Figure 4.7 shows the response of the ECAL to laser light. We see significant changes in the response (crystals + photodetectors) due to irradiation at the LHC. The response shows a characteristic zigzag behavior beyond the gradual decrease over time. This behavior is caused by stopping and starting the LHC. During machine run time, there is a decrease in the frequency of color center creation and increases the response. However, when the machine stops, the color centers recover, leading to the attenuation of light yield, decreasing the response again.

4.2 CMS Tracker

The CMS tracker is the the sub-detector closest to the interaction point. It is 5.5 *m* in length, 2.5 *m* in diameter and is constructed from silicon modules. It measures the tracks of charged particles and can also be used to determine the position of secondary vertices, essential for *b*-tagging. The part closest to the interaction point is the pixel detector, which is surrounded by layers of strip detectors. The strip detector has 10 layers.

The work with pixel detector was an important component of the research projects covered in this thesis. A detailed description of the pixel detector is provided in Section 5.

4.2.1 Status of the strip tracker

Figure 4.8 shows the fraction of inactive components of the Silicon Strip Tracker as a function of the delivered LHC integrated luminosity. Each point on the plot represents a single run. The fraction of unresponsive components remained relatively stable throughout Run 2 at about 4%. Moreover, the fraction of active components (96%) has not changed even after Run 2, and the detector will have a similar fraction of active components going into Run 3.

The sources of inactive components include: unresponsive readout channels excluded from the cabling (typically Front End Drivers), un-powered groups of modules, and single APV25

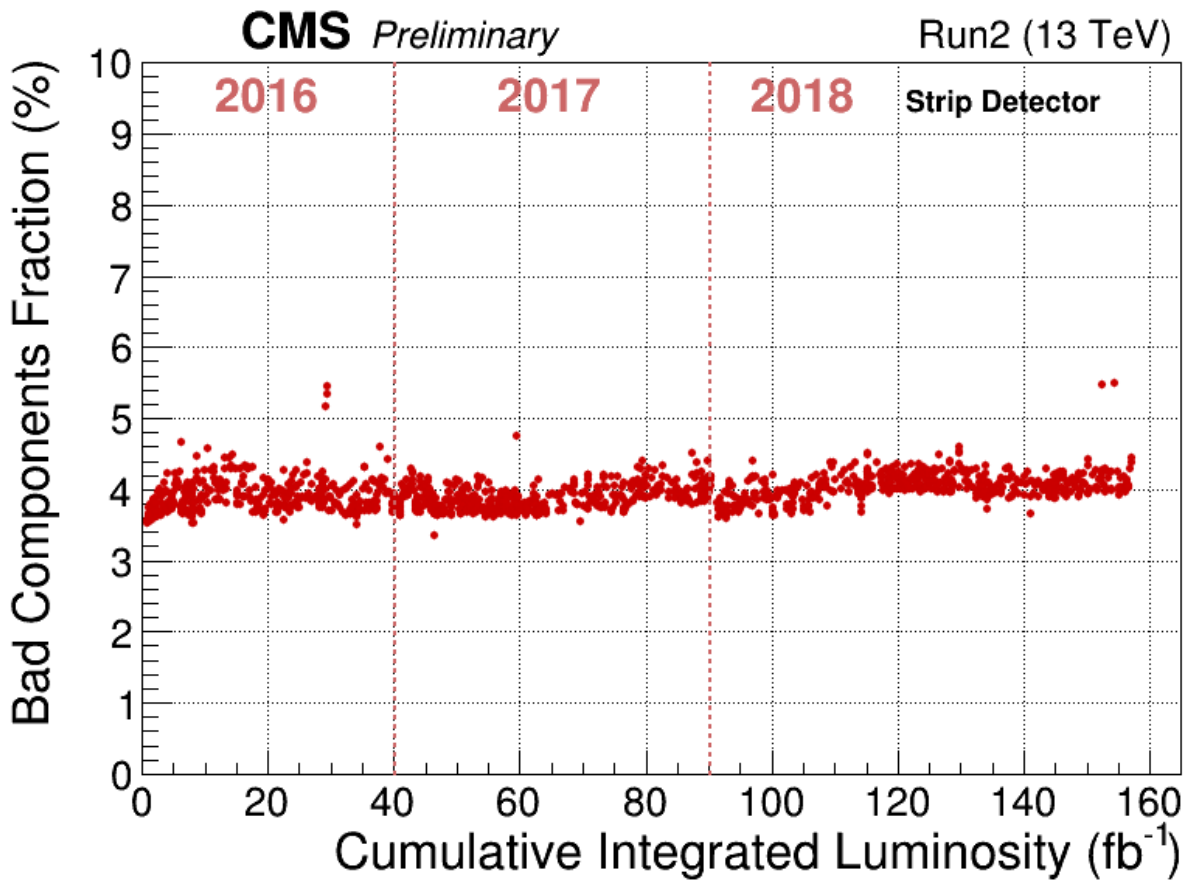


Figure 4.8: The fraction of inactive components for the CMS silicon strip detector as a function of the delivered LHC integrated luminosity [46].

chips or groups of strips masked from the offline reconstruction by a Prompt Calibration loop algorithm [47]. The algorithm identifies noisy pixels based on the median occupancy.

4.3 Performance of the Strips Tracker

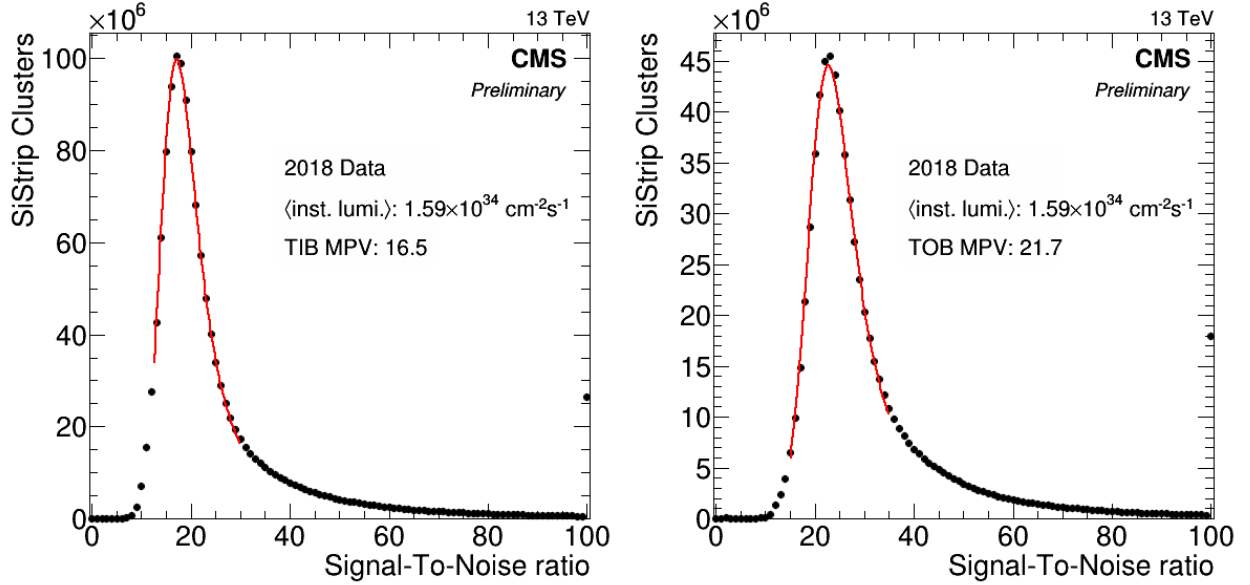


Figure 4.9: The signal-to-noise ratio for modules in the TIB(left) and TOB(right), corrected for path length inside the silicon sensors. The position of the Most Probable Value (MPV) is estimated using a fit to a Landau convoluted to a Gaussian and represents the signal-to-noise ratio [48].

The signal-to-noise ratio (S/N) for hits on reconstructed particle paths is one of the most important performance measures of the silicon strip tracker. This quantity determines the discriminating power of the strip tracker in differentiating between real signals generated by charged particles and fluctuations in detector noise. Figure 4.9 shows the S/N distributions for modules in TIB and TOB. The distributions are fitted with a Landau convoluted to a Gaussian. The Most Probable Value (MVP) can be extracted using this fitting procedure and is used as an estimate of the S/N value. The values of the MVP are pretty high (> 16 for TIB and > 21 for TOB) and signify enhanced capability to differentiate between signal and noise.

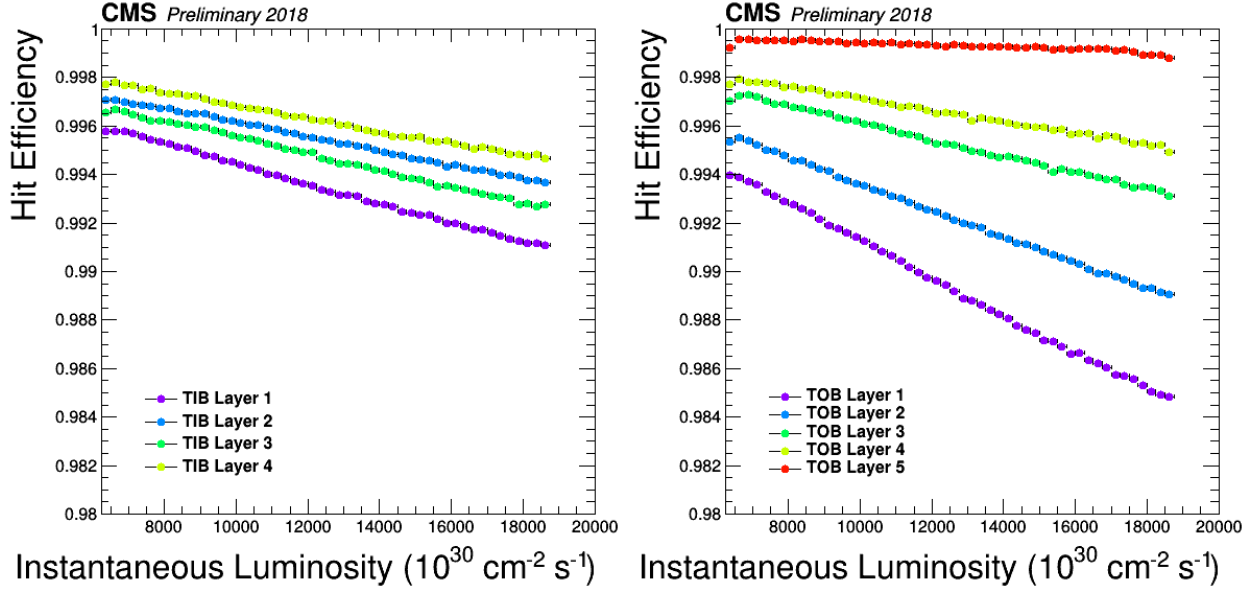


Figure 4.10: The hit efficiency of s silicon strip detectors for four TIB (left) and five TOB (right) layers as a function of instantaneous luminosity [48].

Figure 4.10 shows the hit efficiency for various layers of the TOB and TIB. The hit efficiency is still greater than 98 % at even the highest instantaneous luminosity. So, in addition to a high signal-to-noise ratio, the strip tracker can also achieve high hit efficiency.

The hit efficiency varies approximately linearly with instantaneous luminosity and is layer dependant. For instance, layers closer to the interaction point has lower hit efficiency than layers further away.

Figure 4.11 shows the momentum resolution of muon as a function of p_T , with the muon system only, the inner tracker only and then both. It can be seen that the presence of the tracker significantly improves the muon momentum resolution and brings the resolution down to sub percent.

Figure 4.12 shows the muon reconstruction efficiency for the tracker as a function of pseudorapidity η .

The excellent performance of the tracker in terms of the muon momentum resolution and the reconstruction efficiency allows the search for very narrow dimuon resonance.

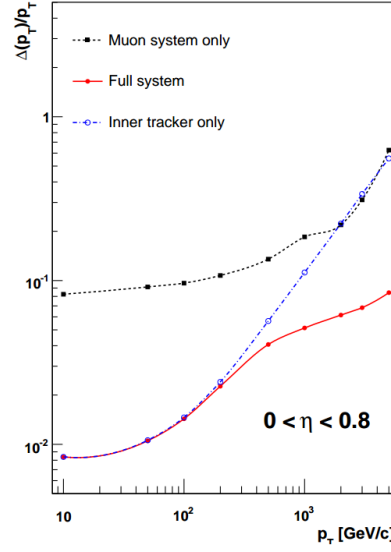


Figure 4.11: The muon momentum resolution as a function of transverse momentum, using muon system and only, inner tracker only and both. Reprinted from Reference [41].

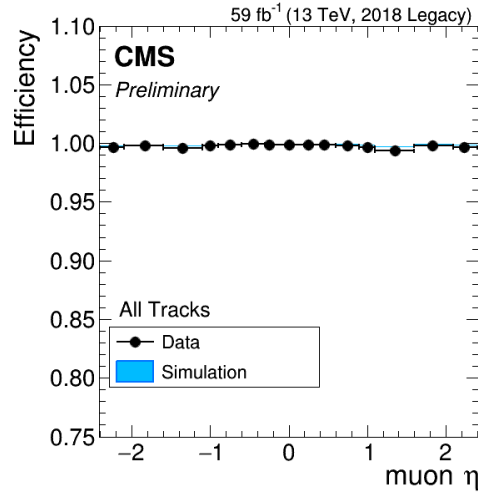


Figure 4.12: Muon reconstruction efficiency as a function of pseudorapidity for the tracker.

4.4 Hadronic Calorimeter

Radially outside the ECAL is the Hadronic calorimeter (HCAL) which is a sampling calorimeter. It contains brass as absorbers, which plays a passive role, and plastic scintillator as active material that emits scintillating light. Photo-detectors eventually detect the light. HCAL measures the energy deposits from strongly interacting particles (hadrons). It can measure energy from both charged and neutral hadrons, which can take the form of jets and sometimes result in missing energy.

The HCAL is positioned between the ECAL and the inner part of the magnetic coil, putting a constraint on the total amount of material that can absorb the hadronic shower. The material choice and design of the HCAL were thus made, keeping the radial restrictions of the HCAL in mind.

The HCAL has divided into four parts: the HCAL barrel (HB), HCAL endcap (HE), outer (HO) and forward (HF) calorimeters. The various parts of the HCAL are shown in Figure 4.13

4.4.1 HB

The HB is part of the HCAL covering the barrel region with the pseudorapidity range $|\eta| < 1.3$. The HB consists of two half-barrels (HB+ on +z and HB, -z). Each half-barrel is divided into 36 azimuthal (ϕ) wedges. The wedges are further sub-divided into four azimuthal sections.

The wedges are made of brass absorber plates (cartridge brass/ C26000). The plates are bolted together in a staggered fashion so that particles cannot pass through gaps, and there is essentially no dead area in the whole radial extent. Each wedge has about 14 brass absorber plates sandwiched between two steel plates. The total thickness is expressed in terms of the **interaction length** (λ_I), to be about 5.82 (λ_I). The effective thickness of the HB, however, increases with the polar angle(θ) as $1/\sin\theta$ and can get up to 10.6 (λ_I) at $|\eta| = 1.3$.

The scintillator used in HB as the active material is primarily 3.77mm thick plastic scintillator (Kuraray SCSN81). The plastic scintillators were used for their moderate radiation

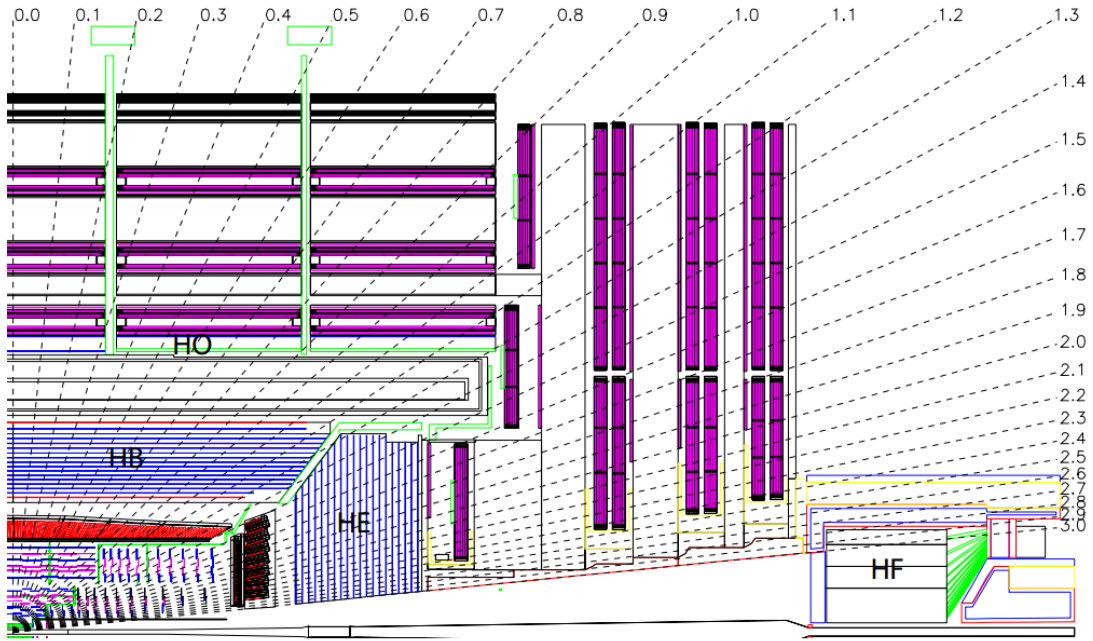


Figure 4.13: Schematic view of the CMS detector showing parts of the HCAL. The locations of the Hadron barrel (HB), endcap (HE), outer (HO) and forward (HF) calorimeters. [41].

hardness and long-term stability. The plastic scintillator is divided into 16 $|\eta|$ layers inside the wedge. The 16 layer has a much thicker (9 *mm*) plastic scintillator, to correct for late developing showers that leaks out of the barrel region. After passing the scintillator the light reaches the Wavelength shifting fibres (WLS). The WLS are in turn spliced to the Kuraray double-clad clear fibres, which go to the optical connectors at the end of the tray. The light is then taken to the Optical Decoding Unit (ODU) by the optical fibre. The optical fibres are arranged into readout towers by the ODU. The final stage of the readout used to be hybrid photodiodes (HPD) before but during LS2, the photo diodes were replaced by **Silicon PhotoMultipliers (SiPMs)** [49].

4.4.2 HE

The HE is the sub-section of the HCAL covering the endcap region. The pseudorapidity range it covers is $1.3 < |\eta| < 3.0$. HE covers a substantial portion of the pseudorapidity range, and incidentally, this is the range in which roughly 34% of the particles are produced. Multiple factors need to be considered when choosing the material for the HE. HE is close to the interaction point, which means that material experiences a high counting rate due to the High luminosity and has to endure a substantial amount of radiation. A radiation-hard material is, therefore, an ideal choice. In addition, HE is put at the ends of a 4*T* magnet, so this also requires the use of a non-magnetic material. Finally, the interaction length of the material should also be small to fully contain the hadronic shower. The material that fits all requirements is C26000/ cartridge brass.

The absorber used for HE is shown in the Figure 4.14. The (brass) absorbers are bolted together in a staggered fashion to maximize absorption by having no effective “dead material”. The brass plates have gaps between them to accommodate the scintillators. The total length of the calorimeter is $10\lambda_I$, which is more than enough to contain the hadronic shower.

The scintillators used in HE are plastic (3.7 *mm* SCSN81 and 9 *mm* Bicron BC408) scintillators. The scintillators are trapezoidal in shape and the scintillation light is collected by the WLS fibres. One end of the scintillators is covered with aluminium to increase the light yield while the other is connected connected through a clear fibre to an optical

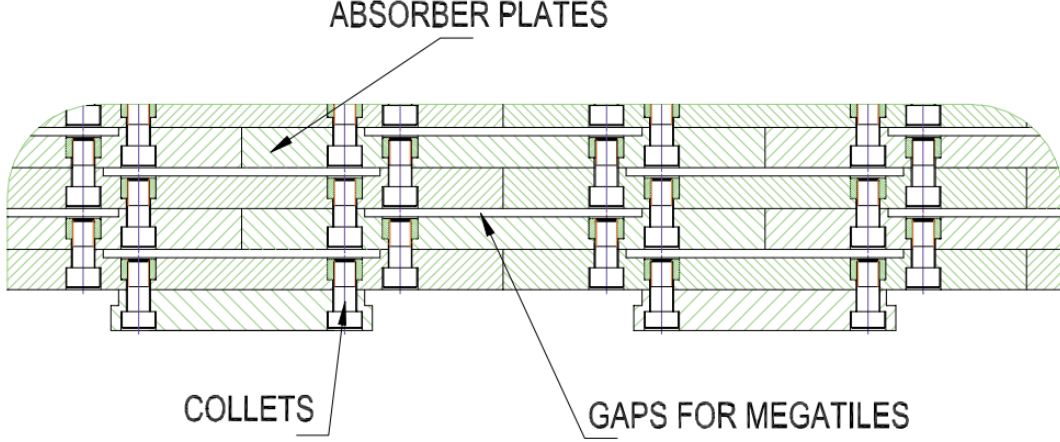


Figure 4.14: Schematic diagram showing the HE absorber. [41].

connector. The scintillators are wrapped in Tyvek and covered on both sides by duraluminum sheets. The granularity of the HCAL is different for different pseudorapidity ranges, it is $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for $|\eta| < 1.6$ and $\Delta\eta \times \Delta\phi = 0.17 \times 0.17$ for $|\eta| \geq 1.6$. The scintillators are shown in the Figure 4.15. The light from the scintillators is again collected by SiPMs, which were used to replace the HPDs during Run 2 (early 2017).

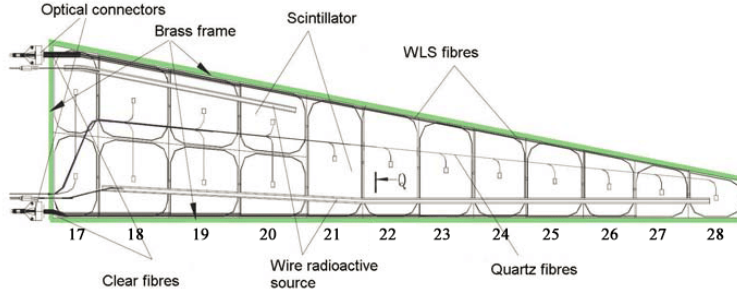


Figure 4.15: Diagram showing the HE scintillator tray. [41].

4.4.3 HO

The HO is a means of measuring the hadronic shower when the HB cannot fully contain it. This additional absorber ensures an adequate sampling depth for $|\eta| < 1.3$. With the presence of the HO, the total thickness of the HCAL becomes much more than $10 \lambda_I$. It has

been determined from various studies involving QCD events that the inclusion of HO results in the reduction of energy leakage and improves the measurement of missing energy.

In each of the first iron yoke rings, HO acts as the first sensitive layer. Two layers of HO scintillators are located on either side for the central ring, but a single layer of HO is present for all the other rings.

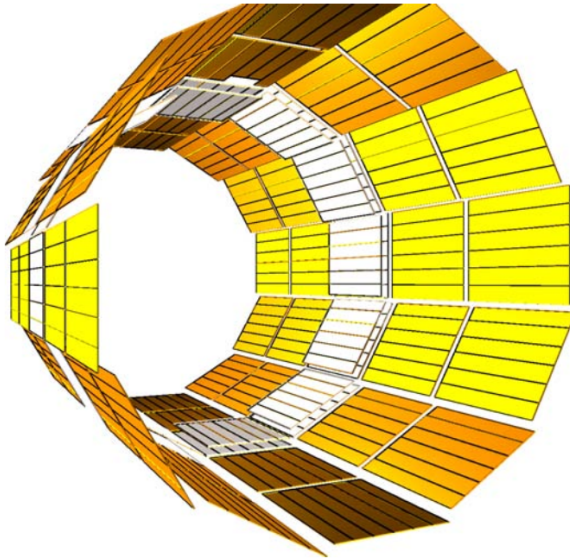


Figure 4.16: Schematic diagram showing the layout of the HO trays.[41].

The geometry of the muon system lining the HO (and HCAL in general) constrains the HO. The layout of the HO is shown in Figure 4.16. HO has 12 identical sectors for different ϕ and is supported by the same stainless steel that supports the muon system.

The scintillator tiles are the smallest working unit of the HO; they are geometrically different but functionally similar to the tiles in the other part of HCAL. WLS fibres are held inside grooves of these tiles. The tiles are grouped together into trays and there are about 6 trays for each ϕ section. Figure 4.17 shows a schematic view of the HO tray with one tile mapped to a HB tower.

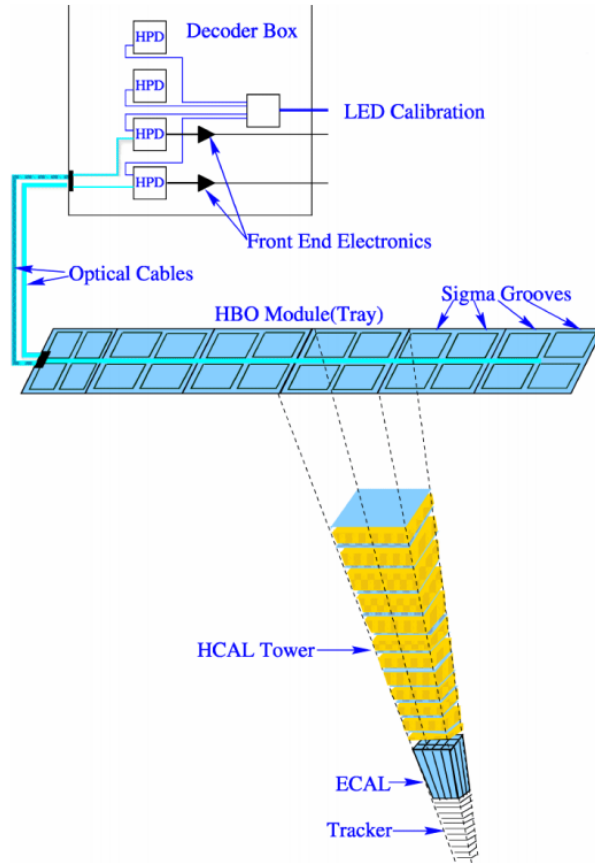


Figure 4.17: Schematic view of an HBO tray shown with individual tiles and the corresponding grooves for WLS fibres. Each optically independent (four WLS fibres) tile is mapped to an HB tower. Optical fibres from the tray are routed to the decoder box, which contains the photodetector and read-out electronics.[41].

4.4.4 HF

The forward calorimeter is the part of the HCAL which experiences the most particle flux due to its positioning. Due to its proximity to the beam line, radiation hardness is critical for successful operation, and hence quartz fibers are used as the active medium. When particles pass through the medium, Cherenkov light is produced when charged shower particles carry energy that is greater than the Cherenkov threshold. A small portion of the generated light is captured. And the fraction is given by:

$$f_{trap} = NA/2n_{core}^2 \quad (4.1)$$

NA is the numerical aperture and n_{core} is the refractive index of the quartz core. The acceptance of light into the forward calorimeter is dependant on the angle. When the light hits the core-cladding at an angle larger than the critical angle of 71° , it becomes part of the calorimeter signal.

The absorber structure in the calorimeter is made of steel and consists of really narrow (5 cm) grooved plates. The fibres are inserted into the grooves.

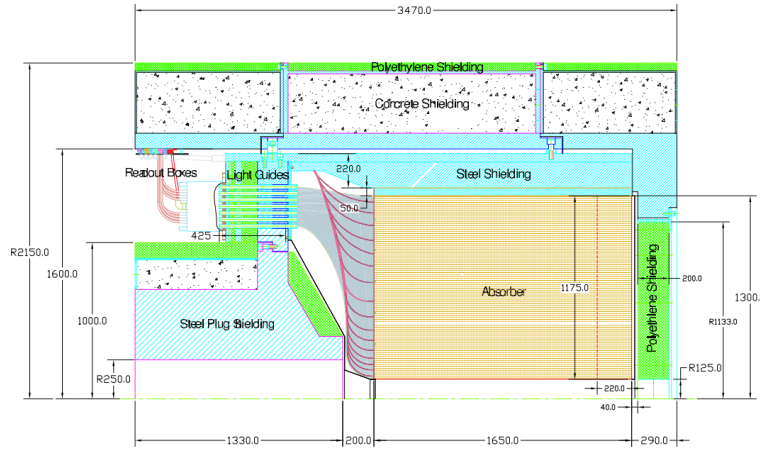


Figure 4.18: The cross sectional view of the HF calorimeter [41].

One of the main features of the HF design is the ability to distinguish between the hadronic showers and electromagnetic showers. The discriminating power is achieved by

dividing the detector into two longitudinal segments. Half of the segment has fibres that cover the entire depth of the absorber, while the other half begin at a depth of 22 *cm* from the front of the detector. With this design, it becomes possible to distinguish between hadronic and electromagnetic showers, as hadronic showers produce equal signals in both segments, while electromagnetic showers tend to deposit a large fraction of energy in the first 22 *cm*. The various parts of the HF is shown in the Figure 4.18.

4.5 Muon Chambers

Finally, outside the HCAL is what we call the muon system. The muon system consists of 4 muon stations that are located at various distances from the centre of CMS. They are located between iron acting as the return yoke of the magnetic field and are separated by steel plates. Several detectors using similar principles (gaseous ionization) to detect the muons.

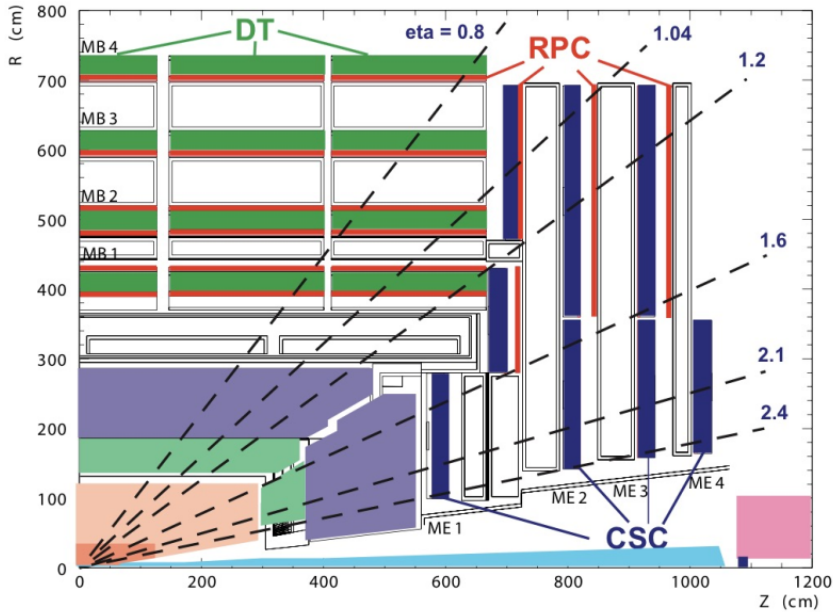


Figure 4.19: A schematic diagram of the Muon system geometry.[50].

This involves a gas chamber with a wire, maintained at a high voltage with respect to the chamber. The passage of charged particles (muons) causes the gas to ionize and the

resulting electrons move towards the wire. During their motion, the electrons ionize more gas molecules, creating a stream of electrons, which makes a measurable signal. There are drift tubes (DTs) in the barrel region, cathode strip chambers (CSCs) in the endcap region and resistive plate chambers (RPCs) which complements both the previous detectors in the two regions. A schematic diagram of the Muon chambers is shown in Figure 4.19.

The DT system is the part of the Muon chambers primarily present in the barrel region, covering the pseudorapidity range $|\eta| < 1.2$. The DT system is divided into 4 stations arranged radially. Each station is divided into 5 wheels in z direction. Each wheel is divided into 12 sectors in ϕ , each sector covering an azimuthal angle of 30° . The layout of the DT is shown in the Figure 4.20.

Figure 4.20: Layout of the DT chambers in one of the 5 wheels[41].

and electrons move towards the anode wire. The setup is shown in the Figure 4.21. Drift tubes are used in the barrel region for low residue magnetic field and low particle flux. The DT chambers are made up of 3 super layers (SL). Two of the outer super layers are able to carry out measurements in the $r - \phi$ plane, while the inner SL is able to take measurements in the $r - z$ plane. The designed resolution for the drift chamber is about $100 \mu\text{m}$ per chamber.

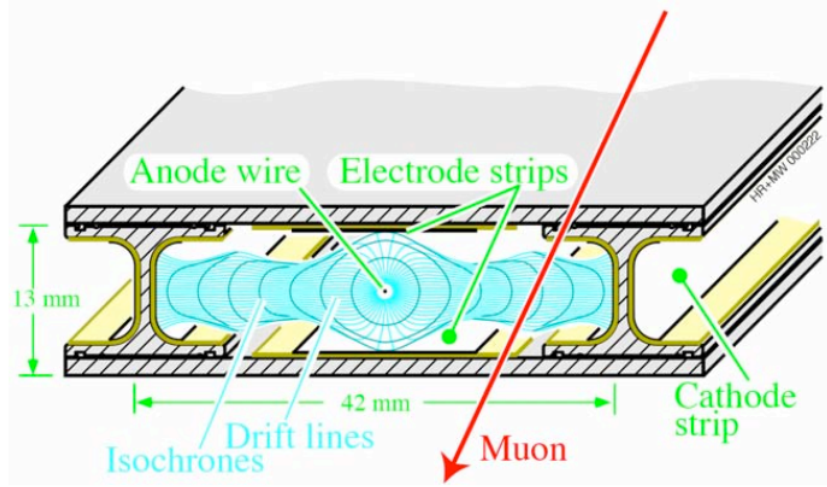


Figure 4.21: Sketch of a cell showing drift lines and isochrones[41].

4.5.2 Cathode strip chambers

The CSCs are present primarily in the endcap region. The corresponding pseudorapidity is $0.9 < |\eta| < 2.4$. Each CMS endcap has 4 CSC stations arranged in z direction. The chambers are positioned such that they are perpendicular to the beamline and in between the flux return plates. The cathode strips in each chamber are arranged radially, allowing measurement in the $r - \phi$ plane, while the anode wires are arranged azimuthal direction and perpendicular to the chambers, facilitating measurements in the η direction as well as timing measurements for each muon. The anode wires allow fast timing measurements, and the cathode strips give a good spatial resolution (1 mm). There are a total of 540 chambers, and there are 6 layers per chamber. The layout of the CSC is shown in Figure 4.22.

The working principle of CSC is gaseous ionization, and the gas used inside the CSC unit is a $\text{Ar} - \text{CO}_2 - \text{CF}_4$ mix. When a muon passes through the CSC, the gas inside each unit

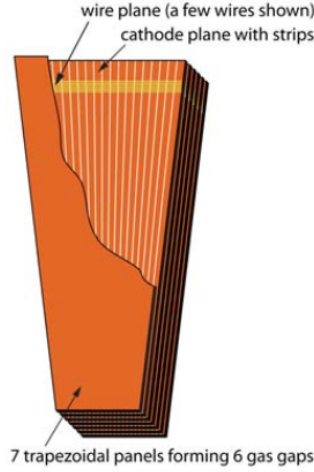


Figure 4.22: Layout of a CSC[41].

is ionized, and an electron avalanche occurs when muons traverse the planes of the station. The charged particles are then attracted to either the anode wires or the cathode strips, depending on the sign of the charged particles. The charges induced on the cathode strips by the positive avalanche ions near a wire can be interpolated to obtain the precise location of an avalanche along a wire; this results in precise measurement of $r - \phi - z$ in all 6 layers. The working principle is shown in the Figure 4.23 .

4.5.3 Resistive plate chambers

The RPC are present in both the endcap and the barrel region , complementing both the DT and the CSC. There are 6 layers of RPC in the barrel region and 4 layers of RPC in the endcap region. The two innermost layers in the barrel region improve the the performance at low p_T . The RPC have superior time resolution (nS) allowing them correctly assign an ionizing event to a Bunch Crossing (BX).

The RPC are gaseous parallel plate detectors that use double gap technology operating in avalanche mode. The two gaps are referred to as the **up** and the **down** gaps, respectively and the total induced signal is the sum of the two single-gap signal.

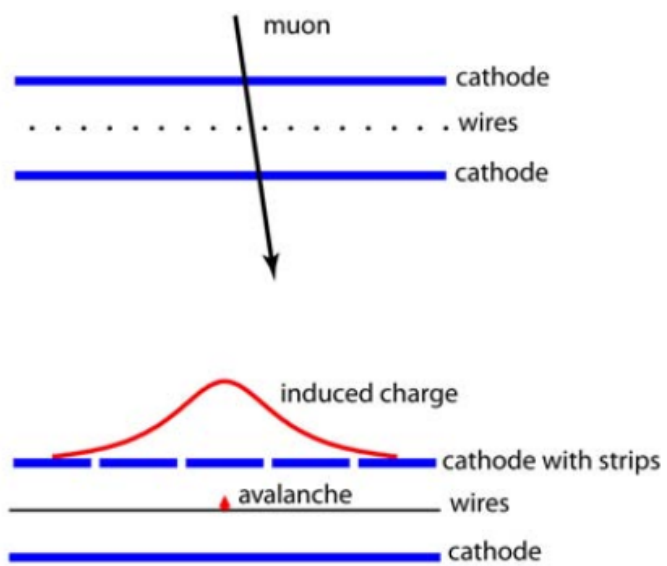


Figure 4.23: The operational principle of the CSC[41].

CHAPTER 5

THE PIXEL DETECTOR

5.1 Pixel Detector and Its Upgrade

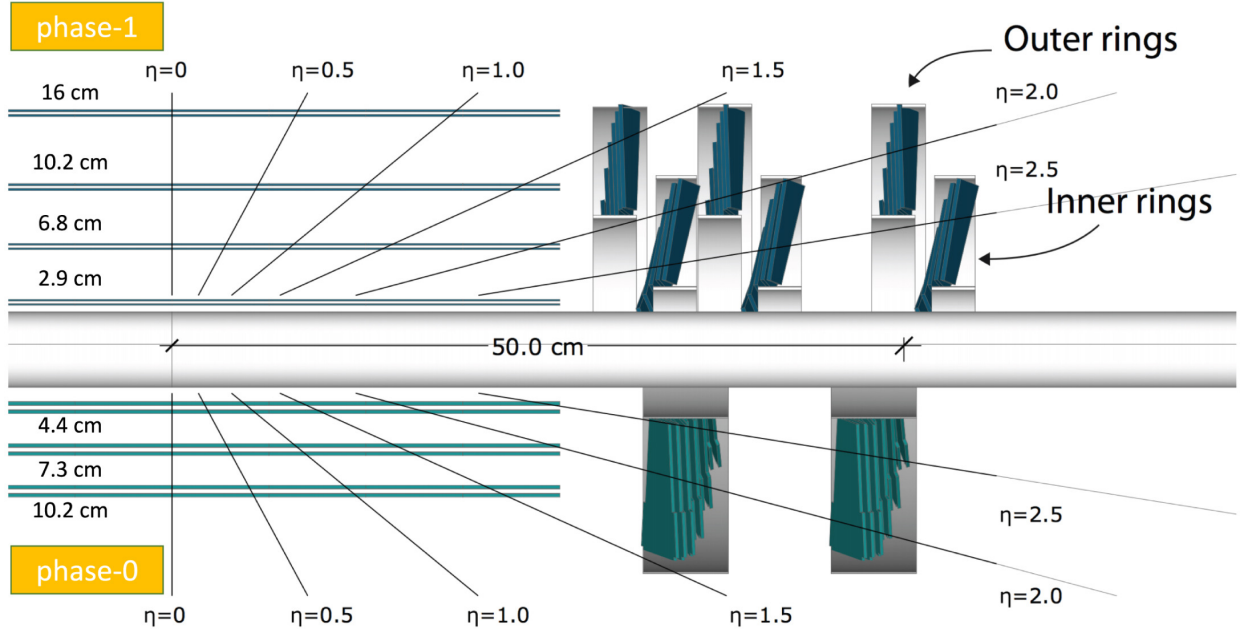


Figure 5.1: A conceptual layout comparing the different layers and disks in previous and the current pixel detector [51].

The pixel detector is the inner part of the CMS tracker used to track the positions and trajectories of charged particles. It is constructed of silicon sensors. The sensors adopt the same n^+ -in- n technology as already employed in the Phase-0 detector [41]. The detection principle is based on a fully depleted junction sensitive to the passage of charged particles, which creates charge carriers and hence signals.

The pixel detector underwent an upgrade in 2017 [51]. The previous design involved three hits for tracking. This was achieved by using three barrel layers (BPix) at $r = 4.4, 7.3$ and 10.2 cm, and two endcap disks (FPix) at $z = \pm 32.5$ cm and ± 46.5 cm. With the increase in

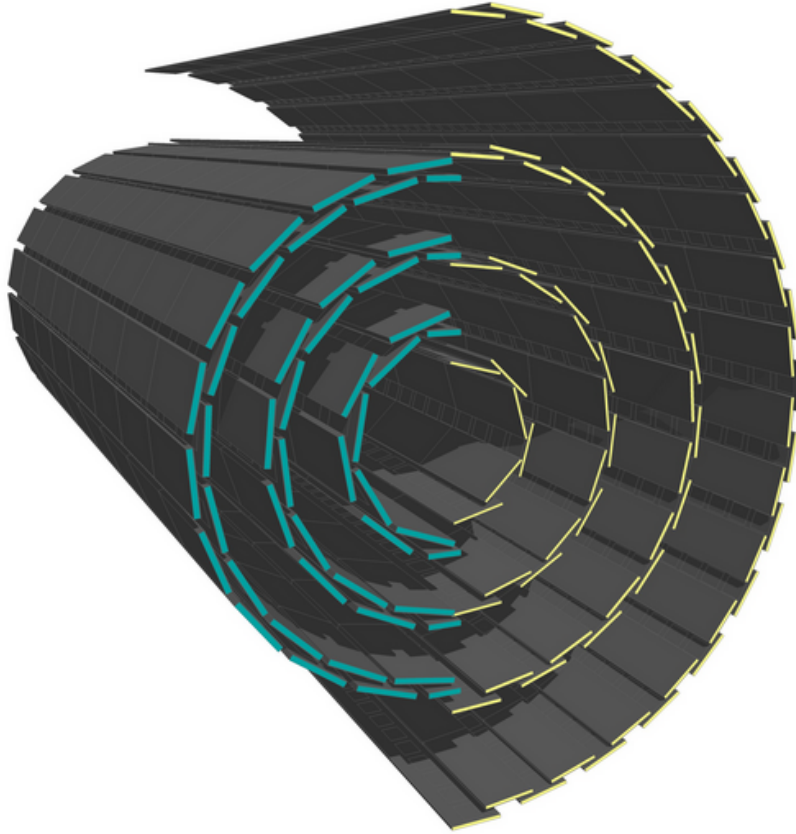


Figure 5.2: A transverse view comparing the pixel barrel layers in the previous and the current pixel detector [51].

luminosity at the LHC there is a necessity to maintain high tracking efficiency despite more challenging readout conditions. The upgrade provides four pixel hits to improve tracking. This is necessary as the increased luminosity results in a large track multiplicity per collision. The mentioned fourth hit is achieved by an additional barrel layer at $r = 16$ cm and an extra set of endcap disks on each end. The endcap disks were inserted at $z = \pm 29.1$ cm, $z = \pm 39.6$ cm and ± 51.6 cm. The innermost pixel layer is moved closer to the interaction point, with a radius of $r = 2.95$ cm. The other two barrel layers are roughly at the same radius $r = 6.8$ cm and $r = 10.9$ cm. Figure 5.1 and Figure 5.2 shows the comparison between the layout of the CMS Phase-1 pixel detector and the original pixel detector.

The upgrade also included the update of the original readout chips used in the FPix and BPix outer layers to a new and improved version (PSI46 to PSI46DIG), as well as the introduction of a new readout chip for the innermost layer of the BPix (PROC600), designed to have lower dead time at higher luminosity among other things.

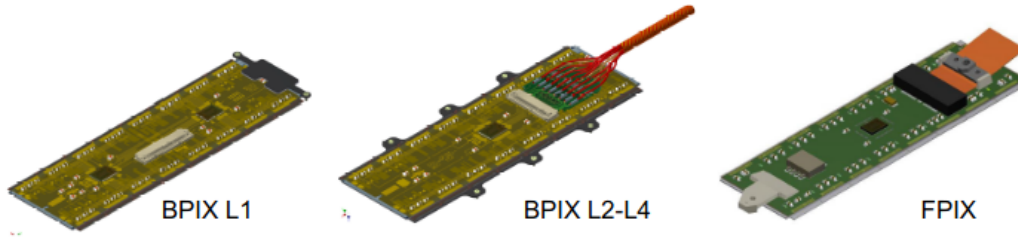


Figure 5.3: Pixel modules for BPix layer 1 (left), BPix layer 2-4 (middle), and the FPix (right). [52].

The pixel sub-detector's most basic functional unit is the **pixel module**. Each module has 16 readout chips (ROCs)[53], discussed further in section 5.2.1. The fully depleted silicon sensors are sensitive to the passage of charged particles that induce the creation of electron-hole pairs in the sensor. The silicon sensors are bump-bonded to the readout chips that amplify the signal obtained from the silicon sensors and store the signal for the readout if it is above a certain threshold. The data are stored in a data buffer with the timestamp information [51]. A high density interconnect (HDI) is attached to the top of the silicon

sensors and is responsible for signal and power distribution to the readout chips. The CMS Phase-1 pixel detector modules are shown in Figure 5.3.

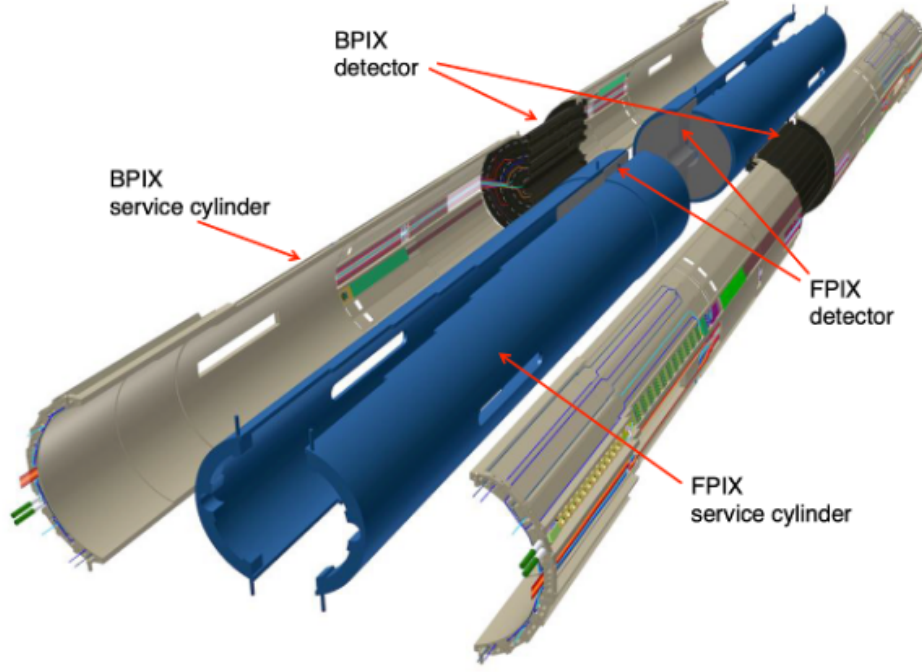


Figure 5.4: Phase-1 BPix and FPix detectors together with the service half-cylinders that hold the readout and control circuits as well as power and cooling lines [52].

The token bit manager (TBM) controls the readout of the ROCs [54]. It will be discussed further in section 5.2.1. When the Level-1 (L1) trigger issues the L1 accept (L1A) signal, readout is initiated from all the sub-detectors and this is the first step of the physics event selection process. If a L1A trigger signal is received for the timestamp that was stored in the readout chip, the signal buffer is read out. The data from the TBM are sent to the Front End Driver (FED) through an optical link. The data are initially read out as electrical signals by the TBM from the readout chips. The electrical signals undergo optical conversion in the opto-electric interface of the Pixel Opto Hybrid (POH), located in the service cylinder. Until this point the data are still inside the detector. The optical signals are then transmitted through optical fibers to the back-end receiver of the FED. The FED is situated in a counting

room inside the Underground Service Cavern (USC), 65 meter away from the CMS detector [55]. The FED is part of the CMS data acquisition system. The BPix and the FPix along with their service half-cylinders are shown in Figure 5.4.

5.2 Phase-1 Pixel DAQ and Control System

The DAQ and control system of the Phase-1 pixel detector, shown in Figure 5.5 involves Front-end ASICs, Back-end components, optical components as well as auxiliary electronics.

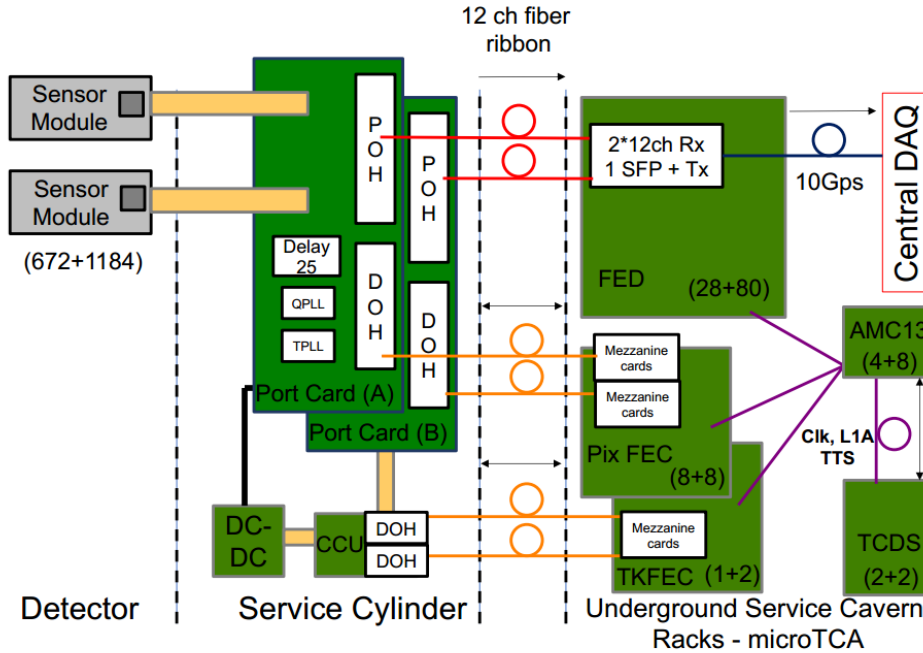


Figure 5.5: Overview of the Phase-1 pixel DAQ [55]. It shows the communication between the DAQ components. The hit data from the modules go to the FED through the POH, and from there to the Central DAQ. Configuration data for the modules comes from the computer to the Pixel Front-End Controller (PixFEC) and then are forwarded through the modified Digital OptoHybrid (mDOH) to the modules. Configuration data for the auxiliary electronics are sent from the Tracker Front-end Controller (TkFEC) to the Command and Control Unit (CCU) and then to the portcard (through the Digital OptoHybrid (DOH)). Advanced Mezzanine Card 13 (AMC13) distributes clock and triggers to all the components.

5.2.1 Front-end ASICS

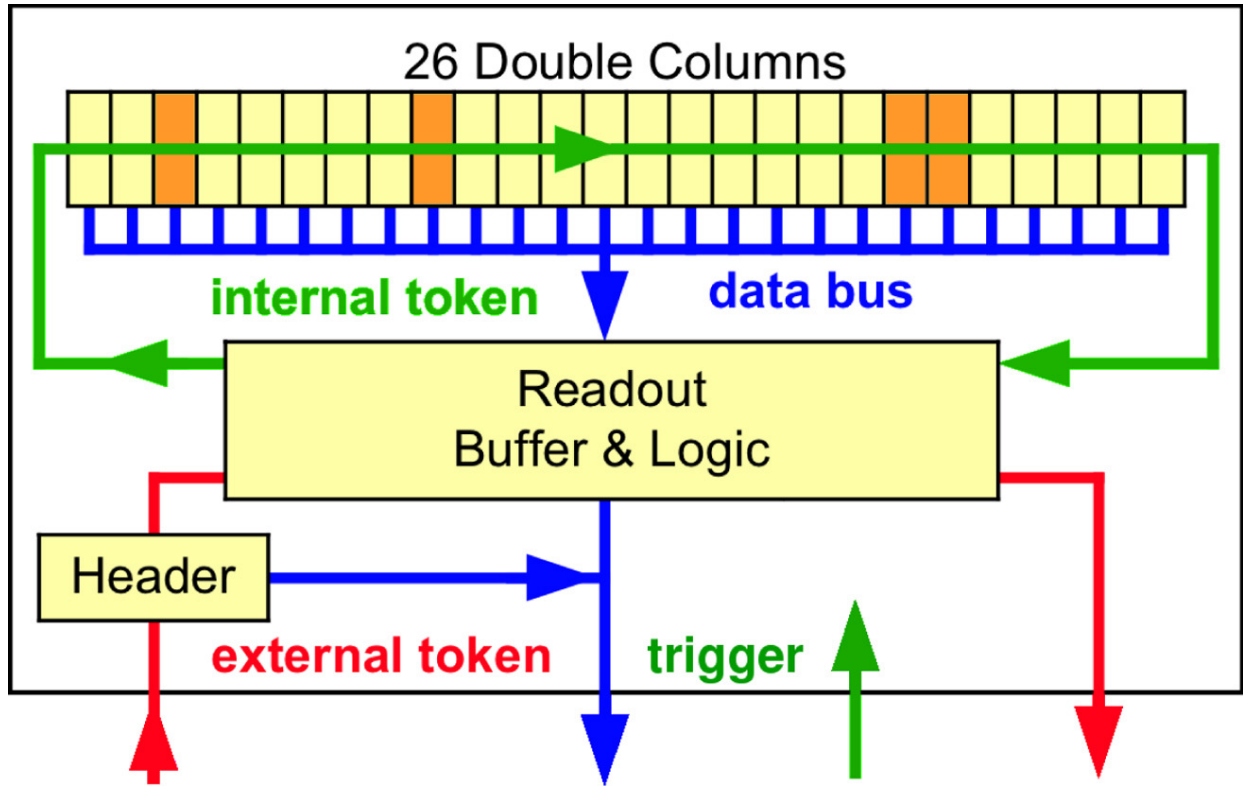


Figure 5.6: Readout scheme for readout chips showing the passing of the token and the double column readout [56].

TBM. The TBM is a radiation-tolerant integrated circuit that controls the readout of the ROCs by passing a token from ROC to ROC [54]. The TBM is mounted as a bare die, wire bonded to the HDI. The primary functions of the TBM are as follows:

- The distribution of L1A trigger, clock, and fast signals (e.g., reset, resync) to the ROCs.
- Distribution of configuration data from the PixFEC to the ROCs.
- Readout of the ROCs (either 8 or 16 ROCs per TBM depending if it is a BPix layer 1 module or BPix layer 2,3,4/FPix module).

The readout scheme is shown in Figure 5.6. The readout mechanism is initiated by the L1A signal. When the TBM receives the L1A, a token bit is passed to every readout chip in series.

Table 5.1: The different types of TBMs and their various properties. partially reprinted from [55].

TBM type	Groups of ROCs	Number of ROCs per group	Number of 400 Mb/s channels
TBM08	2	8	1
TBM09	4	4	2
TBM10	4	2	2

Each readout chip receives the token and sends the data that is stored in the data buffer out to the TBM at a 160 MHz stream, along with a header and a trailer. In this case, double columns containing the pixels above the threshold are read out from each readout chip. At the end of the readout, the token returns to the TBM. For each token bit that is passed, the TBM writes a header and a trailer to the data stream to be passed to the FED. A timely (within $4\mu s$) L1A is essential for the readout of the data buffers and the data transfer to the FED.

There are three versions of TBM used in different parts of the pixel detector. TBM08 is used in the lower event rate in FPix and BPix Layers 3 and 4. TBM09 and TBM10 are used in BPix Layers 1 and 2, respectively. The newly installed Layer 1 has TBM10d. The TBMs can have one or two cores, depending on the version of the TBM. The different types of the TBMs are shown in Table 5.1.

The cores collect data from different groups of ROCs and send data streams to the **Datakeeper** at 160 MHz . TBM08 obtain data from two groups of ROCs, while TBM09 and TBM10 obtain data from four groups of ROCs. The datakeeper is a block inside the TBM chip responsible for the combination of 160 $Mbits/s$ (or MHz) and creates a single 400 $Mbits/s$ stream. Inside the datakeeper, two 160 $Mbits/s$ streams are multiplexed to 320 $Mbits/s$ streams and encoded with a 4b/5b scheme to create the 400 $Mbits/s$ stream. A schematic diagram of the various parts of TBM09/TBM10 is shown in the figure 5.7.

The Readout Chip (ROC). The readout chip records the hit information from each individual pixel. There are 4160 pixels per chip. The signal arriving at a pixel from the sensor is first amplified by a preamplifier and then shaped by a shaper which removes any voltage fluctuations caused by leakage currents. It then reaches the comparator which decides

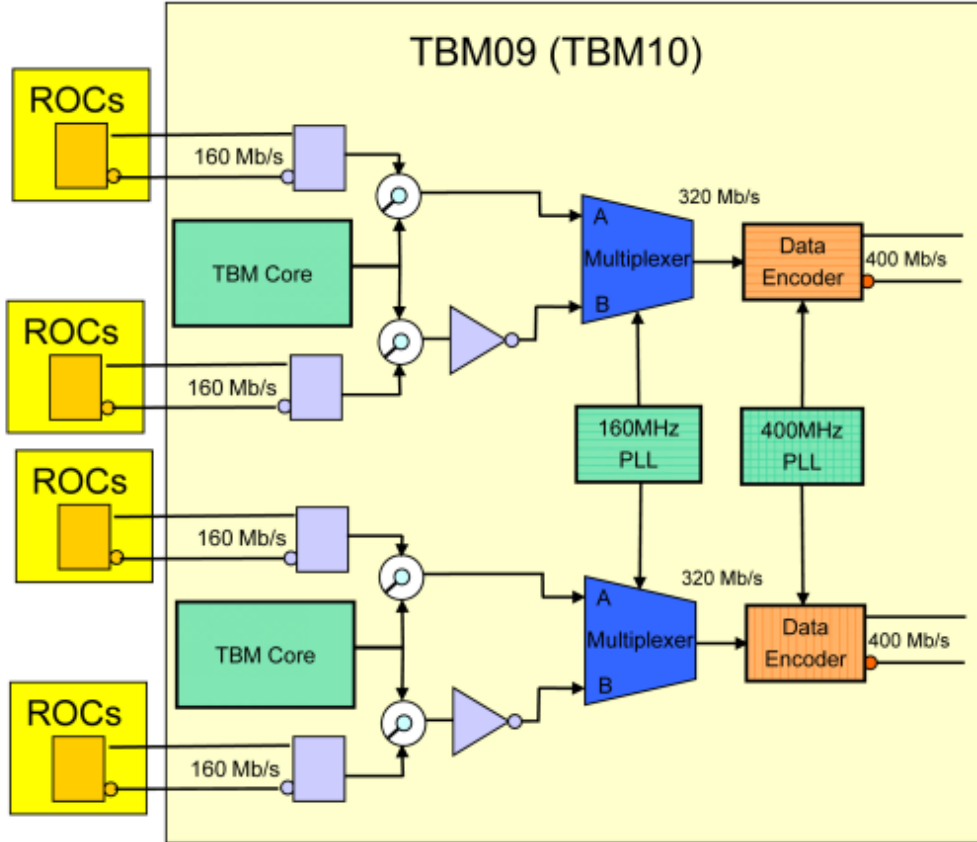


Figure 5.7: Schematic diagram of the TBM chip that shows the path that readout data follow, as well as the different components taking part in the procedure. The data from the ROCs are transmitted to the TBM at the speed of 160 Mbit/s. For each TBM core they are then multiplexed into streams of 320 Mbit/s and then encoded (400 Mbit/s), before they are sent out to the FED. [55].

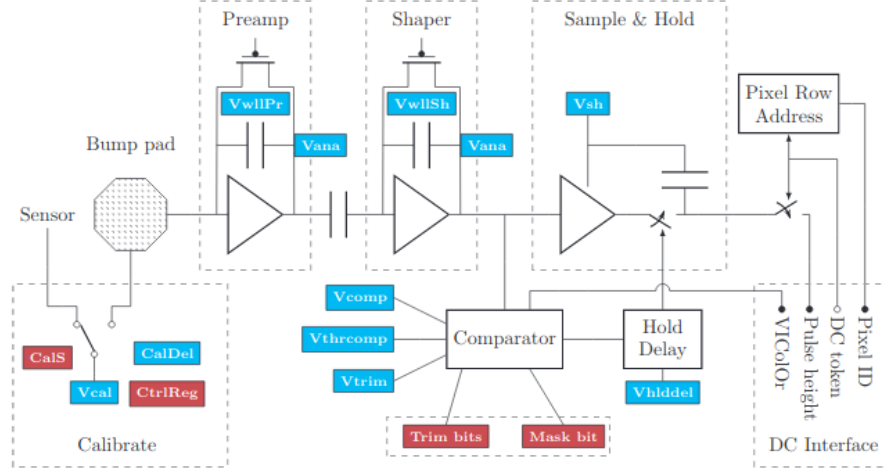


Figure 5.8: The parts of a pixel unit cell [57].

whether the signal is above a noise threshold. All these components make up the pixel unit cell (PUC). The various parts of the PUC are shown in the figure 5.8. If the signal is above the threshold, the signal is stored and a notification is sent to the chip periphery. The pulse-height information along with the pixel address is stored in a data buffer while the timestamp is stored in a timestamp buffer.

There are two types of readout chips used in the pixel detector: PSI46DIGv2.1 in layers 2-4 and in FPix, and PROC600 in layer 1. The design of PROC600 allows it to have faster hit transfer from pixels to the periphery as well as buffer management without any dead time. These characteristics make PROC600 suitable for use in layer 1 [52].

The PSIDIGv2.1 chip has a total of 4160 pixels (52×80) organized into 26 double columns of 2×80 pixels. Each double column has dedicated data/hit buffers (80) and timestamp buffers (24), both of which are improvements from the original PSI46 (32 and 12). It also consists on an analog-to-digital (ADC) which initiates the on chip digitization of the signal. Whenever the chip receives token form the TBM it carries out the readout of the pixels using the **double column drain** mechanism. The double columns are serially drained and the information from the corresponding buffers are sent to the TBM. The specifics of the chip

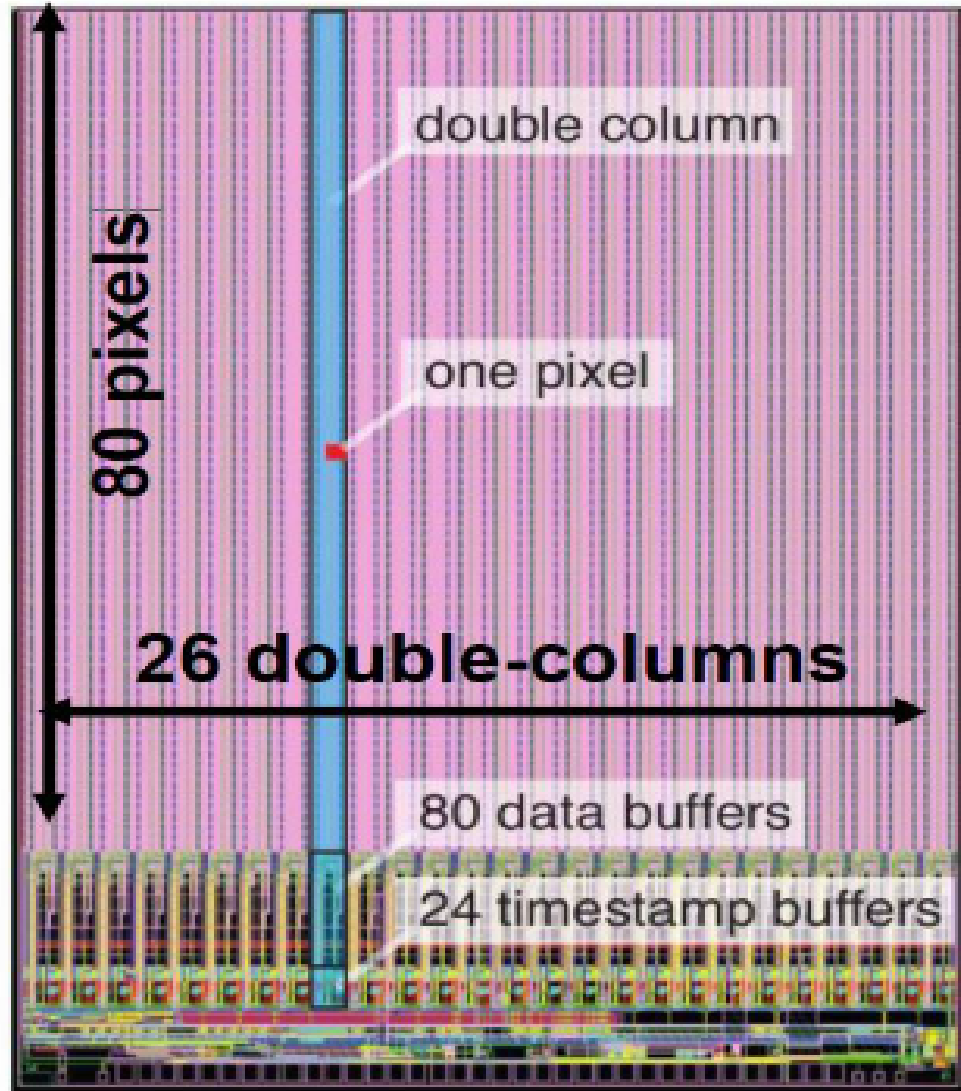


Figure 5.9: PSI46dig chip[58]. On the top part of the chip the pixels are organized in 26 double columns of 2x80 pixels each. Below the pixels are the 80 data buffers, and after that the 24 timestamp buffers.

is shown in the figure 5.9.

The PROC600 has a different readout architecture which makes it an ideal candidate for layer 1. The readout is carried out pixel by pixel but in pixel clusters. The readout architecture is called the **dynamic cluster column drain**. The readout is carried out in 2×2 pixel cluster and information stored in larger timestamp (40) and data buffers. The readout architecture allows the chip to cope with higher data rate and it maintains $>90\%$ efficiency at $600\text{MHz}/\text{cm}^2$.

The effective functioning of the readout chips is ensured by the interplay of both analog and digital components. The readout chips requires two low voltages (LV) for the analog and the digital circuits. Two different power supplies provide the analog and digital voltages to the analog and the digital circuits, respectively, through internal voltage regulators. High voltage (HV) is required to fully bias the sensors and is distributed via a separate line [52].

5.2.2 Back-end

The back-end hardware is based on micro Telecom Computing Architecture (muTCA) modular electronics. The base components are FC7 cards which are Advanced Mezzanine Card (AMC) holding Xilinx Kintex 7 Field Programmable Gate Array (FPGA).

FED. The FED is responsible for transferring the data from the modules to the central DAQ. The FED receives data from the ROCs via the readout initiated by the TBM. The data from the multiplexed to a 360 Mbit/s stream by the TBM then encoded with a 4b/5b schema resulting in an output of 400 Mbits/s (after encoding). The output is then converted to optical signals by the Pixel Opto-Hybrid (POH) before reaching the FED. The FED decodes the data it receives, de-serializes it, builds an event and sends it to the central DAQ. The FED consists of an FC7 board and a mezzanine card. The mezzanine is a Receiver-FMC(Rx-FMC) mezzanine with two 12-channel optical receivers. To send data to the central DAQ, the FED uses a small form-factor pluggable (SFP+) 10 Gbit/s S-Link transceiver located on the mezzanine card. The FED can read data from 24 fibers (channels per fiber = 48 channels) and transmit the data at a speed of 10 Gbit/s.

Pixel FEDs 80/28 BPIX/FPIX

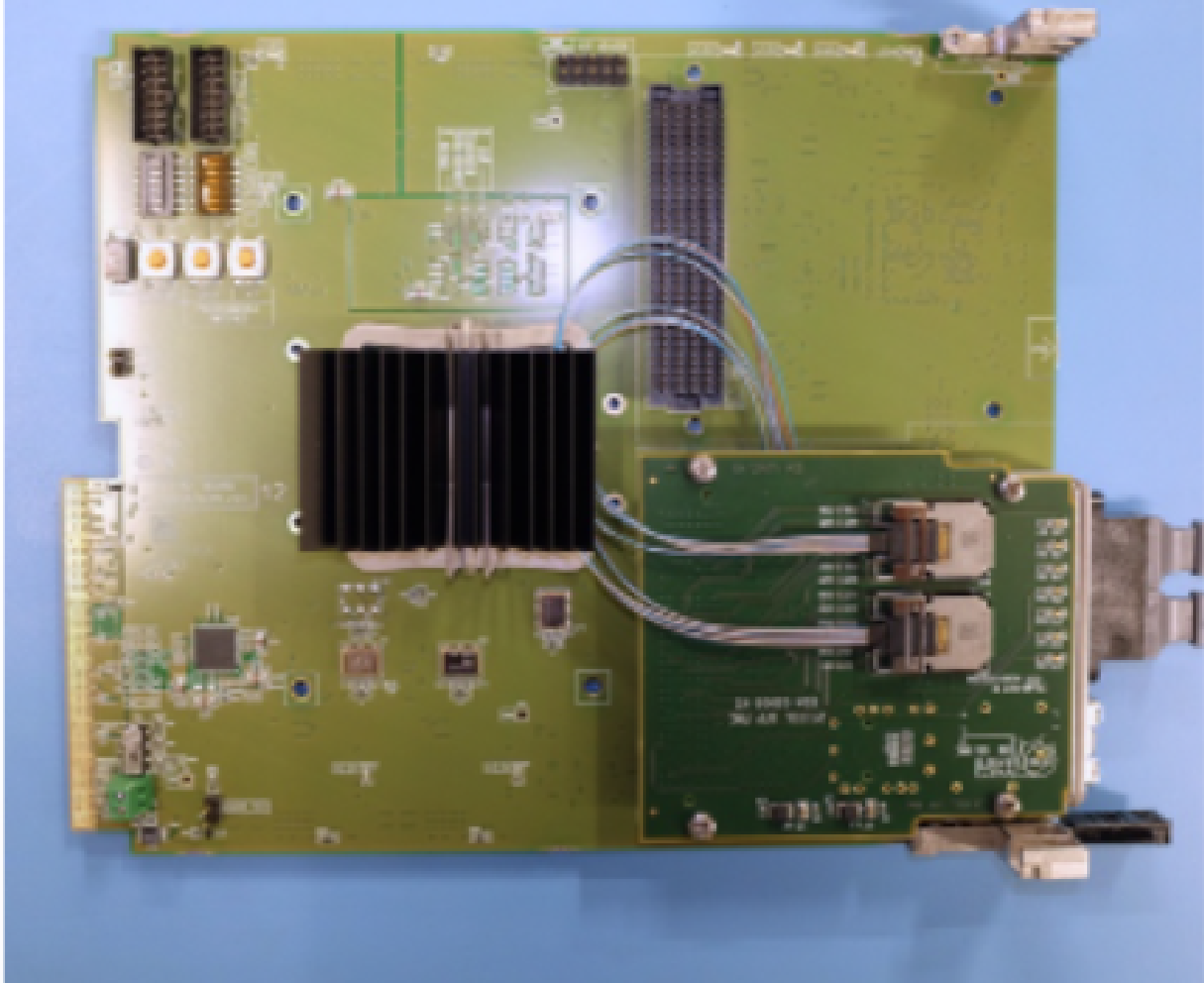


Figure 5.10: The Pixel FED card consists of an FC7 board and the Rx-FMC mezzanine card. BPix uses 80 FEDS while FPix uses 28 FEDs [59].

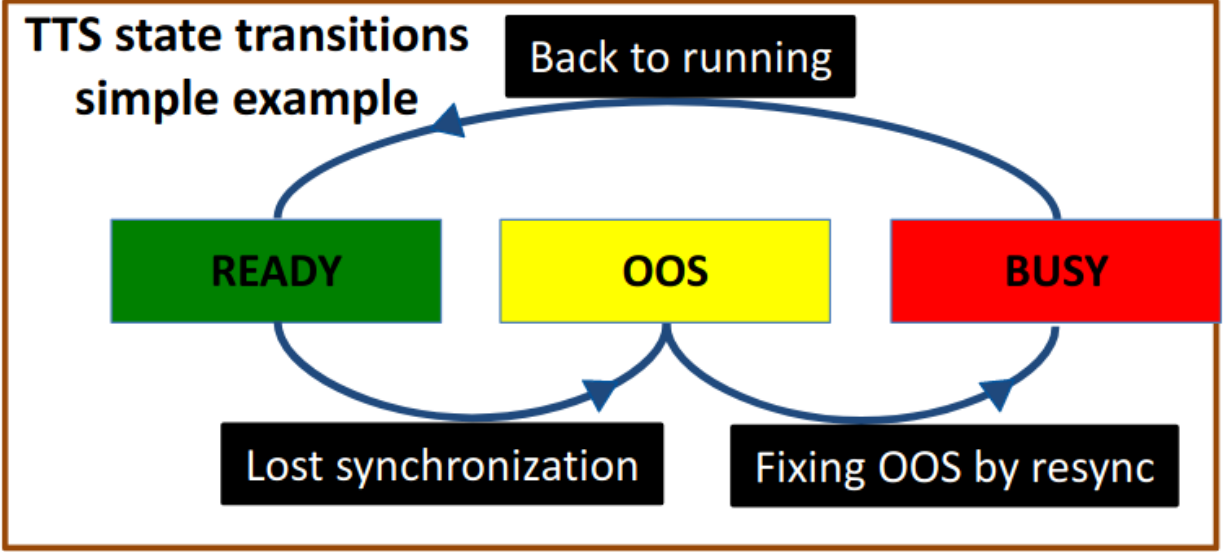


Figure 5.11: The different states of FED [59].

The FED receives clock and triggers from the Timing and Control Distribution System (TCDS) and AMC 13 through the backplane of the mTCA crate. The FED also sends a trigger-throttle system (TTS) signal to the AMC13 about its state. A FED can be found in three TTS states.: **RDY** (ready-0x8), **BSY**(busy-0x4) and **OOS** (out of sync-0x2). The states are shown in the figure 5.11. If the FED is in RDY state, it is ready to receive triggers. The BSY state occurs when the buffers are almost full. In this state, the triggers are blocked until FED goes back to the RDY state. The FED can go into OOS state for various factors which cause loss of synchronization. There could be multiple event number mismatches between FED and TBM or because the FED did not receive data for a specific number of events. When in OOS state, the FED waits for the re-sync command issued by the TCDS and propagated via the AMC13 to the FEDs. After the re-sync command, synchronization is re-established, and FED goes back to the RDY state [55].

PixFEC. The PixFEC is responsible for programming various aspects of the Front-end ASICs. PixFEC is responsible for the distribution of clock, triggers and fast signals to the front-end components of the detector (TBM, ROCs) and programming of the Digital-to-Analog Converter(DAC) registers of the TBMs and ROCs of the modules.

Pixel FECs 8/8 BPIX/FPIX

TK FECs 2/1 BPIX/FPIX



Figure 5.12: FEC (Pix and TK) cards have the same FC7 board as the FEDs but a different mezzanine card. TkFEC and PixFEC have the same hardware and differs only in firmware. BPix uses 80 FEDs, 8 PxFECs and 2 TkFECs. FPix uses 28 FEDs, 8 PxFECs and 1 TkFEC [59].

The clock, triggers and fast-signals arriving from the AMC13 are interpreted and forwarded to the modules through to the mDOH. The configuration data of the TBMs and ROCs are fetched and then sent with the optical fibers through the mDOH to the modules. The mDOH enables two-way communication between the modules and the PixelFEC, allowing the PixFEC to also read back configuration data from the modules [59].

TkFEC. The TkFEC is responsible for programming the auxiliary electronics of the Pixel Detector, and it is an entirely independent operation from programming the modules. It programs the registers of the auxiliary electronics of the pixel detector. The auxiliary electronics include the Direct Current to Direct Current converters (DC-DC converters) and the I2C devices (Delay25, Opto-hybrids, POH, DOH). Parallel interface AdapterS (PIA) registers can control the DC-DC converters, while the I2C devices can be read and written by the I2C protocol. TkFECs use the FC7 cards as hardware, which is the same as the PixFECs. The firmware loaded on the two hardware is, however, different and tailored to FEC functionalities.

Since the TkFEC is involved in programming the auxiliary electronics, the first step in programming the detector is to correctly power and program the TkFEC. If the TkFEC is not programmed correctly, the connection to the front-end is impaired.

TkFECs achieve the programming of the auxiliary electronics using the Command and Control Unit (CCU) and the DOH. The TkFEC first communicates with the CCU and then the other ancillary electronics through the DOH. TkFEC performs programming with the help of a CCU ring, which has a semi-redundant arrangement. This arrangement ensures a bypass procedure in case a single DOH or CCU fails, preventing any disruption to the programming.

The DOH enables two-way communication, allowing both configuration data transmission to the CCU and readback data from the electronics to be transmitted to the TkFEC.

5.2.3 Portcards

The portcard is an auxiliary electronic device physically present on the FPix and is a virtual concept on the BPix. It is present on the FPix service cylinders, which provide

structural support and other services like powering, cooling, and optical connection to the detector [55]. There are 24 port cards per FPix half-cylinder and a total of 96 in the whole detector [52].

The portcard hosts the OptoHybrids like the POH and mDOH. The POH is responsible for taking away hit information from the FED, while mDOH brings clock, trigger, and programming instructions from the PixFEC. It also holds the DAQ register for the DC-DC converters. The DC-DC converters are responsible for delivering low voltage power to the pixel modules. The Portcard is connected to the DOH, and it receives all the programming instructions from the TkFEC through this OptoHybrid. A detailed description of the portcard, DC-DC converters, and the other Optical components just mentioned can be obtained in Section C.

5.3 Operational Challenges of the Pixel Detector

One of the significant operational challenges for the Phase-1 pixel detector during Run 2 was posed by the failure of the **DC-DC converters**. The DC-DC converters are essential for powering the pixel modules, so their failure during 2017 operations led to inactive detector modules. By the end of 2017, 5% of the DC-DC converters were not operational, with almost 11% of the whole detector not working [52]. In the 2017-2018 LHC year-end technical stop (YETS), the DC-DC converters were replaced with ones with larger on-board chips and tolerant to higher current.

The reason for the failure of the DC-DC converters was not known until mid-2018 [60]. In May 2018, it was determined that the failure was due to a fault in the FEAST[61] ASICs design. When the FEAST chip is disabled, irradiation with doses above 10 kGy results in radiation-induced leakage current, causing a charge build-up on the circuit [62]. The disabled state prevents the current from flowing to the ground, and this damages the circuit.

The DC-DC converters had to alternate between enable/disable states due to another problem. Enable/disable cycles of the DC-DC converters were necessary because the TBM had a design flaw and would get stuck due to single event upsets (SEU), only recovering after a power reset using the DC-DC. Once the problem with the FEAST chip was understood,

the DC-DC converters were always kept enabled, and the power supply system was used to do the power cycling necessary to reset the TBMs.

In LS2, the DC-DC converters were replaced with a new version of FEAST chips which allows a path to ground for the leakage current, thereby preventing chip damage due to charge build up[52].

Quite early in Run 2, it was apparent that layer 1 modules were suffering from rate dependant **Cross-talk** (sometimes called noise). Layer 1 featured a different ROC to cope with the higher rate (as mentioned above), and Cross-talk “noise” hits started to appear several clocks after the real hits. The thresholds in layer 1 were raised to suppress this Cross-talk effect. Fig.5.13 shows the threshold distribution in terms of number of electrons for all layers of the BPix. The thresholds for layers 2, 3 and 4 were adjusted to ~ 1300 electrons for optimum performance. For layer 1, the threshold had to be raised to ~ 2000 electrons.

The Fig.5.14 shows the hit efficiency for various layers and disks of the Phase-1 pixel detector. Layer 1 is seen to suffer from drop in efficiency at very high ($> 1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) and very low ($< 1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$) luminosities [60]. This **dynamic inefficiency** is due to a glitch that caused a loss of synchronization between the data buffer storing the hit information and the timestamp buffer storing the timestamp information.

Both the problem with the Cross-talk and the dynamic inefficiency were addressed in the newest version of the ROC (PROC600v4), which is a part of the latest layer 1, installed in LS2. The thresholds for all layers were found to be pretty uniform during tests with the new layer 1.

5.4 Performance of the Pixel Detector

Despite the operational challenges, the Phase-1 pixel detector showed excellent performance throughout Run 2. In Fig. 5.14 we see that the hit efficiencies of layers 2, 3, 4, and the disks are $\geq 99\%$. Layer 1 showed a hit efficiency $> 97\%$, despite dynamic inefficiency. With the newly installed layer 1, much higher efficiency is expected for Run 3.

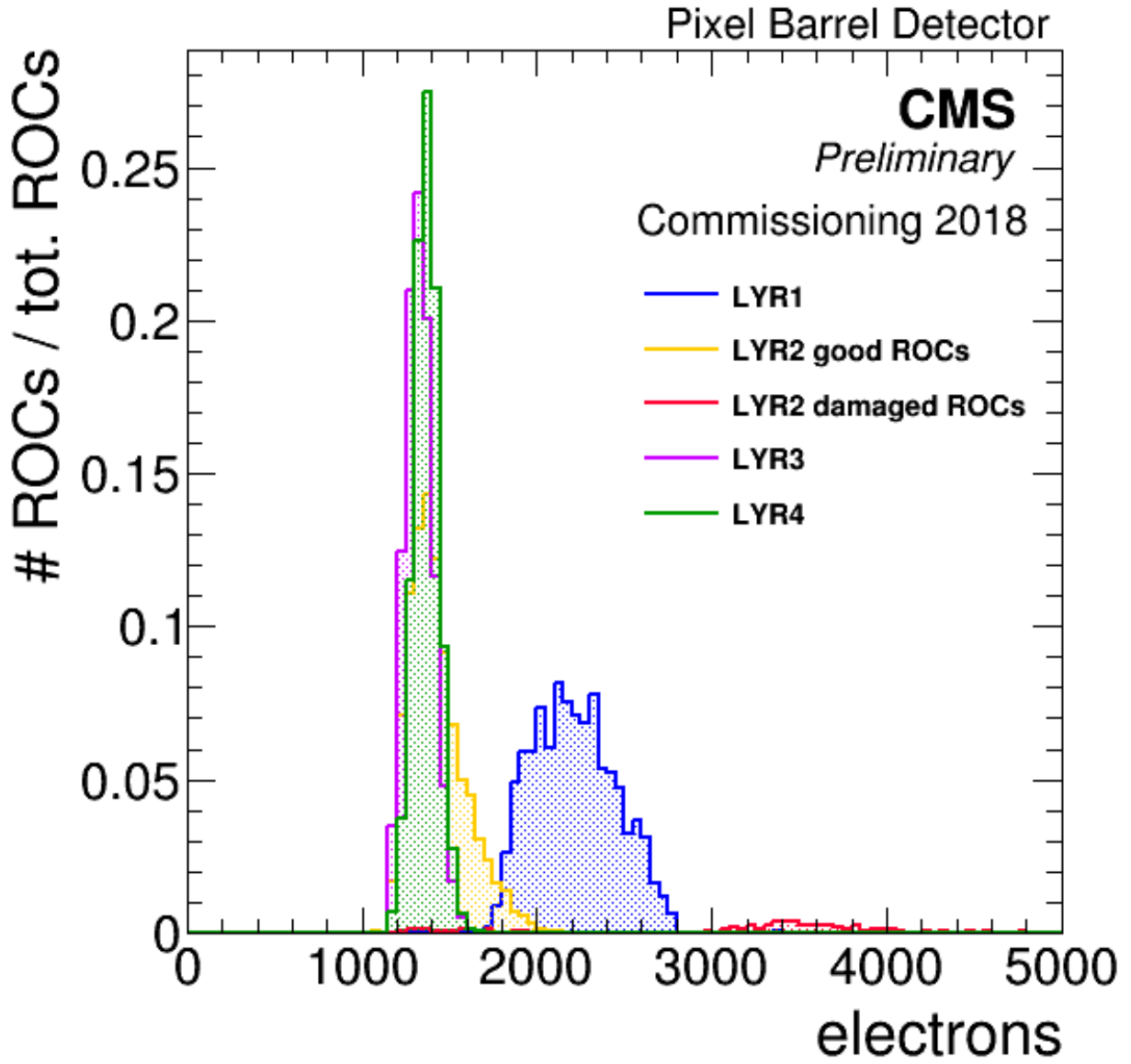


Figure 5.13: Distribution of the ROC thresholds in terms of number of electrons for all four layers of the BPix [63].

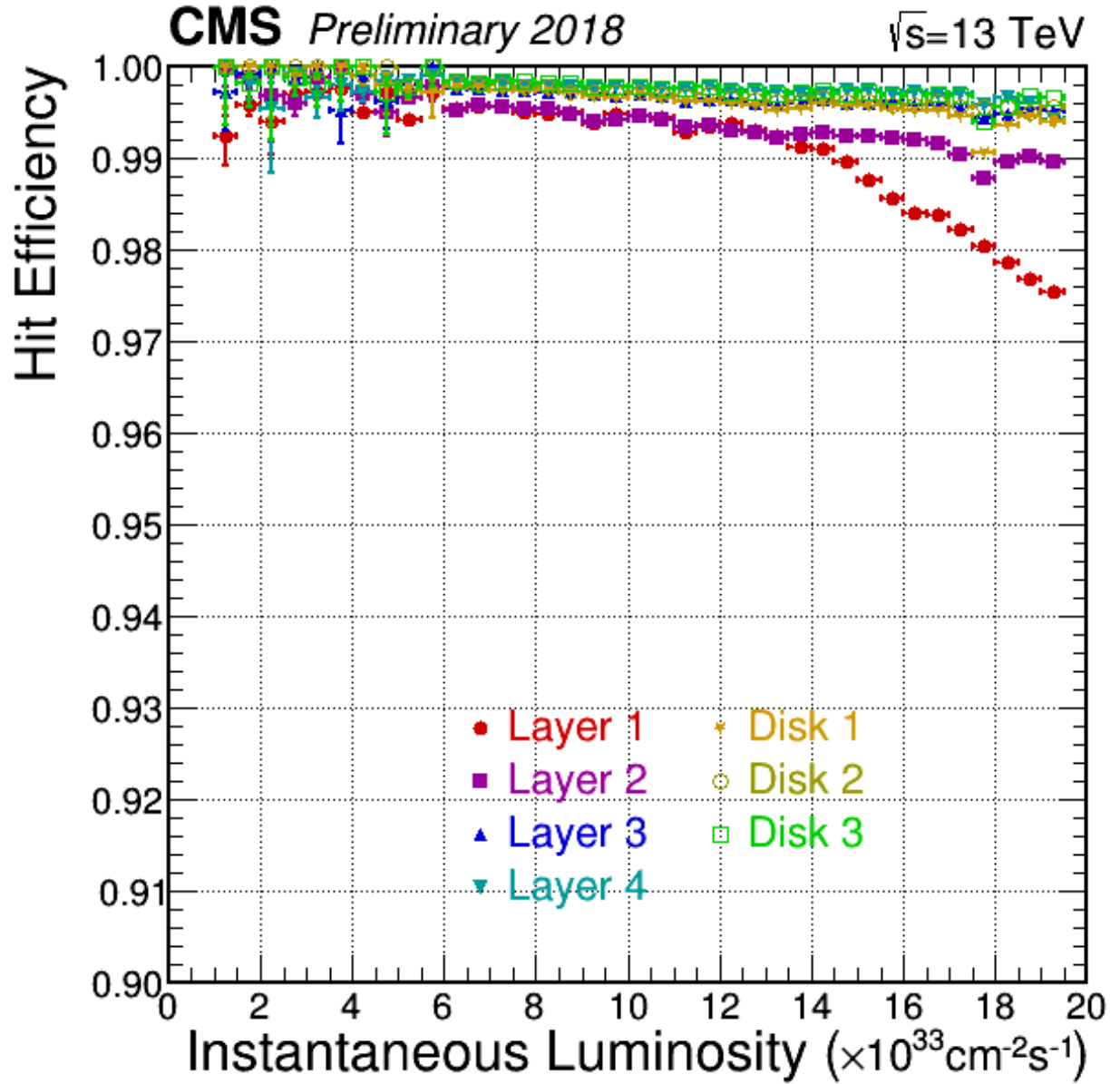


Figure 5.14: Hit efficiency of various layers and disks of the Phase-1 pixel detector.

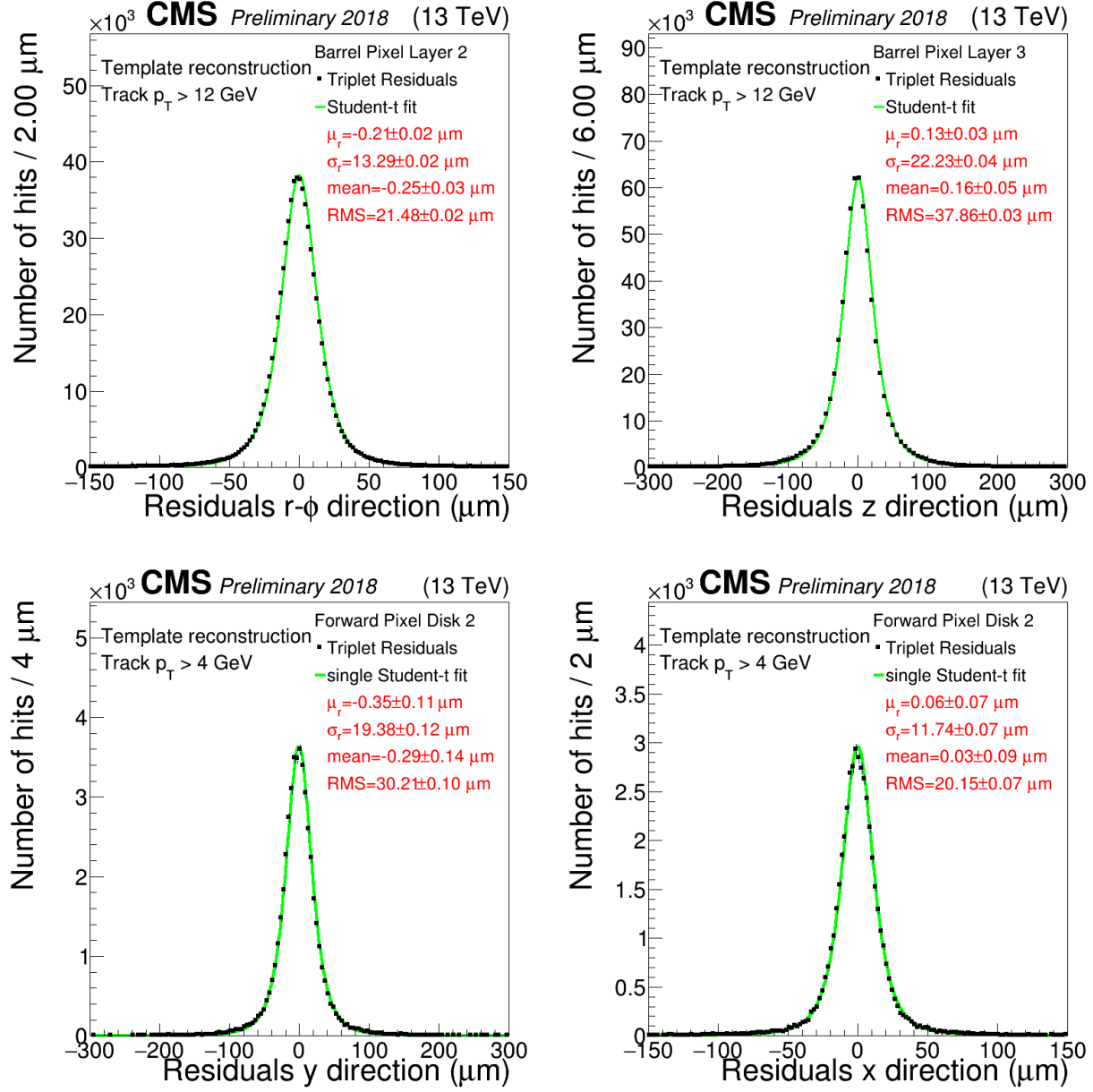


Figure 5.15: Hit residuals for layer 2 (top left), layer 3 (top right) and disk 2 (bottom) using the triplet reconstruction method [64].

In addition to excellent hit efficiency the Phase-1 pixel detector also maintained a high resolution of hit reconstruction, throughout Run 2. Fig. 5.15 shows the hit residuals for layer 2, layer 3 and disk 2. The hit residuals are calculated using the triplet reconstruction method [64]. The hit residuals are not exactly similar to hit resolutions but can be considered as an upper limit. From the residuals plots, it can be inferred that the resolution for layer 2 in r - ϕ direction is $13\ \mu\text{m}$, and for layer 3 in the z -direction is $22\ \mu\text{m}$. Additionally, the resolution for disk 2 in the y -direction is $19\ \mu\text{m}$ and in the x -direction is $12\ \mu\text{m}$, at maximum. Here, the quantities x and y refer to local module coordinates and correspond to the short ($100\ \mu\text{m}$) and long ($150\ \mu\text{m}$) directions of the pixels, respectively. The Phase-1 pixel detector has, therefore, maintained high resolution across all its sub-units throughout Run-2.

5.5 Refurbishment, Re-installation and Commissioning



Figure 5.16: Part of FPix detector undergoing cooling repairs (left) and a part of BPix being craned over from the clean room to the CMS underground tunnel prior to installation (right).

The CMS Tracker (mostly the Pixel detector) went through a phase of refurbishment before the eventual re-installation during LS2. There were several commissioning steps before the installation and warm/cold testing before and after the installation to ensure that the detector was in an optimal state.

The CMS Strip Tracker did not go through significant structural changes. However, the gas distribution racks underwent refurbishment, new membranes were installed on the membrane plant, and the dry air system underwent repairs for better dew points.

The pixel detector went through substantial changes during LS2. For the BPix, a new layer 1 was installed with a new ROC (PROC600v4), new TBM (TBM10d), and a new High-Density Interconnect (HDI) design. The accessible DC-DC damaged modules were replaced in layer 2. New DC-DC converters were installed with a new version of the FEAST chip (FEAST v2.3). For the FPix, the broken cooling pipes were repaired with custom Vacuum Coupling Radiation (VCR) fittings to prevent further damages in the future. New DC-DC converters were installed on all disks. A broken fiber bundle leading to the Front End Driver (FED) was fixed. The filter boards underwent replacement, and the new ones had redundant High-Voltage (HV) connections. DC-DC cooling bridges were replaced to get better thermal contact.

CHAPTER 6

PIXEL PROJECTS

6.1 Radiation Damage Correction Studies

6.1.1 The readback mechanism

The readout chips used in the pixel detector have the functionality to read back analog and digital voltages and analog current for each ROC. The measurements are taken in analog-to-digital converter (ADC) values which in turn can be converted to voltages and currents. The conversion is done using a formula and parameters that resulted from calibrations during module testing, using external current and voltage measurements for reference. The formulae are shown in Appendix The parameters are unique to each ROC.

The quantities read back by the ROC (voltages and current) are crucial because their values and their fluctuations are indicative of whether a ROC is functioning properly or whether it is inefficient and needs to be reprogrammed, power-cycled or recalibrated and tuned in any manner. Moreover, analog voltages are used to set the analog pulse height while digital voltages power the rest of the electronics for the readout, and a drop of any one of them may indicate something wrong with the corresponding ROC or larger parts of the detector.

A complete readback involves 16 bits. The first 4 bits represent the **ROC number**, with minimum value 0 and maximum value 15. This is a convenient way to represent ROC numbers from 0-15. The next 4 bits represent the **Digital to Analog Converter (DAC) setting** programmed in the ROC, again with minimum value 0 and maximum value 15. Only the values 8, 9, 10, 11 and 12 are representative of the different readback types but the entire 4 bits are needed for a succesful readback. The readback code always does a cross check of the first 8 bits to make sure that the readback bits are reliable (explained

Table 6.1: The readback types and their corresponding values.

Value	Readback type
8	V_d/V_{dig}
9	V_a
10	V_{ana}
11	V_{bg}
12	I_{ana}

in more details in the following paragraph). The last 8 bits represent **readback payload data** where the minimum value is 0 and the maximum value is 255. A **readback register** usually orchestrates the readback mechanism and determines the type of data that is read back [65].

The different readback types and their corresponding values are shown in Table 6.1.

To further explain the process of the readback, let us consider 16 bits: aaaa bbbb dddddddd

aaaa $\rightarrow$ ROC number (0-15)

bbbb $\rightarrow$ readback DAC setting programmed in the ROC (only 8, 9, 10, 11 and 12 are used for different readback types)

dddddddd $\rightarrow$ readback payload data

The readback code will always do a cross check of aaaa and bbbb to make sure that the ROC number and the DAC settings make sense and the readback bits are valid[66]. There can be two outcomes:

- aaaa and bbbb match to what is expected of them and the readback code prints the contents of dddddddd, which is between 0 and 255;
- aaaa and/or bbbb do NOT match what is expected of them and the code will then print the contents of

$$1000 * (\text{decimal representation of aaaabbbb}) + (\text{decimal representation of dddddddd})$$

Here dddddddd is in ADC units so it is possible to get back the data payload by doing : *value* % 1000.

The quantities (different readback types) that are read back are:

- V_d , also referred to as V_{dig} - unregulated digital voltage that arrives at the chip;
- V_a - unregulated analog voltage that arrives at the chip;
- V_{ana} - regulated analog voltage. The readout chip includes a regulator which transforms the unregulated analog voltage to a constant voltage that is further used within the chip;
- V_{bg} - bandgap reference voltage, an internal voltage needed by the chip;
- I_{ana} - analog current drawn by the chip.

The readback quantities for 2017 and 2018 data are shown in Figures 6.1 - 6.5.

Only the values that fall within a valid range in terms of ADC units i.e. $0 < \text{ADC counts} < 255$ and their corresponding voltages were considered for these plots. At each timestamp, all the ROCs on a certain layer (BPix) or ring (FPix) were used to calculate an average per layer/ring. For the BPix in particular, LYR1_new are the modules installed during the winter shutdown of 2017/2018. A few modules were replaced following the damage caused by the DC-DC converter problems. The FPix rings only have values in ADC units as the conversion parameters are not available like for BPix. A decreasing trend is observed in the readback quantities V_d , V_a and V_{bg} particularly for the new layer 1 modules. When it comes to the readback quantity I_{ana} , a decreasing trend is observed in both the new layer 1 modules and the old ones.

The readback quantities for partial 2018 data are shown in Appendix.

6.1.2 Radiation damage correction studies

Various studies have been conducted concerning radiation damage corrections to readback quantities. The radiation damage correction procedure is dependent on the quantity of interest, the radiation damage correction procedure for voltages is different from that for the current. The procedure has to take into account the delivered luminosity, the estimated dose (derived from the delivered luminosity) as well as the corresponding change in the quantity of interest.

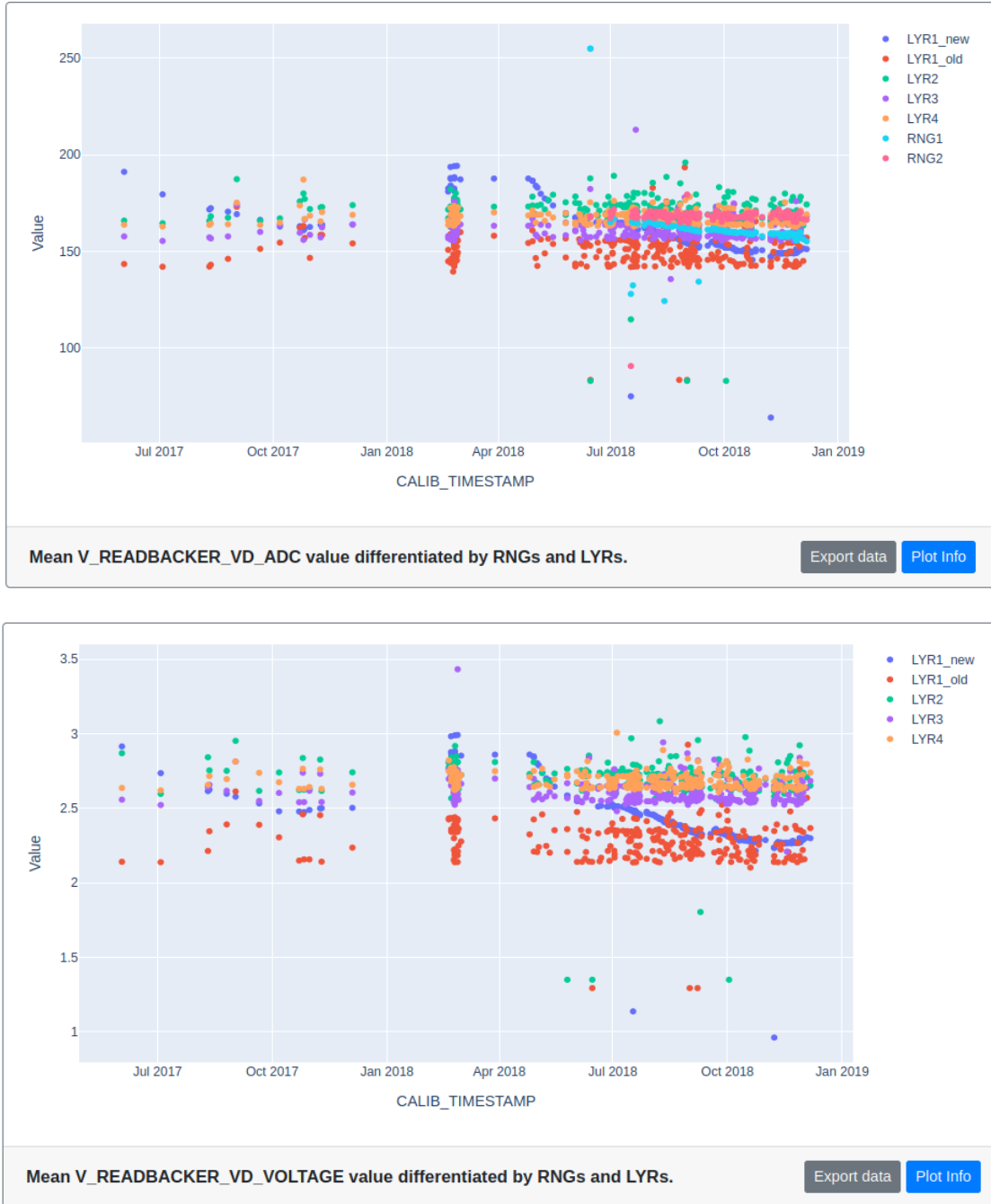


Figure 6.1: Average value of V_d in ADC units (top) and after conversion to volts (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.

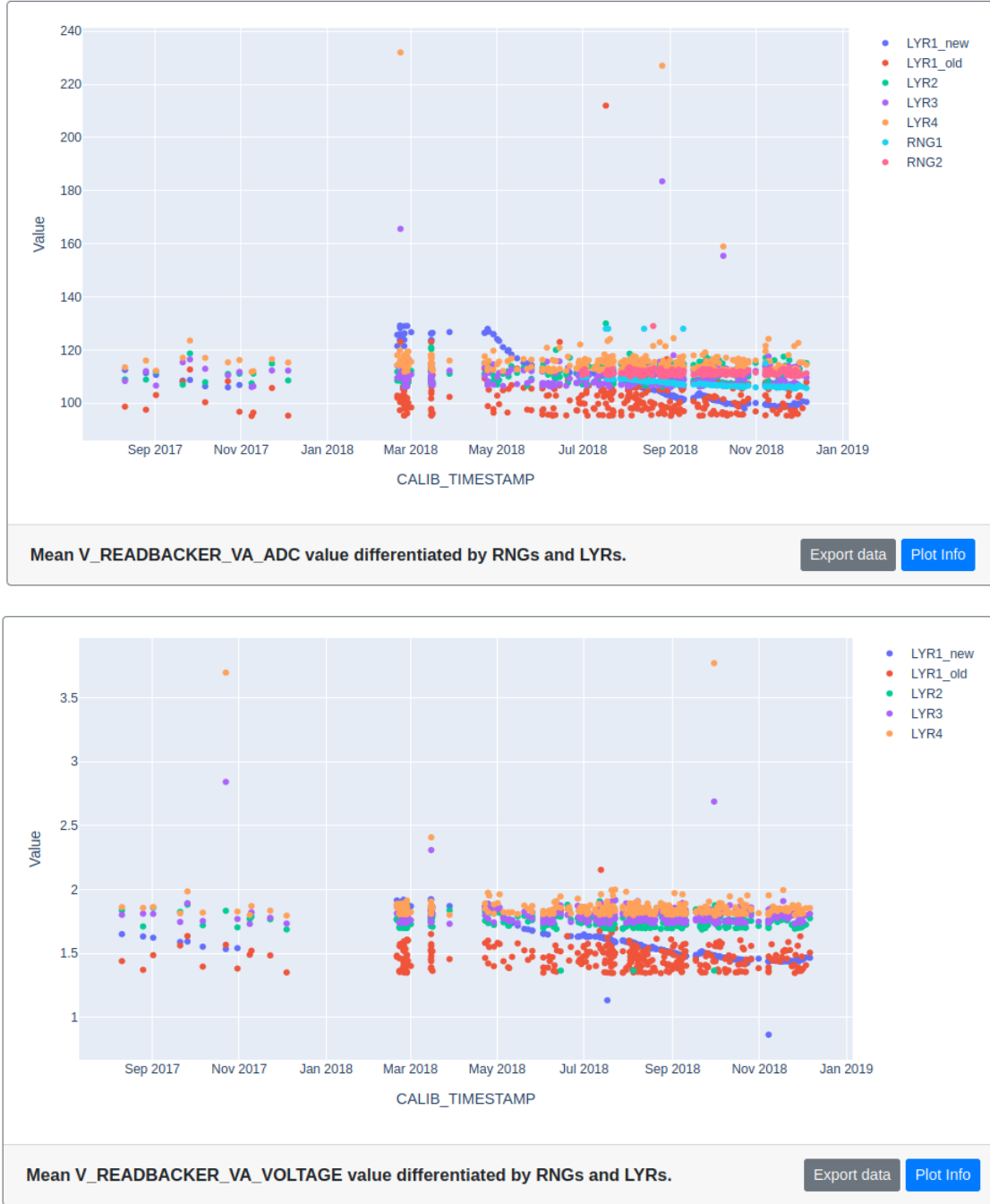


Figure 6.2: Average value of V_a in ADC units (top) and after conversion to volts (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.



Figure 6.3: Average value of V_{ana} in ADC units (top) and after conversion to volts (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.



Figure 6.4: Average value of V_{bg} in ADC units (top) and after conversion to volts (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.

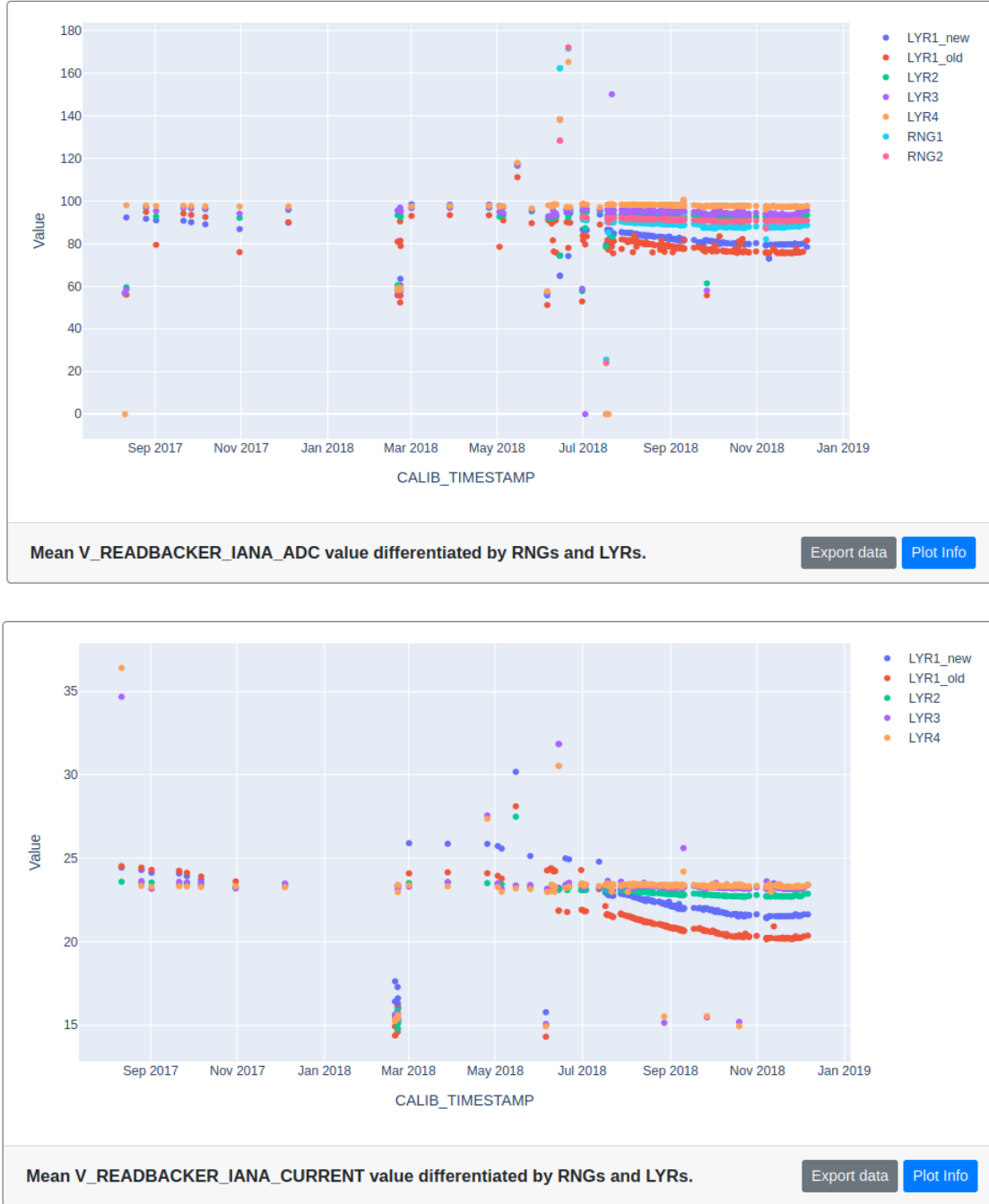


Figure 6.5: Average value of I_{ana} in ADC units (top) and after conversion to mA (bottom) for BPix layer 1 (old and new modules), layer 2, layer 3, layer 4, and FPix ring 1 and ring 2 during 2017 and 2018.

The amount of radiation damage that a ROC experiences depends heavily on its position in the detector. For instance, a ROC in layer 1 is situated a lot closer to the beamline than the ROCs in the other layers and therefore has greater exposure to radiation. Thus for the same delivered luminosity, different parts of the detector experience different doses and therefore different levels of radiation damage. This also means that different parts of the detector need to have different levels of radiation damage corrections.

6.1.3 Formulation for radiation damage correction

The formulation of the radiation damage correction for the voltages in particular depends on the bandgap reference voltage (V_{bg}). The bandgap voltage is a property of the chip and should **ideally** remain constant even if the chips are exposed to any form of radiation. The value of V_{bg} should be 1.2 V, though it does vary slightly across the detector. Since the bandgap voltage is a characteristic of the chip, each ROC has its individual value of the bandgap voltage. Now, the bandgap voltage also changes with damage acquired due to radiation. The fact that each ROC has an unique measured value of the V_{bg} means that the change in V_{bg} with radiation damage is an indication of the radiation damage in the ROC.

The measured voltage can then be corrected as follows:

$$V = V_{[measured]} \times \frac{V_{bg}[\text{module testing}]}{V_{bg}[\text{measured}]} \times \text{shift}[V_{bg}] \quad (6.1)$$

In the formulation of the radiation damage correction studies (Eq.6.1), the value of a certain measured quantity (for instance V_a) is corrected two-fold [67]. Firstly, the quantity is multiplied by the ratio of V_{bg} measured during module testing to the V_{bg} measured at the same time as the quantity. The value of V_{bg} measured during module testing is stored for each individual ROC, which enables us to look into radiation damage correction for each ROC separately, by looking into the change in V_{bg} . Thus the radiation damage correction of the voltage measurement can be carried out at the granularity of per ROC. The other correcting factor is the percentage shift of V_{bg} . The variation of V_{bg} with irradiation dose was determined from previous irradiation studies [68]. The variation of V_{bg} as well as the percentage shift of V_{bg} is shown in Figure 6.6.

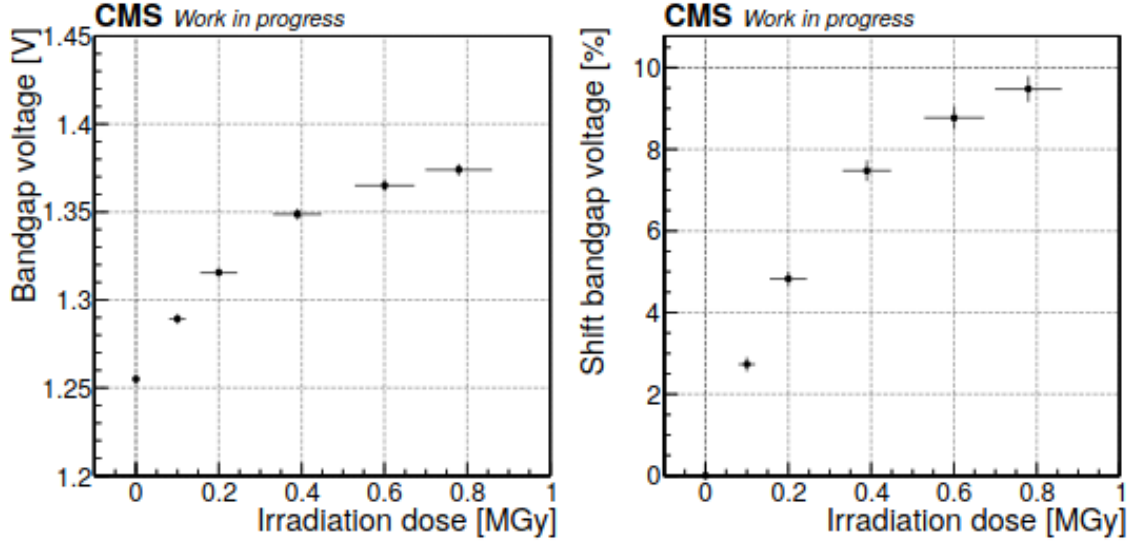


Figure 6.6: The change in bandgap voltage (left) and percentage shift in bandgap voltage (right) with irradiation dose. The values were taken for PROC600 chips [68].

The irradiated dose experienced by a chip is in turn calculated from the total delivered luminosity using Fluka estimates [69]. Given a certain quantity for a certain ROC at a certain point in time, we first get the total delivered luminosity that was delivered to the ROC up to that point in time. The delivered luminosity is then converted to radiation dose using Fluka estimates. A (average) percentage shift in V_{bg} corresponding to the radiation dose is then applied, scaled by the ratio of V_{bg} module testing to measured for the specific ROC.

In the sections that follow, the procedure of applying a radiation damage correction will be discussed.

Obtaining the delivered luminosity. In order to apply the correction factor for a certain ROC at a certain point in time, one needs to determine the radiation dose and hence the delivered luminosity. It is important to use the correct type of luminosity (delivered as opposed to recorded) and for the correct time period, otherwise the radiation dose may be incorrectly estimated.

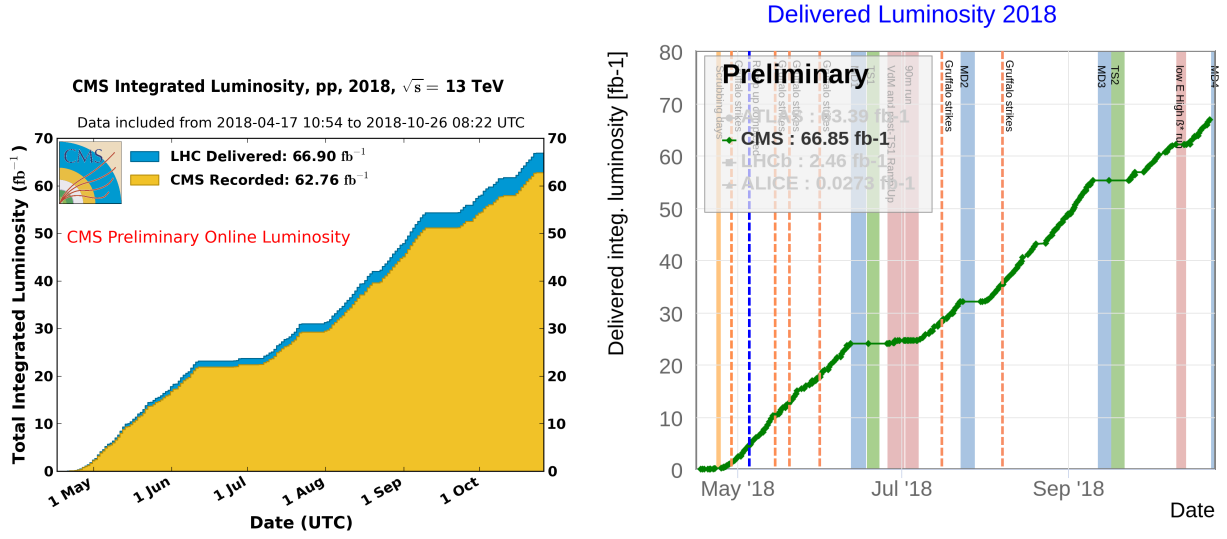


Figure 6.7: Total delivered luminosity for the year 2018 from CMS public plots (left) [70] and LHC performance plots (right) [71] .

Figure 6.7 shows the total delivered luminosity for 2018 from two different sources. Table 6.2 shows the delivered luminosity for various modules by the end of 2018 and the estimated fluence.

There are several ways to obtain the delivered luminosity for a certain time stamp.

- Using the BRIL work suite [72]. A query can be made from the database with the begin and end time as well as other flags like units, normtag (calibration/correction function defined by a tag, bound to a specific luminometer) etc.
- Querying from the CMS_RUNTIME_LOGGER table in the Online Master Data Base (OMDS) to get the total delivered luminosity between two time stamps.

The second process is faster and is more convenient for testing purposes. Figure 6.8 shows the delivered luminosity over time. The plots were made using information from the CMS_RUNTIME_LOGGER table in the OMDS. OMDS is the central oracle database used in CMS.

While making the query for the delivered luminosity for a certain ROC, it is important to have information about the installation status of the module/ROC. For instance, some new modules were installed during the beginning of 2018. For these specific modules the

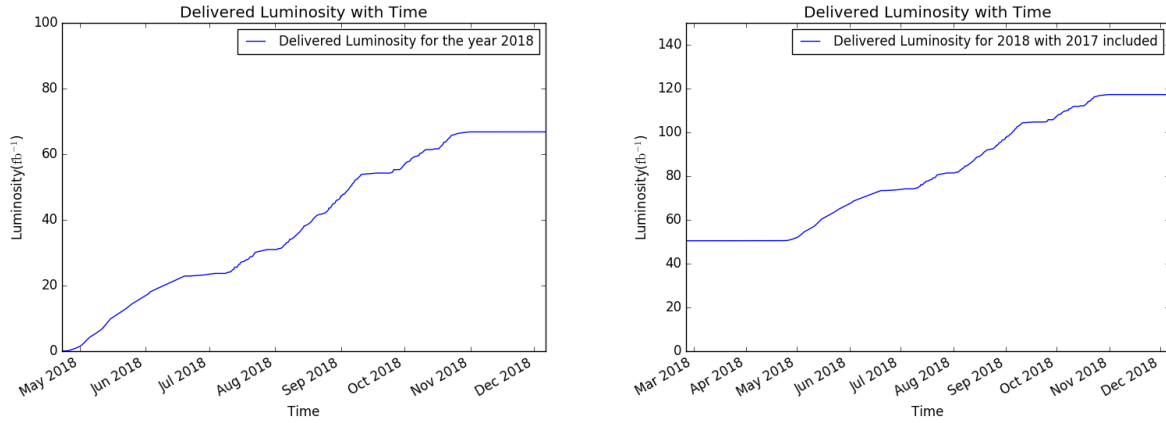


Figure 6.8: Total delivered luminosity for 2018 (left) and the total delivered luminosity with 2017 included (right).

Table 6.2: The delivered luminosity for various modules by the end of 2018 and the estimated fluence using the per fb^{-1} values from Ref. [73]. The values were only given for the BPix layers.

Location of modules	Delivered luminosity in fb^{-1}	Fluence ($\times 10^{14}$)
Layer1 (new modules)	66.80	6.60
Layer1	117.27	11.59
Layer2	117.27	2.19
Layer3	117.27	1.14
Layer4	117.27	0.68
Ring1	117.27	-
Ring2	117.27	-

start date for calculating the delivered luminosity should be the installation date. Choosing a correct time period to extract the luminosity allows better estimates of irradiation dose.

Obtaining the estimated dose. After the process of obtaining the delivered luminosity for a certain timestamp, we convert the luminosity to irradiated dose using Fluka (v3.40.0.0) estimates [74]. The estimate takes into account the layer the ROC is in, and applies different conversion factors to translate the luminosity in fb^{-1} to radiation dose in Mrad or MGy. For instance, the irradiation dose of a layer 3 ROC is much lower compared to that of a layer 1 ROC for the same delivered luminosity as layer 3 is further away from

the beamline. The Fluka estimates take into account this difference and give corresponding values of irradiation dose. The conversion formulae used in the Fluka estimates are described in Appendix.

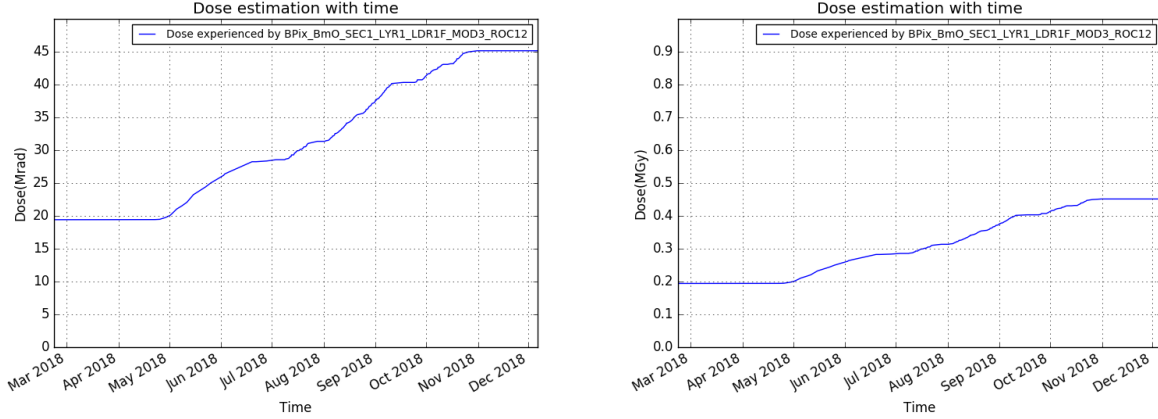


Figure 6.9: Radiation dose for a layer 1 ROC (BPix_BmO_SEC1_LYR1_LDR1F_MOD3_ROC12) in Mrad (left) and MGy (right) as a function of time in 2018.

Figure 6.9 shows the radiation dose of a layer 1 ROC as a function of time. The plot is a result of converting all the delivered luminosity values at each timestamp to a corresponding radiation dose.

Figures 6.10 - 6.12 show radiation dose for ROCs in layer 2 - layer 4 as a function of time.

Figure 6.13 shows the radiation dose for ROCs in different layers as a function of time in 2018.

Table 6.3 shows the dose estimation for each layer by the end of 2018, using Fluka estimates.

The percentage shift in bandgap voltage and the correction factor. Once the radiation dose for a certain ROC is obtained over time, the next step is to translate the dose to correction factors in terms of the percentage shift in V_{bg} . The relation between percentage shift in V_{bg} and the dose is shown in Figure 6.6. A function is extracted using a third degree polynomial fit to the data points. The function allows us to determine the correction factor/percentage shift in V_{bg} for any value of the radiation dose.

Table 6.3: Radiation dose estimate for each (BPix) layer by the end of 2018 calculated using the Fluka estimates. The dose estimate for each (FPix) ring is determined using an unofficial estimate which depends on the ring radius [75].

Location of modules	Radiation dose (MGy)
Layer 1	0.450
Layer 2	0.180
Layer 3	0.099
Layer 4	0.040
Ring 1	0.123
Ring 2	0.058

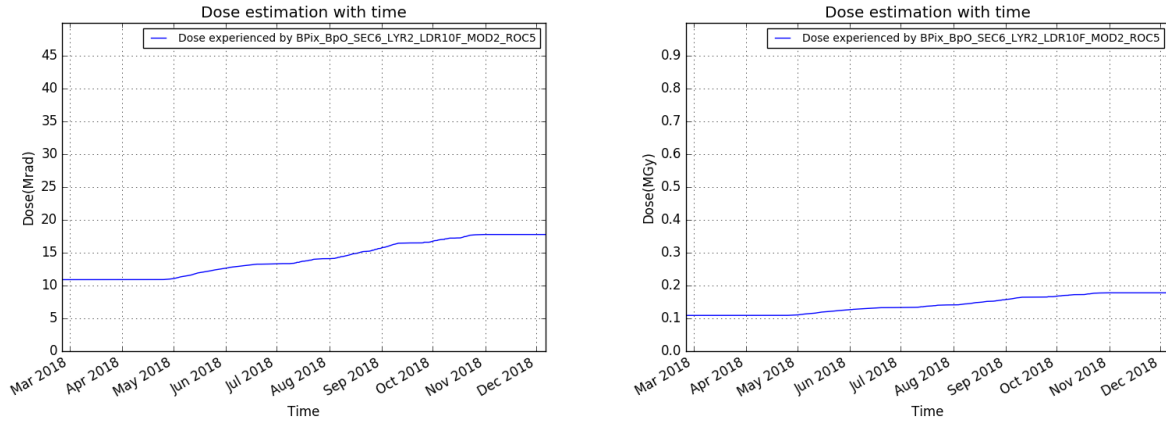


Figure 6.10: Radiation dose for a layer 2 ROC (BPix_BpO_SEC6_LYR2_LDR10F_MOD2_ROC5) in Mrad (left) and MGy (right) as a function of time in 2018.

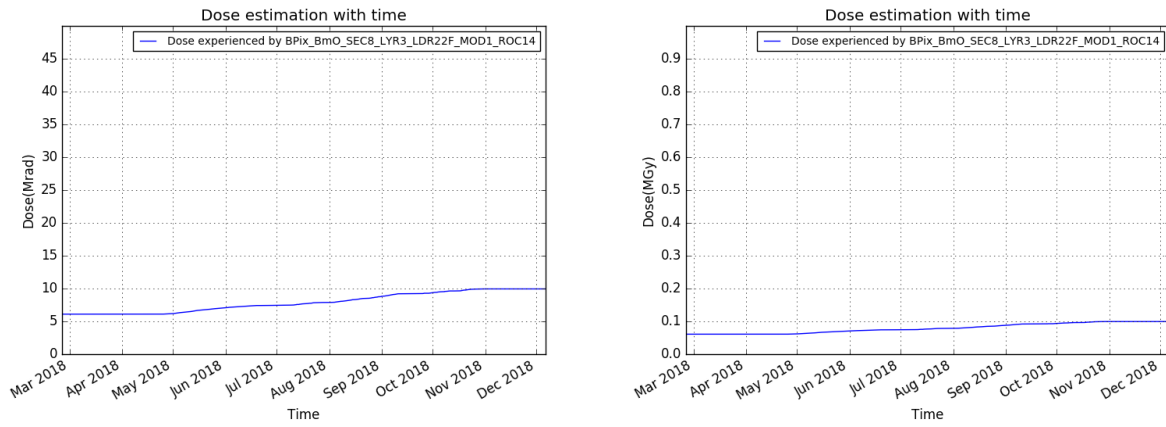


Figure 6.11: Radiation dose for a layer 3 ROC (BPix_BmO_SEC8_LYR3_LDR22F_MOD1_ROC14) in Mrad (left) and MGy (right) as a function of time in 2018.

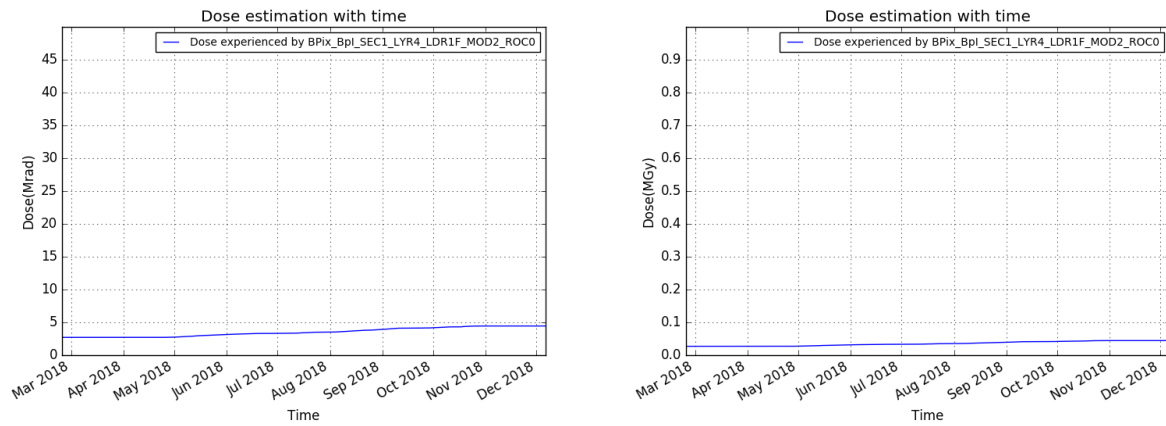


Figure 6.12: Radiation dose for a layer 4 ROC (BPix_BpI_SEC1_LYR4_LDR1F_MOD2_ROC0) in Mrad (left) and MGy (right) as a function of time in 2018.

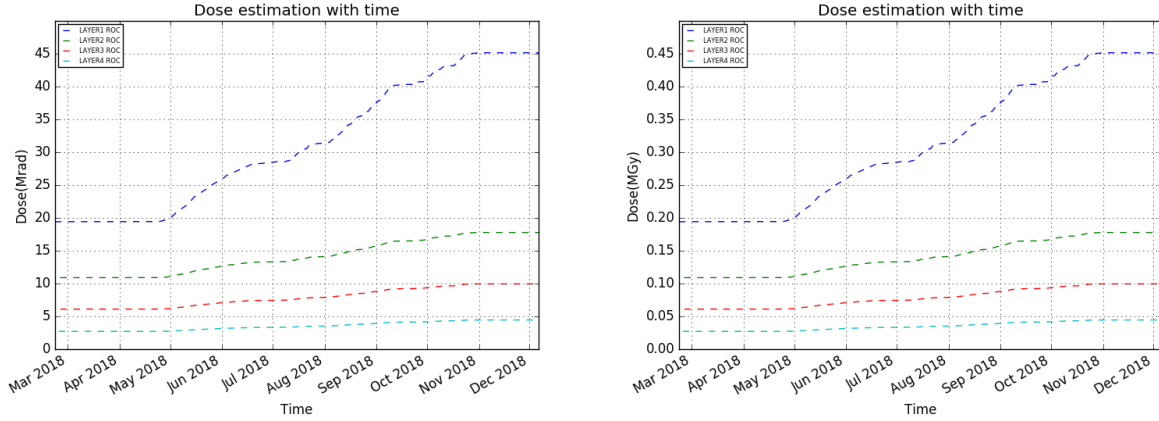


Figure 6.13: Radiation dose for ROCs in different layers, in Mrad (left) and MGy (right) as a function of time in 2018.

Table 6.4: Percentage (average) shift in V_{bg} for each layer at the end of 2018.

Layer	Percentage shift in V_{bg}
Layer 1	7.85
Layer 2	4.51
Layer 3	2.79
Layer 4	1.32

Figure 6.14 shows the procedure of fitting the data to obtain a functional dependence of the percentage shift of bandgap voltage on the dose. This functional dependence can be used to extract a value of percentage shift of V_{bg} at each value of irradiation dose at a certain timestamp.

Table 6.4 shows the percentage shift in V_{bg} for each layer at the end of 2018.

The application of radiation damage corrections. As discussed earlier, the radiation damage corrections are applied in two steps. First, the readback value for a quantity is multiplied by the ratio $\frac{V_{bg}[\text{module testing}]}{V_{bg}[\text{measured}]}$. Then the resulting value is again multiplied by the percentage shift in V_{bg} , which is calculated using a function extracted by fitting the data of percentage shift in V_{bg} as a function of irradiation dose.

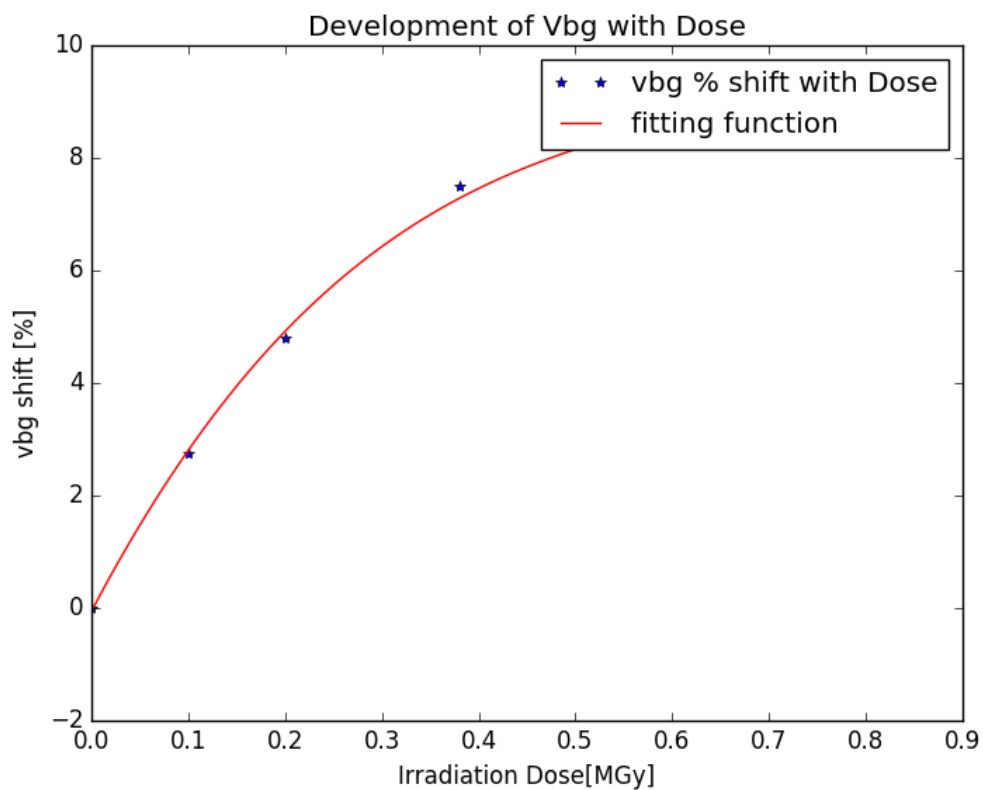


Figure 6.14: Fit to the graph in order to obtain the percentage shift in bandgap voltage at any value of the dose.

Figure 6.15 shows the unregulated analog voltage $V_a[V]$ after the two step correction mentioned above.

It is seen that the corrected values are higher than the uncorrected ones. The uncorrected voltages gradually decrease over time. This behavior is absent after correction: the corrected values remain more or less flat over time.

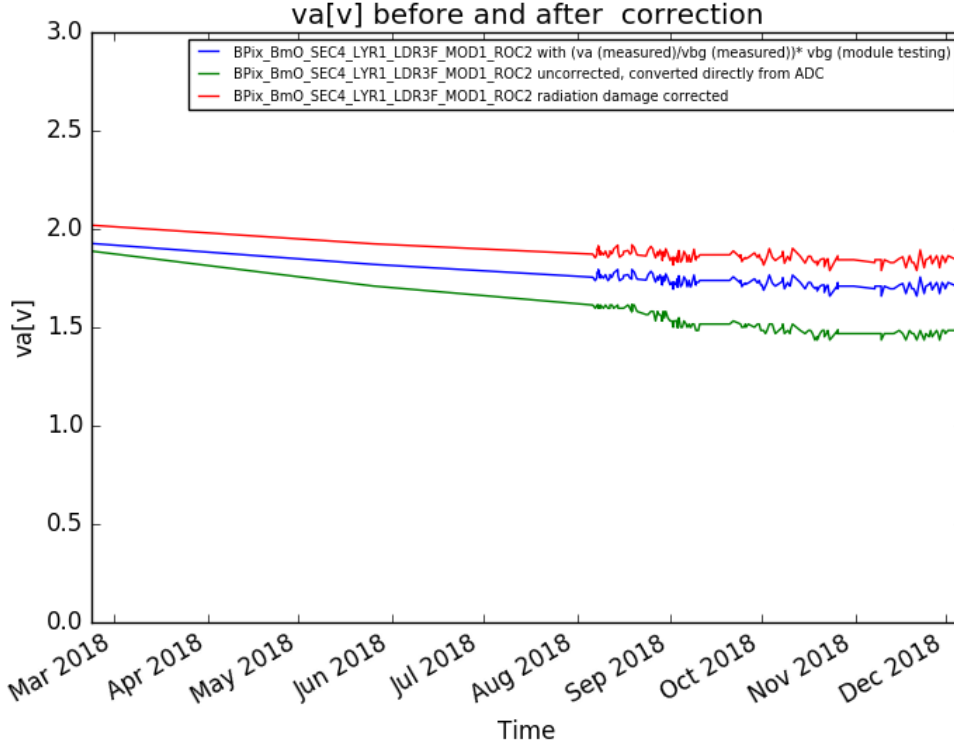


Figure 6.15: The $V_a[V]$ uncorrected value (green), the value multiplied by ratios of V_{bg} (blue), and the corrected value (red) as a function of time.

6.1.4 Results

Examples of results for radiation damage corrections for various quantities for different layers are shown in Figures 6.15 - 6.17. The uncorrected voltage values show a decreasing trend. This is the result of radiation damage accumulated by the readout chips (both ADC

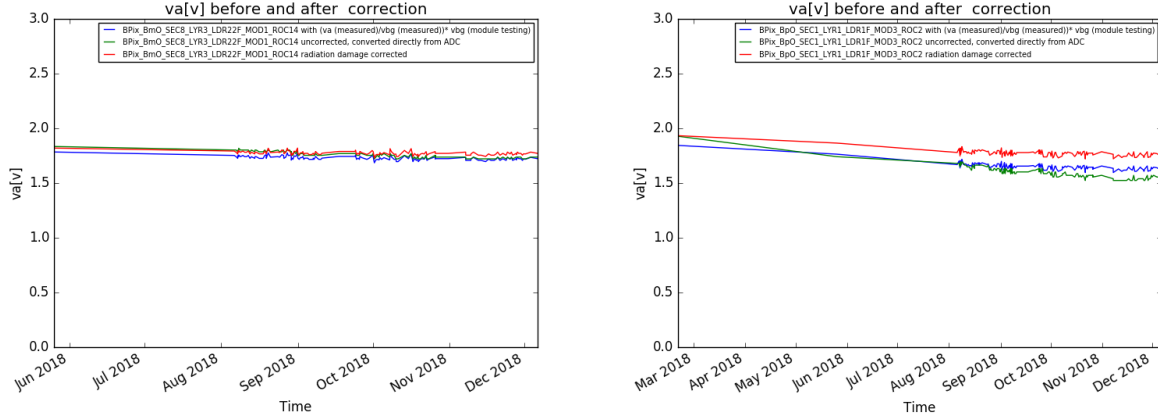


Figure 6.16: Radiation damage correction results for ROCs in layer 3 (left) and layer 1 (right). Both plots show the $V_a[V]$ uncorrected (green), the values multiplied by ratios of V_{bg} (blue), and the corrected values (red) as a function of time.

and bandgap reference voltage) over time. The radiation damage correction effectively corrects the effect caused by radiation damage and thus results in a flatter distribution over time. It can be seen from Figures 6.15 and 6.16 that the radiation damage correction has a significant effect on layer 1 as opposed to layer 3.

6.1.5 Conclusion

The readbacker quantities for the Phase-1 pixel detector have been introduced along with their manner of readout. A procedure for the study of the radiation damage correction for readbacker voltages has been presented.

As of now, there is still no validated radiation damage correction procedure for the readbacker current. The readback mechanism for voltage and current is different and thus the correction factors used per ROC for the voltages cannot be applied to the current. For the current there is a bigger spread among the ROCs and the change in readback value after the irradiation cannot be measured at ROC level.

The radiation damage correction effectively corrects the effect caused by radiation damage and thus results in a flatter distribution over time, as mentioned in Section 4.2. The

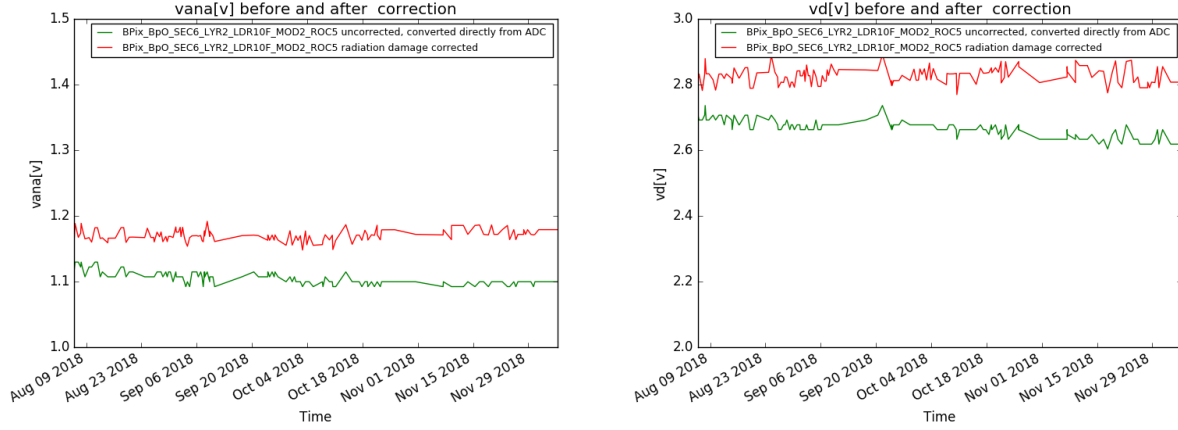


Figure 6.17: Radiation damage correction results for ROCs in layer 2. The quantities shown are the uncorrected (green) and corrected (red) values for $V_{\text{ana}}[\text{V}]$ (left) and $V_d[\text{V}]$ (right) as a function of time.

correction factors are dependent on the value of the irradiation dose so different layers receive different radiation damage corrections.

We only had correction factors determined previously for PROC600V2. We used the same correction factors for both PROC600V2 and PSIDIGv2. Both these chips have structural similarities and are expected to respond in a similar way to radiation damage.

The Fluka estimates provided us with a single estimate of dose for a given layer and a given timestamp. All the readout chips on a certain layer would have the same estimated dose provided the delivered luminosity was the same for all these ROCs. At the moment, we do not have yet the ability to tune our dose estimates to take into account the variations in r and z coordinates of the readout chips.

6.2 The Automatic Timing Scan

6.2.1 Pixel timing scan

The Pixel sub-detector, like any other sub-detector, is composed of smaller sub-units. Each sub-unit has a number of configuration parameters responsible for their efficient and optimum function. There are several timing delays across several parts of the pixel detec-

tor. And it is of prime importance to get all those delays such that we get the optimum performance from the whole detector.

The first delay that the whole pixel has to experience is the **Trigger delay**. This is the time between the bunch crossing and time it takes for the signal to arrive at the pixel readout chips. This global trigger latency is timed at around $3.2 \mu s$ and is the dominant source of delay. But other sources of delay are unique to different parts of the pixel, for instance, the fiber length traversed to reach a certain part of the sub-detector or the electronic responses along the path. These delays are critical as these could vary widely among different sub-detector parts and need to be taken into consideration. A timing delay that will work for the whole pixel will take both the trigger delay and the individual delays into account.

The pixel readout chips record the hits corresponding to each of the bunch crossings and store the hit information in the data buffer. Given the trigger delay, the pixel readout chips have to associate the hits to the correct bunch crossing that occurred earlier. For the hit to match correctly with the correct bunch crossing without being too early or late, a configuration parameter called the **WBC** (Which Bunch Crossing) is used. The WBC is determined through a calibration procedure, and it associates the hits with the correct bunch crossing in the near past prior to the trigger delay. In addition to matching with the correct bunch crossing, an additional delay between the clock and the trigger can be tuned to get the best signal quality. Adjusting this additional delay for each pixel sub-part allows one to reach a specific delay/timing setting, giving uniform response and the highest hit efficiency across the pixel sub-detector. Figure 6.18 shows how the WBC and the clock/trigger delay tuned to register a timely hit as opposed to a late/early hit.

The **Timing Scan** is performed to obtain a timing/delay setting such that the trigger signal arriving at the modules matches the correct bunch crossing and within the bunch crossing the best delay to have a uniform response from the pixel detector. The uniform response is characterized a the plateau in the hit efficiency. The constant and optimal response could also be represented by maximum cluster charge/size. In the timing scan, we scan through the different timing settings in the pixel detector and probe the hit efficiency, cluster charge, and cluster size. An ideal timing setting would result in the highest hit

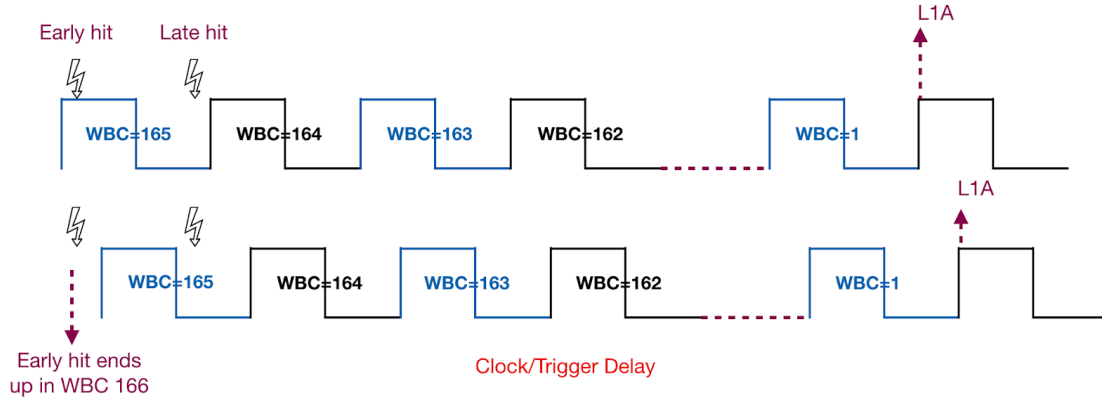


Figure 6.18: WBC and clock/trigger delay to correctly time the signal/hit.

efficiency, cluster charge, and size [76]. Figure 6.19 shows the timing scan for the BPix and the FPix.

6.2.2 Timing scan procedure for Run 2

The timing scan was carried out once a year in Run 2. The last timing scan was carried out in 2018. The timing scans carried out in Run 2 were mostly manual procedures because the scans needed a significant amount of expert intervention to run.

The Pixel DAQ expert had to co-ordinate closely with the central DAQ(cDAQ) shifter to carry out the timing scan. Each timing scan point/setting that needs to be explored in a timing scan can be described equivalently in terms of two other configuration parameters, the WBC and the **globalDelay25**. The Pixel DAQ expert, with the help of the cDAQ, scans over the complete range of timing scan points by changing the WBC and globalDelay25 every time.

The Pixel DAQ expert would create a "Physics" key every time by changing the globalDelay25 and WBC and would rely on the cDAQ to start a new Run with the said key. The process had to be repeated for each timing scan point with a new and unique Physics key, and the cDAQ had to reload the total configuration setting every time (Green Recycle).

Figure 6.20 shows the status of the LHC, pixel, and tracker during a timing scan run in 2018. The timing scan procedure took 4 hours to complete. For each WBC/globalDelay25

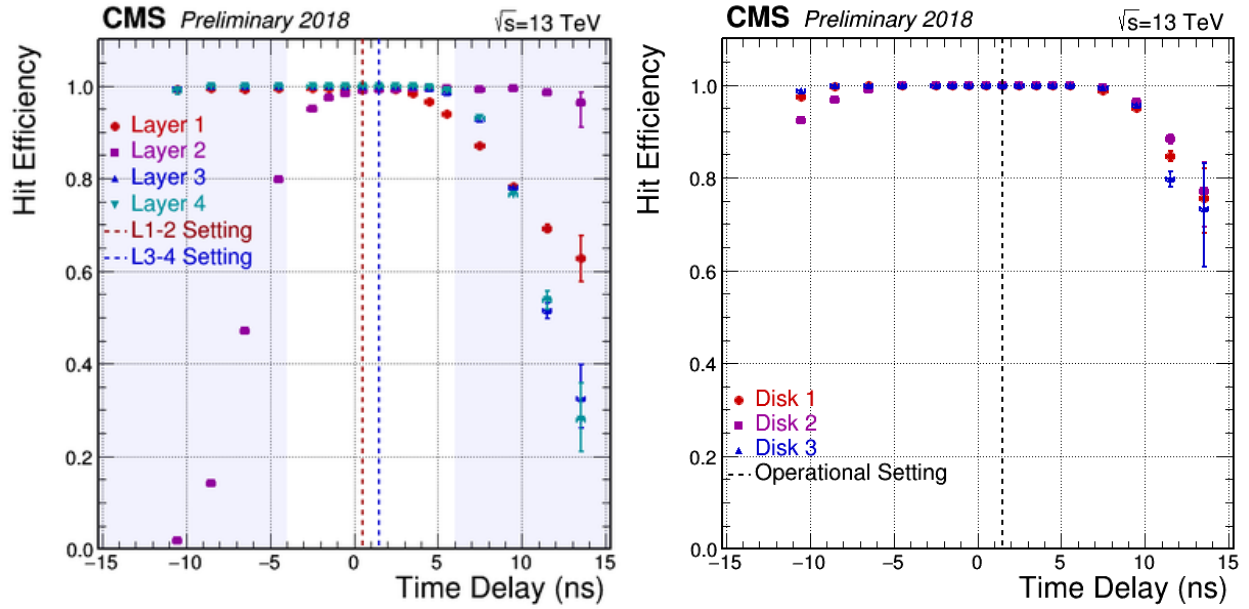


Figure 6.19: The Timing scan for (left) several layers of the BPix and (right) various disks of the FPix.

combination, the run of the detector was roughly 8 minutes, and there were a total of 20 runs corresponding to 20 separate timing/delay settings. There are 3 minutes of additional time needed to start and stop the run and reload configuration setting. This means for each 8 minute run in stable beams corresponding to a particular timing setting, around 3 minutes of stable beam time is lost.



Figure 6.20: LHC and Pixel Status for a Timing scan performed during Run 2 (2018).

6.2.3 Motivation for the automatic timing scan

There are several factors that lead to the necessity of automating the timing scan process. As mentioned above for each run with a timing setting that is 8 minutes long, 3 minutes of stable beam time is lost. This is a substantial portion of lost time per run considering the fact that reloading the configuration settings takes much less time (11 sec). We want to minimize the amount of stable beam time lost during the procedure and the automation is an essential step in doing so.

The timing scan for Run 2 needed a lot of expert intervention. It required proper coordination between the Pixel DAQ expert and cDAQ shifter. The steps involving the creation of new physics keys for each run, reloading the configurations, starting and stopping the runs every time needed a certain level of expertise, so not everyone could perform this job. Thus, in Run 2, a Pixel DOC (Detector On-Call) shifter could not carry out the timing scan, and expert intervention was always necessary. Moreover, since the process depended heavily on actions performed by different individuals, it was always prone to human errors. For Run 3, the goal is to make the timing scan more user-friendly so that even a Pixel DOC can run it, and we want to minimize the dependence on experts. The automatic timing scan addresses these Issues. With minimal instructions, a Pixel DOC should be able to initiate the automatic timing scan by merely clicking a single button from the user interface; this would not require any further intervention from the experts like the Pixel DAQ expert and cDAQ shifter. the

6.2.4 Procedure of the automatic timing scan

The Automatic Timing Scan procedure uses a pre-existing method of the pixel called the **Soft Error Recovery (SER)**. The SER method is used by pixel to recover from minor(soft) errors while running. The recovery is achieved through the reprogramming/re-configuring of the configuration settings. The SER method usually takes place in the portcard. When a soft error is detected in the portcard, the flag from the pixel is transferred to the cDAQ and the other sub-detectors. This causes the pausing of the triggers and the cDAQ starts the reconfiguration process. The time needed to reconfigure the pixel is about 4.6 seconds.

6.2.5 Status

The major Implementation of the automatic timing scan as an independent calibration is done, only part like the lumi-section counting is still to be implemented. The Initial test on an test setup showed that the whole timing scan (except the lumi-section counting) could be finished in 4 minutes, which is a significant improvement from the previous timing of 4 hours. The user interface is still is under construction and it is waiting to be tested during physics/collision runs in June/July 2022.

6.3 Pixel Monitoring

The Pixel sub-detector is particularly for our search. The analysis of the $2\mu 2\tau$ final state involves the reconstruction of multiple tracks and the pixel detector is critical for track seed-ing. The position resolution of the pixel, mentioned in section 3, enables the disambiguation of many nearby track. This allows the efficient identification of the interaction vertices and proper association of tracks to vertices. The analysis procedure we follow, involves the reconstruction on the invariant mass peak, which makes it important to be able to associate the muons and taus to the same(correct) primary vertex.

My monitoring work included monitoring quantities of the pixel ROCs the Detector Control Units (DCUs). A lot of parameters of the readout chips can be monitored and tuned using 26 digital-to-analog converters(DAC) and 3 registers [77]. The Parameters can be analog, digital voltages, timing for the internal calibrations signal.

6.3.1 ROC monitoring project

The ROCs have the functionality to read back analog and digital voltages and currents for each ROC. The measurements of the quantities are done as a part of the Readbacker Calibration that is done daily during beam downtime. The measurements are taken in analog-to-digital converter[ADC] values and they are changed to the respected voltages and currents. The conversion is done using a formula and parameters that resulted from calibrations during module testing. The parameters are unique to each ROC. The quantities are crucial

because the values of these quantities and their fluctuations are indicative of whether a ROC is functioning properly or whether it is inefficient and needs to be reprogrammed/power-cycled or fixed in any manner. Moreover, analog voltages are used to set the analog pulse height while digital voltages power rest of the electronics for the readout, and a drop of any one of them may have adverse effects. The five most important quantities readback during this readbacker calibration are v_d/v_{dig} , v_a , v_{bg} , v_{ana} , v_{bg} , i_{ana} . They are described in detail in Section 6.1.1.

Part of the work involved creating an automated way to read the quantities stored in files produced by the readbacker calibration and load them to the official CMS database. They were then fetched from the database and a web-based plotting interface is used (also was being developed) to allow daily monitoring of various ROCS with time. This was to part of Pixel Online Monitoring(POM) software package and would eventually become part of the Tracker Online Monitoring(TOM) software package. Most of the monitoring eventually migrated to OMS(a global CMS monitoring software package) .

CHAPTER 7

ANALYSIS

7.1 Analysis Strategy

This analysis looks for the decay of scalar Higgs boson (H) to a pair of pseudoscalar bosons (a), one of which decays to a pair of taus while the other decays to a couple of muons ($H \rightarrow aa \rightarrow \mu\mu\tau\tau$). The range of H masses that is searched for in this analysis starts from the standard model Higgs boson (125 GeV) up to 1TeV.

The pseudoscalar mass falls within the range $m_a \in [2m_\tau, m_H/2]$. The large mass difference between the Higgs and the pseudoscalar means that the final tau lepton decay products are highly boosted in the decay direction and collimated. The complete range of Higgs and pseudoscalar masses explored in the analysis is shown in Figure 7.1. A modified version of tau reconstruction is used to account for the highly overlapping decay products. The modified algorithm is described in section 7.2.3.

Combination of discriminants is to differentiate between the $H \rightarrow aa \rightarrow \mu\mu\tau\tau$ signal and (standard model background). Several combinations of discriminants were tested, and finally, the most optimal combination of discriminants was chosen. The optimal combination turned out to be a 2D distribution of dimuon ($\mu\mu$) invariant mass and four body ($\mu\mu\tau\tau$) visible mass. The optimal discriminant allows one to extract the potential signal while minimizing the expected upper limit on the signal cross-section. The 2D distribution of the discriminants is parametrically fit with a model of signal plus background. This allows one to extract the size of the potential signal as well as the pseudoscalar and scalar masses. Monte Carlo simulation of the signal processes is used to generate the signal models for a range of H and a mass combinations.

It is essential to estimate the background in the analysis, and the primary source of background is the Drell Yan + jet events. In a typical DY+ jet event, a dimuon pair and jets misidentified as an isolated di-tau pair could easily mimic the signal. Therefore, the

background is estimated using the control region in the data. The control region is chosen in a phase space such that it has an abundance of jets but lacks signal events. Then each event in the control region is weighted by the probability for the jet to fake or mimic an isolated ditau pair. There are benefits to using a control region to estimate the background. The use of the control region removes any dependencies of the final estimate on the MC modeling of the low mass dimuon continuum. The abundance of statistics in the control region allows higher statistical precision to be obtained as the number of MC events passing the analysis selection cuts is limited, leading to limited statistical precision.

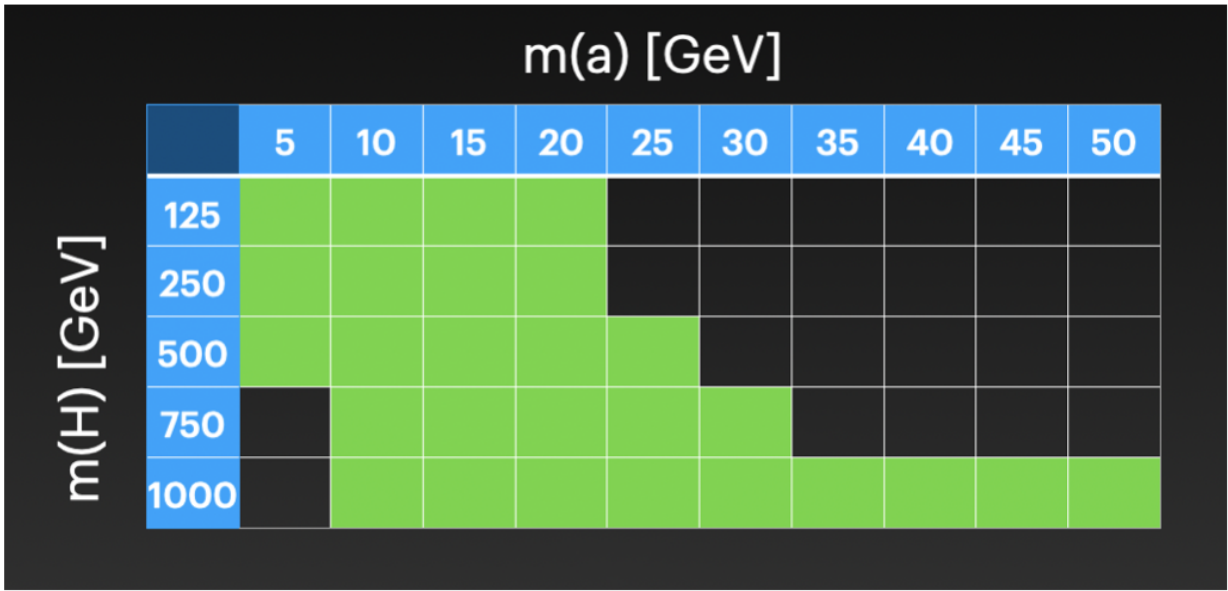


Figure 7.1: The masses of Higgs boson and of pseudoscalars (a) that are searched in this analysis.

7.1.1 Tau decay channels and Run 2 final states

The taus in the final state can decay both leptonically and hadronically. The leptonic decays result in an electron or a muon, while the hadronic decays could have a range of final decay products. The hadronic decays products consist of one or three charged hadrons and one or two neutral pions. The combination of hadronic and leptonic decays from two taus of the ditau pair can result in various final states. In this analysis the entire Run 2 data is

considered as well as all possible final states. The final states, along with their branching fractions, are shown in the figure 7.2.

The final states in the analysis are as follows:

- **Semi - leptonic final states** ($\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$) - These are the final states where one of the taus decays leptonically to electron or a muon, and the other tau decays hadronically. The two to final states combined command a significant portion of the branching fraction and is also sensitive to modified tau reconstruction algorithm. The modified reconstruction technique gives higher reconstruction efficiency than the standard tau reconstruction and better signal significance and background rejection. The modified tau reconstruction is only applicable to the semi-leptonic final states and not the others.
- **Fully - leptonic final states** ($\mu\mu\tau_\mu\tau_\mu$, $\mu\mu\tau_\mu\tau_e$, $\mu\mu\tau_e\tau_e$) - The fully leptonic final states are where both taus decay leptonically to an electron or a muon. After initial studies, which included all the channels, it was decided to move forward with just $\mu\mu\tau_\mu\tau_e$, based on the comparative statistics and the amount of sensitivity it the analysis. And this specific channel seems to have little or no SM background to mimic the signature.
- **Fully - hadronic final state** ($\mu\mu\tau_\mu\tau_\mu$) - This is the final state where both the tau decays occur hadronically. This final state has a lot of SM background, and there is a dedicated approach for this state based on Deep neural networks.

7.1.2 $\mu\mu\tau_e\tau_h$ final state

The advantages of the $2\mu 2\tau$ final state over the 4τ final state has already been discussed in section 2.6. My work is with the, $\mu\mu\tau_e\tau_h$, where one of the taus decays hadronically and the other has electrons as final products. Since both the taus are boosted, the $\tau_e\tau_h$ pair is highly collimated and τ_e overlaps with τ_h . The previous iterations of the analysis involved work with $\tau_\mu\tau_h$, i.e when the other tau decayed into muons. The combined information from the muon system and the CMS tracker make it easier to reconstruct a muon from the τ_μ . It is substantially tougher to reconstruct an electron from the τ_e as there is a high possibility of jets faking electrons both in the CMS tracker and in the ECAL. The study of $\mu\mu\tau_e\tau_h$ is worthwhile as it would greatly increase the signal acceptance, the branching fractions

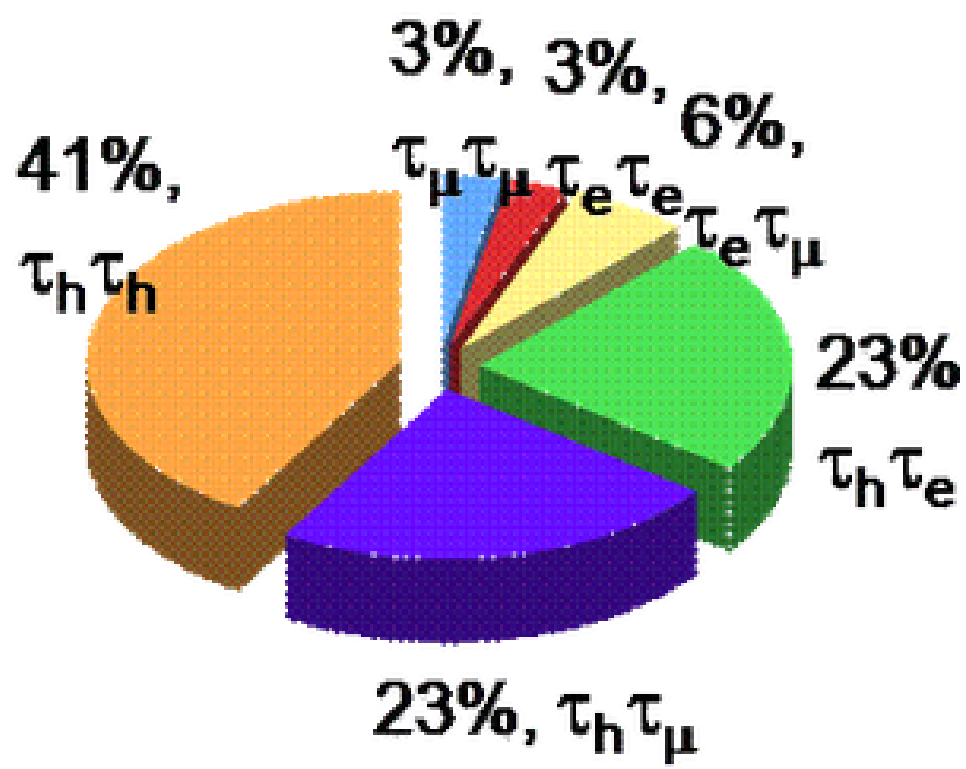


Figure 7.2: Tau decay channels considered in the analysis.

Table 7.1: Various cuts of the loose working point of the cut based electron ID.

Cuts	$electron_{Barrel},$ $ \eta_{supercluster} < 1.479$	$electron_{EndCap},$ $ \eta_{supercluster} > 1.479$
$Full\ 5 \times 5\ \sigma_{in\eta}$	<0.011	<0.0341
$ \Delta\eta\ in\ Seed $	<0.00477	<0.0868
$ \Delta\phi_{in} $	< 0.222	< 0.213
H/E	<0.298	<0.101
$ 1/E - 1/p $	< 0.241	< 0.14
expected missing inner hits	≤ 1	≤ 1
conversion veto	pass	pass
d_{xy}	$<0.05\text{cm}$	$<0.10\text{cm}$
d_z	$<0.1\text{cm}$	$<0.20\text{cm}$

of $\mu\mu\tau_e\tau_h$ being similar to $\mu\mu\tau_\mu\tau_h$. A certain selection is applied to separate out prompt electrons from jets, this will be covered later in this section.

7.2 Objects

7.2.1 Electrons

The electrons in the analysis are required to pass the Loose Working Point(WP) criteria of the cut-based electron identification. The electron has different cuts applied depending on whether it is in the Barrel region or the Endcap region. Table(7.1) shows the necessary cuts.

The $Full\ 5 \times 5\ \sigma_{in\eta}$ and H/E are shower-shape variables which allow one to differentiate between a prompt electron and a jet based on how their showers spread. Both $|\Delta\eta\ in\ Seed|$ and $|\Delta\phi_{in}|$ helps to match the track to the seed cluster, should ideally be smaller for prompt electrons. The $|1/E - 1/p|$ checks that there is a close enough match between the energy deposit in the ECAL and the momentum calculated from the track. The cut on the expected number of missing inner hits again ensures that the desired object is a prompt electron. The conversion veto gets rid of any $\gamma \rightarrow e^+e^-$ conversion. The impact parameter cuts ensures that the electron is from the primary vertex.

The electrons in this analysis are non-isolated, at least for the $\tau_e\tau_{had}$ channel has no isolation requirement as it contradicts the boosted topology.

Broadly speaking, the selection criteria is :

- $p_T > 7 \text{ GeV}$
- $|\eta| < 2.5$
- standard cutBased electron ID (`isLooseElectron`)

7.2.2 Muons

The muons in this analysis should all pass the basic selection criteria.

- $p_T > 3 \text{ GeV}$
- $|\eta| < 2.4$
- `isPFMuon` and (`isTrackerMuon` OR `isGlobalMuon`)

isPFMuon - This represents a particle that is identified as a muon by Particle-Flow event reconstruction.

isTrackerMuon - Muons that have tracks in the tracker and compatible muon segments in the muon system, the tracks are extrapolated to the muon system. The muons have improved efficiency at low p_T .

isGlobalMuon - A Global Muon first has to be a Standalone Muon. A Standalone Muon is reconstructed by combining hits and segments from different muon stations. If a Standalone Muon track has additionally a compatible track in the tracker, refit is performed using hits from the matched tracks. The result is a global muon.

Signal regions are defined by the isolation of the dimuon pair. The muon from the tau decay has no isolation requirement. These isolated muons must additionally pass (or fail in the anti-isolated case):

- Relative isolation < 0.25

7.2.3 Taus

A modified version of the Hadron-Plus-Strips (HPS) algorithm is used to reconstruct the hadronically decaying taus(τ_h)[78]. The HPS algorithm is used to reconstruct hadronic tau decays from anti- k_T $R = 0.4$ particle flow jets (“ak4PFJets”)[79]. It is seen that the $\tau_e\tau_h(\tau_\mu\tau_h)$ pair is highly collimated and the $\tau_e(\tau_\mu)$ overlaps with the τ_h decay products. The $\tau_e(\tau_\mu)$ would be, in many cases, in the constituents of the jet that seeds the τ_h reconstruction. The $\tau_e(\tau_\mu)$ can appear among the isolation constituents of the τ_h reconstructed with the HPS algorithm. This type of jet contamination can be avoided by a special procedure. Before the start of HPS, the jet constituents passing the loose working point of the cut-based electron identification criteria (**isLooseMuon** criteria), is removed for the $\mu\mu\tau_e\tau_h(\mu\mu\tau_\mu\tau_h)$ channel. This procedure is known as the **Jet cleaning**. In the majority of cases, only one soft muon (electron) is removed from a jet, but if more than muon (electron) is removed, the highest p_T removed muon (electron) is identified as the τ_μ/τ_e . Figure 7.3 shows the a diagram for the process. In cases of lower boost, the jet constituents passing the **isLooseElectron/ isLooseMuon** criteria and present in the isolation region (as opposed to inside the jet cone) are still removed. This is called **Isolation region cleaning**.

The cleaned jet constituent collection is then labeled as muon (electron) cleaned. A new ak4PFJet (henceforth referred to as the **cleaned** jet after the removal of the muon (electron)) is then reconstructed from the remaining PF constituents. These cleaned jets are submitted to the HPS algorithm and reconstructed as τ_h candidates. The τ_h are also termed as **electron/muon cleaned** τ_h .

Both the cleanings (jet and isolation) allow the reconstruction both the τ_h and τ_μ/τ_e separately, by preventing jet contamination. Thus higher signal efficiency and equal or lower $\text{Jet} \rightarrow \tau$ fakerate is achieved for the semi-leptonic channels. The tau reconstruction efficiency of the cleaned τ_{μ_h} as opposed to the standard τ_{μ_h} is shown in Section B. And the jet to tau fake rate is shown in Section A.

The hadronically decaying taus that are reconstructed after the electron cleaning pass the following criteria:-

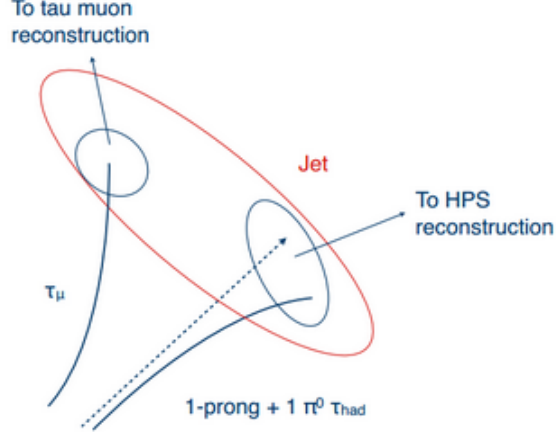


Figure 7.3: Schematic diagram of jet cleaning, reprinted from [80].

- $p_T > 10 \text{ GeV}$
- $|\eta| < 2.3$
- decayModeFinding-This ensures that the tau decays considered agree with valid decay modes of hadronic decay.
- byIsolationMVARun2v1DBoldDMwLTraw > -0.5 -Multivariate based isolation variable
- $d_{xy} < 0.2 \text{ cm}$ and $d_z < 0.5 \text{ cm}$

7.2.4 DiTau pair $\tau_h \tau_h$

One of the challenging channels to deal with in this analysis is the Fully hadronic channel. Both taus decay hadronically ($\tau_h \tau_h$) to various final states involving one or three charged hadrons and one or two neutral pions. The analysis focusses on the signal topology where there is a significant mass difference between the H and a (boosted topology). Thus, the two taus decay with partially and completely overlapping decay cones. The conventional tau reconstruction techniques fail in this scenario as it is tough to assign the decay products to the correct and extremely difficult to differentiate the decay products from other Standard Model backgrounds.

In this analysis, a Deep neural network, the **DeepDiTau**, is used to identify a pair of taus decaying hadronically. In a boosted topology, the decay products of two taus are contained

within a jet for a majority of the cases, and DeepDiTau uses this criterion. DeepDiTau determines the probability that an AK4 jet originated from a pair of hadronically decaying taus.

In principal DeepDiTau output is a score which becomes a discriminating factor and allows one to differentiate between $\tau_h\tau_h$ and other jets. Information related to the training, network architecture, the inputs as well as the preliminary performance will be described in Section D.

7.3 Signal Selection and Background Rejection

Monte Carlo simulation of both background and signal is used to design the analysis. One of the most useful variables to study is the visible mass of final state particles in the $\tau_e\tau_{had}$ decay. The term "visible" refers to the fact that there are neutrinos in the decay which cannot be reconstructed and thus contribute to missing transverse energy (MET), while the remaining particles can be reconstructed. The visible mass should have a wide distribution due to the loss of neutrinos, but should roughly peak at the mass of the psuedoscalars. This peak for the visible mass is an important discriminating characteristic which differentiates signal from background.

7.4 Event Selections

For the events passing the HLT_IsoMu24 / HLT_IsoMu27 or HLT_IsoTkMu24 / HLT_IsoTkMu27 trigger, necessary selections are applied to identify the important objects in the event and to optimize the signal sensitivity. The selections vary with the decay channels. The selections include the dimuon and $\tau_\mu\tau_h/\tau_e\tau_h$ objects for the semi leptonic decay channels, $\tau_\mu\tau_e$ for the full leptonic decay channels and $\tau_h\tau_h$ object for full hadronic decay channel. All these objects come from the two light presudoscalars, a .

The selection below is defined as the *preselection*.

7.4.1 Semi leptonic decay channels

$\mu\mu\tau_\mu\tau_h$. The selected events are required to pass:

- Trigger:
 - HLT_IsoMu24_v* OR HLT_IsoTkMu24_v* (2016)
 - HLT_IsoMu24_v* OR HLT_IsoTkMu24_v*
OR HLT_IsoMu27_v* OR HLT_IsoTkMu27_v* (2017)
 - HLT_IsoMu24_v* (2018)
- Dimuon selection ($\mu_1\mu_2$)
 - Two opposite-sign muons
 - Leading isolated muon (μ_1) $p_T > 26$ GeV and matched to the trigger
 - Subleading muon (μ_2) $p_T > 3$ GeV
 - $2.5 < m(\mu_1, \mu_2) < 60$ GeV (for 125 GeV Higgs, might vary for higher higgs masses)
 - Smallest $dR(\mu_1, \mu_2) < 1.0$
- Ditau selection ($\tau_\mu\tau_h$)
 - Opposite-sign muon-tau pair
 - Muon passes Loose muon ID
 - Muon (μ) $p_T > 3$ GeV
 - Muon cleaned hadronic tau (τ_h) $p_T > 10$ GeV
 - Smallest $dR(\tau_\mu, \tau_h) (< 0.8)$
- Cross-cleaning
 - $dR(\mu_1, \tau_\mu) > 0.4$
 - $dR(\mu_2, \tau_\mu) > 0.4$
 - $dR(\mu_1, \tau_h) > 0.8$
 - $dR(\mu_2, \tau_h) > 0.8$
- Veto event if τ_h jet passes CSVv2 Medium WP

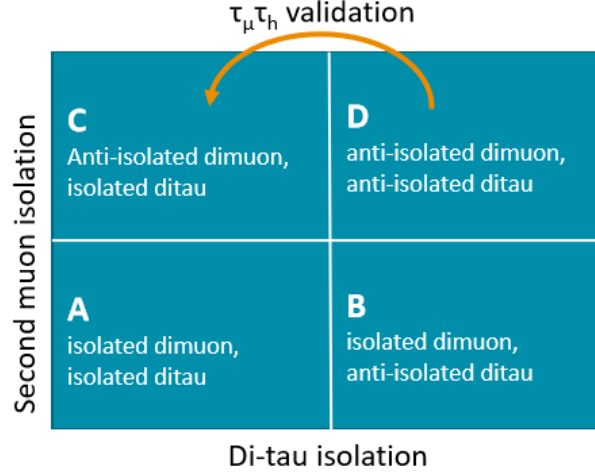


Figure 7.4: Graphic depicting ABCD method for $\mu\mu\tau_\mu\tau_h$. Region definitions for $\mu\mu\tau_e\tau_h$ and $\mu\mu\tau_h\tau_h$ are similar.

From this data set, events are further categorized into four regions base on μ_2 and τ_h isolation.

- Region A: isolated μ_2 , isolated τ_h
- Region B: isolated μ_2 , anti-isolated τ_h
- Region C: anti-isolated μ_2 , isolated τ_h
- Region D: anti-isolated μ_2 , anti-isolated τ_h

Region A will sometimes be referred to as the *signal region* and region B will sometimes be referred to as the *sideband*. These regions are used to estimate background contributions in the signal region through a data driven fakerate method. Regions C and D will be used to validate this method. Figure 7.4 shows a graphical representation of the regions and their definitions for $\mu\mu\tau_\mu\tau_h$. This is described in more detail in Section 7.7

$\mu\mu\tau_e\tau_h$. The selected events for this channel are required to pass:

- Trigger: same
- Dimuon selection ($\mu_1\mu_2$)
 - Two opposite-sign muons

- Leading isolated muon (μ_1) $p_T > 26$ GeV and matched to the trigger
- Subleading muon (μ_2) $p_T > 3$ GeV
- $2.5 < m(\mu_1, \mu_2) < 60$ GeV (for 125 GeV Higgs, might vary for higher higgs masses)
- Smallest $dR(\mu_1, \mu_2) (< 1.0)$
- Ditau selection ($\tau_e \tau_h$)
 - Opposite-sign muon/electron-tau pair
 - Electron passes Loose Electron ID
 - Electron (e) $p_T > 7$ GeV
 - Electron cleaned hadronic tau (τ_h) $p_T > 10$ GeV
 - Smallest $dR(\tau_e, \tau_h) (< 0.8)$
- Cross-cleaning
 - $dR(\mu_1, \tau_e) > 0.4$
 - $dR(\mu_2, \tau_e) > 0.4$
 - $dR(\mu_1, \tau_h) > 0.8$
 - $dR(\mu_2, \tau_h) > 0.8$
- Veto event if τ_h jet passes CSVv2 Medium WP

The events are then further categorized to four regions A, B, C and D based on μ_2 and τ_h isolation, similar to the $\tau_\mu \tau_h$ channel.

7.4.2 Full leptonic decay channels

$\mu\mu\tau_\mu\tau_e$. The selected events for this channel are required to pass:

- Trigger: same
- Dimuon selection ($\mu_1\mu_2$)
 - Two opposite-sign muons
 - Both pass Loose muon ID

- Leading isolated muon (μ_1) $p_T > 26$ GeV and matched to the trigger
- Subleading muon (μ_2) $p_T > 3$ GeV
- $2.5 < m(\mu_1, \mu_2) < 60$ GeV
- Smallest $dR(\mu_1, \mu_2) (< 1.0)$
- Dilepton selection ($\tau_\mu \tau_e$)
 - Opposite-sign electron-muon pair
 - Muon pass Loose muon ID
 - Muon pass Loose muon Iso (< 0.25)
 - Electron pass Tight Electron ID
 - Smallest $dR(\tau_\mu, \tau_e) (< 1.0)$
- Cross-cleaning
 - $dR(\mu_1, \tau_e) > 0.4$
 - $dR(\mu_2, \tau_e) > 0.4$
 - $dR(\mu_1, \tau_\mu) > 0.4$
 - $dR(\mu_2, \tau_\mu) > 0.4$

The events are then further categorized into four regions 4P, 3P1F1, 3P1F2 and 2P2F based on the isolation of τ_μ and the ID of τ_e . The signal region (4P) is depicted by Loose muon isolation for τ_μ and Tight electron ID for τ_e and the other regions are described in section 7.7, where they are mentioned in context of background estimation.

7.4.3 Full hadronic decay channel

$\mu\mu j$.

- Trigger: same
- Dimuon selection ($\mu_1 \mu_2$)
 - Two opposite-sign muons
 - Both pass Loose muon ID
 - Leading isolated muon (μ_1) $p_T > 26$ GeV and matched to the trigger

- Subleading muon (μ_2) $p_T > 3$ GeV
- $2.5 < m(\mu_1, \mu_2) < 60$ GeV
- Smallest $dR(\mu_1, \mu_2) (< 1.0)$
- Jet selection
 - Jet $p_T > 20$ GeV
 - Jet passes Tight jet ID
 - Jet passed bVeto Loose
 - Jet passes deepDiTau discriminator raw value (TBD)
- Cross-cleaning
 - $dR(\mu_1, \text{Jet}) > 0.4$
 - $dR(\mu_2, \text{Jet}) > 0.4$

7.5 Tau Scale Factor Measurement

The signal processes involve scenarios with both standard model H mass of 125 GeV all the way up to 1000 GeV. Now, for the H mass of 125 GeV specifically and for an a mass range of 4 to 20 GeV, it is common to encounter softer taus in the final state. It is necessary to include these taus, which mostly lie within the p_T range $10 < p_T < 20$ GeV, in order to increase the statistics. Tau (Physics Object Group) POG studied the tau ID in the region $p_T > 20$ GeV and provided scale factors with uncertainties for analysis groups including taus in their final state. For this analysis a customized MVA tau ID efficiency study is performed for low p_T ($10 < p_T(\tau_h) < 20$ GeV) region .

The procedure followed is similar to the one used by the Tau POG in deriving the official scale factors [81]. The τ_h identification efficiency is estimated in $\tau_\mu\tau_h$ final states of Z/γ events. In this study, final states included one muon passing medium ID with relative isolation < 0.15 as "tag", and τ_h candidate that passes loose pre-selection criteria as "probe". An exhaustive list with detailed descriptions will be provided below as the pre-selection sequence. After pre-selection, the τ_h candidate should pass the medium MVA isolation discriminant.

Full RunII data and Monte Carlo samples are used, as described in Table 7.5. The study was carried out using pre Ultra Legacy samples and then repeated with Ultra Legacy samples to have the most updated results.

The following list is the pre-selection sequence.

- Trigger selection
 - `HLT_IsoMu24_v*` OR `HLT_IsoTkMu24_v*`
- Muon selections
 - `isPFMuon`
 - $p_T(\mu) > 26$ GeV, therefore p_T is above trigger turn on threshold
 - $|\eta| < 2.4$
 - relative isolation < 0.15
 - Pass `isMediumMuon`
 - Veto second μ with $p_T > 10$ GeV
- Tau selections
 - HPS algorithm for hadronic tau
 - $p_T(\tau_h) > 10$ GeV
 - $|\eta| < 2.3$
 - Pass `decayModeFinding`
 - Pass medium MVA tau discriminant
- $\tau_\mu\tau_h$ selections
 - $dR(\tau_\mu, \tau_h) > 0.5$
 - $M_T(\tau_\mu, E_T^{\text{miss}}) < 40$ GeV
 - τ_μ and τ_h needs to be same or opposite sign depending on region defined below
- $p_\zeta^{\text{miss}} - 0.85p_\zeta^{\text{vis}} > -25\text{GeV}$

The $Z \rightarrow \mu\tau_h$ (signal) yield is extracted from the simulated Z+jets events, considering cases where the reconstructed τ_h is matched with a generated τ_h , according to $dR(\tau_h^{gen}, \tau_h) < 0.15$. The main backgrounds are QCD, W+jets, $t\bar{t}$, a μ mis-identified as a τ_h when a Z boson decays to two muons, a jet mis-identified as a τ_h from Z+jets, and di-boson (VV). The QCD background yield and its correction factor are estimated using the data. The W+jets background yield is estimated using the simulated events, while its correction factor is estimated using a data-driven approach. The background of a μ mis-identified as a τ_h is extracted from simulated Z+jets events, when the reconstructed τ_h is matched with a μ at the generator level. Besides the $Z \rightarrow \mu\tau_h$ contribution and the fraction of a μ mis-identified as a τ_h , the rest of the events remaining in the simulated Z+jets events are treated as the background of a jet mis-identified as a τ_h . Other backgrounds are directly derived from their simulated events.

Initially, the assumption is made that the QCD and W + jets backgrounds have an unity re-scaling factor, and the resulting distributions of dynamic variables can be seen in Figures 7.5 and 7.6.

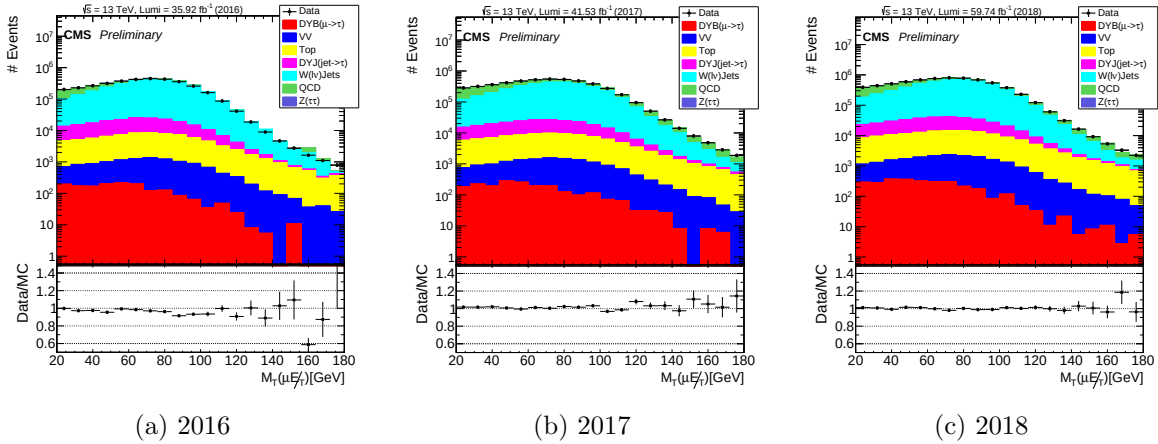


Figure 7.5: Comparison between data and simulation for $10 < p_T(\tau_h) < 20$ GeV in the distribution of $M_T(\tau_\mu, E_T^{\text{miss}})$ in different years, regardless of the requirement in $M_T(\tau_\mu, E_T^{\text{miss}})$. These are pre-fit results. The error bars stand for statistical uncertainties.

The tau efficiency measurement uses a same sign control region to extract the shape of QCD on an opposite sign region in which the signal is present. The QCD distribution in the

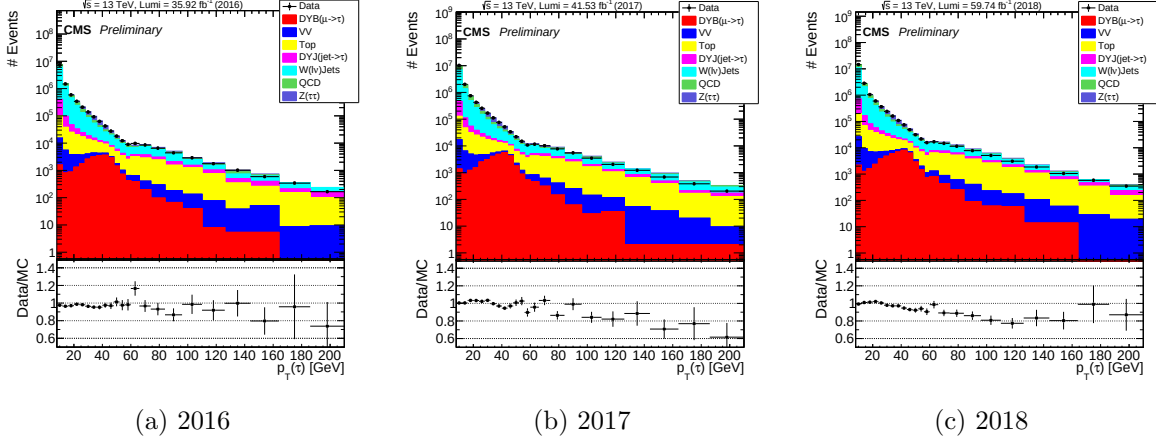


Figure 7.6: Comparison between data and simulation for $10 < p_T(\tau_h) < 20$ GeV in the distribution of $p_T(\tau_h)$ in different years, regardless of the requirement in $p_T(\tau_h)$. These are pre-fit results. The error bars stand for statistical uncertainties.

same sign region is expected to be nearly identical to the distribution in the opposite sign region. In the previous tau ID POG study, this ratio is measured out to be 1.05, though their study was based on p_T above 20 GeV. This ratio is re-calculated for this analysis when $10 < p_T(\tau)h < 20$ GeV.

First, a control region is defined specifically for this QCD transfer ratio study as events passing all above pre-selections, except with the muon isolation inversed. Because this anti-isolated muon control region is dominated by the QCD background in the data, data is used to extract the ratio of QCD in the opposite region to the same sign region. The ratio is calculated as a function of $M^{vis}(\mu\tau_h)$ (visible mass of $\mu\tau_h$), and fitted with a linear function to estimate the shape uncertainty of the QCD background. Figure 7.7 shows the differential QCD re-scaling factors.

The rescaling factor of W+jets is calculated in another control region of OS when $M_T(\tau_\mu, E_T^{\text{miss}}) > 80$ GeV, where the W+jets dominates in the data. After subtracting other simulated background and the extrapolated QCD contribution from the data, and ratio between the data and simulated W+jets is treated as the rescaling factor. It is also estimated as a function of $M^{vis}(\mu\tau_h)$ and fit with a linear function, as shown in figure 7.8.

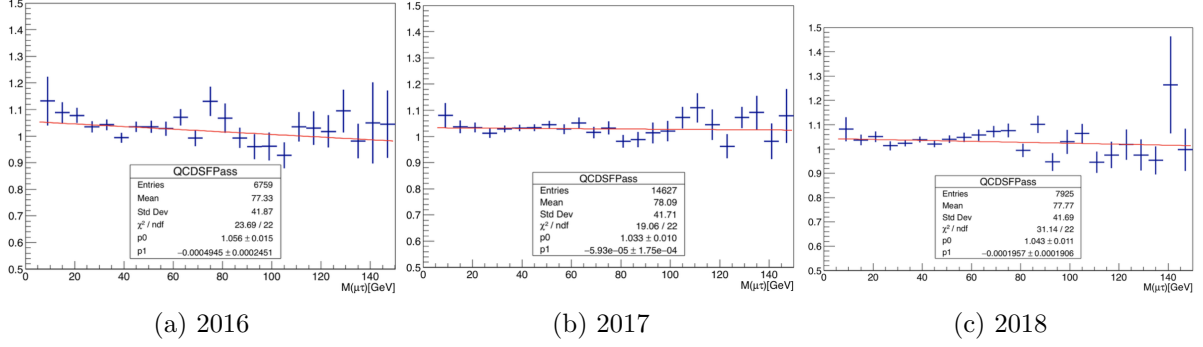


Figure 7.7: The re-scaling factor of the QCD background as a function of $M^{\text{vis}}(\mu\tau_h)$ for $10 < p_T(\tau_h) < 20$ GeV, using the data taken in different years. The error bars stand for statistical uncertainties from a data-driven approach.

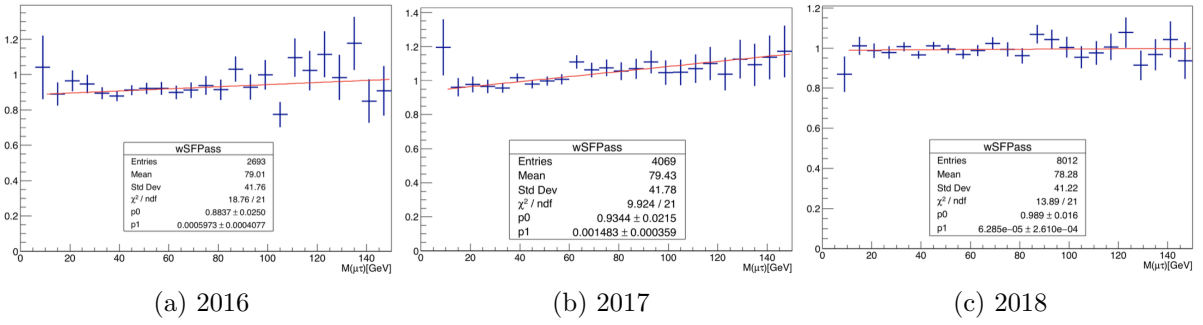


Figure 7.8: The re-scaling factor of the W+jets background as a function of $M^{\text{vis}}(\mu\tau_h)$ for $10 < p_T(\tau_h) < 20$ GeV, using the data taken in different years. The error bars stand for the quadrature summation of the statistical uncertainties of the data and MCs.

The data-to-simulation scale factor for τ_h identification efficiency is extracted from a maximum-likelihood fit of the visible invariant mass distribution of the reconstructed $\tau_\mu\tau_h$ system, referred to as $M^{vis}(\mu\tau_h)$. The nuisance parameters considered in the fit procedure with their initial uncertainties are summarized in table 7.2. Besides them, the shape uncertainties of the QCD and W+jets are also considered. The “shape up” distribution is obtained by multiplying the differential rescaling factor to the nominal distribution of $M^{vis}(\mu\tau_h)$, while the “shape down” distribution is estimated from the nominal distribution of $M^{vis}(\mu\tau_h)$ divided by the differential rescaling factor. The shape variations for QCD and W+jets backgrounds before the fitting procedure are shown in Figures 7.9 and 7.10.

Table 7.2: The list of the nuisance parameters with their initial systematic uncertainties.

Nuisance parameter	Initial uncertainty
Signal cross section	3%
μ fake τ_h	30%
Jet fake τ_h	15%
QCD multi-jet renormalization	10%
$t\bar{t}$ renormalization	10%
Di-boson renormalization	10%
Wjets renormalization	10%
Luminosity	2.3%
Muon efficiency	1.2%

The prefit and postfit of $M^{vis}(\mu\tau_h)$ are shown in Figures 7.11 and 7.12. General agreement between data and simulation is seen, within range of uncertainties.

The fitted scale factor of tau identification is summarised in table 7.3.

Table 7.3: The list of the tau ID scale factors and their uncertainties measured using the full runII data. The numbers in the brackets stand for the measured results for $p_T(\tau_h) > 20$ GeV (not elaborated here).

Years	tauID SF	uncertainty
2016	0.68 (0.90)	0.17 (0.05)
2017	0.71 (0.89)	0.16 (0.04)
2018	0.73 (0.90)	0.12 (0.04)

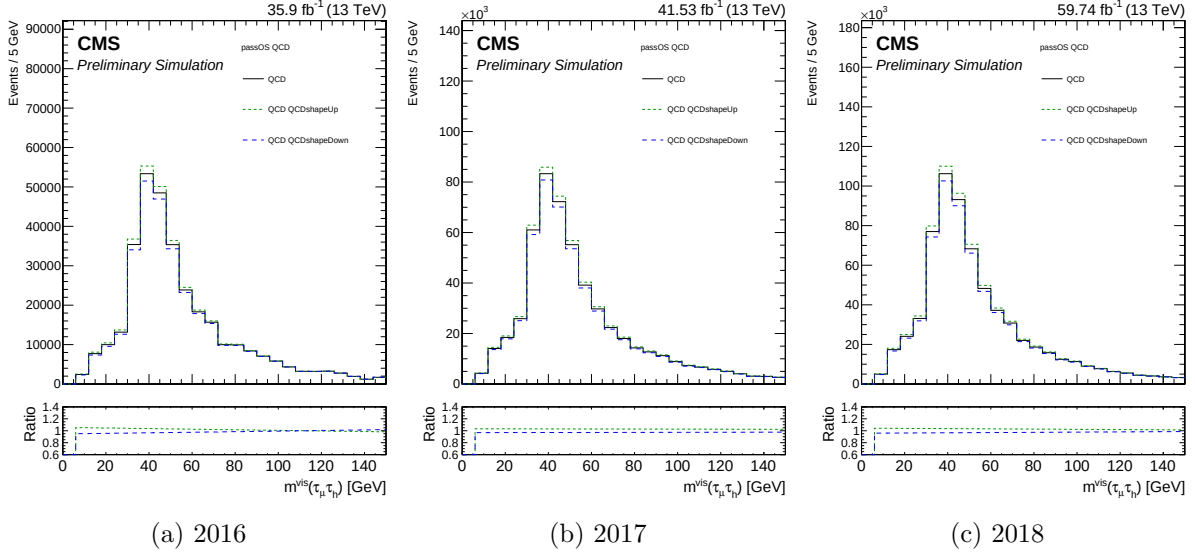


Figure 7.9: The shape varied distribution of the QCD background as a function of $M^{vis}(\mu\tau_h)$ for $10 < p_T(\tau_h) < 20$ GeV, using the data taken in different years.

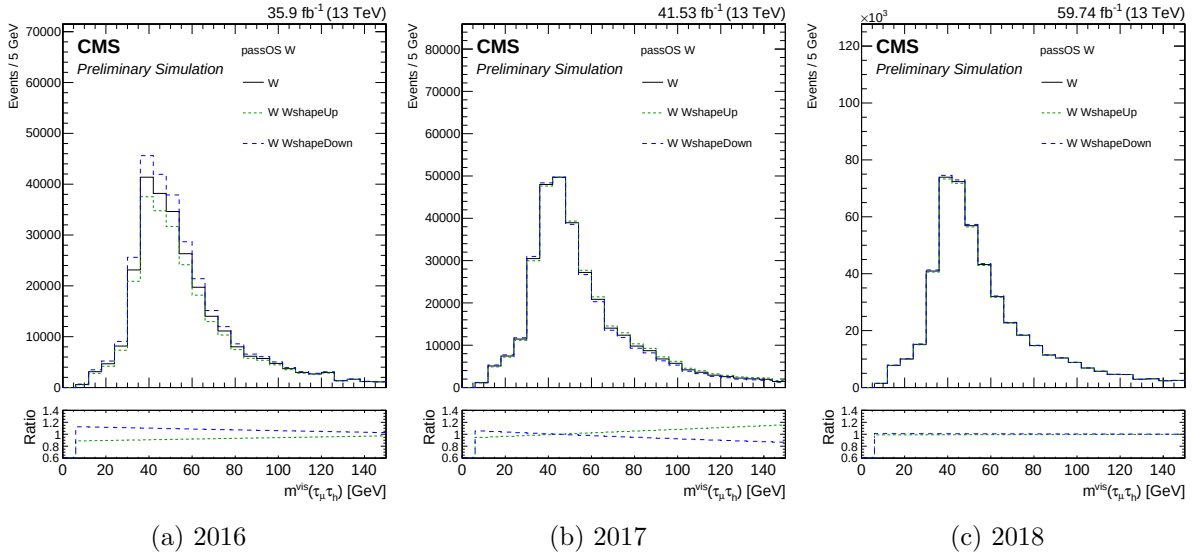


Figure 7.10: The shape varied distribution of the W+jets background as a function of $M^{vis}(\mu\tau_h)$ for $10 < p_T(\tau_h) < 20$ GeV, using the data taken in different years.

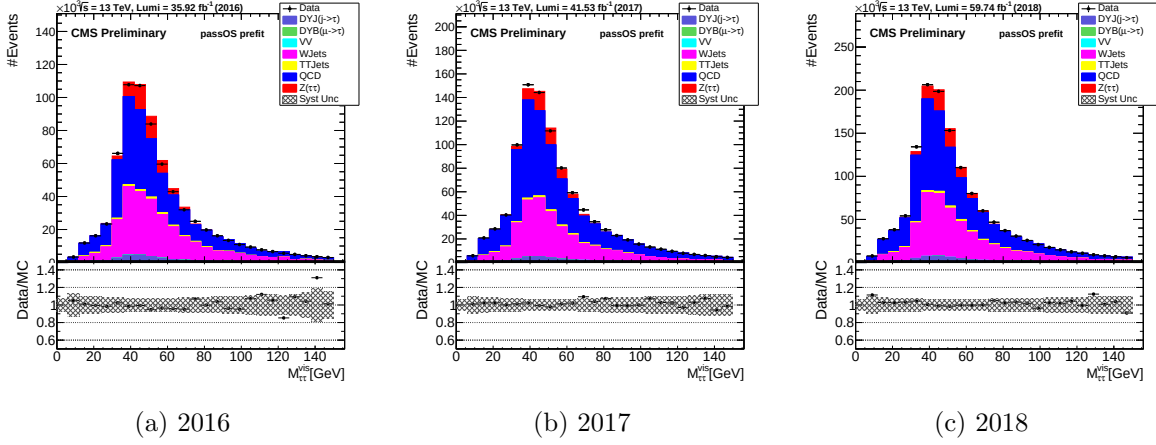


Figure 7.11: Comparison between data and simulation for $10 < p_T(\tau_h) < 20$ GeV in the distribution of $M^{vis}(\mu\tau_h)$ in different years. These are pre-fit results. The error bars stand for statistical uncertainties, while the systematic uncertainties are amounted as the fence bands.

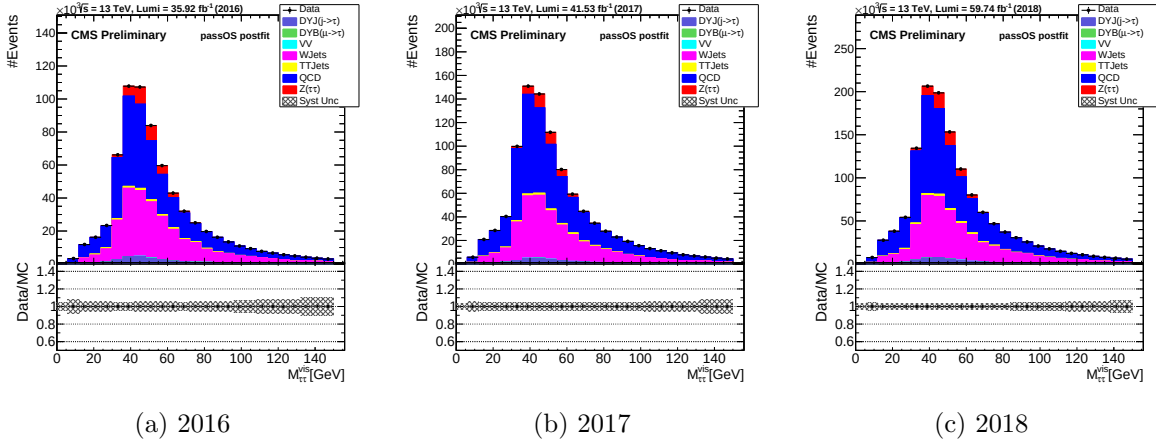


Figure 7.12: Comparison between data and simulation for $10 < p_T(\tau_h) < 20$ GeV in the distribution of $M^{vis}(\mu\tau_h)$ in different years. These are post-fit results. The error bars stand for statistical uncertainties, while the systematic uncertainties are amounted as the fence bands.

7.6 Datasets and Trigger

The analysis is a search for a light pseudoscalar (a_1) decaying to a pair of muons and a pair of tau-leptons and it is based on the data collected by the CMS experiment during 2016, 2017, and 2018, at $\sqrt{s} = 13$ TeV. The datasets used for the analysis are **SingleMu** primary datasets with a single isolated muon trigger with a transverse momentum greater than 24 GeV. The trigger is a or between two triggers called `HLT_IsoMu24` and `HLT_IsoTkMu24` which require the presence of at least one isolated muon with $p_T > 24$ GeV. The names of the datasets along with the run ranges and integrated luminosity are shown in Table 7.4, which corresponds to a total integrated luminosity of 137 fb^{-1} .

Table 7.4: Collision datasets and integrated luminosity

Dataset	$\mathcal{L}(\text{fb}^{-1})$
2016	35.92
/SingleMuon/Run2016B-ver2_HIPM_UL2016_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2016C-HIPM_UL2016_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2016D-HIPM_UL2016_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2016E-HIPM_UL2016_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2016F-HIPM_UL2016_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2016F-UL2016_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2016G-UL2016_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2016H-UL2016_MiniAODv2-v2/MINIAOD	
2017	41.53
/SingleMuon/Run2017B-UL2017_MiniAODv2-v1/MINIAOD	
/SingleMuon/Run2017C-UL2017_MiniAODv2-v1/MINIAOD	
/SingleMuon/Run2017D-UL2017_MiniAODv2-v1/MINIAOD	
/SingleMuon/Run2017E-UL2017_MiniAODv2-v1/MINIAOD	
/SingleMuon/Run2017F-UL2017_MiniAODv2-v1/MINIAOD	
2018	59.74
/SingleMuon/Run2018A-UL2018_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2018B-UL2018_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2018C-UL2018_MiniAODv2-v2/MINIAOD	
/SingleMuon/Run2018D-UL2018_MiniAODv2-v3/MINIAOD	

7.6.1 Monte Carlo samples

The background MC samples from 2016, 2017, and 2018 used in this analysis are summarized in the Table 7.5. A detailed version of the table showing full names can be found in Table E.1.

7.7 Background Estimation

The background estimation techniques are different for the different channels. The semi-leptonic channels ($\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$) have the same method of background estimation. The fully leptonic channels ($\mu\mu\tau_\mu\tau_\mu$, $\mu\mu\tau_\mu\tau_e$) also have the same method for background estimation. The following sections will describe the background estimation methods for various channels.

7.7.1 Fully-leptonic final states

The backgrounds can be categorized into Irreducible and reducible. For the irreducible backgrounds, all the distributions of the kinematic variables are the same as the signal, so it is impossible to reduce them by applying selections/cuts on kinematic variables. On the other hand, reducible backgrounds can be reduced by a suitable selection of restrictions applied to the kinematic variables.

Irreducible background. As mentioned above, the irreducible background is still present after applying selections on kinematic variables because the distributions of the kinematic variables are very similar to that of the signal, so it is impossible to reduce them by applying selections/cuts on kinematic variables. The irreducible background for the fully leptonic channels is ZZ decaying to four leptons.

Reducible background. The reducible background for the fully leptonic channels occurs from processes with four lepton final states where there can be one or more non-prompt leptons. The primary sources of non-prompt leptons are processes that give rise to non-isolated electrons and muons. Non-isolated electrons and muons can result from heavy flavor meson decay, decay of light flavor bound states, and misreconstructed jets and hadrons.

Table 7.5: Background MC samples for the 2016,2017 and 2018.

Year	Physics processes	Dataset name (Partial)	σ (pb)
2018	Z/γ^*	DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8	5398.0
	$t\bar{t}$	TTJets_TuneCP5_13TeV-amcatnloFXFX-pythia8	750.5
	W-Jets	WJetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8	53870.0
	Di-Boson WW	WW_TuneCP5_13TeV-pythia8	75.95
	Di-Boson WZ	WZ_TuneCP5_13TeV-pythia8	27.59
	Di-Boson $W(\ell\nu)Z(\ell\ell)$	WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8	5.213
	Di-Boson ZZ	ZZ_TuneCP5_13TeV-pythia8	12.17
	Di-Boson $Z(\ell\ell)Z(\ell\ell)$	ZZTo4L_TuneCP5_13TeV_powheg-pythia8	1.325
2017	Z/γ^*	DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8	5358.0
	$t\bar{t}$	TTJets_TuneCP5_13TeV-amcatnloFXFX-pythia8	750.5
	W-Jets	WJetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8	53870.0
	Di-Boson WW	WW_TuneCP5_13TeV-pythia8	75.95
	Di-Boson WZ	WZ_TuneCP5_13TeV-pythia8	27.59
	Di-Boson $W(\ell\nu)Z(\ell\ell)$	WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8	5.219
	Di-Boson ZZ	ZZ_TuneCP5_13TeV-pythia8	12.17
	Di-Boson $Z(\ell\ell)Z(\ell\ell)$	ZZTo4L_TuneCP5_13TeV_powheg-pythia8	1.325
2016	Z/γ^*	DYJetsToLL_M-50_TuneCP5_13TeV-amcatnloFXFX-pythia8	6404.0
		DYJetsToLL_M-50_TuneCP5_13TeV-amcatnloFXFX-pythia8	6404.0
	$t\bar{t}$	TTJets_TuneCP5_13TeV-amcatnloFXFX-pythia8	750.5
		TTJets_TuneCP5_13TeV-amcatnloFXFX-pythia8	831.7
	W-Jets	WJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-pythia8	67350
		WJetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8	53870.0
	Di-Boson WW	WW_TuneCP5_13TeV-pythia8	75.95
		WW_TuneCP5_13TeV-pythia8	75.95
	Di-Boson WZ	WZ_TuneCP5_13TeV-pythia8	27.59
		WZ_TuneCP5_13TeV-pythia8	27.59
	Di-Boson $W(\ell\nu)Z(\ell\ell)$	WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8	5.213
		WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8	5.213
	Di-Boson ZZ	ZZ_TuneCP5_13TeV-pythia8	12.17
		ZZ_TuneCP5_13TeV-pythia8	12.17
	Di-Boson $Z(\ell\ell)Z(\ell\ell)$	ZZTo4L_M-1toInf_TuneCP5_13TeV_powheg-pythia8	13.74
		ZZTo4L_M-1toInf_TuneCP5_13TeV_powheg-pythia8	13.74

Non-isolated electrons in particular also result from γ conversions. The non-prompt leptons from any of the sources mentioned above will be termed henceforth as "fake lepton", and this would include the "fake muon" and "fake electron". Likewise, any electron originating from photon conversion will also be called a "fake electron".

The rate of the background processes can be determined by measuring the probabilities that fake muons or fake electrons will pass the **loose** selection criteria. This specific criterion is described in section 7.2.3 and is a requirement for the signal region. The probabilities for fake electron and fake muon to pass the loose selection criteria are described as muon and electron fake rates (FR) respectively and noted by f_μ and f_e . The electron and muon fake rates are applied to the control samples in order extract the background yield in the signal region.

The lepton fake rates f_μ and f_e are measured using samples of $Z(ll) + e$ and $Z(ll) + \mu$ events. Since the events are chosen close to the Z peak, they are mostly expected to have a Z boson and a fake lepton. The events are required to have a pair of the same flavor, oppositely charged leptons with $p_T > 26/20 \text{ GeV}$, passing the tight selection criteria. These leptons form the Z candidate and are the **tag** pair. An additional lepton is required to pass the loose selection criteria described above. This third lepton is used as the **probe** lepton for fake rate measurement.

In order to reduce the contribution from photon (asymmetric) conversions populating low masses, the fake rates/ratios are evaluated using the tight requirement $|M_{inv}(l_1, l_2) - M_z| < 10 \text{ GeV}$. The fake rates are measured in bins of the transverse momentum of the loose lepton in the barrel and endcap region. For 2016, 2017 and 2018 data, the electron and muon fake rates are measured within $|M_{inv}(l_1, l_2) - M_z| < 10$ and $E_T^{miss} < 20 \text{ GeV}$ separately for each year. Figure 7.13 shows the comparison between data and MC backgrounds as a function of p_T of the probe muon in the control region, using 2017 data. Similarly, Figure 7.14 shows the comparison between data and MC backgrounds as a function of p_T of the probe electron in the control region, using 2017 data. Figures 7.15 and 7.16 show the comparison of data-driven jet faking muon/electron efficiency as a function of muon/electron p_T with different muon isolation or electron id requirements.

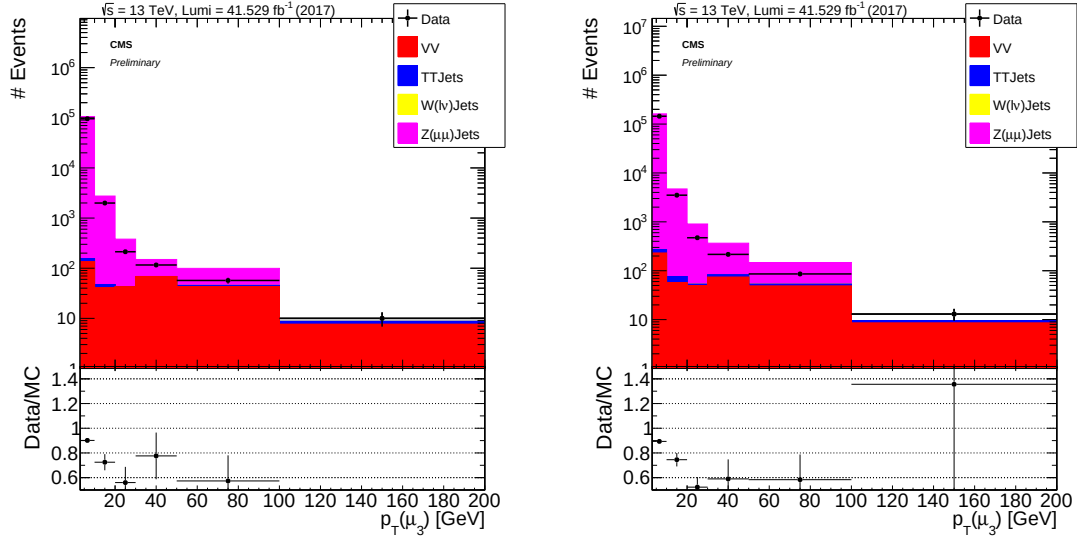


Figure 7.13: Comparison between 2017 data and simulation with the tight requirement $|M_{inv}(\mu_1, \mu_2) - M_Z| < 10$ GeV, and additional μ_3 with isolation < 0.15 (left) and with isolation < 0.4 (right).

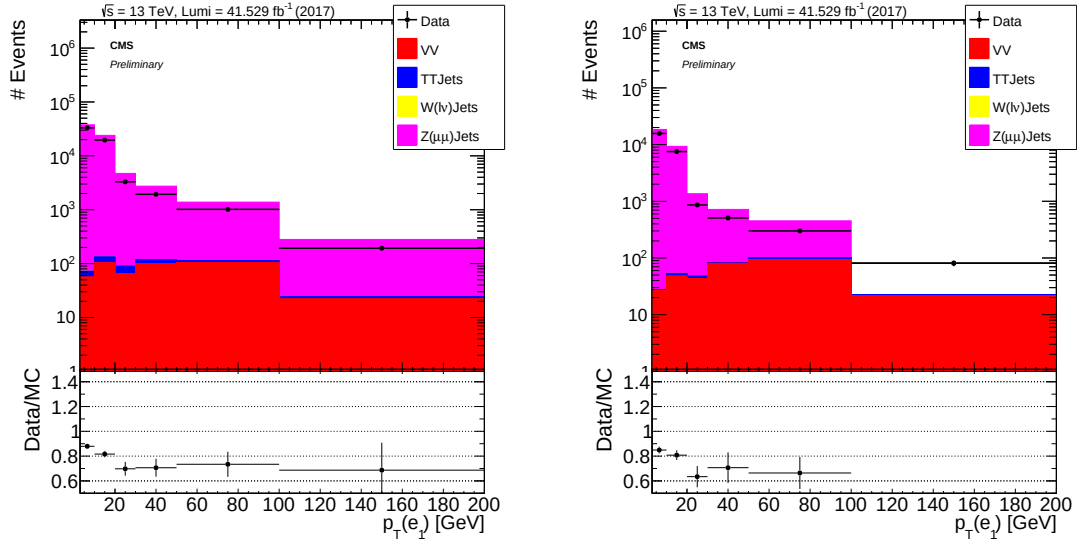


Figure 7.14: Comparison between 2017 data and simulation with the tight requirement $|M_{inv}(\mu_1, \mu_2) - M_Z| < 10$ GeV, and additional electron with loose electron ID (left) and with veto electron ID while isolation < 0.6 (right).

The background estimation involves declaring two control samples as subsets of the four leptons passing the first (a) selection step. The first a step consists in finding a pair of the same flavored, oppositely charged leptons(muons) that pass the d_{xy} and d_z cuts and is consistent with coming from an a decay. After identifying the di-muon pair coming from the a decay, one can now impose conditions on the remaining lepton pair to declare the control samples.

In order to define the first control sample, two additional leptons are searched for beyond the dimuon pair, which do not form an a candidate and do not pass the final selection criteria. The sample is termed as the “2Prompt + 2 Fail” (**2P + 2F**) sample. This sample is expected to be populated by events which intrinsically have 2 prompt leptons (QCD multi-jets and a small fraction of DY , $t\bar{t}$ and $Z\gamma$ events).

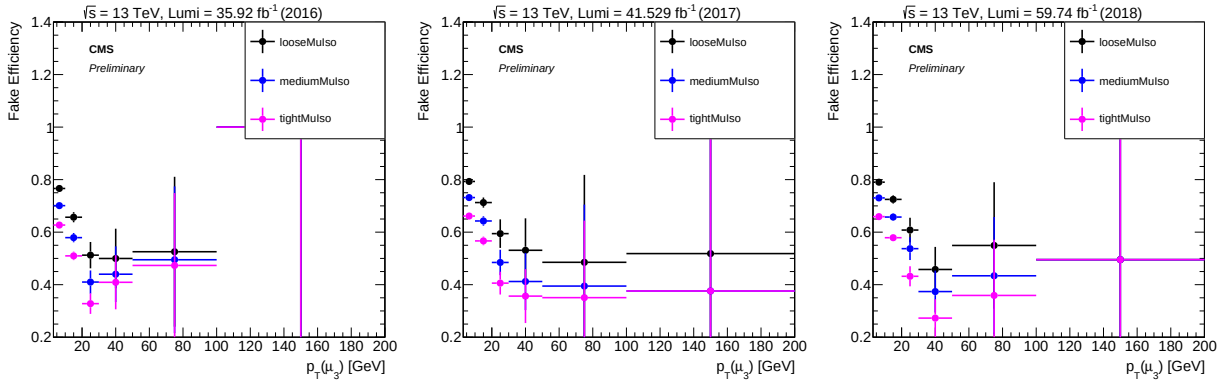


Figure 7.15: Fake rates as a function of the probe p_T for muons which satisfy the loose selection criteria, measured in a $Z(\ell\ell)+\ell$ sample in the 2016 (left), 2017 (middle), 2018 (right) data at 13 TeV. Comparison of data with tight requirement $|M_{inv}(\mu_1, \mu_2) - M_Z| < 10$ GeV, and an additional μ_3 with different isolation requirements.

The second control sample is defined by requiring one of the four leptons to be fake. One of the four leptons does not pass the final selection criteria. The sample is denoted as “3 Prompt + 1 Fail” (**3P + 1F**) sample. Consequently, the other three leptons, including the dimuon pair and another lepton, should pass the final selection criteria. This sample is expected to be filled with events that already populate the 2P + 2F region, with different relative proportions, along with some WZ events that primarily have three prompt leptons.

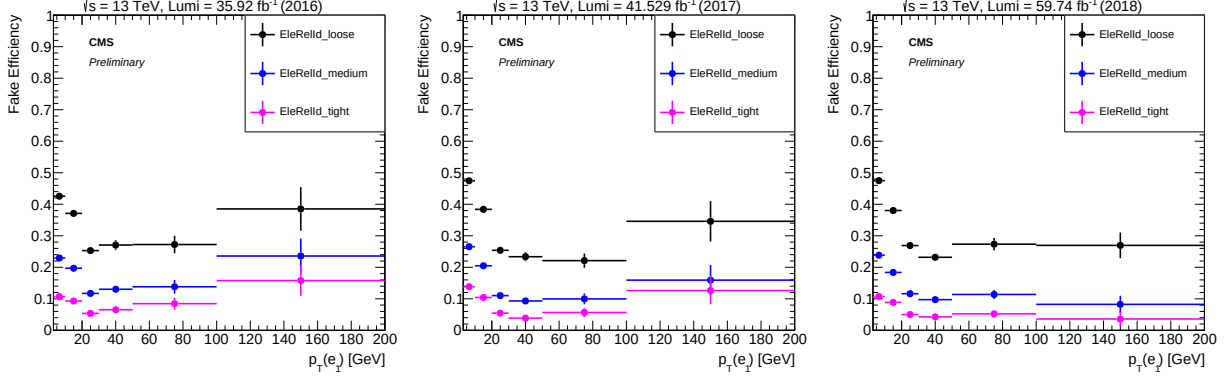


Figure 7.16: Fake rates as a function of the probe p_T for electrons which satisfy the loose selection criteria, measured in a $Z(\ell\ell)+\ell$ sample in the 2016 (left), 2017 (middle), 2018 (right) data at 13 TeV. Comparison of data with tight requirement $|M_{inv}(\mu_1, \mu_2) - M_Z| < 10$ GeV, and an additional electron with different electron IDs.

The control regions described above are enriched in fake leptons and are used to estimate the contribution of reducible background in the signal region. These regions are also orthogonal to the signal regions by construction. The invariant mass distribution of events selected in the 2P+2F control sample is shown in Figures 7.17 and 7.18.

The expected number of reducible background events in the 3P+1F region, N_{3P1F}^{bkg} , can be computed from the number of events observed in the 2P+2F control region, N_{2P2F} , by weighting each event in the region with the factor $(\frac{f_i}{1-f_i} + \frac{f_j}{1-f_j})$, where f_i and f_j correspond to the fake rates of the two loose leptons:

$$N_{3P1F}^{bkg} = \sum (\frac{f_i}{1-f_i} + \frac{f_j}{1-f_j}) N_{2P2F} \quad (7.1)$$

Figures 7.19 and 7.20 show the invariant mass distributions of the events selected in the 3P+1F control sample, together with the expected reducible background estimated from Eq. 7.1, stacked on the distribution of WZ and of irreducible background ($ZZ, Z\gamma^* \rightarrow 4\ell$) taken from the simulation.

If the measured fake rates were from a sample with the same background composition as 2P+2F, a fair agreement would be expected between the observed number of events 3P+1F and the expected background predicted from the 2P+2F sample. And the difference could be

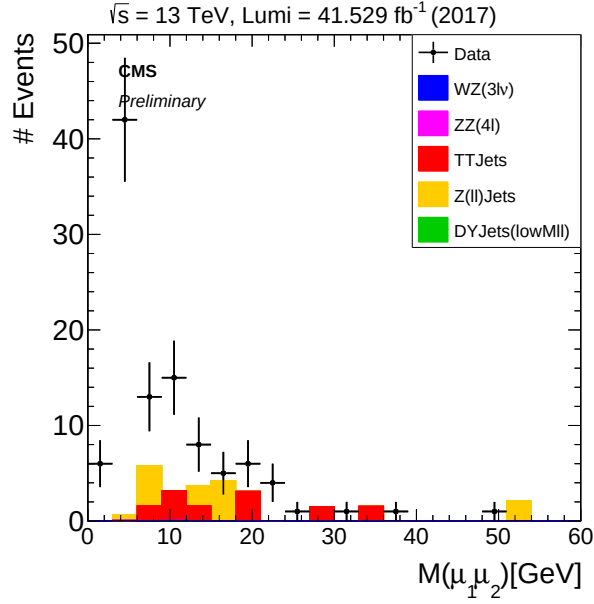


Figure 7.17: Dimuon invariant mass distribution of the events selected in the 2P+2F control sample in the 2017 dataset for the $\mu\mu\tau_\mu\tau_e$ channel.

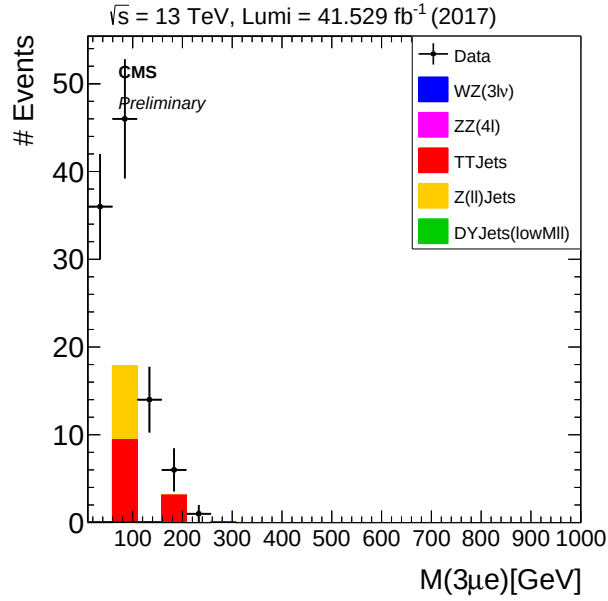


Figure 7.18: Four-lepton invariant mass distribution of the events selected in the 2P+2F control sample in the 2017 dataset for the $\mu\mu\tau_{\mu e}\tau_e$ channel.

attributed to the contribution from WZ (small) and $Z\gamma_{conv.}$. Instead a substantial difference is observed in the 3P+1F observed events and background prediction from the 2P+ 2F sample, primarily because the fake rates calculated from 7.1 do not account for the background composition of the 2P+2F sample.

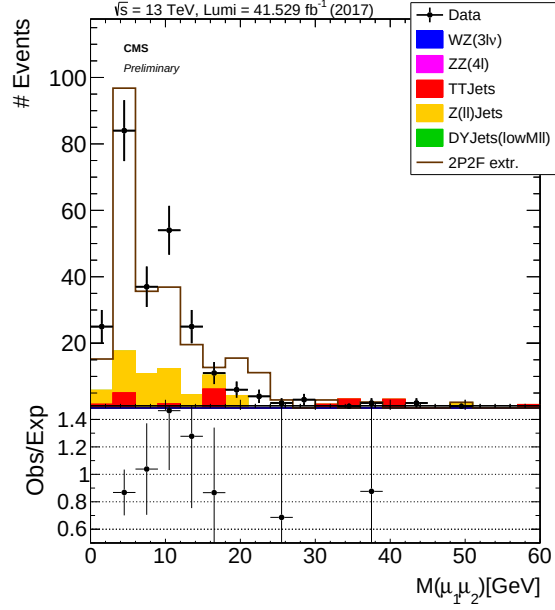


Figure 7.19: Dimuon invariant mass distribution of the events selected in the 3P+1F control sample in the 2017 dataset for all the considered channels: 4μ (left), $2\mu 2e$ (middle) and $3\mu e$ (right).

Incidentally, the difference between the data observed in the 3P + 1F region and the prediction from the 2P+2F region can be used to recover missing contributions from photon conversions. When calculating the reducible background in the signal region, one can use the difference mentioned above as a correction factor to account for the inability of fake rates to represent the background composition of the 2P+2F region.

Thus the expected reducible background in the signal region receives contribution from two terms corresponding to two control samples. They are:

- **“2P+2F component”** - This component is obtained from the number of events observed in the 2P+2F control region N_{2P2F} . Each event is weighted by a factor $\frac{f_i}{1-f_i} \frac{f_j}{1-f_j}$, where f_i and f_j are the fake rates of the non-prompt/ Fail leptons.

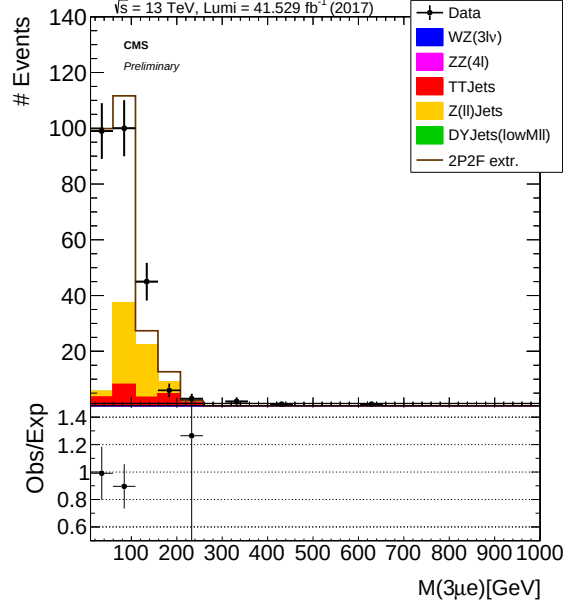


Figure 7.20: Four-lepton invariant mass distribution of the events selected in the 3P+1F control sample in the 2017 dataset for the $\mu\mu\tau\mu\tau_e$ channel.

- **“3P+1F component”** - This is obtained from the difference between the number of observed events in the 3P+1F control region, N_{3P1F} , and the expected contribution from the 2P+2F region and ZZ processes in the signal region, $N_{3P1F}^{ZZ} + N_{3P1F}^{bkg}$. The N_{3P1F}^{bkg} is given by Eq. 7.1 and N_{3P1F}^{ZZ} is the contribution from ZZ which is taken from the simulation. The difference $N_{3P1F} - N_{3P1F}^{bkg} - N_{3P1F}^{ZZ}$, which may be negative, is obtained for each (p_T, η) bin of the “F” lepton, and is weighted by $\frac{f_i}{1-f_i}$, where f_i denotes the fake rate of this lepton. This “3P1F component” accounts for the contribution of reducible background processes with only one fake lepton (like WZ events), and for the contribution of other processes (e.g., photon conversions) that are not properly estimated by the 2P2F component, because of the fake rates used.

Therefore, in terms of the lepton fake rates and event number in every control region, the background prediction in the signal region is given by :

$$N_{SR}^{bkg} = \sum \frac{f_i}{(1-f_i)} (N_{3P1F} - N_{3P1F}^{bkg} - N_{3P1F}^{ZZ}) + \sum \frac{f_i}{(1-f_i)} \frac{f_j}{(1-f_j)} N_{2P2F} \quad (7.2)$$

This equation is implemented on each of the full-leptonic final states.

The invariant mass distribution of the predicted events obtained from the combination of the results in the 2P+2F and 3P+1F control samples are shown in Figures 7.21 and 7.22.

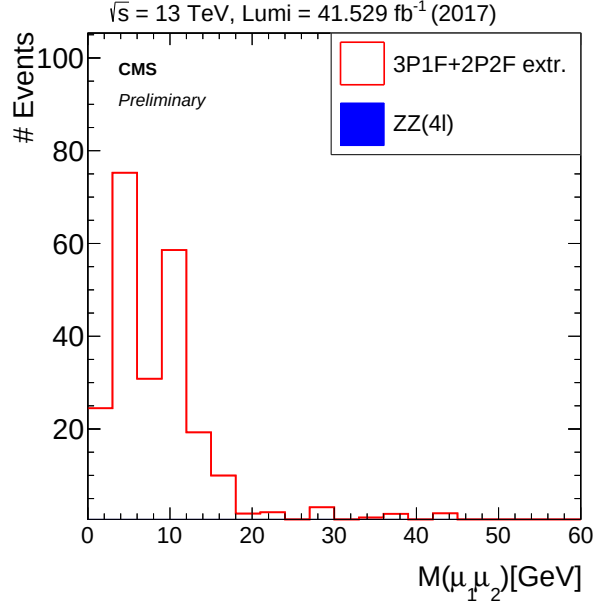


Figure 7.21: Dimuon invariant mass distribution of the events extrapolated in the signal region in the 2017 dataset for the $\mu\mu\tau_\mu\tau_e$ channel.

7.7.2 Semi-leptonic final states

As mentioned above, the background estimation technique for the semi-leptonic decay channels ($\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$) is similar.

The primary source of background for semi-leptonic final states is Drell-Yan ($Z \rightarrow \mu\mu$) associated with jet(s). Where the Drell-Yan fakes the dimuon pair, and the jet fakes the ditau pair coming from the other pseudoscalar ($a \rightarrow \tau_e\tau_h/\tau_\mu\tau_h$).

The background is reduced by carrying out the ditau reconstruction such that only the prominent dimuon resonances within the mass range considered in the analysis can contribute. The known dimuon resonances between mass range of 3.6 and 25 GeV are : ψ' ($m_{\psi'} = 3.69$ GeV), $Y(1S)$ ($m_{Y(1S)} = 9.46$ GeV), $Y(2S)$ ($m_{Y(2S)} = 10.0$ GeV), and $Y(3S)$ ($m_{Y(3S)} = 10.4$ GeV).

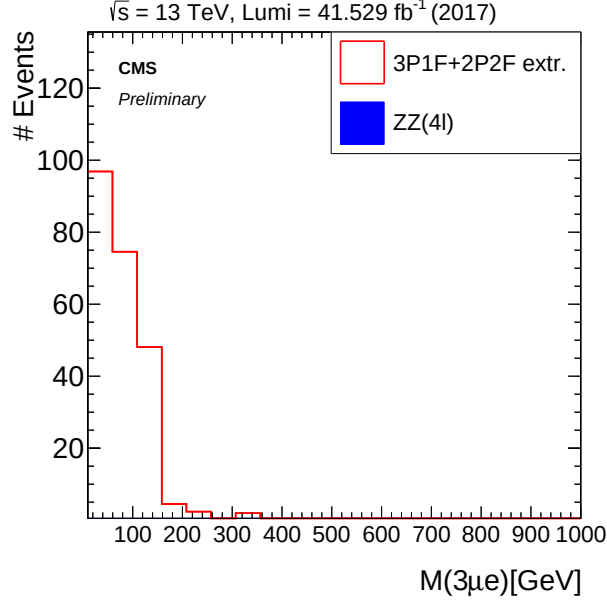


Figure 7.22: Four-lepton invariant mass distribution of the events extrapolated in the signal region in the 2017 dataset for the $\mu\mu\tau_\mu\tau_e$ channel.

When a (background) distribution of reconstructed dimuon invariant mass $m(\mu, \mu)$ is made, the known resonances mentioned above would appear as bumps on the Drell-Yan continuum. In the 4-body visible mass distribution for both the semi-leptonic channels ($m(\mu\mu\tau_e\tau_h), m(\mu\mu\tau_\mu\tau_h)$), the dimuon + jet background appears as an exponentially falling distribution with turn on around 40 – 60 GeV. The turn on in the distribution is due to the transverse momentum thresholds of the reconstructed muons (and/or electrons) and the reconstructed hadronically decaying tau.

The signal on the other hand can be characterized by a narrow bump on the dimuon invariant mass spectrum at the pseudoscalar mass due to the decay of the pseudoscalar and a broader resonance on the 4-body visible mass distribution.

The search strategy involves fitting $m(\mu\mu)$ against $m(\mu\mu\tau\tau)$ in 2D with analytical models. The fitting is done for signal and background shapes in each dimension. The fitting procedure is described later in section 7.8. The background shape model for the Drell-Yan continuum, the meson resonances mentioned above, and additionally the J/ψ ($m_{J/\psi} = 3.10$

GeV) resonance comes from a data control region enriched in dimuon + jet events (the “sideband” region described below and in Sec. 7.8).

Jet $\rightarrow \tau_\mu\tau_h/\tau_e\tau_h$ fake rate . The aim is to calculate the probability of a jet being misidentified as a τ_h for both the $\tau_\mu\tau_h/\tau_e\tau_h$. The fakeable object method is used to estimate the contribution of misidentified objects (jets misidentified as τ_h) in the signal region.

Four regions are defined based on the status of dimuon and ditau isolation. The isolation of the non-triggering muon is inverted to define the anti-isolated dimuon region. Similarly, an anti-isolated ditau region is defined by inverting the hadronic tau isolation. The anti-isolated dimuon region is called the **sideband** (Region B) while the fully isolated region is called the **signal region** (Region A).

Region B is used to predict the normalization of the background in Region A. A majority of the events that form the background in Region B are mostly dimuon resonances with a jet and muon, which are misreconstructed as a $\tau_\mu\tau_h/\tau_e\tau_h$ pair. The primary source of background in this case are Low-mass dimuon resonances.

A Z + jets sample is to estimate the fake rates of jets to ditau objects. The fake rate is obtained from events that pass the Z control region selections (close to the Z peak). The fake rates are estimated using a data-driven method as the simulation is not sufficient to account for the distribution in data after all the selections. The fake rates are thus calculated in data after the residual contribution from diboson processes is subtracted. The residual contribution of diboson is estimated in simulation.

The fake rates are calculated as a function of p_T (8-20 GeV, 20-30 GeV, 30-50 GeV, 50-100 GeV, and >100 GeV). The fake rates are additionally divided by decay mode (0,1 and 10). Figures 7.23 and 7.24 show these tau fake rates. The statistics become poor at high p_T region.

The fakerate method is applied to region B to estimate the background in region A. The full analysis selections are applied to construct regions A and B. A single event in region B will then contribute a weight

$$\frac{f_\tau}{1 - f_\tau} \tag{7.3}$$

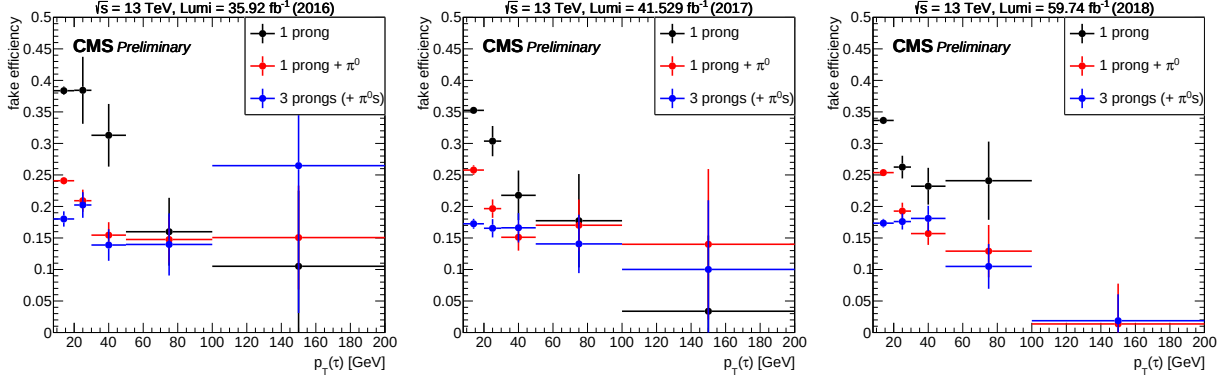


Figure 7.23: The tau fake rates used in estimating the signal region for $\tau_\mu\tau_h$ pair, using 2016 (left), 2017 (middle), and 2018 (right) data. The denominator consists of "jets" selected as a muon cleaned tau from the HPS algorithm passing "decayModeFinding". The numerator are the "jets" that pass the medium MVA isolation. Rates are separated by decay mode: DM0 (one prong), DM1 (one prong + π^0), and DM10 (3 prongs + π^0 s).

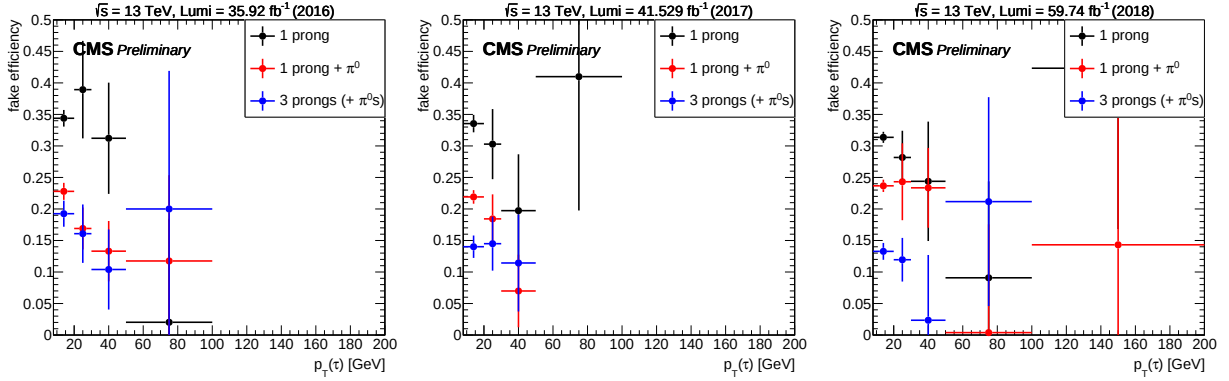


Figure 7.24: The tau fake rates used in estimating the signal region for $\tau_e\tau_h$ pair, using 2016 (left), 2017 (middle), and 2018 (right) data. The denominator consists of "jets" selected as a electron cleaned tau from the HPS algorithm passing "decayModeFinding". The numerator are the "jets" that pass the medium MVA isolation. Rates are separated by decay mode: DM0 (one prong), DM1 (one prong + π^0), and DM10 (3 prongs + π^0 s).

to region A, where f_τ is the fake efficiency for a jet to fake a tau. The total background contribution to the signal region is then:

$$N_A^{exp} = \frac{f_\tau}{1 - f_\tau} \cdot N_B, \quad (7.4)$$

where N_A^{exp} is the expected yield in a given bin of region A and N_B is the observed yield in a given bin of region B.

Fake estimate robustness checks. This fake rate method is validated in the two anti-isolated muon regions: regions C and D. The data in region C itself is compared to an estimate of region C by applying the tau fake rate to region D data. Plots of this comparison are shown. The uncertainties on these plots include the statistical uncertainty from the sideband and the uncertainty on the fake rate values from the fake rate measurement control regions.

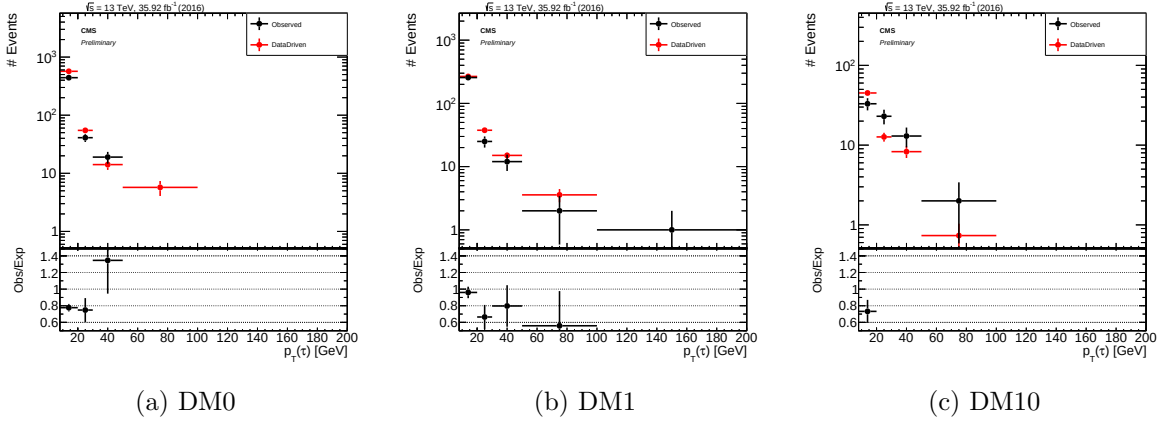


Figure 7.25: Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_\mu\tau_h$ channel, using 2016 data. Additionally, total events are split by decay mode.

With this validation, it is shown that there is some discrepancy between the expected background from the datadriven method and the observed yields in Region C.

The above calculation makes the assumption the prompt efficiency is 1. That is, the efficiency for a real tau or muon to enter the signal region is 1. This is not the case. Because

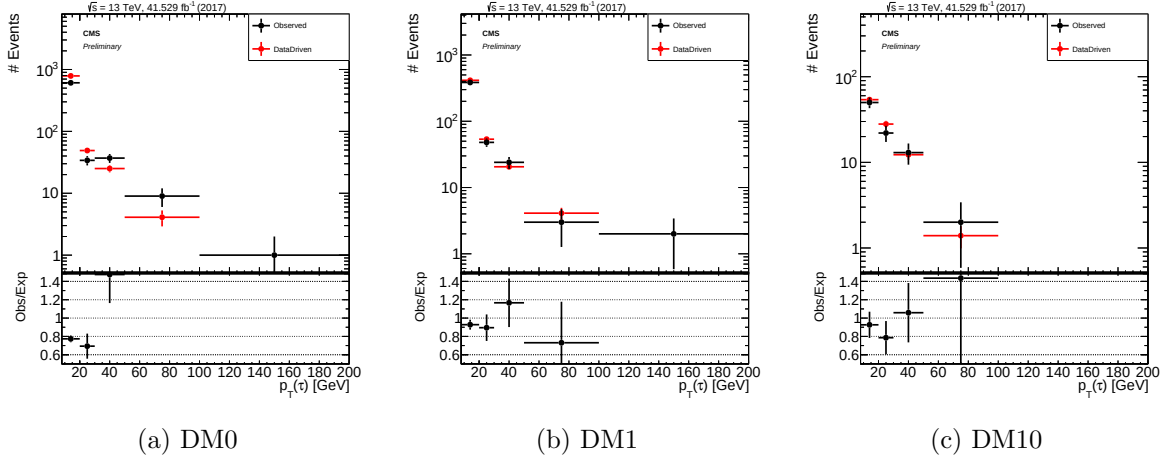


Figure 7.26: Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_\mu\tau_h$ channel, using 2017 data. Additionally, total events are split by decay mode.

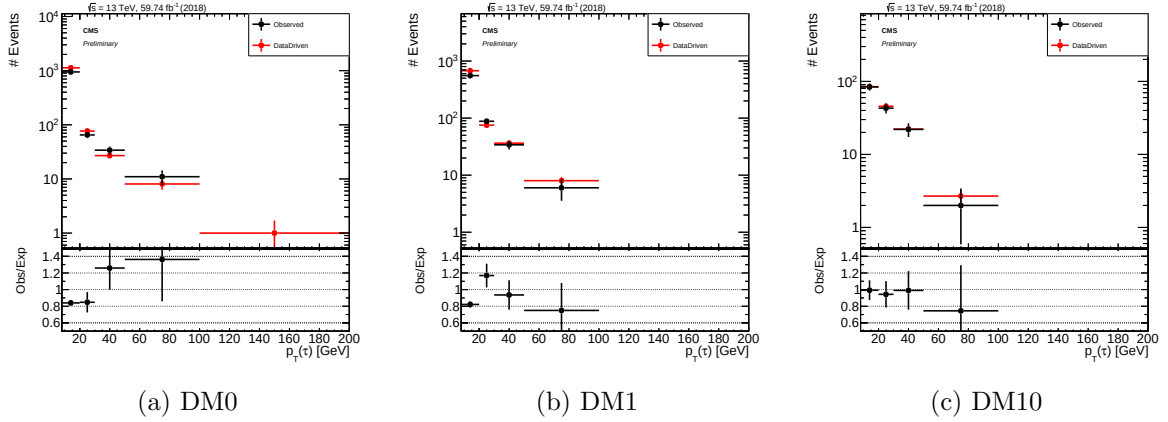


Figure 7.27: Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_\mu\tau_h$ channel, using 2018 data. Additionally, total events are split by decay mode.

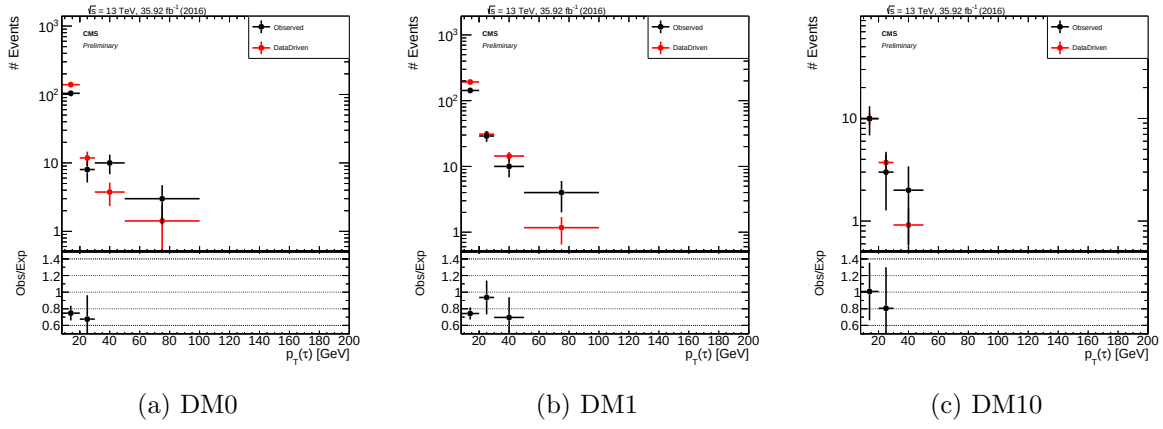


Figure 7.28: Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_e\tau_h$ channel, using 2016 data. Additionally, total events are split by decay mode.

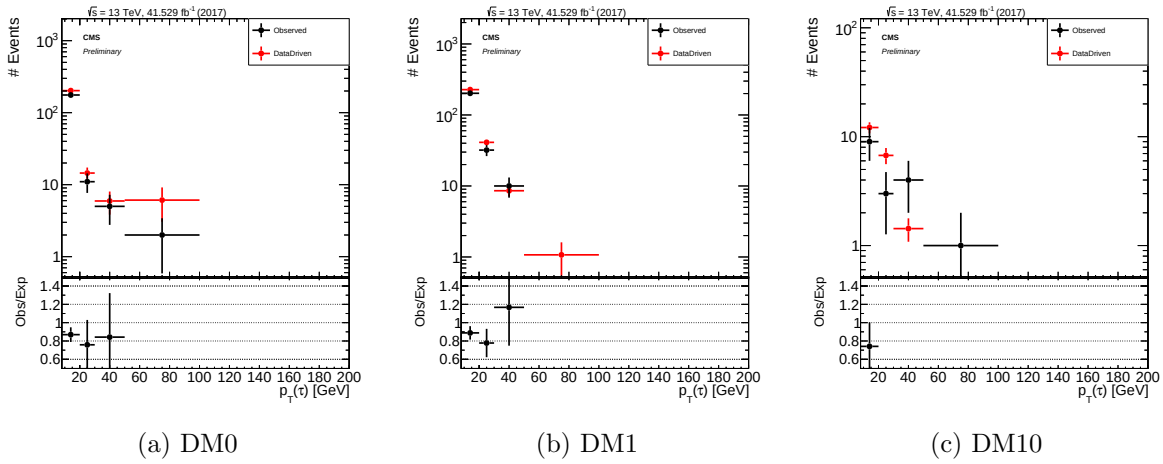


Figure 7.29: Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_e\tau_h$ channel, using 2017 data. Additionally, total events are split by decay mode.

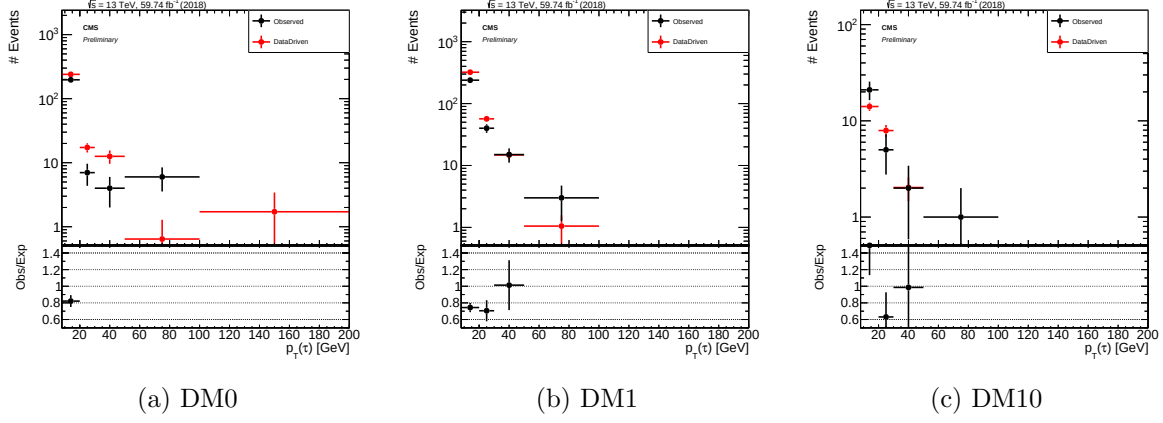


Figure 7.30: Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_e\tau_h$ channel, using 2018 data. Additionally, total events are split by decay mode.

of this, there will be some signal contribution to the sideband and will be handled by a simultaneous fit of the signal region and sideband.

Fake rate uncertainty estimate. The fake rate uncertainty is pretty similar to the fake rate robustness check that it is performed in the two anti-isolated muon regions: regions C and D. We apply the fake rate to the region C (validation sideband) and obtain a **datadriven** estimate. The datadriven estimate is compared to the **observed** data in region D (validation region). All the tau decay modes are combined together in this estimation to get for statistics. When looking at the discrepancy, the low p_T taus are mostly considered as we have more statistics in low p_T regions. The low p_T bins are mostly considered in order to add a value to the fake rate uncertainty. Figures 7.31 and 7.32 show the fake rate uncertainties for $\tau_\mu\tau_h$ and $\tau_e\tau_h$ channels. Looking at the first three low p_T bins in each case, a value of 20% is chosen for the discrepancy.

7.7.3 Fully hadronic final state

The main source of background in this channel is also Drell-Yan dimuon production in association with at least one jet that fakes the $\tau_h\tau_h$ decay. The method to estimate and

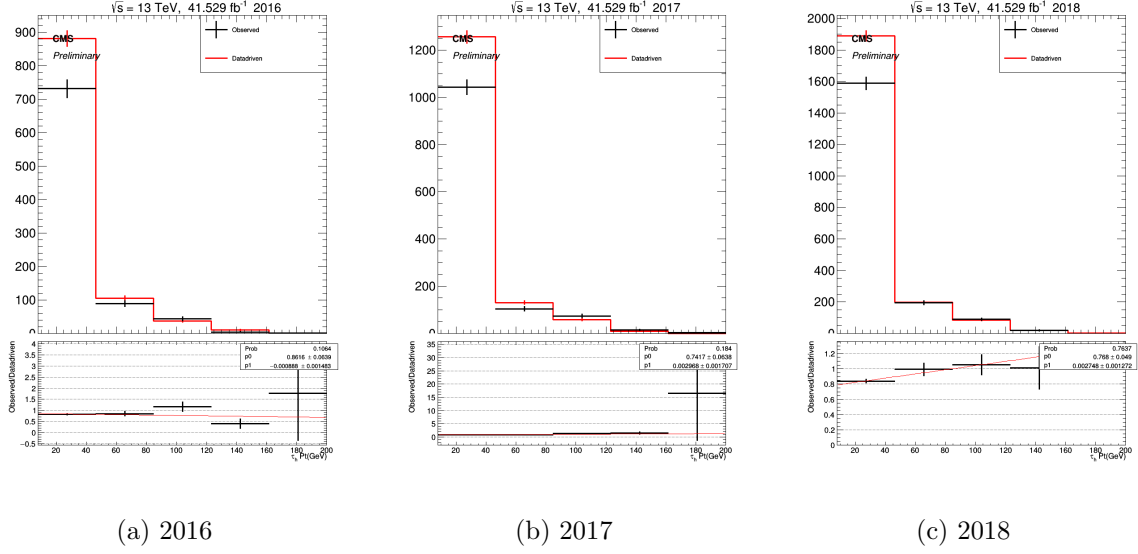


Figure 7.31: Fake rate uncertainty estimation for in $\tau_\mu \tau_h$ channel, using 2016, 2017, and 2018 data. All decay modes are added and discrepancy compared in low p_T regions.

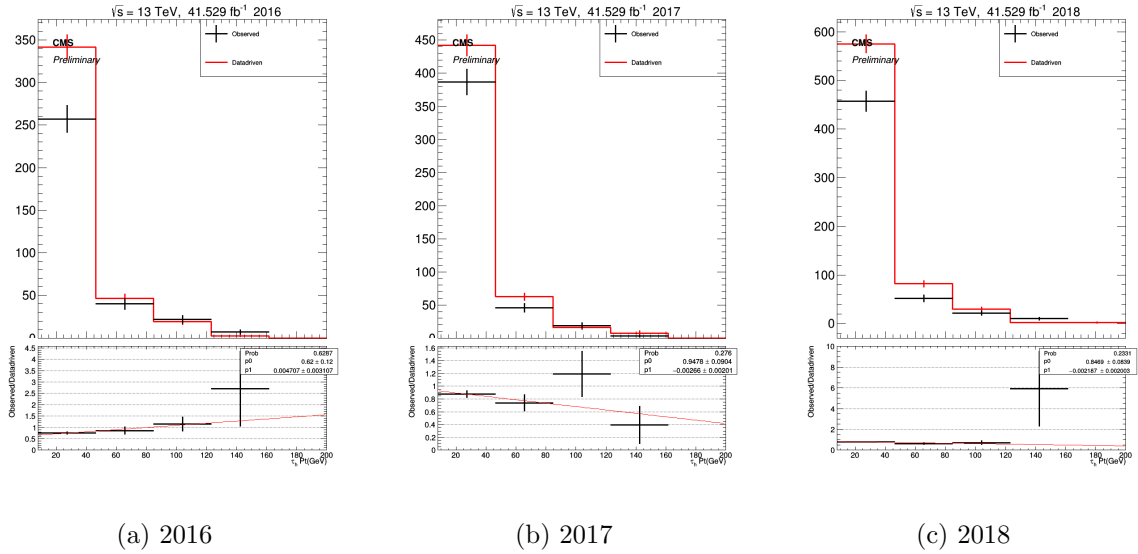


Figure 7.32: Fake rate uncertainty estimation for in $\tau_e \tau_h$ channel, using 2016, 2017, and 2018 data. All decay modes are added and discrepancy compared in low p_T regions.

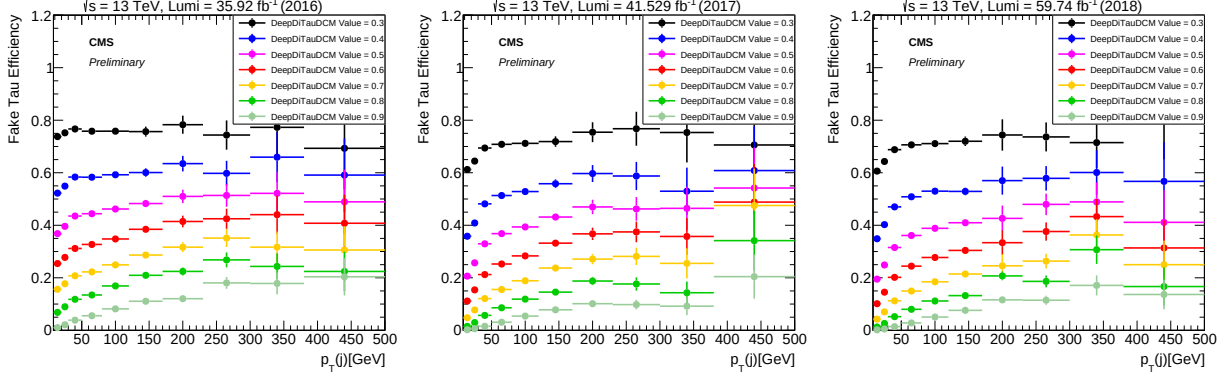


Figure 7.33: The fake rates used in estimating the signal region for $\tau_h\tau_h$ pair, using 2016 (left), 2017 (middle), and 2018 (right) data. The denominator consists of a reconstructed jet selected with very loose working point (0.2) of “DeepDiTau” discriminator. The numerator are having a “jet” that pass the different customized working points of “DeepDiTau” discriminator.

validate the main background is similar to Sec. 7.7.2. A Z+jet sample is obtained from the events passing the Z control region selections.

The fake rates are calculated in data with the residual contribution from diboson, $t\bar{t}$, and W+jets processes subtracted as estimated in simulation.

The fake rates are calculated as a function of p_T (8-20 GeV, 20-30 GeV, 30-50 GeV, 50-80 GeV, 80-120 GeV, 120-170 GeV, 170-230 GeV, 230-300 GeV, 300-380 GeV and >380 GeV).

The fake rates are compared by use of different working points of the “DeepDiTau” discriminators applied to the leading jet. Figure 7.33 show these fake rates as a function of the leading jet p_T .

Fake estimate robustness checks. Similar to Sec. 7.7.2, this fake rate method is validated in the two anti-isolated muon regions: regions C and D. The data in region C itself is compared to an estimate of region C by applying the tau fake rate to region D data. Plots of this comparison are shown in figure 7.34. The uncertainties on these plots include the statistical uncertainty from the sideband and the uncertainty on the fake rate values from the fake rate measurement control regions.

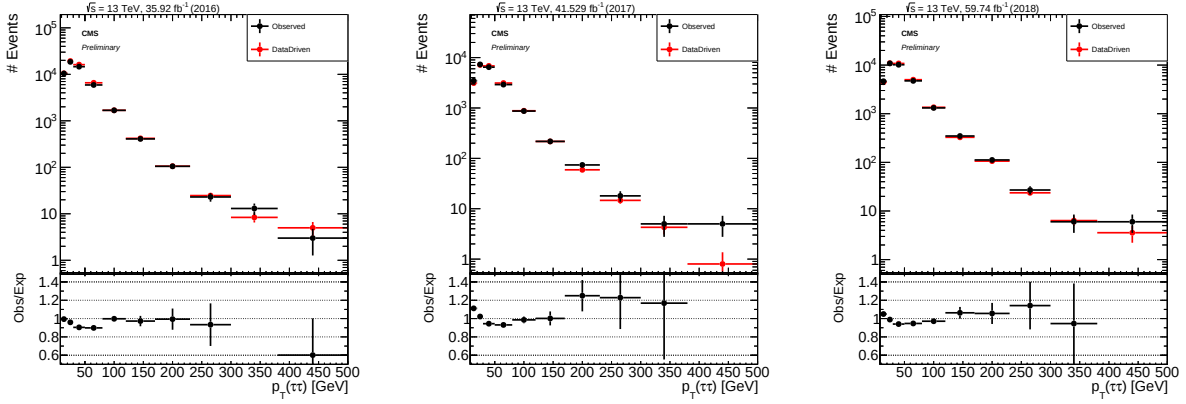


Figure 7.34: Kinematic comparisons between region C and region C estimation from region D using the fake rate method in $\tau_h \tau_h$ channel, using 2016 (left), 2017 (middle), and 2018 (right) data.

7.8 Fitting Strategy

Parametric functions are used to model the background in this analysis. The parametric fit allows one to extract the upper limit on signal confidence interval or the signal significance.

Dedicated studies determined different models to be most performant for different final states. The most performant model for the fully leptonic final states was determined to be a 1-dimensional fit of the dimuon invariant mass. The best model for the fully hadronic and semi-leptonic final states was a 2-dimensional fit of the dimuon invariant mass and visible 4-body mass. Different PDFs are used for both models to fit the signal and the background.

The signal is fit using a Voigtian PDF for the dimuon invariant mass fit. Using the parameters of the Voigtians for each of the generated signal samples, an extrapolation is performed between the signal mass points. In order to model the background, it is necessary to model the falling continuum as well as the Y resonances and the J/ψ resonances. The sum of 2 exponential is used to model the continuum. 3 Voigtians are used to model the Y resonances along with two Voigtians to model the J/ψ resonances.

In order to fit the signal for visible 4-body mass, it is necessary to take into account the smearing effect that happens as a result of the loss of neutrinos. Therefore, a double-sided Gaussian PDF is used to fit the signal. The parameters of the double-sided Gaussian for

each of the generated signal samples is used to extrapolate between the signal mass points. In order to model the background a convolution of an error function and the sum of two exponential is used.

The following section will describe the background fitting procedure for fully leptonic, fully hadronic, and semi- leptonic final states.

7.8.1 Fit for the fully leptonic final states

The same fitting strategy is used for fully leptonic final states like $\mu\mu\tau_\mu\tau_\mu$, $\mu\mu\tau_\mu\tau_e$ and $\mu\mu\tau_e\tau_e$. A simultaneous fit is performed for the signal and control regions. The control region is described by the presence of two muons close to the Z peak and no requirement of the ditau object. The histogram representing the background contribution in the signal region is estimated using the procedure described in section 7.7.

The dimuon resonance (J/ψ and Υ) parameters like the mean, sigma, width, and relative normalization are shared between the signal and the control regions. The parameters are set to the same value in the two regions and thus relate the signal region to the control region. A binned fit of the control region is performed to determine the initial value of the parameters. The parameters for the continuum background are allowed to float freely in both regions. Initial values for the freely floating parameters are set via a binned prefit procedure (i.e., before passing the workspace to the combine tool with the datacard).

In order to account for the correlation between the dimuon and visible 4-body masses the fit is split into different dimuon mass regions. The fit is split into 3 regions of dimuon invariant mass: a low mass region with $m(\mu\mu) < 8.5$ GeV, a region around the Y resonance with $8.6 < m(\mu\mu) < 11.5$ GeV and a high mass region with $m(\mu\mu) > 11.5$ GeV. Each region has the y component parameters of the background model corresponding to the visible 4-body mass left freely floating and independent of each other.

The fitting procedure is as follows:

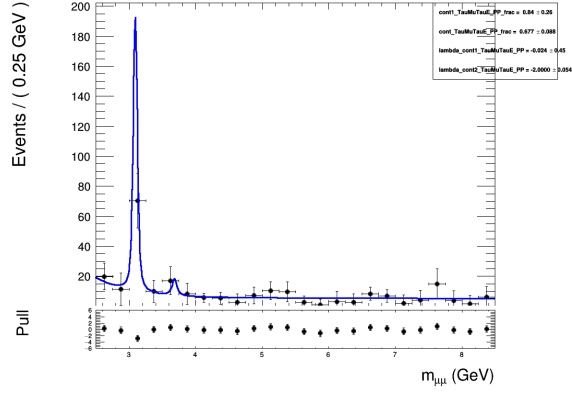
1. Construct the control region PDF of 5 resonances over a double exponential continuum
2. Fit the control region

3. Fix the parameters of the resonances and their relative normalizations
4. Construct the signal region PDFs (x PDF same as control, y PDF as described above)
5. Fit the signal region with systematic uncertainty shifted up and down (3 fits)
6. Unfix the parameters of the resonances and continuum and their relative normalizations
7. Set the parameters of the resonances to their best fit values (freely floating and shared between all regions)
8. Set the parameters of the continuum to their best fit values (freely floating in control region, allowed to float within the systematic uncertainty in the signal region) (TODO: subject for discussion)
9. Set the leading resonances' (J/ψ and Y 1S) normalizations to their best fit value in the control region and signal region (freely floating but separate parameters for each region)
10. Construct the parameters (3) for the relative normalizations between the leading resonance and sub-leading resonances with initial values set to those measured in the control region (freely floating and shared between all regions)
11. Set the subleading resonances' (ψ' and Y 2S and 3S) normalizations to the product of the relative normalization scale factors and the respective leading resonance normalization
12. Construct the signal region normalizations with values floating within the systematic uncertainty

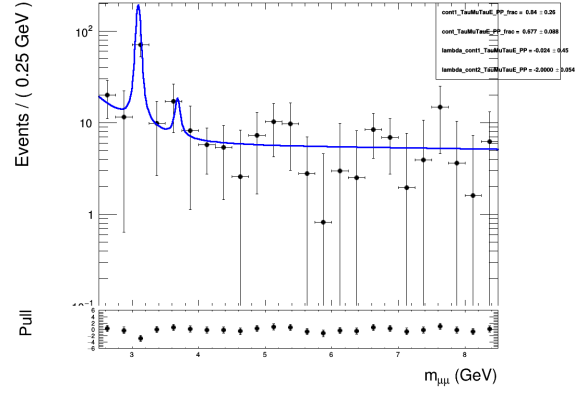
The prefit distributions for the control region are shown in Fig. 7.36. The prefit distributions for the background prediction in the signal region for the $\tau_\mu\tau_e$ channel is shown in Fig. 7.35. The fitting is done for each of the 2016, 2017, and 2018 datasets separately. Only the 2017 results are shown here as an example.

7.8.2 Fit for semi-leptonic and fully hadronic final states

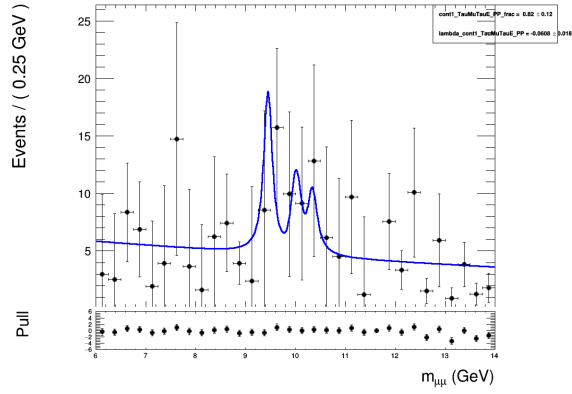
A similar fitting strategy is used for $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$ and $\mu\mu\tau_h\tau_h$ final states. The fitting strategy involves the simultaneous fit of the signal, sideband, and control region. The “signal



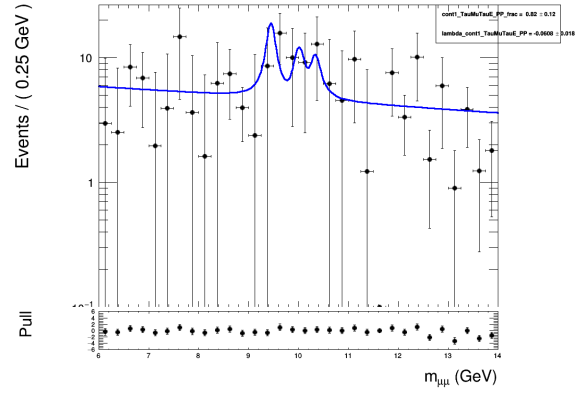
(a)



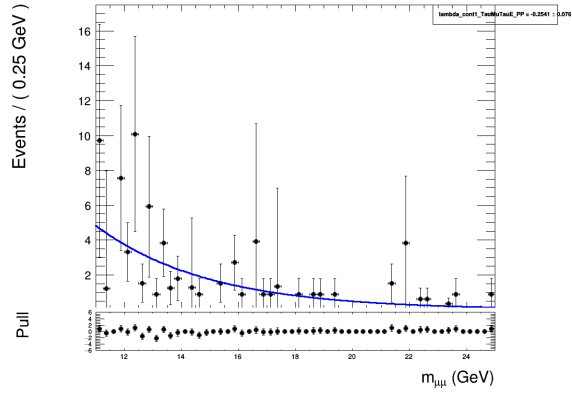
(b)



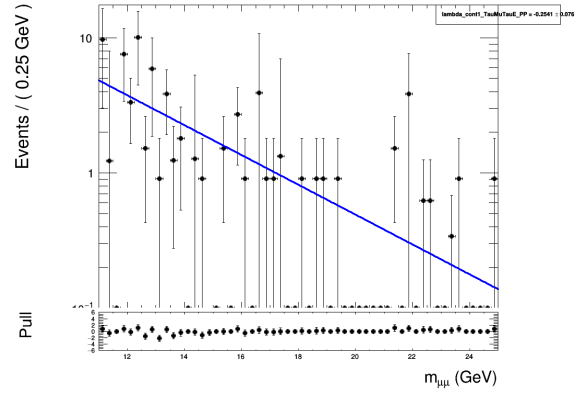
(c)



(d)



(e)



(f)

Figure 7.35: Prefit dimuon mass distributions for the signal region in the $\tau_\mu\tau_e$ final state.

region” requires a reconstructed ditau object with the hadronic tau passing the MVA isolation requirement. The “sideband” requires a ditau object, but in this case, the hadronic tau fails the MVA isolation requirement. On the other hand, the “control” region just requires the presence of a dimuon pair without any requirement on the ditau object. Taking out the muon isolation requirement for the second muon of the dimuon pair in the signal region creates the “validation region” and doing the same for the sideband forms the “validation sideband”. The validation region and the validation sideband are used to validate the background estimation applying transfer factors calculated in the control region. The transfer factors are applied on the sideband to obtain background estimation in the signal region.

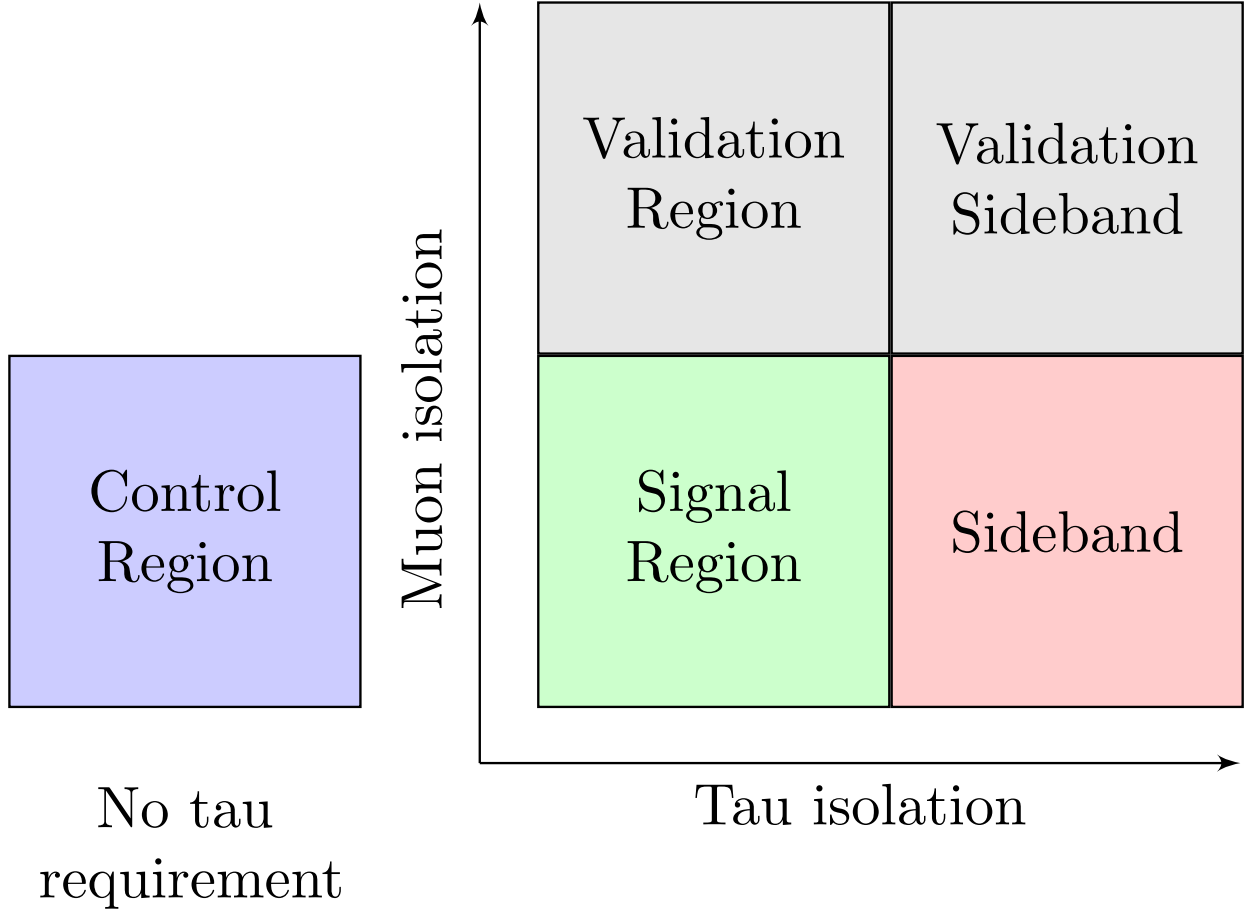
The signal and the control region share the same parameters for the dimuon resonances (J/ψ and Y). The parameters are, for instance, the mean, width, sigma, and relative normalization. A binned fit of the control region is performed to obtain the initial values of the parameters. The parameters for the continuum background are allowed to float freely. Initial values for the freely floating parameters are set via a binned prefit procedure.

In account to for the correlation between the dimuon and visible 4-body masses the fit is split into different dimuon mass regions. The fit is split into 3 regions of dimuon invariant mass: a low mass region with $m(\mu\mu) < 8.5$ GeV, a region around the Y resonance with $8.6 < m(\mu\mu) < 11.5$ GeV and a high mass region with $m(\mu\mu) > 11.5$ GeV. Each region has the y component parameters of the background model corresponding to the visible 4-body mass left freely floating and independent of each other.

To account for a correlation between the dimuon and 4-body masses, the fits are split into 3 region of dimuon invariant mass: a low mass region with $m(\mu\mu) < 8.5$ GeV, a region around the Y resonances with $8.5 < m(\mu\mu) < 11.5$ GeV, and a high mass region with $m(\mu\mu) > 11.5$ GeV. Each region has the y component parameters of the background model corresponding to the 4-body invariant mass left freely floating and independent of each other

The fitting procedure in this case is as follows:

1. Construct the control region PDF of 5 resonances over a double exponential continuum
2. Fit the control region



(a)

Figure 7.37: Schematic of the fit regions in the semi-leptonic final states. Events with two isolated muons enter the control region (blue). Events which additionally have a ditau candidate are further divided on the isolation of the ditau object with isolated ditau candidates forming the signal region (green) and anti-isolated ditau candidates forming the sideband (red). Additionally, anti-isolating the dimuon candidates forms two analogous regions for the misidentification efficiency validation (gray).

3. Fix the parameters of the resonances and their relative normalizations
4. Construct the sideband and signal region PDFs (x PDF same as control, y PDF as described above)
5. Fit the sideband region
6. Fit the signal region with fake rate uncertainty shifted up and down (3 fits)
7. Unfix the parameters of the resonances and continuum and their relative normalizations
8. Set the parameters of the resonances to their best fit values (freely floating and shared between all regions)
9. Set the parameters of the continuum to their best fit values (freely floating in sideband and control region, allowed to float within the fake rate uncertainty in the signal region)
10. Set the leading resonances' (J/ψ and Υ 1S) normalizations to their best fit value in the control region and sideband region (freely floating but separate parameters for each region)
11. Construct the parameters (3) for the relative normalizations between the leading resonance and subleading resonances with initial values set to those measured in the control region (freely floating and shared between all regions)
12. Set the subleading resonances (ψ' and Υ 2S and 3S) normalizations to the product of the relative normalization scale factors and the respective leading resonance normalization
13. Construct the signal region normalizations with values floating within the fake rate uncertainty (central value fixed to the sideband normalizations via a scale factor measured during the initial fits)

The prefit distributions for the control region are same as above and shown in Fig. 7.36. The prefit distributions for the background prediction in the sideband region for the $\tau_e\tau_h$, $\tau_\mu\tau_h$, and $\tau_h\tau_h$ channels are shown in Fig. 7.38, Fig. 7.39, and Fig. 7.40 respectively. The fitting is done for each of the 2016, 2017, and 2018 datasets separately. Only the 2017 results are shown here as an example.

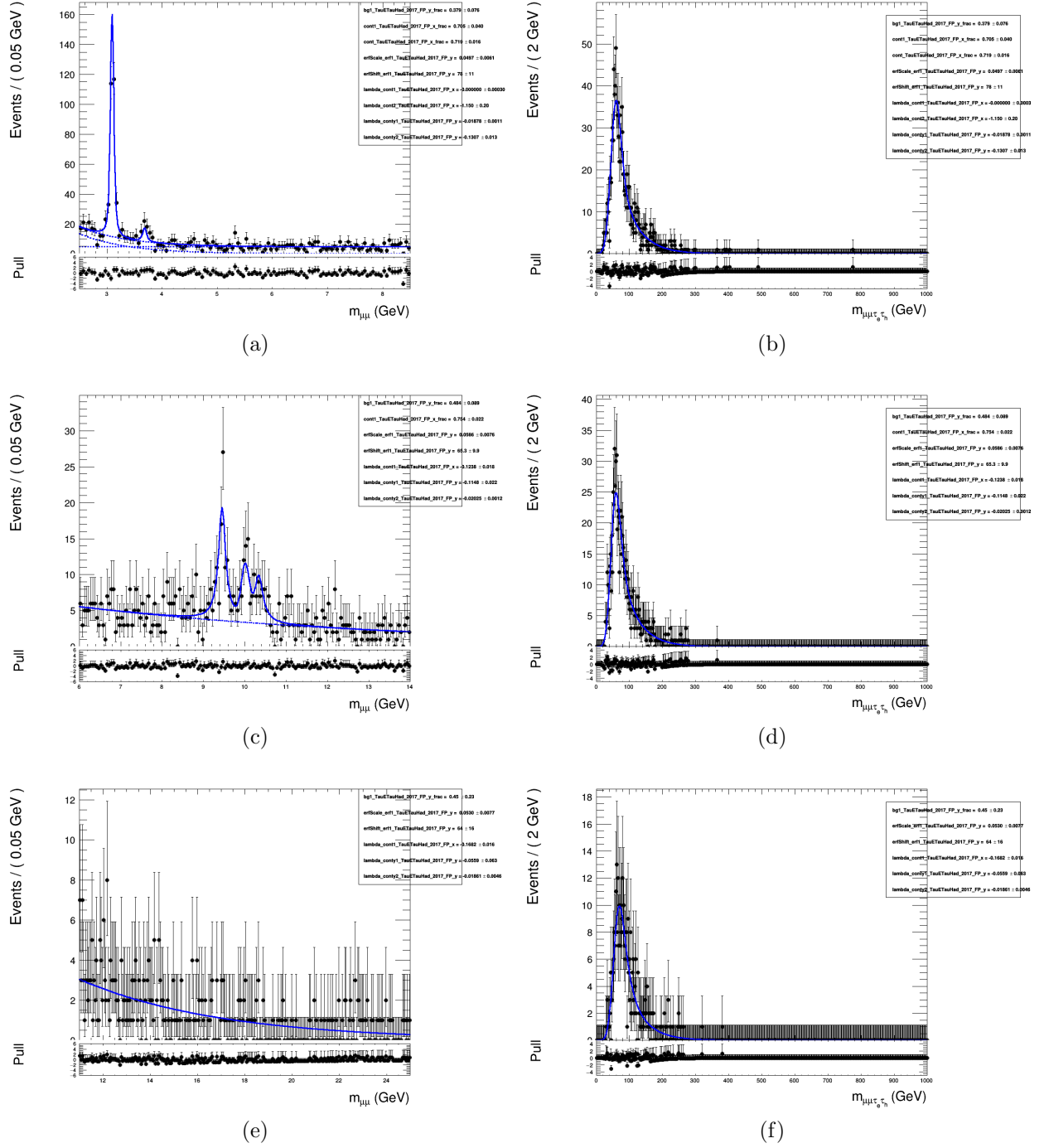


Figure 7.38: Prefit dimuon (left) and 4-body (right) visible mass distributions for the side-band region in the $\tau_e \tau_h$ final state.

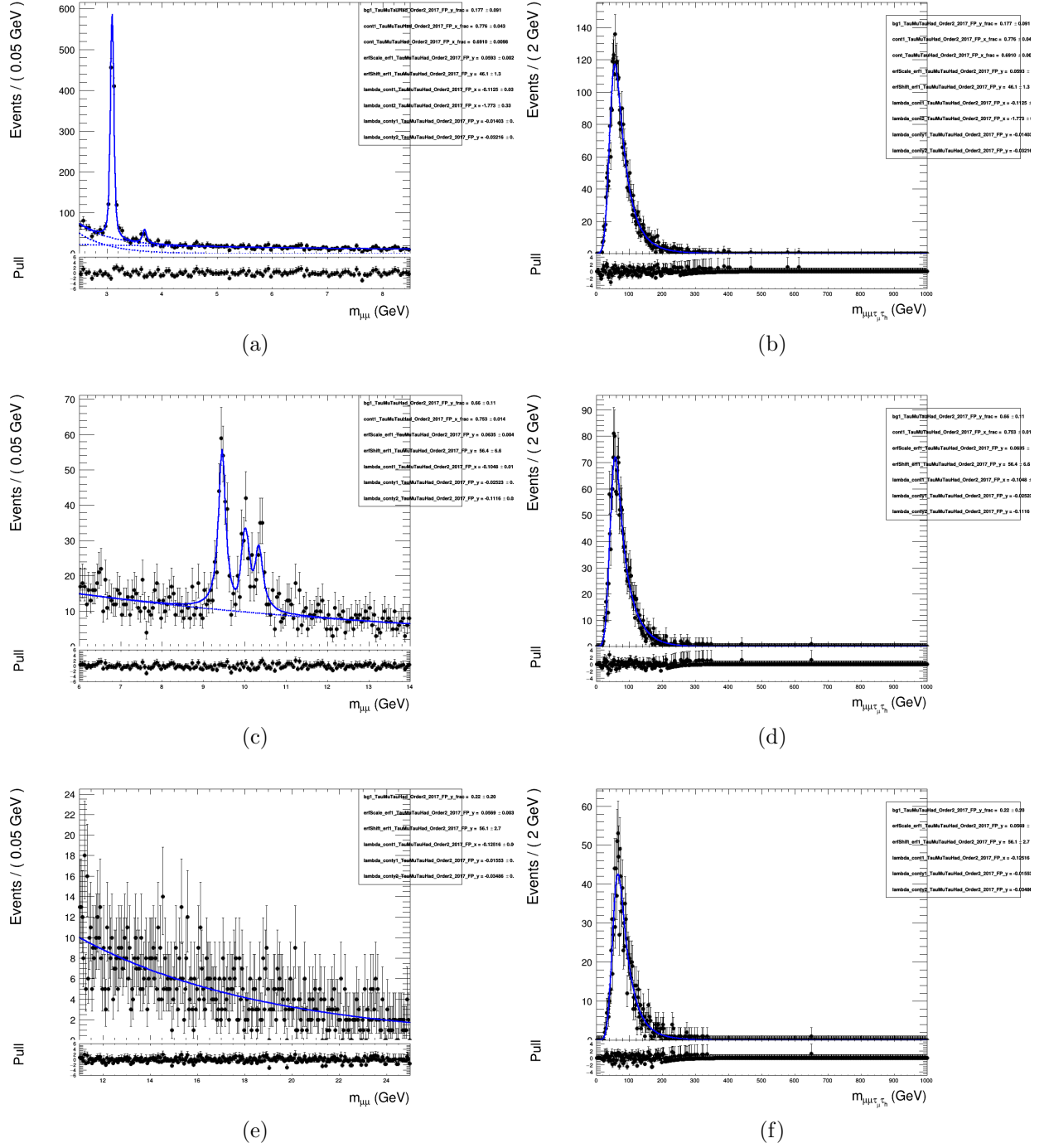


Figure 7.39: Prefit dimuon (left) and 4-body (right) visible mass distributions for the side-band region in the $\tau_\mu\tau_h$ final state.

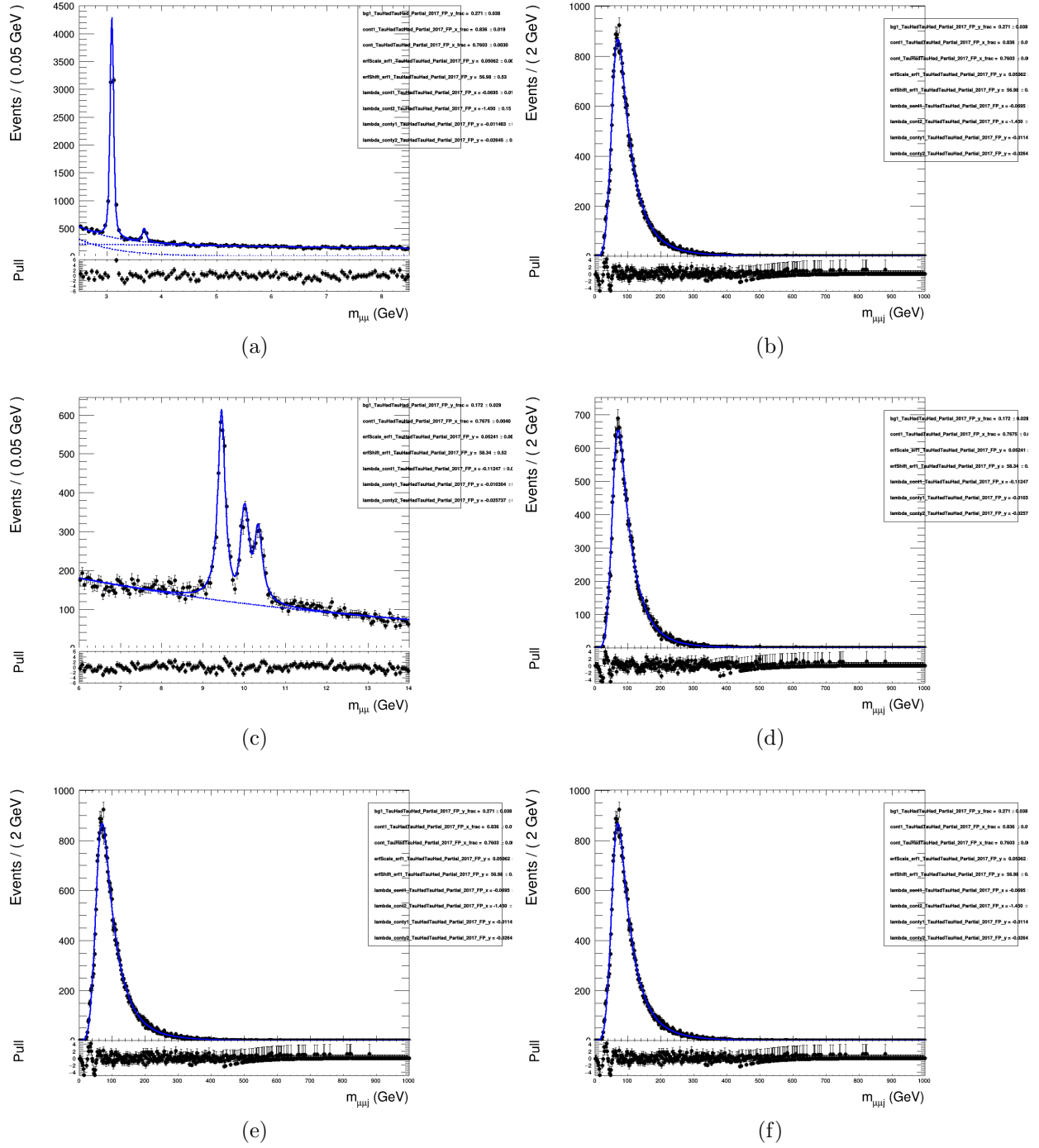


Figure 7.40: Prefit dimuon (left) and 4-body (right) visible mass distributions for the side-band region in the $\tau_h \tau_h$ final state.

7.8.3 Signal modelling

As mentioned earlier in the text, dimuon invariant mass is fit with a Voigtian PDF and the four body visible mass is fit with a double-sided Gaussian PDF. The signal model splines are built from the signal fits at each generated pseudoscalar mass. For a given mass point, the signal is fit to the PDF described above and a spline interpolation is constructed based on the fitted parameters. The fits in signal region for 5, 10 and 20 GeV pseudoscalars and 125 GeV in $\mu\mu\tau_\mu\tau_h$ channel is shown in the Figure 7.41. The signal region fit for pseudoscalar masses 10 and 20 GeV and 250 GeV Higgs mass is shown in the Figure 7.42. The splines for the mean, sigma, width, and integral for the signal fit in the $\mu\mu\tau_\mu\tau_h$ channel are shown in Fig. 7.43 and Fig. 7.44. Results shown here are from 2017 simulation. Further examples can be seen in the appendix.

7.9 Systematic Uncertainties

The systematic uncertainties in this analysis can be broadly classified into two types. The first type is the Normalization uncertainties, modifying all the bins in the analysis with a normalization factor. They have an equal effect on all the analysis bins.

The other type is the shape uncertainties that cause an overall change in the spectrum. One can use the model parameters to manifest the effects of the shape uncertainties on the result. A new variable is created corresponding to the desired shape uncertainty and varies between $-j1$ and 1 with a default value of 0. The variable is created in the RooWorkSpace. The setup is such that a one sigma shift in shape uncertainty corresponds to a change in the variable by 1.

A change in shape uncertainty can cause an effect on the normalization, and it is necessary to correctly correlate the change in shape uncertainty to the change in normalization.

The different sources of uncertainty and their evaluation is described in 7.9.1. The effect of these various systematic uncertainties on the expected signal significance or the expected exclusion in the absence of a signal can be evaluated using the Higgs combine utility.

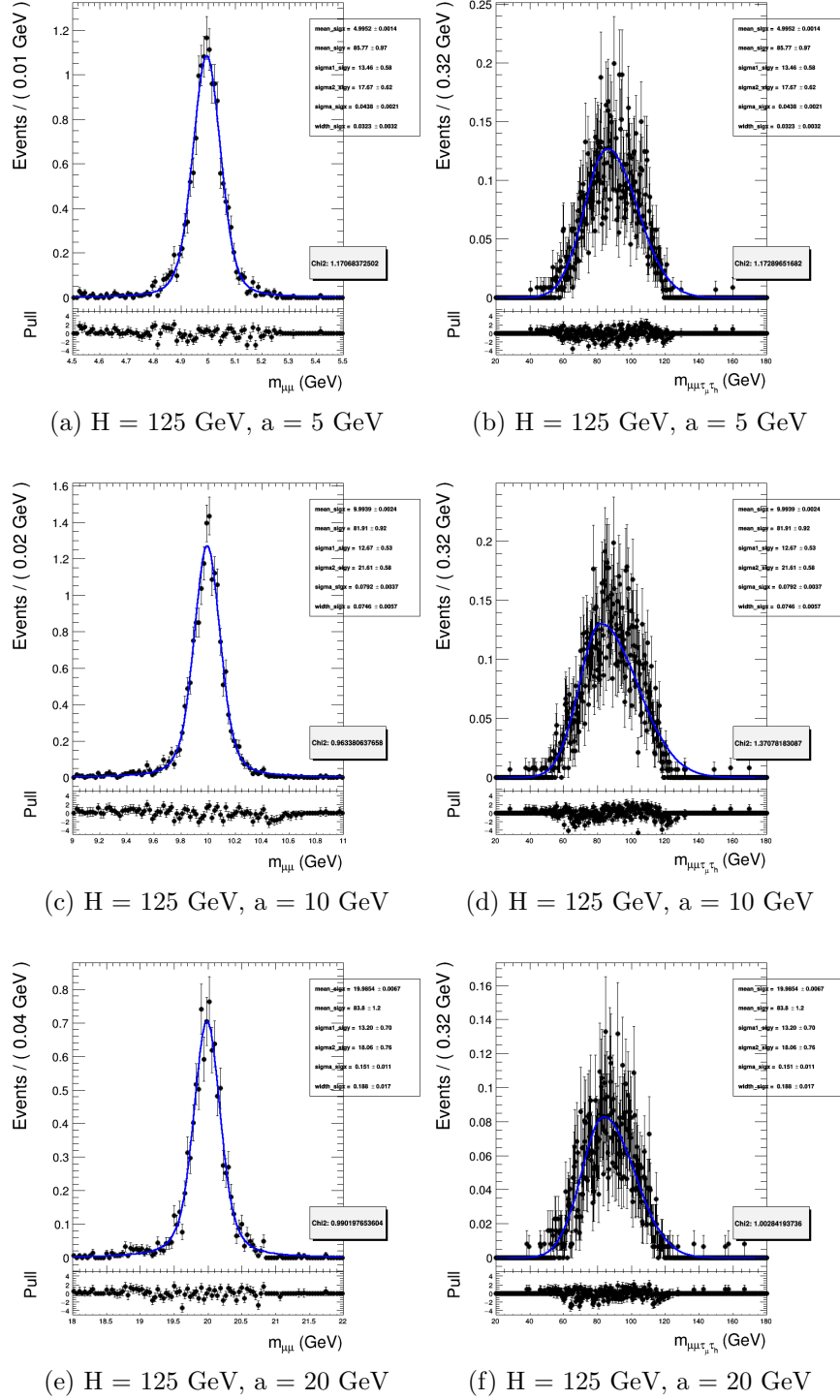
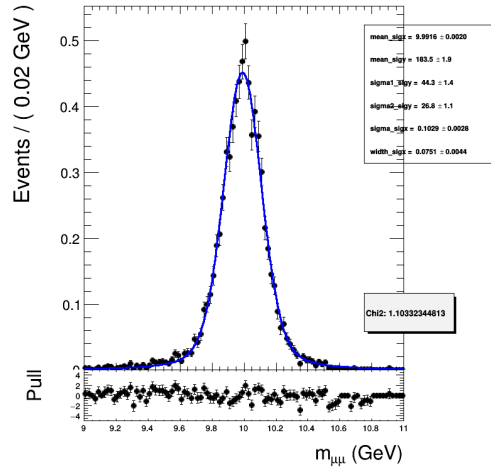
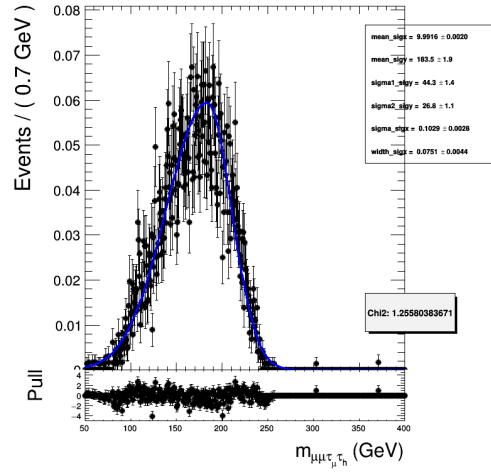


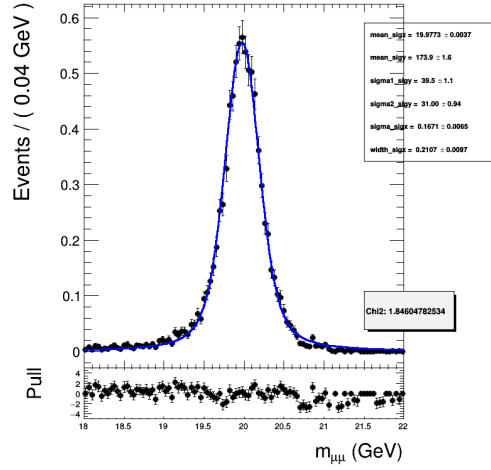
Figure 7.41: Modelling of the signal dimuon (left) and 4-body (right) visible mass distributions for various pseudoscalar masses, $H = 125 \text{ GeV}$.



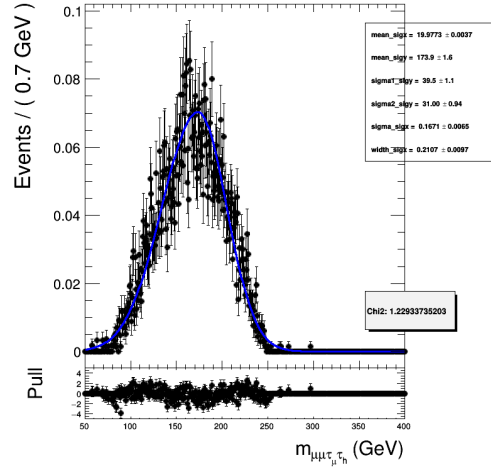
(a) $H = 250$ GeV, $a = 10$ GeV



(b) $H = 250$ GeV, $a = 10$ GeV



(c) $H = 250$ GeV, $a = 20$ GeV



(d) $H = 250$ GeV, $a = 20$ GeV

Figure 7.42: Modelling of the signal dimuon (left) and 4-body (right) visible mass distributions.

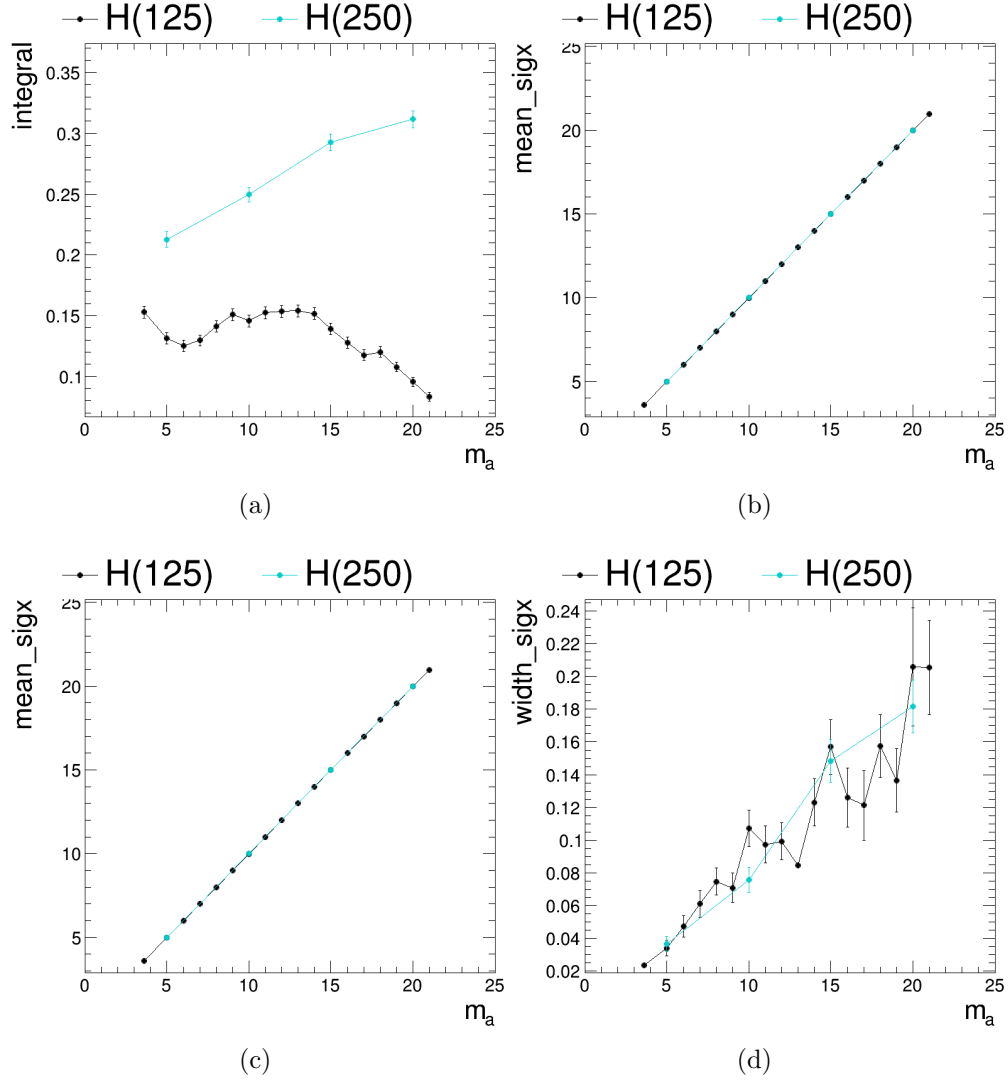


Figure 7.43: Spline interpolation of the signal integral and dimuon mass modelling.

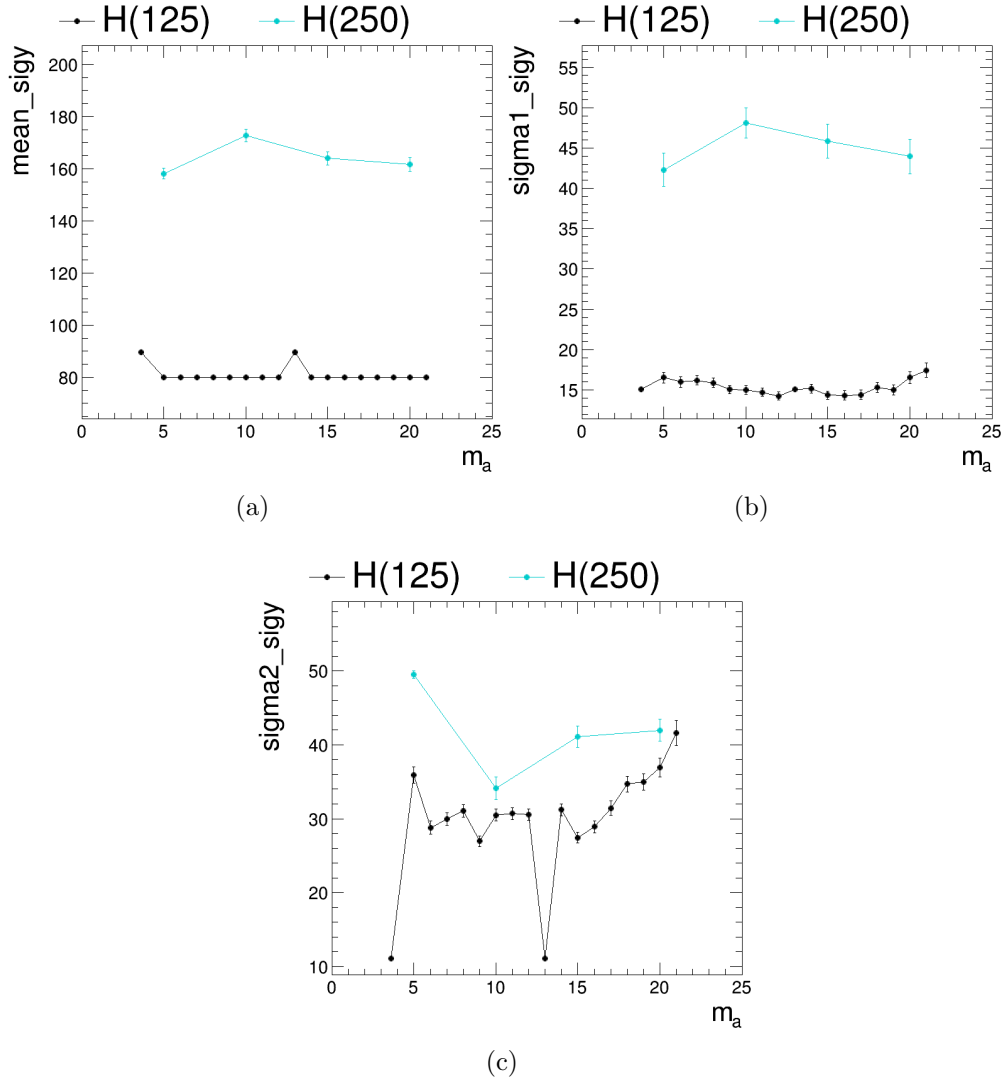


Figure 7.44: Spline interpolation of the signal 4-body mass modelling .

7.9.1 Sources of systematic uncertainties

Table 7.6: Systematic uncertainties.

Uncertainty source	Combine type	Uncertainty
Trigger efficiency	normalization	0.5%
Luminosity	normalization	2.5%
Muon identification	normalization	1%
Muon isolation	normalization	0.5%
Tau identification	shape	5-18%
Fake rate uncertainty	shape	20%
Muon energy scale	shape	0.2% (5%) $p_T < 100\text{GeV}$ ($p_T \geq 100\text{GeV}$)
Tau energy scale	shape	1.2-3%
Meson resonance yields	normalization	5-20%
Higgs PDF+ α	normalization	3-4% (From YR4)

The sources of the systematic uncertainties are given in Table 7.6.

- **Luminosity** - The uncertainty in integrated luminosity of the 2016, 2017 and 2018 datasets are 1.2 %, 2.3 % and 2.5 % respectively [82]. These are applied as normalization uncertainties.
- **Muon, Electron, Tau energy scale** - In order to propagate the energy scale uncertainty of the leptons to the final result, the energy of the underlying objects is scaled by their corresponding uncertainties (both up and down), followed by rerunning the analysis selections and fits.
- **Muon id and isolation** - A global scaling factor (Id/isolation) is applied on the total count of the selected signal events. The scale factor is varied up and down by 1 sigma as the constrain for the combine fit.
- **Tau ID** - The Tau ID scale factors were re-studied for this analysis as low p_T taus are used. The scale factors are applied to the event distributions and this varies with years and decay modes. The ID scale factor uncertainties are accounted for by scaling the events by the corresponding uncertainties (both up and down), and then constraining the uncertainties within 1 sigma variation for the combine fit.
- **Pileup reweighting** - The uncertainty on the pileup reweighting procedure is obtained by varying the minimum bias cross-section of 69.2mb by 4.6% and propagating the modified weights.

- **Background estimation** - This uncertainty in background estimation has multiple components.
 - First, the statistical uncertainties of the fake efficiencies calculated in the Drell–Yan plus fake control region are propagated to the signal region.
 - Second, the parameters of the meson resonance distributions (means, widths, and sigmas) are constrained via a simultaneous fit to the control region.
 - Finally, the background meson resonance relative yields of Ψ' and Υ 2S and 3S from J/Ψ and Υ are estimated from the control region and propagated to the signal and sideband expected yields.
 - A deviation from the expectation is observed in the Region C and D distributions. The yields of the Υ 2S and 3S are given an uncertainty of 5% and 10%, respectively while the yield of Ψ' are given a 20% uncertainty.

In the present state of the analysis **most of the normalization uncertainties and the Tau ID scale factor and fake rate systematic uncertainties have been applied to get the final result.**

7.10 Discovery and Limit Setting

The variable that gives the most discriminating power seems to be the di-muon invariant mass. The variable gives a sharp resonant peak over a smoothly falling background. In the 2D fit, the other variable that is considered is the visible four lepton invariant mass.

The exclusion limits calculated in this analysis are obtained using the CLs method, using modified frequentist approach [83, 84]. The LHC test statistic used is the following:

$$q_0 = -2 \ln \left[\mathcal{L} \left(data | r = 0, \hat{\theta}_0 \right) / \mathcal{L} \left(data | r = \hat{r}, \hat{\theta} \right) \right]. \quad (7.5)$$

Systematic uncertainties are represented as nuisance parameters assuming a log-normal PDF in the likelihood fit for uncertainties in the expected yields and a Gaussian PDF of uncertainties in the signal and background model parameters.

Significance and expected exclusions are calculated using the Higgs Combine tool [85]. The analysis is using the `AsymptoticLimits` method for now. This method uses the asymptotic approximation [86] of the LHC test-statistic to obtain fast results.

7.11 Results and Interpretation

Model-independent (expected) upper limits at 95% CL set on $\sigma_H/\sigma_{\text{SM}} \times \mathcal{B}(H \rightarrow aa \rightarrow \mu\mu\tau\tau)$ for the channels $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_h\tau_h$, $\mu\mu\tau_\mu\tau_e$ is shown in the Figure 7.45. Similar plots for $H = 250$ GeV is shown in Figure 7.46. Note, the limits for $H = 250$ GeV still don't have the tau ID scale factor uncertainties incorporated. The limits will change when all the systematic uncertainties are taken into account. The **observed** limits for $\mu\mu\tau_\mu\tau_h$ is given in the Figure 7.47. The Higgs mass considered is the Standard Model 125 GeV and the data used is Full Run 2. The observed distributions of data in the (low mass) signal region for various channels and the year 2018 are shown in Figures 7.48 and 7.49. Figures 7.50 - 7.53 show the observed data distribution in the upilon and high mass region for the year 2018. The observed data distribution for the years 2016 and 2017 are in appendix E.

7.12 Conclusion

The search for light pseudoscalar Higgs boson is performed using data collected by the CMS experiment at the LHC. The search looked into the full Run 2 data collected at centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 137.60 fb^{-1} . A good agreement is observed with the Standard Model expectations and no significant excess was observed. As a result, upper limits on the production cross section multiplied by the branching ratio are set as a function of m_a .

As mentioned in Section 7.10, CL_s method was used for the upper limit calculations and systematic uncertainties were included. A detailed description of the uncertainties is given in Section 7.9. Model-independent observed limits at 95% CL were set on $\sigma_H/\sigma_{\text{SM}} \times \mathcal{B}(H \rightarrow aa \rightarrow \mu\mu\tau\tau)$ and are presented in Figure 7.47. Here, the σ_H is taken from [87], this consists of the ggF cross-section. For the heavier Higgs bosons, σ_{model} is the SM-like cross section for each corresponding Higgs boson mass, is also taken from [87].

The search has some significant improvements in methodology compared to its predecessor, where only $\mu\mu\tau_\mu\tau_h$ final state was analyzed using 2016-only data [33]. While the previous iteration of the analysis only featured jet cleaning, the present version involves an

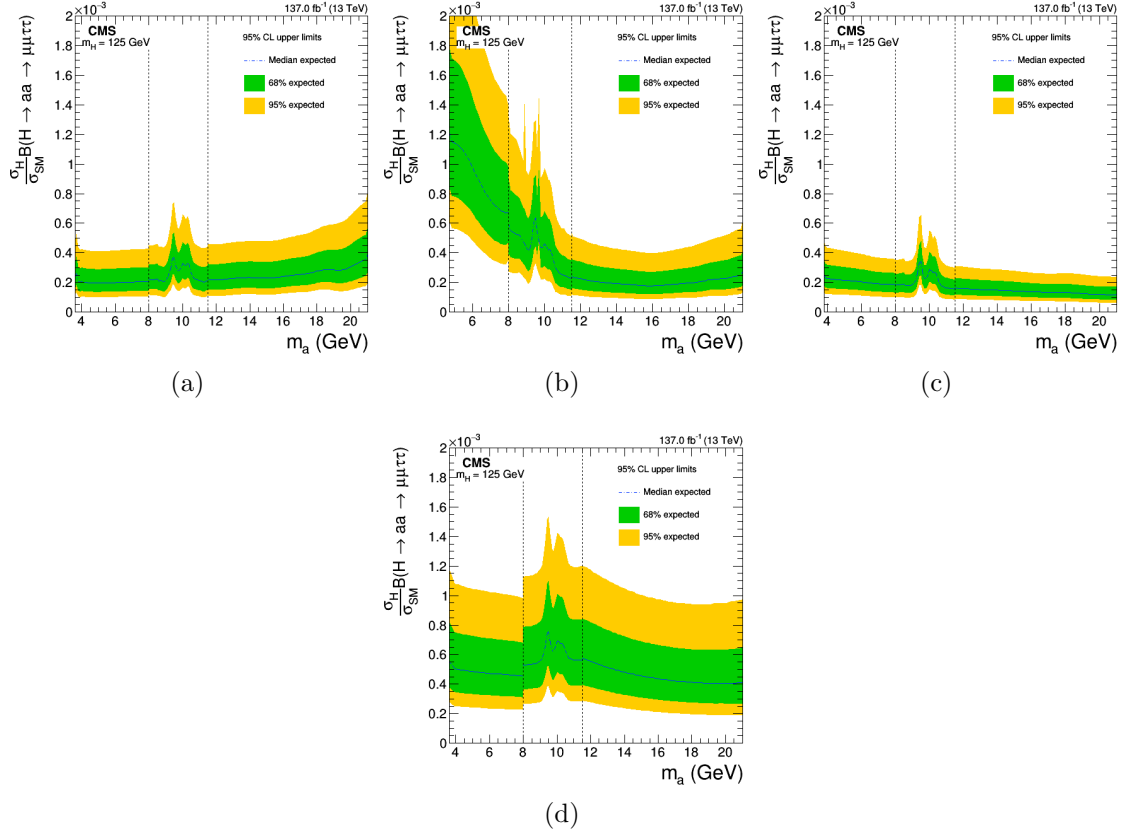


Figure 7.45: Full Run 2 expected limits for channels $\mu\mu\tau_\mu\tau_h$ (a), $\mu\mu\tau_e\tau_h$ (b), $\mu\mu\tau_h\tau_h$ (c), $\mu\mu\tau_\mu\tau_e$ (d). $H = 125$ GeV.

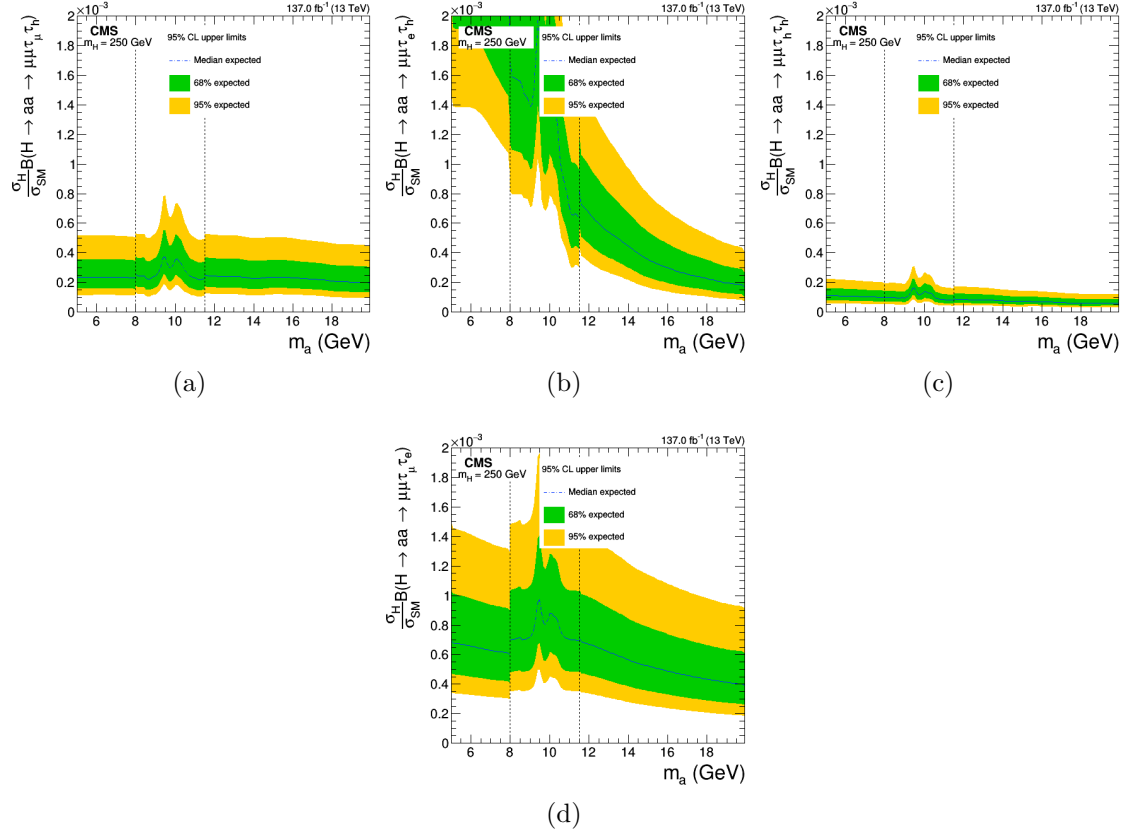
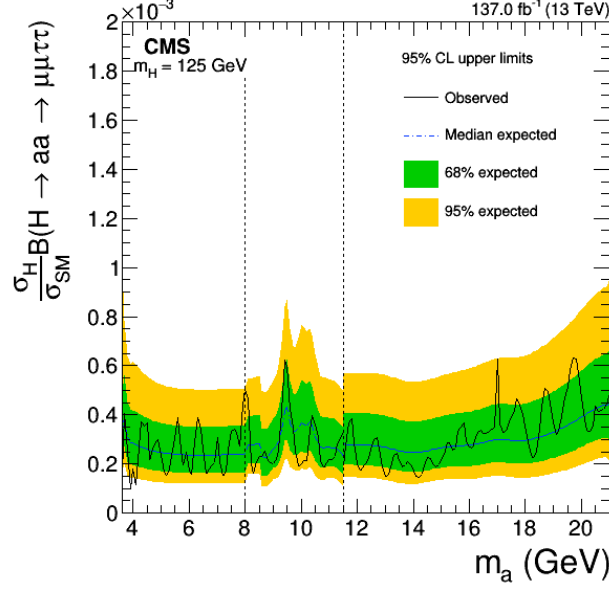


Figure 7.46: Full Run 2 expected limits for channels $\mu\mu\tau_\mu\tau_h$ (a), $\mu\mu\tau_e\tau_h$ (b), $\mu\mu\tau_h\tau_h$ (c), $\mu\mu\tau_\mu\tau_e$ (d) . $H = 250$ GeV.



(a)

Figure 7.47: **Observed Limit** for channel $\mu\mu\tau_\mu\tau_h$.

additional isolation region cleaning for the semi-leptonic final states. The isolation region cleaning cleans out the μ / e candidates from the isolation region. It thereby adds to the enhancement in efficiency that is brought about by the process of jet cleaning. The reconstruction of the ditau pair is further aided by the additional cleaning in the isolation region and results in increased signal efficiency in the boosted topology we are working with and helps with our signal sensitivity.

One of the other major improvements of this iteration of the analysis is the prevention of cross-channel contamination. The previous iteration involved $\mu\mu\tau_\mu\tau_h$ final state, and although the final set of events was intended to be exclusive to the channel of interest only, there was cross-channel contamination from other channels. The final set of events contained events from the $\mu\mu\tau_\mu\tau_e$ and $\mu\mu\tau_\mu\tau_\mu$ channels. For the present analysis iteration, the events that pass the initial kinematic selections are further categorized as part of the semi-leptonic, fully leptonic, and fully hadronic final states. The events that become part of a certain channel are exclusive to that channel only, and there is no cross-channel contamination. The prevention of the cross-channel contamination was a suggested improvement of the previous

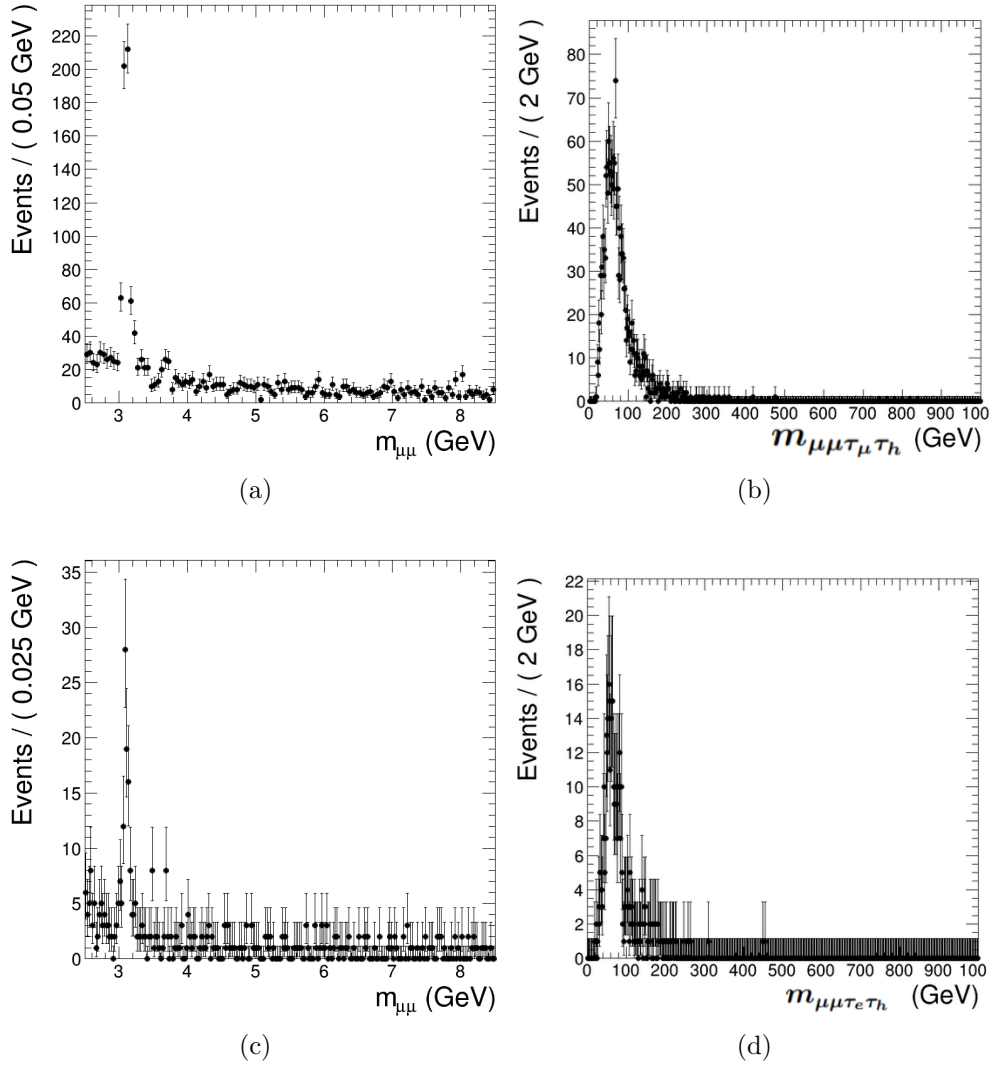


Figure 7.48: Observed data in 2018 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots are in the (dimuon) **low** mass region (2.5 GeV to 8.5 GeV).

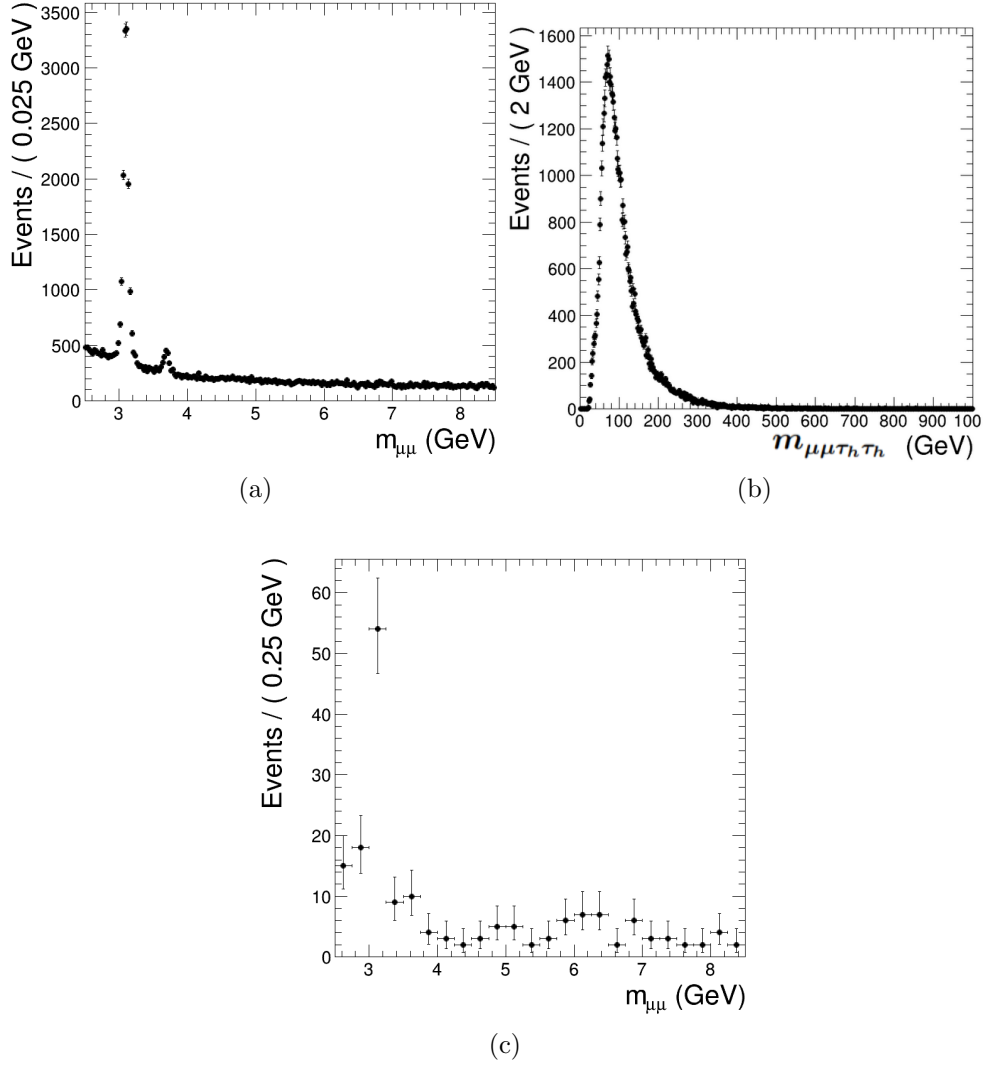


Figure 7.49: Observed data in 2018 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The plots are in the low mass region.

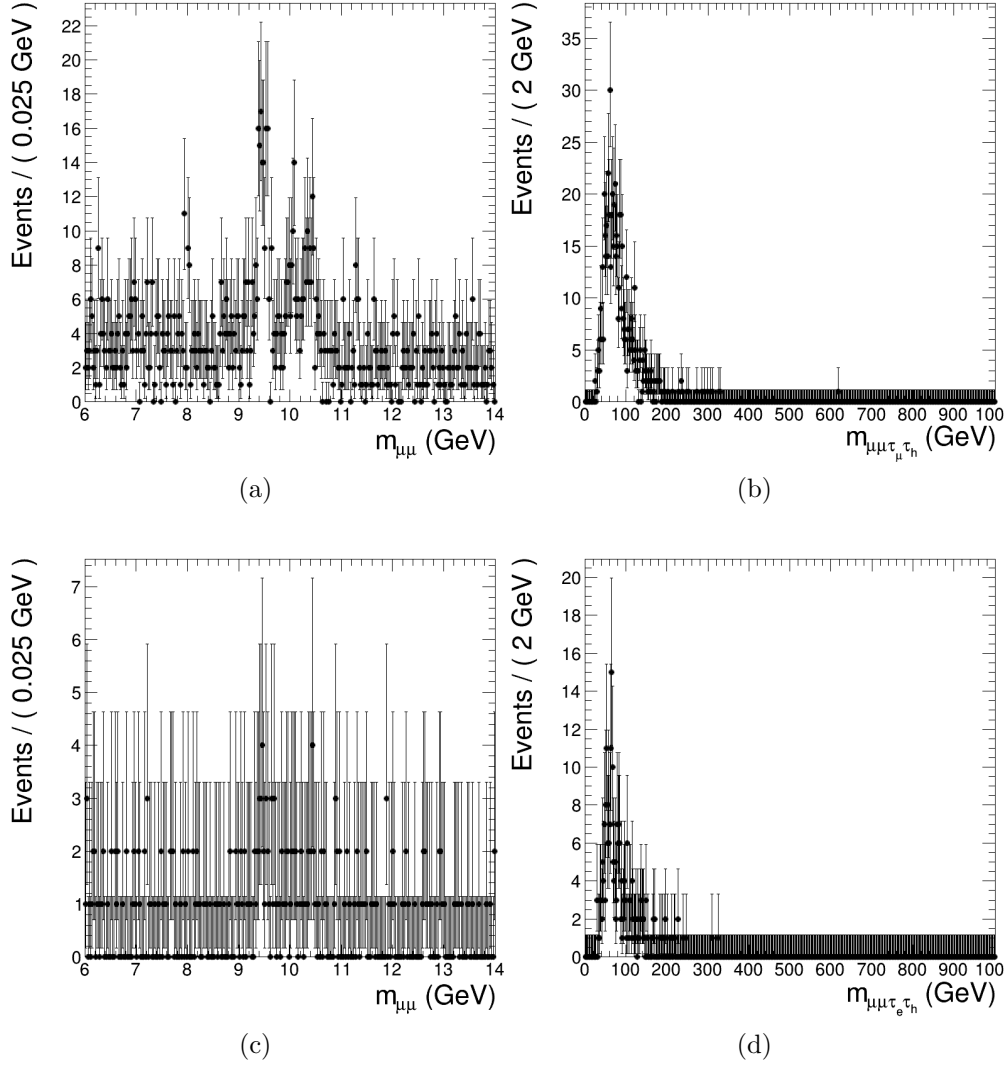


Figure 7.50: Observed data in 2018 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots are in the (dimuon) **upsilon** region (6 GeV to 14 GeV).

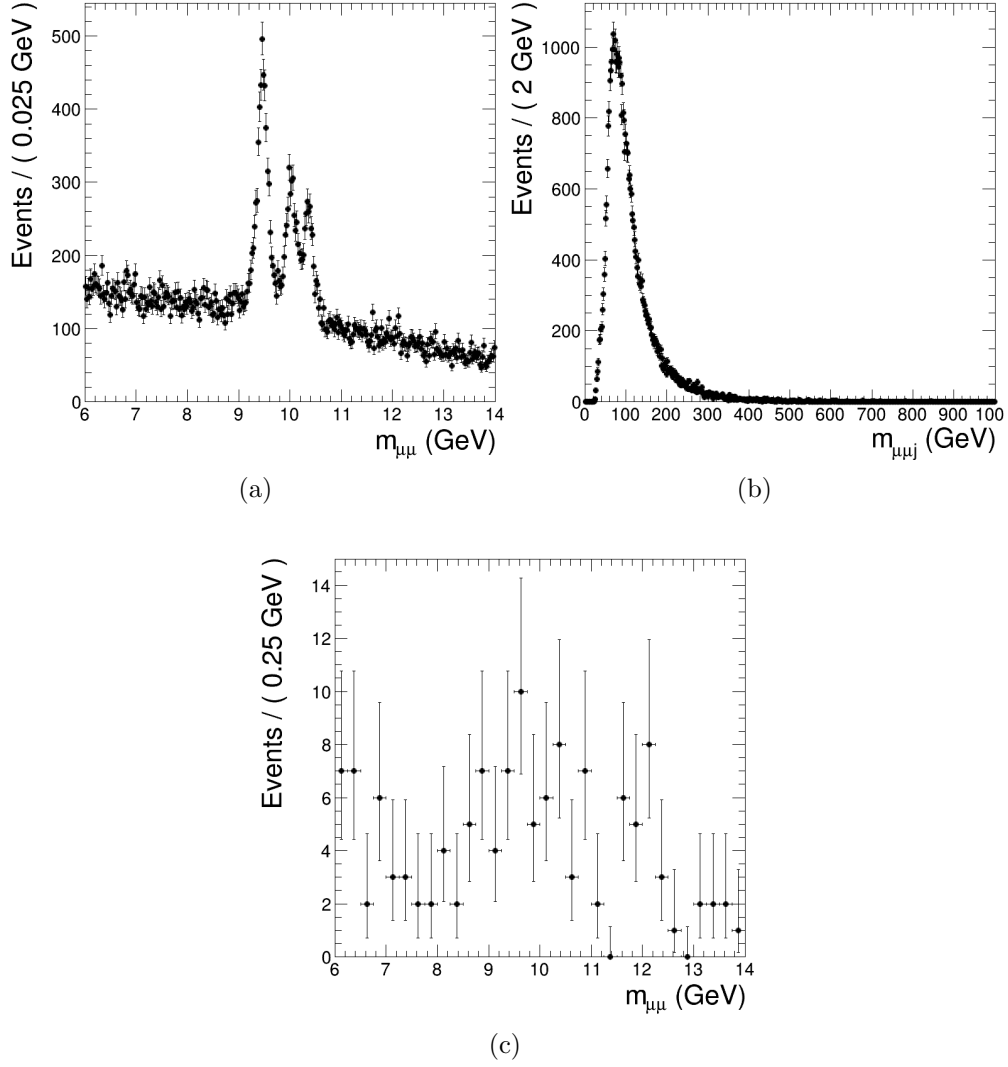


Figure 7.51: Observed data in 2018 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The plots are in the upsilon region.

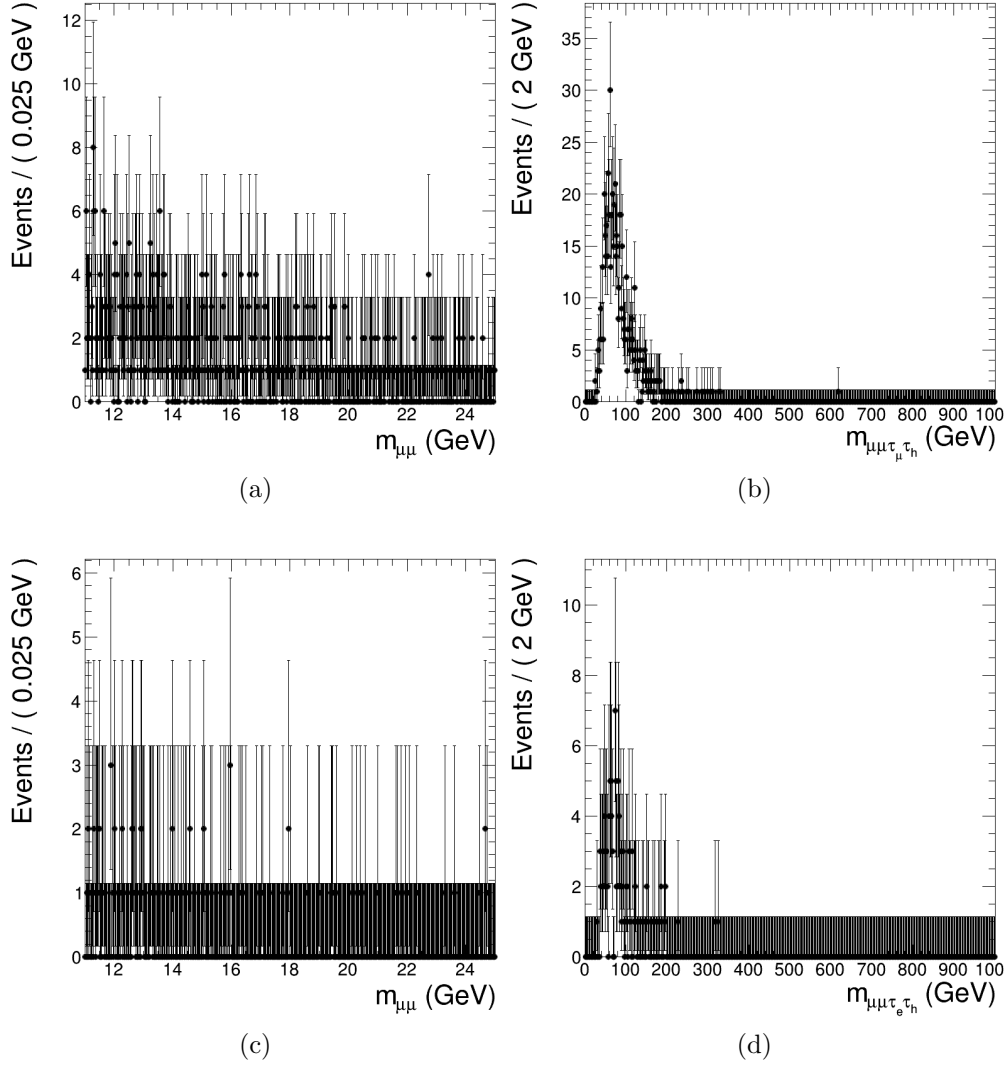


Figure 7.52: Observed data in 2018 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots are in the (dimuon) **high mass** region (11.5 GeV to 24.5 GeV).

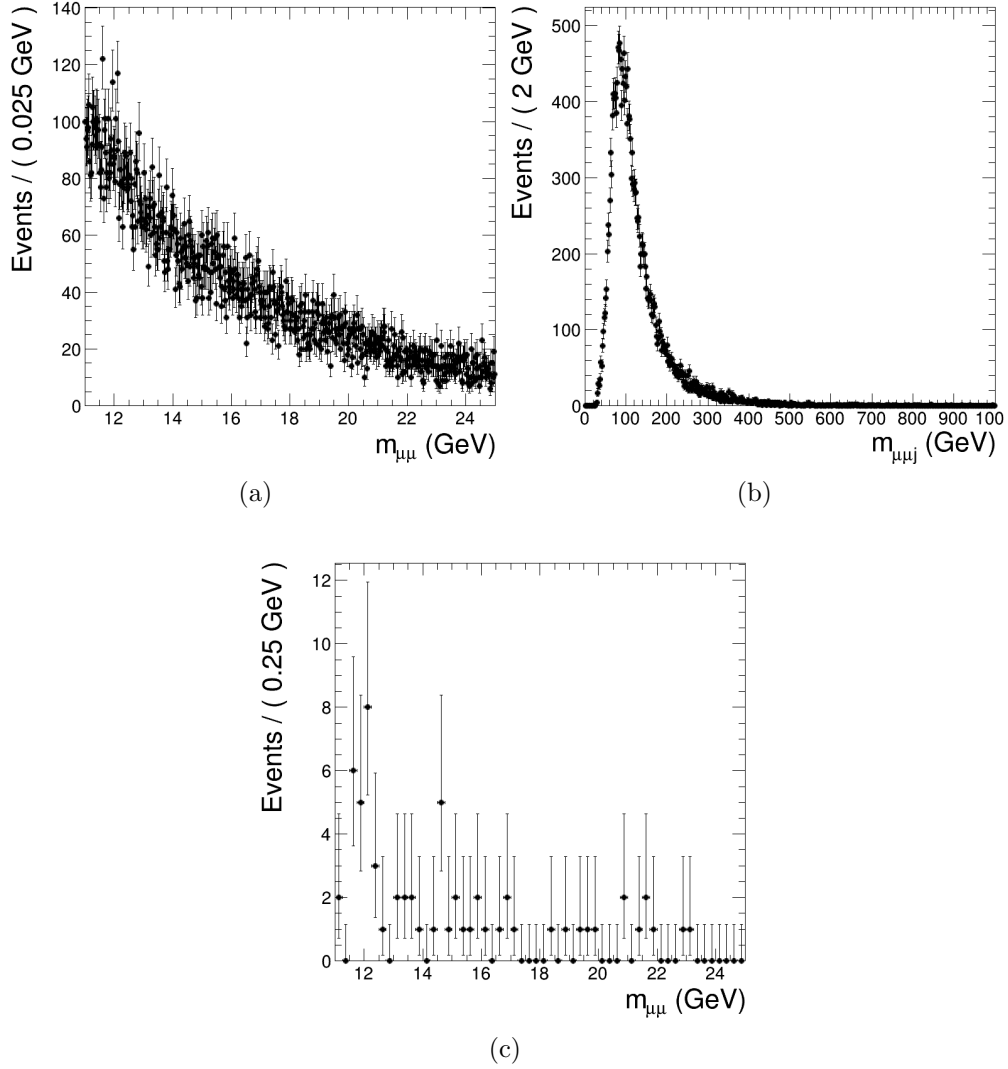


Figure 7.53: Observed data in 2018 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The plots are in the high mass region.

iteration of the analysis and was achieved for the present version.

Apart from the improvements in the implementation, there are also improvements in the quality of the input data used. The present iteration of the search used Ultra Legacy (UL) full Run 2 data and simulation, which have better-understood reconstruction, the latest calibrations, and alignments. The previous version of the analysis used partial data from 2016.

Despite the improvements that were implemented for this search, some areas still needs further investigation and tuning. At present double-sided gaussian is being used to fit the four-body mass distributions in signal. Although the fitting function has worked particularly well for the 125 GeV Higgs interpretation, it became increasingly difficult to get good quality fits as the Higgs mass increased. It would be worth investigating into other possible functions to fit the four body mass in order to get better initial parameters.

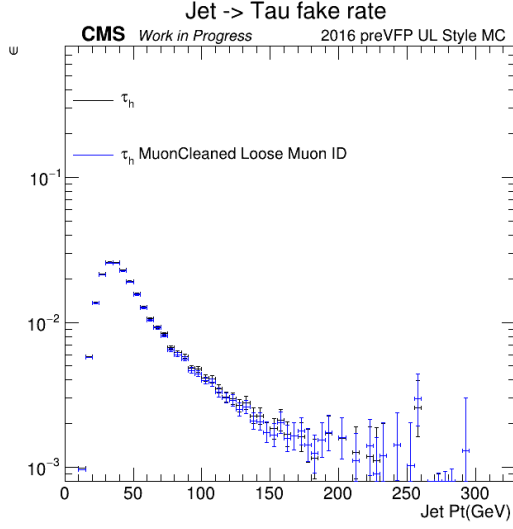
The Tau ID scale-factors used in this analysis are applicable for single τ_h decays, but we have a fully hadronic channel ($\mu\mu\tau_h\tau_h$) where we encounter a DiTau pair $\tau_h\tau_h$. It is, therefore, necessary to derive scale factors for the DiTau pair objects. Studies are still ongoing to derive the scale factors for the DiTau pair.

In the fully hadronic channel ($\mu\mu\tau_h\tau_h$), the score of the output node $\tau_h\tau_h$ essentially becomes the Deep DiTau discriminant. Choice of analysis regions in the case of the fully hadronic channel is made based on cuts on the Deep DiTau discriminant value. The discriminant still needs to be tuned to work efficiently for a wide range of boosts. Behaviors at high and low boosts still need to be understood to optimize the discriminant's performance. Among other things, the DiTau discriminant needs to be trained on 2016 and 2018 data as opposed to 2017 only for the present iteration.

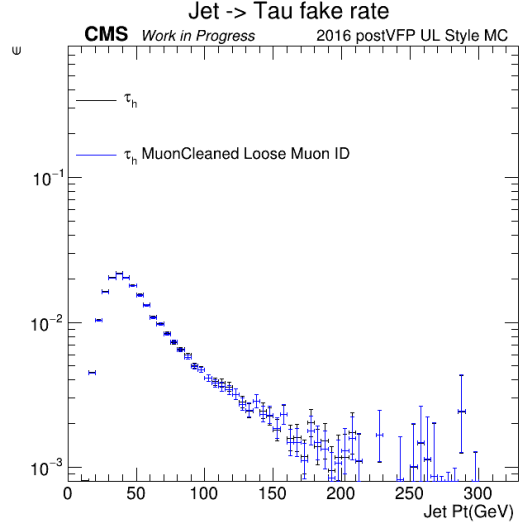
APPENDIX A

JET TO TAU FAKE RATE

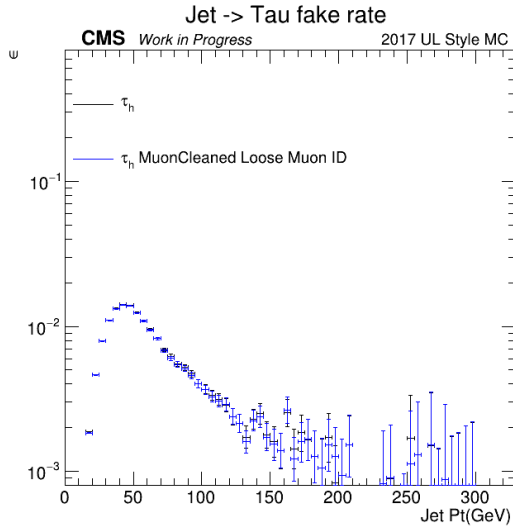
The study of jet $\rightarrow$ Tau fake rate is carried out to determine the relative performance of the e/μ cleaned versions of τ as opposed to the standard Uncleaned τ . The Background Monte Carlo sample used in the study was Z + jets. The jets used in the the study are required to be further away from the leptons which comes from the Z boson decay, this ensures that the leptons from the Z decay are not misidentified as jets. This is done in practice through the application of a $dR > 0.4$ cut. . The jet $\rightarrow$ Tau fake rate is defined as the ratio of the number of jets that are identified as τ_h candidates with $p_T > 10 \text{ GeV}$ and $|\eta| < 2.3$ (i.e passing DecayModeFinding and Isolation), to the total number of jets with $p_T > 10$ and $|\eta| < 2.3$. The jet fake Tau efficiency is an important quantity to consider when looking for the optimum Muon or Electron ID to use for cleaning. The best performing ID is expected have the highest Tau reconstruction efficiency for the lowest jet $\rightarrow$ Tau efficiency.



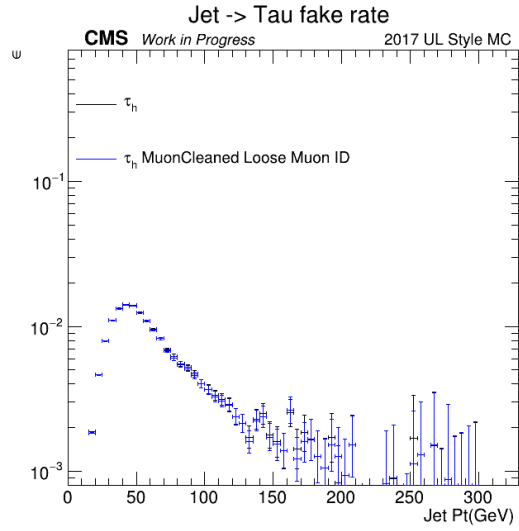
(a)



(b)

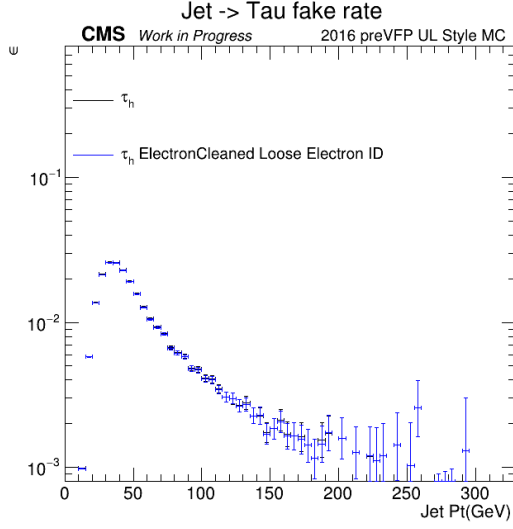


(c)

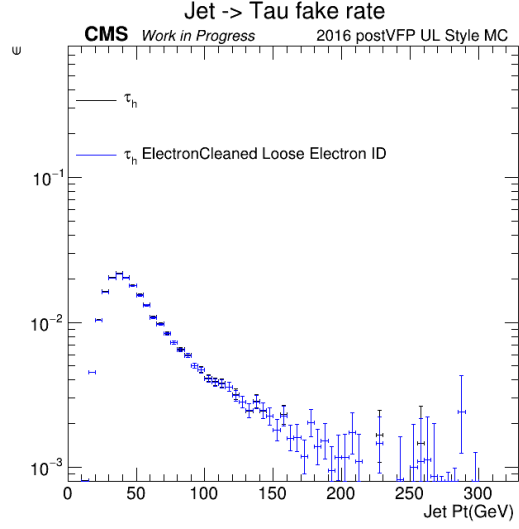


(d)

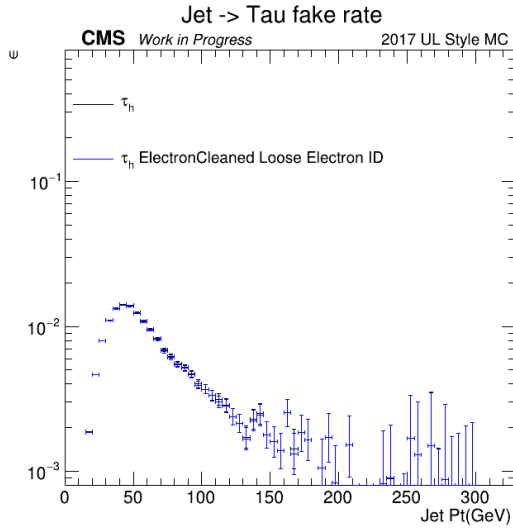
Figure A.1: Jet $\rightarrow$ tau fake rate for μ cleaned taus and standard taus for various years as a function of Jet Pt.



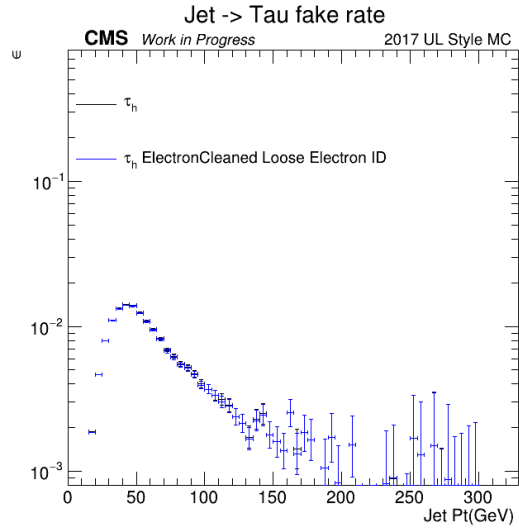
(a)



(b)



(c)



(d)

Figure A.2: Jet $\rightarrow$ tau fake rate for e cleaned taus and standard taus for various years as a function of Jet Pt.

APPENDIX B

TAU EFFICIENCY

The τ reconstruction efficiency is calculated for a range of pseudoscalar masses with respect to each Higgs (H) mass. The range of masses is chosen to cover regions of highest and lowest boost. We use Signal Monte Carlo samples for this study. For the Higgs mass of 125 GeV the pseudoscalar mass range considered is $4 - 20 \text{ GeV}$. For higher Higgs masses, we consider corresponding higher pseudoscalar mass ranges. For the $\tau_\mu\tau_h$ and $\tau_e\tau_h$ final states, the μ / e cleaning is expected to work best at high boost where the decay cones of the τ 's start to coincide and the decay products overlap as a result of the collimation. This behavior is seen in the lower pseudoscalar masses, where the pseudoscalars achieve a considerable boost due to the huge mass difference between the Higgs and the pseudoscalars. The associated boost is low for higher pseudoscalar masses, and the decay cones are further apart. The μ / e has no considerable effect when the cones are further apart. The cleaning is therefore expected to enhance the τ reconstruction efficiency in the high boost / low pseudoscalar mass regime while having a negligible effect on the efficiency at low boost / high pseudoscalar mass. The efficiencies are plotted as a function of several variables like the τ_h visible p_T , τ_{lep} generator level p_T , and $dR(\tau_h, \tau_{lep})$. The cases in which μ 's are cleaned are plotted separately from the ones in which e 's are cleaned from the jets and isolation regions. We use Loose working point of muon/electron ID for cleaning the μ/e . Information on the Tau efficiency, combined with the knowledge of the $\text{jet} \rightarrow \text{Tau}$ fake rate, allows us to compare the performance of cleaned Tau collection as opposed to the standard uncleaned taus.

In our analysis, we look into two different types of τ reconstruction efficiencies. The Hadronic Tau reconstruction efficiency τ_h and the Di-Tau efficiencies ($\tau_\mu\tau_h$ and $\tau_e\tau_h$). For the Di-Tau reconstruction efficiency, we take into account the reconstruction efficiencies of the corresponding leptonically decaying Taus (τ_μ/τ_e).

B.1 Hadronic Tau Reconstruction Efficiency

In the τ_h reconstruction efficiency calculation, we apply the following selections in the denominator:

- Generator Level
 - $p_T(\tau_\mu) > 3.0\text{GeV}$ and $\eta(\tau_\mu) < 2.4$ (for μ cleaned)
 - $p_T(\tau_e) > 7.0\text{GeV}$ and $\eta(\tau_e) < 2.5$ (for e cleaned)
 - $p_T(\tau_h) > 10.0\text{GeV}$ and $\eta(\tau_h) < 2.3$
- Reconstruction Level
 - $p_T(\mu_1) > 26.0\text{ GeV}$ and $\eta(\mu_1) < 2.4$ and `isLooseMuon` and relative Isolation < 0.25
 - $p_T(\mu_2) > 3.0\text{GeV}$ and $\eta(\mu_2) < 2.4$ and `isLooseMuon` and relative Isolation < 0.25
 - $p_T(\tau_\mu) > 3.0\text{GeV}$ and $\eta(\tau_\mu) < 2.4$ and `isLooseMuon/` (for μ cleaned)
 - $p_T(\tau_e) > 7.0\text{GeV}$ and $\eta(\tau_e) < 2.5$ and `isLooseElectron/` (for e cleaned)

We further require the Reconstruction level μ / e to match to their Generator level counterparts with the lowest dR match.

If an event is to be included in the numerator of the efficiency calculation, the following additional selection criteria must be met:

- $p_T(\tau_h) > 10.0\text{GeV}$ and $\eta(\tau_h) < 2.3$ for μ / e cleaned HPS.
- τ_h passes `decayModeFinding`, `byIsolationMVARun2017v2DBoldDMwLTraw2017` > -0.5 , and tau ID “`byMediumIsolationMVARun2017v2DBoldDMwLT2017`”

The hadronically decaying tau reconstructed from the μ / e cleaning algorithm must pass the following criteria:

- $p_T > 10\text{GeV}$
- $\eta < 2.3$
- `decayModeFinding`

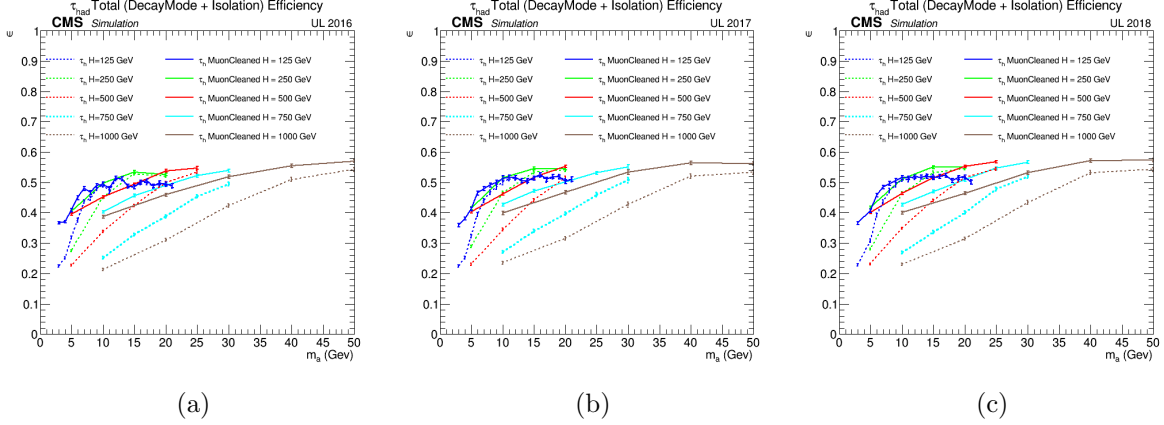


Figure B.1: The reconstruction efficiency of the standard tau HPS (dashed line) and μ cleaned HPS (solid line) reconstruction as a function of pseudoscalar masses for different years and for $m_H = 125, 250, 500, 750$ and 1000 .

- $\text{byIsolationMVArun2017v2DBoldDMwLTraw2017} > -0.5$
- $\text{dR}(\text{Reco } \tau_h, \text{Gen } \tau_h) < 0.1$

In addition, including the hadronic tau isolation requirement allows us to define our signal region.

- Pass tau ID “byMediumIsolationMVArun2017v2DBoldDMwLT2017”

Figure B.1 shows the τ_h reconstruction efficiency for several years and Higgs masses, as a function of the pseudoscalar mass. The dashed lines represent the standard tau collection, and the solid lines represent the μ cleaned tau collection.

Figure B.1 shows the τ_h reconstruction efficiency for several years and Higgs masses, as a function of the pseudoscalar mass. The dashed lines represent the standard tau collection, and the solid lines represent the e cleaned tau collection.

B.2 Di-Tau Reconstruction Efficiency

When calculating the Di-Tau ($\tau_\mu \tau_h$ and $\tau_e \tau_h$) reconstruction efficiency, we take into account the reconstruction efficiency of both the hadronically decaying taus as well as the

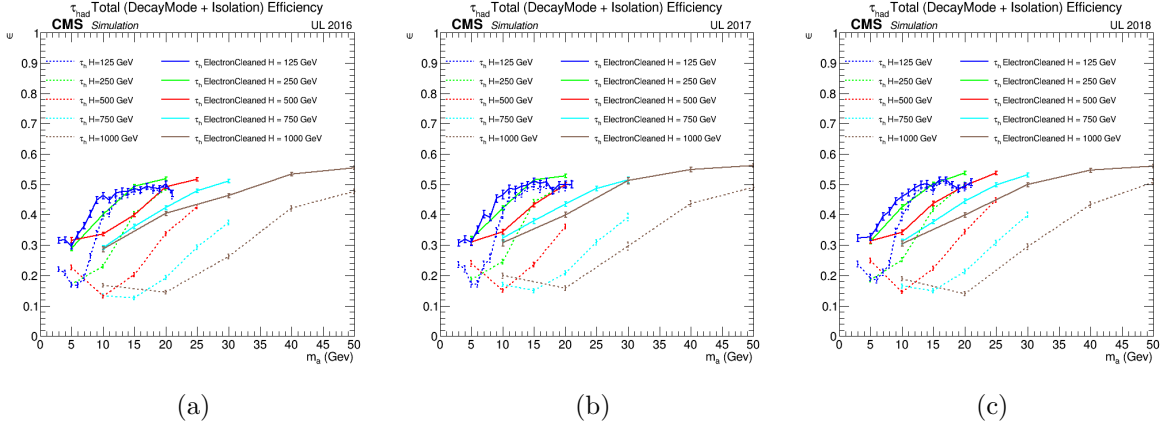


Figure B.2: The reconstruction efficiency of the standard tau HPS (dashed line) and e cleaned HPS (solid line) reconstruction as a function of pseudoscalar masses for different years and for $m_H = 125, 250, 500, 750$ and 1000 .

taus decaying to μ / e leptons. For an event to make it into the denominator of the efficiency calculation, it must pass the following selections:

- Generator Level

- $p_T(\tau_\mu) > 3.0 \text{ GeV}$ and $|\eta(\tau_\mu)| < 2.4$ (for $\tau_\mu\tau_h$)
- $p_T(\tau_e) > 7.0 \text{ GeV}$ and $|\eta(\tau_e)| < 2.5$ (for $\tau_e\tau_h$)
- $p_T(\tau_h) > 10.0 \text{ GeV}$ and $|\eta(\tau_h)| < 2.3$

- Reconstruction Level

- $p_T(\mu_1) > 26.0 \text{ GeV}$ and $|\eta(\mu_1)| < 2.4$ and `isLooseMuon` and relative Isolation < 0.25
- $p_T(\mu_2) > 3.0 \text{ GeV}$ and $|\eta(\mu_2)| < 2.4$ and `isLooseMuon` and relative Isolation < 0.25
- $p_T(\tau_\mu) > 3.0 \text{ GeV}$ and $|\eta(\tau_\mu)| < 2.4$ and `isLooseMuon` (for $\tau_\mu\tau_h$)
- $p_T(\tau_e) > 7.0 \text{ GeV}$ and $|\eta(\tau_e)| < 2.5$ and `isLooseElectron` (for $\tau_e\tau_h$)

If an event is to be included in the numerator of the efficiency calculation, the following additional selection criteria must be met at the reco level:

- $p_T(\tau_h) > 10.0 \text{ GeV}$ and $|\eta(\tau_h)| < 2.3$ for μ / e cleaned HPS.

- $\Delta R(\tau_\mu, \tau_h) < 0.8$ (for $\tau_\mu \tau_h$)
- $\Delta R(\tau_e, \tau_h) < 0.8$ (for $\tau_e \tau_h$)
- τ_h passes decayModeFinding, byIsolationMVArun2017v2DBoldDMwLTraw2017 > -0.5 , and tau ID “byMediumIsolationMVArun2017v2DBoldDMwLT2017”
- Reco τ_μ and Gen τ_μ Lowest dR matched. (for $\tau_\mu \tau_h$)
- Reco τ_e and Gen τ_e Lowest dR matched. (for $\tau_e \tau_h$)

Like before, the hadronically decaying tau must pass the following selection criteria:

- $p_T > 10 \text{ GeV}$
- $\eta < 2.3$
- decayModeFinding
- byIsolationMVArun2017v2DBoldDMwLTraw2017 > -0.5
- $dR(\text{Reco } \tau_h, \text{Gen } \tau_h) < 0.1$
- Pass tau ID “byMediumIsolationMVArun2017v2DBoldDMwLT2017” (Definition of signal region)

The Di-Tau reconstruction efficiency for both the μ and e cleaned cases are plotted for several years and various Higgs masses, as a function of the pseudoscalar mass. The dashed lines represent the standard tau collection while solid lines represent the μ / e cleaned tau collection. The plots are shown in Figures B.3 and B.4.

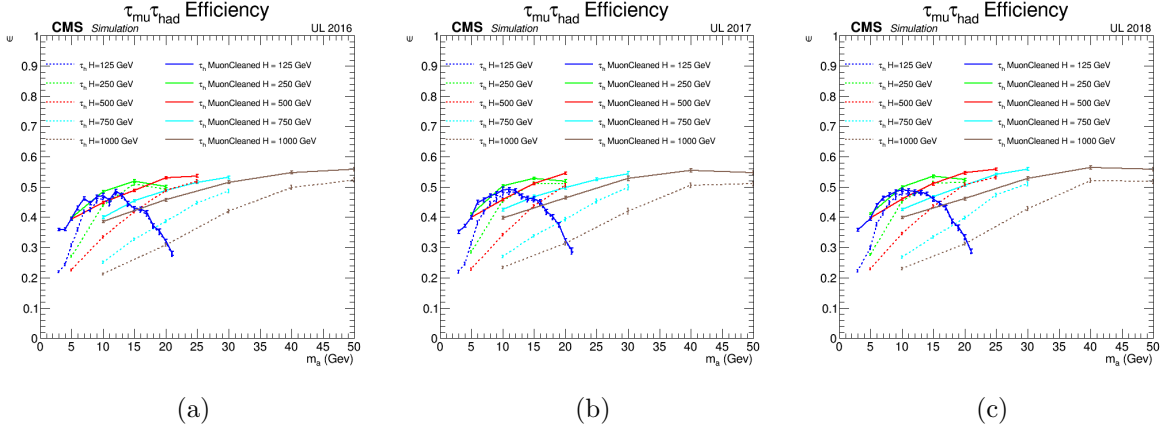


Figure B.3: The Di-Tau reconstruction efficiency of the standard tau HPS (dashed line) and μ cleaned HPS (solid line) reconstruction as a function of pseudoscalar mass for different years and for $m_H = 125, 250, 500, 750$ and 1000.

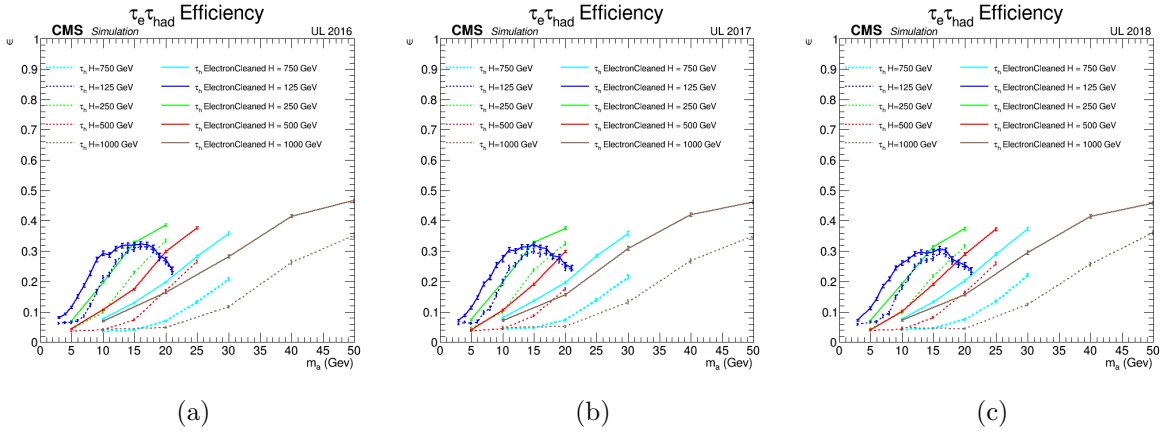


Figure B.4: The Di-Tau reconstruction efficiency of the standard tau HPS (dashed line) and e cleaned HPS (solid line) reconstruction as a function of pseudoscalar mass for different years and for $m_H = 125, 250, 500, 750$ and 1000.

APPENDIX C

AUXILIARY ELECTRONICS AND OPTICAL COMPONENTS - DETAILS

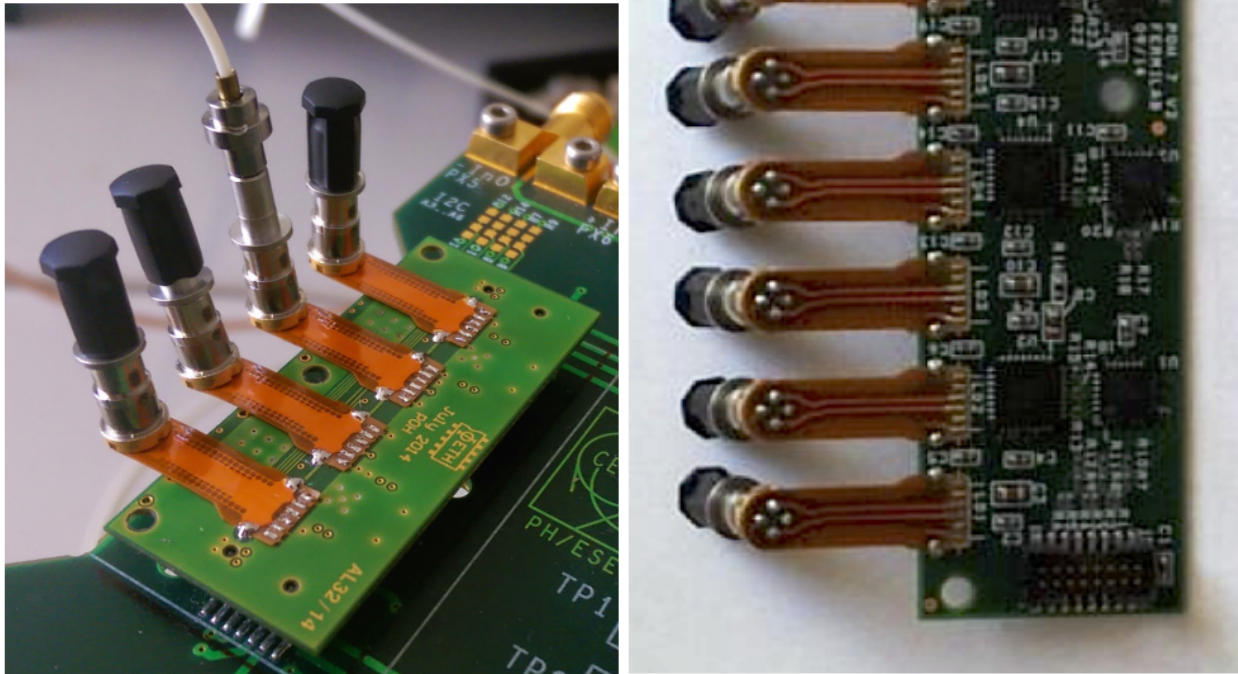


Figure C.1: POH4 (left) and POH7 (right). The POH's are named based on the number of output optical fibres. POH4 is used in BPix while POH7 is used in FPix [55].

C.1 POH

The POH is the Optical component involved with the optical readout. It is mounted on the service cylinders and is responsible for converting and transmitting data from the modules. It converts the electrical signals from the TBMs (with hit and timestamp information) to optical signals and transfers them to the FED.

There are two types of POH in the pixel detector. POH7 (containing seven optical fibers) is present on the FPix, while POH4 (containing four optical fibers) is present on the BPix. On the FPix, the POH is present on the portcard, while on the BPix, it is present on the POH motherboard. There is no portcard on the BPix, but it is kept as a virtual component on the software framework for programming convenience.

Figure C.1 shows the two types of POH present in the Pixel detector.

C.2 DOH

The DOH is the OptoHybrid which acts as the optical control link. It is also mounted on the service cylinder and allows communication between the TkFEC and the auxiliary electronics. It converts electrical signal from the CCU to optical signal for the TkFEC and vice-versa. It enables the exchange of configuration data as well as the trigger, clock, and control signals.

The DOH was developed for the phase 0 pixel detector and is still used in the phase 1 detector [88]. Additionally, a modified version of DOH, the mDOH, is used for two-way communication between the PixFEC and the modules.

C.3 DC-DC Converters

The DC-DC converters are Auxiliary electronics responsible for providing the modules with the required LV [89]. Since the modules have both analog and digital components, DC-DC converters provide both analog and digital LV. The DC-DC converters convert High voltage (input voltage 9 V) at low current to LV at high current to the modules. The LV output can either be 2.4 -2.5 V or 3.5 V depending on whether analog or digital voltage is



Figure C.2: Four DC-DC converters on the a bus board. A pair of the converters are analog while the other pair is digital [52].

supplied. The low current at the input end means lower heat loss in the power cables, and the low voltage at the output is sufficient for providing power to the modules.

In the FPix, the DC-DC converters occur in groups of four or in pairs of two. One pair of DC-DC converters supplies analog voltage while the other pair delivers digital voltage. Each pair provides power to seven modules. In the BPix, DC-DC converters are arranged in groups of two or a single pair and can supply power to various modules, depending on the layer. For example, one pair of DC-DC converters can supply LV to one layer-1 module, two to three layer-2 modules, or four layer-3/ layer-4 modules.

Figure C.2 shows a DC-DC converter on a bus board.

C.4 Portcards

The portcard is an auxiliary electronic device physically present on the FPix and is a virtual concept on the BPix. It is present on the FPix service cylinders, which provide structural support and other services like powering, cooling, and optical connection to the detector [55]. There are 24 port cards per FPix half-cylinder and a total of 96 in the whole detector [52].

The portcard hosts the electronics essential for the communication of the modules with the back-end (PixFEC and FED). The OptoHybrids (POH,mDOH) are responsible for taking away hit information to the FED and bringing clock, trigger, fast signals, and programming



Figure C.3: Picture of a portcard used in an FPix test setup. [90].

instructions from the PixFEC. The portcard has a top and a bottom part, and each has one POH. The POH on the FPix portcard has seven output fibers (POH7), and each fiber has two channels. Thus, one portcard can connect to 14 FPix modules.

In addition to the optical components, the portcard also hosts auxiliary chips like Tracker Phase Locked Loop (TPLL), Quartz-based Phase Locked Loop (QPLL), Delay25, Gatekeeper, Low-Current differential signal (LCDS) drivers. Furthermore, it also contains the DAQ registers for the DC-DC converters.

BPix has the same auxiliary electronics as FPix (POH,mDOH), but the electronics are present separately and not on a common board. For programming convenience, the Opho-Hybrids are together called a "portcard" in BPix. The "portcard" for BPix always hosts electronics for layers 1 and 2 or layers 3 and 4. The number of modules attached to each "portcard" on the Bpox varies as modules from different layers have different input channels. For instance, a layer 1 module has eight channels; layer 2 module has four channels each, modules from layers 3 and 4 have two channels each.

APPENDIX D

DEEP NEURAL NETWORK APPLICATION FOR FULLY HADRONIC FINAL STATE

D.1 Training Information

The DeepDiTau has three output nodes representing light jet, b jet and $\tau_h\tau_h$). The output is interpreted as a vector of three “scores”, one for each output node. The scores are normalized such that they sum to 1 for each AK4 jet. The score for the $\tau_h\tau_h$ channel eventually becomes a discriminating metric that allows us to differentiate between $\tau_h\tau_h$ and other jets (light and b). We cut on the $\tau_h\tau_h$ score and define several working points like any other standard ID. The best working point is selected after detailed optimization studies.

DeepDiTau was trained over a sample of 3.2 million AK4 jets. The sample consists of three components: light jets from QCD, b jets from TTbar, and $\tau_h\tau_h$ from signal samples. The training is always done over equal numbers of light jets, and b jets, and jets from $\tau_h\tau_h$. Any excess light jets and b jets are ignored.

The input features to the tagger (neural net) are variables from global (AK4) jets (40 variables) and their constituent particles: charged hadrons (up to 10 objects, each with 18 variables), neutral hadrons (up to 10 objects, each with 5 variables), and photons (up to 4 objects, each with 6 variables).

D.2 Network Architecture

The distribution for each input feature normalized to have a mean on 0 and a standard deviation of 1, the only exception being the jet η , jet ϕ and jet p_T . Jet η and jet ϕ are linearized from 0 to 1, and the jet p_T is log linearized. The jet particle flow constituents are transformed so that their features are relative to the jet axis.

In order to make the p_T and η distributions of light jet and b jet match those of the $\tau_h\tau_h$ re-weighting factors are applied. The distribution of the weights applied is shown in the Figure D.1.

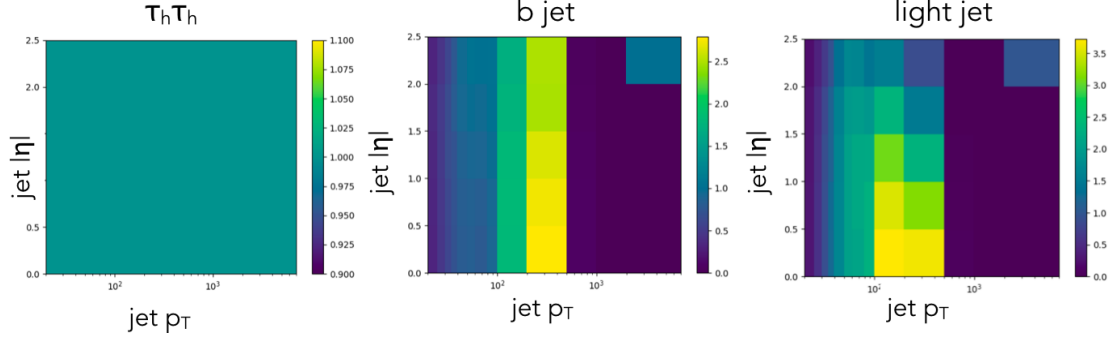


Figure D.1: The light-jet and b-jet distributions in p_T and η are re-weighted to match those of the τ_h, τ_h .

All input features are sent to a dense neural net. The neural net has a width of 256 which means that there is a total of 256 nodes in each layer and the depth of the neural net is 8, which means that there are a total of 8 layers excluding the input layer. The constituent particle flow objects of each jet go through a **LSTM** (long short term memory) layer before being concatenated with the global jet input features and sent to the neural net. The inputs of each layer are normalized to have a mean of 0 and a standard deviation of 1, this is called Batch normalization. A dropout layer is incorporated between each layer, to avoid over-fitting. The dropout layer sets input units to 0 with a frequency equal to the rate at each step during training time. The neural net is trained by minimizing a cross entropy loss function. There is a validation fraction of 0.1, which is used to draw the validation lines on the accuracy and loss plots, shown in Figure D.2.

D.2.1 Performance

The confusion matrix in Figure D.3 shows the general performance of DeepDiTau. The performance as a function of p_T is shown in Figure D.5 and the performance as a function of η is shown in Figure D.5.

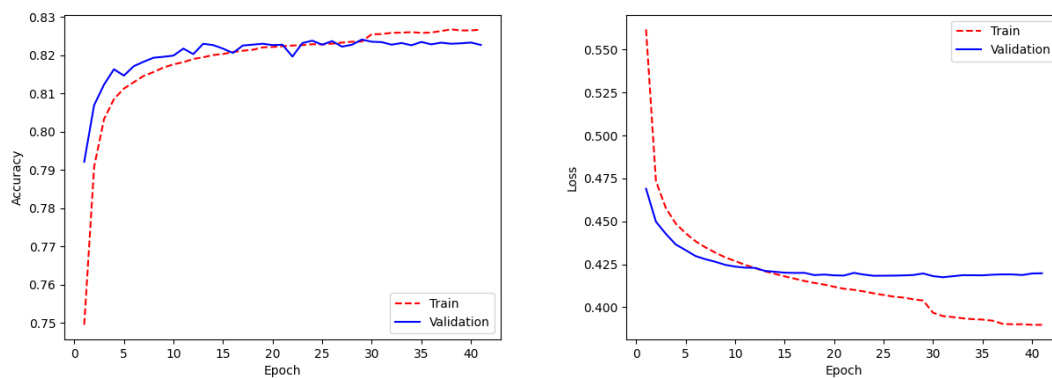


Figure D.2: Accuracy and loss plots of DeepDiTau.

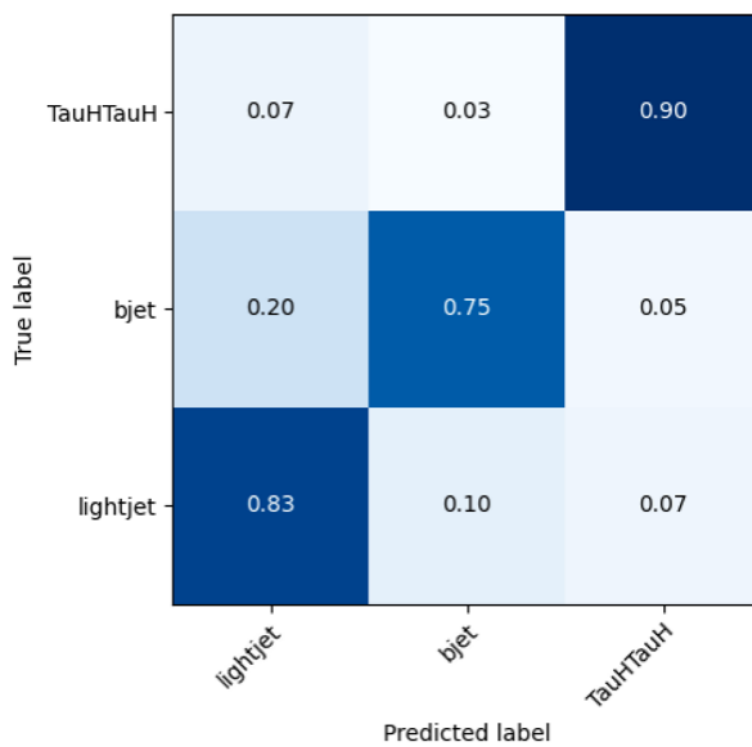


Figure D.3: The confusion matrix for DeepDiTau.

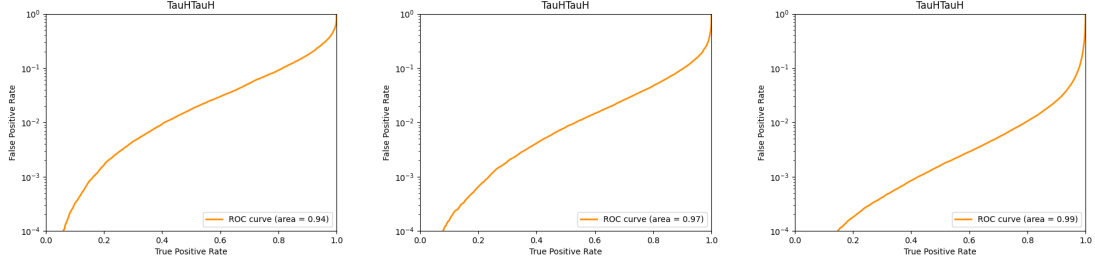


Figure D.4: The performance of DeepDiTau in p_T ranges of $20 - 50 \text{ GeV}$, $50 - 100 \text{ GeV}$, $100 - 1000 \text{ GeV}$

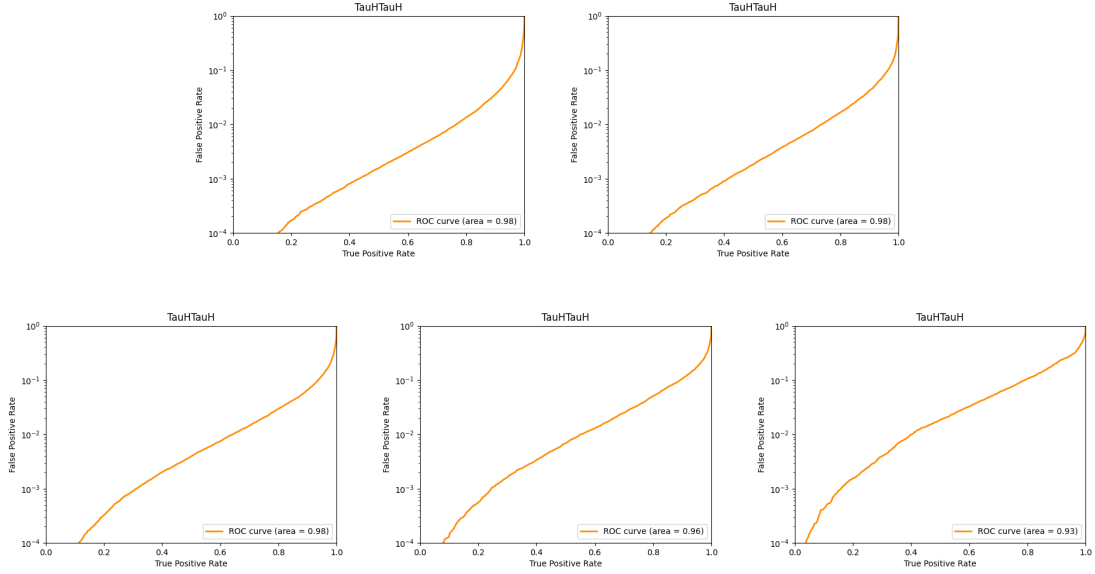


Figure D.5: The performance of DeepDiTau in η ranges of $0 - 0.5$, $0.5 - 1.0$, $1.0 - 1.5$, $1.5 - 2.0$, $2.0 - 2.5$

APPENDIX E

OBSERVED DATA

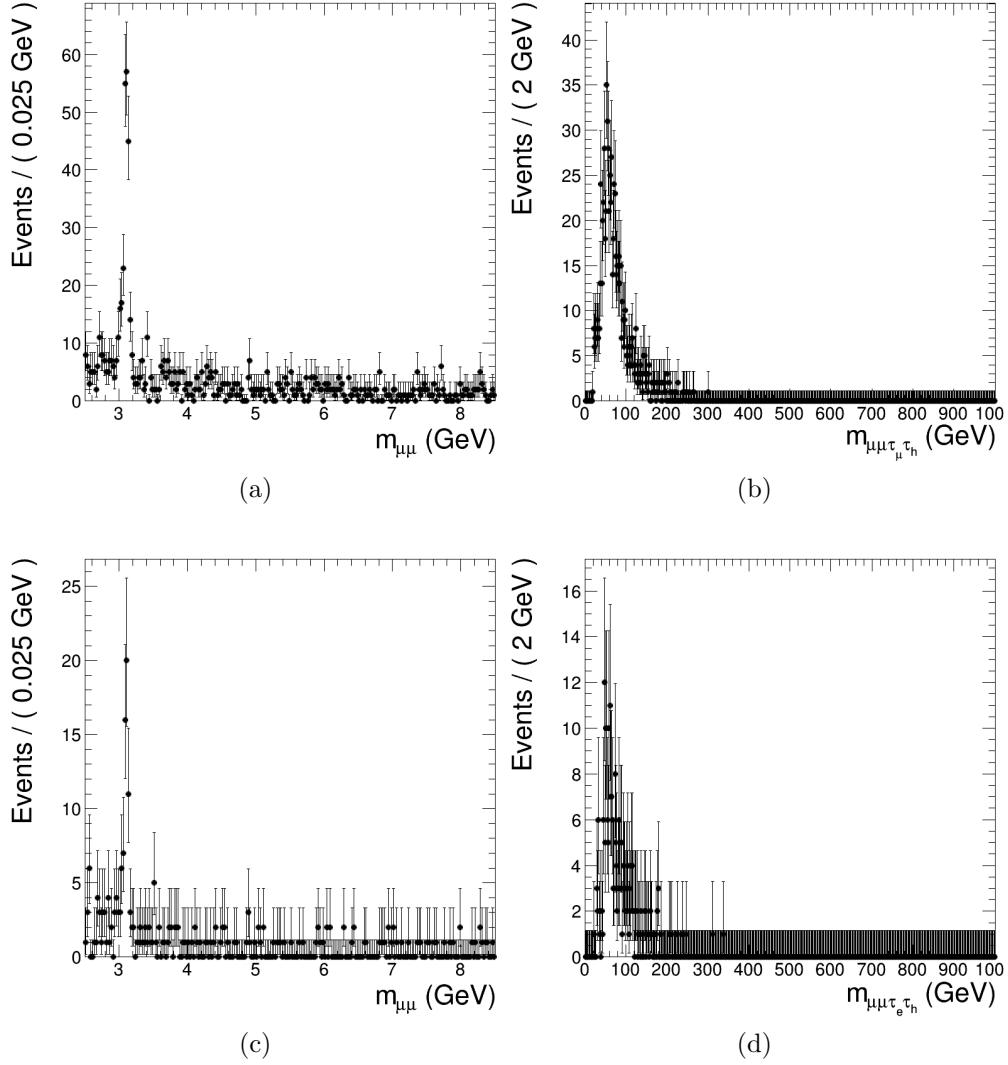


Figure E.1: Observed data in 2016 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. The data are in the low mass region.

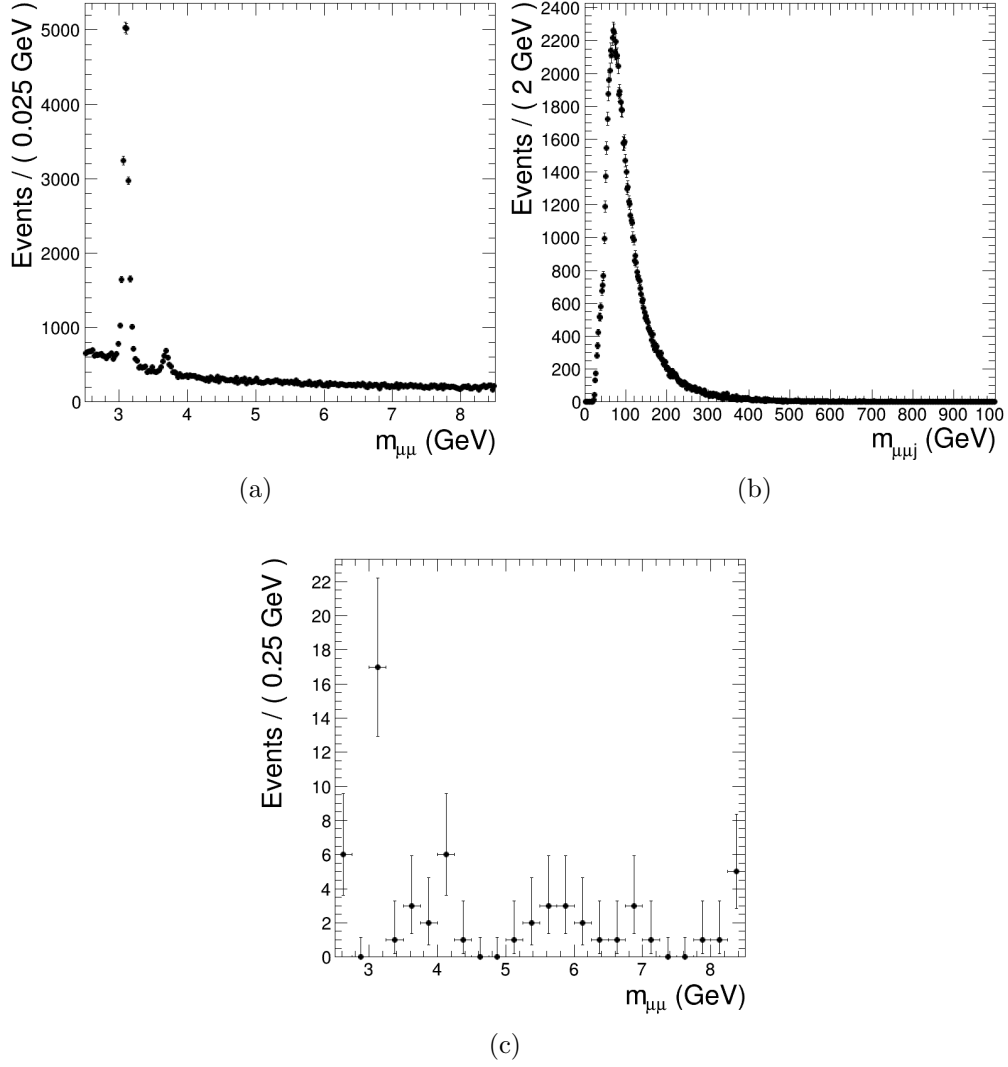


Figure E.2: Observed data in 2016 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The data are in the low mass region.

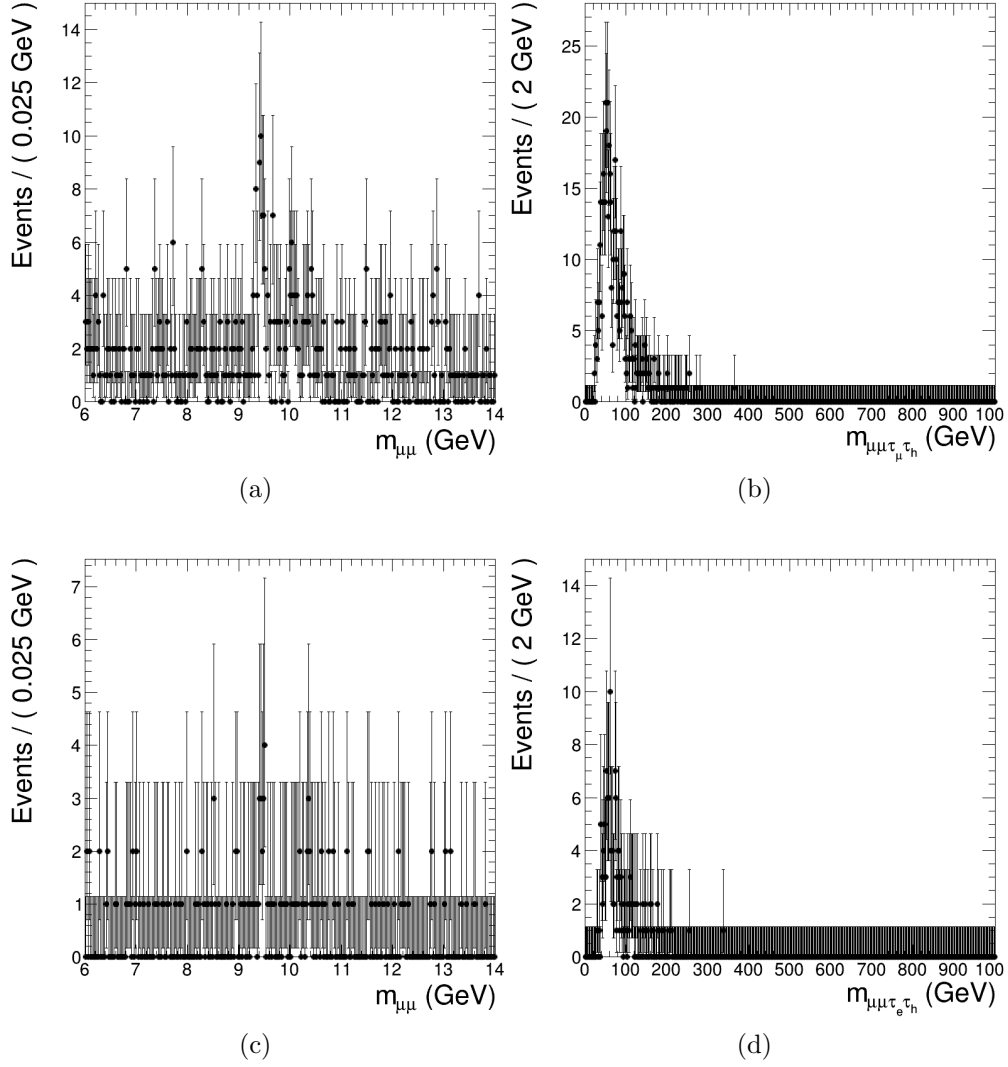


Figure E.3: Observed data in 2016 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. The data are in the epsilon region.

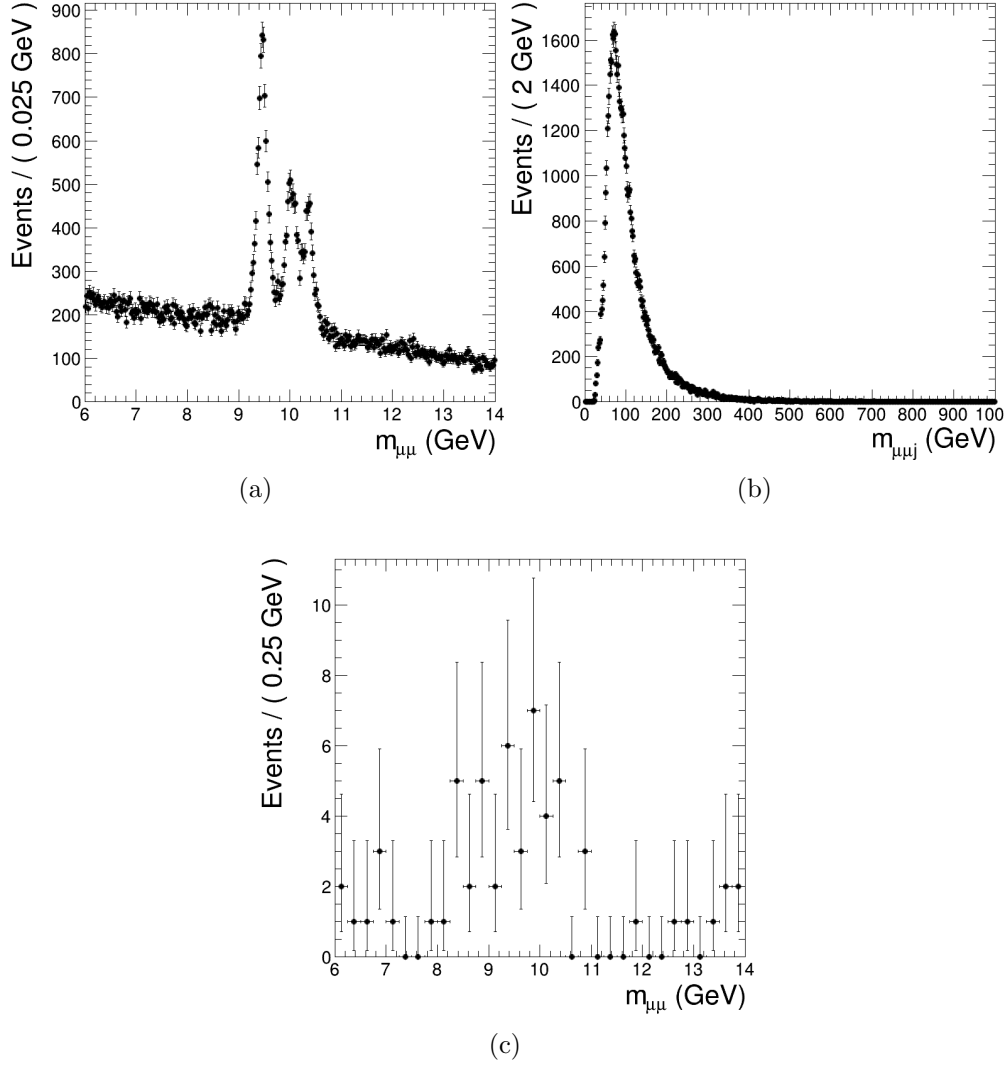


Figure E.4: Observed data in 2016 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The data are in the upsilon region.

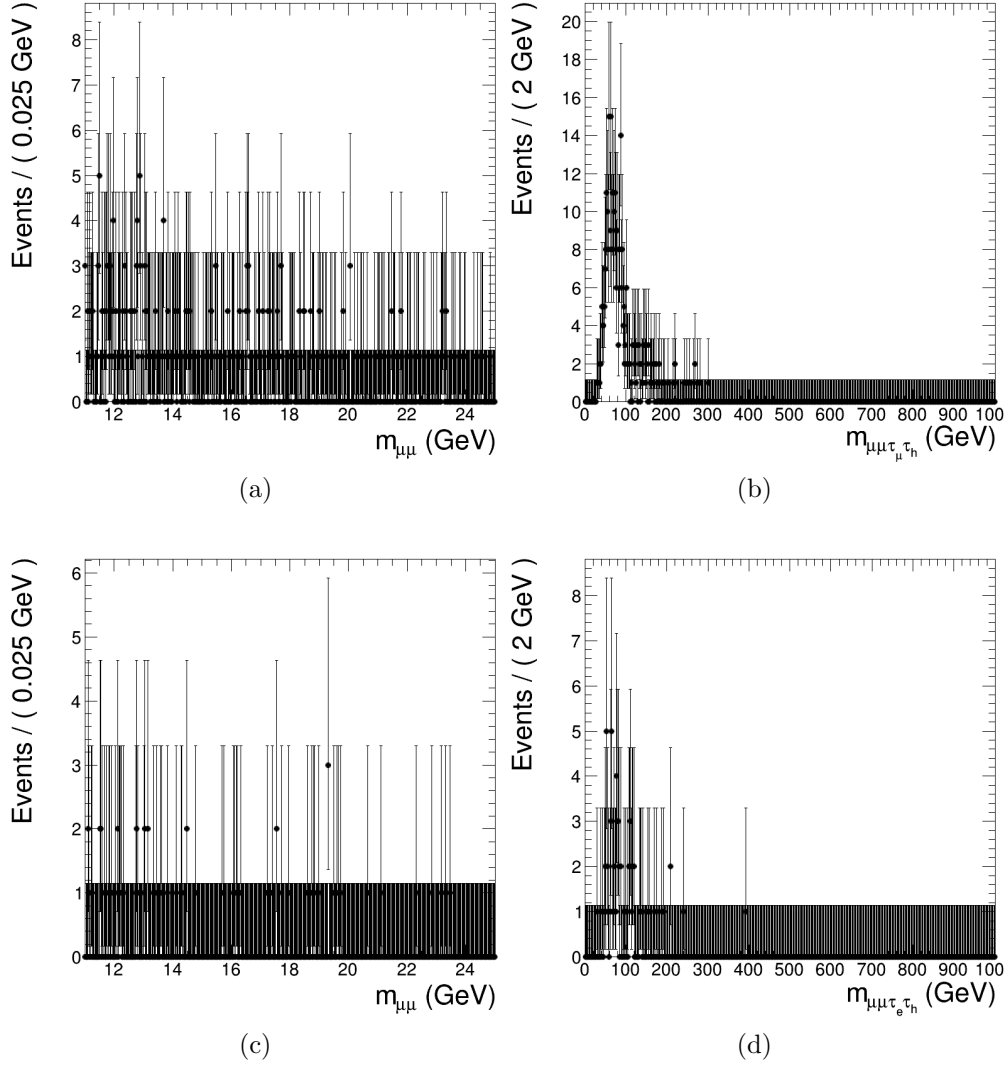


Figure E.5: Observed data in 2016 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. The data are in the high mass region.

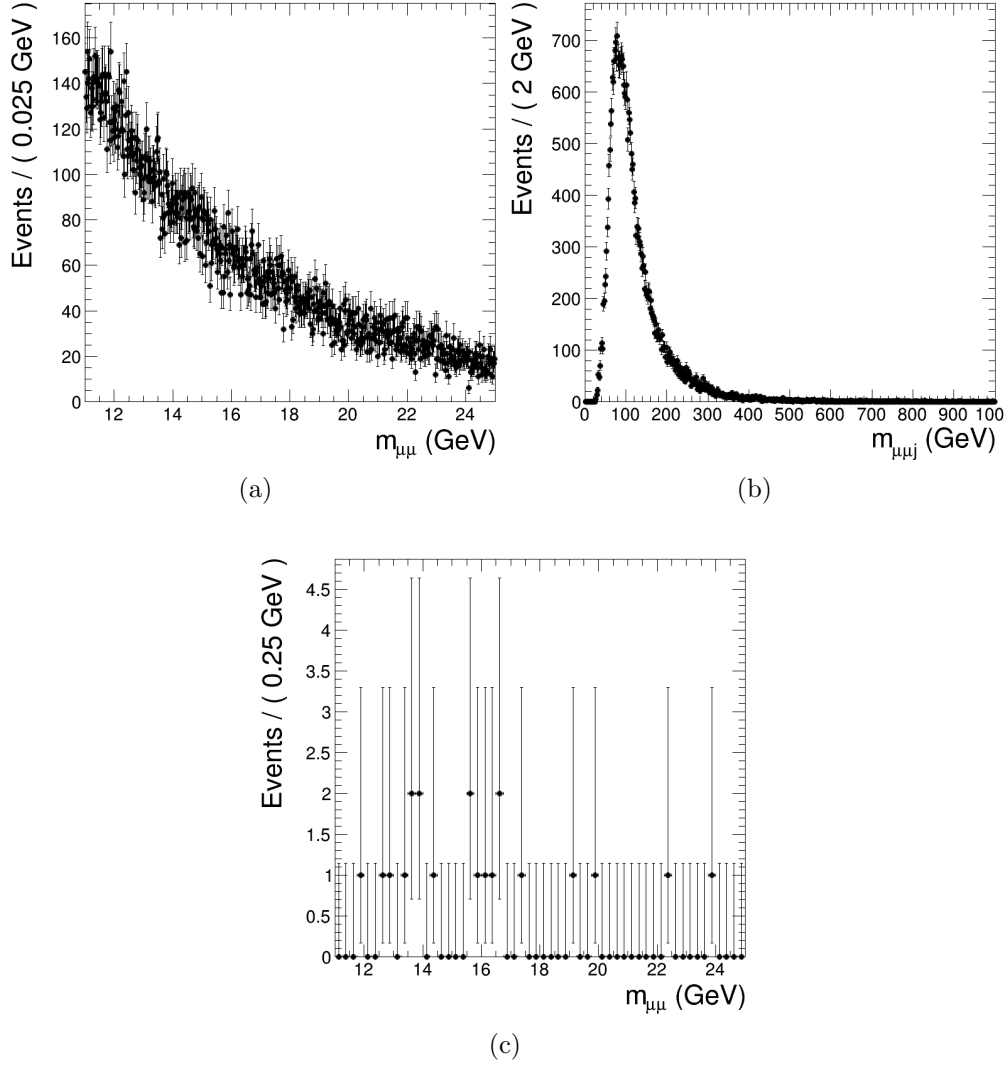


Figure E.6: Observed data in 2016 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. The data are in the high mass region.

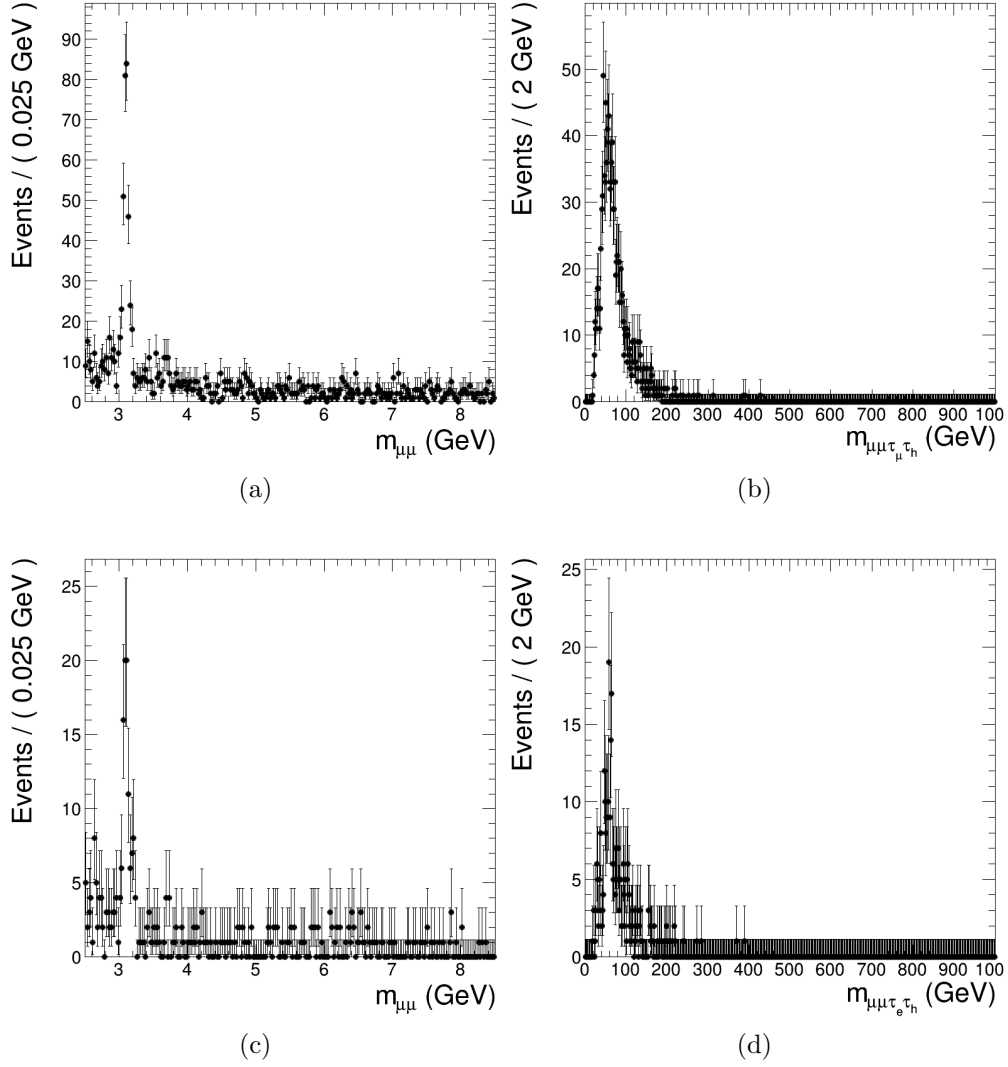


Figure E.7: Observed data in 2017 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots show the low mass region.

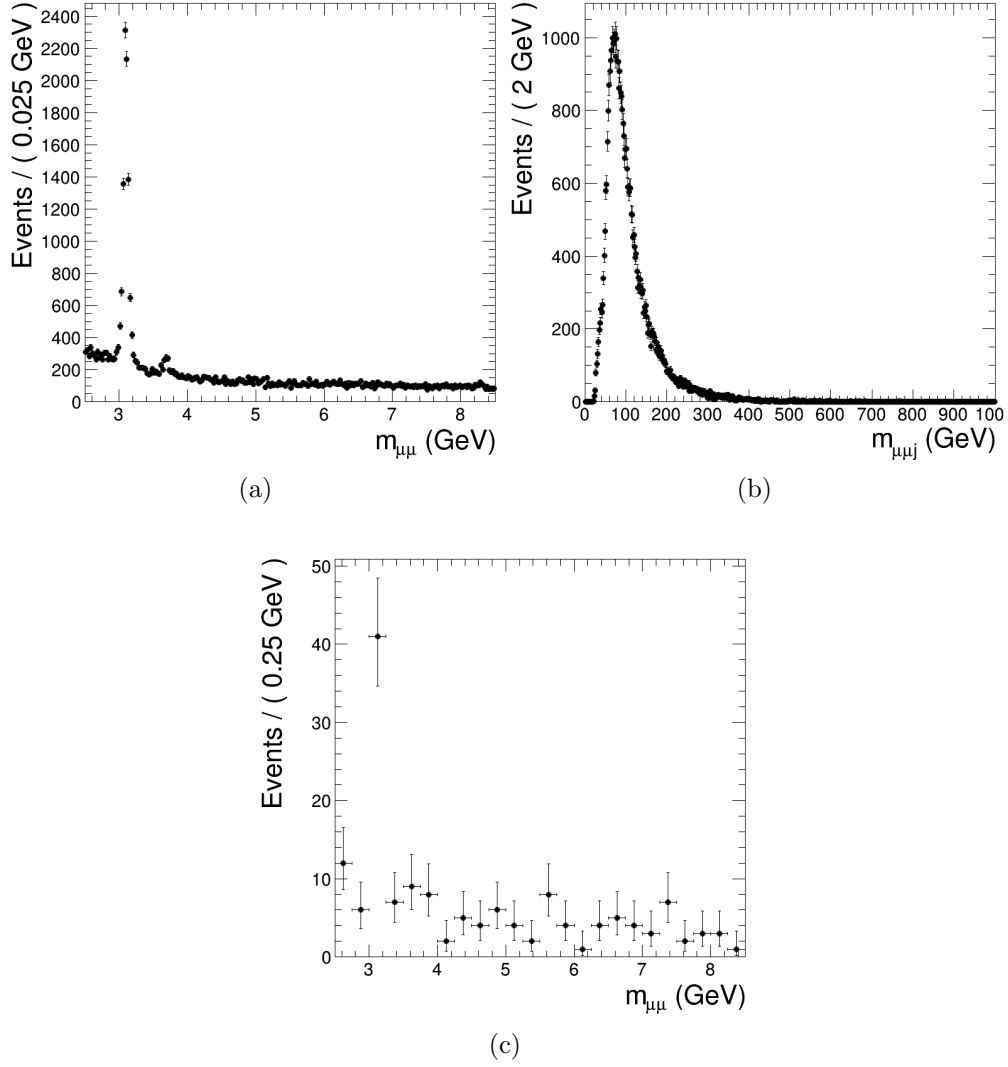


Figure E.8: Observed data in 2017 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. These plots show the low mass region.

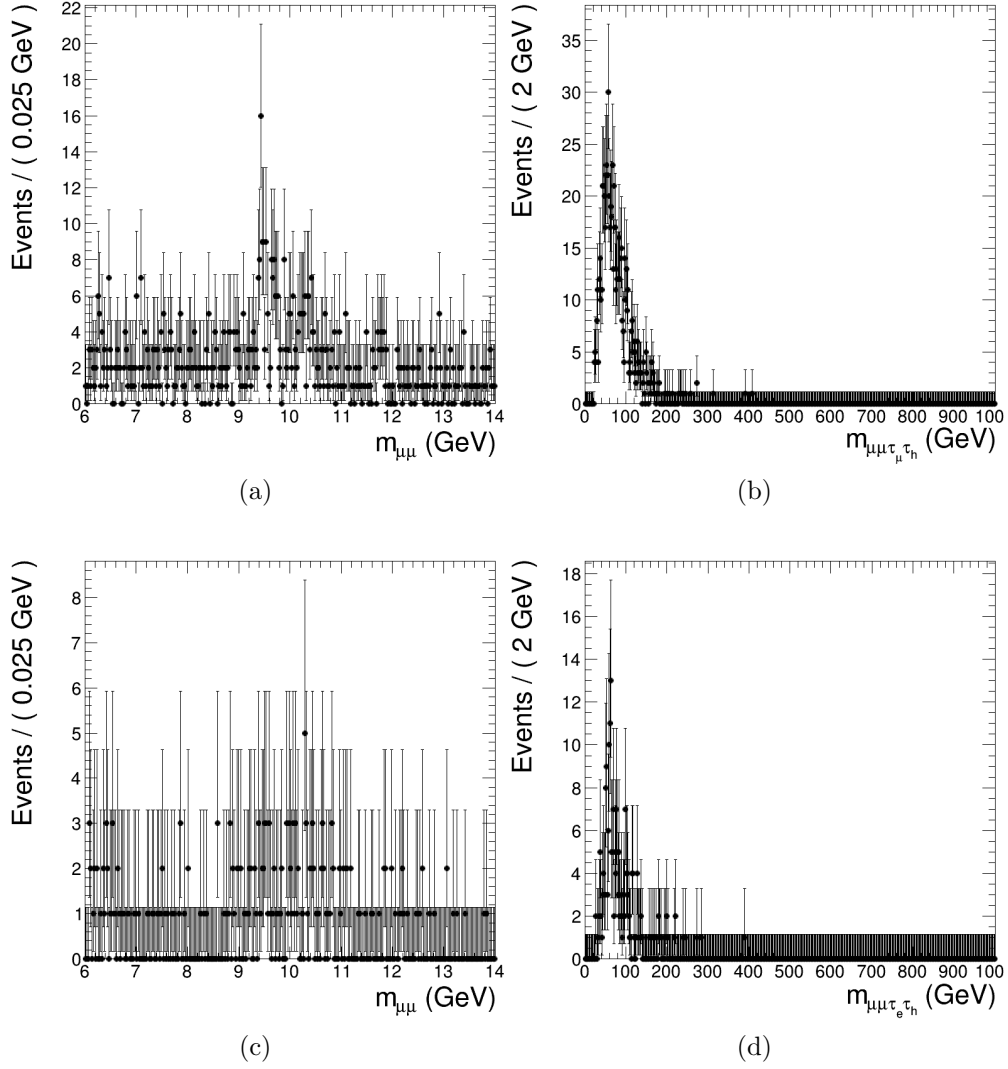


Figure E.9: Observed data in 2017 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots show the upsilon region.

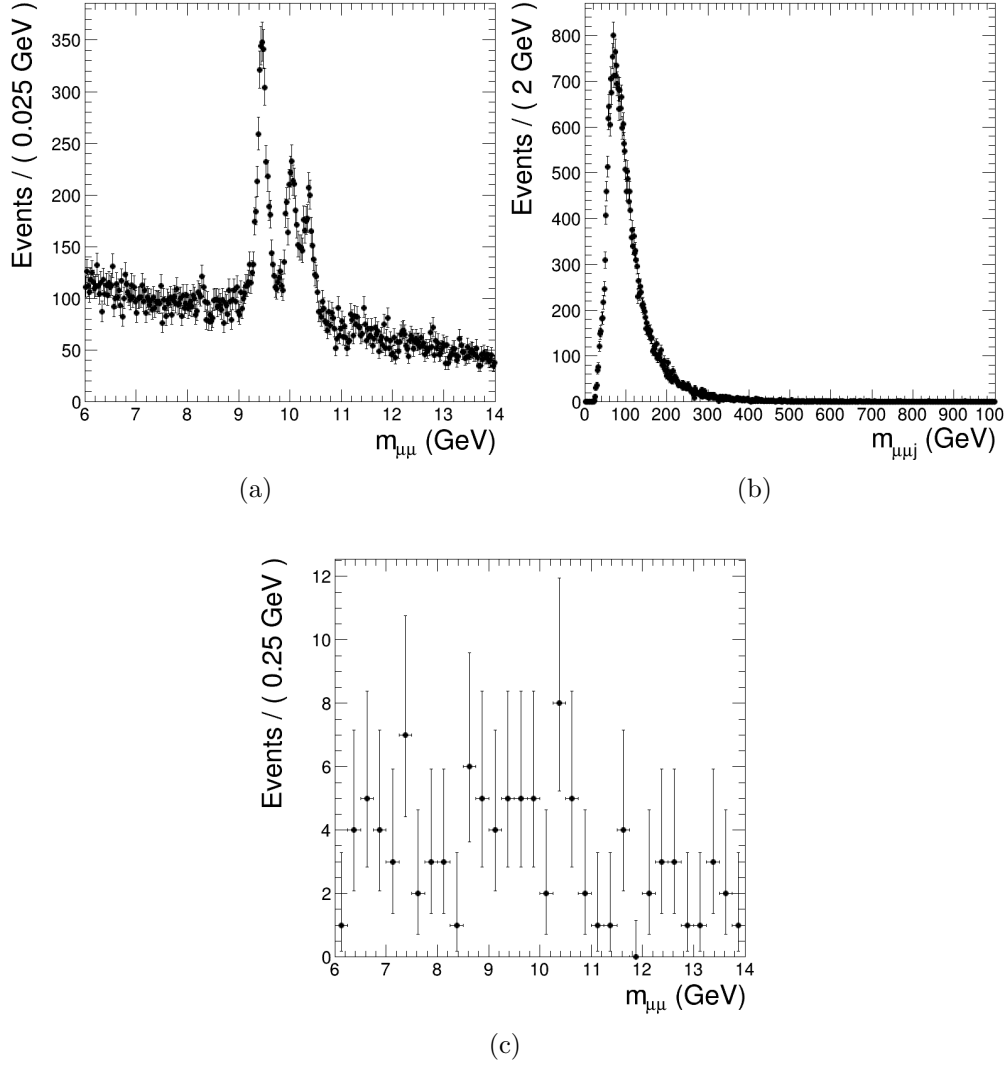


Figure E.10: Observed data in 2017 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. These plots show the upsilon region.

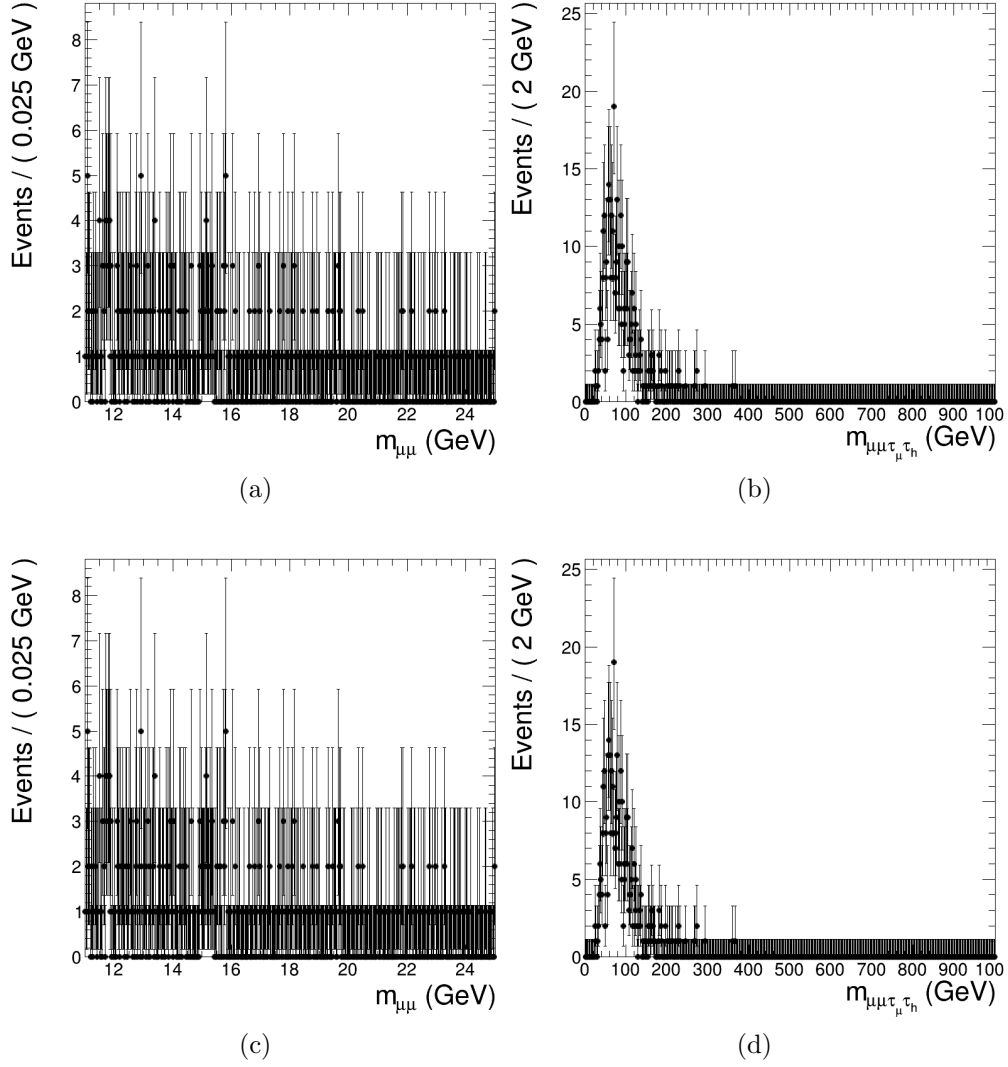


Figure E.11: Observed data in 2017 as a function of dimuon invariant mass (left) and 4-body visible mass (right) for the $\mu\mu\tau_\mu\tau_h$ (top) and $\mu\mu\tau_e\tau_h$ (bottom) channels. These plots show the high mass region.

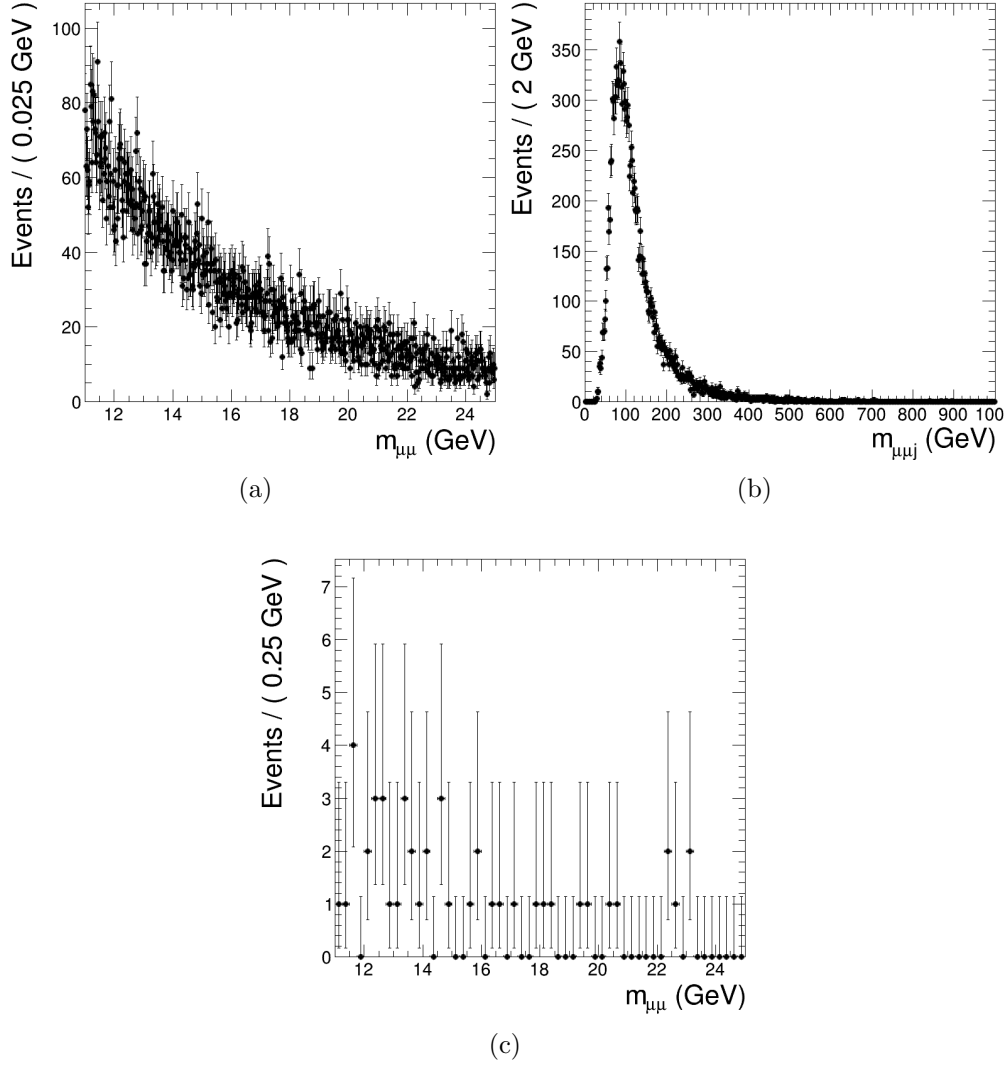


Figure E.12: Observed data in 2017 as a function of dimuon invariant mass (a) and 4-body visible mass (b) for the $\mu\mu\tau_h\tau_h$ channel and as a function of dimuon invariant mass (c) for the $\mu\mu\tau_\mu\tau_e$ channel. These plots show the high mass region.

Table E.1: Table showing in detail the Background MC samples for the 2016,2017 and 2018. Era, pythia tune, campaign and version information included.

Year	Physics processes	Dataset name	σ (pb)
2018	Z/γ^*	DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIISummer20UL18MiniAODv2-106X_upgrade2018_realistic_v16.L1v1-v2/MINIAODSIM	5398.0
	$t\bar{t}$	TTJets_TuneCP5_13TeV-ancatnloFxFX-pythia8/RunIISummer20UL18MiniAOD-106X_upgrade2018_realistic_v11.L1v1-v1/MINIAODSIM	750.5
	W-Jets	WJetsToLLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIISummer20UL18MiniAODv2-106X_upgrade2018_realistic_v16.L1v1-v1/MINIAODSIM	53870.0
	Di-Boson WW	WW_TuneCP5_13TeV-pythia8/RunIISummer20UL18MiniAODv2-106X_upgrade2018_realistic_v16.L1v1-v1/MINIAODSIM	75.95
	Di-Boson WZ	WZ_TuneCP5_13TeV-pythia8/RunIISummer20UL18MiniAODv2-106X_upgrade2018_realistic_v16.L1v1-v1/MINIAODSIM	27.59
	Di-Boson $W(\ell\nu)Z(\ell\ell)$	WZTo3LLNu_TuneCP5_13TeV-ancatnloFxFX-pythia8/RunIISummer20UL18MiniAODv2-106X_upgrade2018_realistic_v16.L1v1-v2/MINIAODSIM	5.213
	Di-Boson ZZ	ZZ_TuneCP5_13TeV-pythia8/RunIISummer20UL18MiniAOD-106X_upgrade2018_realistic_v11.L1v1-v2/MINIAODSIM	12.17
	Di-Boson $Z(\ell\ell)Z(\ell\ell)$	ZZTo4L_TuneCP5_13TeV_powheg-pythia8/RunIISummer20UL18MiniAODv2-106X_upgrade2018_realistic_v16.L1v1-v2/MINIAODSIM	1.325
2017	Z/γ^*	DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIISummer20UL17MiniAODv2-106X_mc2017_realistic_v9-v2/MINIAODSIM	5358.0
	$t\bar{t}$	TTJets_TuneCP5_13TeV-ancatnloFxFX-pythia8/RunIISummer20UL17MiniAODv2-106X_mc2017_realistic_v9-v2/MINIAODSIM	750.5
	W-Jets	WJetsToLLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIISummer20UL17MiniAODv2-106X_mc2017_realistic_v9-v1/MINIAODSIM	53870.0
	Di-Boson WW	WW_TuneCP5_13TeV-pythia8/RunIISummer20UL17MiniAODv2-106X_mc2017_realistic_v9-v1/MINIAODSIM	75.95
	Di-Boson WZ	WZ_TuneCP5_13TeV-pythia8/RunIISummer20UL17MiniAODv2-106X_mc2017_realistic_v9-v1/MINIAODSIM	27.59
	Di-Boson $W(\ell\nu)Z(\ell\ell)$	WZTo3LLNu_TuneCP5_13TeV-ancatnloFxFX-pythia8/RunIISummer20UL17MiniAODv2-106X_mc2017_realistic_v9-v2/MINIAODSIM	5.219
	Di-Boson ZZ	ZZ_TuneCP5_13TeV-powheg-pythia8/RunIISummer20UL17MiniAODv2-106X_mc2017_realistic_v9-v1/MINIAODSIM	12.17
	Di-Boson $Z(\ell\ell)Z(\ell\ell)$	ZZTo4L_TuneCP5_13TeV_powheg-pythia8/RunIISummer20UL17MiniAODv2-106X_mc2017_realistic_v9-v2/MINIAODSIM	1.325
2016	Z/γ^*	DYJetsToLL_M-50_TuneCP5_13TeV-ancatnloFxFX-pythia8/RunIISummer20UL16MiniAODAPVv2-106X_mcRun2_asymptotic_preVFP_v11-v1/MINIAODSIM	6404.0
	$t\bar{t}$	DYJetsToLL_M-50_TuneCP5_13TeV-ancatnloFxFX-pythia8/RunIISummer20UL16MiniAOD-106X_mcRun2_asymptotic_v13-v2/MINIAODSIM	6404.0
	W-Jets	TTJets_TuneCP5_13TeV-ancatnloFxFX-pythia8/RunIISummer20UL16MiniAODAPV-106X_mcRun2_asymptotic_preVFP_v8-v1/MINIAODSIM	750.5
	Di-Boson WW	WW_TuneCP5_13TeV-pythia8/RunIISummer20UL16MiniAOD-106X_mcRun2_asymptotic_v13-v1/MINIAODSIM	831.7
	Di-Boson WZ	WZ_TuneCP5_13TeV-pythia8/RunIISummer20UL16MiniAODAPV-106X_mcRun2_asymptotic_preVFP_v8-v1/MINIAODSIM	67350
	Di-Boson $W(\ell\nu)Z(\ell\ell)$	WZTo3LLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIISummer20UL16MiniAODv2-106X_mcRun2_asymptotic_v17-v1/MINIAODSIM	53870.0
	Di-Boson ZZ	ZZ_TuneCP5_13TeV-pythia8/RunIISummer20UL16MiniAODv2-106X_mcRun2_asymptotic_preVFP_v11-v1/MINIAODSIM	75.95
	Di-Boson $Z(\ell\ell)Z(\ell\ell)$	ZZTo4L_M-1toInf_TuneCP5_13TeV_powheg-pythia8/RunIISummer20UL16MiniAODAPVv2-106X_mcRun2_asymptotic_preVFP_v11-v1/MINIAODSIM	13.74

BIBLIOGRAPHY

- [1] Stephen P. Martin. A Supersymmetry primer. *Adv. Ser. Direct. High Energy Phys.*, 18:1–98, 1998.
- [2] David Curtin et al. Exotic decays of the 125 GeV Higgs boson. *Phys. Rev. D*, 90(7):075004, 2014.
- [3] Serguei Chatrchyan et al. Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC. *Phys. Lett. B*, 716:30–61, 2012.
- [4] Albert M Sirunyan et al. Combined measurements of Higgs boson couplings in proton–proton collisions at $\sqrt{s} = 13$ TeV. *Eur. Phys. J. C*, 79(5):421, 2019.
- [5] Georges Aad et al. Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV. *JHEP*, 08:045, 2016.
- [6] Albert M Sirunyan et al. Combined measurements of Higgs boson couplings in proton–proton collisions at $\sqrt{s} = 13$ TeV. *Eur. Phys. J. C*, 79(5):421, 2019.
- [7] Carsten Burgard. Standard model of physics.
- [8] CERN. The standard model.
- [9] office of science. Doe explains...the standard model of particle physics.
- [10] CPEP. Fundamental particles and interactions.
- [11] P.A. Zyla et al. Review of Particle Physics. *PTEP*, 2020(8):083C01, 2020.
- [12] Michael Edward Peskin and Daniel V. Schroeder. *An Introduction to Quantum Field Theory*. Westview Press, 1995. Reading, USA: Addison-Wesley (1995) 842 p.
- [13] Georges Aad et al. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett. B*, 716:1–29, 2012.
- [14] Y. Fukuda. Evidence for oscillation of atmospheric neutrinos. *Phys. Rev. Lett.*, 81:1562–1567, Aug 1998.

- [15] M. Maniatis. The Next-to-Minimal Supersymmetric extension of the Standard Model reviewed. *Int. J. Mod. Phys. A*, 25:3505–3602, 2010.
- [16] Alejandro Celis, Victor Ilisie, and Antonio Pich. LHC constraints on two-Higgs doublet models. *JHEP*, 07:053, 2013.
- [17] Benjamin Grinstein and Patipan Uttayarat. Carving Out Parameter Space in Type-II Two Higgs Doublets Model. *JHEP*, 06:094, 2013. [Erratum: *JHEP* 09, 110 (2013)].
- [18] Baradhwaj Coleppa, Felix Kling, and Shufang Su. Constraining Type II 2HDM in Light of LHC Higgs Searches. *JHEP*, 01:161, 2014.
- [19] Nathaniel Craig, Jamison Galloway, and Scott Thomas. Searching for Signs of the Second Higgs Doublet. 5 2013.
- [20] Lei Wang and Xiao-Fang Han. Status of the aligned two-Higgs-doublet model confronted with the Higgs data. *JHEP*, 04:128, 2014.
- [21] Beranger Dumont, John F. Gunion, Yun Jiang, and Sabine Kraml. Constraints on and future prospects for Two-Higgs-Doublet Models in light of the LHC Higgs signal. *Phys. Rev. D*, 90:035021, 2014.
- [22] S. F. King, M. Mühlleitner, R. Nevzorov, and K. Walz. Natural NMSSM Higgs Bosons. *Nucl. Phys. B*, 870:323–352, 2013.
- [23] Junjie Cao, Fangfang Ding, Chengcheng Han, Jin Min Yang, and Jingya Zhu. A light Higgs scalar in the NMSSM confronted with the latest LHC Higgs data. *JHEP*, 11:018, 2013.
- [24] David G. Cerdeno, Pradipta Ghosh, and Chan Beom Park. Probing the two light Higgs scenario in the NMSSM with a low-mass pseudoscalar. *JHEP*, 06:031, 2013.
- [25] G. Chalons and F. Domingo. Analysis of the Higgs potentials for two doublets and a singlet. *Phys. Rev. D*, 86:115024, 2012.
- [26] Search for a light NMSSM Higgs boson produced in supersymmetric cascades and decaying into a b-quark pair. 2015.
- [27] Albert M Sirunyan et al. A search for pair production of new light bosons decaying into muons in proton-proton collisions at 13 TeV. *Phys. Lett. B*, 796:131–154, 2019.
- [28] Serguei Chatrchyan et al. Search for a Light Pseudoscalar Higgs Boson in the Dimuon Decay Channel in pp Collisions at $\sqrt{s} = 7$ TeV. *Phys. Rev. Lett.*, 109:121801, 2012.

- [29] Roel Aaij et al. Search for a dimuon resonance in the Υ mass region. *JHEP*, 09:147, 2018.
- [30] V. Khachatryan et al. Search for light bosons in decays of the 125 GeV Higgs boson in proton-proton collisions at $\sqrt{s} = 8$ TeV. *JHEP*, 10:076, 2017.
- [31] Albert M Sirunyan et al. Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state of two muons and two τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JHEP*, 11:018, 2018.
- [32] Morad Aaboud et al. Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton events with the ATLAS detector at $\sqrt{s} = 13$ TeV. *JHEP*, 06:166, 2018.
- [33] Albert M Sirunyan et al. Search for a light pseudoscalar Higgs boson in the boosted $\mu\mu\tau\tau$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV. *JHEP*, 08:139, 2020.
- [34] CERN website. The Large hadron Collider, 2017.
- [35] CERN Press. LHC the guide, 2017.
- [36] Barbara. Travel Theme; Circles The biggest man-made circle in the world.
- [37] Lyndon Evans and Philip Bryant. LHC machine. *Journal of Instrumentation*, 3(08):S08001–S08001, aug 2008.
- [38] CERN website. Taking a closer look at LHC.
- [39] ECAL Group. *The CMS electromagnetic calorimeter project: Technical Design Report*. Technical design report. CMS. CERN, Geneva, 1997.
- [40] Marzena Lapka. Materials for CMS ECAL POSTER.
- [41] S. Chatrchyan et al. The CMS Experiment at the CERN LHC. *JINST*, 3:S08004, 2008.
- [42] Julian Williams. CMS ECAL Endcaps photographs.
- [43] Philippe Bloch, Robert Brown, Paul Lecoq, and Hans Rykaczewski. *Changes to CMS ECAL electronics: addendum to the Technical Design Report*. Technical design report. CMS. CERN, Geneva, 2002.
- [44] cms-dpg-conveners ecal@cern.ch. ECAL 2016 refined calibration and Run2 summary plots, Apr 2020.

- [45] cms-dpg-conveners ecal@cern.ch. CMS ECAL Response to Laser Light, Mar 2019.
- [46] CMS Silicon Strip Tracker Performance during Run 2. Mar 2021.
- [47] Gianluca Cerminara and Broen Toon L Van Besien. Automated workflows for critical time-dependent calibrations at the CMS experiment. Technical report, CERN, Geneva, May 2015.
- [48] Silicon Strip Tracker Performance results 2018. Sep 2018.
- [49] Nadja Strobbe. The upgrade of the CMS hadron calorimeter with silicon photomultipliers, 2016.
- [50] A. M. Sirunyan et al. Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV. *JINST*, 13(06):P06015, 2018.
- [51] A Dominguez. CMS Technical Design Report for the Pixel Detector Upgrade. Technical Report CERN-LHCC-2012-016, CMS-TDR-11, Tracker, 2012.
- [52] The Tracker Group of the CMS Collaboration. The CMS Phase-1 Pixel Detector Upgrade. *accepted by JINST*, 2020.
- [53] R. Stringer. A digital readout system for the CMS Phase I Pixel Upgrade. *JINST*, 10(04):C04037, 2015.
- [54] Edward Bartz. The $0.25\mu\text{m}$ token bit manager chip for the CMS pixel readout. *Conf. Proc. C0591210*, page 25, 2005.
- [55] The Tracker Group of the CMS Collaboration. The DAQ and Control System for the CMS Phase-1 pixel detector upgrade. *JINST*, 14:P10017, 2019.
- [56] Marco Rossini. Readout chip for the CMS pixel detector upgrade. *Nucl. Instrum. Meth.*, 765:209 – 213, 2014.
- [57] Paul Schütze. Silicon Pixel Detectors - Performance after Irradiation and Application in Three-dimensional Imaging, 2019.
- [58] Danek Kotlinski. Pixel ASICs, March 2018.
- [59] Bora Akgun. DAQ Setups, July 2018.
- [60] Atanu Modak. CMS Phase-1 Pixel Detector: Operational Experience, Performance and Lessons Learned. *PoS, Vertex2019:009*, 2020.

- [61] CERN. DCDC project.
- [62] F.F Faccio. Feast 2.1 irradiation in the irradi facility, 2018.
- [63] Phase-I Pixel ROC Thresholds and DC-DC Converter Characterization in 2018. Feb 2020.
- [64] cms-dpg-conveners tracker@cern.ch. The Phase-1 Pixel Detector Performance in 2018. Mar 2021.
- [65] Daniel Pitzl. Psi46digv2.1-documentation.
- [66] Redwan Habibullah. CMS Phase-1 pixel detector readback current and voltages, 2019.
- [67] Lea Caminada. Analysis of BPIX readback voltages and currents.
- [68] Maren Meinhard. Radiation hardness of PROC600V2.
- [69] Redwan Habibullah. Pixel ROC Readback voltage Monitoring and Analysis.
- [70] Georgios Krintiras. CMS Luminosity - Public Results.
- [71] LPC. LPC Performance plots.
- [72] CMS. BRIL Work Suite.
- [73] Danek Kotlinski. BPix - Radiation doses, projections.
- [74] BRIL Radiation Simulation group. Radiation Simulation Plotting tool v.2.4.
- [75] Jory Sonneveld. Fluence and dose from FLUKA and estimate formulas into database.
- [76] Redwan Md Habibullah. Automatic timing scan.
- [77] Sarah Dambach. *CMS pixel module readout optimization and study of the B lifetime in the semileptonic decay mode*. PhD thesis, ETH Zurich, 2009. presented 2009.
- [78] Vardan Khachatryan et al. Reconstruction and identification of τ lepton decays to hadrons and ν_τ at CMS. *JINST*, 11(01):P01019, 2016.
- [79] Matteo Cacciari, Gavin P Salam, and Gregory Soyez. The anti-ktjet clustering algorithm. *Journal of High Energy Physics*, 2008(04):063–063, apr 2008.

- [80] Search for Higgs Decays to New Light Bosons in Boosted Tau Final States. 2015.
- [81] A. M. Sirunyan et al. Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV. *JINST*, 13(10):P10005, 2018.
- [82] Joscha Knolle. Luminosity Physics Object Group (Lumi POG) , 2021.
- [83] A L Read. Presentation of search results: theCLstechnique. *Journal of Physics G: Nuclear and Particle Physics*, 28(10):2693–2704, sep 2002.
- [84] Thomas Junk. Confidence level computation for combining searches with small statistics. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 434(2):435–443, 1999.
- [85] Higgs combine. <https://cms-hcomb.gitbooks.io/combine/content/>.
- [86] Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. Asymptotic formulae for likelihood-based tests of new physics. *Eur. Phys. J. C*, 71:1554, 2011. [Erratum: 10.1140/epjc/s10052-013-2501-z].
- [87] Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector. 2/2017, 10 2016.
- [88] J. Troska, G. Cervelli, F. Faccio, K. Gill, R. Grabit, R.M. Jareno, A.M. Sandvik, and F. Vasey. Optical readout and control systems for the cms tracker. *IEEE Transactions on Nuclear Science*, 50(4):1067–1072, 2003.
- [89] L. Feld, W. Karpinski, K. Klein, M. Lipinski, M. Preuten, M. Rauch, St. Schmitz, and M. Wlochal. The DC-DC conversion power system of the CMS Phase-1 pixel upgrade. *JINST*, 10(01):C01052, 2015.
- [90] Theoni Prousalidi. User guide for the pixel detector test-setups, 2019.

BIOGRAPHICAL SKETCH

Redwan Md Habibullah completed his B.Sc in Physics from the Department of Physics, University of Dhaka in 2015. He started his Ph.D at Florida State University in August 2016, where he worked in the field of High energy experimental particle physics. He searched for physics beyond the standard model and contributed to the Research, development and operations of silicon based particle detectors. He plans to graduate in summer 2022 and is intended to take up a position as a Product and Integration Engineer at Intel.

Due to the nature of his work, Redwan spent a significant portion of his Ph.D travelling between Europe and the USA. He was stationed in the France-Swiss border for roughly 2.5 years, where he worked at the CMS experiment at the LHC. While living in Tallahassee, Florida for the remaining part of his Ph.D , he actively participated in different Student Organizations. He was a member of executive committee for both Bangladesh Student Association (BSA) and Physics Graduate Student Association (PGSA).