

Single top-quark production cross-section measurement in
association with Z boson and performance studies
of the RPCs with the CMS detector using
8 TeV pp collisions at the LHC



by

Muhammad Shoaib

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
AT
QUAID-I-AZAM UNIVERSITY
ISLAMABAD, PAKISTAN
MARCH, 2017



CERTIFICATE

The undersigned hereby certify that the research work presented in this thesis titled “**Single top-quark production cross-section measurement in association with Z boson and performance studies of the RPCs with the CMS detector using 8 TeV pp collisions at the LHC**” by **Muhammad Shoaib** is carried out under my supervision in partial fulfillment of the requirements for the degree of **Doctor of Philosophy**.

Supervisor:

Prof. Hafeez R. Hoorani

Director General

National Center For Physics

Quaid-i-Azam University Campus

Islamabad, Pakistan

Submitted Through:

Prof. Dr. Arif Mumtaz

Chairman

Department of Physics

Quaid-i-Azam University

Islamabad, Pakistan

*Dedicated to my wife Samina Faiz, my son Abdul Ahad,
and my family*

Abstract

In this thesis, the measurement of the tqZ production cross-section for both the inclusive and exclusive cases are reported. The top quark being the heaviest particle in the Standard Model (SM) has been discovered about two decades ago but many of its properties have still not been fully investigated. The production cross-section of single top quark in association with a Z boson is an unmeasured rare SM process and also an irreducible background to many important searches at the Large Hadron Collider (LHC). The process is studied by using the three final state leptons (electrons, muons) for an integrated luminosity of 19.7 fb^{-1} recorded by the Compact Muon Solenoid (CMS) detector at the LHC using 8 TeV center-of-mass energy of proton-proton (pp) collisions. The predicted cross-section times branching ratio for this process is $0.008 \pm 0.001 \text{ pb}$ at the Next-to-Leading Order (NLO) in Quantum Chromodynamics (QCD), which is comparable to the measured cross-section $\sigma_{tqZ} = 0.018 \text{ (stat.)}_{-0.009}^{+0.011} \text{ (Syst.)}_{-0.004}^{+0.004} \text{ pb}$. The significance of the tqZ inclusive cross-section as well as the exclusive one for all the leptonic combinations is also presented. The observed significance of inclusive channel is reported to be 1.80, which is consistent to the predicted value.

The Resistive Plate Chamber (RPC) is a dedicated trigger detector at the CMS experiment. The RPC has a significant contribution in the trigger decisions and reconstruction of muon trajectories in the detector. In this thesis, the stability and performance of the RPC detector is also discussed for the 2012 data-taking period. The detector stability is studied through the high voltage scans to determine the optimal operating working voltage for each individual RPC chamber installed in the CMS experiment. The RPC performance is found to be very stable and almost caused no interruption in the CMS data-taking during 8 TeV pp collisions. The CMS down time due to the RPC was less than 1.5 %, and the fraction of active channels was about 97.5% during the 2012 data-taking period. The background radiation measurements at the RPC remained within the expectation values and no significant issues were observed at the nominal luminosity. Over the last few years of the CMS data-taking, the performance of the RPC detectors both as a triggering and reconstruction system remained well within the CMS specification.

Acknowledgment

It is my pleasure to acknowledge all those people who have helped me on the way to achieve this milestone, which manifests itself in this thesis. First and the foremost, I would like to thank my parents, for their prayers, love and never ending support which made this possible.

I would like to thank my supervisor, **Prof. Hafeez R Hoorani**, for providing me the extraordinary opportunity to work in the CMS experiment at CERN. Without his vision and support, I never imagined that I would travel half way around the world and will be participating in cutting-edge physics, or be present at CERN during the Higgs discovery announcement. He always encouraged me whenever I was in trouble either in research or in my daily life. Whenever I had discussion, I found him kind and humble.

I would like to have bundle of thank to Dr. Ashfaq Ahmad, who always helped and encouraged me to achieve this milestone. He did put lot of efforts, support and given me guidance to complete this analysis work. Due to his continuous support, it was possible to produce value able results in single top group.

I would like to extend my thanks to the people who worked for the construction of the machine and the experiment, hundreds of scientist and engineers who designed and constructed the LHC and the CMS experiment. I would like to acknowledge the crew working for on-line and offline monitoring of the detectors. I would like to thank **Higher Education Commission (HEC)** for providing financial support during my studies.

I also would like to have special acknowledgment to NCP tqZ group and to CMS single top group conveners for all their support, feedback, and direction that has lead to the results discussed in this thesis. Thanks to Rebeca Gonzalez Suarez, Abidha Jafferi, Alberto Orso and my special thanks to Muhammad Waqas for his work and support during the analysis. I had lot of valuable discussion with him during this research and without his hard work it was not possible to conclude this analysis.

I started my work from RPC detector. I would like to thank to the community of RPC who helped me from scratch to become an expert of RPC. I always learned and enjoyed their company. My thanks goes to Dr. Irfan Ashgar, Hassan Shahzad, A. Dimitrov, S. Buontempo, Karol Bunoski and P. Paolucci. My special thanks to R. Hadjiiska, she always helped me whenever it was needed.

I have many friends which are integral part of my like. I would like to acknowledge to all my friends, colleague and all who helped me during my PhD. My special thanks go to Muhammad Ahmad, Asif Siddique and Wajid Ali. It was their nice company that made it possible to complete thesis successfully. I would like to thank all group members at NCP, Khurram, Atiq,

Binish, Arif and everyone who were part of the group during this time.

At last but not least, my special thanks goes to my family, my sisters, brothers and brother-in-laws. Special thanks goes to my younger brother Capt. Junaaid Akbar and cousin brother Asmat Ullah. At the end without the sacrifice and sincerity of my beloved wife Samina Faiz it was not possible to achieve this milestone.

At the end, I would like to say that "this work would not have been possible without all of you"

Thank You!

Muhammad Shoaib

Table of Contents

Abstract	iv
Acknowledgment	v
Table of Contents	vii
List of Tables	xi
List of Figures	xiii
1 Introduction	1
2 The Standard Model and Top quark Physics	3
2.1 The Standard Model	4
2.2 Fundamental Interactions	5
2.3 Limitations of the Standard Model	7
2.4 Top Physics	8
2.5 The Top Quark Production	9
2.5.1 Top Quark Pair Production	9
2.5.2 Single Top Production	10
2.5.3 Properties of the top quark	12
2.6 Motivations for Single top Physics	16
2.6.1 Single top quark production in association with Z boson (tqZ)	17
3 Experimental Setup	20
3.1 The Large Hadron Collider	20
3.1.1 Luminosity Measurement	23
3.2 The Compact Muon Solenoid	24
3.2.1 Coordinate System	25
3.2.2 Superconducting magnet	26
3.2.3 The Tracker	27
3.2.4 Silicon Pixel Detector	27
3.2.5 Silicon Microstrip Tracker	28
3.2.6 Electromagnetic Calorimeter	29
3.2.7 Hadron Calorimeter (HCAL)	30
3.2.8 The CMS Muon System	32
3.2.9 CMS Trigger System	35

4	Physics Object Reconstruction	38
4.1	Event Generation	38
4.1.1	Parton Distribution Functions	40
4.1.2	Parton Shower	41
4.1.3	Hadronization	42
4.1.4	Underlying Event	42
4.1.5	Detector Simulation	42
4.2	Particle-Flow (PF) Algorithm	43
4.2.1	The Linking Algorithm	44
4.3	Physics Objects	45
4.3.1	Track Reconstruction	45
4.3.2	Primary Vertex Reconstruction	47
4.3.3	Electron	47
4.3.4	Jets Reconstruction	49
4.3.5	Reconstruction of b-Jets	52
4.3.6	Missing Transverse Energy (MET)	55
4.3.7	Muons Reconstruction	58
5	The tqZ Event Selection	60
5.1	The Datasets	60
5.1.1	Analysis Object Datasets (AOD)	61
5.1.2	MC Datasets	61
5.2	Trigger Selection	62
5.3	Event Selection	63
5.3.1	Analysis Main Steps	63
5.3.2	Event Vertex Selection	64
5.3.3	Muon selection:	65
5.3.4	Electron Selection	67
5.3.5	Jet Selection	68
5.3.6	b-tag Jet Selection	71
5.3.7	The Missing Transverse Energy (MET) Selection	74
5.4	Preselection	76
5.5	Di-lepton (Z boson) Invariant Mass after Event Pre-selection	78
5.6	Data MC Comparison after Pre-selection	79
5.7	tqZ Signal Selection	81
5.8	Summary	81
6	The tqZ Cross-Section Measurement	88
6.1	Introduction to Cross-Section	88
6.2	Background Estimation	89
6.2.1	$t\bar{t}Z$ Background	89
6.2.2	WZ Background	90
6.2.3	Fake Leptons Backgrounds	91
6.2.4	Other Backgrounds	96
6.3	Systematic Uncertainties	96
6.3.1	Jet Energy Scale (JES)	102

6.3.2	Jet Energy Resolution (JER)	103
6.3.3	Lepton selection and Trigger	103
6.3.4	Luminosity	103
6.3.5	b-tagging	103
6.3.6	E_T^{miss} modeling	104
6.3.7	Pileup re-weighting	104
6.3.8	PDF Uncertainty	104
6.3.9	Factorization Scale (Q^2)	106
6.3.10	ME/PS matching thresholds	106
6.4	Uncertainty Summary	111
6.5	The tqZ Cross-Section	111
6.6	Exclusion Limits	112
6.7	Summary	119
7	RPCs Performance at the CMS	120
7.1	Introduction	120
7.1.1	Working Principle of RPCs	120
7.1.2	CMS RPCs	121
7.1.3	RPC Design Requirements	123
7.1.4	Layout of RPC Detector	123
7.2	The RPC Power system	126
7.2.1	RPC EASY SYSTEM	128
7.3	Gas Supply of RPCs	129
7.4	Readout System of RPCs	131
7.4.1	RPC DCS System	132
7.5	Operational Parameters of RPCs	133
7.5.1	Efficiency	134
7.5.2	RPC Cluster Size	134
7.5.3	Dark Current	134
7.6	Hardware status	134
7.6.1	RPC Efficiency Measurement Method	135
7.6.2	RPC Working Points (WP)	136
7.6.3	Detector Stability	138
7.6.4	Noise	139
7.6.5	Background Radiation	141
7.7	Conclusion	142
	Conclusion	144
A	Datasets and Trigger	146
A.1	AOD Datasets	146
A.2	Trigger	146
A.3	MC Datasets	147
B	Systematic Uncertainties Plots	150

C	Lepton Isolation	155
C.1	Muon Isolation	155
C.2	Electron Isolation	155
D	MC Correction Factors	157
D.1	Pileup Re-weighting	157
D.2	b-tag Scale Factors	158
D.3	Lepton trigger Scale Factors	160
D.4	Lepton Identification and Isolation Scale Factors	160
	Bibliography	162

List of Tables

2.1	The twelve fundamental fermions divided into quarks and leptons. The quarks and leptons in the SM having three generations. The quarks and leptons are listed with their properties.	4
2.2	The SM bosons along with their corresponding charge, mass and spin.	5
2.3	The production cross-sections for the t -channel, the s -channel and the associated production at LHC at the center-of-mass energy of 8 TeV. The uncertainties account for the renormalization, factorization scales and the PDF uncertainties in the calculation.	11
3.1	The Large Hadron Collider (LHC) designed parameters for nominal operation. .	23
5.1	Di-lepton ($\mu\mu$, ee) and MuEG ($\mu e\gamma$) datasets, expressed with time period of data taking and also taken Runs in that specific period.	61
5.2	MC simulated datasets used for tqZ signal and backgrounds are mentioned with their cross-sections.	62
5.3	HLT trigger paths used in the analysis	63
5.4	Muons identification criteria used in the analysis [90]	66
5.5	Electrons identification criteria used in the analysis [91].	68
5.6	The electron multivariate identification utilizing Boosted Decision Tree (BDT). The cuts on BDT value are dependent on the p_T and η of the particular electrons.	69
5.7	CSV b-tagging discriminant threshold for different working points of the algorithm [93]. The approximate light-jet mis-identification and b-jet identification efficiencies are also given in last two columns.	74
6.1	Scale Factors (SFs) obtained in Z mass window [78,102] GeV in 0 b -jet bin. Errors are statistical only.	91
6.2	Summer12 systematic samples used in the analysis	102
6.3	Summary of systematic uncertainties on the signal selection and expectation in $\mu\mu e$ channel.	107
6.4	Summary of systematic uncertainties on the signal selection and expectation in μee channel.	108
6.5	Summary of systematic uncertainties on the signal selection and expectation in eee channel.	109
6.6	Summary of systematic uncertainties on the signal selection and expectation in $\mu\mu\mu$ channel.	110

6.7	The tqZ events cut-flow table after requiring final signal selection. The various columns represents the number of events in the data and MC simulation for each combination.	114
6.8	The tqZ measured cross-section (σ) in three leptons final state for four exclusive and inclusive channels using Higgs combination tool. The statistical and systematics uncertainties for each channel are also given.	115
6.9	The expected and measured significance of inclusive and exclusive combinations of tqZ cross-section (σ) are given within the standard deviations with respect to the background hypothesis.	116
6.10	The observed and expected upper limits with 95% Confidence Level (CL) with the one and two standard deviations with respect to the background by using CL_S method.	117
7.1	RPCs basic for construction and operation	122
7.2	CMS RPCs general technical requirement	123
7.3	CMS RPCs general HV and LV power supply requirements [114]	127
A.1	MuEG Datasets expressed accordingly time period of data taking, used in the analysis	146
A.2	Double Electron Datasets with total number of events in each run period, used in the analysis	147
A.3	Double Mu datasets for each run period collected by CMS experiment, which have been used in this analysis	147
A.4	Trigger applied in the analysis	148
A.5	Simulated Datasets used in the analysis	149
D.1	Trigger efficiencies and data-to-MC scale factors are given in the table for four exclusive channels of tqZ	160
D.2	Muon Scale Factors.	161
D.3	Electron Scale Factors.	161

List of Figures

2.1	Feynman diagram for the top quark decay into b and W	6
2.2	Representative Feynman diagrams for Leading Order (LO) production of the top quark pair: (left) quark-antiquark annihilation, (middle) and (right) shows gluons fusion. Quark-antiquark annihilation is the suppressed production channel at the LHC	9
2.3	The leading order (LO) Feynman diagrams for the single top quark production via electroweak interaction are shown: top left is the s -channel diagram, top right is the t -channel diagram and the two bottom diagrams show the associated production of single top quark	10
2.4	Representative Leading Order (LO) and Next to Leading Order (NLO) Feynman diagrams for the single top production in the t -channel.	11
2.5	The Next-to-Leading-Order (NLO) Feynman diagrams for the production of single top-quark in the s -channel: (a) quark anti-quark fusion, (b) initial-state gluon radiation and (c) final state gluon radiation.	12
2.6	The single top production in associated production modes (with emission of real W boson).	12
2.7	The top quark decay	13
2.8	The branching fraction of the top quark in various decay channels.	14
2.9	Summary of the top quark mass measurements from year 2010 to 2012 of the CMS collaboration.	15
2.10	Feynman diagrams for the rare decays of the top quark through the emission of the W boson. The Z boson radiation can occur in any of three legs of the diagram.	16
2.11	Leading-order tZq production Feynman diagrams (all but bottom-right). The initial and final-state quarks denoted q and q' are predominantly first generation quarks, although there are smaller additional contributions from strange- and charm-initiated diagrams. The bottom-right diagram represents the NLO nonresonant contribution to the tZq process	17
2.12	Next-to-Leading-Order (NLO) inclusive cross-sections for the single top and top pair $t\bar{t}$ production with and without an accompanying Z boson [42].	18
2.13	Schematic diagram for the production of tqZ , showing Z boson as emitted radiation.	19

3.1	The Large Hadron Collider (LHC) Cascade Acceleration of proton beams, the beam injection layout from Linear Accelerator (LINAC) to the LHC main ring. This is an overview of the European Organization for Nuclear Research (CERN) accelerator complex.	21
3.2	The integrated Luminosity recorded by the Compact Muon Solenoid (CMS) detector and delivered luminosity by the Large Hadron Collider (LHC).	24
3.3	The Compact Muon Solenoid (CMS) detector installed at the LHC, all the sub-detectors showed around cylindrical symmetry of experiment	25
3.4	General artistic view of the 5 modules composing the cold mass inside the cryostat, with details of the supporting system	27
3.5	Schematic of the Compact Muon Solenoid (CMS) tracker in the rz -plane, showing the positions of the pixels and various strip subsystems.	28
3.6	Description of the Electromagnetic Calorimeter (ECAL) system, installed at the Compact Muon Solenoid (CMS) experiment.	30
3.7	The energy resolution of Electromagnetic Calorimeter (ECAL) as a function of energy.	31
3.8	The Compact Muon Solenoid (CMS) detector with longitudinal view, all sub-detectors of Hadron Calorimeter (HCAL) have been shown: the hadron barrel (HB), endcap (HE), outer (HO), and forward (HF) calorimeters.	32
3.9	The location of Compact Muon Solenoid (CMS) muon chambers in polar coordinate (r, z), location of Drift Tubes (DT) in muon detector is showed with green, Resistive Plate Chambers (RPC) with red and Cathode Strip Chambers in blue.	33
3.10	The Compact Muon Solenoid (CMS) Drift Tubes (DTs) chamber basic principle.	34
3.11	The layout of a Cathode Strip Chambers (CSCs) made of 7 trapezoidal panels. A schematic view of a single gap illustrating the principle of CSC operation. [47]	34
3.12	The Resistive Plate Chambers (RPCs) at the Compact Muon Solenoid (CMS).	35
3.13	Architecture of the Level-1 Trigger [56]	36
4.1	The MSTW (left) and the CTEQ (right) Parton distribution functions at the factorization scale $Q = 100$ GeV. Fig. 4.1 taken from [66]	40
4.2	The process involved after proton-proton collision, hadronization and parton showering	41
4.3	The visualization of a simulated events of $Z \rightarrow jj$ in Compact Muon Solenoid (CMS) detector using GEANT4 platform.	43
4.4	Reconstruction of physical objects via Particle Flow (PF) algorithm.	44
4.5	The transverse view of the Compact Muon Solenoid (CMS) slice with all sub-detectors, showing physics objects hits in various sub-detectors and iron return yoke interspersed with the muon chambers	46
4.6	The primary-vertex reconstruction efficiency as a function of the number of tracks in a cluster, measured in minimum-bias data and MC simulation.	48

4.7	The electron reconstruction in the Compact Muon Solenoid (CMS) detector, the arc of tracks shows the bending in the magnetic field and energy cluster are shown in the Electromagnetic Calorimeter (ECAL). The ECAL clusters due to the electron and its bremsstrahlung photons are shown as green squares. The super-cluster is boxed in blue.	49
4.8	The schematic representation of jets production stages in a pp collision	50
4.9	The jets calibration states applied on Data and MC.	52
4.10	The reconstructed secondary vertices, b -tagging is based on secondary vertex [81].	54
4.11	The reconstruction of b -tagged jets using secondary vertex technique.	55
4.12	The measured b -jet tagging efficiency by using the FTC method and scale factors (SF_b) as a function Combined Secondary Vertex (CSV) discriminator, for the data and simulations (upper panel) [82].	56
4.13	In a simulated CMS event, the missing transverse energy along with direction and magnitude is shown.	57
4.14	(a) The longitudinal ($r - z$) and (b) the transverse ($r - \phi$) views of the Compact Muon Solenoid (CMS) muon system for pp collisions, where four muons have been reconstructed.	58
4.15	The muon p_T resolution ($\Delta p_T/p_T$) as a function of p_T using muon system only (black dashed curve), the inner tracker only (blue dashed-dotted curve), and both (red solid curve), for the $ \eta < 0.8$ (left) and $1.2 < \eta < 2.4$ (right) regions [85].	59
5.1	Plots of the pileup reweighing procedure. Left: distribution of the number of reconstructed primary vertices for signal Monte Carlo (MC) and data. The solid blue line representing the number of primary vertices before applying the re-weight while the solid red line represent number of primary vertex after applying the pileup re-weighting which shifted towards data point Right: Comparison of distribution of the number of reconstructed primary vertices for MC and data after applying pre-selection as discussed in section 5.4. The data is shown with dots having error bars and filled histograms for backgrounds. The background is normalized to the data	65
5.2	The multiplicity of muons after the requirement of three leptons in event before pre-selection criteria.	66
5.3	After applying pre-selection criteria, inclusive muon p_T in different combinations of three leptons final state. The figure at the top shows the p_T in $ee\mu$ channel, left bottom figure shows p_T in $e\mu\mu$ channel and right bottom represents the p_T in $\mu\mu\mu$ combination. Good agreement between data and MC and dominant background is WZ	67
5.4	The multiplicity of electrons after the three lepton requirement and before the pre-selection.	69

5.5	The transverse momentum (p_T) of electron in different combinations of three leptons final state after applying pre-selection criteria. The figure at the top shows the p_T in $ee\mu$ channel, left bottom figure shows p_T in $e\mu\mu$ channel and right bottom represents the p_T in eee combination. There is a good agreement between data and MC, and dominant background is WZ	70
5.6	The light jets eta (η) after the three leptons requirement.	71
5.7	The light jets multiplicity for four different combinations after applying pre-selection criteria. top-left: multiplicity in $\mu\mu e$ combination, top-right: multiplicity in $ee\mu$ combination, bottom-left: multiplicity in eee combination, bottom-right: multiplicity in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	72
5.8	Leading light jets transverse momentum (p_T) after applying pre-selection criteria. top-Left: Jet p_T in $\mu\mu e$ combination, top-right: Jet p_T in $ee\mu$ combination, bottom-left: Jet p_T in $e\mu\mu$ combination, top-right: Jet p_T in $ee\mu$ combination, bottom-left	73
5.9	The b -jets multiplicity in all four combinations after applying pre-selection criteria. top-left: b -jets multiplicity in $\mu\mu e$ combination. top-right: the b - jets multiplicity in $ee\mu$ combination, bottom-left: the b - jets multiplicity in eee combination, b -jets multiplicity in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	75
5.10	B jet discriminant after requiring the three leptons in an event.	76
5.11	MET distributions for four different combinations after applying pre-selection. top-Left: MET distribution in $\mu\mu e$ combination, top-Right: MET distribution in $ee\mu$ combination, bottom-left: MET distribution in eee combination, bottom-right: MET distribution in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	77
5.12	The multiplicity of three tight isolated leptons, before the pre-selection requirement requirement. An event must contain at-least three leptons to be selected as a signal.	78
5.13	The invariant mass of Z boson for four, $\mu\mu e$, $ee\mu$, eee , $\mu\mu\mu$, combinations after applying pre-selection criteria. top left: Z boson invariant mass in $\mu\mu e$ combination, top right: Z boson invariant mass in μee combination, bottom left: Z boson invariant mass in eee combination and bottom right: Z boson invariant mass in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	79

5.14	Inclusive Z boson invariant mass after applying pre-selection criteria. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	80
5.15	The transverse momentum (p_T) of Z boson in four different combination of tqZ after applying pre-selection criteria. top-left: Z boson p_T in $\mu\mu e$ combination, top-right: Z boson in $p_T \mu ee$ combination, bottom-left: Z boson in $p_T eee$ combination and bottom-right: Z boson in $p_T \mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	82
5.16	Inclusive transverse momentum (p_T) of Z boson after applying the pre-selection criteria. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	83
5.17	The W boson transverse mass (M_T) after applying pre-selection. top-left: W boson transverse mass distribution in $\mu\mu e$ combination, top-right: W boson transverse mass distribution in μee combination, bottom-left: W boson transverse mass distribution in eee combination and bottom-right: W boson transverse mass distribution in μee combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	84
5.18	Inclusive W boson transverse mass after applying pre-selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	85
5.19	The inclusive transverse momentum of the light quark jets after pre-selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	85
5.20	Top quark transverse mass after pre-selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	86
5.21	The invariant mass and transverse momentum (p_T) of Z boson after applying the final signal selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	86
5.22	The transverse mass and transverse momentum (p_T) of W boson after applying the final signal selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	87

5.23	The transverse momentum of the top quark after applying the final signal selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	87
6.1	The Feynman diagram of $t\bar{t}Z$ production, via gluon-gluon fusion. The gluon fusion is predominant source of $t\bar{t}Z$ process, which is one of the significant background the in tqZ cross-section measurement.	90
6.2	The Feynman diagram of WZ production which further decays to three leptons and neutrino, a dominant background process in the tqZ cross-section measurement and estimated by using the data driven technique.	90
6.3	The shape comparison of di-lepton mass in different combinations in 0 b -jet and 1 light jet bins using signal Monte Carlo (MC) where red color represents signal MC in pre-selection plus 0 b -jet region and blue color is for pre-selection plus 1 light jet region. The upper left plot shows invariant Z boson mass in $e\mu\mu$ combination, upper right shows invariant Z boson mass in $ee\mu$. The bottom left plot shows invariant Z boson mass in eee and bottom right shows invariant Z boson for $ee\mu$ combination.	92
6.4	The shape comparison of inclusive di-lepton mass in 0 b -jet and 1 light jet bins. Left: Inclusive di-lepton mass in signal Monte Carlo where red color represents signal MC in pre-selection plus 0 b -jet region and blue color is for pre-selection plus 1 light jet region. Right: Inclusive di-lepton mass in data where black color dot represents data in pre-selection plus 0 b -jet region and red color dot is for pre-selection plus 1 light jet region.	93
6.5	The invariant mass of Z boson for four, $e\mu\mu$, $ee\mu$, eee , $\mu\mu\mu$, combinations after applying pre-selection criteria plus 0 b -jets which corresponds to WZ enriched region. top left: Z boson invariant mass in $e\mu\mu$ combination, top right: Z boson invariant mass in $ee\mu$ combination, bottom left: Z boson invariant mass in eee combination and bottom right: Z boson invariant mass in $\mu\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	94
6.6	The invariant mass of Z -boson after scaling with WZ MC Scale Factors (SFs) shown in Table 6.1, for four, $e\mu\mu$, $ee\mu$, eee , $\mu\mu\mu$, combinations. These plots shows pre-selection criteria plus 0 b -jets which corresponds to WZ enriched region. top left: Z boson invariant mass in $e\mu\mu$ combination, top right: Z boson invariant mass in $ee\mu$ combination, bottom left: Z boson invariant mass in eee combination and bottom right: Z boson invariant mass in $\mu\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	95

6.7	Event yields after applying final selection. The left plot shows event yield in each combination before applying WZ Scale Factors (SFs). The right plot shows event yield in each combination after applying WZ SFs.	96
6.8	The W boson transverse mass (M_T) after applying pre-selection. top-left: W boson transverse mass distribution in $\mu\mu e$ combination, top-right: W boson transverse mass distribution in μee combination, bottom-left: W boson transverse mass distribution in eee combination and bottom-right: W boson transverse mass distribution in μee combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	97
6.9	W boson transverse mass (M_T^W) plots in Control Region (CR) specified for fake rate measurement. In the CR, dominant background is $Z + Jets$ and peaking towards zero. top left: W boson transverse mass in eee combination, top right: W boson transverse mass in $\mu\mu\mu$ combination, bottom left: W boson transverse mass in $ee\mu$ combination and bottom right: Z boson invariant mass in $e\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	98
6.10	Missing Transverse Energy (MET) plots in signal region. In the signal region, dominant backgrounds are di-boson and $t\bar{t}Z$. Top left: Missing Transverse Energy (MET) in eee combination, top right: Missing Transverse Energy (MET) in $\mu\mu\mu$ combination, bottom left: Missing Transverse Energy (MET) in $ee\mu$ combination and bottom right: Missing Transverse Energy (MET) in $e\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	99
6.11	Missing Transverse Energy (MET) plots in the CR for fake rate estimation. Plots shows the dominant contribution of $Z + Jets$ background in specified CR. Top left: Missing Transverse Energy (MET) in eee combination, top right: Missing Transverse Energy (MET) in $\mu\mu\mu$ combination, bottom left: Missing Transverse Energy (MET) in $ee\mu$ combination and bottom right: Missing Transverse Energy (MET) in $e\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.	100
6.12	Di-lepton invariant mass is shown with PDF re-weighting per event. Relative uncertainty is shown in the bottom plots. Left: distribution of di-lepton invariant mass with MSTW PDF re-weighting. Right: distribution of di-lepton invariant mass with CTEQ PDF re-weighting.	106

6.13	The event cut-flow comparison between the data and Monte Carlo (MC) simulation presented after applying the pre-selection (PS) and final signal selection (FS) criteria. The plot shows the contribution of backgrounds after each step. Before three leptons requirement the dominant Drell-Yan (DY) and $t\bar{t}$ (blue) are dominant backgrounds, in PS region WZ (pink) is dominant and also have some contribution from $Z + Jets$ (gray). After FS $t\bar{t}Z/W$ (Yellow) is leading while WZ is sub-leading background. The ratio between the data and MC is shown in the bottom panel.	113
6.14	The tqZ measured inclusive and exclusive cross-sections (σ) in three lepton final state by using 19.7 fb^{-1} CMS 2012 data at center-of-mass energy 8 TeV. The Standard Model (SM) expected cross-section is shown with blue dotted line while the dots with error bars represent the measured values of σ for inclusive and exclusive combinations.	115
6.15	Expected and observed significance with one and two standard deviation bands using Higgs combine tool. The red dotted line is for measured significance while the solid black line shows the expected. The yellow band shows the one standard deviation whereas the green is for second standard deviation.	116
6.16	The upper limit with 95% confidence level on signal strength $\mu = \sigma/\sigma_{SM}$ using the CMS 2012 data for the tqZ inclusive and exclusive cross-section. The observed (solid line) and expected (dotted line) upper limits, along with one (yellow) and two (green) standard deviations on the expected values are shown.	118
7.1	Charged particle passes through the RPC gas gap, generates a signal at the readout strips [110].	121
7.2	Schematic cross-sectional view of CMS RPC double gap [111].	122
7.3	RPCs installed at CMS detector with η distribution. The CMS detector, R-Z cross-section of a quadrant where the horizontal axis (z) is running parallel to the beam and radius (r) increasing upward. The η -values (and the equivalent θ -angles) are shown at the top and right. At the lower left corner, there is an interaction region. Various Muons stations have been shown and the steel disks (red areas). The labels of four stations of drift tubes (DT) are MB ("Muons Barrel"), where the labels ME ("Muons Endcap") represents the cathode strip chambers. Resistive plate chambers (RPC, in green) are in both the barrel and the endcaps of CMS	124
7.4	One of the barrel wheel schematic layout, All wheels are divided into 12 sectors and numbering is shown on the wheel [112]	125
7.5	View of the front side (Positive side) of YE-3 (front) and the back side (Negative side) of YE-1.	126
7.6	View of RE disk, showing that two chamber of ring 2 and ring 3, are connected to one HV module	128
7.7	Schematic representation of RPC power supply system, RPC power system is based on the CAEN EASY Technology	129

7.8	Closed loop circulation system of RPC [47].	130
7.9	RPC barrel wheel is divided into two regions and each station (2 chambers) is provided with a gas line [47].	131
7.10	RPC endcap disk has been divide into two rings (a) RE1 chambers has divided into 60^0 sector (b) RE2,3 has been divided in 30^0 sector, containing 3 chambers of internal ring and 3 from external one. Two independent gas lines supplied to every sector [47].	131
7.11	RPC readout electronics block diagram, Figure taken from [117].	132
7.12	The RPC power system Mainframe works independently to handle modules and can communicate with RPC DCS [118], The DCS monitors the system status and sends commands to the Mainframe.	133
7.13	Left: chambers of barrel in Single Gap mode (SG) during the data taking, a comparison between 2010 - 2012. (Right) SG mode of endcap chambers.	135
7.14	RPCs efficiency measurement by extrapolation method, A DT or CSC track segment is linearly extrapolated to the RPC strip plane. RPC hits are sought in the acceptance region around the extrapolated impact point.	135
7.15	Efficiency measurement (in %) as a function of the effective High Voltage HV_{eff} (in KV) for a typical chamber. The "knee" and the optimal working point, shown in the picture, are defined in the text.	137
7.16	Average Barrel and EndCap efficiency during the High Voltage Scan performed in 2012 superimposed with the High Voltage Scan in 2011. The similarity in the curves shows the stability of the system, no aging effects for the CMS RPC chambers.	137
7.17	For barrel, distribution of $HV_{50\%}$ has been shown in the left curve and with curves red and green, and for endcap rolls showed with the black and green curves. Here the red and green curves show 2012 data. 50% of the asymptotic efficiency obtained at $HV_{50\%}$	138
7.18	Left: chambers efficiency map for the wheel +1. The plot shows the 12 sectors on x axis and the 6 RPC layers on y axis. Right: chambers efficiency map in disk -1. The 36 sectors are shown on x axis and the 3 layers on y axis.	138
7.19	Left: Barrel efficiency (in %) as a function of the run number, i.e. as a function of time, for runs taken between April 2011 and October 2011. The two regions, before and after the automatic $HV_{eff}(P,T)$ correction, are shown in the plot. Right: Endcap cluster size (in number of strips), as a function of the run number, for the same run range between April and October 2011.	140
7.20	Average cluster size for the barrel (left) and for the endcap (right), in number of strips, as a function of the atmospheric pressure P (in mbar), for runs before (left, blue curve) or after (right, red curve) the automatic $HV_{eff}(P,T)$ correction. Preliminary results with 2011 data are shown.	140
7.21	Explanation of extrapolation method for the muon trigger and efficiency measurement	140

7.22	Distributions of the noise rate for barrel (left) and for the endcap (right) for the 3 years running 2010 - 2012.	141
7.23	Measured noise rate map in one of the barrel wheel -2 (left) and rate map in the endcap Disk+2 (right)	141
7.24	Measurement performed for background rate in barrel wheels as a function of the LHC luminosity in 2012 (wheel 0 is the closest one to the interaction point, +2 and -2 are the farthest).	142
7.25	Background rate as function of instantaneous luminosity in the endcap station 2 and 3 of the negative disk 2 and 3.	142
B.1	Comparison of di-lepton invariant mass with and without trigger up/down systematic uncertainty in signal Monte Carlo. Left: distribution of di-lepton invariant mass in $\mu\mu e$ channel. Right: distribution of di-lepton invariant mass in $ee\mu$ channel.	150
B.2	Comparison of di-lepton invariant mass with and without trigger up/down systematic uncertainty in WZ Monte Carlo. Left: distribution of di-lepton invariant mass in $\mu\mu e$ channel. Right: distribution of di-lepton invariant mass in $ee\mu$ channel.	151
B.3	Comparison of di-lepton invariant mass with and without trigger up/down systematic uncertainty in $t\bar{t}Z$ Monte Carlo. Left: distribution of di-lepton invariant mass in $\mu\mu e$ channel. Right: distribution of di-lepton invariant mass in $ee\mu$ channel.	151
B.4	Comparison of di-lepton invariant mass with and without trigger up/down systematic uncertainty in ttZ Monte Carlo. Left: distribution of di-lepton invariant mass in $\mu\mu e$ channel. Right: distribution of di-lepton invariant mass in $ee\mu$ channel.	152
B.5	Comparison of di-lepton invariant mass for different tri-lepton combinations with and without pileup up/down systematic uncertainty in signal Monte Carlo. . .	152
B.6	Comparison of di-lepton invariant mass for different tri-lepton combinations with and without pileup up/down systematic uncertainty in WZ Monte Carlo. . . .	153
B.7	Comparison of di-lepton invariant mass for different tri-lepton combinations with and without pileup up/down systematic uncertainty in ttZ Monte Carlo. . . .	154
D.1	No. of primary vertices reconstructed using simulation	158
D.2	b-tagging efficiency using signal MC and two dominant backgrounds, ttZ and WZ	159
D.3	Table shows the leptons Scale Factors as a functions of (η, p_T) , for muons (left) and electrons (right).	161

Chapter 1

Introduction

The study of top quark physics is of great importance in the Standard Model (SM) of particle physics and beyond. The large mass and shorter lifetime than the time required for hadronization make the top quark an important subject in both the electroweak theory and Quantum Chromodynamics (QCD). A single top quark is always produced via electroweak interactions whereas top pairs are produced via strong interactions. The first evidence of top quark was announced by the CDF and D0 experiments at the Tevatron in 1995 [1, 2].

This thesis is mainly focused on the study of single top quark along with the associated production of Z boson with an additional light quark, named as tqZ process, which is a rare SM process. This process is studied by using the 2012 data of proton-proton (pp) collisions recorded by the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC). The associated production of Z boson may appear as radiation from the quarks scattering or from the W boson exchange between the quarks. The LHC provides a first opportunity to study this rare SM process, as the previous generation of accelerators (Tevatron and LEP) could not access this process due to low beam colliding energies. Therefore, this work can explore some exciting features of the SM and probably the new physics as well, which were never studied before.

The cross-section measurement of tqZ process is the main goal of this work, which is a suppressed electroweak process in the SM [3]. The process is directly related to the sensitivity of the Z boson coupling to the top quark. An increase in the coupling strength could increase the tqZ cross-section beyond the prediction of the SM. Therefore, the choice of this study does not only provide a test of the SM but also it could give a hint of new physics. This measurement has been performed by using simple cut and count technique. The decay channels involving only leptons (electrons, muons) in the final state are selected to study because of their clean

signature in the detector. The top quark always decays to a W boson and a b -quark, the W boson can further decay into a lepton and a neutrino, while the Z boson decays into a lepton, anti-lepton pair. Thus the final state of tqZ process has three leptons containing the lepton and anti-lepton pair from the Z boson decay, a neutrino appearing as missing energy at detector level and at least two quarks and one of them is the b -quark. Since tqZ cross-section is very small, the other processes having the same final state signature, like WZ , $t\bar{t}Z$, tH are therefore the main backgrounds of this study, which are estimated by using data-driven methods.

The second major work of this thesis is dedicated to the study of performance of the Resistive Plate Chambers (RPCs), a sub-detector system installed at the CMS experiment. The RPCs are double-gap gaseous detectors, operating in avalanche mode to ensure the good performance at high particles collisions rates. The RPCs are dedicated trigger detectors at the CMS with an excellent time resolution suitable to work at the high LHC luminosities.

Chapter 2 provides a theoretical introduction of the SM and motivation to study the single top quark physics and its unique properties as a particle along with a brief discussion on its associated production. Chapter 3 describes the CMS experiment at the LHC with the explanation of various sub-detector systems of the CMS. Chapter 4 contains a brief discussion on event generation, detector simulation and particle reconstruction algorithms. The three subsequent chapters discuss the main analysis. Chapter 5 describes the datasets, both the data and Monte Carlo (MC) samples for the tqZ process. This chapter also explains the kinematic regions and object selection criterion in detail. Chapter 6 explains the cross-section measurement of tqZ with the three leptons in the final state, dominant background estimation procedure and systematic uncertainties. In Chapter 7, the basic working principle of the RPCs is described along with the study of performance of the detector.

Chapter 2

The Standard Model and Top quark Physics

All known matter is composed of atoms, and all the atoms are made up of a nucleus consisting of neutrons and protons, surrounded by electrons. However, neither the neutron nor the proton is fundamental, they are composite states of quarks. The electrons and quarks do not have any sub-structures and they are therefore the fundamental particles. The electron belongs to the family of leptons. The leptons and quarks are categorized in three generations, as shown in Table 2.1. The electron (e), muon (μ) and tauon (τ) and their respective neutrinos (ν_e, ν_μ, ν_τ) are divided in three generations of leptons. The up (u) and down (d), the charm (c) and strange (s), and the top (t) and bottom (b) are the three generations of quarks. Each quark can have three colors red (r), green (g) and blue (b). Typically quarks only exist in a colorless bound states [4]. The bound states of quarks are called hadrons. The hadrons have two types, baryons and mesons. A baryon contains three quarks (qqq), whereas meson consists of a quark and an anti-quark pair ($q\bar{q}$). The proton (uud) and pi-meson ($u\bar{d}$) are the examples of baryons and mesons, respectively.

The interactions between the fundamental particles are described through a theoretical framework, called as the Standard Model (SM) of particle physics.

The analysis is dedicated to the study of associated production of the single top quark with the Z boson. After a brief description of the SM, the second half of this chapter is dedicated to the top quark physics.

2.1 The Standard Model

The SM is a theoretical framework based on quantum field theory that summarizes our current knowledge of elementary particles and their interactions [5, 9]. The model was developed in 70's during last century and emerged as an established theory consistent with the experimental results.

In the SM, there are two types of particles, fundamental fermions (half-integer spin) and fundamental bosons (full-integers spin). The leptons and quarks are fermions. The interaction between fermions is mediated through the exchange of force carriers, called as gauge bosons, as shown in Table 2.2.

Table 2.1: The twelve fundamental fermions divided into quarks and leptons. The quarks and leptons in the SM having three generations. The quarks and leptons are listed with their properties.

Generation	Symbol	Quarks		Leptons		
		Charge	Mass[MeV/c ²]	Symbol	Charge	Mass[MeV/c ²]
1	u	$+\frac{2}{3}$	1.5 to 4	ν_e	0	$<3.10^{-6}$
1	d	$-\frac{1}{3}$	4 to 8	e^-	-1	0.511
2	c	$+\frac{2}{3}$	$(1.15 \text{ to } 1.35).10^3$	ν_μ	0	<0.19
2	s	$-\frac{1}{3}$	80 to 130	μ^-	-1	106
3	t	$+\frac{2}{3}$	$(172 \pm 0.4).10^3$	ν_τ	0	18.2
3	b	$-\frac{1}{3}$	$(4.1 \text{ to } 4.4).10^3$	τ^-	-1	1777

The particle interactions are described in the form of four fundamental forces, the electromagnetic, the weak, the strong and the gravitational forces. The SM framework incorporates all the forces except gravitational force. These forces are part of a mechanism responsible for generating matter and antimatter (pair production), changing particles from one to another (e.g. beta decay) or even binding particles together. The electromagnetic force is mediated by photons, i.e. particles having electric charges couple via photons. The weak force is mediated by three massive vector bosons $W^\pm$, Z^0 . The vector bosons couple to particles through the weak isospin charge. The strong force is mediated by eight gluons, which carry color charge. The electromagnetic force has no self-coupling of gauge bosons, as photons do not carry any type of charge. Since the gluons and weak vector bosons carry color and weak isospin charges, respectively, therefore, they undergo through self-coupling interactions.

Table 2.2: The SM bosons along with their corresponding charge, mass and spin.

Boson	Charge	Mass (GeV)	Spin
photon (γ)	0	0	1
W	± 1	80.4	1
Z	0	91.2	1
gluon (g)	0	0	1
Higgs (H)	0	125.4	0

2.2 Fundamental Interactions

As the SM incorporates all the forces or interactions except gravity, the coupling constants of these forces depend on the energy scale, which is described later in this section. The SM describes the interactions between the fermions through the strong, weak and electromagnetic forces via exchange of various gauge bosons. In the SM, there is a self-coupling of gauge bosons $W^\pm$, Z^0 and gluons but not for the case of photons.

The SM is a gauge theory, which is based on the $SU(3) \times SU(2) \times U(1)$ symmetry group. The $SU(3)$ is a gauge group of strong interactions and has eight generators and these generators correspond to eight gluons. Since the gluons mediate interactions between the quarks, which are bound in hadrons due to strong interactions. The QCD is known as the theory of strong interactions.

Quantum Electrodynamics (QED) is the $U(1)$ gauge theory that describes electromagnetic interactions. The $U(1)$ is a unitary group and corresponds to a single generator, the massless photon. The electromagnetic force between two charges is mediated via exchange of photons. The photons are virtual particles because they are not observable directly, rather exchanged between the two charged particles.

The weak force is mediated by three gauge bosons, which are W^+ , W^- and Z^0 . These gauge bosons are produced by the spontaneous symmetry breaking of the electroweak group $SU(2) \times U(1)$ [10, 12]. These bosons are massive and can have three polarization states. There are two kind of weak interactions: charged interactions are mediated by $W^\pm$ and neutral interactions by Z^0 bosons. The mediators of weak force are massive unlike the massless gluons and photon. The weak interaction is the only place in the SM where parity is not conserved. The parity violating nature of an interaction can be linked directly to the form of the interaction

vertex, which makes it different from QED and QCD [13]. The strength of weak interaction can directly be determined from the lifetime of muon.

The electroweak unification is a procedure where two independent couplings, the electromagnetic ($g = g_e$) and the weak ($g' = g_w$) coupling constants are replaced by a single unified coupling along with the weak mixing angle [14]. The electroweak force is the combination of weak and electromagnetic forces, as proposed by Glashow, Weinberg and Salam [15]. It is responsible for the transitions of quarks, from one to another flavor via exchange of W bosons. The decay of top quark into a b quark via exchange of a W boson is an example of weak interactions, as shown in the Fig. 2.1. The probability of transition of a quark from one to another flavor is represented by the Cabibbo-Kobayashi-Maskawa matrix (CKM) in the SM. The CKM matrix is shown in the following Eq. 2.1,

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}. \quad (2.1)$$

where V_{tb} , for example, gives the transition probability of top to bottom quark. The Lagrangian

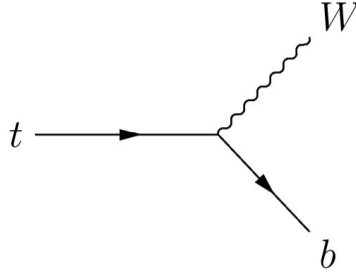


Figure 2.1: Feynman diagram for the top quark decay into b and W

for the electroweak interaction can be represented by the following Eq. 2.2,

$$\mathcal{L}_{EWK}^{quark} = i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{e}_R \not{D} e_R - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}, \quad (2.2)$$

where a summation is over the fermionic generations, $\not{D} = \gamma_\mu D^\mu$ and $Q_L^m = \begin{pmatrix} u_L^m \\ d_L^m \end{pmatrix}$ is $SU(2)_L$ doublet for the left-handed fermions, m denotes the three generations of fermions. The three gauge bosons $W_\mu^i, i = 1, \dots, 3$, correspond to the three $SU(2)_L$ generators. They are described in the adjoint representation. The $U(1)_Y$ group adds a fourth field B_μ . The co-variant derivative is

$$D_\mu = \partial_\mu - ig \frac{\sigma^i}{2} W_\mu^i - ig' \frac{Y}{2} B_\mu, \quad (2.3)$$

where g and g' are the coupling constants for the $SU(2)_L$ and $U(1)_Y$, σ^i are the Pauli matrices and Y is the weak hyper-charge. The field strength tensors are given as

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon^{ijk}W_\mu^jW_\nu^k, \quad (2.4)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad (2.5)$$

where ϵ^{ijk} is the Levi-Civita symbol, which is a structure constant of $SU(2)$ group.

From Eq. 2.2, the part of Lagrangian $\mathcal{L}_{Higgs}$, due to the scalar Higgs field (ϕ) is given as

$$\mathcal{L}_{Higgs} = (D_\mu\Phi)^\dagger D^\mu\Phi - V(\Phi^\dagger\Phi), \quad (2.6)$$

where $\Phi = (\phi^+, \phi^0)^T$ is an $SU(2)_L$ doublet of complex scalar fields with a weak hyper-charge $Y_H = 1$. The Higgs potential ($V(\Phi^\dagger\Phi)$) is given as following

$$V(\Phi^\dagger\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2, \quad (2.7)$$

where λ and μ are the parameters, and $\lambda > 0$. The Yukawa coupling between the Higgs field and the fermions is given by the following equation

$$\mathcal{L}_{Yukawa} = -Y_{mn}^u \bar{Q}_{Lm} \tilde{\Phi} u_{Rn} - Y_{mn}^d \bar{Q}_{Lm} \Phi d_{Rn} - Y_{mn}^e \bar{L}_{Lm} \Phi e_{Rn} + h.c., \quad (2.8)$$

where $\tilde{\Phi} = i\sigma_2\Phi^*$ and $Y_{mn}^{u,d,e}$ are the Yukawa coupling constants for up- and down- type quarks and charged leptons, indices m and n are for generations. These interactions are responsible for generation of fermions masses.

The self-coupling of the scalar field (ϕ) is responsible for the mass of Higgs boson itself. It was the last missing link of the SM until July 2012, when the discovery of the Higgs boson was announced at CERN [16].

2.3 Limitations of the Standard Model

The SM of particle physics has provided a compact and successful description of the properties of basic blocks of universe and interactions between them. But still it is not a perfect theoretical model and has some limitations. The SM does not incorporate gravitational interactions due to incompatibility of the theory of general relativity with the quantum field theory. In the SM, neutrinos have been treated as a massless entity but there is developing indications, from solar and atmospheric anomalies that neutrinos are massive [17, 18]. The model contains more than 20 arbitrary parameters (masses, mixing angles, coupling constants etc.) and it is not

possible to obtain the values of these parameters from the theory. The SM does not explain why there are only three generations of quarks and leptons. Also the model is inadequate to explain the existence of dark matter. Cosmological observations suggest the existence of dark matter in the universe, which is needed to describe large scale gravitational effects. The matter is said to be dark because it emits no detectable electromagnetic radiation. There is a large asymmetry between the matter and anti-matter and the observed baryon asymmetry between matter and antimatter cannot quantitatively be described by the CP violating parts of the SM alone. It is clear that the SM will be an integral part of a more complete theory of particle in the future [19,20]. The electromagnetic and weak forces get unified within the gauge group $SU(2) \times U(1)$ after Glashow-Salam-Weinberg (GSW) model of unification. The electroweak and strong interactions are not unified yet. Any theory that does unify these three forces is called a Grand Unification Theory (GUT).

The SM does not address the famous hierarchy problem that why there is a large difference between the electroweak scale ($O(\text{TeV})$) and the Planck scale ($O(10^{19} \text{ TeV})$). In other words, the apparent mass of the Higgs boson is much smaller than the bare Higgs boson mass having quantum corrections in it. The SM has no solution to this problem.

A number of theoretical models have been developed to solve some of these problems. Therefore, in addition to testing the SM, physics analysis are also dedicated to find signatures for the new physics.

2.4 Top Physics

The top quark, most massive ($m(t) > m(H) > m(Z) > m(W)$) fundamental particle in the SM, and its existence was predicted in the late 1970s. The discovery of the top quark in 1995 at Fermilab, Tevatron, by the CDF [21] and D0 [22] collaborations, was one of the outstanding confirmation of the SM predictions. After the discovery of the bottom quark in 1977 at Fermilab [23], the top quark has been predicted to be missing weak isospin partner of it, the top quark was postulated as an up-type quark. Due to high mass in comparison to the other fermions (≈ 35 times the mass of the next heaviest quark), the top quark provides a rich phenomenology [24]. The top quark has lifetime $\approx 10^{-24}$ sec, which is about 10 times shorter than the characteristic formation time of the hadrons [25]. Thus the top quark decays before the formation of top mesons or top baryons. Therefore, the top quark spin is transferred to its decay products without being depolarized by the strong interaction. The study of top quark

therefore provides a unique possibility to explore a quasi-free quark through its decay products. In the following sections, the top quark production, decay and some of its key features have been described.

2.5 The Top Quark Production

The LHC machine is a top factory, which has produced a large amount of the top quarks during Run-I. The machine has yielded about 800,000 top-antitop ($t\bar{t}$) pairs for the CMS experiment alone in year 2011. Therefore the physics of top quark has already entered into the era of a precision. At the LHC, the top quarks are produced in two different ways; $t\bar{t}$ pairs are produced as a result of gluon-gluon fusion and annihilation of $q\bar{q}$, which is through the strong interactions. On the other hand, the production mechanism of single top quark is through the electroweak interactions. The top quarks tend to be produced more abundantly in the forward and backward directions, while the top antiquarks are preferentially produced in the central region. Based on the LHC center-of-mass energy of the colliding beam and the parton distribution functions (pdfs), the dominant production for $t\bar{t}$ pair is from gluon-gluon fusion.

2.5.1 Top Quark Pair Production

The production of $t\bar{t}$ pair through gluon-gluon fusion ($gg \rightarrow t\bar{t}$) and quarks annihilation ($q\bar{q} \rightarrow t\bar{t}$) are shown in Fig. 2.2, but the second process is suppressed. The top quark pair production

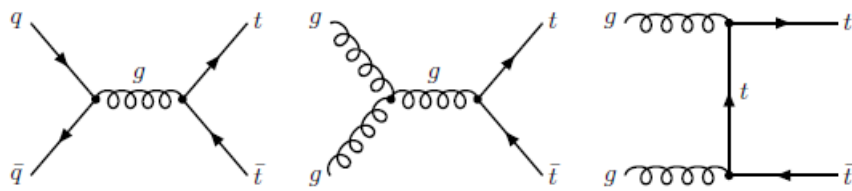


Figure 2.2: Representative Feynman diagrams for Leading Order (LO) production of the top quark pair: (left) quark-antiquark annihilation, (middle) and (right) shows gluons fusion. Quark-antiquark annihilation is the suppressed production channel at the LHC

via quark-gluon scattering processes ($qg/\bar{q}g \rightarrow t\bar{t}$) only appear in the Next to Leading Order (NLO) terms in the QCD perturbative expansion. The total $t\bar{t}$ production cross-section in pp collisions at 8 TeV center-of-mass energy has been calculated at Next-to-Next-to-Leading Order (NNLO) accuracy, $\sigma_{t\bar{t}}(\text{NNLO}) = 245.8^{+8.8}_{-10.6}$ pb [26], corresponding to 173.3 GeV top

mass. However, differential production cross-sections are calculated up to approximate NNLO accuracy level only by resumming the soft-gluon emission near the partonic production threshold [27].

2.5.2 Single Top Production

At hadron colliders, production mechanism of the single top quark is through charged-current electroweak interactions involving Wtb vertex that contributes the factor $\frac{-ig_w}{2\sqrt{2}}|V_{tb}|\gamma^\mu(1 - \gamma^5)$ into the cross-section. The cross-sections for the processes, t -channel, s -channel and associated production are directly proportional to $|V_{tb}|^2$. Therefore, the production of single top quark provides a unique opportunity of a direct determination of $|V_{tb}|$ vertex. Since the production mode has different topology from each other therefore these modes have distinct event kinematics. These production modes of the single top quark are also sensitive to any new physics.

The single top quark production via weak interactions was first discovered at Tevatron in 2009 [28, 29]. There are three different production modes of the single top quark within the SM: the t -channel, the s -channel and the associated production as shown in Fig 2.3.

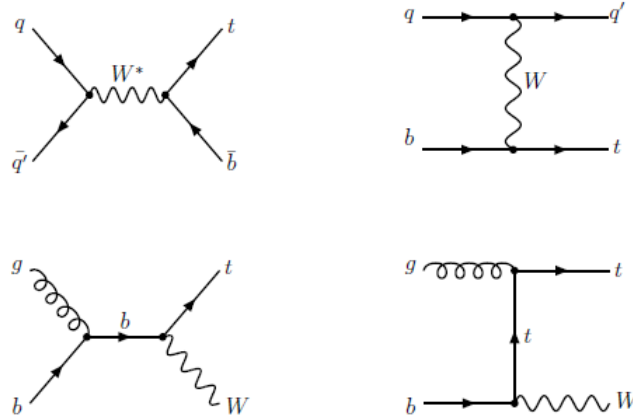


Figure 2.3: The leading order (LO) Feynman diagrams for the single top quark production via electroweak interaction are shown: top left is the s -channel diagram, top right is the t -channel diagram and the two bottom diagrams show the associated production of single top quark

Table 2.3: The production cross-sections for the t -channel, the s -channel and the associated production at LHC at the center-of-mass energy of 8 TeV. The uncertainties account for the renormalization, factorization scales and the PDF uncertainties in the calculation.

Channel	Cross Section [pb]
t -channel	$87.2^{+3.4}_{-2.4}$
s -channel	5.55 ± 0.22
tW -channel	22.2 ± 1.5

The distinction between three production processes is via virtuality of the W boson ($Q^2 = -q^2$, where q is the four-momentum of the W). The production of the single top quark depends on whether the W -boson is *time*-like, *space*-like or real. This distinguishes among the s -channel, the t -channel and the tW -channels, respectively. The detail description of the modes is following:

1. **t -channel Production:** In the t -channel process, W boson is space-like ($q^2 < 0$), this virtual W -boson interacts with a b -quark coming from the parton sea. The production of the single top quark via t -channel is also known as W -gluon fusion mode, since the b -quark originates from a gluon splitting into a $b\bar{b}$ pair. The Feynman diagram for t -channel production of a single top quark is shown in Fig. 2.4. The t -channel production of the single top is a dominant process for the production of the top quark at the LHC energies, as described in the Table 2.3.

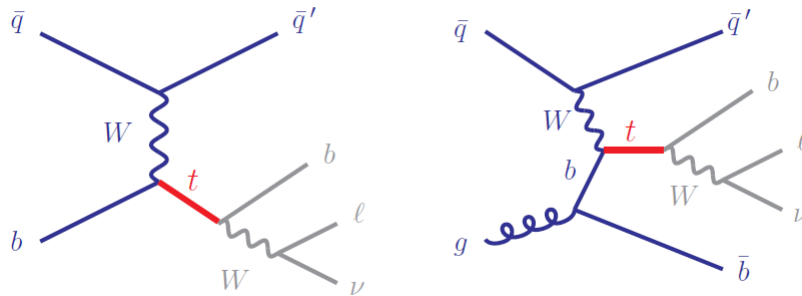


Figure 2.4: Representative Leading Order (LO) and Next to Leading Order (NLO) Feynman diagrams for the single top production in the t -channel.

2. **s -channel Production:** This production mode of the single top quark is Drell-Yan type process. The Feynman diagrams for the NLO production of single top via s -channel are

shown in Fig. 2.5. In this process, a *time-like* W boson is produced as shown in Fig. 2.5, having $q^2 > (M_{top} + m_b)^2$.

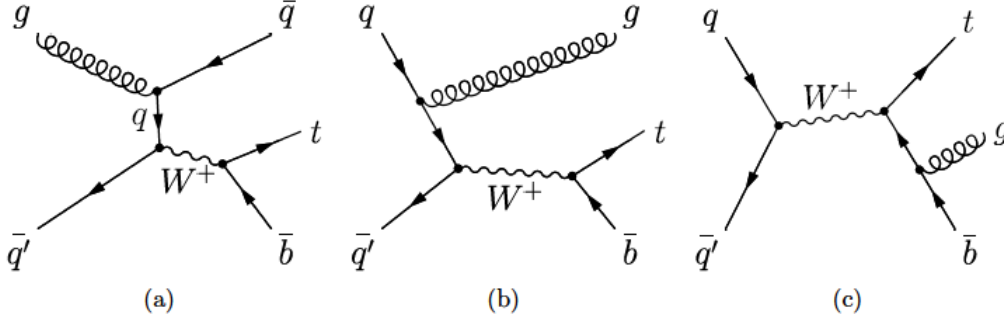


Figure 2.5: The Next-to-Leading-Order (NLO) Feynman diagrams for the production of single top-quark in the s -channel: (a) quark anti-quark fusion, (b) initial-state gluon radiation and (c) final state gluon radiation.

3. **Associated Production:** In this production mode, the single top quark is produced in association with the real W boson ($q^2 = M_w^2$). The main partonic processes for t and $\bar{t}$ productions are $gb \rightarrow tW^-$ and $gb \rightarrow tW^+$ respectively, whereas gs and gd contributions are CKM suppressed. The Feynman diagrams of associated production mode in the Leading Order (LO) are shown in Fig. 2.6.

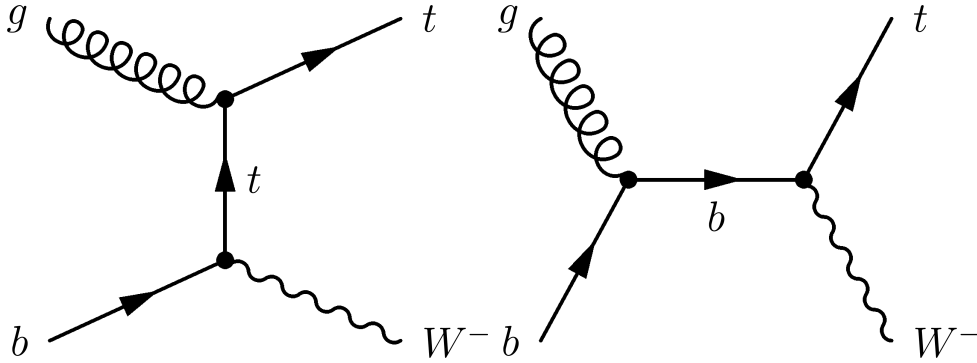


Figure 2.6: The single top production in associated production modes (with emission of real W boson).

2.5.3 Properties of the top quark

1. **Top Quark Decays:** Since the top quark has very large mass and corresponding shorter lifetime ($\approx 10^{-25}$ sec) as compared to the characteristic hadronization scale of QCD. The top quark decays before the formation of any bound states and it is therefore

the only quark that can be studied before hadronization. As a result, the top quark decay offers a unique window to the properties of a bare quark free from the long-range effects of QCD, such as confinement. The top quark decay through electroweak interactions is shown in following Eq. 2.9

$$t \rightarrow q + W^+ (q = d, s, b) \quad (2.9)$$

where q can be a down type quark. Since $V_{tb} \gg V_{ts} > V_{td}$, the top quark therefore only (approximately 99.8%) decays into W boson and a bottom quark, as shown in the Fig. 2.7. In the SM, the dominant decay mode of the top quark is $t \rightarrow b + W^+$, and any deviation will be a hint for the fourth generation of quarks. The total decay rate of the

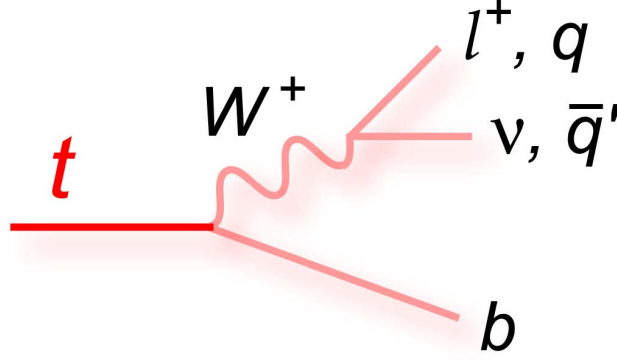


Figure 2.7: The top quark decay

top quark is given by the following formula [30]

$$\Gamma(t \rightarrow Wb) = \frac{G_F m_t^3}{8\sqrt{2}\pi} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + \frac{m_W^2}{m_t^2}\right), \quad (2.10)$$

where G_F is the Fermi constant, with the measured value of top mass $m_t = 173$ GeV, $m_W = 80.4$ GeV. The total decay width (Γ_t) of the top quark is

$$\Gamma_t = 1.5 \text{ GeV} \quad (2.11)$$

Other than $t \rightarrow Wb$ decay, allowed decays in the SM are not only rare but mostly too difficult to identify experimentally.

In the CKM matrix, other than $t \rightarrow bW$, there are also off-diagonal modes of the top quark decays, for example $t \rightarrow dW$, $t \rightarrow sW$. Also the Flavor-changing neutral currents (FCNC) decays, $t \rightarrow X^0 q$ where $X^0 = g, \gamma, Z, H$ and $q = c, u$, which are suppressed by GIM mechanism [31].

Top Pair Decay Channels

$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	ee	$e\mu$	$e\tau$	electron+jets	
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

Figure 2.8: The branching fraction of the top quark in various decay channels.

- Top Quark Mass and Spin:** The mass of the top quark is used as input in the global electroweak fits that probes the self consistency of the SM and its value has implications for the stability of the SM vacuum [32]. In the SM, Brout-Englert-Higgs spontaneous symmetry breaking mechanism is responsible for the mass of fermions. The mass of the top quark is a fundamental parameter of the SM which places constraints on the Higgs boson mass and electroweak symmetry breaking [33]. The recent precision measurement of the top quark mass, by the CMS experiment has been shown in the Fig. 2.9. A precise knowledge of the top quark mass is a cornerstone for the search of new physics that could manifest a small deviations from SM predictions [34].

Due to the angular momentum conservation and the well-studied spins of the b -quark and the vector boson, the spin of the top quark has been determined to be $1/2$. Given that the top quark does not hadronize before the decay, spin polarization and correlation are passed to the decay products resulting in characteristic angular distributions. The spin correlation can be measured through the spin correlation coefficient in terms of a coefficient A , which is a fractional difference of number of events in which top quark and anti-top quark spins are aligned and those where alignment is in opposite direction. The ATLAS detector measures the strength of the spin correlation to be $A_{\text{helicity}}^{\text{SM}} = 0.34^{+0.15}_{-0.11}$

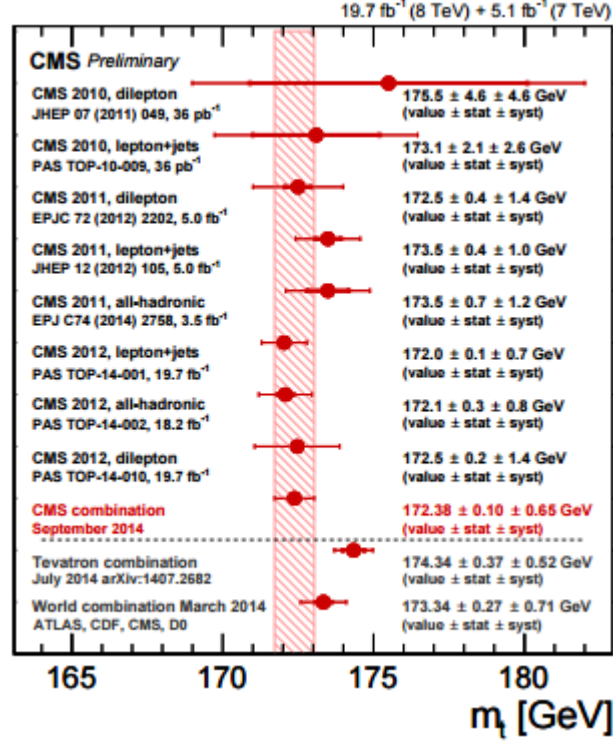


Figure 2.9: Summary of the top quark mass measurements from year 2010 to 2012 of the CMS collaboration.

[35], whereas the CMS detector measures it to be $A_{\text{helicity}}^{\text{SM}} = 0.24_{-0.08}^{+0.02}$ [36]. Both the numbers are in agreement with the SM prediction of $A_{\text{helicity}}^{\text{SM}} = 0.31$ [37].

- Rare Decays:** The top quark mostly decays into bW with branching ratio almost equal to 1 as shown in Fig. 2.8, due to the fact that $|V_{tb}| \sim 0.991$. The decays which are forbidden at tree level in the SM are only possible via higher order corrections, the penguin diagrams. The rare decays are suppressed by GIM mechanism. Thus the studies of the rare top quark decays are not only the test of the SM but also provide the window for new physics. The rare decays can be studied via two process, charged currents and via FCNC, suppressed in the SM up to the order $\sim 10^{-14}$. Since the LHC is a top factory which allows probing the top couplings to both the known and new particles which are involved in possible top decay channels other than the main top decay channel $t \rightarrow bW$. Thus the LHC provides a good opportunity to study such rare processes. Since the tqZ is a rare process with branching ratio $\sim 10^{-7}$, as shown in the Fig. 2.10 has been studied using the LHC data.

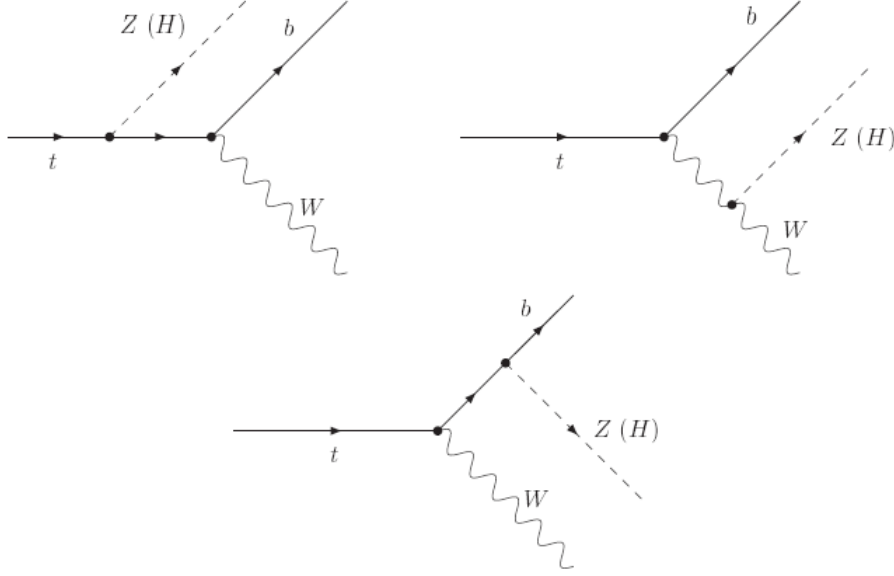


Figure 2.10: Feynman diagrams for the rare decays of the top quark through the emission of the W boson. The Z boson radiation can occur in any of three legs of the diagram.

2.6 Motivations for Single top Physics

The top quark has been discovered long ago and many advances have been made for the understanding its properties but still there are many to be explored. The LHC, during Run-I (2010 - 2012) contributed many results in understanding the top quark. Since the top quark is heaviest among the fermions family, it is therefore believed that it will provide a probe to new physics. Particularly in case of the single top quark it is expected to be more sensitive to the new physics. For instance, the corresponding production rates can significantly be modified by the new physics interactions, such as heavy resonances or non-standard flavor-changing vertices. Productions of the single top quark proceeds via three modes, these modes are sensitive to the new physics because any signature of deviation from the SM will indicate a new coupling with the single top quark. In addition to the SM measurements involving single top production, many models of physics beyond the SM would affect the production of single top quarks. Each of the single top channel could be a probe to different types of new physics. The precise measurement of each of the three channels is important for finding or ruling out new models [38,40]. The models with new exotic bosons or enhanced flavor changing neutral currents would result in enhancements to the t and s channel production mechanisms.

2.6.1 Single top quark production in association with Z boson (tqZ)

The energy and luminosity frontiers being explored by the LHC allow the precision measurement of the electroweak properties of the top quark for the first time. The couplings between the top quark and the vector bosons are among these properties. The couplings between the top quark and the neutral vector bosons (γ and Z) can also be inferred through the analysis of direct production of single top quark in association with the Z boson. The Z boson is radiated off from one of the quark legs or from the exchanged W boson between the quarks. Due to the presence of Z boson, the process is highly suppressed at the tree level and was not studied at Tevatron due to very low cross-section. The leading order Feynman diagrams of the tqZ process are shown in the Fig. 2.11. The predicted cross-sections of tqZ at NLO are given in

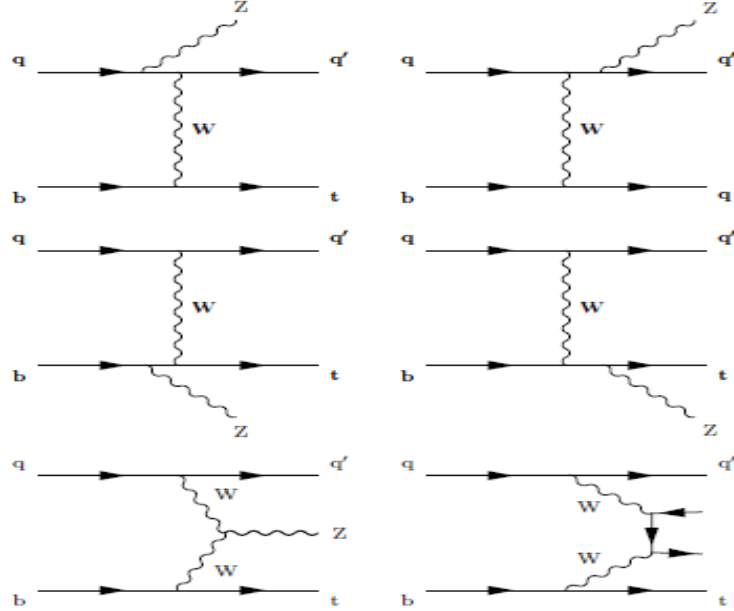


Figure 2.11: Leading-order tZq production Feynman diagrams (all but bottom-right). The initial and final-state quarks denoted q and q' are predominantly first generation quarks, although there are smaller additional contributions from strange- and charm-initiated diagrams. The bottom-right diagram represents the NLO nonresonant contribution to the tZq process

the Eq. 2.12, 2.13.

$$\sigma_{NLO}(tZ) = 160^{+7}_{-2}(scale)^{+11}_{-11}(pdf)\text{fb} \quad (2.12)$$

$$\sigma_{NLO}(\bar{t}Z) = 76^{+4}_{-1}(scale)^{+5}_{-5}(pdf)\text{fb} \quad (2.13)$$

These theoretical predictions of cross-sections are based on the pp collisions at the center-of-mass energy of 8 TeV. For the production of single top quark accompanied by a boson which

can couple with the down-type quark or up-type quark as shown in Fig 2.11. For cases where boson couples with down-type quark it must have electrical charge ($Q = \pm 1$) and in the case of up-type quark boson must be electrically neutral. Thus leading to an overall cross-

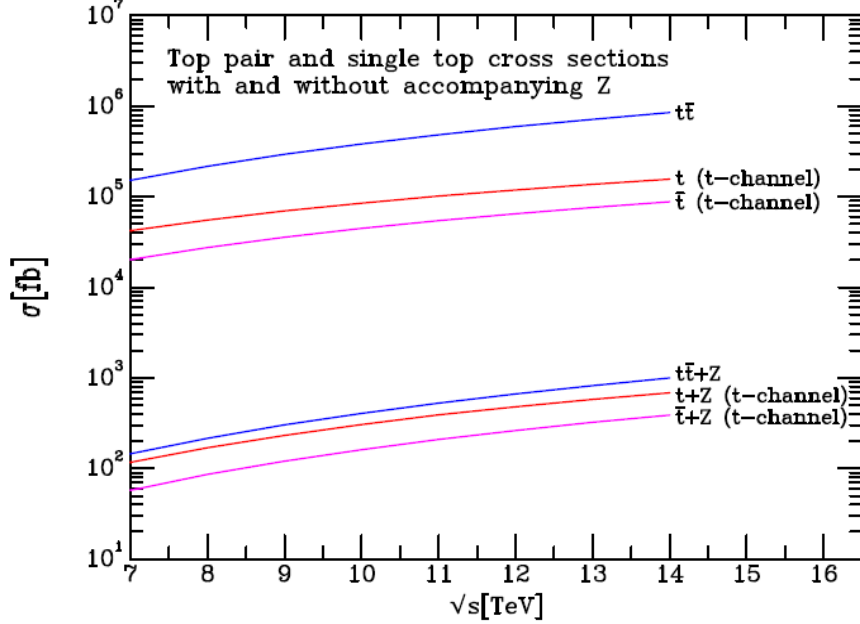


Figure 2.12: Next-to-Leading-Order (NLO) inclusive cross-sections for the single top and top pair $t\bar{t}$ production with and without an accompanying Z boson [42].

section for tqZ production of 236^{+19}_{-16} fb [42]. The predicted cross-section was determined by using the CTEQ6M set of Parton Distribution Functions (PDFs) [41]. The $\bar{t}qZ$ cross-section is approximately half that of tqZ , because the ratio of the up quark PDF to the down quark PDF is approximately 0.5 in the x range typical for this process at LHC energies. The total cross-section (sum of top and anti-top) of tqZ calculated using *aMC@NLO* in the 4 Flavor Scheme (FS) and by considering leptonic decay of Z boson is: $\sigma_{tqZ} = 23.1^{+1.1}_{-1.7} (\text{scale})^{2.3}_{2.3} (\text{PDF})$ fb. The notation tqZ will hereafter be used to refer to both tqZ and $\bar{t}qZ$ production, no attempt is made to differentiate between the two in this analysis. The predicted production cross-sections for tZ and $t\bar{t}Z$ can be seen from Fig. 2.12 taken from [42]. The tqZ cross-section scales with center-of-mass energy similarly the $t\bar{t}Z$ at the LHC energies. The production cross-section of tZ is comparable to the production of $t\bar{t}Z$ [42], which suggests that a search for tZ production should be feasible in Run-I data. This is supported by the most recent results from the CMS in the search for $t\bar{t}Z$ production using the 2012 dataset [43].

The measurement of tqZ has been performed with a topology of tri-leptons, as shown in the Fig. 2.13. This tri-lepton selection is only possible by having a good control over the SM

backgrounds. Since tqZ is highly suppressed process of the SM, therefore the clean tri-lepton final states are chosen for this analysis. The tqZ is analyzed in the fully leptonic mode so both

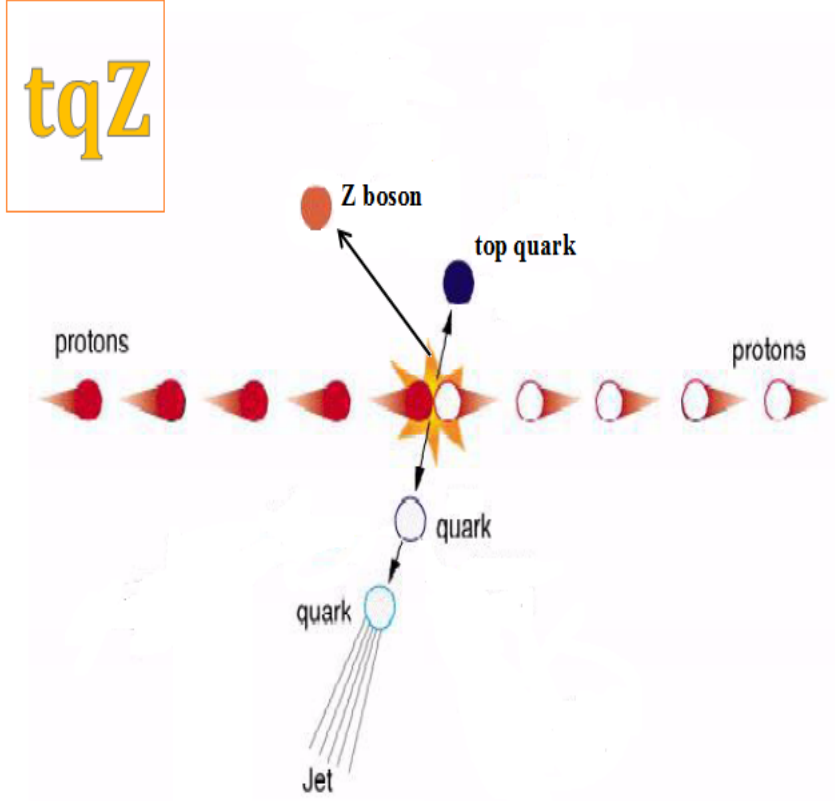


Figure 2.13: Schematic diagram for the production of tqZ , showing Z boson as emitted radiation.

the top and on-shell Z boson give a tri-leptonic final state. As leptons from the Z boson have the same flavor and opposite sign and third lepton is coming from the W boson decay. The missing transverse energy is introduced into the analysis via leptonically decaying W boson. The final part of the event topology is the hadronic jets. There should be at least two jets in the final state, one jet originating from the b -quark, and other from the light quark.

Chapter 3

Experimental Setup

The analysis described in this thesis has been performed using pp collisions recorded by the CMS detector during 2012. The CMS is one of the general purpose detector at the LHC ring, which is installed at European Organization for Nuclear Research (CERN) near Swiss-French border in Geneva, Switzerland. This chapter will describe the various sub-detectors of the CMS with an explanation on the tracking detector, the Electromagnetic Calorimeter (ECAL), the Hadronic Calorimeter (HCAL) and the muon spectrometers along with a brief description of the LHC.

3.1 The Large Hadron Collider

The LHC [44] is a giant ring with 27 Km circumference installed 100 m beneath the surface of Swiss-French borders. It is designed to accelerate two proton beams moving clockwise and anti-clockwise directions with the 14 TeV center-of-mass energy. The goal of building such a huge accelerator was search for the undiscovered particle physics predicted by the SM and possibly beyond. The main motivation of the LHC was the search of the SM Higgs boson, the last missing link of the model. After the discovery of Higgs boson in 2012, particle physicist are also excited to look beyond the SM theories such as super-symmetry and theory of extra dimensions.

The basic working principle of the LHC is to use electric field to accelerate the charged particles. There are 1,232 dipole magnets used to keep the beams on their circular path, while an additional 392 quadrupole magnets are used to keep the beams focused. To keep the magnets at a operating temperature of 1.9 K, the super-fluid helium-4 gas is used. Protons are circulated around the LHC ring in the form of bunches. There are 2808 bunches in the LHC

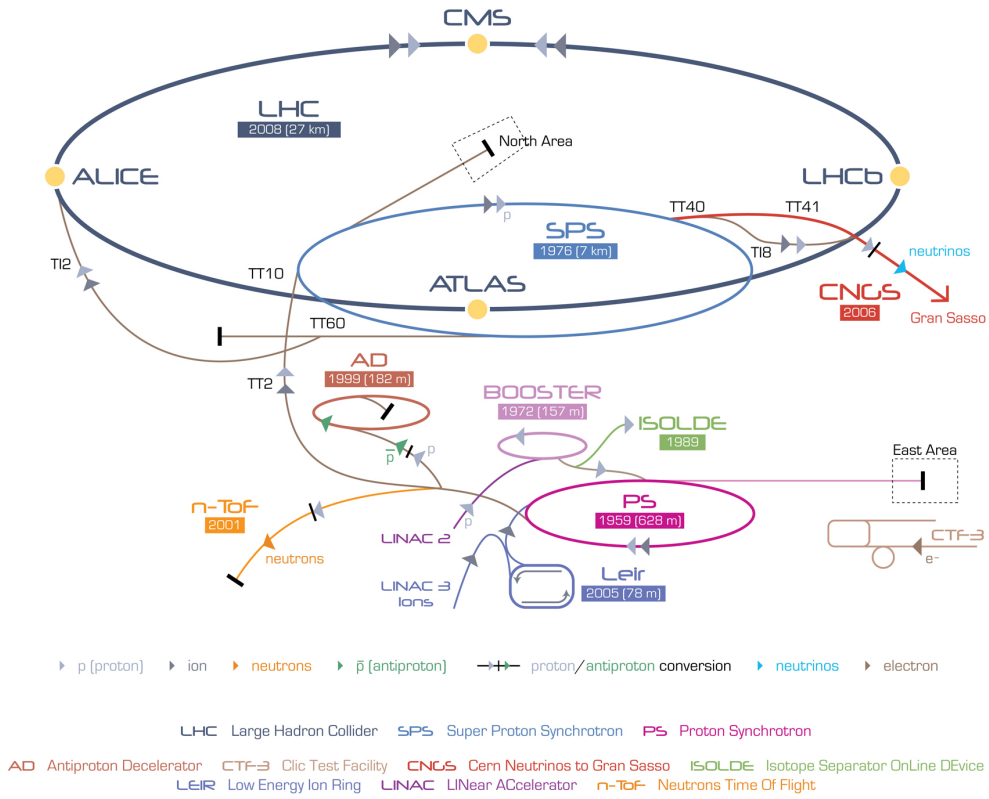


Figure 3.1: The Large Hadron Collider (LHC) Cascade Acceleration of proton beams, the beam injection layout from Linear Accelerator (LINAC) to the LHC main ring. This is an overview of the European Organization for Nuclear Research (CERN) accelerator complex.

storage ring and each bunch contains 115 billion protons corresponding to a collision rate of 40 MHz at the collision points.

Before the injection of proton beams into the LHC ring for collision, the beams are being accelerated through a number of small particle accelerators. These small accelerators gradually increase the energy of protons and convert them into bunches, which are separated by 25 ns. The LHC has its four major interaction points, which are clearly visible from the overview diagram of the CERN accelerator complex, as shown in Fig. 3.1. A Linear Accelerator (LINAC2) at the start of this cascade acceleration, produces 50 MeV protons. These protons are then delivered to the Proton Synchrotron Booster (PSB), which accelerates further up to the energy of 1.4 GeV. The protons are injected to the further stage, which is the Proton Synchrotron (PS). The synchrotron produces bunches of protons with a 25 ns spacing and also accelerates them to attain 26 GeV energy. After the PS, these bunches are transferred to the Super Proton Synchrotron (SPS). The SPS accelerates them further to increase the energy up to 450 GeV. Finally bunches are injected into the LHC. The LHC can achieve the optimum energy of 7 TeV per beam in order to obtain the 14 TeV center-of-mass energy at collision points.

The LHC is designed to study pp collisions at a center-of-mass energy of 14 TeV with a luminosity up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. However the heavy ions (e.g lead-lead) collisions are also studied at the LHC. Once these beams reach their maximum energy, they are collided at four different places on the LHC ring.

The LHC has four major detectors installed in the underground caverns around the collision points, and the CMS is one out of two general purpose detectors. The nominal number of protons per bunch is typically 10^{11} : bunches will have a very small transverse spread, $\sigma_x \sim \sigma_y \sim 15 \text{ } \mu\text{m}$, while they are normally 7.5 cm long in the z direction at the collision points. The main features of the accelerator are summarized in the Table 3.1.

Table 3.1: The Large Hadron Collider (LHC) designed parameters for nominal operation.

Parameter	Value
Circumference (km)	27
Beam Energy (TeV)	7
Number of magnet dipoles	1232
Dipolar magnetic field (Tesla)	8.386
Magnet Temperature (Kelvin)	1.96
Maximal number of bunches	2,808
Protons per bunch	1.05×10^{11}
Bunch length [cm]	7.5
Bunch spacing (ns)	25
Maximum Luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	10^{34}

3.1.1 Luminosity Measurement

In experimental high energy physics experiments, the luminosity is the measure of interactions per unit time per unit area. It gives the amount of data collected during particle collisions in the accelerator. For a physics analysis, a precise measurement of the integrated luminosity is required to convert observed number of events into cross-section. However, one may also need the measurement of the instantaneous luminosity, possibly bunch-by-bunch. The cross-section (σ) of a physical process at hadron colliders is linked to the event rate dN/dt via luminosity $\mathcal{L}$ as

$$\frac{dN}{dt} = \mathcal{L} \times \sigma, \quad (3.1)$$

where σ depends on the center-of-mass energy ($\sqrt{s}$) of collisions. The instantaneous luminosity ($\mathcal{L}$) characterizes the collider performance and is defined as

$$\mathcal{L} = \frac{\gamma f N_p^2 k_B F}{4\pi\epsilon_n\beta^*}, \quad (3.2)$$

where f is the revolution frequency, γ is the Lorentz factor, N_p is the number of protons in a bunch, k_B is the number of bunches, ϵ_n is the normalized transverse emittance (with a design value of $3.75 \mu\text{m}$), β^* is the betatron function at the interaction point, and F is the reduction factor due to the crossing angles. In the years 2010 and 2011, the LHC has taken data with a center-of-mass energy of 7 TeV and delivered the integrated luminosities of 50 pb^{-1} and 6 fb^{-1} , respectively. In 2012 the LHC center of mass energy was increased to 8 TeV corresponding to 23 fb^{-1} of the data, as shown in Fig. 3.2.

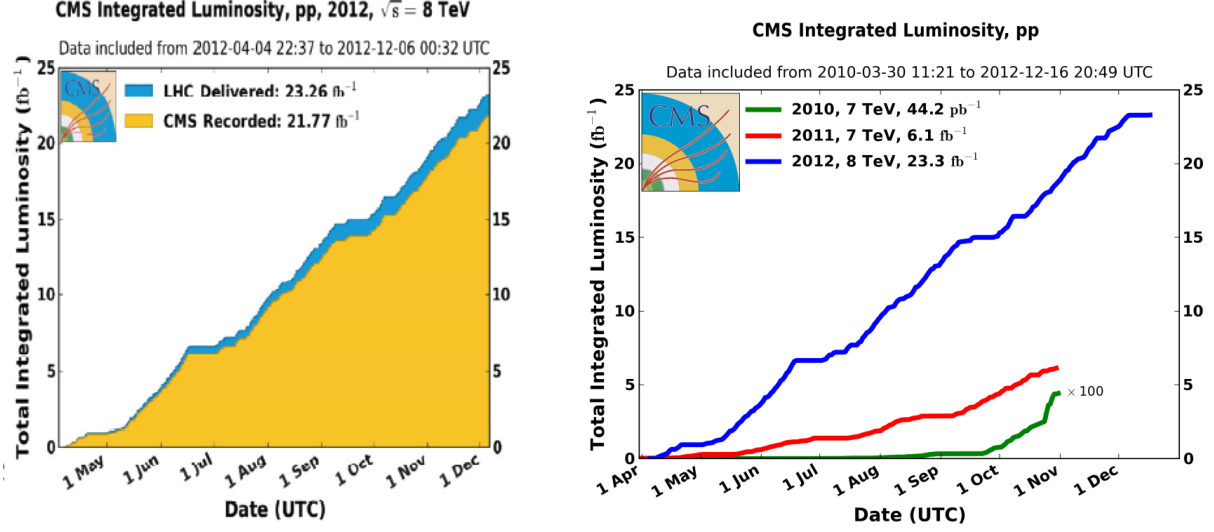


Figure 3.2: The integrated Luminosity recorded by the Compact Muon Solenoid (CMS) detector and delivered luminosity by the Large Hadron Collider (LHC).

3.2 The Compact Muon Solenoid

The CMS detector [46, 47] is one of the largest experiments ever built for the particle detection. It is a general purpose detector installed at the LHC ring. The detector is installed 100 meter underground close to the French village of Cessy, between Lake Geneva and Jura mountains. The detector is 21.6 m long with a diameter of 14.6 m and a total weight of 12500 ton. The main feature of the CMS detector is a superconducting solenoid of 6 m internal diameter that produces a magnetic field of 3.8 T. A schematic view of the CMS detector is shown in Fig. 3.3.

The primary goal of the CMS detector is to fulfill the physics objectives of the LHC with a good muon identification, momentum resolution, reconstruction of charged particles and missing transverse energy. The CMS detector is capable of measuring the muon charge precisely, and also the invariant mass of the di-muon, di-electron and di-jet systems with a good resolution. For the efficient tracking of out going particles and the tracking detectors are placed close to the interaction point. The CMS detector can achieve a very high resolution for the Electromagnetic Calorimeter (ECAL) and hermetic Hadronic Calorimeters (HCAL) for a good reconstruction of the missing energy and jets. The detector has a high performance muon system and strong magnetic field for the best momentum measurement of highly energetic muons.

The inner tracking system, ECAL and HCAL are residing inside the superconducting solenoid and Muon spectrometers are fixed in iron return yokes. Since the CMS detector

has a cylindrical symmetry, having sub-detectors in the barrel and the endcap regions. In order to understand the structure of the detector, it is good to define the CMS coordinate first.

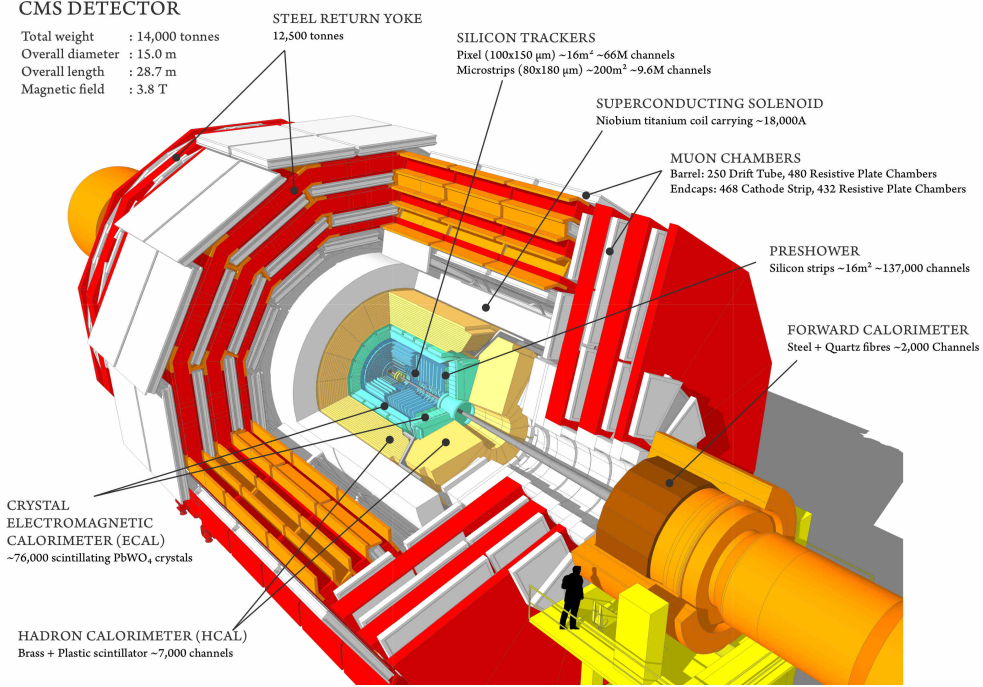


Figure 3.3: The Compact Muon Solenoid (CMS) detector installed at the LHC, all the sub-detectors showed around cylindrical symmetry of experiment

3.2.1 Coordinate System

For the reconstruction and measurements of an event it is useful to define a coordinate system, which has its origin at the nominal collision point. The CMS has incorporated the Cartesian coordinate system and adopted the following convention:

- the x -axis points towards the center of the LHC ring,
- the y -axis points upwards, towards the surface,
- the z -direction coincides with the CMS cylinder axis.

The cylindrical symmetry of the CMS experiment allows to introduce pseudo-angular reference coordinate system, given by the variable (r, ϕ, η) , where r is the radial distance from beam axis, ϕ is azimuthal angle measured with respect to the x -axis in the x - y plane and η represents

the angular distribution in the apparatus and also known as the pseudo-rapidity,

$$\eta = -\ln \tan \frac{\theta}{2}, \quad (3.3)$$

where θ is the polar angle with respect to z -axis. The advantage of using the pseudo-rapidity instead of the polar angle is that over an equal distance in η the particle flux is approximately a constant and $\Delta\eta$ between the two vectors is Lorentz invariant. For high energy particles pseudo-rapidity is a good approximation of rapidity (y), which is defined with the following equation.

$$y = \frac{1}{2} \ln \left(\frac{E + P_L}{E - P_L} \right), \quad (3.4)$$

where E is the energy of outgoing particles and P_L is the momentum of the particle projected along the beam axis. Due to Lorentz invariance, rapidity is the variable of interest at hadron colliders. It follows from its definition that the pseudo-rapidity is null for $\theta = 90^\circ$ and increases in absolute value when approaching the beam pipe, asymptotically reaching infinity at $\theta = \pi$ on the z -axis means in the direction of beam. The next sub-section will introduce the super-conducting magnets installed in the CMS.

3.2.2 Superconducting magnet

The superconducting solenoid is a distinguished feature of the CMS apparatus [48]. The high energy of colliding beams also produces the particles with high energies. For the measurement of momentum and tracks of outgoing particles, a strong magnetic field is a necessary requirement. The CMS solenoid is the most powerful solenoid ever built is a 6 m long cold bore, 13 m in diameter, which is hosting the inner tracking system having crystal ECAL and HCAL in it, as shown in Fig. 3.4. The superconducting solenoid is made of NbTi. The CMS magnet achieves a magnetic field of 3.8 T at the full current of 20,000 Amperes, and the energy stored in the magnet is 2.6 GJ. The flux is returned via iron yoke, which is composed of 5 barrel wheels and 3 endcap disk on each side. The tracking of muons in the CMS is controlled through magnetic field of returned yoke, which is 1-2 T. The magnet system includes a cryogenic system, power supply, quench protection, vacuum pumping and control system. Whenever magnet loses its superconducting property due to quenching, all the stored energy is dumped to resistors within a time of 200 sec. The CMS super-conducting contains the tracking detectors therefore in the next sub-section discussion is about the tracker detector.

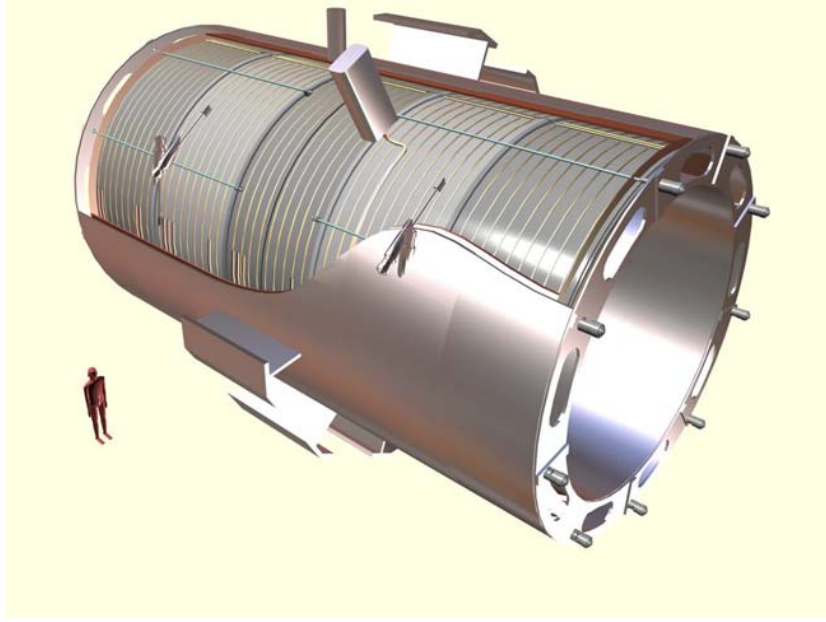


Figure 3.4: General artistic view of the 5 modules composing the cold mass inside the cryostat, with details of the supporting system

3.2.3 The Tracker

The CMS inner most sub-detector is the tracker detector [49], which is the closest to the interaction point. The designed luminosity of the LHC is very high. The efficient tracking system is therefore an important requirement of the CMS. The basic working goal for the tracker detector is the vertex and tracks of charged particle reconstructions. The tracker is completely based on the semiconductor detectors built for the reconstruction of the primary vertices, lepton identification via matching charged tracks of electromagnetic calorimeter and muons spectrometers, reconstruction of secondary vertices for the B -meson and τ decays. Within the tracker detector, particles can be detected within the pseudo-rapidity range of $|\eta| < 2.5$. The silicon tracker is divided into two parts: the Silicon Pixel Detector and the Silicon Microstrip Detector, as shown in the Fig. 3.5.

3.2.4 Silicon Pixel Detector

The silicon pixel detector consist of 66 million silicon pixels covering the whole range of pseudo-rapidity, $|\eta| < 2.5$. The pixel detector is closest to the CMS interaction point and provides reconstruction of secondary vertices to form the seed tracks for the outer track reconstruction and high level triggering. A good reconstruction resolution is of particular interest for the further identification of jets originating from b -quarks.

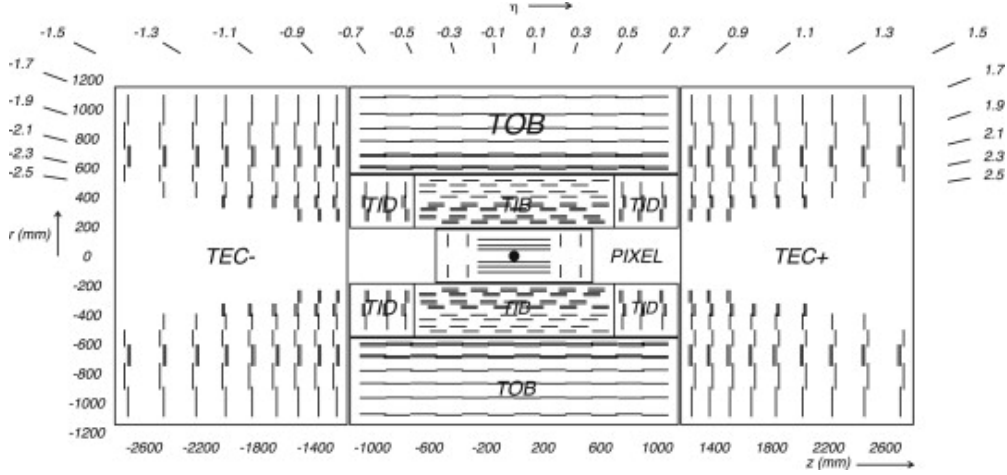


Figure 3.5: Schematic of the Compact Muon Solenoid (CMS) tracker in the rz -plane, showing the positions of the pixels and various strip subsystems.

In the pixel detector, each silicon pixel cell has a size of $100 \times 150 \text{ } \mu\text{m}$. This allows precise measurement of the impact parameter in the transverse plane. The pixel tracker consists of three cylindrical module layers surrounding the beam-pipe and two disks of modules on each side. There are three barrel pixel layers around the beam pipe at the radii of 4 cm, 7 cm and 10 cm and each of them having a length of 53 cm. The endcap pixel consists of two layers on each side at $z = \pm 32.5 \text{ cm}$ and $\pm 46.5 \text{ cm}$.

3.2.5 Silicon Microstrip Tracker

The silicon microstrip tracker surrounds the pixel tracker detector. It has four main parts and composed of 15148 silicon strip modules covering an area of 200 m^2 . The strip tracker covers the complete range of pseudo-rapidity $|\eta| < 2.5$ and provides a slightly lower transverse momentum and impact parameter resolution. There are four parts of tracker detector.

- Tracker Inner Barrel (TIB) has four concentric layers of cylindrical shape at different radii. Four TIB layers are placed in the detector with radius of 25.50 cm , 33.90 cm, 41.85 cm and 49.80 cm from the center of detector, respectively, with a length of 1.4 m along beam pipe having interaction region at the center. The first two layers have double-sided modules while the outer two layers have single-sided modules.
- Tracker Inner Disk (TID) has three disks on both sides of barrel. There are three rings of modules on each disk.

- Tracker Outer Barrel (TOB) contains a single mechanical cylindrical structure supporting 688 module sub-assemblies (from a total of 5200 Silicon modules), called rods. Every rod gives support and cooling for 6 or 12 silicon detector modules together with their interconnection and readout electronics. There are six layers of rods on TOB with average radii of 608 mm, 692 mm, 780 mm, 868 mm, 960 mm and 1080 mm. The cylinder has a total length of 2360 mm and inner and outer radii of 555 mm and 1160 mm, respectively, such that it covers the TIB/TID sub-detector.
- Tracker endcap (TEC) has two endcaps wedge shaped carbon fiber support plate called plates. These plates carry up to 28 modules arranged in 7 radial rings on each side. A total of 6400 modules are mounted on 288 petals to form 18 such disks for TEC+ and TEC-. The endcaps extend radially from 220 mm to 1135 mm and from ± 1240 mm to ± 2800 mm along the z -direction. Other than above seven disks there are 2 more disks on each side of endcap serving as front/back termination.

Despite all the advantages of the CMS tracker detector, there are also some disadvantages with respect to drift tubes tracking used at the DELPHI and CDF. Since tracker material has very high density, particles such as electrons radiate in the multiple scattering with the dense material and lose all energy by producing photons. These photons either reach the ECAL and produce an energy hit without an associated track, or they convert into electron-positron pairs leading to two additional tracks and subsequently the ECAL hits [50]. At the outer side of the tracking detector there is the ECAL, which is described in detail in the next sub-section.

3.2.6 Electromagnetic Calorimeter

The calorimeters are the detectors which measure energy deposition. The ECAL [51] is designed to measure the energy of electrons, photons and positrons, as shown in the Fig. 3.6. Muons and hadrons dump small fraction of their energy in the ECAL. The ECAL is a hermetic homogeneous detector made of 61200 lead tungstate (PbWO_4) scintillator crystals mounted in the central barrel part of the CMS detector. The crystal calorimeter has capability to provide an outstanding energy resolution, very quick response and radiation hardness [52]. The scintillation light is detected with the help of avalanche photodiodes (APDs) and vacuum phototriodes (VPTs) in the barrel and endcap regions, respectively. The barrel part of ECAL (EB) is made of 61200 crystals and covers the $|\eta| < 1.479$, at front face these crystals have a

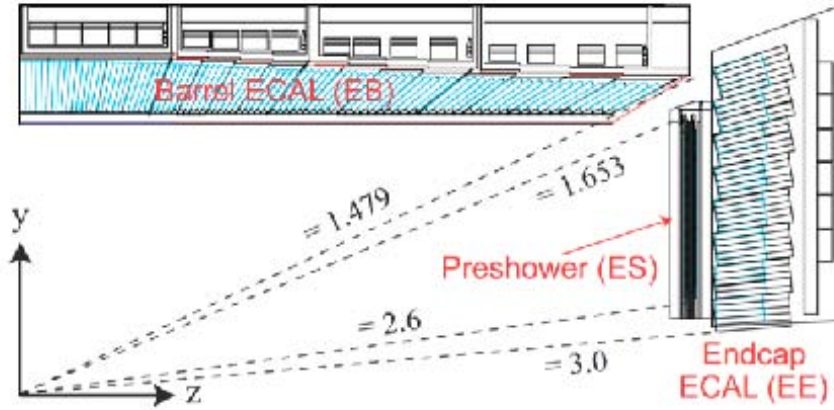


Figure 3.6: Description of the Electromagnetic Calorimeter (ECAL) system, installed at the Compact Muon Solenoid (CMS) experiment.

size of $22 \times 22 \text{ mm}^2$, which corresponds approximately to 0.0174×0.0174 resolution in the $\eta - \phi$ space, and each one of them have a total length of 230 mm. Each of the two ECAL endcaps (EE) consists of 7324 crystals and covers the $1.479 < |\eta| < 3.0$. and have a front face size of $28.62 \times 28.62 \text{ mm}^2$ and a length of 220 mm. The photons produced in the scintillator crystals are detected in photodetectors. A large amplification is needed to ensure the fast detection and not much affected by the radiation and magnetic field inside the CMS detector. Therefore the avalanche photo-diodes are used in the BE and vacuum phototriodes in the EE. The ECAL energy resolution has been parametrized as a function of incident electron/photon energies, as shown in the following equation

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2, \quad (3.5)$$

where E is the energy in GeV, S is the stochastic term, N the noise term, and C is the constant term, as shown in the Fig. 3.7. The detailed study of energy resolution of calorimeter is given in [53].

3.2.7 Hadron Calorimeter (HCAL)

The HCAL lies radially outside the CMS tracker and ECAL. It is a sampling detector, which is made of copper alloy (70 % copper and 30 % zinc) and plastic scintillators. The CMS hadron calorimeters have been designed particularly for the measurement of hadron jets and exotic particles resulting in apparent missing transverse energy [54].

The HCAL is composed of four sub-detectors: the hadronic barrel (HB) part covers the

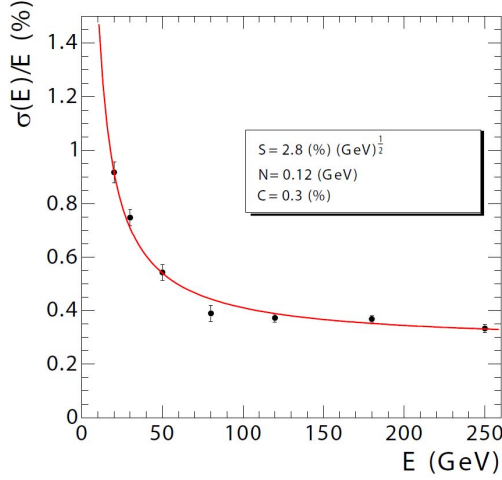


Figure 3.7: The energy resolution of Electromagnetic Calorimeter (ECAL) as a function of energy.

range $|\eta| < 1.3$, the hadronic endcap (HE) covering $1.3 < |\eta| < 3.0$, the HCAL Outer (HO) calorimeter covering $|\eta| < 1.3$, and the HCAL Forward (HF) calorimeters covering $2.9 < |\eta| < 5.0$. All the HCAL sub-detectors has been shown in Fig. 3.8.

The Hadronic Barrel

The HB has been divided into two parts (HB+ and HB-) and each part of HB has been inserted from either ends of the CMS superconducting solenoid. The HB is radially located between the outer layer of electromagnetic calorimeter at $R = 1.77$ m and the magnet cryostat and coil $R = 2.95$ m. The structure of barrel hadron calorimeter is polygon type and consists of two part of equal lengths of 4.33 m. A half part HCAL barrel contains 18 wedges and each wedge has azimuthal angle 20° . The hermiticity of HB has been maintained by placing 16 scintillator with minimal uninstrumented gaps having resolution of $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$.

The Endcap Hadronic (HE) Calorimeter

The Endcap Hadron calorimeter (HE) covers a substantial portion of the rapidity range, $1.3 < |\eta| < 3$. The layered construction of the HE is similar to that of the HB using 79 mm thick brass absorbers followed by plastic scintillators. The resolution of the HE towers is $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$ for $|\eta| < 1.6$ and $(\Delta\eta, \Delta\phi) = (0.17, 0.17)$ for $|\eta| > 1.6$.

The Hadron Outer (HO) Calorimeter

The space between superconducting solenoid and the ECAL limits the amount of absorber material in the HB and may not be enough to stop the highly energetic hadron showers. Therefore

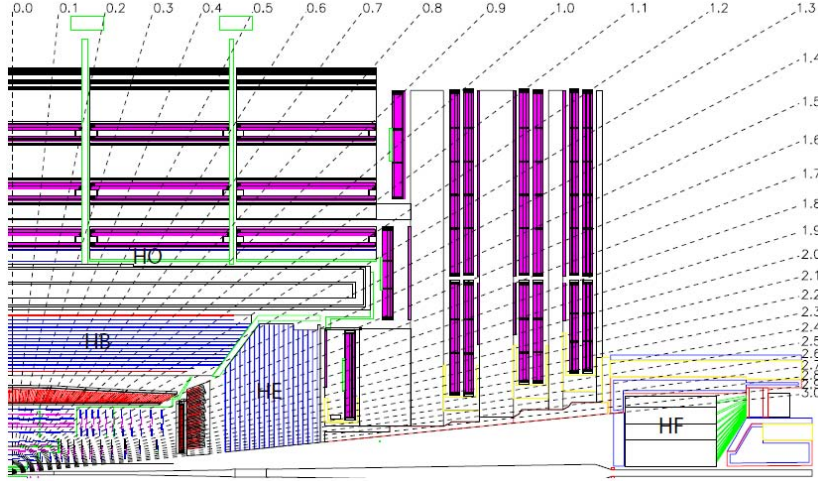


Figure 3.8: The Compact Muon Solenoid (CMS) detector with longitudinal view, all sub-detectors of Hadron Calorimeter (HCAL) have been shown: the hadron barrel (HB), endcap (HE), outer (HO), and forward (HF) calorimeters.

an additional absorber, the HO has been added outside the CMS superconducting solenoid. The HO consists of two scintillator tiles outside the solenoid to increase the effective thickness of the HCAL by using superconducting solenoid as an additional absorber.

The Hadron Forward (HF) Calorimeter

The Hadron Forward (HF) is a forward calorimeter detector located at a distance of 11.2 m from nominal interaction point outside the solenoid, with pseudo-rapidity range $3.0 < |\eta| < 5.0$ and almost hermetic with very high missing transverse energy absorption. Due to extremely high energy particles and radiation flux, the calorimeter consists of material of two units, the steel absorber and embedded radiation hard quartz fibers. The fibers collect Cherenkov radiation emitted by relativistic particles. The HF phototubes are faster as compared to the HE hybrid photodiodes. The HF has resolution of $(\Delta\eta, \Delta\phi) = (0.175, 0.175)$. The large range of the HF makes it possible to detect forward jets, which are typical signatures of the single top t -channel process. After the HCAL radially outside the solenoid, the muon system is interleaved in the return iron yoke. The CMS muon system is explained in the next sub-section.

3.2.8 The CMS Muon System

The detection of muons at CMS is the central feature of the experiment. The identification and measurement of muons is critical to physics goals of CMS. The muon interactions with matter

are very weak and they pass all sub-detectors after losing only a small fraction of their energy. Outside the CMS superconducting solenoid, the muon system is embedded in iron return yoke having a non-uniform magnetic flux. The CMS muon system, as shown in the Fig. 3.9, has three main functions: muon identification, muon momentum measurement and triggering. The muon system contains the three types of gaseous detectors, which are installed in the barrel and endcap regions of the CMS detector. All the three muon sub-detectors with their corresponding pseudo-rapidity coverage [55] are shown in Fig. 3.9. The Drift Tubes (DT) are installed in the barrel part of the CMS, and have the pseudo-rapidity coverage of $|\eta| < 1.2$. The Cathode Strip Chambers (CSC) are also muon detectors installed in the endcap region and cover the pseudo-rapidity range $0.9 < |\eta| < 2.4$. The Resistive Plate Chambers (RPCs) gaseous muon detectors are installed both in the barrel and endcap regions of the CMS detector. The RPCs cover the range $|\eta| < 1.6$. The DT is a gaseous detector mounted on the wheels of iron return

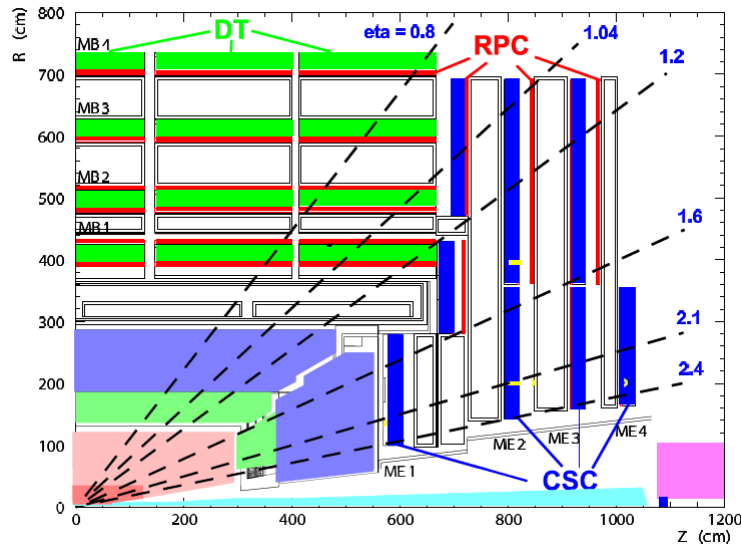


Figure 3.9: The location of Compact Muon Solenoid (CMS) muon chambers in polar coordinate (r, z) , location of Drift Tubes (DT) in muon detector is showed with green, Resistive Plate Chambers (RPC) with red and Cathode Strip Chambers in blue.

yoke in the barrel region of the CMS detector, have 85% Argon (Ar) and 15 % carbon dioxide (CO_2). There are 4 stations of the CMS barrel muon detectors forming concentric cylinders around the beam pipe: the 3 inner cylinders have 60 drift chambers each and the outer cylinder has 70 drift tubes. There are about 172000 sensitive wires. Since the magnetic field is expected to be low in the barrel region, the DT chambers are therefore used as a tracking detectors. A single chamber of DT is made of 3 (or 2) superlayers (SL), each made of 4 layers of rectangular drift cells staggered by half a cell. In the 2 outer SLs, the wires are parallel to the beam line

providing a measurement of track bending in the magnetic field in the plane (r - ϕ). The wires in the inner SLs are orthogonal to the beam pipe providing the measurement of z position along the beam [55]. The block diagram of the DT is shown in Fig. 3.10. The CSCs are multiwire

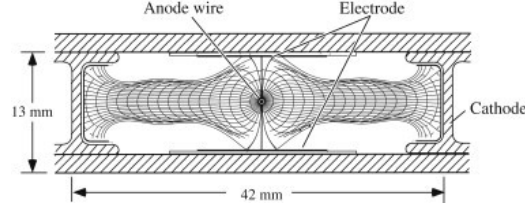


Figure 3.10: The Compact Muon Solenoid (CMS) Drift Tubes (DTs) chamber basic principle.

proportional chambers installed at the CMS endcap return yoke, as shown in Fig. 3.11. The CMS endcap muon system consist of 468 CSCs arranged in 4 disk as follow: 72 Muon Endcaps (ME) ME1/1, 72 ME1/2, 72 ME1/3, 36 ME2/1, 72 ME2/2, 36 ME3/1, 72 ME3/2, and 36 ME4/1. The CSCs are trapezoidal in shape and each chamber covers either 10° or 20° except for the ME1/3 ring, which provides an overlap in ϕ . The CSCs strips are extended radially and provide a measurement in ϕ and anode wires are running in the azimuthal direction providing measurement along the z -axis. The outermost station of the CSC, the ME4, contains a single ring of 18 chambers. In total, the CSC is comprised of 468 chambers, with 220,000 cathode strips and 180,000 anode readout channels. The CMS RPCs are gaseous muons detectors and

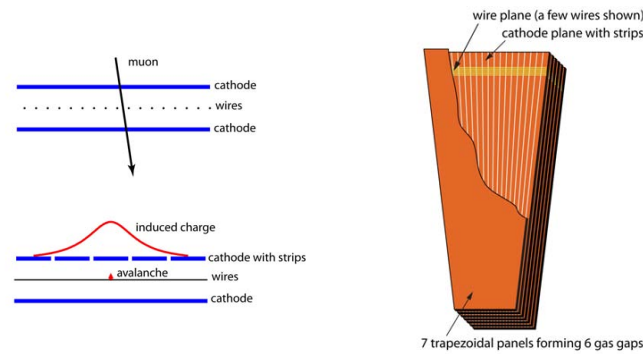


Figure 3.11: The layout of a Cathode Strip Chambers (CSCs) made of 7 trapezoidal panels. A schematic view of a single gap illustrating the principle of CSC operation. [47]

stationed both in the endcap and barrel region. The RPCs are double gap Bakelite detectors, as shown in Fig. 3.12 and operate in the avalanche mode. The RPCs are fast detector and can perform a few nano seconds measurements shorter than the 25 ns bunch spacing. The RPCs are the dedicated detectors for the muon trigger and can distinguish muons coming from different bunch crossings, even in the presence of high background expected at the LHC. In the

barrel region, there are six layers of the RPCs, two in each of the first two stations and one in each of the last two stations.

The first three endcap stations of the CMS are equipped with the RPCs [55].

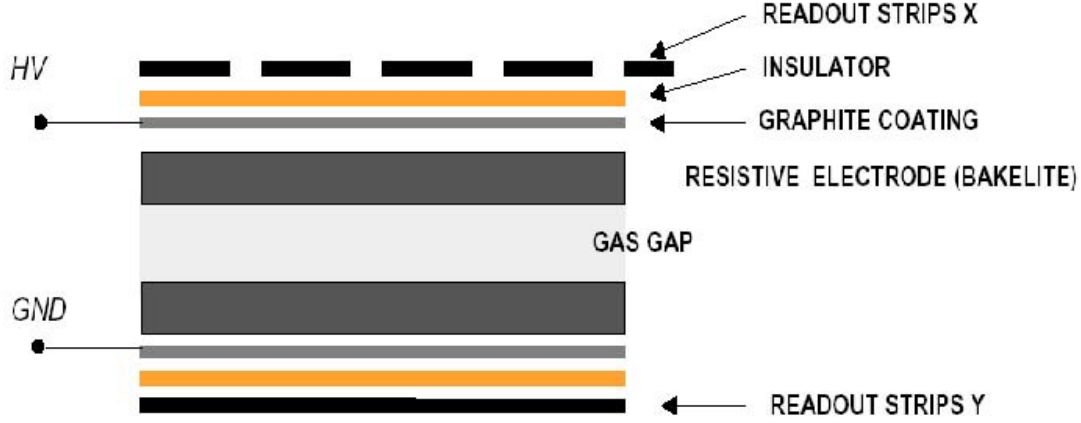


Figure 3.12: The Resistive Plate Chambers (RPCs) at the Compact Muon Solenoid (CMS).

3.2.9 CMS Trigger System

The running conditions at the LHC impose severe constraints on the design of the trigger systems mainly due to the enormous data rate and harsh radiation environment. The LHC being a pp collider at very high center-of-mass energy of 14 TeV, has a very high interaction rate $\approx 10^9$. The bunches of protons have spacing of 25 ns with a crossing frequency of 40 MHz. At the nominal designed luminosity $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$, typically around 20 or more simultaneous events are expected. Since it is impossible to store and process the large amount of data associated with the resulting high number of events, only interesting events are selected for the processing. Then a drastic rate reduction is achieved for the events with known physics [56]. To keep a separate information of each event, the detectors are required to have a good time resolution. This is achieved through a proper trigger system. The trigger is one of the most critical part to select all the potentially interesting events in presence of huge backgrounds by discarding all the less important processes [57]. The trigger is the start of the event selection for important physics goals at the CMS. The triggering system reduces the event rate down to 100 Hz. The CMS trigger system is a multiple stage process, and the rate is reduced in two steps called Level-1 (L1) trigger and High-Level Trigger (HLT) [57], respectively as shown in the Fig. 3.13.

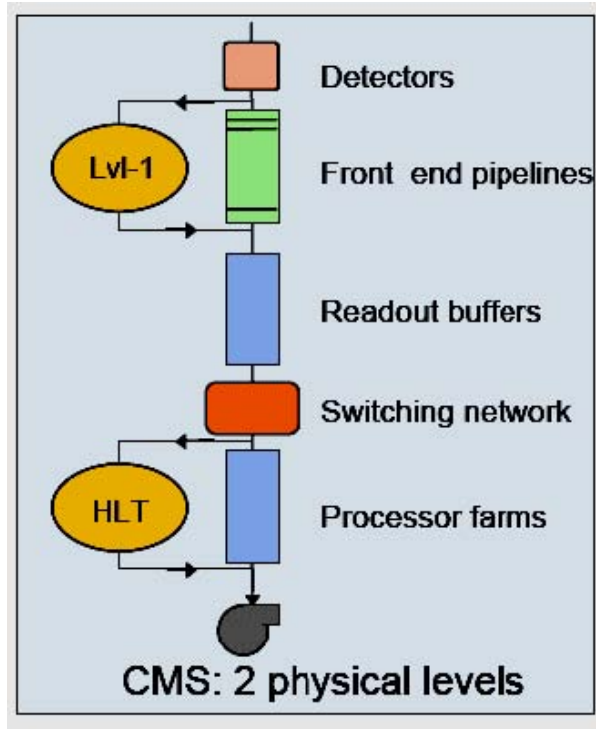


Figure 3.13: Architecture of the Level-1 Trigger [56]

The CMS Level 1 Trigger

The first level trigger is an immensely challenging part of the online data selection and obligatory to have very fast custom designed electronics with a significant portion placed close to the CMS detector. The L1 trigger is a pure custom-built electronic system, it has to take the decision to accept or reject an event in a short time of a few microseconds. The L1 trigger is tremendously fast self-regulating and selects events with interesting physics. The L1 trigger is just like a scanner that picks events for a given physics specifications. The trigger objects are sorted according to their rank determined from transverse energy, momentum and quality information. The highest rank objects are always sent to the global trigger, which then applies thresholds and other selection criteria according to physics or technical requirements. Other than particles momenta and energy selection, the CMS L1 Global Trigger has distinguish feature of keeping the information of location information, notably pseudo-rapidity and azimuthal angle.

The top level of L1 trigger is global trigger that receives the information from the CMS muon system and calorimeter. The trigger objects are electrons, muons and jets. These objects are recorded by the corresponding sub-detectors. The first step is the production of the local trigger information, called as trigger primitives collected by the calorimeters and the muon

system. The proton bunches colliding with 40 MHz frequency input to level-1 trigger. The L1 returns 100 KHz maximum output rate which is determined by the speed of the trigger electronics. The maximum rate that can be tolerated at the input of the Second Level Trigger.

High Level Trigger (HLT)

The High Level trigger [57] is purely software based trigger and has a very long processing time with respect to L1. The processing is done via commercial computer farms. The HLT algorithms have access to the data from all sub-detectors of the CMS including the tracker, with full granularity and resolution. In contrast to L1 trigger, the HLT algorithm calculates quantities with resolution comparable to the final state of the detector. The HLT output quantities have better resolution, purity and efficiency as compared to the L1 trigger output. The maximum HLT input rate is 100 KHz and the output rate is about 100 Hz.

Chapter 4

Physics Object Reconstruction

In order to perform the event selection for tqZ analysis, a brief knowledge of physics objects used in the analysis is described in this chapter. For both the data and MC simulation, the reconstruction of electrons, muons, jets and missing transverse energy in the scope of CMS experiment along with the adopted techniques are also discussed. This chapter also includes the summarized detail about the event generation and about the main generators used for MC simulation.

4.1 Event Generation

In the field of high energy physics at the LHC, different event generators are used to study the data events produced as a result of pp collisions. There are several MC generators for different physics needs, which are interfaced with the CMS experiment. The main focus of these generators is to provide a description of hadron collisions at the LHC as accurate as possible. These generators are based on theoretical models with different physics goals, such as hard and soft interactions, parton distributions, initial and final state parton showers, multiple interactions, fragmentation and decay. A factorized approach is used for the event generation. The major steps for the event generation are following:

- modeling the hard scattering parton showers, i.e. initial and final state radiations,
- incorporating the beam remnant and hadronization, and
- taking multiple interactions into account.

In general, the MC simulation at the CMS involves two steps: the generation of physics process of interest and simulation of how particles propagate through detector. The outcome

from a MC generator is a process that depends on the probability distributions of interesting observables as a result of particle collisions. Many MC generators with different properties and techniques are used to describe the parton scattering physics for the pp collisions at the LHC. The MC generators used in this analysis are briefly described below.

The PYTHIA [58] MC generator is used to generate the QCD multijet events. It is a multi-purpose generator which provides a link between theory (quarks, gluons) to experiment (meson, hadrons). The PYTHIA is capable for performing calculations of hard and soft interactions, initial and final state radiations. Along with hard processes, it can also take into account, UE, parton showers and hadrons decay. In PYTHIA fragmentation is based on the Lund model [59]. The PYTHIA can produce hard scattering events to LO in perturbation theory, the NLO calculation can be performed by introducing different tunes.

The MADGRAPH [60], event generator is used for the calculation of a matrix element of a certain process. The amplitudes of relevant sub-processes generate automatically and produces the mapping for the phase space integration. The generator is not a full simulator and therefore needs an interface with other generators, for example PYTHIA, to describe a complete event. The complete chain of simulated process could be based on MADGRAPH + PYTHIA. The MADGRAPH is capable for calculating the Born amplitudes for processes $2 \rightarrow n$, including jets can be used to calculate cross-sections, making it a natural choice for processes with high-multiplicity final states. Also the different Flavor Schemes (FS) like 4FS, 5FS are also supported by the combination of MADGRAPH+PYTHIA.

aMC@NLO Physics for which we are interested at LHC involves high-multiplicity processes for which we need at-least the first non-trivial order in perturbation theory, i.e. the Next-to-Leading Order (NLO). The amplitudes for the processes having NLO corrections can be calculated with aMC@NLO [61]. It is capable of generating standalone all possible NLO processes. This generator produces matrix elements only and basic idea is to use it for the calculation of cross-sections.

POWHEG (Positive Weight Hardest Emission Generator), is another approach to NLO matrix elements which are matched with the parton showers. The Powheg package provides combination of a parton shower with NLO QCD calculations. Powheg works with the interface of POWHEG Box. The basic idea of this MC generator is to generate the hardest radiation first and then feed the event to any shower generator for softer radiations. POWHEG is frequently combined with Pythia to simulate showering and hadronization [62, 63, 64].

The tqZ signal MC is generated by using the MADGRAPH event generator and then compared with the MC sample generated by using the aMC@NLO generator. The dominant backgrounds $t\bar{t}Z$, $t\bar{t}W$, WZ and $Z + Jets$ are also generated by using MADGRAPH. The other backgrounds like ZZ are generated by using POWHEG and WW are generated by using PYTHIA event generator.

4.1.1 Parton Distribution Functions

The physics of PDFs is very important for the calculation of the production cross-sections that depends upon the distribution of the momentum fraction x and the virtuality Q^2 of the partons (quarks and gluon's) [65]. The PDF knowledge is continuously improved by taking inputs from the data analysis of high energy collisions, at the LHC. The important part of the PDFs is obtained from the global fits of deep inelastic scattering to predict the cross-sections at the NLO and NNLO accurately. For a process $ij \rightarrow k$, the cross-section is given by the Eq. 4.1

$$\sigma_{ij \rightarrow k} = \int dx_1 \int dx_2 f_i^1(x_1) f_j^2(x_2) \hat{\sigma}_{ij \rightarrow k}, \quad (4.1)$$

where $\hat{\sigma}$ is the cross-section for the hard partonic processes, $f_i^a(x)$ are the partonic distribution functions, these partonic distributions describe the probability to find a parton i inside beam particle a , with parton i carrying fraction x of the total momentum of a . In case of processes with many particles in the final state it is replaced by an integral over the allowed final-state phase space. The pdfs also depend on the momentum scale Q^2 as shown in Fig. 4.1 that characterizes the hard process. Since hadrons, such as protons, are the composite objects made

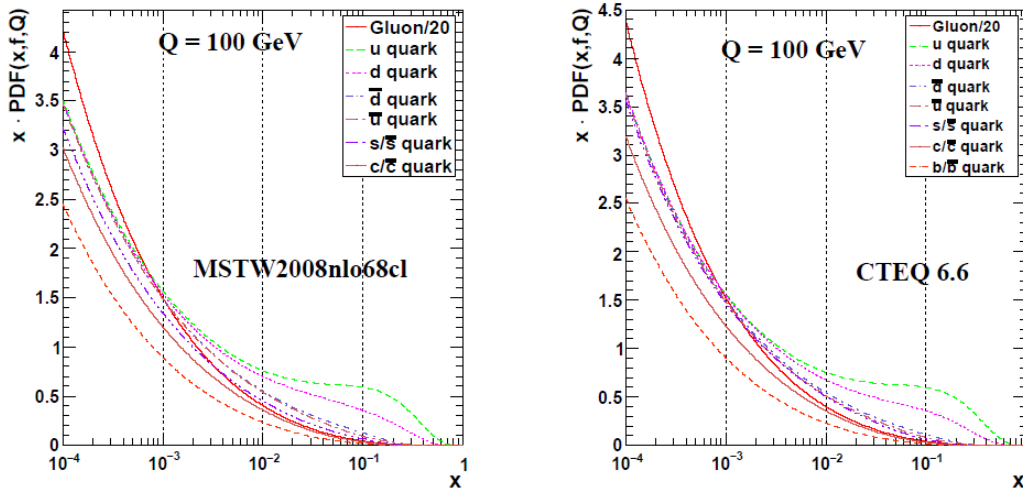


Figure 4.1: The MSTW (left) and the CTEQ (right) Parton distribution functions at the factorization scale $Q = 100$ GeV. Fig. 4.1 taken from [66]

of quarks and gluons are typically described by the pdfs. The QCD is not a well understood subject, the description of hadron distributions still does not exist. Therefore to pin down the distribution function, it is necessary to rely on parametrization. The composite structure

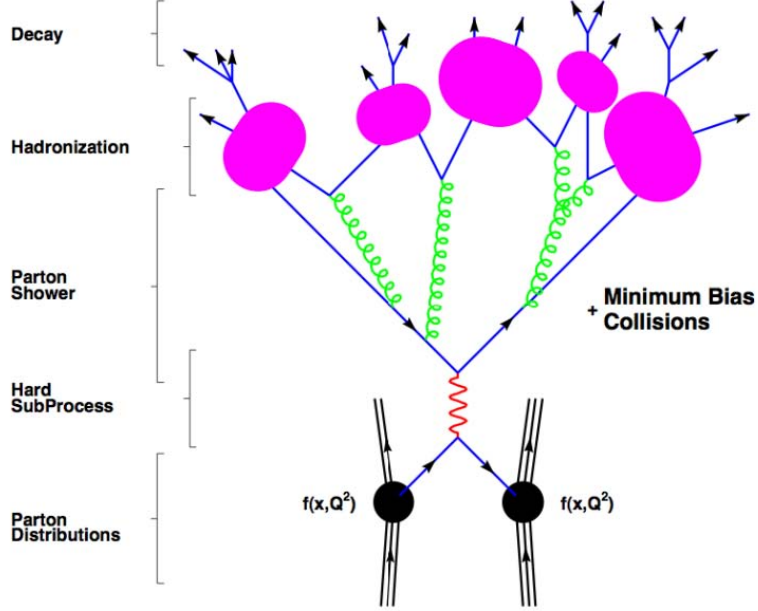


Figure 4.2: The process involved after proton-proton collision, hadronization and parton showering

of hadrons allow for multiple parton-parton scatterings to occur, in which correlated parton distributions are used to describe the multi-parton structure of the incoming beams [67, 69]. The most CTEQ10 and MSTW08 recent versions of the PDFs which are used to study the hadronization and also QCD processes.

4.1.2 Parton Shower

In high energy collisions, the hard sub-process have very large momentum transfer and therefore involve partons having large momentum. Similar to a QED process where accelerating charges radiate (photons), the accelerated partons radiate gluons having color charge and can radiate further into gluon, quark-antiquark pairs by producing outgoing parton showers. These partons are generally simulated by Markov chain, where one or more partons are added to the final state, which is called as a parton shower algorithm. The models for parton shower iteratively produce parton splitting, which reduces the energy scale of the event. The process of parton showering start, at the maximum scale of energy Q_0 with the start of hard scattering and continues until the minimum energy reached Q_{min} . Experimentally partons are not distinguishable at Q_{min}

because they are either soft (low energetic) or their emission direction is towards parent parton. The values of Q_{min} and Q_0 are user defined parameters in the simulation by which the amount of radiation can be regulated during the parton showering.

4.1.3 Hadronization

During the process of hadronization as shown in Fig. 4.2, a set of colored partons are transformed into a color-singlet hadrons, which may subsequently decay into secondary hadrons. This process leads to the formation of final state hadrons. After the parton collision, at some point the evolution through perturbation theory becomes invalid, whereas the dynamics becomes non-perturbative resulting into the formation of hadrons. The currently available non-perturbative techniques are not capable to calculate hadronization processes, therefore, the event generators models are only based on the general features of QCD.

The widely used Lund model is one of the most sophisticated models for the hadronization. Basically there are two main types of hadronization, strings based and clusters based. The strings transform directly into hadrons while clusters had intermediate stage of cluster objects having mass in few GeV [70].

4.1.4 Underlying Event

In the pp collisions, everything other than the hard scattering process is a collective part of Underlying Events (UE) like beam-beam remnants, pileup, detector noise and multiple parton interactions. These UE events consume very small fraction of energy of the incoming partons. The interactions involved in the UE are the result of these remnants. The colliding beams consist of several partons have a high probability to undergo through a separate hard or semi-hard scatterings during the same collision. At high luminosity of the LHC, several collisions happen between beam particles in the same or consecutive beam crossing, referred to as pile-up events. The pileup events are the part of hard scattering. The Multiple Parton Interaction (MPI) and the Beam-Beam Remnants (BBR) constitute the underlying events interleaved with the Initial State Radiation (ISR) and the Final State Radiations (FSR).

4.1.5 Detector Simulation

At the hadron collider, thousands of particles are produced as a result of pp collisions. These particles travel through the detector material, leaving behind hits in tracker or deposit energy

in the calorimeter. In case of MC generators, after applying all the physics process on the final state particles, an accurate and comprehensive simulation of particle detectors is required. The CMS experiment adopted GEANT4 [71] simulation toolkit for including effects due to detector material in an event. The GEANT4 takes care of all physical effects of the experiment as shown in Fig. 4.3 such as energy loss by ionization, bremsstrahlung, electromagnetic and hadronic interactions and simulates the electric response of the read out electronics. To simulate an event having full detector effects requires a lot of time and computing resources, therefore a fast simulation of detector is also developed. The CMS collaboration has developed a Fast MC simulation for the CMS detector which is ≈ 100 times faster than the full simulation [72].

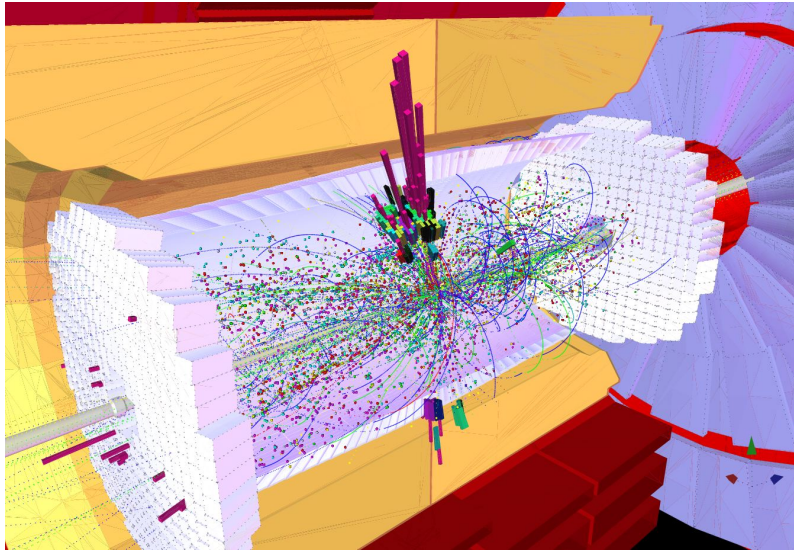


Figure 4.3: The visualization of a simulated events of $Z \rightarrow jj$ in Compact Muon Solenoid (CMS) detector using GEANT4 platform.

4.2 Particle-Flow (PF) Algorithm

The PF event reconstruction is an algorithm that aims to reconstruct and identify individual particles in the event such as; electrons, photons, muons, charged hadrons and neutral hadrons. The reconstruction of physics objects in the CMS experiment is performed by using the Particle Flow algorithm, which is a standard tool used for almost all physics analysis [73]. The main feature of the algorithm is to take all the sub-detectors of CMS into account by analyzing the information on the different position and energy measurements (made by calorimeters, tracking, muon chambers as shown in Fig. 4.5). It combines them in order to characterize the single particle by giving a more precise result with respect to a single detector measurement as

shown in Fig. 4.4. By using the information from all the sub-detectors, the PF algorithm can discriminate the leptons, jets, and missing energy, i.e, neutrinos on event basis. The algorithm takes the calorimeter clusters or the track measurements, then combine them to build the physics objects. The CMS tracker can measure tracks of charged particles with high precision, these tracks provide a seed for the PF algorithm. The track information is then combined with the calorimeter clusters and tracks from muons spectrometers to form a list of particles with determined direction, energy and type. The composite objects such as jets and taus are described with the help of these well reconstructed PF objects. The list of individual particles from the PF algorithm is used, as if it came from a MC event generator, to build jets, (from which the quark and gluon energies and directions are inferred), quantify charged leptons, missing transverse energy (from which we can estimate direction and energy of neutrinos and other invisible particles). The momenta of charged particles are measured using

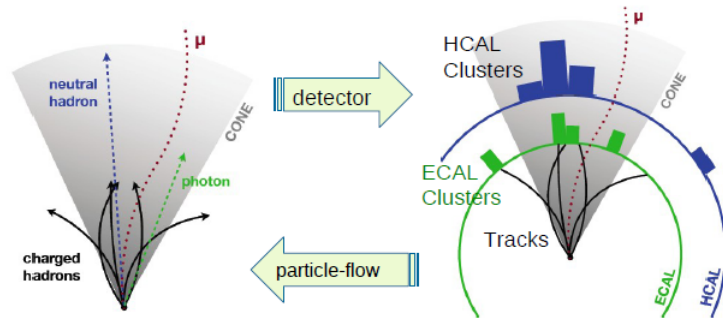


Figure 4.4: Reconstruction of physical objects via Particle Flow (PF) algorithm.

the CMS tracker, which has capability to measure tracks with very high accuracy. For low momenta particles, resolution of tracker is very high relative to calorimeter systems, therefore, the reconstruction of tracks is very important ingredient of the particle flow algorithm. There are two main requirements for the track reconstruction: tracking efficiency almost close to 100% and fake rate of tracks equal to 0. For achieving these requirements, an iterative algorithm is applied on step-by-step basis to loosen the criteria of tracks and mask the identified tracks for the next iteration.

4.2.1 The Linking Algorithm

In the CMS detector, one particle may give rise to many PF elements in the various sub-detectors, therefore, these PF elements are connected with each other through the link algorithm to fully reconstruct a single particle and getting rid of any possible double counting

from different detectors. For each pair of element, the link algorithm is tentatively performed and defines the distance between the two linked elements to ensure the quality of the link. The blocks of elements are being produced by the link algorithm which are connected directly or indirectly. Thanks to the granularity of the CMS detectors, blocks typically contain only one, two or three elements, and constitute simple inputs for the particle reconstruction and identification algorithm. The smallness of the blocks ensures the algorithm performance to be essentially independent of the event complexity. The link between the tracker tracks and calorimeter clusters proceeds due to the extrapolation of track last hit to the Pre-Shower (PS), the ECAL and the HCAL. The distance between two clusters is described in (η, ϕ) -plane which is the distance between two cluster positions. The link algorithm reconstructs muons globally by establishing a link between the charged particle tracks in the tracker and a muon track in the muon station. The link algorithm performs global fit between the two tracks and returns acceptable χ^2 . If there are several tracks lying inside the global fit then the muon track having the smallest χ^2 is retained. The χ^2 defines the link distance in this case.

4.3 Physics Objects

The collision data recorded by a detector undergoes into many processes to achieve final state physics objects (electrons, muons, jets, etc) as shown in Fig. 4.5, which are used later for analysis. The process of physics object reconstruction is always an offline process, in which the detector readout data is converted into physics objects. In this section, the reconstruction of the physics objects in the data and MC is discussed.

4.3.1 Track Reconstruction

One of the most challenging task of the CMS experiment is the reconstruction of charged particles tracks in the silicon tracker. Many algorithms are used for the track reconstruction, every algorithm uses the reconstructed positions (hits) of the charged particles in the tracker. These hits are used to determine the helical trajectories of the charged tracks and hence directions and momenta [74]. The main software designed for the reconstruction of tracks is Combinatorial Track Finder (CTF) based on combinatorial Kalman filter, an extension of Kalman Filter. The track finding software allows pattern recognition and track fitting. For a trajectory, the best estimate of trajectory parameters is calculated by the track fitting module using Kalman filter and smoother. The selection of tracks sets quality flags and rejects tracks failing certain

specified criteria [75]. The CTF algorithms proceed in three ways, seeding, finding and fitting.

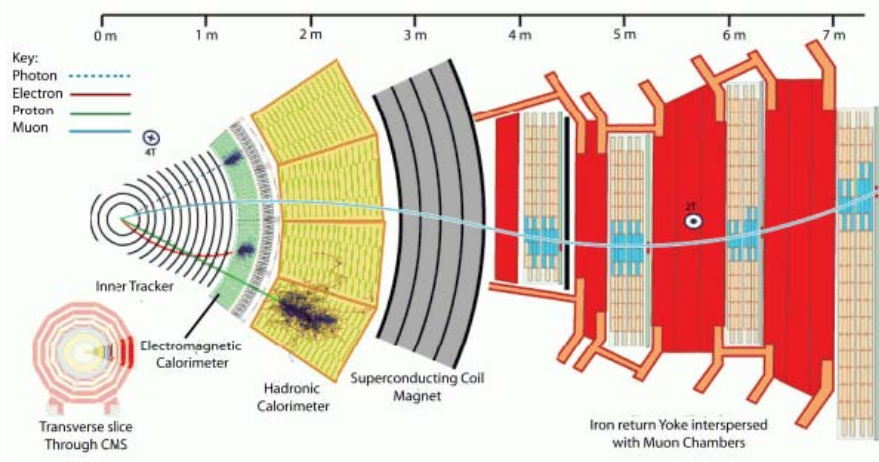


Figure 4.5: The transverse view of the Compact Muon Solenoid (CMS) slice with all sub-detectors, showing physics objects hits in various sub-detectors and iron return yoke interspersed with the muon chambers

At the seeding stage, a pair of hits is considered as a possible candidate of a track provided that p_T above a threshold level and hits are compatible with the interaction region. A seed contains small subsets of position measurements in the tracker itself. The hits in the pixel silicon detector provide best track for seeding because of their three-dimensional position information.

The second step in track reconstruction is finding the good tracks. The tracks finding is based upon the standard approach of Kalman Filter. At this stage, starting point are the seeding parameters then the track trajectory is extrapolated to the nearest tracker layer and compatible hits assigned to a track. The Kalman Filter is a succession of alternating prediction and filtering steps. At every step the filter updates the track parameters with the new hits. The assigned parameters are then passed through the quality checks for the further propagation. Finally, fitting is performed to calculate the track and the Kalman Filter is applied again on the five parameters of each track. At the end of fitting, the least-squares fit is used for each trajectory in two stages. First the forward fit, inside-out from the interaction region, removes the approximations and biases of the seeding and finding stages. In the second outside-in smoother fit yields the best estimates of the track parameters at the primary vertex [76]. Therefore the reconstruction of vertex offers the following benefits:

- Due to the vertex constraints, the momentum estimation of the particles involved can be improved.

- The reconstruction of very short-lived particles or the neutral particle is possible by finding their decay products and common vertices.
- Since particles leave hits in the tracker, therefore, the decay length of short-lived particles can be measured by computing the distance between its estimated production vertex and estimated decay vertex.

4.3.2 Primary Vertex Reconstruction

The production of particles is due to the collision of particles, of two beams or a beam particle and a target particle, the vertex is primary interaction vertex. The production of particles through the decay of an unstable particle or by the interaction of a particle with the material of the detector, then the corresponding vertex is secondary interaction vertex such as vertex of bremsstrahlung.

The Hard scattering phenomena takes place at the Primary Vertex (PV). The PV reconstruction is very important to estimate the number of pileup events and to make a good b -tagging. The base of primary vertex reconstruction is to find the common origin of reconstructed tracks. At the HLT level of trigger, which is an online selection of collision events that takes place very fast, therefore, the PV search is reduced in a way that only the z -coordinate is taken into account. For the precise measurement of PV, there are mainly three selection criteria:

- At least two hits in the pixel detector
- Seven hits in the silicon strip detector
- The χ^2 value of the fit divided by the number of degrees of freedom has to be smaller than 5.

For the high quality track reconstruction, an iterative algorithm used which makes sure a high efficiency, as shown in Fig. 4.6. After the successful reconstruction, tracks fed to the PF algorithm as an input.

4.3.3 Electron

The Gaussian Sum Filter (GSF) algorithm used for the reconstruction of electrons in the CMS. It takes the information of tracks from the tracker and energy cluster information from

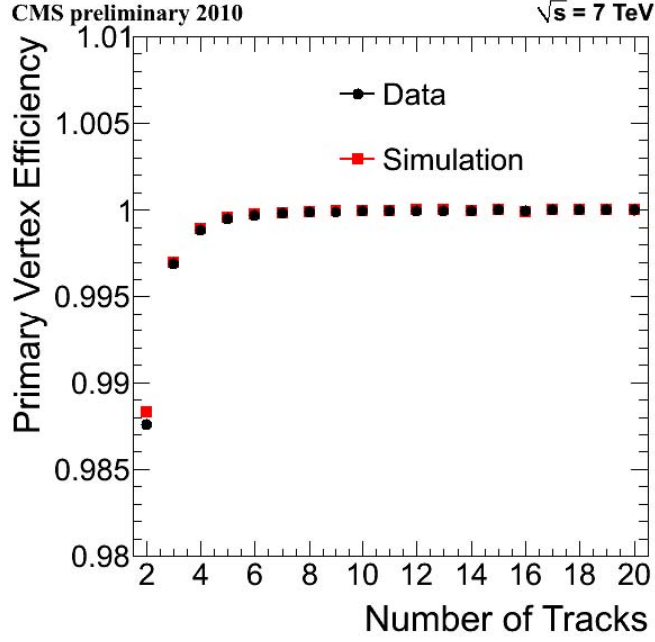


Figure 4.6: The primary-vertex reconstruction efficiency as a function of the number of tracks in a cluster, measured in minimum-bias data and MC simulation.

the ECAL. The basic idea of GSF is to model the energy loss distribution by using the mixture of Gaussian distribution rather than a single Gaussian. It has been observed that the GSF is able to improve the momentum resolution of electrons as compared to the standard Kalman filter [77].

The electrons travel through the magnetic field of the CMS detector and leave hits in the tracker before hitting the ECAL. Then they lose almost all the energy and form a cluster of energy in the ECAL. The electrons change their trajectories due to magnetic field and emit bremsstrahlung photons. These photons have larger cluster size in the ECAL as compared to electrons [78].

There are two complementary methods for the reconstruction of electrons: tracker driven and ECAL driven seeding. The tracker driven method is for the low p_T electrons that often lie inside jets and ECAL driven are optimized for the high p_T electrons coming from the decay of W or Z boson for example, and this is relevant for the tqZ analysis.

The ECAL driven method is defined for electrons having $E_T > 4$ GeV, which starts forming super-clusters (SC) in the ECAL. The method is then optimized for the isolated electrons in the p_T range relevant for Z and W decays up to $p_T \geq 5$ GeV. In clusters, there is a spread in the ϕ direction as compared to the η direction, as shown in Fig. 4.7. This spread in ϕ is due to bremsstrahlung and taken into account for a super-cluster. The electron tracks start from the

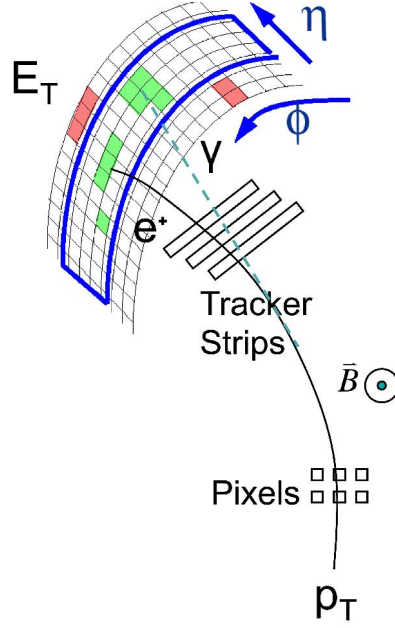


Figure 4.7: The electron reconstruction in the Compact Muon Solenoid (CMS) detector, the arc of tracks shows the bending in the magnetic field and energy cluster are shown in the Electromagnetic Calorimeter (ECAL). The ECAL clusters due to the electron and its bremsstrahlung photons are shown as green squares. The super-cluster is boxed in blue.

matching of super-cluster with the tracker seed, tracker seed provided two to three hits in the inner tracker. After this rest of electron track is generated by using GSF fitting of tracker hits. Due to bremsstrahlung radiation, electrons trajectories becomes smaller. The kinks appear in the trajectories due to radiation, and GSF algorithm takes into account all of these effect. The electron candidates reconstructed with the tracker driven method are based on multivariate analysis, whereas the ECAL driven algorithm is based on the matching between the GSF track and the super-cluster in η and ϕ .

4.3.4 Jets Reconstruction

The high energy pp collisions at the LHC create a very huge amount of QCD data, jets reconstruction is therefore most important for many physics analysis. The tqZ process contains at-least one light quark jet and one b-tagged jet coming from the decay of top quark. Therefore, the algorithms for jet reconstruction play a vital role in this analysis as well. A jet is a bunch of particles generated by hadronization, therefore, the jet algorithm rely on the calorimeters, i.e. the ECAL and the HCAL.

In hard scattering of partons in pp collisions, jets are the signature of quarks and gluons. The quarks and gluons have net color charge and do not exist freely due to color confinement.

The quarks and gluons stick together to form a color-neutral hadron, the process is known as hadronization. Basically, jets are the result of fragmentation function which is a union of showering and hadronization, as shown in Fig. 4.8. Jets are simulated using two mainstream

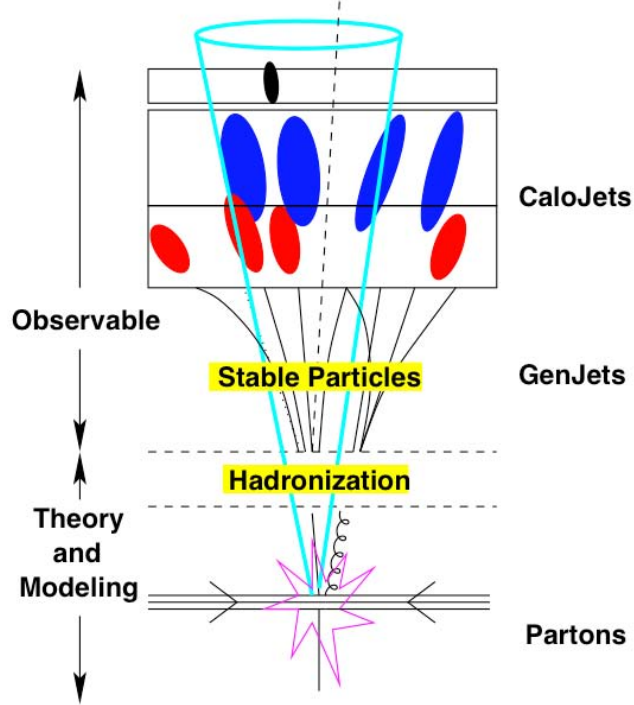


Figure 4.8: The schematic representation of jets production stages in a pp collision

algorithms: cone-type algorithm and sequential clustering algorithms.

The cone-type algorithms are not infrared and collinearly safe. These are typically complex and involve several parameters. The two cone-type algorithms: midpoint cone and sisccone jet algorithm, are used in the CMS experiment [79].

In the CMS, the standard jet clustering software is based on the collinear and infrared-safe anti- k_T algorithm [80]. The anti- k_T algorithm measures the two distances: d_{ij} is the distance between two particles i and j or two pseudo-jets and d_{iB} is the distance between an i th particle and beam line. The minimum of two variables d_{ij} and d_{iB} is calculated, if the distance between pair of particles (i,j) is the smaller than the distance d_{iB} only then i and j are combined. If the smallest distance is d_{iB} , then i will be a jet and it is removed from the list of particles. The two variables mentioned above are defined in Eqs. 4.2 and 4.3.

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \quad (4.2)$$

The transverse momentum of the particle i , is represented by k_{ti} , and the radius parameter is denoted by the letter R and $R = 0.5$ in this analysis. The parameter p governs the relative power

of energy versus geometrical scales to distinguish the three algorithms: $p = 1$ *kt*-algorithm and $p = -1$ represents *anti-kt* algorithm. The distance between beam and the i th particle is defined as:

$$d_{iB} = k_{ti}^{2p}, \quad (4.3)$$

where $\Delta_{ij} = \sqrt{(\phi_i - \phi_j)^2 + (\eta_i - \eta_j)^2}$, ϕ is the azimuthal angle and η is the pseudo-rapidity. The process of calculating the smallest distance defined above is applied over complete dataset to distinguish between jets and other particles. In the process of reconstructing a jet, the algorithm provides a stability against the low particles inside jets. The softer constituents are always clustered around the hard constituent before they cluster each other. When a second hard constituent is present in an event, the behaviors of the algorithm is given below.

- when $\Delta_{ij} > 2R$: it is a simple accumulation of soft constituents within the circle of radius R , which is forming a perfect conical jet.
- $R < \Delta_{ij} < 2R$: the algorithm is resulting into two jets but the harder one will become conical jet, in case of both jets have hard transverse momentum, then neither one can form a perfect conical jet.
- $\Delta_{ij} < R$: thus the constituent 1 and 2 will form a single jet.

Jet Energy Corrections

The response of the CMS calorimeters is non-linear and non-uniform, therefore measurement of the jet energies is not perfect or there is another source of a jet energy which is due to pile-up interactions. However jets have energy mismatch with the original energy deposition in the calorimeters, following are the main source of energy mismatch:

- non-uniform response of calorimeter,
- noise of detector electronics,
- deposition of extra energy due to pile-up effects,
- unclustered energy deposits.

Therefore, the jet energy calibration is necessary to account all these effects after reconstruction of a jet. The reconstructed momentum of a jet can be written as,

$$P_i^{corrected} = C(P_T^{raw}, \eta) P_i^{raw}, \quad (4.4)$$

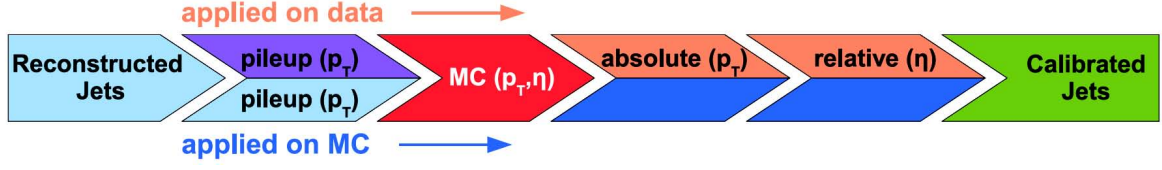


Figure 4.9: The jets calibration states applied on Data and MC.

where P_i^{raw} is the four-momentum of an uncorrected jet, $C(P_T^{raw}, \eta)$ is the scale factor for correction depending upon the p_T and η of uncorrected jet. There are three levels of jet energy calibration: MC truth, relative jet energy scale versus η and absolute jet energy scale versus p_T as described in Fig. 4.9. More explicitly, these correction factor can be expressed in the following Eq. 4.5 with the three levels of jet corrections,

$$p_T^{corr} = [C_{LV1}(p_T).C_{LV2}(p_T, \eta).C_{LV3}(p_T)]p_T^{uncorrec}. \quad (4.5)$$

In order to correct p_T of jets in the data, the correction factors are derived from the MC simulation and then applied to the data as shown in the Eq. 4.5.

The process of jet energy correction is splitted into multiple levels as given below

- **L1FastJet:** Applied to correct energy of a jet coming from a pileup events.
- **L2Relative:** Correction in the non-uniformity of jet energy relative to distribution in each sub-detector.
- **L3Absolute:** This correction which is based on the p_T of jet, and is applied for correcting the nonlinear energy response of the calorimeters.
- **L2L3Residual:** This type of correction is applied to the data for the correction of differences between the data and MC simulation in the $\eta(L2)$ and $p_T(L3)$ based corrections. In order to correct p_T in the data, correction factors are derived from MC simulation and then applied to the data as shown in the Eq 4.5.

4.3.5 Reconstruction of b-Jets

The b -jets are produced from b -quarks. The b -quarks hadronize to form B -hadrons having relatively long life-time and travel almost $500 \mu m$ before decaying, the secondary vertex can therefore be reconstructed easily from the decaying products, as shown in Fig. 4.11. Because

of large mass and coupling to the charm quark, b -quarks can make hadrons with relatively long life-time. Since the B -hadrons have long life-time, therefore, at the decay point it produces Secondary Vertex (SV). This SV is at a large distance from PV and is an indicator of hadronization. The presence of SV in an event is used for the identification of b -jets. The weak decay of the b -quark is suppressed by the CKM matrix. Therefore, the b -quark hadronizes and travels some distance before it decays. The high resolution of the pixel detector allows to measure the decay length. As a result the displaced track originating from a secondary vertex is a strong hint on the existence of a b -jet. Several algorithms exploit these characteristics to identify b -jets.

In the physics objects reconstruction, it is very important to identify b -quark jets (b -tagged), because b -tagging is used in many physics analysis such as the top quark reconstruction and also various new physics processes involving b -quark like super-symmetry models (Fig. 4.10). At hadron collider, due to very high collision rates, it is very challenging to measure the b -tagging efficiency. The cluster of particle flow reconstructed object form jets, since the particle flow algorithm collects and combines information from all parts of CMS sub-detectors to create a consistent set of reconstructed particles for each event.

Thus b -tagging algorithms use several reconstructed objects such as tracks, vertices and leptons to discriminate between the b -quarks and light quarks jets. These algorithms provide a single value of discriminator for each jet. The algorithm clustering these reconstructed particles into jets is anti- kt clustering software. The tracks which fulfill the following criteria are being used for b -tagging.

- $\Delta R < 0.3$, which is the angular distance between jet axis and a track,
- at-least 2 hits in pixel and 8 hits in the tracker including pixel hits,
- The transverse momentum p_T of a track > 2 GeV,
- $\chi^2 < 5$,
- spatial distance between the PV and the point of closest approach between the track trajectory and the jet axis which is decay length and that should be < 5 .

Impact parameter is also very important quantity for the reconstruction of b -quark jet and is defined as the distance between the PV to the track at their point of closest approach in space. The Combine Secondary Vertex algorithm takes the relatively long life-time of B -hadron into

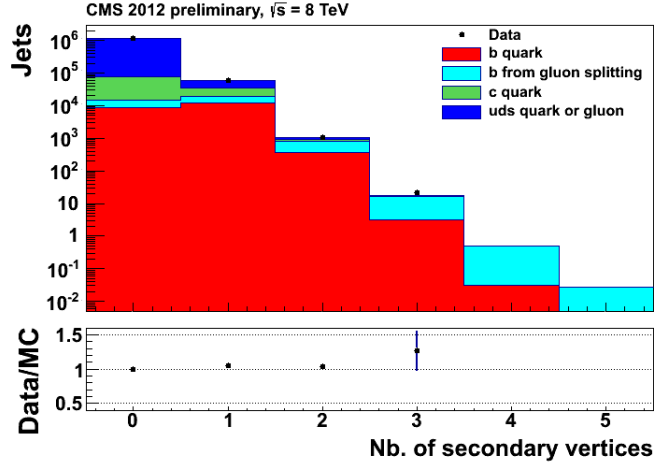


Figure 4.10: The reconstructed secondary vertices, b -tagging is based on secondary vertex [81].

account to identify jets coming from the hadronization of b -quarks, referred to as b -jets as shown in Fig. 4.11. Since the mean free path of B -hadron is long enough, which makes it possible to reconstruct secondary vertices inside the hadronic jet cone, displaced with respect to the primary vertex of the collision.

There are several key features of b -quark such as: relatively large impact parameter of the tracks, higher charged multiplicities, high p_T of decay products with respect to b -flight direction, larger jet mass as compared to the light quark jet and long life-time of the heavy flavor hadrons. These characteristics of b -quark have been used to develop algorithms which play important role to distinguish b -jets from those produced by light-flavor quarks and gluons. The discrimination between b -jets and non b -jets has been performed by using the secondary vertex and the kinematics variables associated with this vertex. During offline event reconstruction at the CMS experiment, different algorithms are used to quantify jets from b -jet, the most efficient known algorithms are:

- **Track Counting High Purity (TCHP):** The TCHP algorithm based on the third track with the highest impact parameter significance.
- **Jet Probability (JP):** The JP algorithm assumes that all the associated tracks are coming from the primary vertex.
- **Simple Secondary Vertex (SSV):** The most discriminating variable for SSV algorithm is the significance of-flight distance (the ratio of the flight distance to its estimated uncertainty).

- **Combined Secondary Vertex (CSV):** The CSV algorithm uses the life-time information of secondary vertex and track, to build a likelihood discriminator. The vertex having a radial distance of more than 2.5 cm with respect to the primary vertex and mass exceeding $6.5 \text{ GeV}/c^2$ are rejected. The vertex candidates are rejected if the flight direction of each candidate is outside a cone of $\Delta R < 0.5$ around the jet direction.

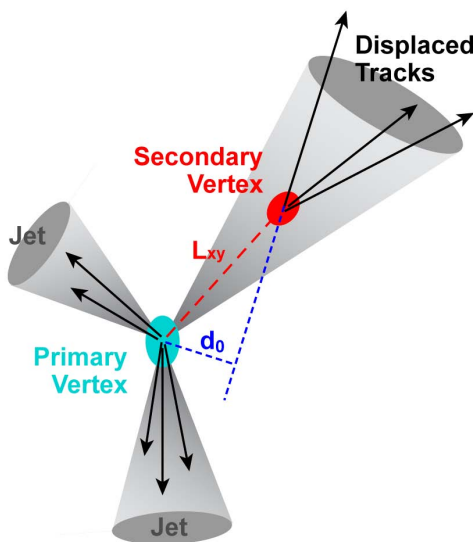


Figure 4.11: The reconstruction of b -tagged jets using secondary vertex technique.

Efficiency

The efficiency ϵ_q of any jet with flavor q to be a b -jet is

$$\epsilon_q = \frac{\# \text{ of jets with flavor } q \text{ tagged as } b}{\# \text{ of jets with flavor } q} \quad (4.6)$$

The efficiency measurements for the CSV tagger using the MC simulations are given in Fig. 4.12

4.3.6 Missing Transverse Energy (MET)

For the detection of particle, it is necessary for the particle to interact with the detector or else particle needs to decay into detectable products. The detectors used for the particle detection have characteristic to make visible interaction of particles with their surrounding. Almost all the stable or long-lived particles are produced during the pp collision at LHC, are being detected by the CMS detector [83]. But neutrinos and hypothetical neutral weakly interacting particles are the exception. These particles leave no signature in the detector, their presence is

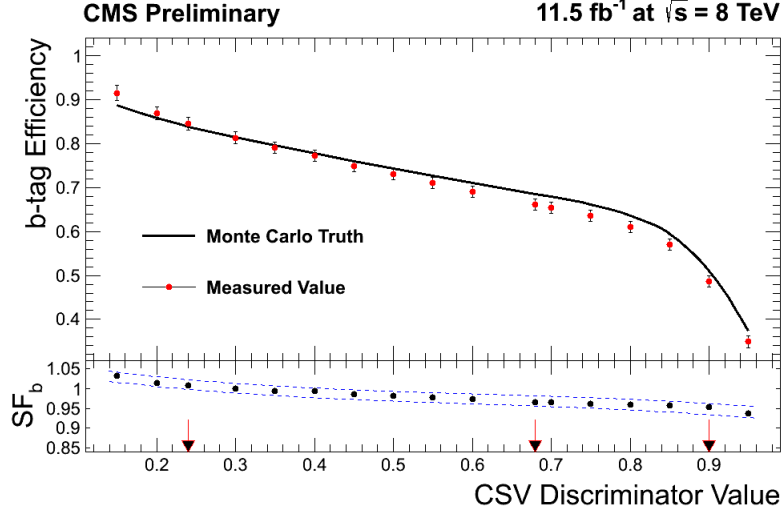


Figure 4.12: The measured b -jet tagging efficiency by using the FTC method and scale factors (SF_b) as a function Combined Secondary Vertex (CSV) discriminator, for the data and simulations (upper panel) [82].

derived from the momentum imbalance in the plane perpendicular to the beam direction which is missing transverse momentum and denoted by $\vec{\cancel{E}}_T$ as shown in Fig. 4.13, the magnitude of missing transverse momentum is denoted by $\cancel{E}_T$ and called as MET. The missing transverse momentum can be defined as $\vec{E}_T = -\sum \vec{p}_T$, where sum is over all stable particles, $\vec{E}_T$ is total transverse momentum of all un-observed particles. In the detector, there are many sources of momentum imbalance:

- particles having no direct signature in the CMS detector like neutrinos or other weakly interacting particles to be discovered,
- detector calibration effects,
- data not coming from collisions, such as beam halo, cosmic, pile-up, and
- every other possible sources.

The MET is defined as follow

$$MET = \vec{E}_T^{total} = \sum_i E_x^i - \sum_i E_y^i \quad (4.7)$$

There are different and distinct techniques used in the CMS detector to reconstruct missing energy.

- **PF E_T** : This is reconstructed by using the particle flow algorithm technique.

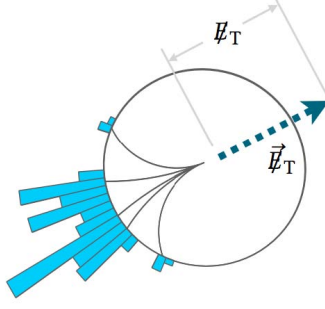


Figure 4.13: In a simulated CMS event, the missing transverse energy along with direction and magnitude is shown.

- **Calo E_T :** In this type of reconstruction the calorimeters energies and geometry of calorimeter tower are used.
- **TC E_T :** This type of missing energy reconstruction includes the track reconstruction by the inner tracker and tracks after corrections, the energy deposition in calorimeter towers.

In this thesis, we have used PF E_T for the analysis. As jets need correction, similarly missing energy also needs correction before being used in any physics analysis. At the CMS detector, mainly three types of correction have been applied. Usually correction applied for better estimations and understanding of MET.

- **Type-I Correction**

$$\vec{\cancel{E}}_T^{\text{raw}} = - \sum_{i \in \text{jets}} \vec{p}_{Ti} - \sum_{i \in \text{uncl}} \vec{p}_{Ti} \quad (4.8)$$

$$\vec{C}_T^{\text{Type-I}} = \sum_{i \in \text{jets}} \vec{p}_{Ti} - \sum_{\text{jet}} \vec{p}_{T \text{ jet}}^{\text{JEC}} \vec{\cancel{E}}_T^{\text{Type-I}} = \vec{\cancel{E}}_T^{\text{raw}} + \vec{C}_T^{\text{Type-I}} \quad (4.9)$$

- **Type-II Correction**

$$\vec{C}_T^{\text{Type-II}} = (1 - C^{\text{uncl.}}) \sum_{i \in \text{uncl.}} \vec{p}_{Ti}. \quad (4.10)$$

If the Type-II correction is added to Type-I corrected MET

$$\vec{\cancel{E}}_T^{\text{Type-I-II}} = \vec{\cancel{E}}_T^{\text{Type-I}} + \vec{C}_T^{\text{Type-II}}, \quad (4.11)$$

- **Type-0 Correction**

Type-0, MET correction

$$\sum_{i \in \text{neuPU}} \vec{p}_{Ti} = -R^0 \sum_{i \in \text{chPU}} \vec{p}_{Ti} \quad (4.12)$$

The Type-0 correction is this estimate plus the last sum in raw MET:

$$\vec{C}_T^{\text{Type-0}} = (1 - R^0) \sum_{i \in \text{chPU}} \vec{p}_{Ti} \quad (4.13)$$

The detailed description of MET correction is given in [84].

4.3.7 Muons Reconstruction

The muons have been reconstructed in multi-faceted way as shown in Fig.4.14, using different technologies of gaseous detectors. There are three different muons reconstructed by the CMS, Global muons, tracker muons, and standalone muons.

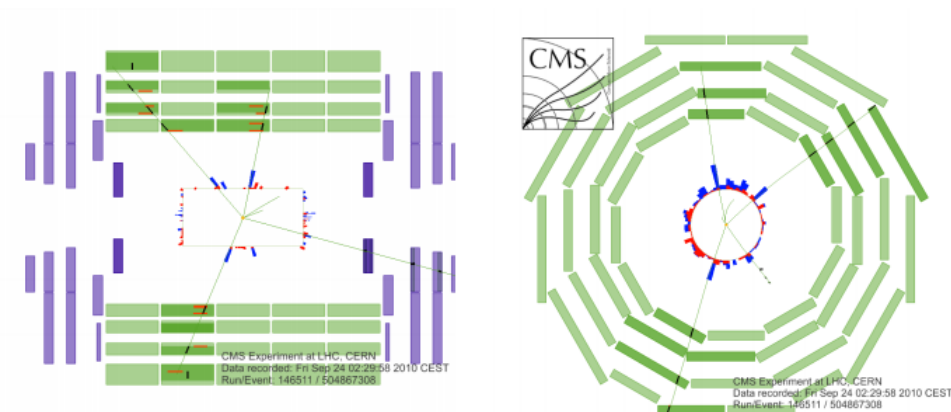


Figure 4.14: (a) The longitudinal ($r - z$) and (b) the transverse ($r - \phi$) views of the Compact Muon Solenoid (CMS) muon system for pp collisions, where four muons have been reconstructed.

Global muon (outside-in): The global muons are reconstructed by the extension of standalone muon tracks to the silicon tracker, where the result of best matching of the reconstructed track of a standalone muon is performed. For finding the global muon, we apply Kalman-filter technique. For high $p_T > 100$ GeV muons, better momentum resolution is achieved through global muon fit as compared to the track-fit only.

Tracker muon (inside-out): The muons in the tracker are reconstructed with the algorithm seeking tracks in the silicon tracker having $p_T > 0.5$ GeV as a muon candidates. These tracks are extrapolated to the muon stations for compatible segments by taking: the

magnetic field, the average expected energy losses, and multiple coulomb scattering in the detector material into account [85]. The matching of tracks-to-segment is performed in local coordinates at the muon stations. The tracks and segments are considered to be matched if the distance between the track and hit is less than 3 cm.

The momentum resolution is better in the silicon inner tracker and for high $p_T > 200$ GeV muons. The global fit improves the momentum resolution, as can be seen from Fig. 4.15.

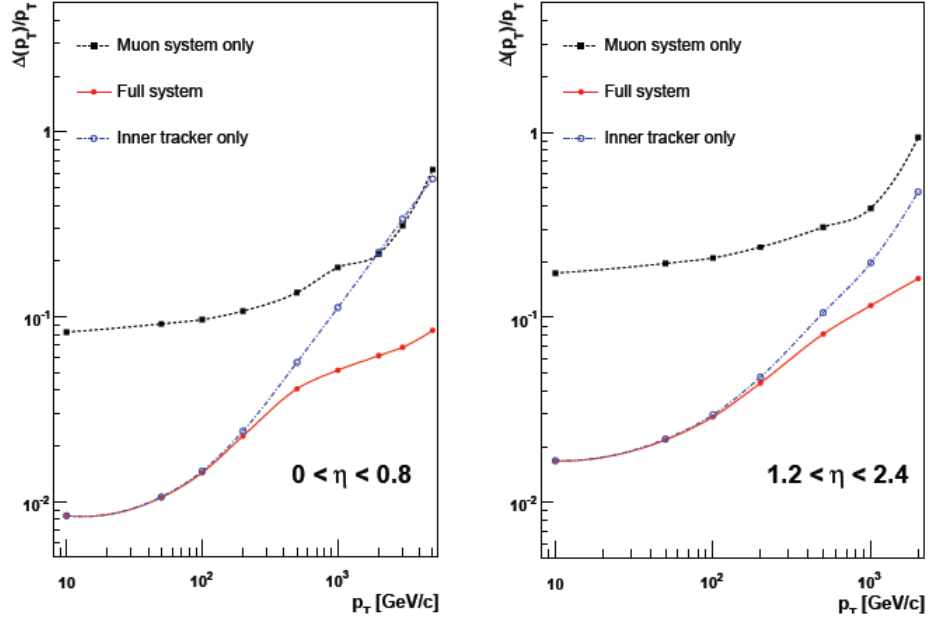


Figure 4.15: The muon p_T resolution ($\Delta p_T/p_T$) as a function of p_T using muon system only (black dashed curve), the inner tracker only (blue dashed-dotted curve), and both (red solid curve), for the $|\eta| < 0.8$ (left) and $1.2 < |\eta| < 2.4$ (right) regions [85].

Chapter 5

The tqZ Event Selection

In the previous chapter 4, event generation, objects reconstruction and the identification have been described in detail. Thus after the identification of physics objects, the next step in analysis is to define the kinematical requirements on the reconstructed objects. The main purpose of tqZ event selection is to produce datasets which will be enriched with the signal events. Since the tqZ analysis is using fully leptonic topology therefore the discussion in this chapter is mainly focused on the selection criteria of final state leptons (e, μ), jets and MET. The data and MC samples have been described along with the trigger selection. The various kinematical regions are defined where the selection criteria is validated and background is estimated. The final state signal selection criteria is discussed in section 5.7. The comparison between the data and MC simulations have been made after applying event selection. The summary of chapter has been given in section 5.8.

5.1 The Datasets

The full 2012 CMS data corresponding to 8 TeV pp collisions with an integrated luminosity of 19.7 fb^{-1} is being used for the analysis. The data used in this thesis have been certified as "good" for physics analysis by the CMS data validation group [86]. During the 2012 pp collision data taking, the bunches of proton beams crossed each other after 50 ns with an average of approximately 1380 bunches per fill. The results obtained from the data have been compared with the prediction by producing the simulated samples by using MC techniques. There are several processes in the SM which can produce tqZ like final state events and hence become potential background to signal. Thus the signal (tqZ) and background processes have been generated by using the MC simulation generators. The tqZ signal MC sample has been

produced by using PYTHIA8 with 4 Flavor Scheme (4FS) and backgrounds WZ , $t\bar{t}$, $t\bar{t}Z$ are produced by using PYTHIA6 and MADGRAPH as shown in Table 5.2.

5.1.1 Analysis Object Datasets (AOD)

The $tqZ \rightarrow b\ell\nu\ell^+\ell^-$ process results in events having three leptons (electrons or muons) in the final state (fully leptonic decay). Therefore the di-muon, di-electron and MuEG data streams are used to study the tqZ final state. The data samples used were collected by using the $\mu\mu$, ee and $\mu e\gamma$ triggers. The CMS experiment recorded these data streams at different time period, and therefore each data stream is a collection of many data Runs. A Run is the time period of CMS data recording during which all sub-systems were in operating mode. All datasets are mentioned in Tables A.1, and 5.1.

Table 5.1: Di-lepton ($\mu\mu$, ee) and MuEG ($\mu e\gamma$) datasets, expressed with time period of data taking and also taken Runs in that specific period.

Data Streams	Data Period	Data Runs
Di-lepton and MuEG	Run2012A-22Jan2013-v1	190456 - 193621
	Run2012B-22Jan2013-v1	193834 - 196531
	Run2012C-22Jan2013-v1	198022 - 203742
	Run2012D-22Jan2013-v1	203777 - 208686

5.1.2 MC Datasets

The MC simulation is used for the prediction of properties of signal and background processes. In the simulation chain the event generation is followed by simulation of the detector response as discussed in detail in chapter 4. The CMS MC version used in this thesis is Summer12 MC, both for signal tqZ selection and for backgrounds. These simulated samples were generated by using PYTHIA (version 6) [58], POWHEG [64], MADGRAPH [67] with tune "TuneZ2Star" [68]. The simulated samples are rescaled to data using NLO or higher order(when available) cross-sections. All the MC simulated datasets being used in the analysis have been generated using the pileup scheme "PU_S10". The simulated datasets with generated cross-section are given in Table 5.2.

Table 5.2: MC simulated datasets used for tqZ signal and backgrounds are mentioned with their cross-sections.

Process	Dataset	$\sigma[\text{pb}]$
Signal (tqZ)	/TZJetsTo3LNuB_8TeV_TuneZ2Star_madgraph_tauola/[1]	0.00783
$t\bar{t}$	/TTJets_FullLeptMGDecays_8TeV-madgraph/[2]	234.
$t\bar{t}W$	/TTWJets_8TeV-madgraph/[1]	0.232
$t\bar{t}Z$	/TTZJets_8TeV-madgraph_v2/[1]	0.2057
WZ	/WZJetsTo3LNu_TuneZ2_8TeV-madgraph-tauola/[1]	1.058
$Z\gamma$	/ZGToLLG_8TeV-madgraph/[1]	132.6
ZZ	/ZZTo4e_8TeV-powheg-pythia6/[1]	0.07691
	/ZZTo4mu_8TeV-powheg-pythia6/[1]	0.07691
	/ZZTo2e2mu_8TeV-powheg-pythia6/[1]	0.1767
$Z + jets$	/DYJetsToLL_M-10To50filter_8TeV-madgraph/[1]	860.5
	/DYJetsToLL_M-50_TuneZ2Star_8TeV-madgraph-tarball/[1]	3532.8
$W\gamma^*$	/WGstarToLNu2E_TuneZ2star_8TeV-madgraph-tauola/[1]	5.873
	/WGstarToLNu2Mu_TuneZ2star_7TeV-madgraph-tauola/[1]	1.914
WW	/WW_TuneZ2star_8TeV_pythia6_tauola/[1]	5.817
[1]	Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	

5.2 Trigger Selection

In section 3.2.9, the trigger system and its objective have been discussed. The high LHC collision rate results enormous amount of data which all can not be stored on disk. Therefore, a super-fast algorithm is needed to select interesting events while suppressing less interesting ones. Thus selection of trigger is doing great job in throwing away unwanted events. The selection of events is based on HLT paths that require the presence of at least two leptons (electron and/or muon), with transverse momenta of leading lepton larger than 17 GeV and momenta of second leading lepton larger than 8 GeV. The muon candidates are reconstructed by using the CMS muon and inner tracker subsystem information without isolation requirements. Electrons candidates are reconstructed by combining silicon tracker and calorimeter information. These are required to full fill very loose identification and isolation conditions. The detailed HLT paths are listed in Table 5.3.

These events in this analysis are required to pass one of the unprescaled di-lepton trigger, i-e, double-electron (ee), double-muon ($\mu\mu$) or muon-electron ($e\mu$). To avoid double counting of events, trigger path is required to be exclusive using the following criteria:

- accept all events from the DoubleMu Primary Dataset which have fired the mentioned di-muon trigger paths as shown in the Table 5.3.

- accept all events from the DoubleElectron Primary Dataset, if they have fired one of the di-electron paths and none of the di-muon paths.
- accept all events from the MuEG Primary Dataset, if they have fired one of the cross-flavor paths as shown in Table 5.3 and neither of the di-muon nor di-electron paths.

Table 5.3: HLT trigger paths used in the analysis

Process	HLT Path
Double Electron	HLT_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL _Ele8_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL
Double Mu	HLT_Mu17_Mu8 HLT_Mu17_TkMu8
MuEG	HLT_Mu17_Ele8_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL HLT_Mu8_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL

5.3 Event Selection

There are many stages in the process of an event selection, to be selected as a signal event. For the data events, there are lot of cleaning filters to exclude the anomalous detector effects. The event selection of analysis starts from the trigger, that must pass at least one required trigger path of analysis. After the proper trigger, physics objects expected to be present in the final state of signal event needs to pass more requirements.

The tqZ analysis has been performed in leptonic final state where the top quark decay into a W boson and b -quark, the W boson decays further into lepton and neutrino. The Z boson decay into pair of leptons having opposite charge and same flavor. Therefore, the tqZ final state contains three leptons (μ and e), there will also be measurable missing transverse energy and at least two jets from which one must be b -tagged. The selection criteria for physics objects have been discussed in the following sections.

5.3.1 Analysis Main Steps

There are many steps which have been followed to perform the tqZ analysis, these are mentioned as follows:

- Processes the required Analysis Object Datasets (AOD) datasets in the form of Physics Analysis Toolkit (PAT) objects.

- Pre-selection has been performed on events in both data and MC simulation.
- Simulated events are being normalized to data, by using the NLO theoretical cross-sections.
- Pileup re-weighting has been applied on simulated events to compare efficiency with the observed data events.
- The comparison between data and MC has been made to validate the analysis.
- Data driven background estimation has been performed to estimate backgrounds due to fake leptons and di-boson.
- Finally cross-section and systematics uncertainties have been calculated by using Higgs combine package [87].

5.3.2 Event Vertex Selection

At hadron colliders like LHC, during each bunch crossing, the presence of several hadron collisions is generally called as pileup (PU) and needs a diligent consideration because particles produced in secondary collisions might add spurious energy to the primary interaction. The reconstruction of collision vertices is being performed after assigning tracks to the vertex candidates and these assignments are based on the track-longitudinal position at the closest distance with respect to the beam axis. In order to ensure that events are not being faked, they must satisfy the good vertex conditions as outlined below. For a good vertex selection the fitted numbers of degrees-of-freedom (NDoF) have to be greater than 5. The longitudinal position of vertex should be within $|z| < 24$ cm and the transverse impact parameter (d_0) has to be $d_0 < 2$ cm.

The average vertex multiplicity distribution is measured in data based on the total pp in-elastic cross-section [88] and the instantaneous luminosity of the events. The simulation events are generated with a distribution of the average number of vertices based on a prior assumptions of the LHC running conditions. The distributions of the number of vertices in data and simulation differ [89] as shown in Fig. 5.1. In Fig. 5.1, the distribution of number of primary vertex is shown before and after applying the pileup re-weighting to the simulation events. A good agreement between the data and simulation is observed.

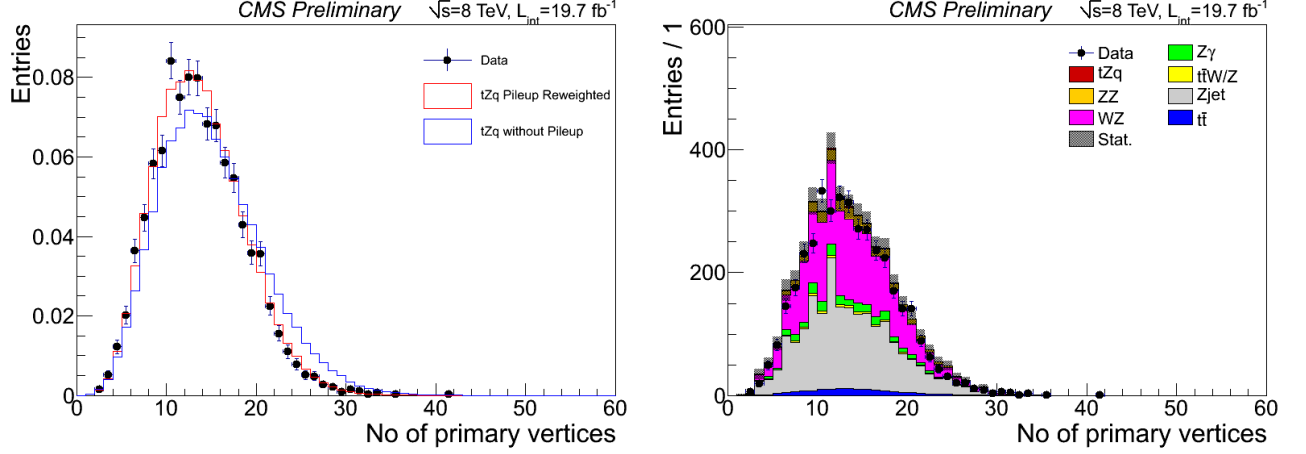


Figure 5.1: Plots of the pileup reweighting procedure. Left: distribution of the number of reconstructed primary vertices for signal Monte Carlo (MC) and data. The solid blue line representing the number of primary vertices before applying the re-weight while the solid red line represent number of primary vertex after applying the pileup re-weighting which shifted towards data point Right: Comparison of distribution of the number of reconstructed primary vertices for MC and data after applying pre-selection as discussed in section 5.4. The data is shown with dots having error bars and filled histograms for backgrounds. The background is normalized to the data

5.3.3 Muon selection:

Muons are considered to be very clean objects and the reconstruction of CMS muons has been discussed in detail in 4.3.7. Since the tqZ study is performed leptonically and muon is a lepton, therefore, there are selection criteria for muon. Muons that have undergone PF reconstruction have already been identified as both Global and Tracker muons. The muons having transverse momentum (p_T) greater 20 GeV and pseudo-rapidity ($|\eta|$) less than 2.4 are being used in this analysis. A muon candidate with the general requirements described in Table 5.4, is called a "tight" muon. For the purpose of the event selection, muons with less stringent criteria are defined as "loose" muons. It is only required to pass the PF identification and satisfy $p_T > 10\text{GeV}$, $|\eta| < 2.5$. The events containing extra loose muons are being vetoed in this analysis. Other than the tight selection criteria, muons must be isolated by removing the neutral hadron and photon contribution from the fixed radius cone. The detail of muons isolation is given in the appendix C.1. This is referred to as the $\Delta\beta$ correction and a muon is considered isolated when $I_{\Delta\beta} < 0.12$ within the cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. For selection of a loose muon, the isolation should be less than 0.2. The detail requirements for

Table 5.4: Muons identification criteria used in the analysis [90]

Criterion	Tight Muon	Loose Muon
Particle Flow Muon ID	PF Muon	PF Muon
Global and Tracker Muon	required	Not required
Global or Tracker Muon	Not required	required
p_T	> 20 GeV	≥ 10 GeV
$ \eta $	< 2.4	≤ 2.4
d_0	< 0.2 cm	-
d_z	< 0.5 cm	-
Global track fit χ^2/n_{dof}	< 10	-
Number of pixel tracker hits	> 0	-
Number of silicon tracker hits	> 5	-
Number of valid muon chamber hits	> 1	-
I_{rel}^μ	< 0.12	≤ 0.2
cone size	0.4	0.4

tight and loose muons are summarized in the Table 5.4. Thus after asking required selection criteria, the transverse momentum of muons in various decay channel of tqZ is shown in the Fig. 5.3.

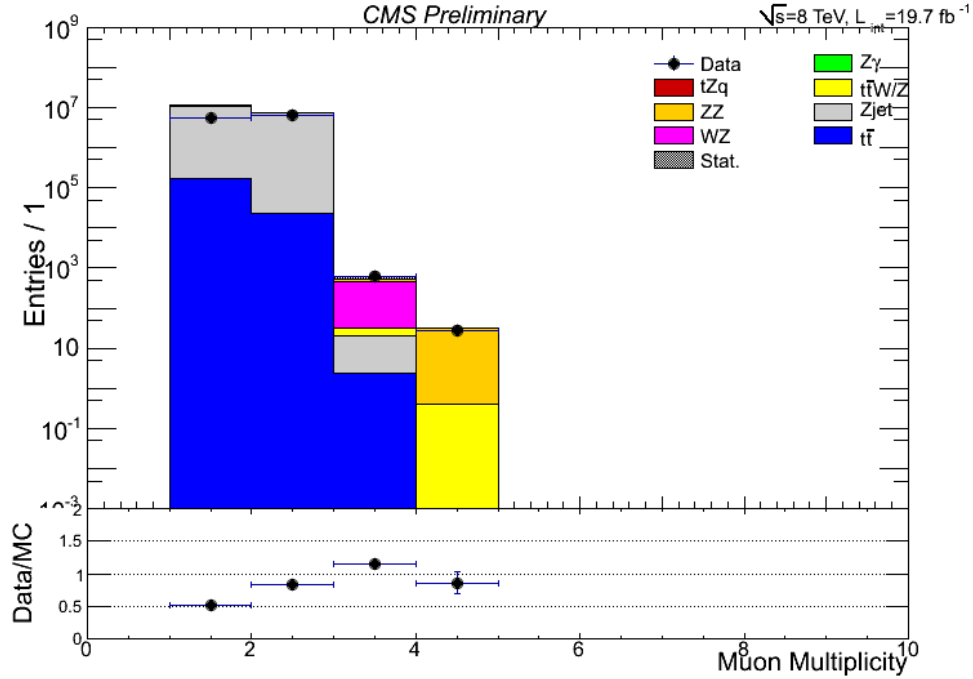


Figure 5.2: The multiplicity of muons after the requirement of three leptons in event before pre-selection criteria.

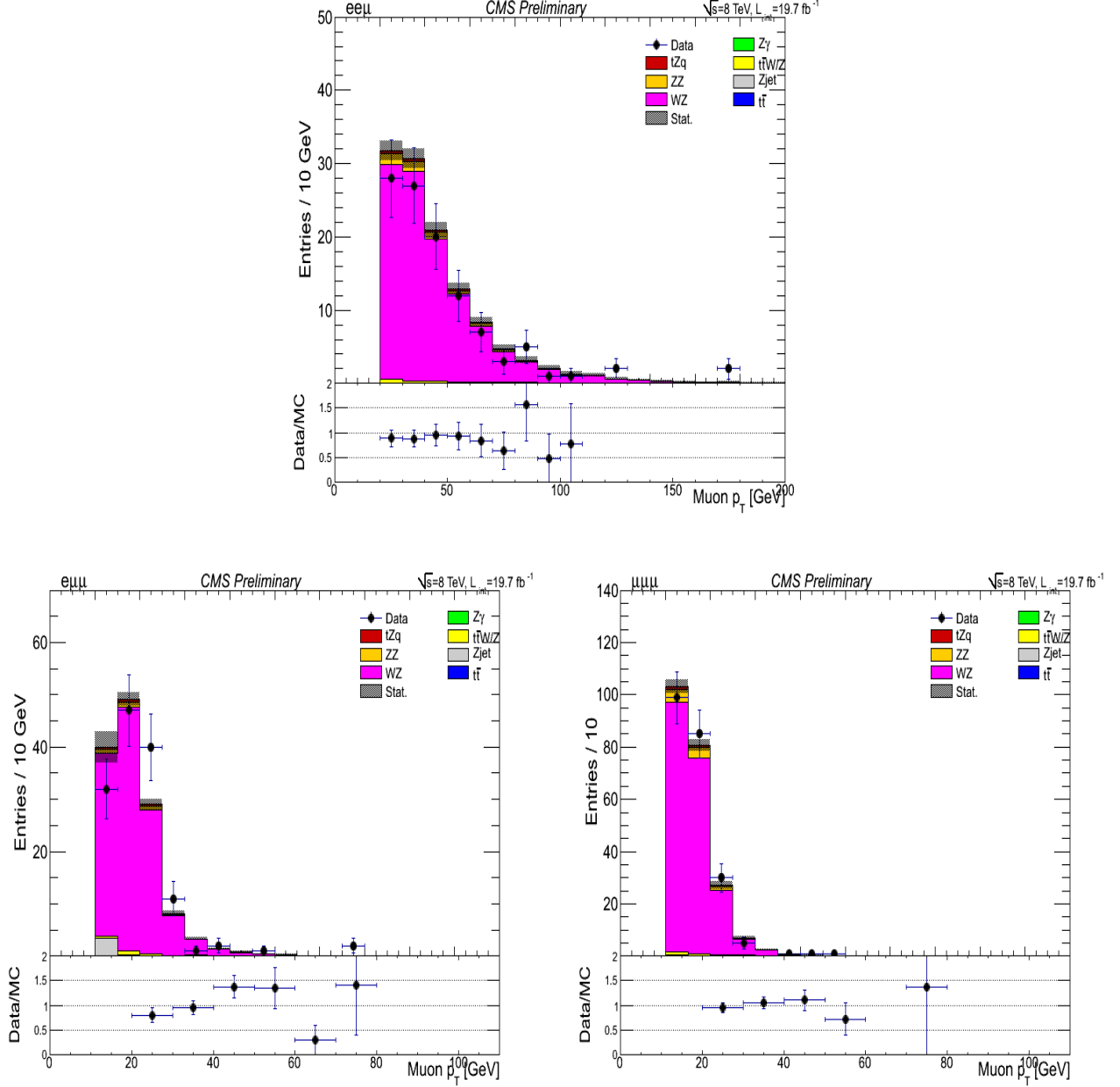


Figure 5.3: After applying pre-selection criteria, inclusive muon p_T in different combinations of three leptons final state. The figure at the top shows the p_T in $ee\mu$ channel, left bottom figure shows p_T in $e\mu\mu$ channel and right bottom represents the p_T in $\mu\mu\mu$ combination. Good agreement between data and MC and dominant background is WZ

5.3.4 Electron Selection

Particle Flow electrons have been used in this analysis which are based on the GSF tracks reconstruction of electrons. The standard selection criteria used in this analysis is recommended

by Physics Object Group (POG). The electrons having transverse momentum, p_T , greater than 20 GeV and pseudo-rapidity range, $|\eta| \leq 2.5$. All the recommended cuts for tight selection of electrons are mentioned in Table 5.5. In addition to the tight criteria, electrons must be isolated to reject leptons from semi-leptonic decays of hadrons, as discussed in appendix C.2. The relative isolation variable, I_{rel} , is an estimator of the additional energy around the track of a given particle. For electron to be considered isolated, it must have a value of $I_\rho < 0.15$ for a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$. After applying the required selection criteria, electron multiplicity is shown in the Fig. 5.4.

Table 5.5: Electrons identification criteria used in the analysis [91].

Criterion	Tight Electrons	Loose Electrons
p_T	> 20 GeV	≥ 10 GeV
$ \eta $	< 2.1	2.5
$ \Delta\eta_{in} $	0.004	-
$ \phi_{in} $	0.030	-
$\sigma_{in\eta}$	0.01	-
d_0^{vtx}	0.020	-
d_z^{vtx}	0.100	-
$\Delta R(e, m)$	> 0.1	-
mva-ID	≥ 0.5	> 0.0
$I_{rel}^{\rho-corr}$	< 0.1	< 0.15
cone size	0.3	0.3

The Particle Flow (PF) algorithm is doing identification of electron at the CMS detector but still there are some additional identification steps. There are many strategies to separate prompt electrons from the background sources. The main contribution come from photon conversion, mis-identification of jets as an electron, or electrons coming from semi-leptonic decay of the b -quark and c -quark. For identification of electrons, multi variate algorithm (MVA) has been used with values of MVA discriminate ranges from -1 and +1 and greater the value o discriminant more probable electron like. The MVA cuts are summarized in Table 5.6. Thus after asking required selection criteria, the transverse momentum of electrons in various decay channel of tqZ is shown in the Fig. 5.5.

5.3.5 Jet Selection

Jets are cluster of object obtained from particle flow algorithm. For light jets and b-jets selection in this analysis, official selection as recommended by CMS top physics group are used

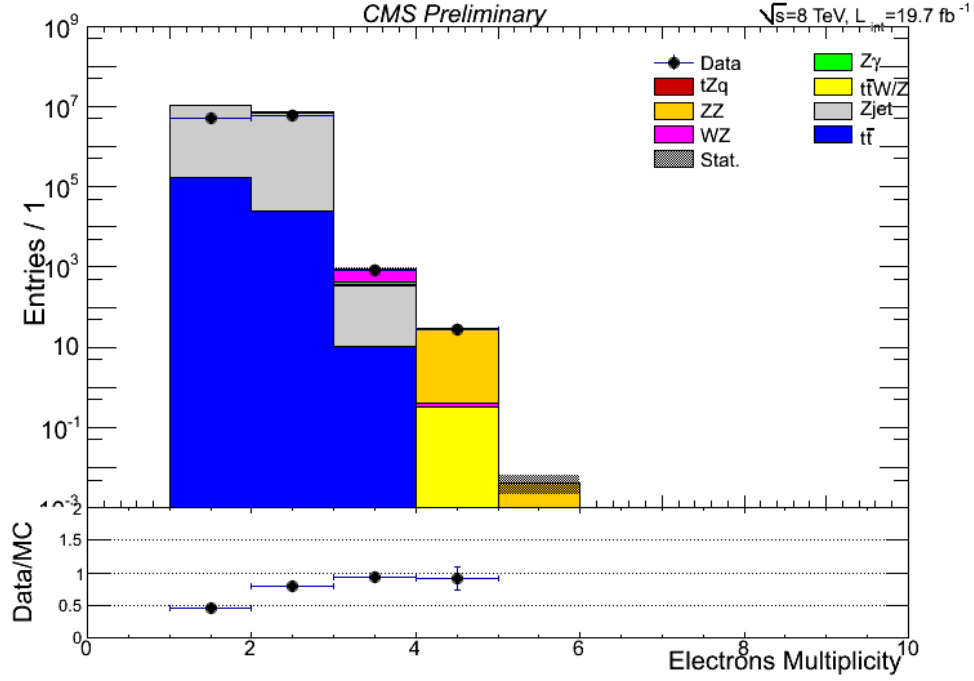


Figure 5.4: The multiplicity of electrons after the three lepton requirement and before the pre-selection.

Table 5.6: The electron multivariate identification utilizing Boosted Decision Tree (BDT). The cuts on BDT value are dependent on the p_T and η of the particular electrons.

p_T	$ \eta $	BDT Output
5 - 10 GeV	< 0.8	> 0.47
	0.8 - 1.479	> 0.004
	> 1.479	> 0.295
> 10 GeV	< 0.8	> -0.34
	0.8 - 1.479	> -0.65
	> 1.479	> 0.60

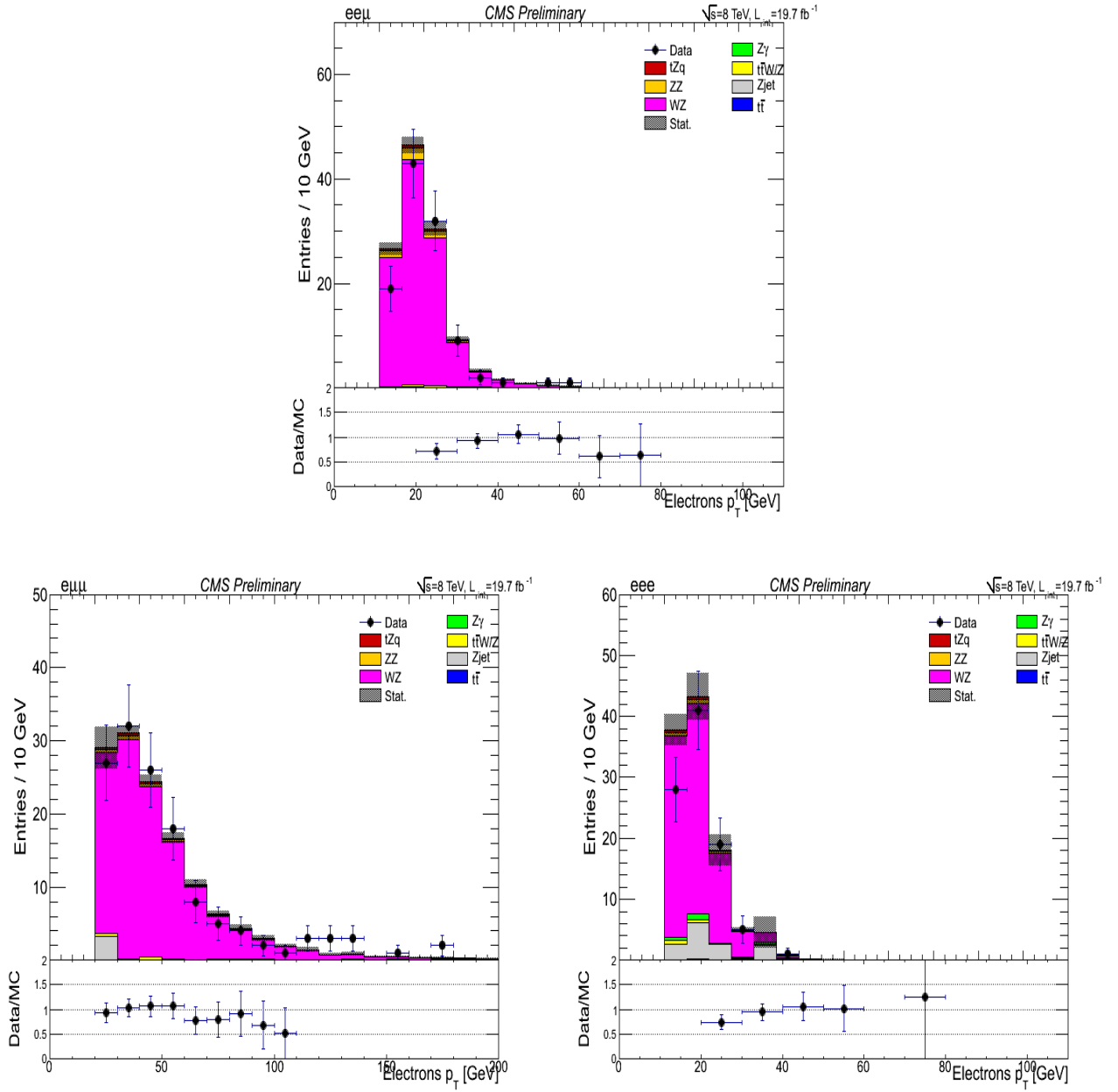


Figure 5.5: The transverse momentum (p_T) of electron in different combinations of three leptons final state after applying pre-selection criteria. The figure at the top shows the p_T in $ee\mu$ channel, left bottom figure shows p_T in $e\mu\mu$ channel and right bottom represents the p_T in eee combination. There is a good agreement between data and MC, and dominant background is WZ .

[92]. The detail discussion of jets is given in section 4.3.4. There are various algorithms for jet reconstruction in CMS which produce generator jets, calorimeter jets, and PF jets with different cone sizes. The PF jets of cone size 0.5 has been used in this thesis, jets are reconstructed using the anti- k_T algorithm and corrected with first three levels of jet energy correction such as L1FastJet, L2Relative, L3Absolute for MC simulation. In addition "L2L3Residual" are applied to data.

Jet are selected in $|\eta| < 4.5$ (Fig. 5.6) range with transverse energy greater than 30 GeV. Other than p_T and η requirement, jets also need to pass a set of quality cuts. The large pseudo-rapidity range has to be considered due to the light quark jet, which is preferably emitted in the forward region. The jets must have neutral hadronic, charged electromagnetic, and neutral electromagnetic energy fractions smaller than 99%. The charged hadronic energy fraction and charged particle multiplicity have to be larger than 1%.

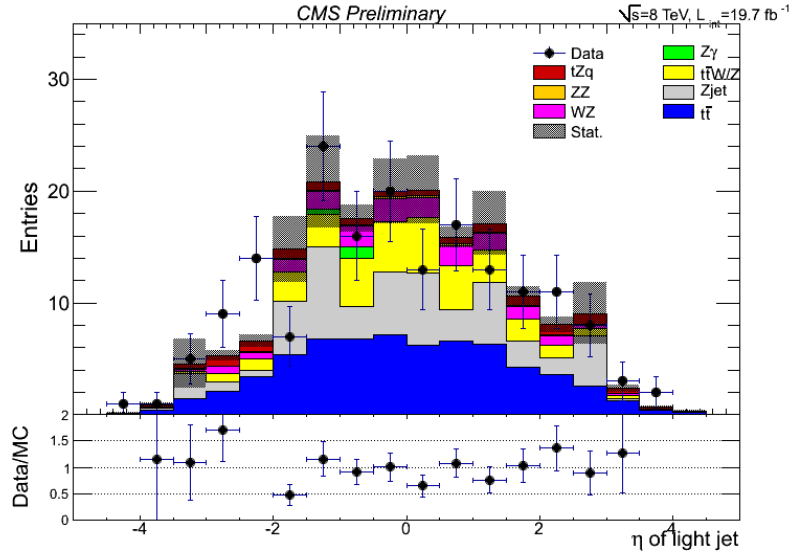


Figure 5.6: The light jets eta (η) after the three leptons requirement.

5.3.6 b-tag Jet Selection

Identification of b-jets or b-tagging is an important and key feature of many processes in experimental high energy physics. Due to large mass, the top quark is being studied for precision measurement of SM and for new physics hints, at the LHC. The efficient reconstruction of the b -quark is therefore necessary. The proper reconstruction of b -quark can reduce the overwhelming background processes of the top quark pairs. The properties of the bottom hadrons can be

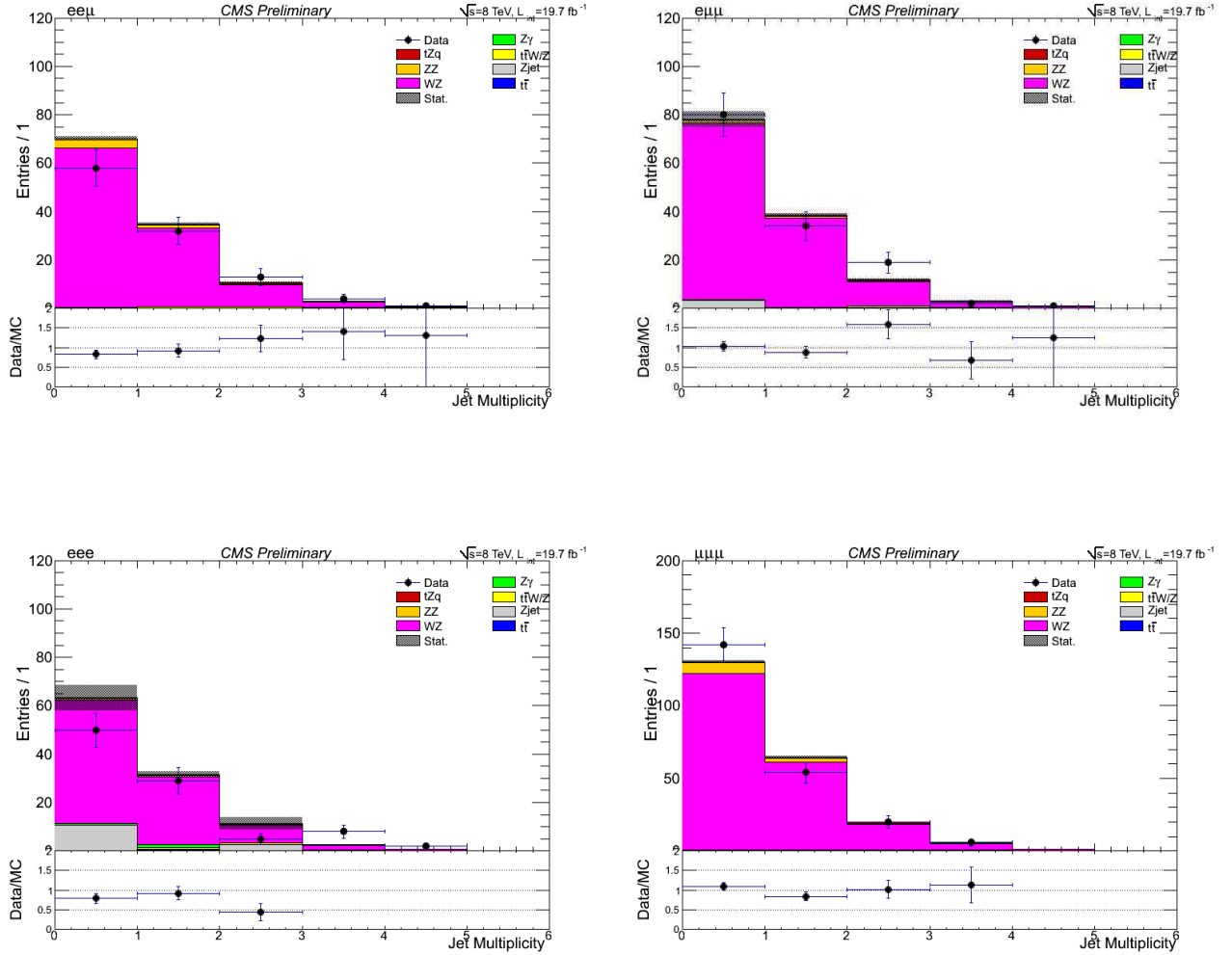


Figure 5.7: The light jets multiplicity for four different combinations after applying pre-selection criteria. top-left: multiplicity in $\mu\mu e$ combination, top-right: multiplicity in $ee\mu$ combination, bottom-left: multiplicity in eee combination, bottom-right: multiplicity in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

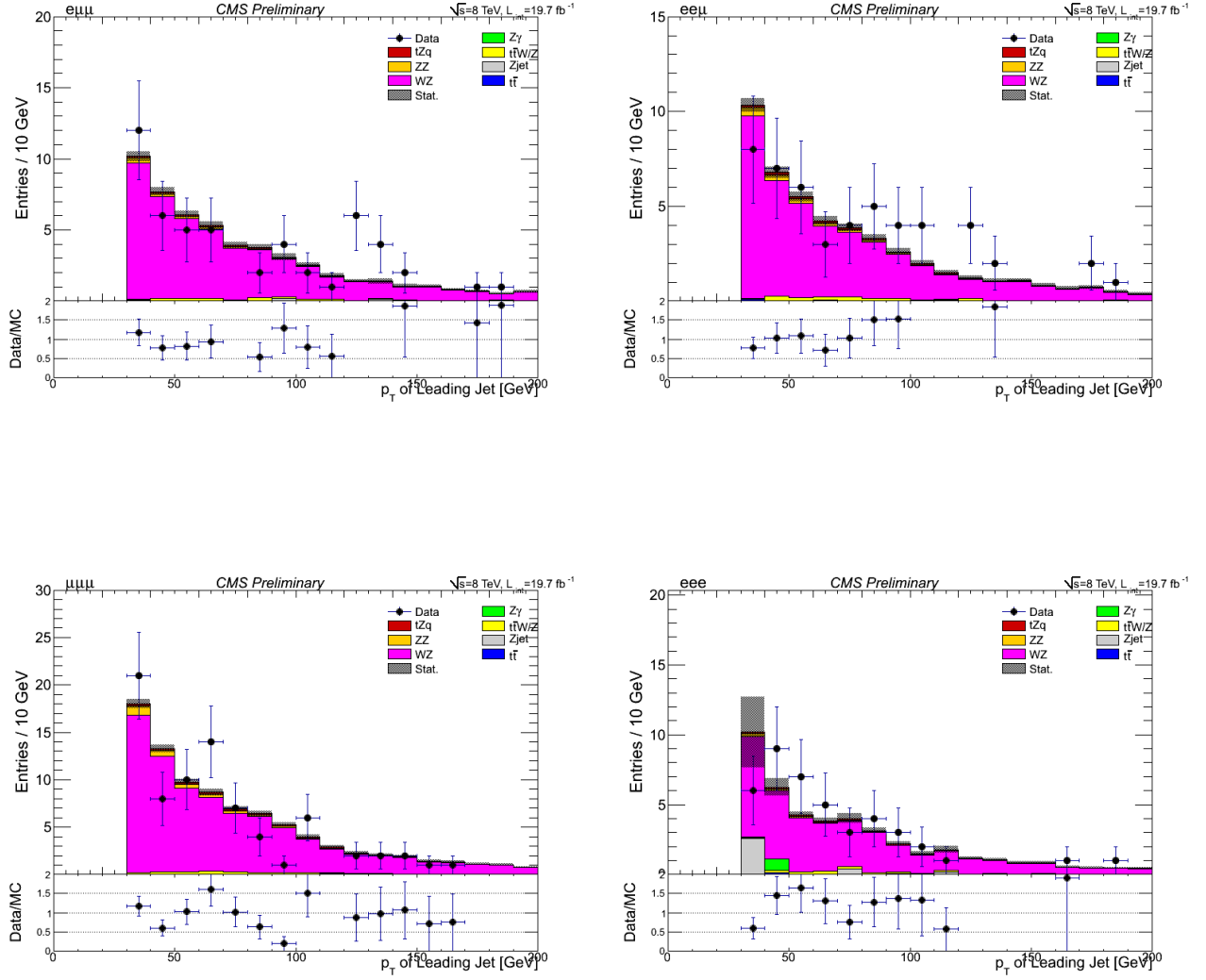


Figure 5.8: Leading light jets transverse momentum (p_T) after applying pre-selection criteria. top-Left: Jet p_T in $\mu\mu\mu$ combination, top-right: Jet p_T in $ee\mu$ combination, bottom-left: Jet p_T in $e\mu\mu$ combination, top-right: Jet p_T in eee combination, bottom-left

used to identify a jet originating from the b -quark. The CSV b-tagging algorithm is used for the identification of b-jets. The detail description of b-tagging algorithm is given in [93] and b-tag jet reconstruction is given in section 4.3.5. The CSV b-tag discriminator varies between 0 to 1 as shown in Table 5.7. In this dissertation, medium working point (Table 5.7) of b-tagging is used which corresponds to efficiency of 65 % for b jet identification. After the selection of discriminator value, the transverse momentum of the b-tagged jet is required to be greater than 30 GeV and $|\eta|$ less than 2.4 . Since b-jet is discriminating variable between tqZ signal and dominant backgrounds, therefore b-jet reconstruction is necessary. After applying required selection criteria of tqZ , b-jet multiplicities in various combination are shown in the Fig. 5.9.

Table 5.7: CSV b-tagging discriminant threshold for different working points of the algorithm [93]. The approximate light-jet mis-identification and b-jet identification efficiencies are also given in last two columns.

CSV Name	CSV Threshold	Light-Jet Efficiency [%]	b-Jet Efficiency [%]
CSVL (Loose)	≥ 0.244	~ 10	~ 80
CSVM (Medium)	≥ 0.679	~ 1	~ 65
CSVT (Tight)	≥ 0.898	~ 0.1	~ 50

5.3.7 The Missing Transverse Energy (MET) Selection

There is a critical role of MET ($\cancel{E}_T$) in many physics analysis at the LHC and its also a key variable for many searches beyond the SM such as super-symmetry, extra dimension and search for dark matter. The precise measurement of MET is also necessary for SM physics involving W bosons and top quarks [94].

The MET is defined as the vectorial sum of all PF particles in the transverse plane with an opposite sign. It is taken as the transverse momentum of the neutrino in the semi-leptonic top quark decay to reconstruct the top quark in the final state. MET is one of the most important variables for reducing the QCD and Drell-Yan backgrounds in the analysis which involves leptonic decays of W bosons such the tqZ cross-section measurement. Thus the PF type-I corrected MET has been selected for the tqZ analysis and transverse energy should be greater than 30 GeV. The detail discussion of MET is given in 4.3.6. The Fig. 5.11 show the distributions of MET, in all four combination (eee , $ee\mu$, $e\mu\mu$, $\mu\mu\mu$) after applying the pre-selection requirements. These plots shows that the dominant backgrounds at pre-selection

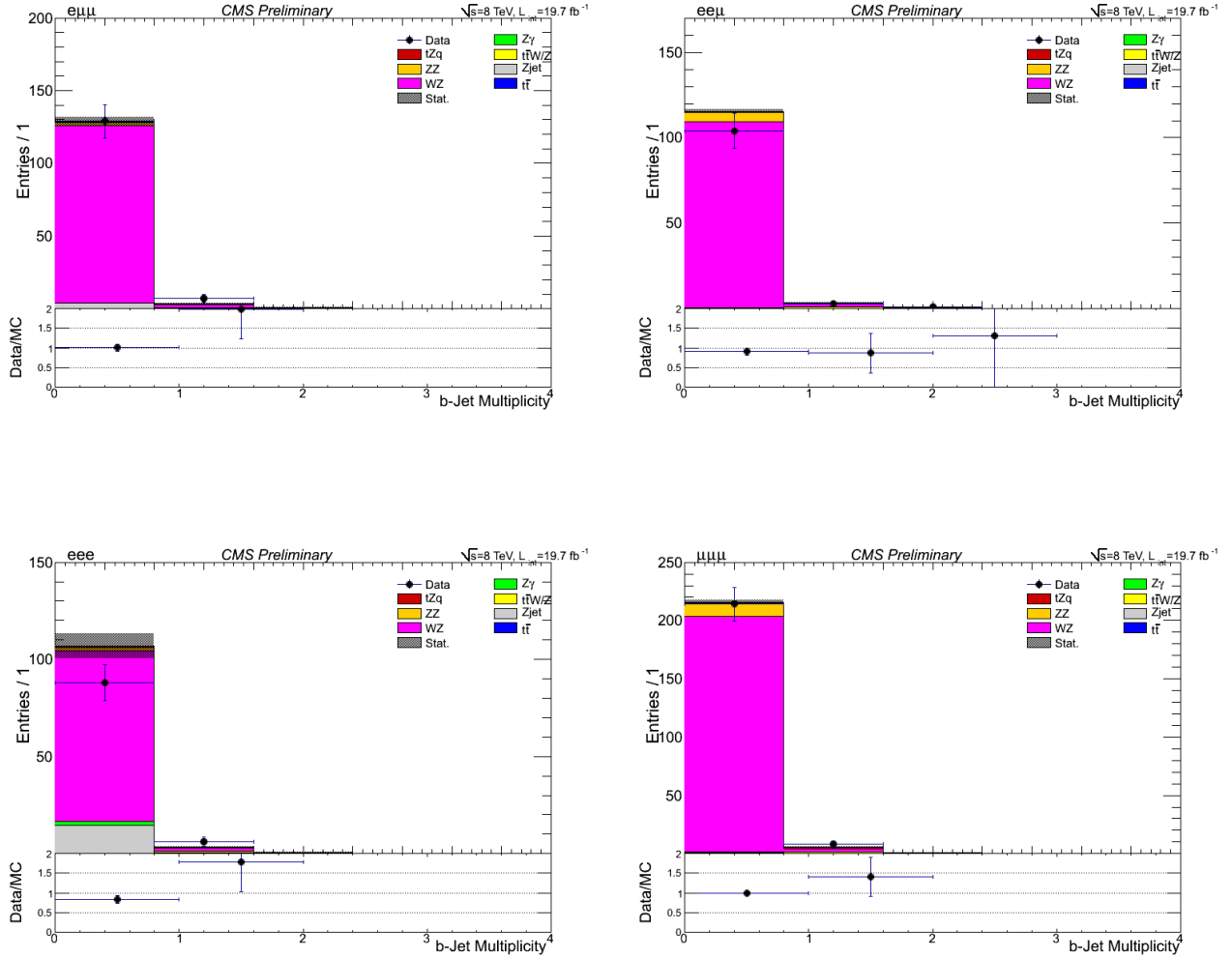


Figure 5.9: The b -jets multiplicity in all four combinations after applying pre-selection criteria. top-left: b -jets multiplicity in $\mu\mu e$ combination. top-right: the b - jets multiplicity in $ee\mu$ combination, bottom-left: the b - jets multiplicity in eee combination, b -jets multiplicity in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

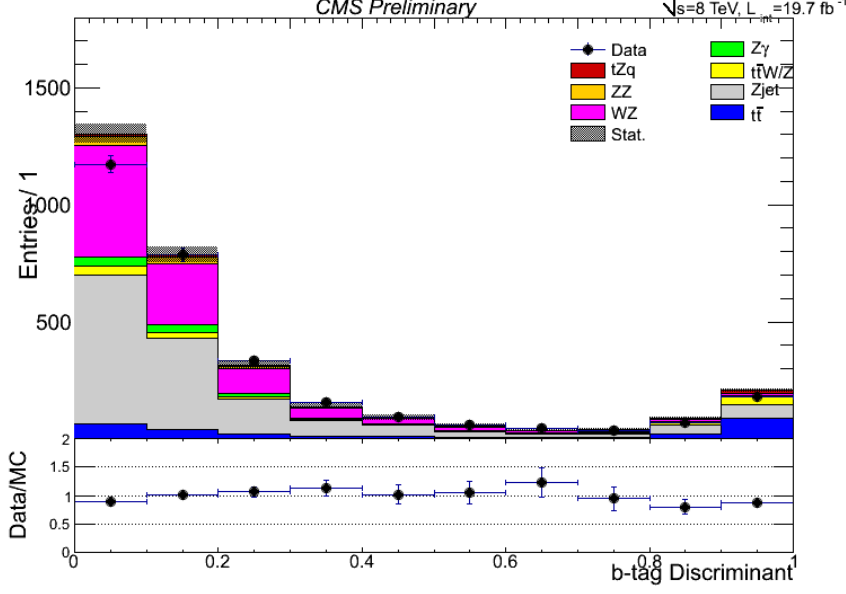


Figure 5.10: B jet discriminant after requiring the three leptons in an event.

level are WZ and ZZ .

5.4 Preselection

After the selection of events which are passing the required analysis trigger, there are set of selection cuts which are being called pre-selection. These selection cuts enhances the signal events and suppress background events. The complete pre-selection is defined as the following,

- require exactly three tight isolated leptons, multiplicity of leptons is given in Fig. 5.12, where lepton is either muon or electron (μ, e). The leptons selection and isolation have been discussed in sections 5.3.3 and 5.3.4.
- two leptons should be making a Z -mass within window $[78, 102]$ GeV. The two leptons which are making Z boson should be same flavor and oppositely charged. The separation $\Delta\phi_{\ell^+\ell^-}$ between the two leptons of the Z boson should be greater than 0.5 .
- third lepton should be from the W boson, which is the decay product of the top quark.
- since third lepton is coming as a decay product of the W boson therefore asking missing transverse energy greater than 30 GeV. The lepton (μ, e) and the neutrino (ν) coming as a decay product of the W boson should be well separated with $\Delta\phi_{\ell\nu} > 1$.

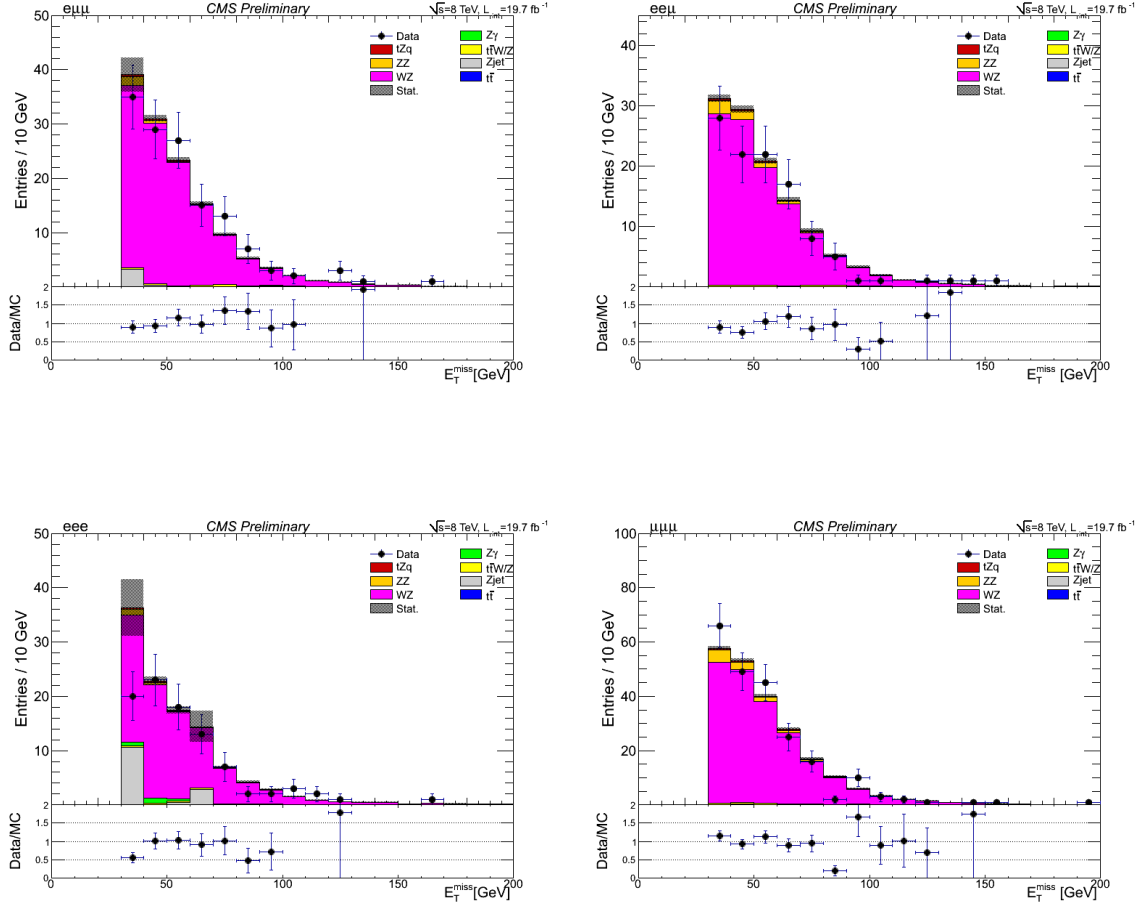


Figure 5.11: MET distributions for four different combinations after applying pre-selection. top-Left: MET distribution in $\mu\mu e$ combination, top-Right: MET distribution in $ee\mu$ combination, bottom-left: MET distribution in eee combination, bottom-right: MET distribution in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

- veto any other loose lepton (μ, e) present in the event.

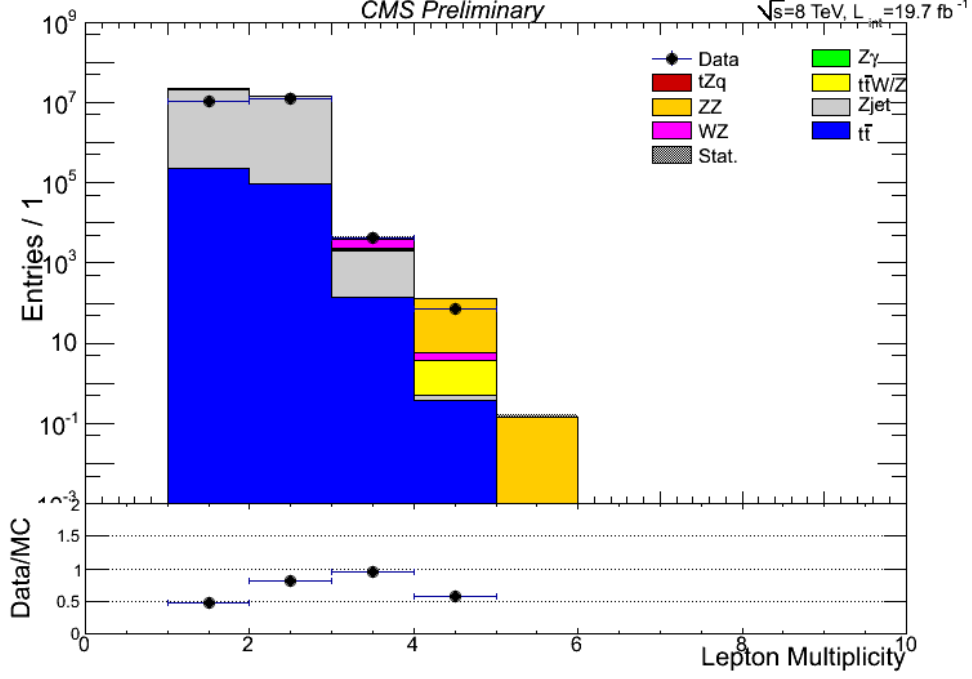


Figure 5.12: The multiplicity of three tight isolated leptons, before the pre-selection requirement requirement. An event must contain at-least three leptons to be selected as a signal.

5.5 Di-lepton (Z boson) Invariant Mass after Event Pre-selection

In the tqZ rare SM process, the Z boson appears as a radiation from the quarks scattering. Therefore it is one of the key features of the analysis to suppress backgrounds such as $t\bar{t}$, which may result in similar final state as signal process. The current analysis is performed in fully leptonic final state where both the top quark and Z boson decays into leptons, i.e, electron or muons. Therefore, the Z boson is required to be made of pair of same flavor opposite sign leptons with invariant mass M_{ll} to lie within a window of $[78,102]$ GeV. To have a very clean signal of Z boson which is produced in association with the top quark, a very strict window of Z boson mass applied. In the event, where more than one pair of di-leptons are in the range close to the Z mass, the pair which is closest to the pole Z mass (91.1876 GeV) [94] is selected as a Z candidate. In Fig. 5.13, invariant mass of the Z boson is shown for four different lepton

combinations, the different colors shows the signal (tqZ) and all relevant backgrounds MC. At the level of pre-selection, the dominant backgrounds are di-bosons, WZ , ZZ and $t\bar{t}Z$.

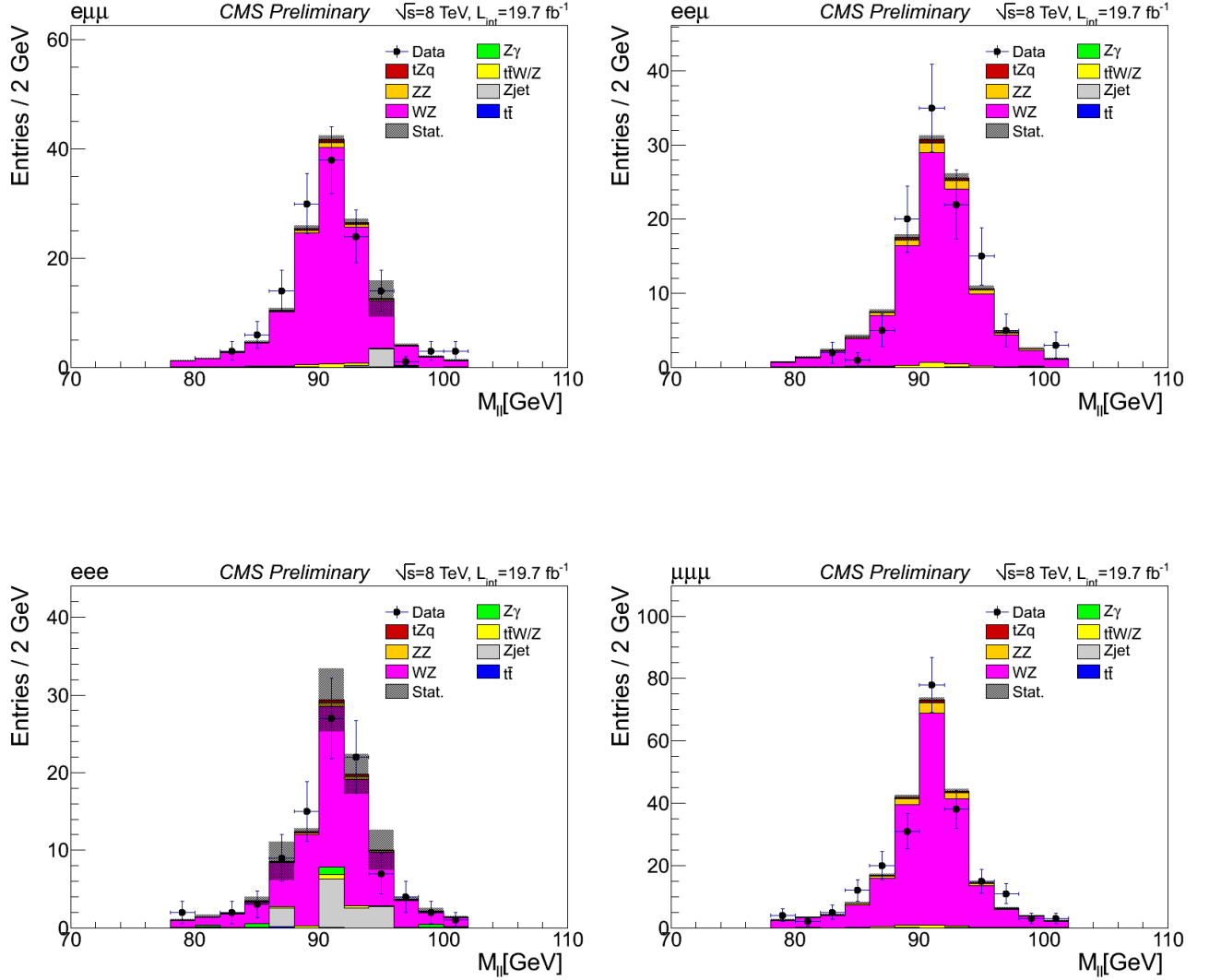


Figure 5.13: The invariant mass of Z boson for four, $\mu\mu e$, $ee\mu$, eee , $\mu\mu\mu$, combinations after applying pre-selection criteria. top left: Z boson invariant mass in $\mu\mu e$ combination, top right: Z boson invariant mass in μee combination, bottom left: Z boson invariant mass in eee combination and bottom right: Z boson invariant mass in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

5.6 Data MC Comparison after Pre-selection

Since the pre-selection is a set of selection cut, to obtain a clean signal of tqZ as described in section 5.4. For tqZ process, the three leptons final state can have four possible combinations

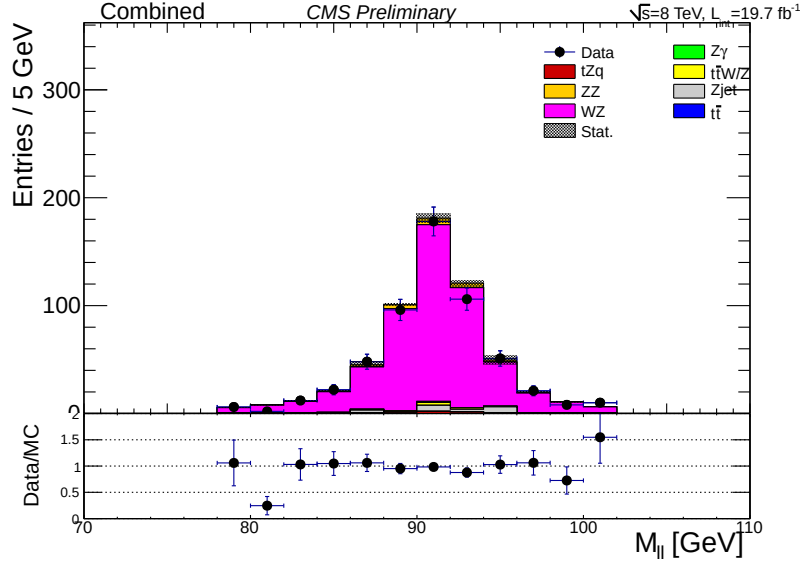


Figure 5.14: Inclusive Z boson invariant mass after applying pre-selection criteria. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

are $\mu\mu\mu$, $\mu\mu e$, μee and eee . The selection process of events starts from the appropriate trigger implementation, which are $\mu\mu$, ee and $\mu e\gamma$. After the trigger selection, the next step is to select three tight isolated leptons and vetoing any fourth loose lepton present in event as discussed in pre-selection and in sections: 5.3.3, 5.3.4. At this stage, a tqZ signal event must contain a W boson, which is the decay product of top quark and a Z boson introduced as a radiation in signal process. The transverse mass of W boson reconstructed by using $W_T = \sqrt{2P_{T\ell}P_{T\nu}(1 - \cos\Delta\phi)}$ where $P_{T\ell}$ is transverse momentum of leptons (e or μ), $P_{T\nu}$ is the neutrino energy or MET and $\Delta\phi$ is the angle between lepton and corresponding neutrino. A well separated lepton and neutrino are required to have $\Delta\phi > 0.5$ to obtain a clean signal of the W boson. The transverse mass of the W boson in all four exclusive and inclusive combinations is shown in Fig 5.17 and Fig. 5.18, respectively. The di-lepton invariant mass ($M_{ll} = E^2 - P^2$) is well understood physical observable at experiments that can be used for the validation of the selection cuts and the understanding of backgrounds. The invariant mass of the Z boson for different four exclusive and inclusive combinations are shown in Fig. 5.14 and Fig. 5.13. The invariant Z boson mass is well reconstructed and shows good agreement between the data and MC. The transverse momentum distributions of Z boson in all combinations and inclusive are shown in Fig. 5.15 and Fig. 5.16.

Since tqZ measurement has been performed leptonocally by using cut and count method. Therefore a very well reconstruction of leptons was a requirement. Muon and electron multiplicities are shown in Fig. 5.2 that shows a good agreement between data and MC. Missing Transverse Energy in all combinations is shown Fig. 5.11. Untagged jets multiplicities in all combinations and for inclusive one are shown in Fig. 5.7 and Fig. 5.19. Distributions of pre-selected leading untagged jets P_T is shown in Fig. 5.8.

The plots are shown to demonstrate the agreement between the data and MC simulation. At pre-selection level, there is no untagged or b-tagged jet requirement. This is done to be able to preserve the b-tag requirement. As it can be seen from cut flow table that number of events in signal and background are much more in pre-selection region than signal selection which includes b-tagged jets. From these plots it is quite evident that the pre-selection is working well and we are able to reconstruct the basic objects in the final state. At pre-selection the contribution of WZ background is dominating. All these plots shown are normalized to data luminosity.

5.7 tqZ Signal Selection

For the final selection of signal events, there are additional requirements from pre-selection described in section 5.4. The event, that is fulfilling the pre-selection set of cuts, must have at least two jets in that specific event. From these two jets one should be b-tagged and the second is light quark jet. The invariant mass of Z boson along with its transverse momentum is shown in Fig. 5.21, after applying the final signal selection criteria. The dominant backgrounds are $t\bar{t}Z/W$, and WZ after final selection which are shown with different colors. The transverse mass and transverse momentum of W boson are shown in Fig. 5.22, similarly the transverse momentum of the top quark is shown in Fig. 5.23.

5.8 Summary

This chapter 5, contains the information about data streams and MC simulation used for the analysis. The trigger used in the analysis has been discussed briefly. The main focus remained on object selection for tqZ analysis and the requirements have been discussed on these physics objects. Since the analysis is using leptons, MET and jets in final state, therefore their selection criteria have been discussed in detail. The tqZ analysis has been performed

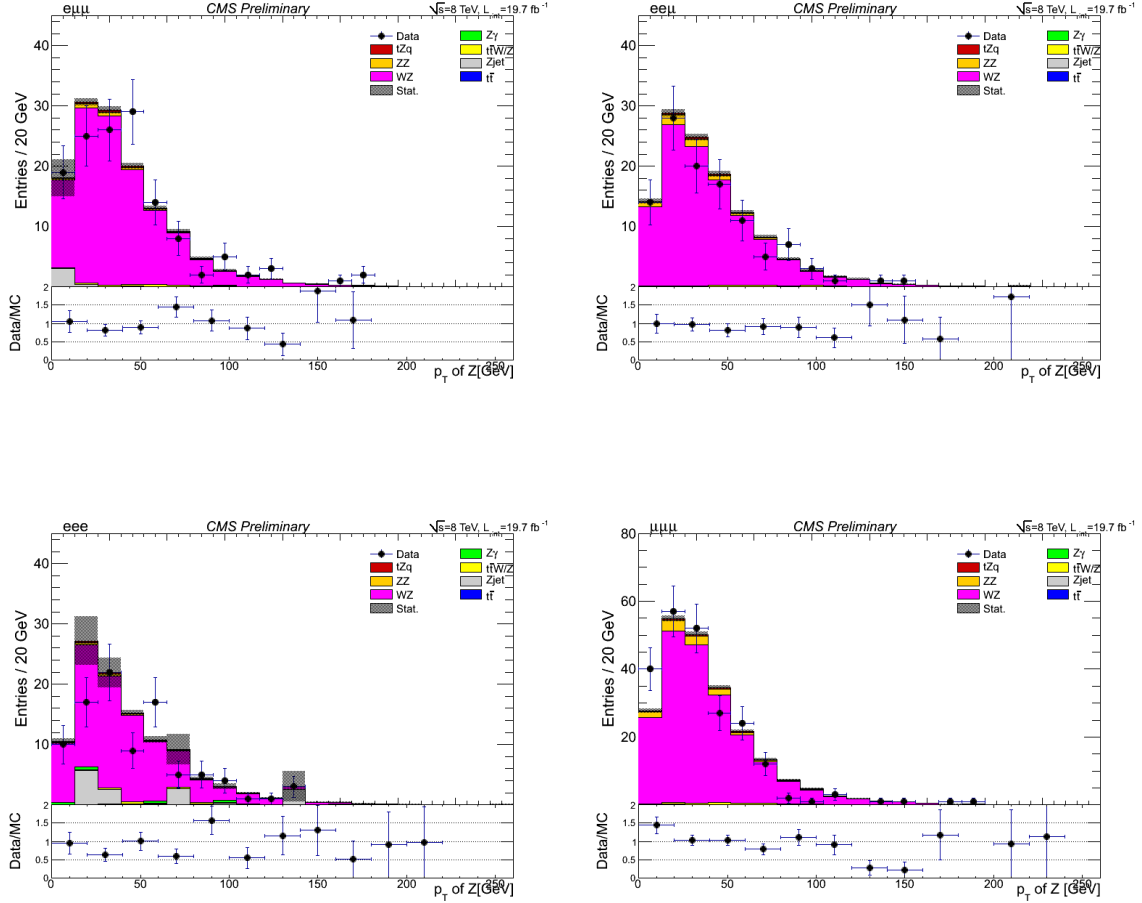


Figure 5.15: The transverse momentum (p_T) of Z boson in four different combination of tqZ after applying pre-selection criteria. top-left: Z boson p_T in $\mu\mu e$ combination, top-right: Z boson in $p_T \mu ee$ combination, bottom-left: Z boson in $p_T eee$ combination and bottom-right: Z boson in $p_T \mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

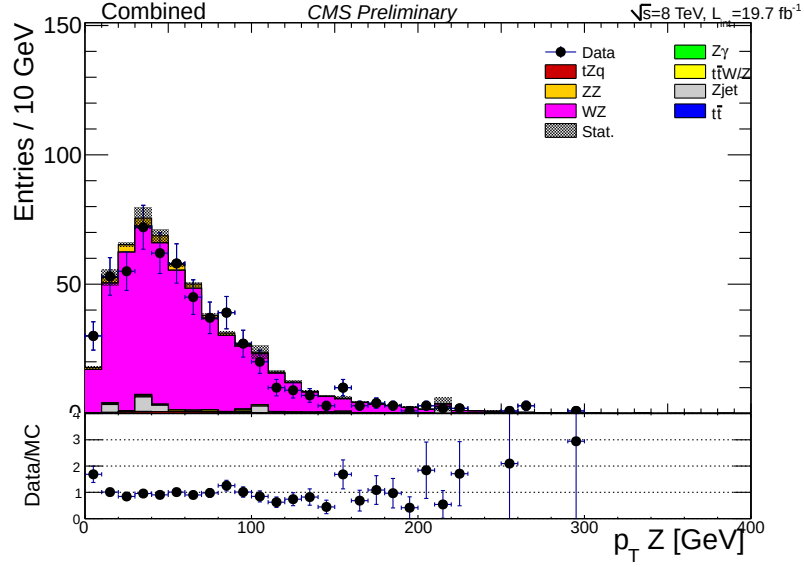


Figure 5.16: Inclusive transverse momentum (p_T) of Z boson after applying the pre-selection criteria. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

by adopting kinematical regions, which are set of selection cuts, therefore these kinematical regions have defined in this chapter like pre-selection and final signal selection regions. At the end of this chapter, after applying the pre-selection criteria comparison between the data and MC simulations have been made. After the pre-selection cuts implementation, the dominant backgrounds are, WZ , $t\bar{t}Z$ and less dominant are $t\bar{t}$, and $Z + Jets$. Since WZ and $t\bar{t}Z$ have similar final state like signal process therefore these appears as dominant backgrounds, whereas the $t\bar{t}$ is less dominant because it has different final state than signal.

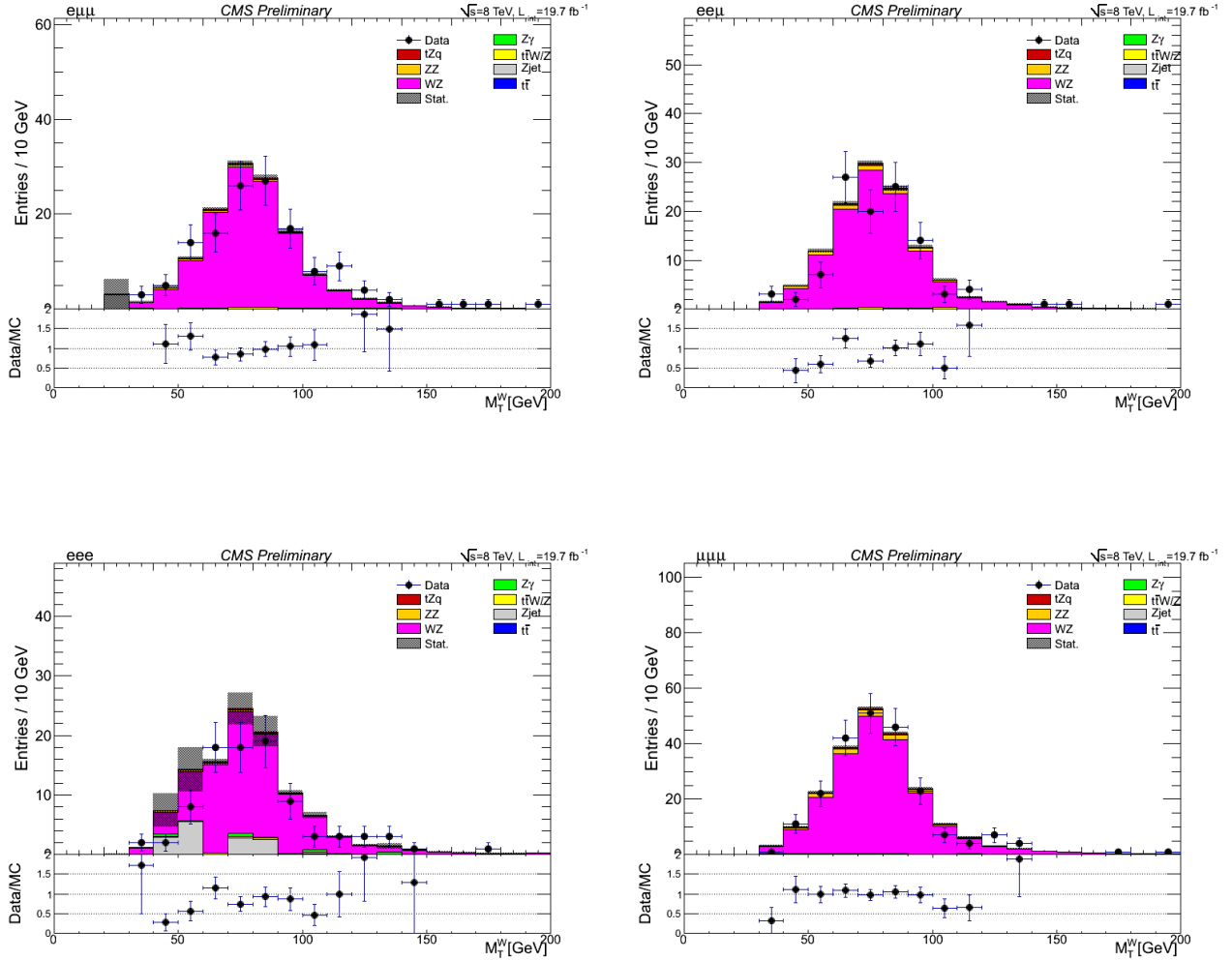


Figure 5.17: The W boson transverse mass (M_T) after applying pre-selection. top-left: W boson transverse mass distribution in $\mu\mu e$ combination, top-right: W boson transverse mass distribution in $ee\mu$ combination, bottom-left: W boson transverse mass distribution in eee combination and bottom-right: W boson transverse mass distribution in $\mu\mu\mu$ combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

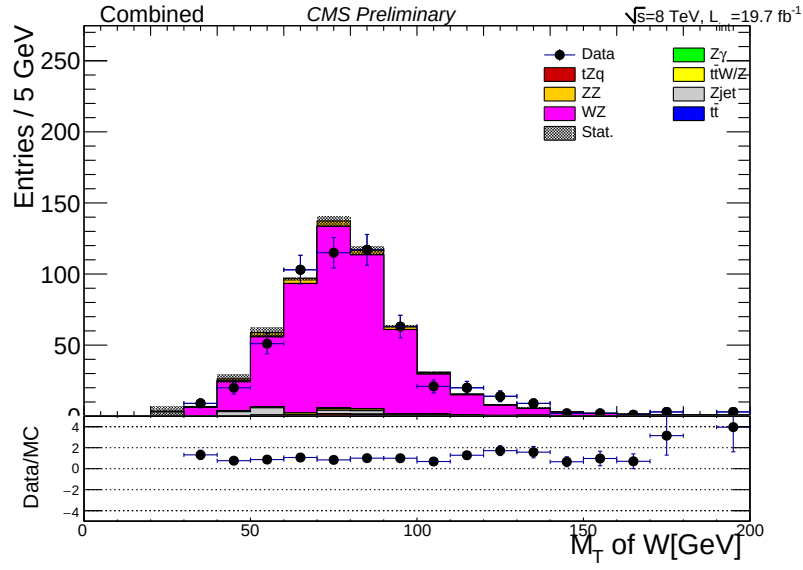


Figure 5.18: Inclusive W boson transverse mass after applying pre-selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

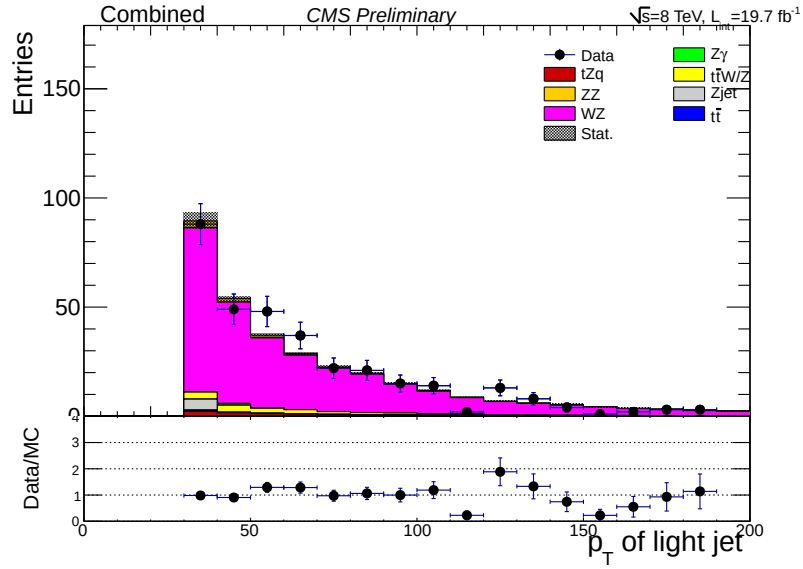


Figure 5.19: The inclusive transverse momentum of the light quark jets after pre-selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

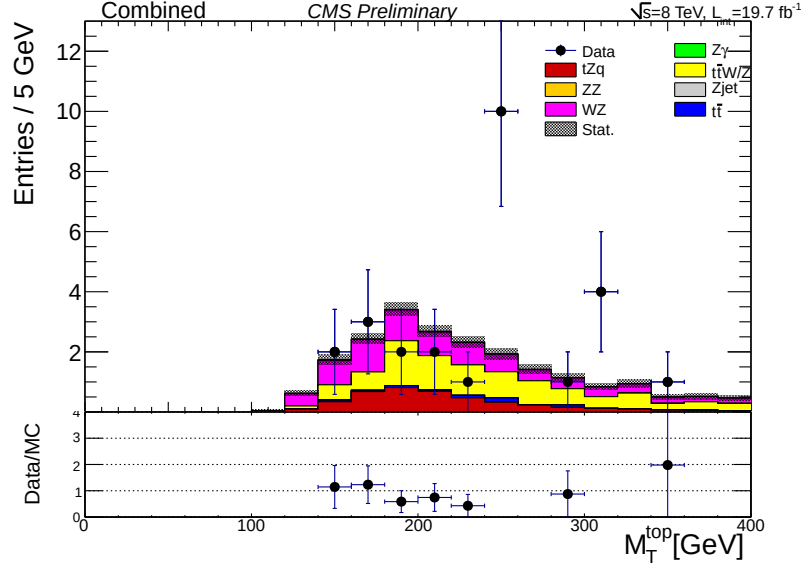


Figure 5.20: Top quark transverse mass after pre-selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

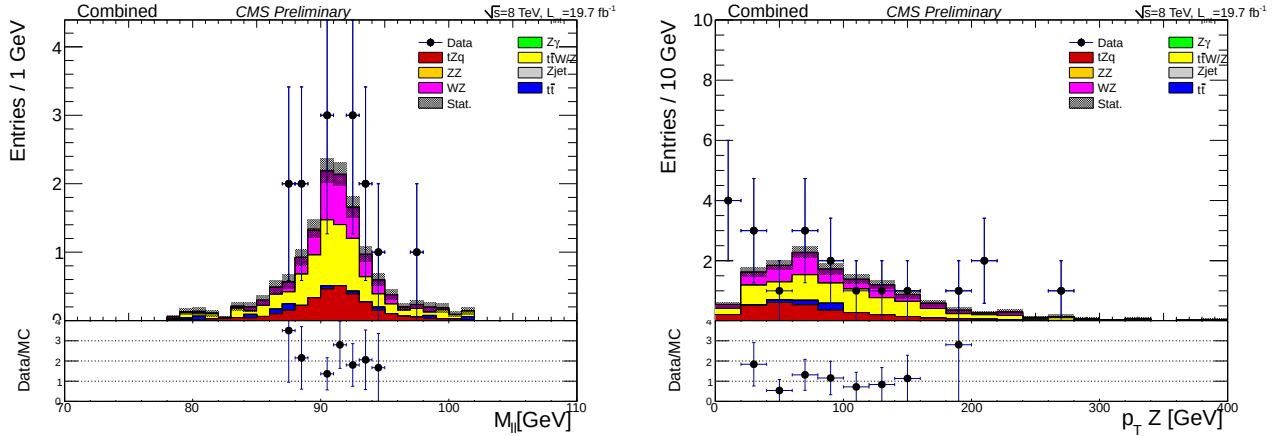


Figure 5.21: The invariant mass and transverse momentum (p_T) of Z boson after applying the final signal selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

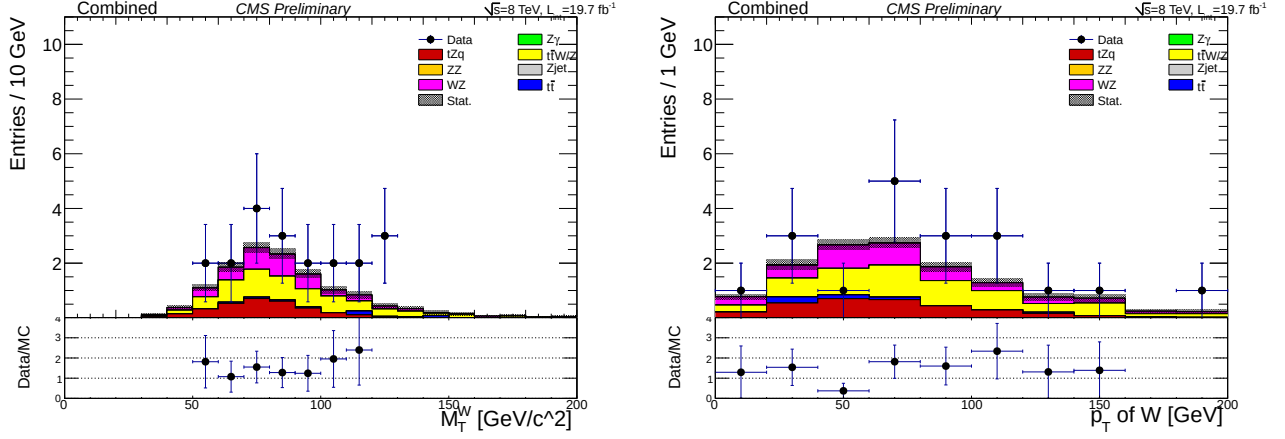


Figure 5.22: The transverse mass and transverse momentum (p_T) of W boson after applying the final signal selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

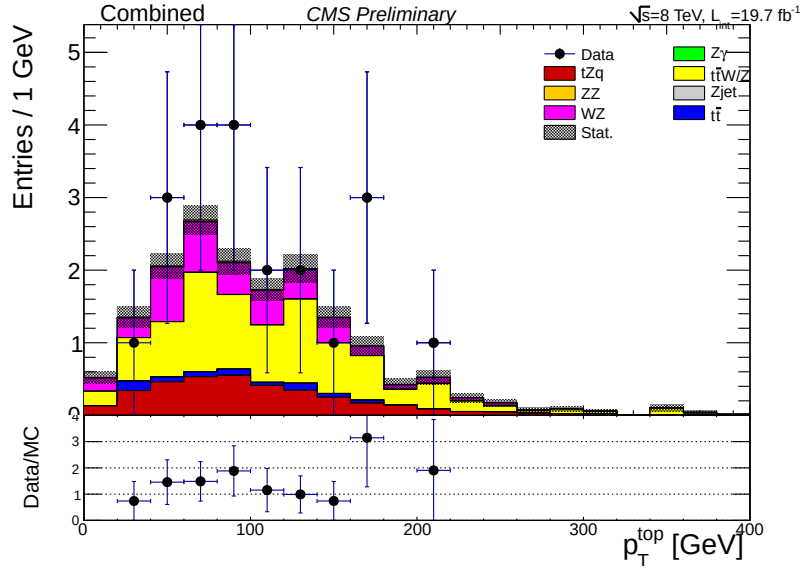


Figure 5.23: The transverse momentum of the top quark after applying the final signal selection. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

Chapter 6

The tqZ Cross-Section Measurement

In this chapter, the measurement of tqZ cross-section has been presented using 19.7 fb^{-1} of data collected by the CMS experiment at 8 TeV during Run-I. The cross-section has been measured in fully leptonic decay mode for the top quark produced in association with Z boson. The Higgs combine package [107] has been used for the cross-section measurement in inclusive as well as four exclusive leptonic combinations which are eee , $ee\mu$, $e\mu\mu$, $\mu\mu\mu$. The systematic uncertainties as well as data driven background estimations have been discussed.

6.1 Introduction to Cross-Section

In the field of experimental high energy physics, the cross-section is one of the important observable which can be compared to the theoretical calculations. The interactions of fundamental particles are described in terms of cross-sections. The cross-section is the probability that an interaction will occur, represented by σ and measured in the units of area. The most frequently used units are, barns (10^{-28} m^2), picobarn etc. In other words, σ is an effective cross sectional area of the target presented to incident particles or projected particles. The interaction cross-section is Lorentz invariant quantity and therefore its form does not depend on the frame of reference. For a process to occur, it depends upon the flux of incident particles, and the number of interaction per unit time per target particles.

The production cross-section of tqZ is measured by counting the number of observed events in the detector and by taking into account the time-integrated luminosity ($\mathcal{L}$), efficiency and acceptance of the detector. Then the measured cross-section of tqZ is compared with the prediction of SM. For the measurement of cross-section with very low interaction probability like tqZ needs sufficiently large number of collisions rate, which is characterized by the $\mathcal{L}$. The

cross-section for any physical process is defined as

$$\sigma = \frac{N_{obs} - N_{bkg}}{L * A * \varepsilon}, \quad (6.1)$$

where N_{obs} is the total number of observed events after applying the final selection criteria, N_{bkg} is the total number of background events in the process, $\mathcal{L}$ is the total integrated luminosity, A is the acceptance and ε is the efficiency of the detector. For rare processes such as tqZ , backgrounds play very important role in the measurement. Therefore the study of background processes is necessary to measure their contributions to the cross-section measurement.

6.2 Background Estimation

The SM processes with very similarly event topology as the tqZ final state are considered as backgrounds. To subtract the background contributions, it needs to be determined very precisely. After applying the pre-selection criteria as described in section 5.4, the dominant background contributions are coming from $t\bar{t}Z$, WZ and $Z + jets$. There are two types of background processes, an event having the same final state with all prompt leptons like signal event is called irreducible background processes like WZ and a background having one or more than one fake leptons and passing signal selection criteria reducible like $Z + Jets$. Data driven technique has been used for the measurement of reducible and irreducible background process. All other backgrounds except WZ and $Z + jets$ are estimated from MC scaled with higher order available cross-sections.

6.2.1 $t\bar{t}Z$ Background

The top quarks pair production in association with Z boson is a reducible background process. The contribution of $t\bar{t}Z$ has been estimated from MC simulations. The gluon-gluon fusion is dominant process for $t\bar{t}Z$ production during pp collisions at the LHC, the Feynman diagram of the process is shown in Fig. 6.1. The $t\bar{t}Z$ background process passes the selection criteria of signal because it also includes the reconstruction of the Z boson in the final state. The $t\bar{t}Z$ process pass the selection cuts because two leptons are coming from the decay of Z boson and the other two are the decay products of $t\bar{t}$. Therefore this constitutes a major background to the tqZ cross-section measurement. The measured contribution of $t\bar{t}Z$ is given in the Table 6.7.

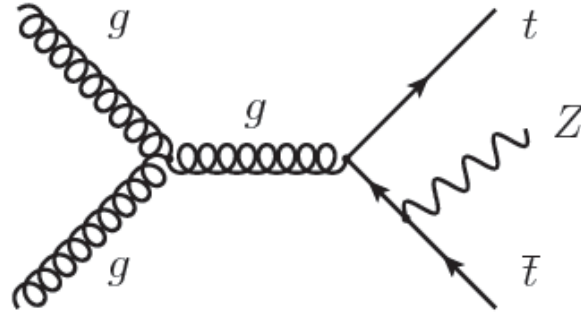


Figure 6.1: The Feynman diagram of $t\bar{t}Z$ production, via gluon-gluon fusion. The gluon fusion is predominant source of $t\bar{t}Z$ process, which is one of the significant background the in tqZ cross-section measurement.

6.2.2 WZ Background

In case of di-boson (WZ), there are three real leptons in the final state and therefore it constitutes irreducible background to signal. The Feynman diagram of the WZ production process is shown in Fig. 6.2. Since this process contains the three real leptons, therefore, pass the final selection criteria as of signal process and appears as a one of the dominant background in the tqZ cross-section measurement. For estimating the contribution of WZ background process, the data driven method has been adopted. The contribution of WZ background is shown in Table 6.7.

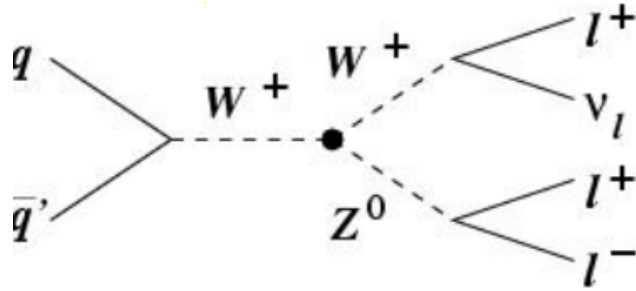


Figure 6.2: The Feynman diagram of WZ production which further decays to three leptons and neutrino, a dominant background process in the tqZ cross-section measurement and estimated by using the data driven technique.

To estimate background, a control region is defined by reconstructing di-lepton mass in the pre-selection with no b-jet in the event. Distributions of di-lepton invariant mass in 0 b-jet bin for all leptons combinations are shown in Fig. 6.5. As visible in all combinations, background is dominated by WZ final states. To estimate WZ background contributions, ratio between

Table 6.1: Scale Factors (SFs) obtained in Z mass window $[78,102]$ GeV in 0 b -jet bin. Errors are statistical only.

Combination	Scale Factor
$\mu\mu\mu$	1.016 ± 0.009
eee	0.822 ± 0.037
$\mu\mu e$	0.938 ± 0.021
$ee\mu$	0.911 ± 0.027
inclusive	0.940 ± 0.010

the data and MC is calculated in the Z mass window $[78,101]$ GeV. The Scale Factors (SFs) derived this way are shown in Table 6.1.

Before extrapolating these SFs to the signal region, comparison of di-lepton invariant mass shapes in 0 b -jet and 1 light jet bins are shown in Fig. 6.3. The mass comparison is made after applying pre-selection cuts. There is no significant difference between Z boson mass shapes in the two regions, which validates the method that the SFs derived can be applied in the final selection regions.

The WZ contribution in the signal region is weighted with the SFs given in Table 6.1. Distributions of di-leptons mass for all combinations after applying pre-selection criteria and scaling WZ background are shown in Fig. 6.6. These distributions are inclusive in all b -jets bins and therefore they include contribution from all b -jet including 0 b -jet bin. There is a good agreement between data and MC as can be seen in the ratio plots in Fig. 6.6. The SFs given in Table 6.1 are finally used to obtain yield of WZ for the final cross-section measurement. Systematic uncertainties on the WZ SFs have been evaluated by varying the Z mass window by 2 GeV.

6.2.3 Fake Leptons Backgrounds

The fake leptons are mis-identified objects especially jets in an event. For any physics analysis, it is necessary to understand and measure the fake objects. Fake is a very broad term, they may be truly fake e.g. jets taken as electrons or real leptons from a heavy flavor decay or electrons from γ conversion. The tqZ event contains a Z -boson and a top quark which further decays into W -boson and b -quark. The tqZ event must contain a Z -boson because event selection process starts from the re-construction of Z -boson. Therefore only lepton coming from the

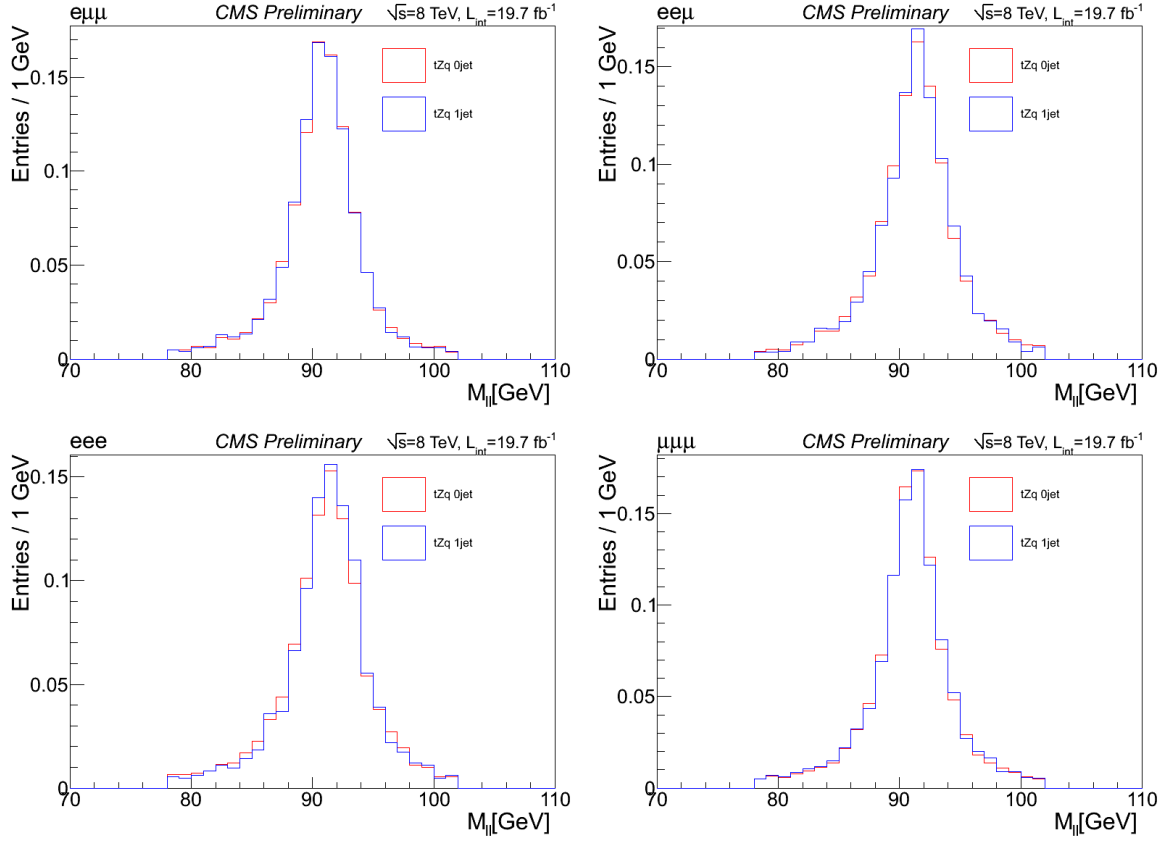


Figure 6.3: The shape comparison of di-lepton mass in different combinations in 0 b -jet and 1 light jet bins using signal Monte Carlo (MC) where red color represents signal MC in pre-selection plus 0 b -jet region and blue color is for pre-selection plus 1 light jet region. The upper left plot shows invariant Z boson mass in $e\mu\mu$ combination, upper right shows invariant Z boson mass in $ee\mu$. The bottom left plot shows invariant Z boson mass in eee and bottom right shows invariant Z boson for $ee\mu$ combination.

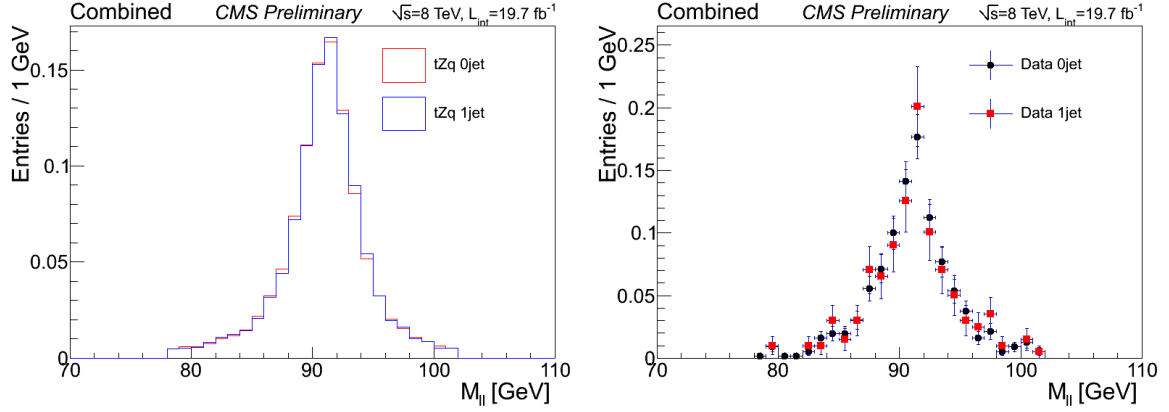


Figure 6.4: The shape comparison of inclusive di-lepton mass in 0 b -jet and 1 light jet bins. Left: Inclusive di-lepton mass in signal Monte Carlo where red color represents signal MC in pre-selection plus 0 b -jet region and blue color is for pre-selection plus 1 light jet region. Right: Inclusive di-lepton mass in data where black color dot represents data in pre-selection plus 0 b -jet region and red color dot is for pre-selection plus 1 light jet region.

decay of W -boson can fake in an event. The backgrounds with one fake lepton are composed of Drell-Yan (DY), WW , $t\bar{t}$ and single top events, the highly dominating fake lepton background is DY. In this analysis, background events with more than one fake lepton are considered as negligible. The tqZ event contains a Z -boson therefore $Z + Jets$ can easily pass the signal selection where jet will fake as a lepton.

The estimation of various backgrounds contribution to the signal region is performed by using simulated samples of the processes expected to contribute. This approach is viable for the majority of background processes. The contribution of two prompt and one fake lepton background events to the signal sample may not be accurately described by simulation because rates of non-prompt leptons are not well modeled. It was found that the limited statistics of the $Z + Jets$ sample in three lepton region results in an inaccurate background estimate. Therefore, simulation cannot be used to determine the $Z + Jets$ background contribution and needs to be estimated using data-driven method. In this method, scale factor has been derived by performing profile likelihood fit on transverse mass (m_T^W) of the W -boson in signal and DY enriched regions. A Control Region (CR) most likely similar to signal region but enriched in $Z + Jets$ is required. In this CR isolation is inverted for third lepton coming from the decay of W -boson and relaxing the cut on MET and creating a sample enriched in the fake leptons of the $Z + Jets$ that pass the signal selection requirements. The transverse mass (m_T^W) is

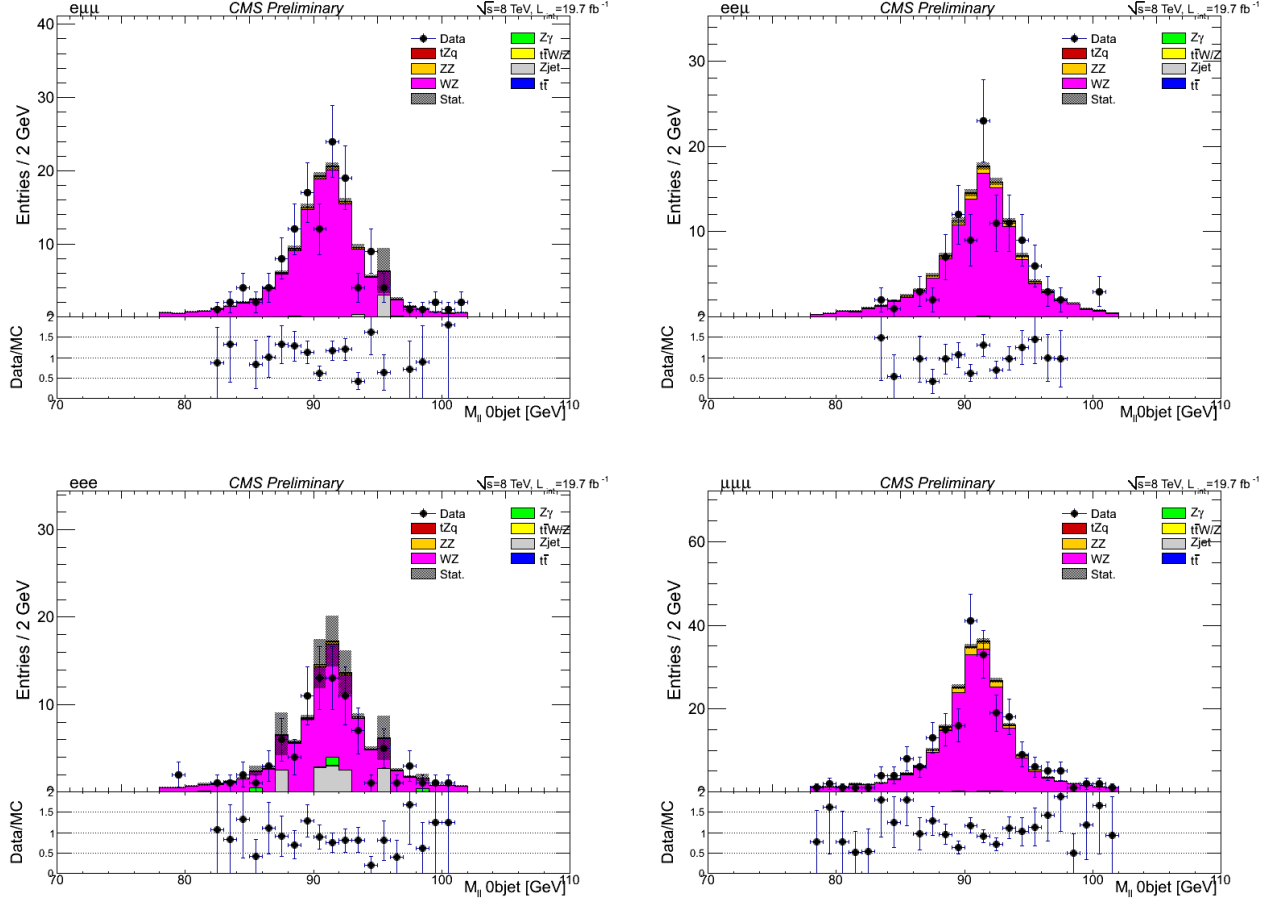


Figure 6.5: The invariant mass of Z boson for four, $e\mu\mu$, $ee\mu$, eee , $\mu\mu\mu$, combinations after applying pre-selection criteria plus 0 b -jets which corresponds to WZ enriched region. top left: Z boson invariant mass in $e\mu\mu$ combination, top right: Z boson invariant mass in $ee\mu$ combination, bottom left: Z boson invariant mass in eee combination and bottom right: Z boson invariant mass in $\mu\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

calculated with following formula

$$m_T^W = \sqrt{2.E_T^{Miss}.p_{T,l}(1 - \cos \Delta\phi)} \quad (6.2)$$

where $p_{T,l}$ is the lepton's transverse momentum which are originating from the W decay, and $\Delta\phi$ is the polar angle between E_T^{Miss} and the leptons coming from the decay of W -boson. Therefore, background processes containing real W -boson decay, such as WZ and $t\bar{t}Z$ events, the transverse mass m_T^W distribution peak is around the mass of W at 80 GeV as shown in Fig. 6.8. On the other hand, the process containing no real W decay, such as $Z + Jets$ events where a falling distribution peaking at 0 is observed as shown in Fig. 6.9. Similarly to validate

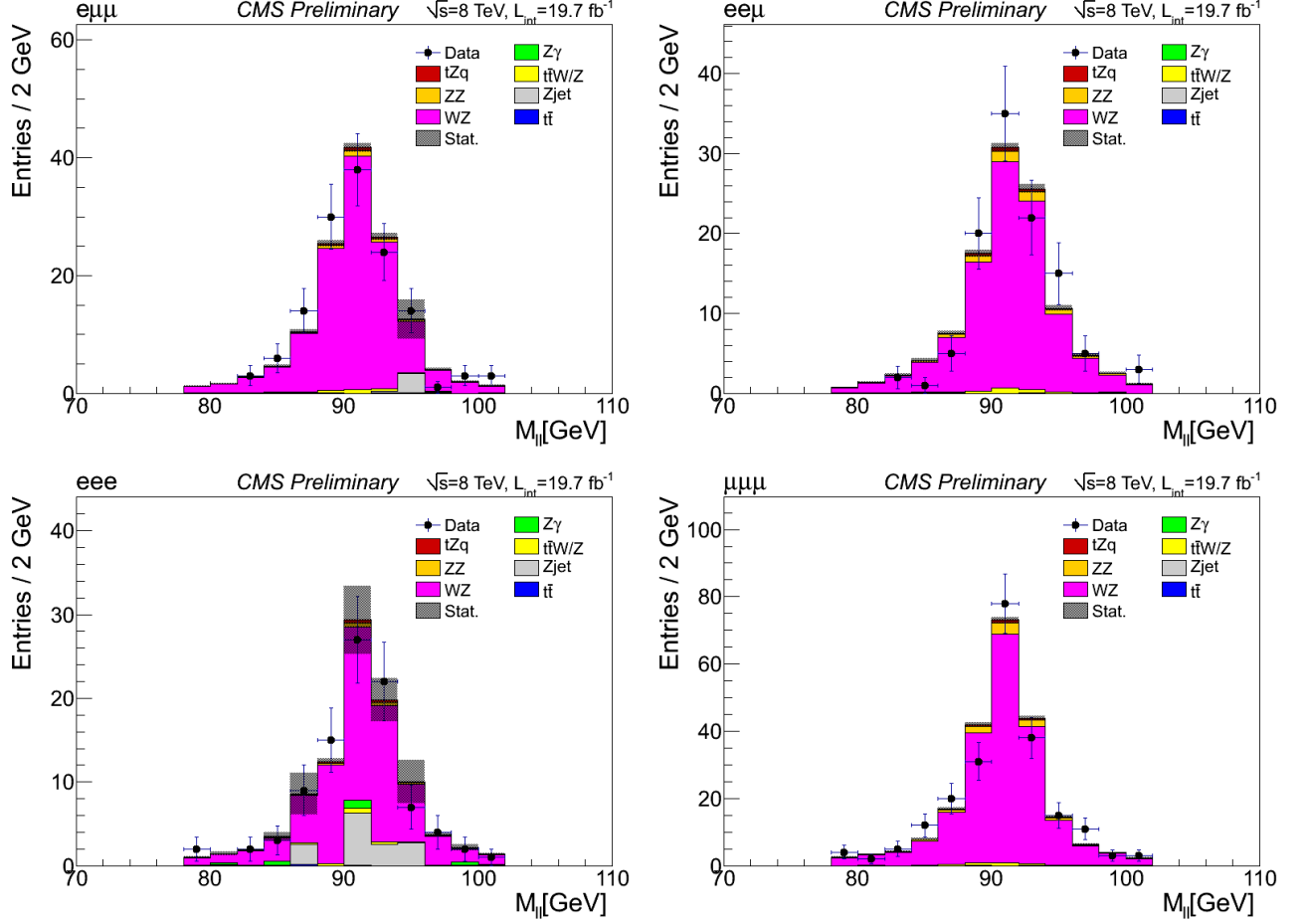


Figure 6.6: The invariant mass of Z -boson after scaling with WZ MC Scale Factors (SFs) shown in Table 6.1, for four, $e\mu\mu$, $ee\mu$, eee , $\mu\mu\mu$, combinations. These plots show pre-selection criteria plus 0 b -jets which corresponds to WZ enriched region. top left: Z boson invariant mass in $e\mu\mu$ combination, top right: Z boson invariant mass in $ee\mu$ combination, bottom left: Z boson invariant mass in eee combination and bottom right: Z boson invariant mass in $\mu\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

the CR for fake rate, MET plots are compared in two regions as shown in Fig. 6.10 and Fig. 6.11. In CR $Z + Jets$ appears as a dominant background with respect to signal region where dominant backgrounds are di-boson and tZ . The W -boson transverse mass distribution is used in profile likelihood fitting. Fitting this distribution allowed a weight to be applied to the data-driven fake lepton background.

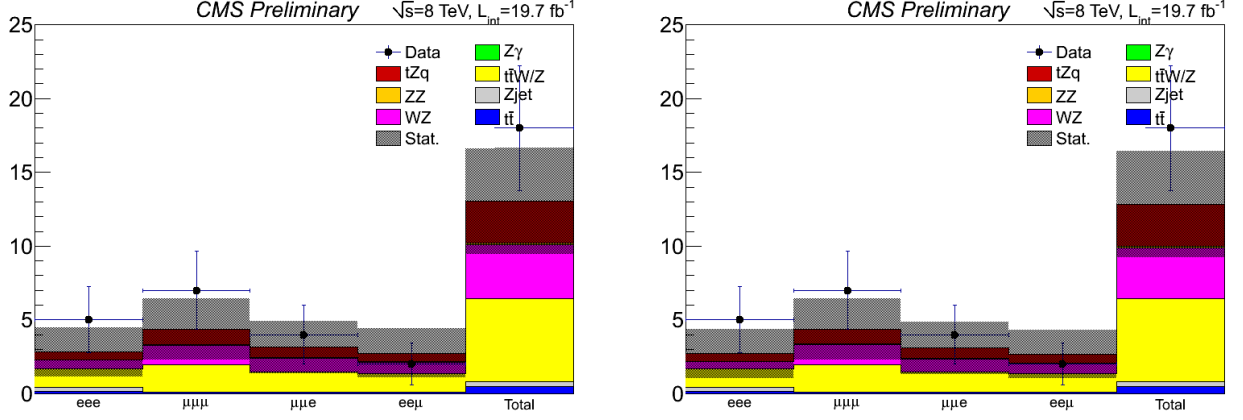


Figure 6.7: Event yields after applying final selection. The left plot shows event yield in each combination before applying WZ Scale Factors (SFs). The right plot shows event yield in each combination after applying WZ SFs.

6.2.4 Other Backgrounds

All other minor backgrounds like $t\bar{t}$, $t\bar{t}W$ and ZZ have been calculated by using MC simulation. Their contribution in the final signal selection is estimated as given in Table 6.7.

6.3 Systematic Uncertainties

The measurement is effected by many sources of systematics which can affect the measurement of cross-section. Therefore, for the assessment of a systematic error due to any particular source, the full analysis procedure be repeated obtaining the new value of the measurement. Thus the difference in the varied and nominal measurement is then quoted as systematic uncertainty. For the comparison of measured and expected data, it's very important to correctly account for uncertainties in the measurement. Several systematic effects have been studied as follows,

- Acceptance and efficiency of the detector is limited, it serves as the source of systematic uncertainty.
- Detector efficiencies are known with certain finite accuracy and any deviation from the true value will cause a shift of the number of selected signal and background events.
- Inefficient measurement technique.
- Uncertainties in the modeling of theory.

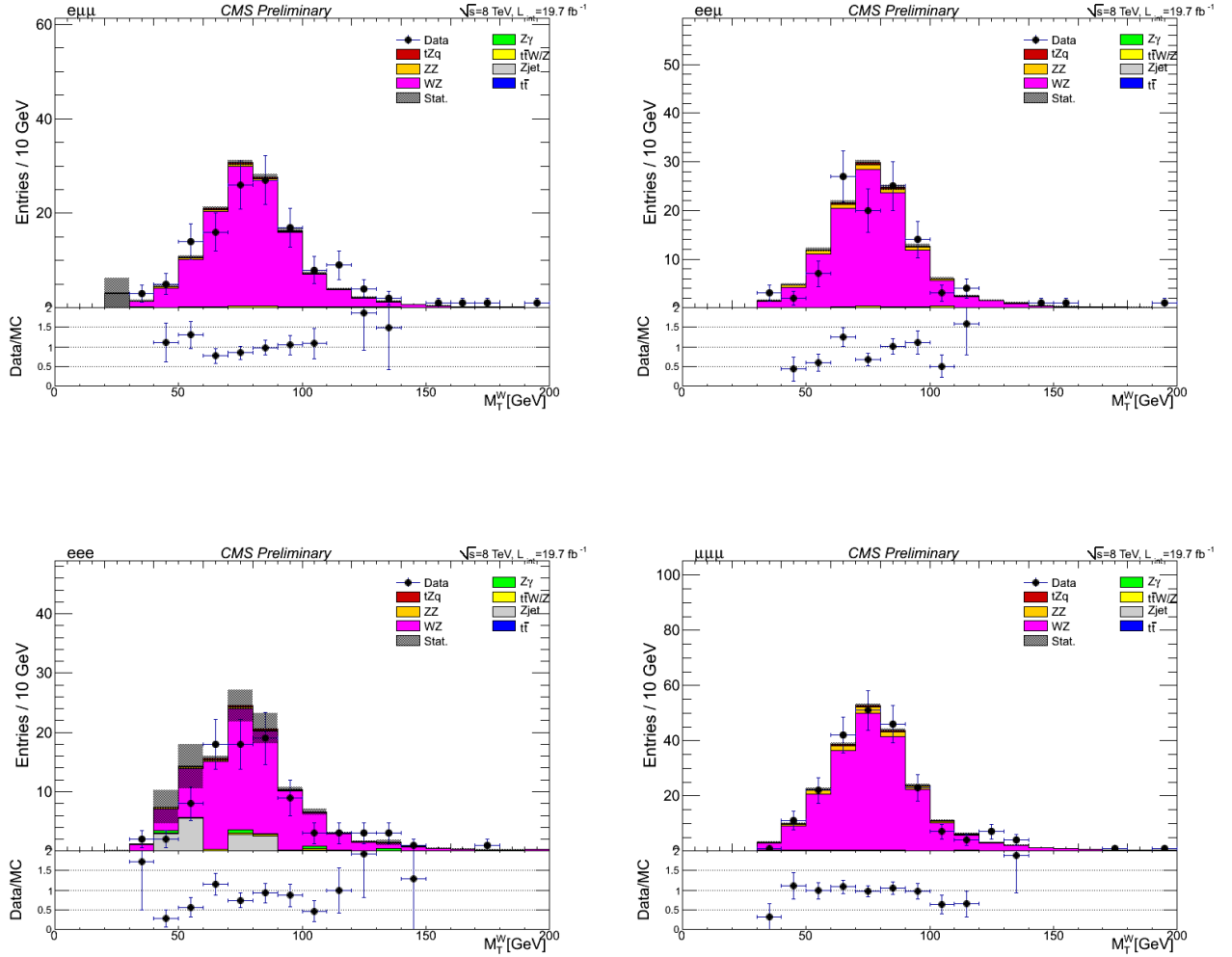


Figure 6.8: The W boson transverse mass (M_T) after applying pre-selection. top-left: W boson transverse mass distribution in $\mu\mu e$ combination, top-right: W boson transverse mass distribution in μee combination, bottom-left: W boson transverse mass distribution in eee combination and bottom-right: W boson transverse mass distribution in μee combination. Dots with error bars correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

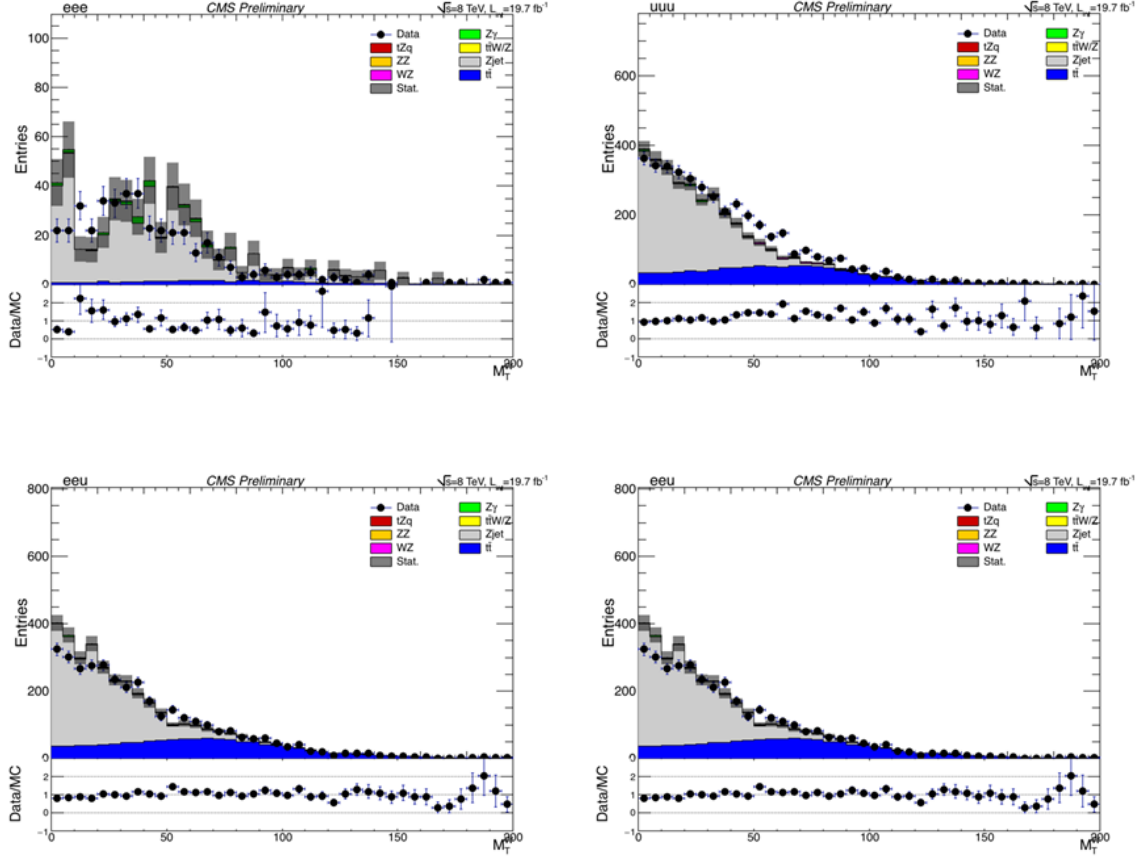


Figure 6.9: W boson transverse mass (M_T^W) plots in Control Region (CR) specified for fake rate measurement. In the CR, dominant background is $Z + Jets$ and peaking towards zero. top left: W boson transverse mass in eee combination, top right: W boson transverse mass in $\mu\mu\mu$ combination, bottom left: W boson transverse mass in $ee\mu$ combination and bottom right: Z boson invariant mass in $e\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

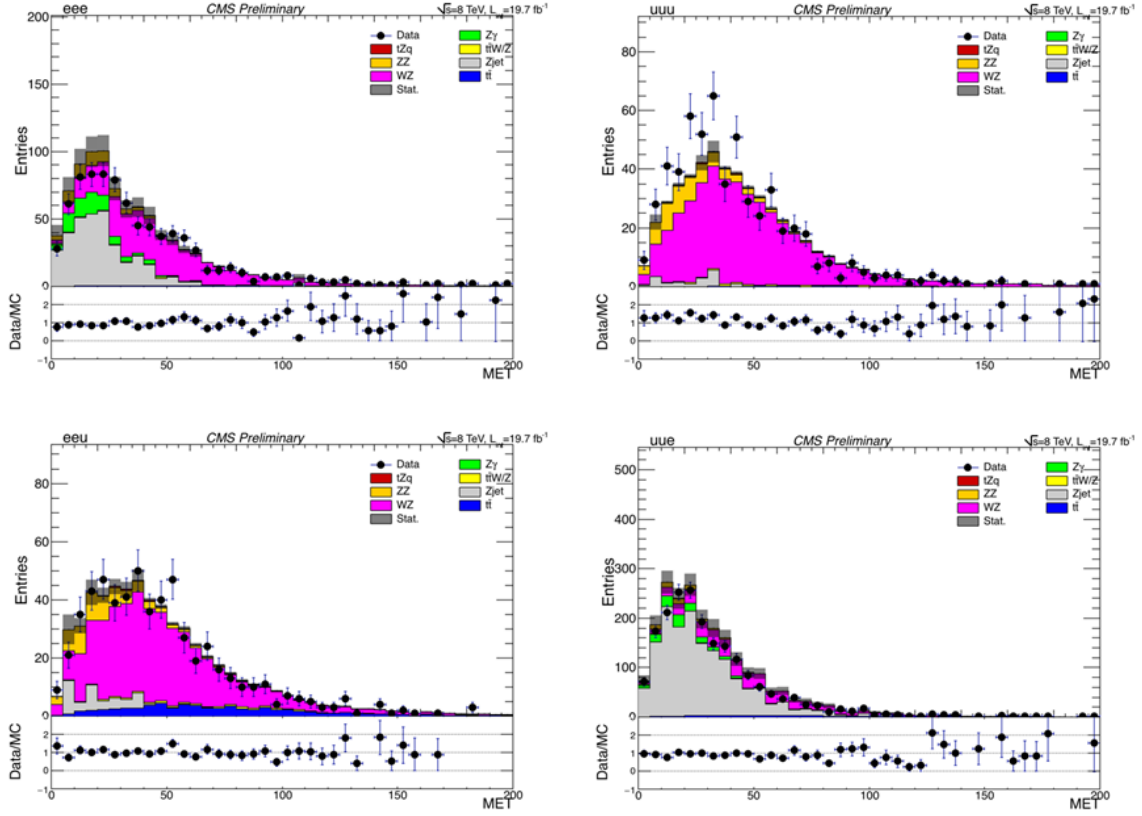


Figure 6.10: Missing Transverse Energy (MET) plots in signal region. In the signal region, dominant backgrounds are di-boson and $t\bar{t}Z$. Top left: Missing Transverse Energy (MET) in eee combination, top right: Missing Transverse Energy (MET) in $\mu\mu\mu$ combination, bottom left: Missing Transverse Energy (MET) in $ee\mu$ combination and bottom right: Missing Transverse Energy (MET) in $e\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

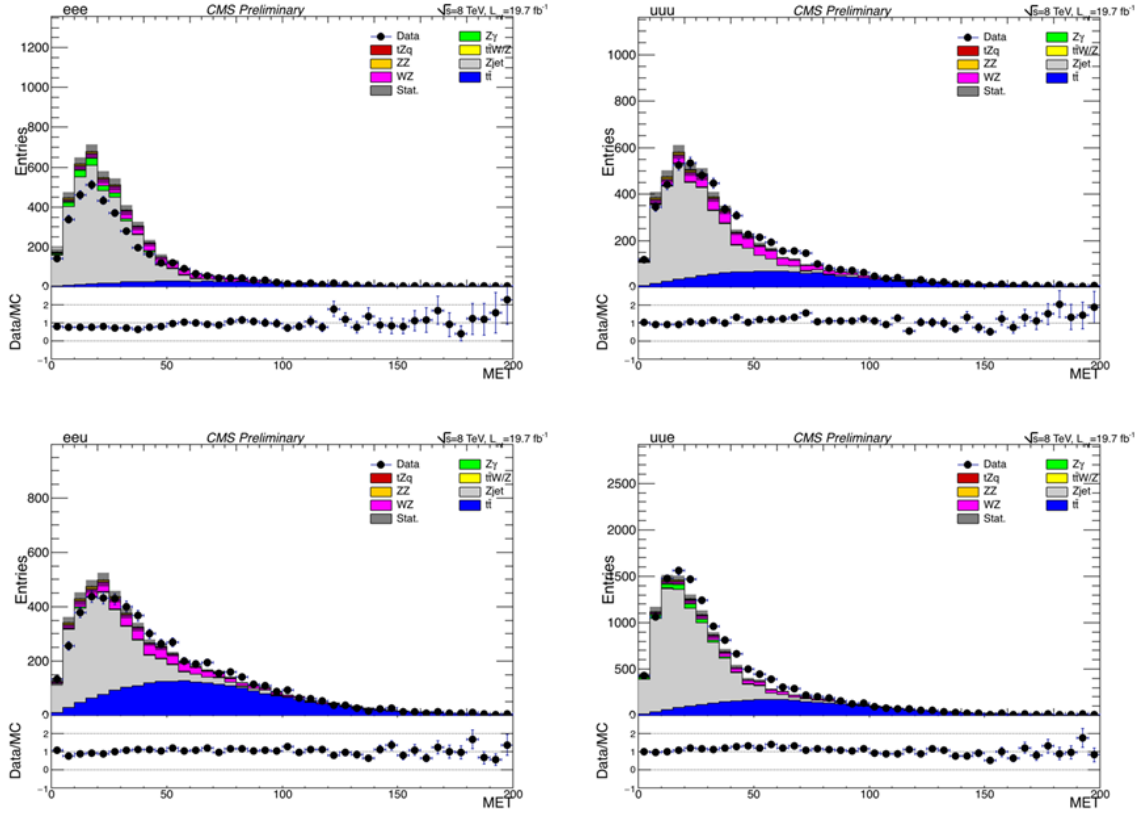


Figure 6.11: Missing Transverse Energy (MET) plots in the CR for fake rate estimation. Plots shows the dominant contribution of $Z + Jets$ background in specified CR. Top left: Missing Transverse Energy (MET) in eee combination, top right: Missing Transverse Energy (MET) in $\mu\mu\mu$ combination, bottom left: Missing Transverse Energy (MET) in $ee\mu$ combination and bottom right: Missing Transverse Energy (MET) in $e\mu\mu$ combination. Dots with error bars which correspond to the observed data, while the background is represented as filled histograms. The legend shows all the MC processes for signal and dominant backgrounds.

$$Systematic = \frac{1}{2} \left(\frac{S_{up} - S_{down}}{S_{nominal}} \right) \quad (6.3)$$

Systematic uncertainties due to experimental setup affects both the signal and background estimation, such as jet energy correction, jet energy resolution, efficiency of b -tagging jets, and leptons reconstruction efficiencies.

The jet energy scale systematic, which comes from the non-linear response of the HCAL in the energy measurement, is the dominant uncertainty. For each jet, a correction is applied to map the measured jet energy to its true energy. These systematics are p_T and η dependent, and these systematics has been derived by using $\gamma/Z + Jets$ MC data samples [95]. The systematic uncertainty due to this correction is used for the jet energy scale systematic estimation, whole analysis has been repeated with the one sigma variation in the systematic scales.

The CMS silicon detector, one of the closest detector from beam pipe is being used for the measurement of the instantaneous luminosity. The luminosity measurement method depends on the fact that the instantaneous luminosity is proportional to the number of reconstructed clusters in the pixel detector in each bunch crossing. The CMS collaboration has assigned 2.6% total uncertainty on the measurement of luminosity [97].

Whenever, several measurements are combined ¹, uncertainties are being considered correlated or un-correlated. Also systematic uncertainties among different samples are allowed to be correlated or anti-correlated.

To calculate the measured and expected significances, we consider the systematical uncertainties due to each of the following sources,

- Jet energy scale
- Jet energy resolution
- b -tagging
- Lepton selection and trigger
- Pile-up re-weighting
- Parton Distribution Functions (PDFs)
- Un-clustered MET

¹In our Analysis, four leptonic channels (eee , $e\mu\mu$, $ee\mu$, $\mu\mu\mu$) are being combined and all systematics are being considered un-correlated

- Factorization Scale Q^2
- ME/PS matching thresholds

The contributions to the total systematic uncertainty from each of these sources are discussed later in these sections.

6.3.1 Jet Energy Scale (JES)

The JES systematic comes from the non-linear response of the HCAL in the energy measurement. For each jet, a correction is applied to map the measured jet energy to its true energy. These systematics are p_T and η dependent, and these systematics have been derived by using $\gamma/Z + Jets$ MC data samples [95]. The systematic uncertainty due to this correction is used for the JES systematic estimation, whole analysis has been repeated with the one sigma variation in the systematic scales.

Jet energy corrections are applied, as suggested by Physics Object Group (POG) [95], to account for differences between measured jet energies in the data and MC simulations. These corrections come with uncertainties thus matter in calculations. To account this, jet transverse momentum has been varied up and down by one standard deviation and compared the change in predicted yields in MC. The resultant uncertainty in different three leptons combinations are listed in Tables [6.3 - 6.6].

Table 6.2: Summer12 systematic samples used in the analysis

Systematic	Process	sample
Q^2 Scale Up	WZ	WZJetsTo3LNu_scaleup_8TeV_TuneZ2Star_madgraph_tauola
	$t\bar{t}Z$	TTZJets_8TeV_scaleup-madgraph-pythia6_TuneZ2star
Q^2 Scale Down	WZ	WZJetsTo3LNu_scaledown_8TeV_TuneZ2Star_madgraph_tauola
	$t\bar{t}Z$	TTZJets_8TeV_scaledown-madgraph_pythia6_TuneZ2star
PS/ME Matching Up	WZ	WZJetsTo3LNu_matchingup_8TeV_TuneZ2Star_madgraph_tauola
	$t\bar{t}Z$	TTZJets_8TeV_matchingup-madgraph-pythia6_TuneZ2star
PS/ME Matching Down	WZ	WZJetsTo3LNu_matchingdown_8TeV_TuneZ2Star_madgraph_tauola
	$t\bar{t}Z$	TTZJets_8TeV_matchingdown-madgraph-pythia6_TuneZ2star

6.3.2 Jet Energy Resolution (JER)

The JER in simulated events is corrected by using $|\eta|$ dependent factors. The 10% uncertainty on the energy resolution of particle flow jets is used to correct the simulated events to match the one measured in the data. The JER is calculated by smearing the jet momentum in simulation as a function of the true and reconstructed η and p_T . The uncertainty measured by varying up and down one standard deviation, i.e, 10%. The change in the momentum is propagated to the E_T^{miss} and JER. The JER uncertainty is measured for the signal MC and for the dominant backgrounds. The uncertainty due to JER for all four combinations of tqZ is found to be less than 1%.

6.3.3 Lepton selection and Trigger

The systematic uncertainty on the lepton identification and isolation is estimated by shifting the central value of SFs by its statistical error up and down. The uncertainty was introduced by shifting the mean scale factor by 0.7% (0.5% for identification and 0.2% for isolation). The systematic uncertainty on the trigger is measured by variations on nominal SFs (given in D.3) up to 3.5%.

6.3.4 Luminosity

The instantaneous luminosity is measured in CMS using the silicon pixel detector, the closest detector to the beam pipe. The method relies in the fact that the instantaneous luminosity is proportional to the number of reconstructed clusters in the pixel detector in each bunch crossing. The total uncertainty on the luminosity determination is calculated to be 2.6% [97], and is treated as a systematic uncertainty on the signal normalization.

6.3.5 b-tagging

The b -tagging algorithm Combined Secondary Vertex (CSV) is used with the medium working point. The b -tagging SFs and uncertainties on these were taken as suggested by physics object group. The scale factors used for correcting the difference in the efficiency in the b -tagging algorithms between data and simulation are varied by one standard deviation [82]. The uncertainties on the b -tag SFs, that are applied to the samples, are taken from [82]. The variations of the shapes for the b -tag and the mis-tag uncertainties are taken into account. The relative

MC signal and background yield differences due to these uncertainties are quoted as b -tagging systematics and are listed in Table [6.3 - 6.6].

6.3.6 E_T^{miss} modeling

The analysis which have neutrino in their final state are affected by an uncertainty due to the modeling of E_T in the simulation. Where the E_T is the vectorial sum of p_T of all particle flow reconstructed objects along with un-clustered energy. The un-clustered energy is the one that is not taken into account by the calorimeter cluster because of isolated object or low p_T . Thus the uncertainty due to un-clustered energy propagates to E_T . During the reconstruction of physics objects, energy correction applied after the reconstruction, but the un-clustered energy does not undergo any such correction, meaning that it effectively dominates the uncertainty in the missing transverse energy. Therefore, to calculate the uncertainty due to un-clustered E_T^{miss} , the p_T of all reconstructed particles is removed the E_T^{miss} and the remaining energy is scaled up and down by 10%. The contribution of un-clustered E_T^{miss} in all combinations is shown in Table [6.3 - 6.6].

6.3.7 Pileup re-weighting

The simulation has been re-weighted according to the data instantaneous luminosity. We take the difference between re-weighted and non-re-weighted samples. CMS detector measures luminosity using silicon pixel detector and this measure luminosity of each bunch crossing times the total inelastic cross-section provides the total number of interactions in the data. So practically two sources of systematic uncertainty are present interaction measurement, which are: uncertainty in the measurement of luminosity and due to total inelastic cross-section [132]. The pileup uncertainty is evaluated by varying the inelastic proton-proton cross section by $\pm 5\%$. The effect on the background yields is taken as a normalization systematic uncertainty.

6.3.8 PDF Uncertainty

The distribution of parton within the proton is described by the PDFs. The PDF represent the probability to find a parton of flavor f with a momentum fraction x at a given scale Q (factorization scale). To estimate PDF uncertainty, the so called re-weighting method is used as described in [65]. The uncertainty due to the choice of the PDF is taken into account by re-weighting the simulation based on the uncertainty in the 22 eigenvalues of the CTEQ

PDF sets. A total of 44 weights are found for each simulated event, following the LHAPDF prescription and the largest and smallest of these are applied as the plus and minus systematic uncertainties.

To assess systematic uncertainty due to PDF, di-lepton mass distribution is re-weighted per event by the set of weights defined by the ratio of PDF values evaluated for the different error PDFs with respect to the best fit PDF. The plots of di-lepton mass distributions CT10nlo PDFs are shown in Fig. 6.12. Systematic uncertainties due to PDF sets are up to 6%.

Normal Distribution

The Gaussian pdf is used for the description of uncertainties on the parameters which can be both positive and negative, and the Gaussian is commonly used for calculation of systematic uncertainties. Gaussian pdf is one of the most suitable distributions for the shape changing systematics. The Gaussian probability density function is given by,

$$\rho(\theta|\tilde{\theta}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\theta - \tilde{\theta})^2}{2\sigma^2}\right), \quad (6.4)$$

where σ is the width of each bin.

Log-Normal Distribution

The log-normal (lnN) is used for the systematics which is affecting the normalization. The log-normal distribution is an alternate to avoid all the difficulties of the truncated Gaussian distributions.

$$\rho(\theta|\tilde{\theta}) = \frac{1}{\sqrt{2\pi}\theta \ln \kappa} \exp\left(-\frac{(\ln \theta - \ln \tilde{\theta})^2}{2 \ln^2 \kappa}\right), \quad (6.5)$$

where the width of the log-normal pdf is characterized by κ , e.g $\kappa = 1.10$ implies that the observable can be larger or smaller by a factor 1.10.

The Gamma Distribution

For the description of statistical uncertainties in the number of events of MC simulations or number of observed events in data, the gamma distribution is being used. In both cases, the event rate n in the signal search region can be related to the number of events N in MC or data through a simple relationship $n = \alpha.N$ [98]. The uncertainties on the predicted rate n associated with the observation of N events is described by the gamma distribution is shown by the Eq. 6.6:

$$\rho(n) = \frac{1}{\alpha} \frac{(n/\alpha)^N}{N} \exp(-n/\alpha). \quad (6.6)$$

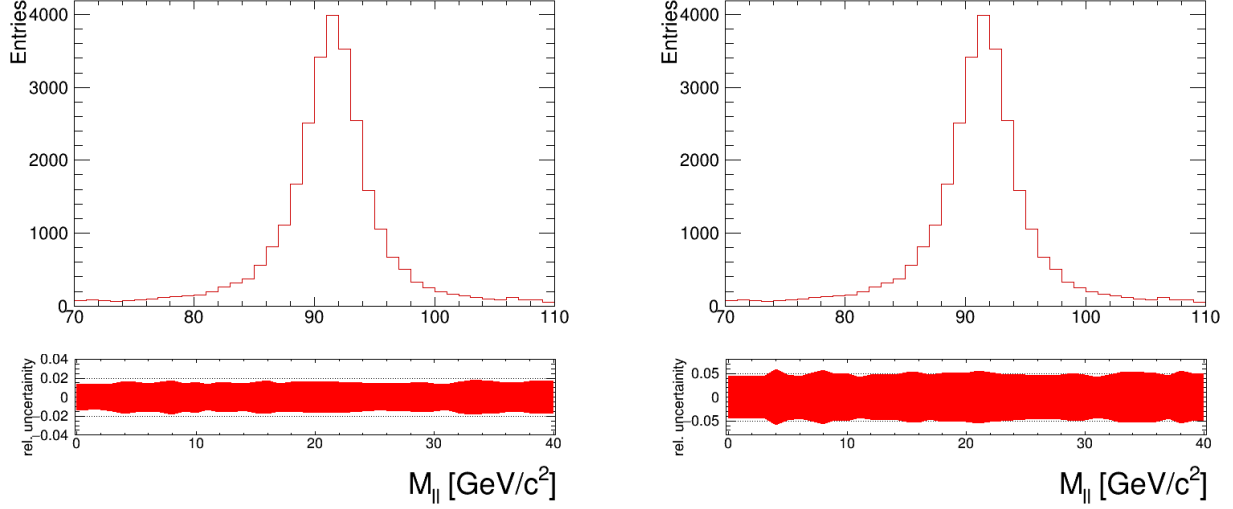


Figure 6.12: Di-lepton invariant mass is shown with PDF re-weighting per event. Relative uncertainty is shown in the bottom plots. Left: distribution of di-lepton invariant mass with MSTW PDF re-weighting. Right: distribution of di-lepton invariant mass with CTEQ PDF re-weighting.

6.3.9 Factorization Scale (Q^2)

The unphysical dependence on the factorization and normalization scales will be a source of systematic uncertainties. Dedicated simulated samples (listed in Table 6.2) where the Q^2 is doubled and halved are produced for the WZ and ttZ backgrounds to investigate the impact on the analysis. Both factorization and renormalization scale uncertainties for the signal tqZ sample are calculated by the *aMC@NLO* generator and included as additional weights in the generated events. The nominal value for the Q^2 scale used in the production of the simulation is defined as $m_t^2 + \sum p_T^2(jet)$ and the systematics samples have the value varied to $4.Q^2$ and $1/4 .Q^2$ for the scaled-up and scaled-down samples, respectively.

6.3.10 ME/PS matching thresholds

PYTHIA uses thresholds for PS/ME matching to generate the parton shower, different choices of which will influence the result of the analysis. Simulated samples with larger and smaller scales are generated for the WZ and ttZ backgrounds and listed in the Table 6.2.

Table 6.3: Summary of systematic uncertainties on the signal selection and expectation in $\mu\mu e$ channel.

Source	Method	tZq (%)	WZ (%)	ttZ (%)
Jet Energy Scale	Momentum Scale	0.79	2.38	1.92
	Up/Down			
Jet Energy Resolution	Momentum Smearing	0.09	0.78	2.56
b-tagging	Discriminant Reweight	2.70	7.21	3.43
Lepton Efficiency	Tag & Probe	1.99	2.00	2.00
Pile-up re-weighting	$\pm 1 \sigma$ of min. bias σ	2.61	2.01	6.42
Trigger	$\pm 1 \sigma$	3.99	3.99	3.99
PDF Systematics	LHAPDF	3.00	-	-
WZ SF Z-mass Window	Z Mass window	-	0.17	-
	variation of 2 GeV			
Non-WZ Contamination	30 % variation of non-WZ contents in WZ control region	-	1.67	-
WZ SF Propagation	Calculated SFs with WZ Nominal , WZ Scale and Matching up/down samples	-	23.5	-
Un-clustered MET	10 % variation in unc. MET	2.95	0.94	8.84
ttZ Normalization	30 %variation of ttZ cross-section	-	-	12.17
ttZ Scale	Q^2 variation	-	-	9.83
WZ scale and matching	Q^2 variation	-	2.36	9.83

Table 6.4: Summary of systematic uncertainties on the signal selection and expectation in μee channel.

Source	Method	tqZ (%)	WZ (%)	ttZ (%)
Jet Energy Scale	Momentum Scale Up/Down	0.77	2.25	0
Jet Energy Resolution	Momentum Smearing	0.05	0.48	0.37
b -tagging	Discriminant Reweight	2.72	6.75	3.75
Lepton Efficiency	Tag & Probe	2.21	2.17	2.21
Pile-up re-weighting	$\pm 1 \sigma$ of min. bias σ	3.05	4.32	4.97
Trigger	$\pm 1 \sigma$	4.002	4.002	4.002
PDF Systematics	LHAPDF	6.00	-	-
WZ SF Z -mass Window	Z Mass window variation of 2 GeV	-	0.36	-
Non-WZ Contamination	30 % variation of non-WZ contents in WZ control region	-	1.63	-
WZ SF Propagation	Calculated SFs with WZ Nominal , WZ Scale and Matching up/down samples	-	16.27	-
Un-clustered MET	10 % variation in unc. MET	3.14	1.02	4.3
ttZ Normalization	30 %variation of ttZ cross section	-	-	12.61
ttZ Scale	Q^2 variation	-	-	1.74
WZ scale and matching	Q^2 variation	-	2.01	-

Table 6.5: Summary of systematic uncertainties on the signal selection and expectation in eee channel.

Source	Method	tqZ (%)	WZ (%)	ttZ (%)
Jet Energy Scale	Momentum Scale Up/Down	0.71	2.08	0.66
Jet Energy Resolution	Momentum Smearing	0.05	0.47	1.97
b -tagging	Discriminant Reweight	2.68	6.66	3.02
Lepton Efficiency	Tag & Probe	2.88	2.90	2.82
Pile-up re-weighting	$\pm 1 \sigma$ of min. bias σ	3.31	2.79	1.25
Trigger	$\pm 1 \sigma$	4.002	4.002	4.002
PDF Systematics	LHAPDF	6.00	-	-
WZ SF Z -mass Window	Z Mass window variation of 2 GeV	-	0.15	-
Non- WZ Contamination	30 % variation of non- WZ contents in WZ control region	-	5.63	-
WZ SF Propagation	Calculated SFs with WZ Nominal , WZ Scale and Matching up/down samples	-	41.27	-
Un-clustered MET	10 % variation in unc. MET	3.32	0.918	5.29
ttZ Normalization	30 %variation of ttZ cross-section	-	-	11.42
ttZ Scale	Q^2 variation	-	-	7.73
WZ scale and matching	Q^2 variation	-	4.29	-

Table 6.6: Summary of systematic uncertainties on the signal selection and expectation in $\mu\mu\mu$ channel.

Source	Method	tqZ (%)	WZ (%)	ttZ (%)
Jet Energy Scale	Momentum Scale	0.82	2.0	0.79
	Up/Down			
Jet Energy Resolution	Momentum Smearing	0.08	0.64	1.98
b -tagging	Discriminant Re-weight	2.40	6.52	3.44
Lepton Efficiency	Tag & Probe	2.95	2.97	2.94
Pile-up re-weighting	$\pm 1 \sigma$ of min. bias σ	1.51	0.48	3.56
Trigger	$\pm 1 \sigma$	3.99	3.99	3.99
PDF Systematics	LHAPDF	6.00	-	-
WZ SF Z-mass Window	Z Mass window variation of 2 GeV	-	0.14	-
Non-WZ Contamination	30 % variation of non-WZ contents in WZ control region	-	1.81	-
WZ SF Propagation	Calculated SFs with WZ Nominal , WZ Scale and Matching up/down samples	-	12.9	-
Un-clustered MET	10 % variation in unc. MET	2.82	0.93	9.44
ttZ Normalization	30 %variation of ttZ cross section	-	-	12.0
ttZ Scale	Q^2 variation	-	-	0.71
WZ scale and matching	Q^2 variation	-	2.01	-

6.4 Uncertainty Summary

In section 6.3, all possible sources of systematic uncertainties appearing in the measurement of tqZ have been discussed. The measured uncertainties for all four combinations on tqZ cross-section have been shown in Tables 6.3 - 6.6. The systematic uncertainties measured for signal MC (tqZ) and for two major backgrounds $t\bar{t}Z$ and WZ .

In $\mu\mu\mu$ channel of tqZ , the major systematic uncertainty in signal MC (tqZ) is due to choice of PDF and followed by trigger. The leading uncertainty in $t\bar{t}Z$ appeared due to the normalization and sub-leading is from un-clustered MET. The prominent uncertainty in WZ is from propagation of SFs and followed by b -tagging. The systematic uncertainties are shown in Table 6.6.

In $\mu\mu e$ channel of tqZ , the major systematic uncertainty in signal MC (tqZ) is due to trigger and followed by choice of PDF. The leading uncertainty in $t\bar{t}Z$ appeared due to the normalization and sub-leading is from MC scaling. The prominent uncertainty in WZ is from propagation of SFs and followed by b -tagging. The systematic uncertainties are shown in Table 6.3.

In μee channel of tqZ , the major systematic uncertainty in signal MC (tqZ) is due to choice of PDF and followed by trigger. The leading uncertainty in $t\bar{t}Z$ appeared due to the normalization and sub-leading is from pileup re-weighting. The prominent uncertainty in WZ is from propagation of SFs and followed by b -tagging. The systematic uncertainties are shown in Table 6.4.

In eee channel of tqZ , the major systematic uncertainty in signal MC (tqZ) is due to choice of PDF and followed by trigger. The leading uncertainty in $t\bar{t}Z$ appeared due to the normalization and followed by MC scaling of $t\bar{t}Z$. The prominent uncertainty in WZ is from propagation of SFs and followed by b -tagging. The systematic uncertainties are shown in Table 6.5.

6.5 The tqZ Cross-Section

The measured inclusive cross-section of tqZ $\sigma_{tqZ} = 0.018 \text{ (stat.)}_{-0.009}^{+0.011} \text{ (Syst.)}_{-0.004}^{+0.004} \text{ pb}$, which is a rare SM process. The cross-sections for each channel, $\mu\mu\mu$, $\mu\mu e$, $ee\mu$, eee and the combination of these channels is measured using the ROOSTAT based Higgs combination package [98, 99], which are given in Table 6.8. The cross-section measurement is in agreement with the SM

prediction. The event yield after applying final signal selection criteria is shown in Table 6.7. The complete cut-flow of the analysis, for both the data and MC simulations is shown in Fig. 6.13. There are total 20 events observed in the data, in which $\mu\mu\mu$ is a dominating channel having 7 events and 5 events for each $\mu\mu e$, eee for each channel, while $ee\mu$ has 3 data events. The total expected events from MC simulation for both the signal (tqZ) and background processes are 15.42, in which the expected signal events are 3.4 and 5.24 from $t\bar{t}Z$ and 3.59 from WZ contributions. The other background processes have small contribution from ZZ and $t\bar{t}W$ which are 0.13 and 0.49, respectively. The dominant background process $t\bar{t}Z$ is estimated from the MC simulations while the second major background process WZ is estimated using data-driven technique. The SFs for WZ background are derived in a region having no b -jets along with pre-selection criteria.

There are many sources of systematic uncertainties on the measurement of cross-sections. These sources are, JES, JER, pileup, b -tagging, lepton identification and due to choice of PDF and MC scaling of WZ and $t\bar{t}Z$ processes. The mentioned systematics have been measured by using tqZ signal MC and two major backgrounds WZ and $t\bar{t}Z$ as shown in Tables [6.3 - 6.6]. The PDF systematic is dominant in the signal MC following by the b -tagging. The WZ SFs propagation are dominant source of uncertainty for WZ MC simulation sample. The systematics uncertainties due to the WZ modeling are accounted by considering renormalization/factorization scale variations and matching the threshold variations. The $t\bar{t}Z$ MC simulation have major systematics due to the normalization and MC scaling.

The corresponding signal significance is estimated by using the Higgs combination package [99]. The observed and expected significance for inclusive cross-section are 1.80 and 0.81, respectively. The one and two standard deviations are also given in Table 6.9. All the expected and measured significances for all the exclusive and inclusive channels are given in Table 6.9 and shown in Fig. 6.15.

6.6 Exclusion Limits

The statistical analysis is used for the interpretation of the data for two possibilities, the existence of signal is excluded when there is no signal, or to confirm the existence of signal after rejecting the background hypothesis strongly. For statistical approach, the two test hypothesis are used: null-hypothesis and alternate-hypothesis.

In the null-hypothesis, there is an assumption that the signal is absent from the process,

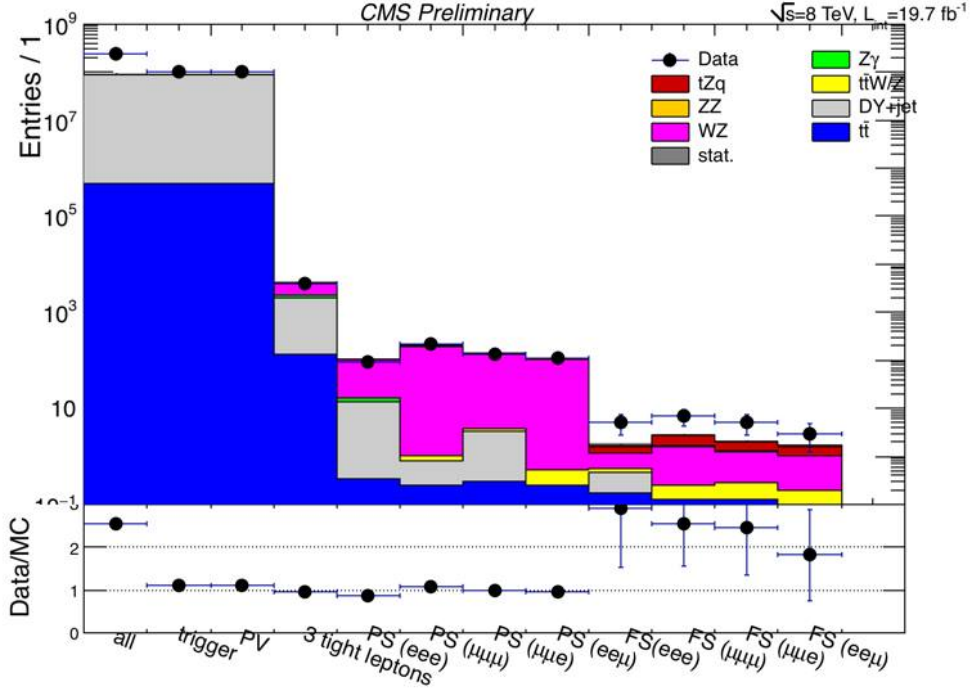


Figure 6.13: The event cut-flow comparison between the data and Monte Carlo (MC) simulation presented after applying the pre-selection (PS) and final signal selection (FS) criteria. The plot shows the contribution of backgrounds after each step. Before three leptons requirement the dominant Drell-Yan (DY) and $t\bar{t}$ (blue) are dominant backgrounds, in PS region WZ (pink) is dominant and also have some contribution from $Z + Jets$ (gray). After FS $t\bar{t}Z/W$ (Yellow) is leading while WZ is sub-leading background. The ratio between the data and MC is shown in the bottom panel.

Table 6.7: The tqZ events cut-flow table after requiring final signal selection. The various columns represents the number of events in the data and MC simulation for each combination.

	Total Data	Total MC	tqZ	ttZ	WZ	ttW	ZZ	fake leptons
eee	5.00 ± 2.24	3.42 ± 0.28	0.63 ± 0.00	1.18 ± 0.15	0.64 ± 0.08	0.10 ± 0.05	0.02 ± 0.00	0.86 ± 0.22
$\mu\mu\mu$	7.00 ± 2.65	5.14 ± 0.23	1.22 ± 0.01	1.71 ± 0.18	1.38 ± 0.12	0.12 ± 0.05	0.06 ± 0.01	0.64 ± 0.07
$\mu\mu e$	5.00 ± 2.24	3.85 ± 0.20	0.85 ± 0.01	1.19 ± 0.15	0.99 ± 0.10	0.16 ± 0.06	0.03 ± 0.01	0.64 ± 0.07
$ee\mu$	3.00 ± 1.73	3.24 ± 0.20	0.70 ± 0.00	1.15 ± 0.15	0.81 ± 0.15	0.12 ± 0.10	0.03 ± 0.05	0.43 ± 0.06
Total	20.00 ± 4.47	15.42 ± 0.47	3.40 ± 0.01	5.23 ± 0.32	3.82 ± 0.21	0.50 ± 0.11	0.14 ± 0.01	2.57 ± 0.25

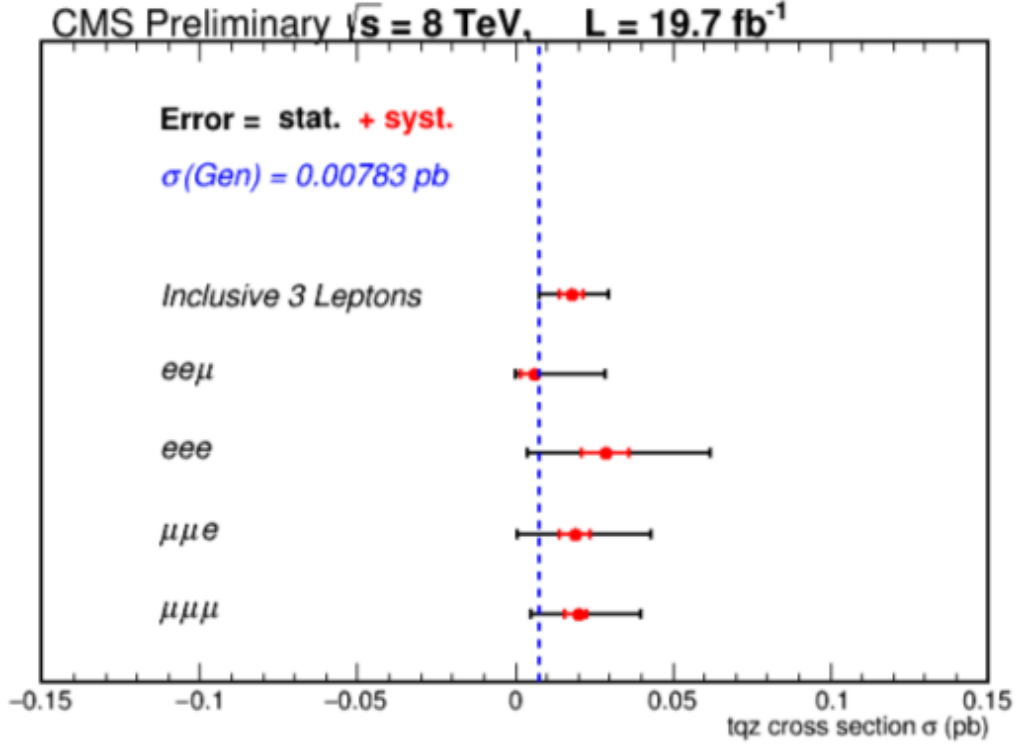


Figure 6.14: The tqZ measured inclusive and exclusive cross-sections (σ) in three lepton final state by using 19.7 fb^{-1} CMS 2012 data at center-of-mass energy 8 TeV. The Standard Model (SM) expected cross-section is shown with blue dotted line while the dots with error bars represent the measured values of σ for inclusive and exclusive combinations.

Table 6.8: The tqZ measured cross-section (σ) in three leptons final state for four exclusive and inclusive channels using Higgs combination tool. The statistical and systematics uncertainties for each channel are also given.

Channel	cross-section (pb)
$\mu\mu\mu$	$0.020 \text{ (stat.)}^{+0.019}_{-0.015} \text{ (Syst.)}^{+0.004}_{-0.003}$
eee	$0.029 \text{ (stat.)}^{+0.032}_{-0.024} \text{ (Syst.)}^{+0.008}_{-0.007}$
$e\mu\mu$	$0.019 \text{ (stat.)}^{+0.024}_{-0.018} \text{ (Syst.)}^{+0.005}_{-0.005}$
$ee\mu$	$0.006 \text{ (stat.)}^{+0.024}_{-0.005} \text{ (Syst.)}^{+0.004}_{-0.000}$
inclusive	$0.018 \text{ (stat.)}^{+0.011}_{-0.009} \text{ (Syst.)}^{+0.004}_{-0.004}$

Table 6.9: The expected and measured significance of inclusive and exclusive combinations of tqZ cross-section (σ) are given within the standard deviations with respect to the background hypothesis.

Channel	Expected Significance			Observed Significance
	Mean	1σ	2σ	
$\mu\mu\mu$	0.66 ± 0.03	0 - 1.45	0 - 2.48	1.35
eee	0.46 ± 0.03	0 - 1.15	0 - 2.18	1.20
$e\mu\mu$	0.61 ± 0.03	0 - 1.35	0 - 2.28	1.04
$ee\mu$	0.53 ± 0.02	0 - 1.16	0 - 2.20	0.32
inclusive	0.81 ± 0.04	0 - 1.59	0 - 2.68	1.80

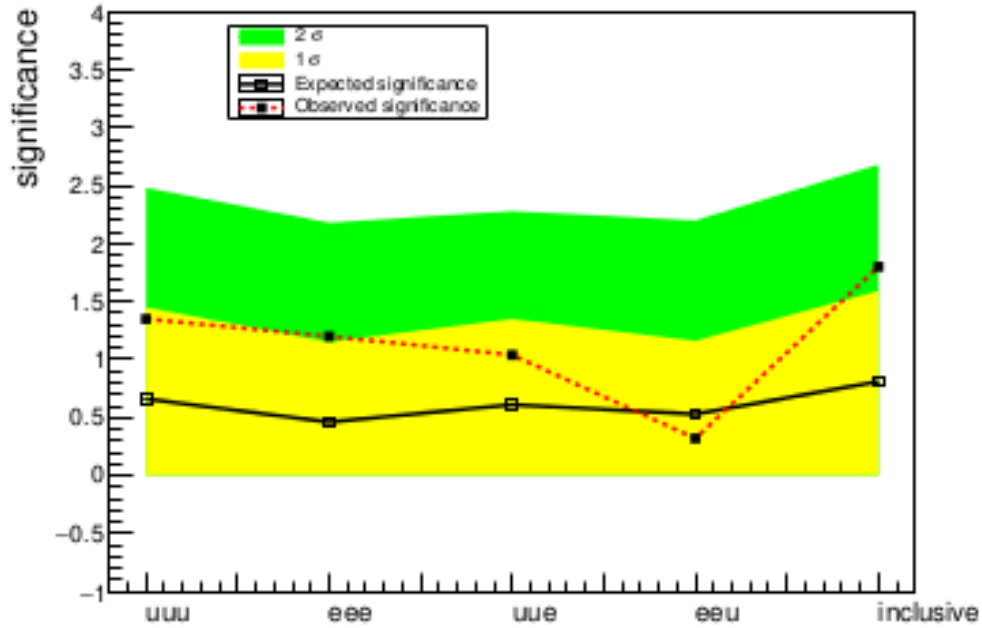


Figure 6.15: Expected and observed significance with one and two standard deviation bands using Higgs combine tool. The red dotted line is for measured significance while the solid black line shows the expected. The yellow band shows the one standard deviation whereas the green is for second standard deviation.

whereas the alternate-hypothesis may confirm the existence of the signal. The statistical analysis requires defining some observables, which comprise the search results. A test-function uses these observables and model parameters of the known background.

In this analysis, the CLs method based on modified-frequentist approach [100, 101] is used to set the upper limits on cross-sections by using signal (CL_S) and signal plus background (CL_{s+b}) hypothesis. For an ambiguous situation, when there is a lack of available information to distinguish between the signal and signal plus background hypothesis, the normalization of the confidence level observed for CL_{s+b} to the background hypothesis only (CL_b) is used in the CLs method. In this approach, it is possible to obtain sensible exclusion limits even in the case of very low signal with respect to background. The modified frequentist can be written as

$$CL_s \equiv \frac{CL_{s+b}}{CL_b} \quad (6.7)$$

Alternatively, it can also be written as, this equation is for the test statistics q_μ about background only and background plus signal hypothesis.

$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}, \quad (6.8)$$

this equation is for the test statistics q_μ about background only and background plus signal hypothesis, where p_μ is the p-value for an observed value of q_μ which is background plus signal hypothesis and the only background hypothesis is represented by p_b .

The exclusion limits for the tqZ inclusive and exclusive cross-sections have been calculated as a function of signal strength. The expected and observed upper limits on the signal strength with 95% Confidence Level (CL) shown in Fig. 6.16 and given in Table 6.10.

Table 6.10: The observed and expected upper limits with 95% Confidence Level (CL) with the one and two standard deviations with respect to the background by using CL_S method.

Channel	Expected Significance			Observed Significance
-	Mean	1 σ	2 σ	-
$\mu\mu\mu$	4.48	1.45 - 2.48	2.12 - 10.36	7.21
eee	7.72	5.09 - 12.18	3.60 - 18.61	11.86
$e\mu\mu$	5.68	3.87 - 9.15	2.73 - 13.82	8.52
$ee\mu$	6.53	4.28 - 10.43	2.99 - 16.10	7.40
inclusive	2.27	1.91 - 4.08	1.40 - 5.83	5.01

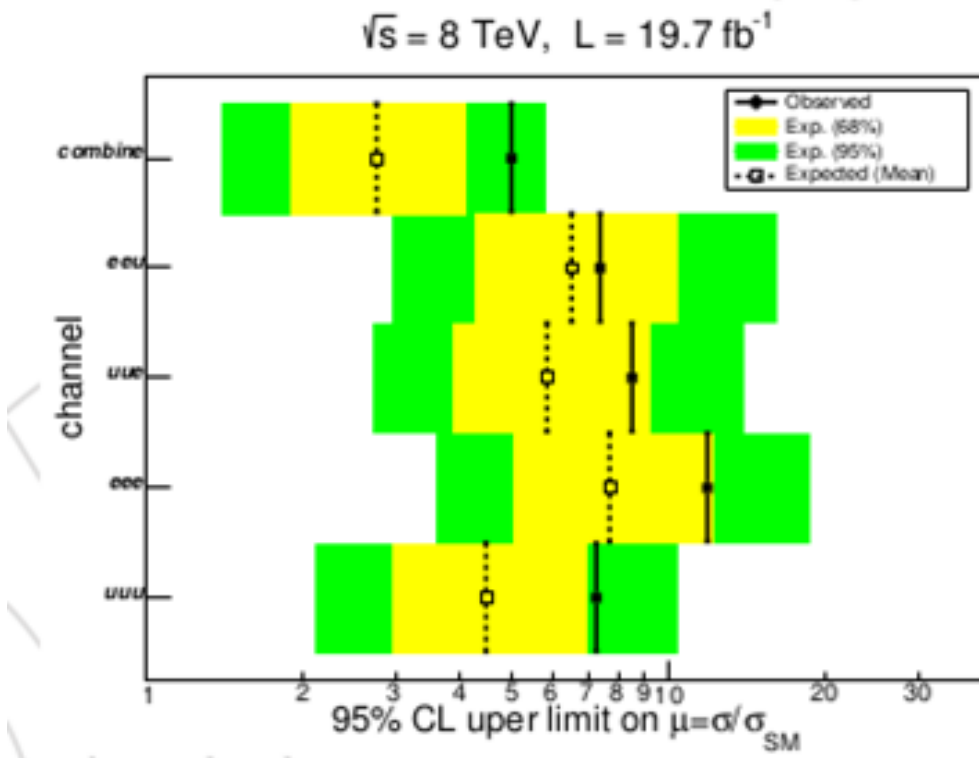


Figure 6.16: The upper limit with 95% confidence level on signal strength $\mu = \sigma/\sigma_{SM}$ using the CMS 2012 data for the tqZ inclusive and exclusive cross-section. The observed (solid line) and expected (dotted line) upper limits, along with one (yellow) and two (green) standard deviations on the expected values are shown.

6.7 Summary

In this chapter, the measurement of the tqZ cross-section for the inclusive and exclusive cases are reported. All the cross-sections are measured by using the Higgs combine tool. The major backgrounds in the measurement are $t\bar{t}Z$ and WZ processes. The $t\bar{t}Z$ is a reducible background and is estimated from the MC simulation. The WZ process is an irreducible background, which is measured by using data-driven technique. The SFs for WZ have been estimated in a kinematical region having no b -jets along with pre-selection criteria. The region enriched with WZ background is used to calculate the SFs, which are estimated from the ratio of the data to MC simulation. The SFs are then implemented to reduce the contribution from WZ in the signal region. The other backgrounds such as ZZ , $t\bar{t}W$, having small contribution in the signal are estimated by using the MC simulations. The contribution of $t\bar{t}$ and Z +Jets are estimated by fake leptons procedure. The fake leptons SFs are derived from the shape analysis and applied to the final signal selection.

All the possible systematic uncertainties in measuring the cross-section are incorporated in the analysis. The uncertainties have been estimated for the signal MC (tqZ) and for the two major background processes, $t\bar{t}Z$ and WZ . In the signal MC, the leading systematic is due to the PDF choice which is followed by trigger selection. In the $t\bar{t}Z$ MC simulation, the dominant systematic is due to the normalization and then from the un-clustered MET. In the WZ MC simulations the prominent uncertainty is due to the WZ SFs propagation and then the second dominant systematic is from b -tagging. The systematic due to fake leptons SFs is taken as 100% and is straight forwardly incorporated.

Finally the significance of the tqZ inclusive cross-section as well as the exclusive cases for all combinations is presented. The observed significance of inclusive channel is reported to be 1.80 while the expected significance is 0.81 with the one and two standard deviations ranges, 0.00 - 1.59 and 0 - 2.68, respectively. The expected and observed upper limits with the 95% Confidence on signal strength are reported.

Chapter 7

RPCs Performance at the CMS

7.1 Introduction

R. Santonico and R. Cardarelli have developed the very first Resistive Plate Chamber (RPC) in 1981 [109]. RPC is a parallel plate gaseous detector working in avalanche mode and consists of electrodes of high volume resistivity, for example electrodes being used nowadays are: Glass electrodes or Bakelite (phenol-formaldehyde polymer). RPC combines a reasonable spatial resolution with a time resolution of about 1 ns. The time resolution of the RPCs allows assigning a detected muon with a specific bunch crossing. Many experiments adopted RPCs because of their robustness, simple to construct and operate. The key attributes of these detectors are large signal output, excellent time as well as position resolutions and low cost per unit area of coverage. From the very beginning of the RPC technology, streamer was the operational mode which was providing large signal, and due to which read out electronics was simple however streamer mode is not capable for high collision rates. The RPCs operate in avalanche mode instead of streamer mode, due to the large collision rate at the LHC. The avalanche mode is based on the application of intense electric field inside the gap for the generation of limited discharge which is localized near the crossing point of the ionizing particle where in the avalanche process the electric field is reduced with the application of robust signal amplification at the front-end electronics. This increases the rate capability of RPCs with more than one order of magnitude.

7.1.1 Working Principle of RPCs

The RPCs are gaseous detectors and their basic working principle is to detect charged particles via ionization phenomena. When a charged particle passes through the detector it leaves

signature in the gas in form of electron ion pair. Electrons produced during ionization drift towards anode and secondary ionization is produced due to the presence of a strong electric field as shown in the Fig. 7.1. The propagation of the growing number of charges induces a signal on a read out electrode. The high voltage that is applied to the parallel plate electrodes leads to a uniform electric field in the gas gap. After applying a proper threshold, signal generated

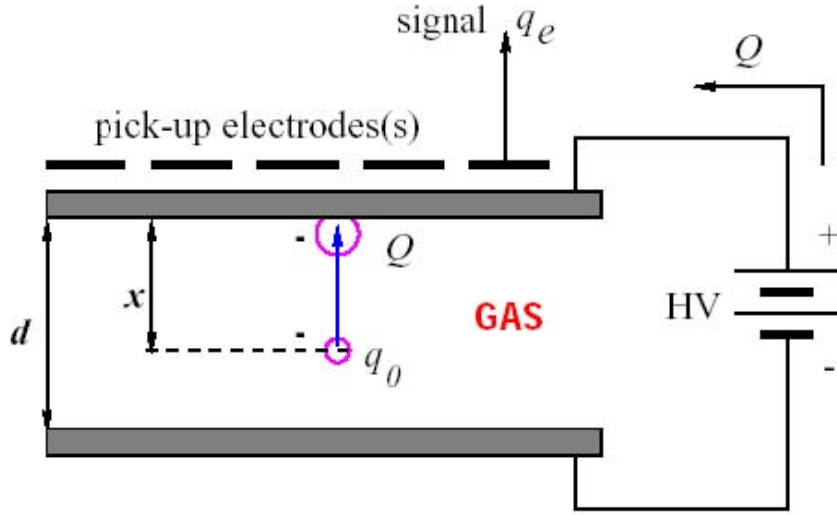


Figure 7.1: Charged particle passes through the RPC gas gap, generates a signal at the readout strips [110].

due to electrons at anode can be detected. The application of proper threshold determines the time delay of the pulse, efficiency and the time resolution of the detector.

7.1.2 CMS RPCs

There are many different configurations of RPC detector. The CMS experiment host the double-gap RPCs as shown in the Fig. 7.2 with a read out plane between the two gas gaps. The read out plane is a roll consisting of a number of detecting strips, which read the incoming signal and determine the spatial coordinate of the incoming signal. The advantage of more than one gas gap is an increase of the electron signal on the read out strips. At the LHC, the RPCs has been chosen as a dedicated muon trigger detector at CMS experiment [112]. For RPC detectors, with the proper choice of the resistivity and thickness of parallel plates, high rate capability can be achieved and for CMS RPCs its Bakelite selected as a resistive material to address the high rate capability. The fundamental requirements of RPCs construction and operation are given in the Table 7.1. The RPC detector is made of two parallel plates of

Table 7.1: RPCs basic for construction and operation

Bakelite thickness	2 mm
Bakelite bulk resistivity	$1 - 2 \times 10^{10} \text{ cm}$
Gap width	2 mm
Gas mixtures	96.2% $C_2H_2F_4$, 0.3% SF_6 , 3.5% $i - C_4H_{10}$
Operating High Voltage	9 - 10 kV
# Gaps	2

Bakelite (phenolic polymer), the bulk resistivity of the Bakelite is $1 - 2 \times 10^{10} \Omega \text{ cm}$ and the distance between two parallel plates is 2 mm as shown in the Table 7.1. The plates are separated by means of spacers that are placed on a $10\text{cm} \times 10\text{cm}$ grid. Inside the gas gaps, a gas mixture is being circulated, three component gas mixture contains $C_2H_2F_4$ 95.2%, $i - C_4H_{10}$ (isobutane) 4.5% and weighted contribution of SF_6 is 0.3 %, with a 35% - 40% humidity at temperature of 21°C [112]. In the CMS experiment, the RPC double gas gap structure is being called a chamber. The whole chamber is made gas tight and the outer surface of the Bakelite plates is coated with a thin conductive graphite layer to form the high voltage (HV) and ground electrodes. The surface resistivity of the graphite coat is of the order of $10^5 \Omega \text{ cm}$. The Fig. 7.2 shows complete schematically view of the RPCs with the double gap geometry. This gas mixture is circulated in a close loop with 10% fresh gas in each cycle and gas mixture

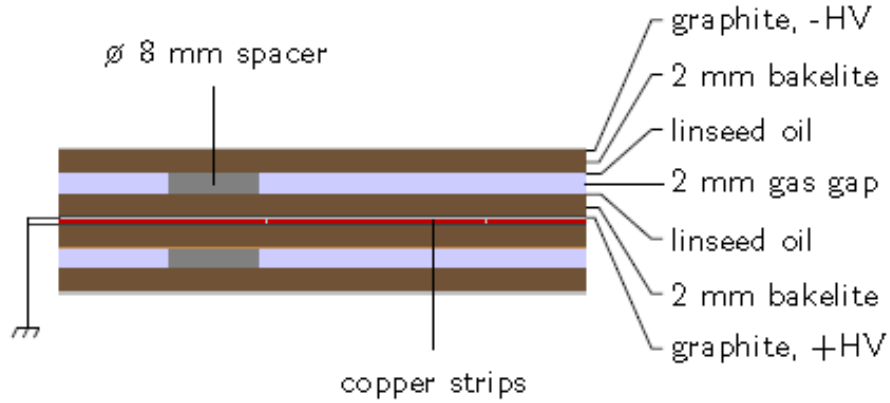


Figure 7.2: Schematic cross-sectional view of CMS RPC double gap [111].

is continuously being observed [114]. At the graphite coated surface, high voltage has been applied to obtain the electric field inside the gas gap, thus along the track of an ionizing particle

this electric field generates a charge avalanche. RPCs are being operated in avalanche mode to address the issue of high rates (1 kHz cm^{-2}). Therefore induced signal due to avalanche process appears on the stripes of copper which are placed outside the gap and these strips are isolated from graphite and connected with front-end electronics. All the parameters of RPC has been optimized to fulfill the general requirements of CMS [113].

7.1.3 RPC Design Requirements

There are fundamental requirements for the RPC detector which need to be fulfilled and these are: good timing, low cluster size, and good rate capability. Other than the general criteria RPCs are expected to have high intrinsic efficiency and in a very high background needs to be with standing long term operation of the detector. For this purpose, the requirements have been described in the Table 7.2. The RPC read out electronics installed at the detectors must

Table 7.2: **CMS RPCs** general technical requirement

Efficiency	$> 95\%$
Time resolution	$\leq 3 \text{ ns}$ (98% within 20 ns)
Average Cluster size	$\leq 2 \text{ strips}$
Rate Capability	$\geq 1 \text{ kHz/cm}^2$
Power Consumption	$< 2 \text{ -} 3 \text{ W/m}^2$
Operation Plateau	$> 300 \text{ V}$
# streamer	$< 10\%$

be radiation tolerant to a level of few Gy per year and also detector should tolerate the effect of magnetic field which is up to 1.5 T near RPCs location. For the RPC detectors at CMS experiment, avalanche mode selected as operational mode which keeps the gas gain very low.

7.1.4 Layout of RPC Detector

The RPC detector is divided into two regions, the barrel region ($0 < |\eta| < 1.2$) and the endcap region ($0.9 < |\eta| < 1.6$). In total RPC detector consist of 912 double gap chambers, having total readout strips 2×10^5 and which are covering the total area of 3400 m^2 . For the purpose of triggering and muons reconstruction, the CMS detector has adopted the gaseous detector technologies. Resistive Plate Chambers are based outside the CMS solenoid in an iron return yoke to trace the muons in an event. The RPCs are detecting the muons with in the time resolution of $\leq 3 \text{ ns}$ and spatial resolution up to 1 cm in both barrel and Endcap regions,

and this detection is possible only up to the pseudo-rapidity range $|\eta| < 1.6$ as shown in the Fig. 7.21.

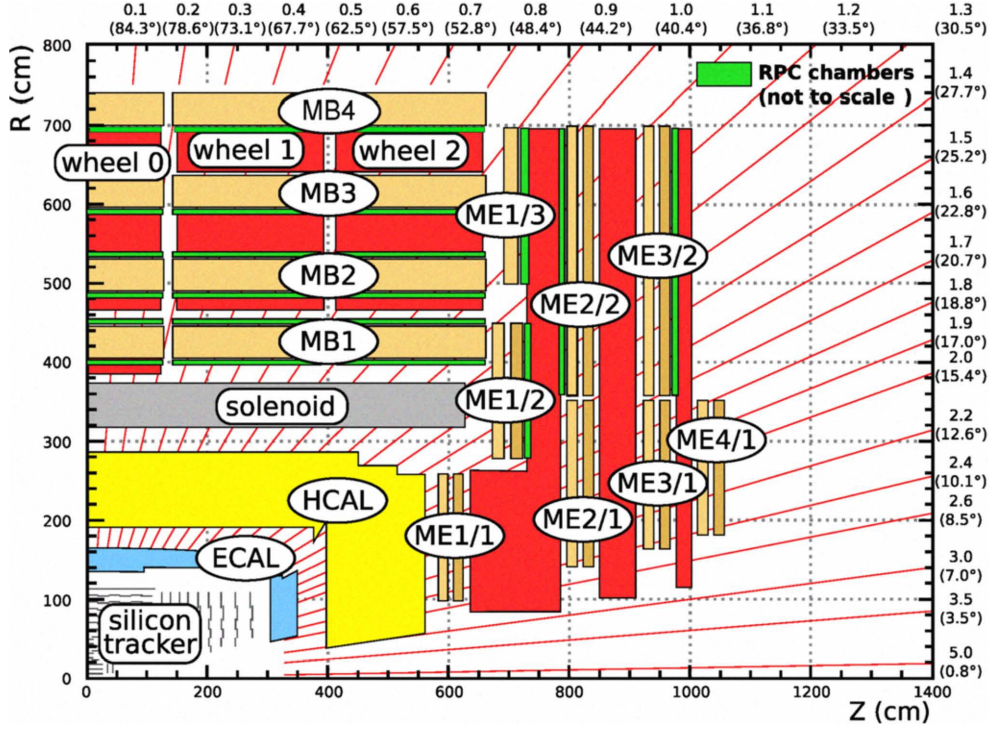


Figure 7.3: RPCs installed at CMS detector with η distribution. The CMS detector, R-Z cross-section of a quadrant where the horizontal axis (z) is running parallel to the beam and radius (r) increasing upward. The η -values (and the equivalent θ -angles) are shown at the top and right. At the lower left corner, there is an interaction region. Various Muons stations have been shown and the steel disks (red areas). The labels of four stations of drift tubes (DT) are MB ("Muons Barrel"), where the labels ME ("Muons Endcap") represents the cathode strip chambers. Resistive plate chambers (RPC, in green) are in both the barrel and the endcaps of CMS

Barrel Region

In the barrel region of the CMS detector, there are four RPC stations, RB1, RB2, RB3 and RB4. There are five wheels (W+2, W+1, W+0, W-1, W-2) in each barrel station and these stations are approximately concentric cylinders. Then these wheels are further divided into 12 sectors, accommodating 4 iron gaps or stations. There are 2 layers on the first and second muon stations and whereas these chambers are located at both sides of DT chambers. At smaller radius RB1in and RB2in are installed whereas at larger radius RB1out and RB2out are installed. There are 2 RPC chambers at the third and fourth station of muons, and these chambers are located on the inner side of DT chambers layer (named RB3+ and RB3-, RB4+ and RB4-).

and RB4-). Fig. 7.4 shows the layout of the RPC system in the barrel region. Muons with transverse momentum p_T between 3 and 6 GeV/c in the barrel region are not able to reach the outer stations RB3 and RB4, therefore, additional layers are inserted in each of the inner stations RB1 and RB2, raising the total amount of sensitive layers in the barrel to six: RB1in, RB1out, RB2in, RB2out, RB3 and RB4.

Barrel region of the CMS equipped with 480 chambers which consist of 68136 strips, these strips are wide from 2.28 to 4.10 cm and total area covered by these chambers is 2285 m^2 .

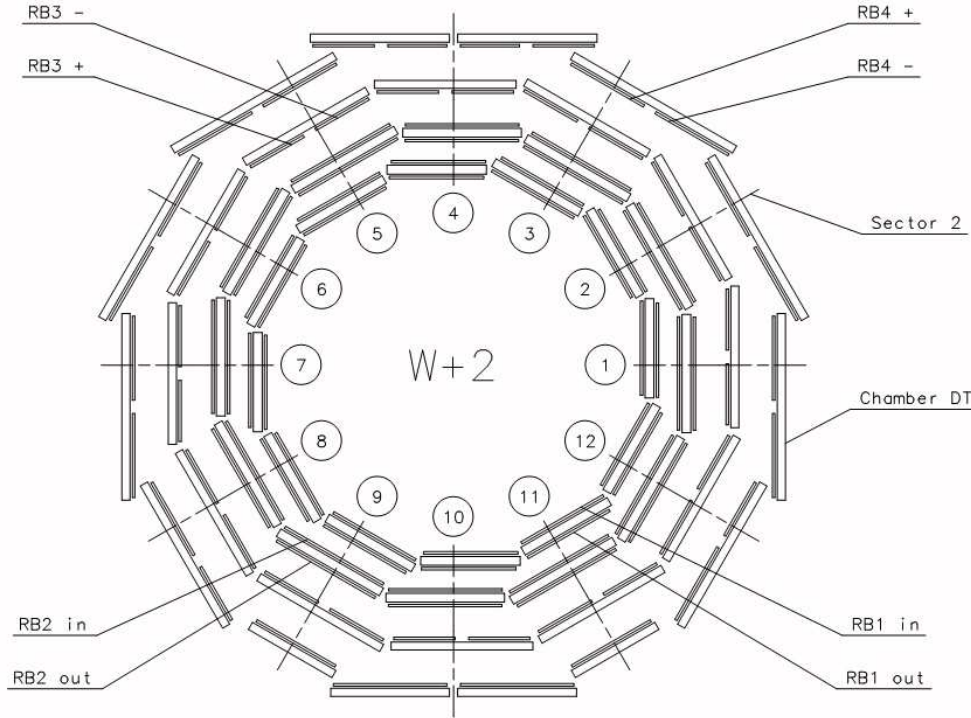


Figure 7.4: One of the barrel wheel schematic layout, All wheels are divided into 12 sectors and numbering is shown on the wheel [112]

Endcap Region

Endcap system of the RPC detector consist of four stations on each side of the interaction point and these four stations are $RE \pm 1 - 4$. These chambers are mounted on the 3 disks in the forward and backward regions. The azimuthal symmetry of the endcap RPC system is clearly visible in the Fig. 7.5. Each station can be divided into three rings (RE/y , $y = 1; 2; 3$) with the changing value of r , which is measured with respect to the beam pipe. A set of 36 RPC chambers in the same station with the same distance r are placed in a given ring.

These rings are divided into six sectors of 60° . Shape of the end-cap RPC is a trapezoidal and each chamber covers 10° in ϕ , and the readout strips of the endcap chambers are also trapezoid. One double gap chamber of endcap contains 96 strips perpendicular to the beam line. The mechanical structure of an RPC (a chamber) in the endcap contains three "rolls", which are the η partitions. The endcap region of CMS detector is equipped with the 432 RPC

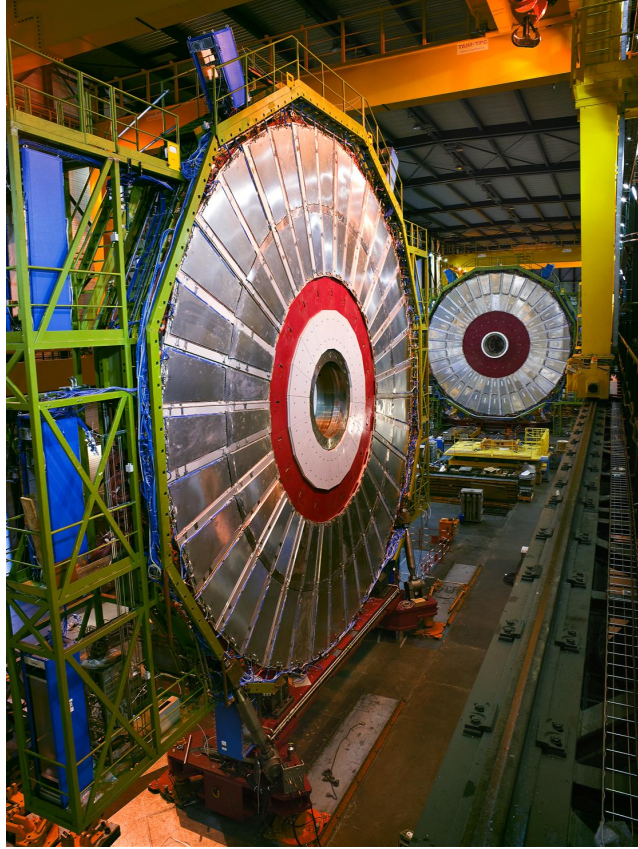


Figure 7.5: View of the front side (Positive side) of YE-3 (front) and the back side (Negative side) of YE-1.

chambers having 41427 strips where width of each strip is between 1.95 to 3.63 cm. The total area covered by the RPC endcap detectors is 668 m^2 .

7.2 The RPC Power system

The power system for the RPCs has to work under very hostile conditions of high magnetic field as well as with very high flux of radiation; therefore a very large portion of the power system is installed near the detector on balcony racks. In the region where RPC are installed the magnetic field can reach up to 1 Tesla and particle flux on average is: $5 \times 10^{10} \text{ protons/cm}^2$

and 5×10^{11} neutrons/cm². To overcome these conditions of experiment, CMS collaboration approved a new design for RPC power system to enable to work in these hard conditions. The general requirements for High Voltage (HV) and Low Voltage (LV) system of RPC detector have been described in the Table 7.3.

Power system for RPC is depending upon master/slave architecture. Mainframe is "master" and controlling the slaves from an accessible area like control room. The "slaves" are sitting near the detector and they are designed to accept both LV/HV in a functional form. These HV/LV modules have to work in a hostile as well as inaccessible area; therefore these modules are based on radiation and magnetic-field tolerant electronics. To make the whole system operationally efficient, "master" to be placed in an accessible area. The power system for

Table 7.3: **CMS RPCs** general HV and LV power supply requirements [114]

	HV	LV for FEB	LV for LBB
Maximum Voltage	12 kV	7 V	4 V
Maximum Current	1 mA	3 A	14 A
Ripple	< 100 mV	10 mA	10 mA
Programmable Voltage	from 0 to 12 kV	from 0 to 7 V	from 0 to 5 V
Current monit. precision	0.1 μ A	100 mA	100 mA
Voltage monit. precision	< 10 V	< 100 mV	< 100 mV
Trip Settings	0 - 100 s	0 -10 s	0 -10 s

RPC detector designed in such a way that environmental conditions were taken into account and all necessary steps have been taken to reduce the probability to have dead regions or operating with less efficiency due to the collapse of power supply channels.

Every double gap RPC chamber requires two independent HV channels, one per layer of gaps. For powering Front End Boards (FEBs), two independent LV channels are needed. High voltage is required to generate the electric field lines inside the gas gap active volume whereas the digital and analogue power supply is needed for FEB chips operation. For barrel and endcap regions, different configurations are adopted to adjust the cost and granularity. Chamber in a barrel region has two gaps joint together to the same HV channel and to supply power to FEBs, two independent LV channels are used. In the endcap region, two chambers are sharing one HV channel but for LV supply two different channels for each chamber are used.

Low voltages are also needed to power up the Link Boards which are mounted on the balconies near the detector inside the experimental cavern. Therefore complete power system for RPCs consists of the following:

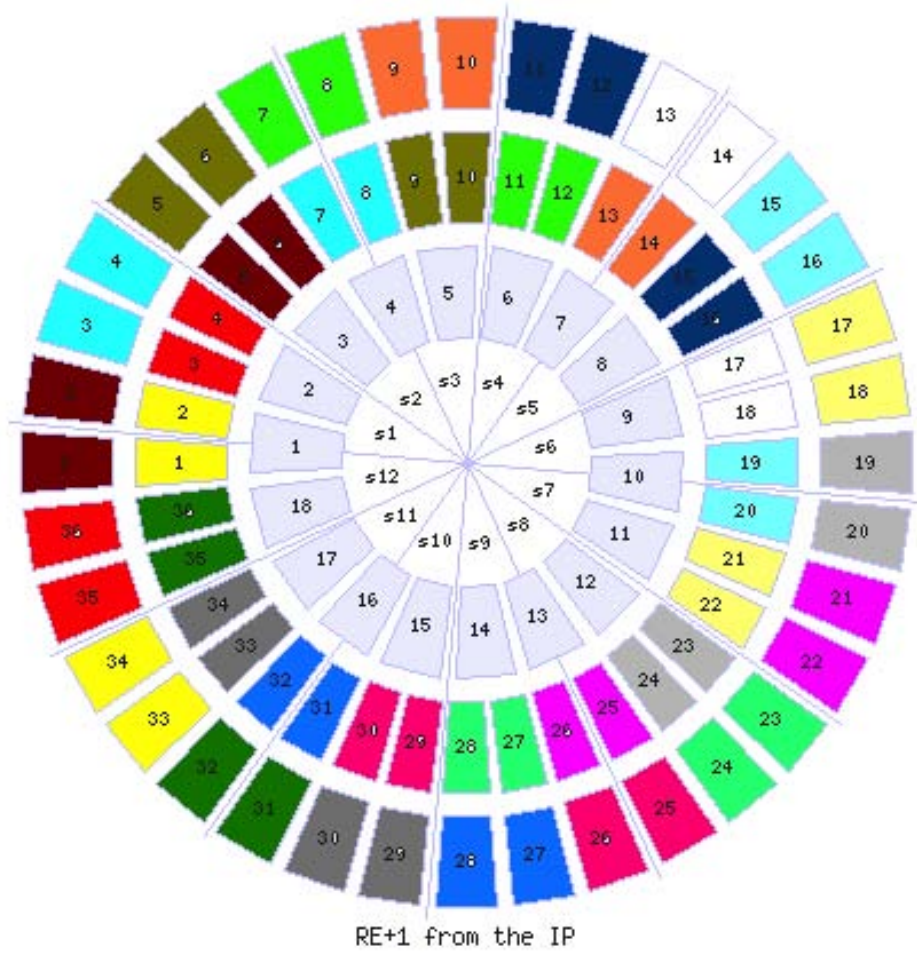


Figure 7.6: View of RE disk, showing that two chamber of ring 2 and ring 3, are connected to one HV module

- 912 total high voltage channels
- ≈ 1000 low voltage channel for the detector front end electronics
- ≈ 300 low channels for the RPC link boards

7.2.1 RPC EASY SYSTEM

RPC power system is based on CAEN [114] EASY Embedded Assembly SYstem (EASY) that is approved by the RPC sub-detector collaboration. This system contains radiation and magnetic field tolerant electronics components. The CAEN system provides opportunity to separate the control of the supply modules allowing them to operate in hostile environment. Standard approach has been used for the power system, it depends upon the common modular system of crates and controllers where different power supply can be selected as per requirement.

Important ingredient of the CAEN EASY technology is the Main Frame controller SY1527, which dictates the crates located several meter away via branch controller boards which controls and communicate with the help of CAEN bus. The two possible configurations have been adopted for RPC power scheme as shown in the Fig. 7.7. One is to put complete power supply underground electronics rooms and second is to separate control units and power modules.

Thus the Power system for RPC contains the 96 EASY CAEN A3009 LV boards for the purpose of FEB powering, 64 EASY CAEN A3016 LV for power system of Link Boards where as HV system of RPC has 116 EASY CAEN A3512N boards [114]. Complete power system is described in the Table 7.3.

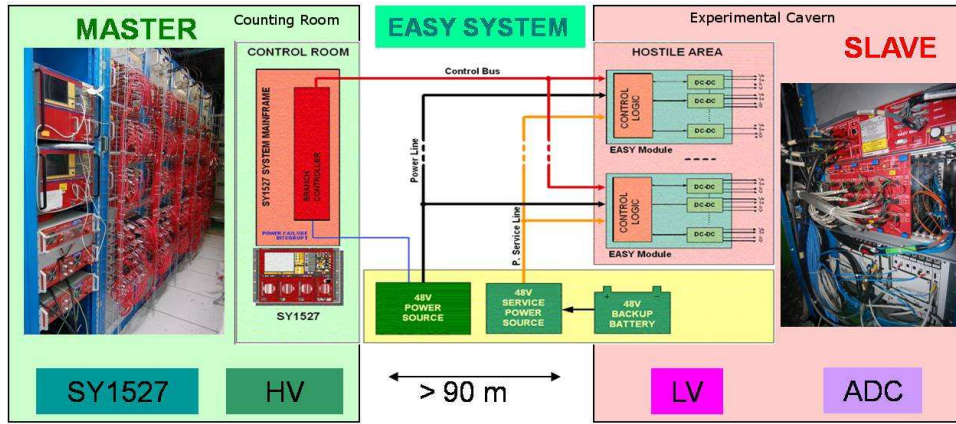


Figure 7.7: Schematic representation of RPC power supply system, RPC power system is based on the CAEN EASY Technology

7.3 Gas Supply of RPCs

The RPCs, dedicated trigger detectors at CMS experiment are gaseous detectors therefore performance, stability and efficiency is strongly correlated with gaseous mixture used in the detectors. The standard mixture approved by the collaboration contains $C_2H_2F_4$ 95.2 %, isobutene $i - C_4H_{10}$ 4.5% and the quencher SF_6 0.3% as shown in the Table 7.1 [116]. Other than gas, most important part of the RPC detectors is Bakelite. In order to maintain the resistivity of Bakelite sheet, up to 40% water vapors are being mixed with the gaseous mixture. Main functionality of the gas system is to mix the different ingredients of the gas and then properly and continuously distribute to all chambers. Since the covered area of the RPC detectors is large and also relatively expensive gas is being used therefore close-loop circulation

of gas is mandatory. The whole gas system consists of many modules, initial gas supply, gas

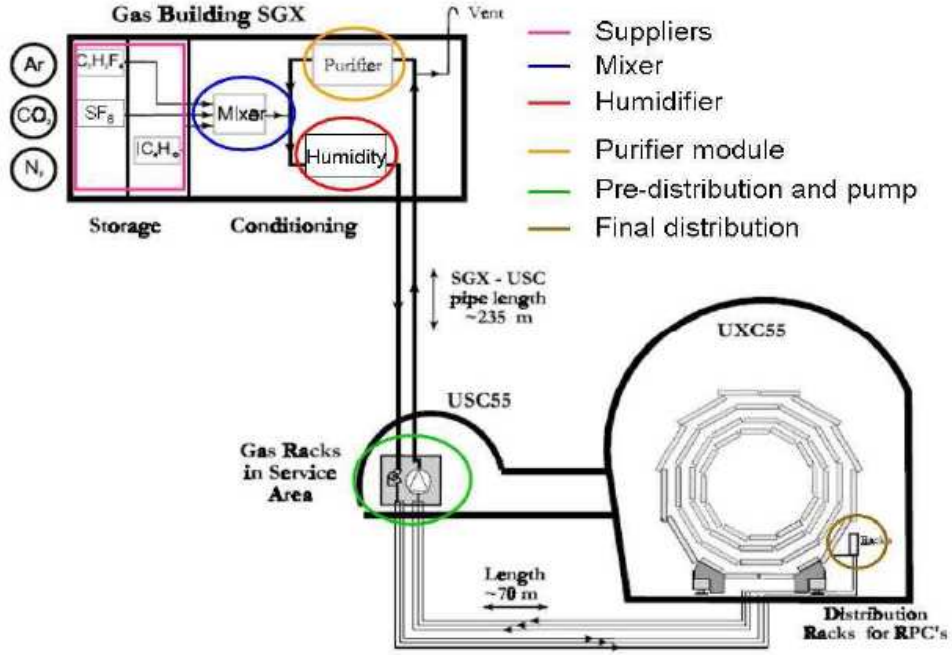


Figure 7.8: Closed loop circulation system of RPC [47].

mixer, and gas circulation system, distributor to chambers, purifier, pump, and gas-analysis station as shown in the Fig. 7.8. For the detector, gas should be non-flammable, therefore it's continuously being observed, if the proportion of isobutane is getting increased then gas automatically stops working. For barrel and endcap, mixed gas is circulated in a common loop. Barrel part of the detector is divided into two regions and for each barrel chamber, there is an independent gas line. Due to this configuration for the full barrel system 250 gas channels are required, implying 50 gas channels for each wheel as shown in the Fig. 7.9. For the endcap system, situation is different from barrel. RPC endcap consists of three disks, RE1, RE2 and RE3, having 216 double gap chambers on each side of the interaction point. There are two rings in each disk containing 36 chambers per ring. Rings of RE1 have been divided into 6 gas sectors of ϕ and every sector contain 6 chambers and gas is being supplied via two line, one for bottom and other for top gaps. For RE2 and RE3 disk, division is in 12 gas sectors corresponding to ϕ , and each gas sector contains 3 chambers of ring 2 and 3, in total six chambers as shown in the Fig. 7.10.

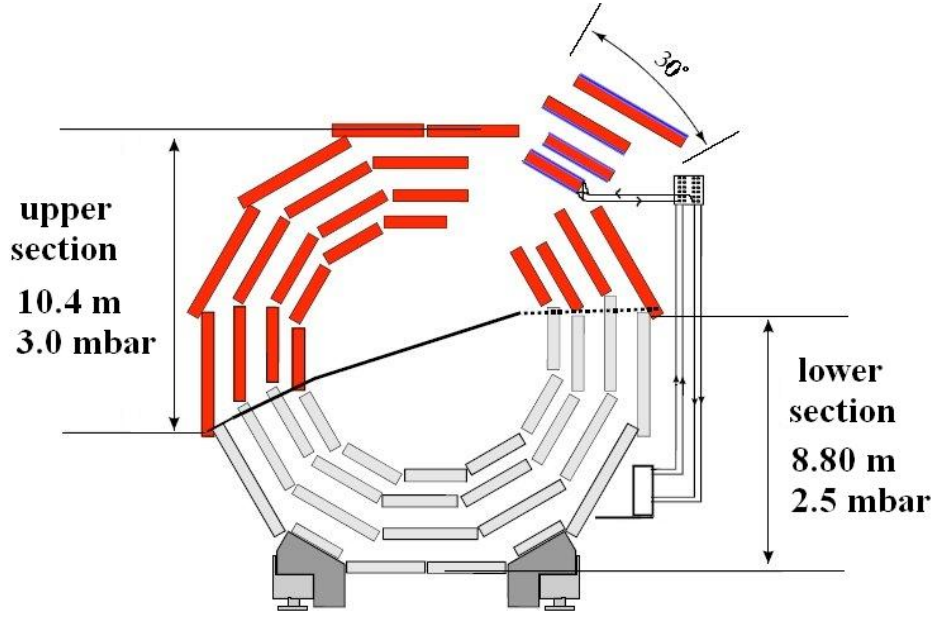


Figure 7.9: RPC barrel wheel is divided into two regions and each station (2 chambers) is provided with a gas line [47].

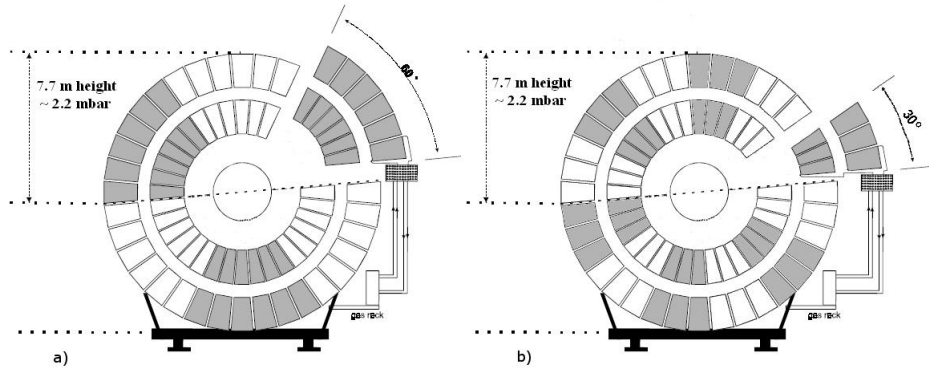


Figure 7.10: RPC endcap disk has been divide into two rings (a) RE1 chambers has divided into 60° sector (b) RE2,3 has been divided in 30° sector, containing 3 chambers of internal ring and 3 from external one. Two independent gas lines supplied to every sector [47].

7.4 Readout System of RPCs

Strips for read-out of signal in RPC detectors are connected to Front-End Boards (FEBs). First, signal are being amplified and discriminated and then unsynchronized signal is being sent to Link Boards (LBs) which are placed around the detector. Synchronization process with the 40-MHz LHC clock is being performed by the LBs and then transmitting this signal toward the trigger system located in the counting room of CMS experiment at a distance of 90-m and

connected via optical link at 1.6 GHz as shown in the Fig. 7.11.

For an event, accurate timing information from the RPC detector is crucial for the assignment of unambiguous bunch crossing, therefore a technique of zero-crossing has been adopted to make the response time amplitude-independent. Range for the RPC signal is quite dynamic i.e. from few tens of fC to 10 pC, due to crossing technique time walk remains below 1 ns, while discrimination due to leading edge technique provides time walk of the order of 10 ns. At the end LVDS driver are being used to send the signal hits to the LBs in differential mode [116].

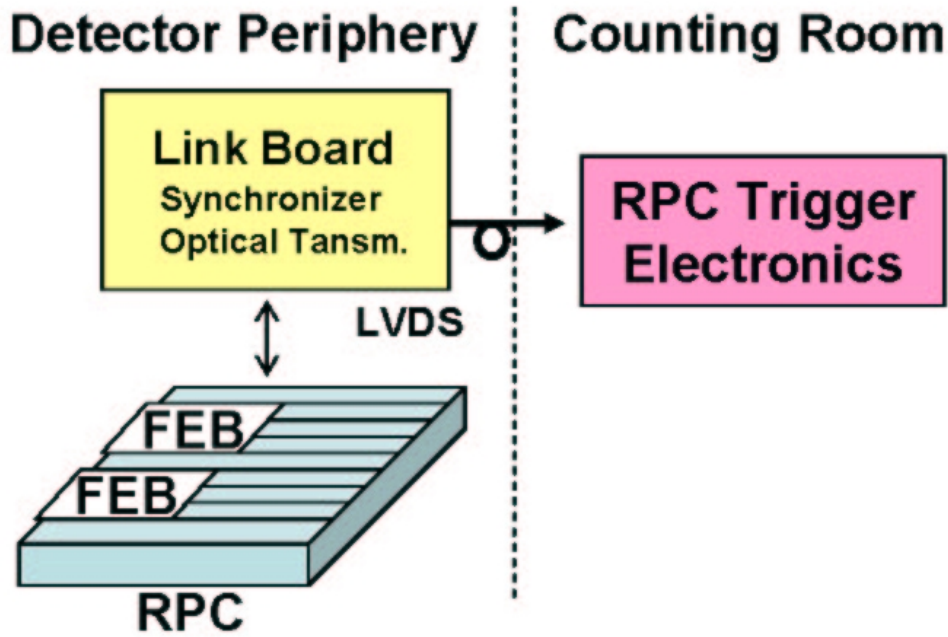


Figure 7.11: RPC readout electronics block diagram, Figure taken from [117].

7.4.1 RPC DCS System

One of the important requirements of the CMS collaboration is most powerful Detector Control System (DCS) to ensure the safe and efficient operation of the detector. Functionality of DCS depends upon the JCOP and PVSS software. DCS closely follows the geometry of the detector. The RPC DCS hierarchical structure allows checking the status of all hardware involved in the operation and problematic hardware can be handled remotely using DCS.

RPC Detector Control System (DCS) constitutes three main parts:

- DCS for the RPC HV and LV system
- RPC TC DCS (Trigger Crate Control), which controls 14 VME crates in 8 racks in CMS counting room

- RPC LB DCS, which comprises the control of the Link Board and FEB

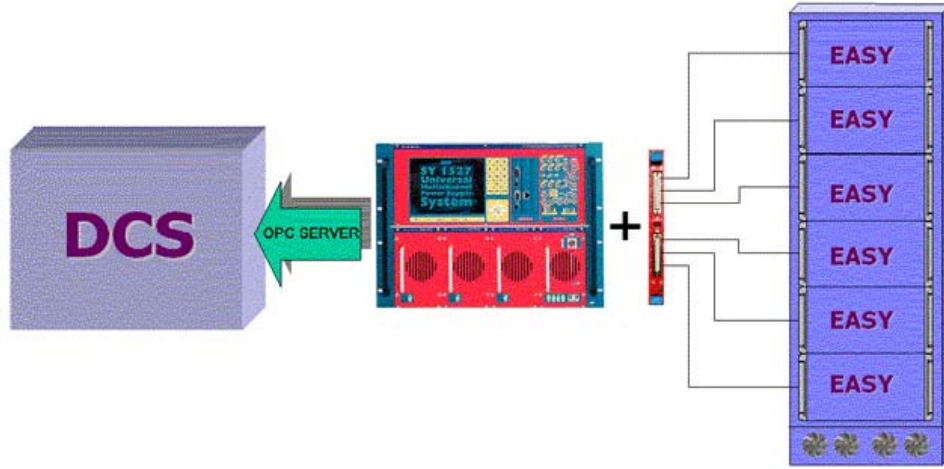


Figure 7.12: The RPC power system Mainframe works independently to handle modules and can communicate with RPC DCS [118], The DCS monitors the system status and sends commands to the Mainframe.

Due to this software, protection at hardware level has been enhanced by implementing several safety checks and it provides an easy and robust interface for system operation. With the help of this detector control, LV and HV can be switched off, gently ramping up or down towards safe conditions in case of problem. Other than, HV and LV, DCS also control cooling system and environment parameters like temperature, pressure and humidity. There are three main states of RPC control, ON, OFF and STANDBY, when problems occur at detector level, it can be hardware or software issue, detector goes to ERROR state. These states of the detector are used whenever needed to ensure uniformity and compatibility with the central CMS DCS.

7.5 Operational Parameters of RPCs

The RPC system at CMS experiment performed very well during 2012 data taking where the instantaneous luminosity $6.6 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ was very high [123]. The CMS collaboration has implemented certain conditions on the performance of the RPCs and those conditions need to be fulfilled during data taking. The performance of RPCs is studied during data taking to verify whether the CMS requirements are fulfilled or not. Numbers of important parameters which are important for the performance study of RPCs are discussed in this chapter.

7.5.1 Efficiency

Efficiency means the ratio of active strips of the detector with the reference of total strips of the detector. The RPC efficiency has been performed by using segment extrapolation technique. In this procedure, segment extrapolation of DT/CSC reconstructed tracks to the RPC planes are used to find the RPC hits around the area of extrapolated point. Thus efficiency is the ratio of the number of observed RPC hits and the expected number of hits from segment extrapolation.

7.5.2 RPC Cluster Size

A cluster is defined as a consecutive set of strips, each of them collecting a charge above the discrimination threshold of 180 fC (230 mV). The number of strips within a cluster is called the cluster size and depends on the pitch (width) of the readout strips, the impact point position with respect to the strip and the track crossing angle.

7.5.3 Dark Current

Current detected in the electronics of the detector without applying the high voltage across the gas gap. The sources of dark current could be leakage current, loose electronics etc.

7.6 Hardware status

Since RPCs performed extremely well during the data taking of Run-I, here comparison has been made for each year of running and the problematic chambers in barrel and endcap regions of the detector are identified. At the end of data taking, status of RPC detector was as follow;

Barrel Chambers:

- RB Chambers in Single Gap (SG) Mode - 15
- RB Chambers OFF - 8
- RB Threshold Problems - 42 (ROLLS)

Endcap Chambers:

- RE Chambers in SG - 29
- RE Chambers OFF - 4
- RE Threshold Problems - 12

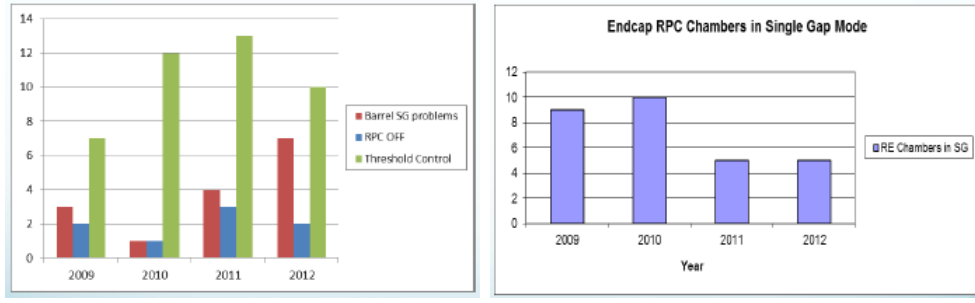


Figure 7.13: Left: chambers of barrel in Single Gap mode (SG) during the data taking, a comparison between 2010 - 2012. (Right) SG mode of endcap chambers.

7.6.1 RPC Efficiency Measurement Method

Efficiency measurement of RPC depends upon the presence of either a DT (in the barrel) or a CSC chamber (in the endcap) which allows to profit by the redundancy of the CMS muon system in order to define the RPC hit efficiency in an independent way, without the need of relying on physics analysis with muons. For the hit efficiency measurement, only those events are being taken into account which have DT or CSC trigger whereas the events only triggered by the RPCs are discarded.

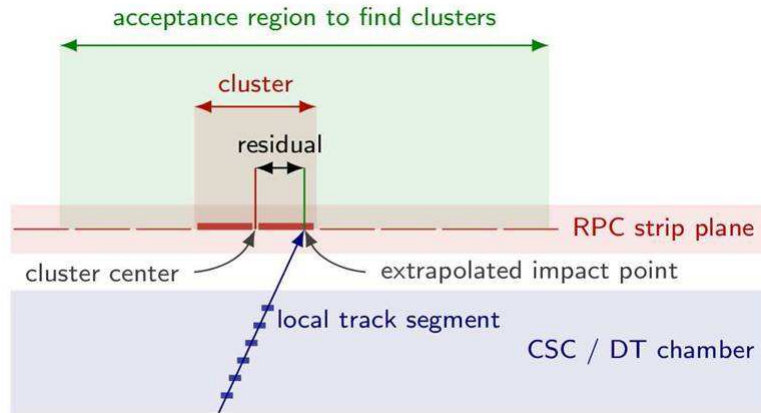


Figure 7.14: RPCs efficiency measurement by extrapolation method, A DT or CSC track segment is linearly extrapolated to the RPC strip plane. RPC hits are sought in the acceptance region around the extrapolated impact point.

RPC hits are predicted by the extrapolation method, track segments of muons, reconstructed with multi-layer detectors DT and CSC, are linearly extrapolated to the RPC strip plane and used to predict RPC hits in a fiducial region around the extrapolated impact points, as illustrated in Fig. 7.14. In this method of extrapolation, every hit which is being extrapolated is being matched with the closest cluster of RPC hits, that cluster is formed by contiguous

fired strips and measured RPC cluster size corresponds to about two strips.

Due to high rate of background particles, some additional requirements have been applied to ensure that only extrapolated segments associated to muon tracks with hits in the central tracker are taken into account, while DT/CSC reconstructed segments due to hits probably originated by neutral background particles are discarded.

7.6.2 RPC Working Points (WP)

High efficiency ($> 95\%$) of muon chambers is the basic requirement of the CMS detector that is why high voltage scans performed at the start of data taking during 2011 and 2012 LHC running for pp collisions. The main purpose of these scans is to find the optimal operating point for every chamber for the sake of high efficiency requirement. Since RPC is a gaseous detector therefore its performance has dependence on the pressure and temperature of the environment. Therefore pressure P and temperature T of the CMS experimental cavern has been taken into account during 2011 - 2012 data taking for the measurement of efficiency. During the collision, data was taken at eleven different values of effective HV (where HV_{eff} defined in Eq.(7.4)). The Range of those eleven different points of HV starts from 8.5 kV to 9.7 kV. The chamber WP has been defined as the HV corresponding to the 95% of the maximum efficiency plus 100V (7.2) for the barrel and 150V (7.3) for the endcap. Then a linear extrapolation of the track segment in the DT and CSC chambers was performed toward the closest RPC strip plane and then matched to RPC cluster in a range of 8 strips around the extrapolated impact point. The high voltage shift between barrel and endcap chambers depends on few microns difference in the spacer's width (located inside the gas gap). A dedicated data stream was used, containing information from the muon detectors and the first level trigger.

A sigmoidal response function, a well-known formula that can describe the efficiency (ϵ) dependence on HV_{eff} which takes into account atmospheric pressure variations and can be written as:

$$\epsilon = \frac{\epsilon_{max}}{1 + e^{-\lambda(HV_{eff} - HV_{50\%})}} \quad (7.1)$$

where ϵ_{max} is the asymptotic efficiency for $HV \rightarrow \infty$, the λ coefficient is proportional to the sigmoid slope at the inflection point, and the High Voltage value $HV_{50\%}$ is the inflection point of the sigmoid, for which 50% of ϵ_{max} reached. Efficiency of an endcap chamber as a function of effective high voltage is shown in the Fig. 7.15. In the Fig. 7.15, it is shown that the "knee" is the value of HV_{eff} at which 95% of the asymptotic efficiency is reached. To make sure that the

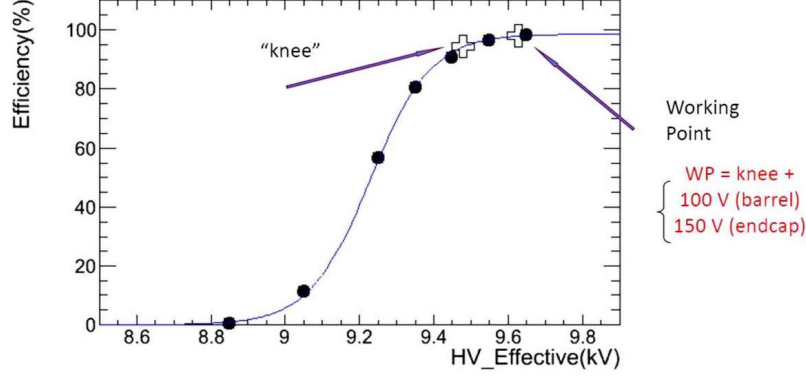


Figure 7.15: Efficiency measurement (in %) as a function of the effective High Voltage HV_{eff} (in KV) for a typical chamber. The "knee" and the optimal working point, shown in the picture, are defined in the text.

chambers are working at high efficiency, the optimal Working Point (WP) is selected beyond the "knee" and in the flat region to minimize the effect of environmental parameters.

$$HV_{wp} = HV_{knee} + 100V \text{ (barrel)} \quad (7.2)$$

$$HV_{wp} = HV_{knee} + 150V \text{ (Endcap)} \quad (7.3)$$

This difference in the WP of endcap and barrel chambers is due to the different trigger

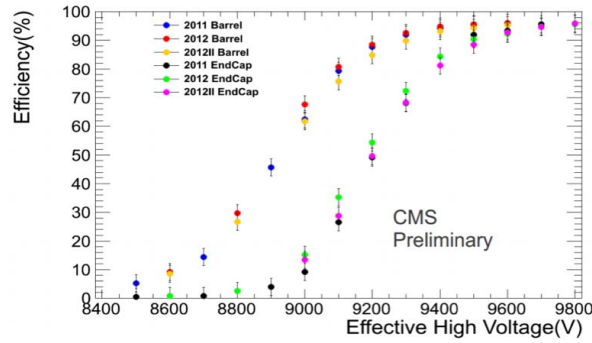


Figure 7.16: Average Barrel and EndCap efficiency during the High Voltage Scan performed in 2012 superimposed with the High Voltage Scan in 2011. The similarity in the curves shows the stability of the system, no aging effects for the CMS RPC chambers.

algorithms. The endcap trigger algorithm, requiring three coincidences out of three planes, is more sensitive to efficiency variations. The resulting WP values are averaged for chambers belonging to the same HV channel. Up to a maximum of two chambers, i.e. up to four rolls in the barrel or up to six rolls in the endcap, are fed by the same HV supply. Output result of the sigmoidal function is highlighted in the Fig. 7.16, and the $HV_{50\%}$ for endcap and barrel chambers is presented in Fig. 7.17. Fig. 7.18 shows the chamber efficiency map as measured

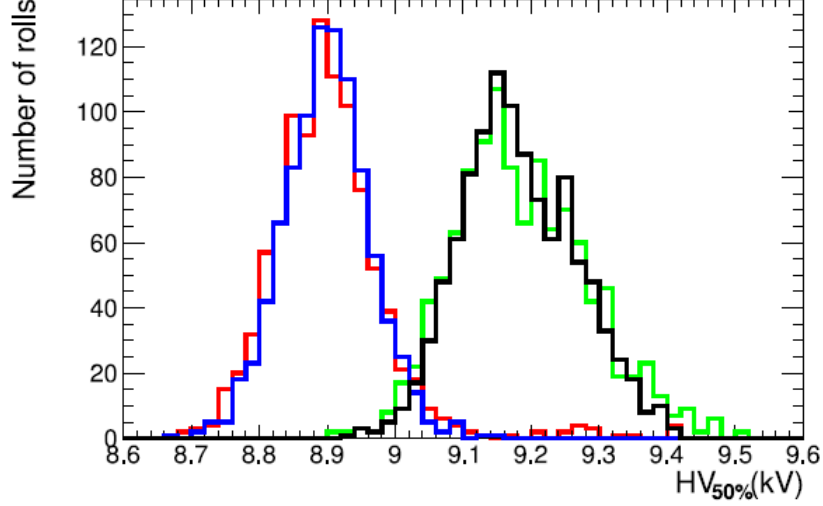


Figure 7.17: For barrel, distribution of $HV_{50\%}$ has been shown in the left curve and with curves red and green, and for endcap rolls showed with the black and green curves. Here the red and green curves show 2012 data. 50% of the asymptotic efficiency obtained at $HV_{50\%}$

in 2012 for one wheel and for one disk. Most of the chambers have an efficiency of more than 95%, except for few cases; the lower efficiency is due to known hardware problems.

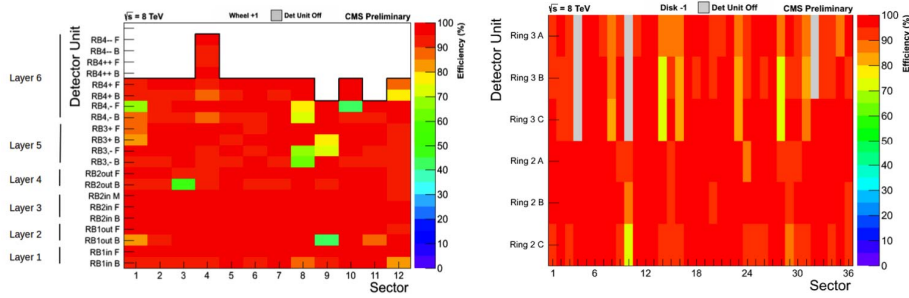


Figure 7.18: Left: chambers efficiency map for the wheel +1. The plot shows the 12 sectors on x axis and the 6 RPC layers on y axis. Right: chambers efficiency map in disk -1. The 36 sectors are shown on x axis and the 3 layers on y axis.

7.6.3 Detector Stability

Since CMS RPC detector is installed underground with very controlled environmental parameters, therefore inside the CMS cavern, the variation in the environmental pressure P and in the temperature T , was taken into account by rescaling the defined reference values ($P_0 = 965\text{mbar}$ and $T_0 = 293\text{K}$) and these changes were considered with the Equation 7.4:

$$HV_{eff}(P, T) = HV \cdot \frac{P_0}{P} \cdot \frac{T}{T_0} \quad (7.4)$$

where $HV_{eff}(P, T)$ is the resulting High Voltage (HV). In the environmental parameters, pressure have dominant effect on the resulting voltage: a 1% variation in the pressure of cavern, of the order of about 10 mbar will produce a considerable $HV_{eff}(P, T)$ difference about 100 V. Starting from July 2011, automatic correction of the Equation (7.4) had been implemented [124]. Results have been obtained on 2011 data with the application of these automatic corrections as shown in the Fig. 7.19 and Fig. 7.20.

After the implementation of automatic correction in the reference parameters i.e. pressure and temperature, improvement is obtained in the stability of the efficiency and cluster size as a function of time. Fluctuation in the efficiency of barrel part of the RPCs as shown in the Fig. 7.19 is mainly due to pressure variations in the CMS cavern and are reduced from about $\pm 1\%$ to about $\pm 0.5\%$. In the first part of 2011 data taking, higher reference value of the pressure has been chosen, so higher average efficiency ($\sim 97\%$ compared to $\sim 96\%$) has been observed during this period.

After proper working of automatic pressure and temperature correction, an increased stability, with reduced fluctuations, is also observed in the endcap cluster size as a function of time (Fig. 7.19, right). As discussed above about the efficiency, the same considerations apply to the average values before and after the $HV_{eff}(P, T)$ correction.

In the Fig. 7.20, average cluster size in the barrel (left) and endcap (right) region has been shown, before and after the application of automatic pressure correction. Both in the barrel and in the endcap, a clear anti-correlation is shown in the first part of 2011, when the correction was not applied. The slight positive correlation in the second part of the year might hint at an over correction in Eq. (7.4).

7.6.4 Noise

Since RPCs are dedicated muon trigger detectors therefore intrinsic noise should be kept low. Noise rate has been measured during no-collision periods, an intrinsic noise well below 0.5 Hz/cm^2 was measured for most of the chambers. Measured noise rate is well below for muon triggering because for trigger system, three or more strips should be fired within the 25 ns window and in a limited spatial region.

The intrinsic noise of the RPC chambers can have an important contribution in the overall efficiency of the system. High values of the noise in chambers can affect the performance of the trigger and efficiency of the pattern recognition of muon tracks. Before every proton

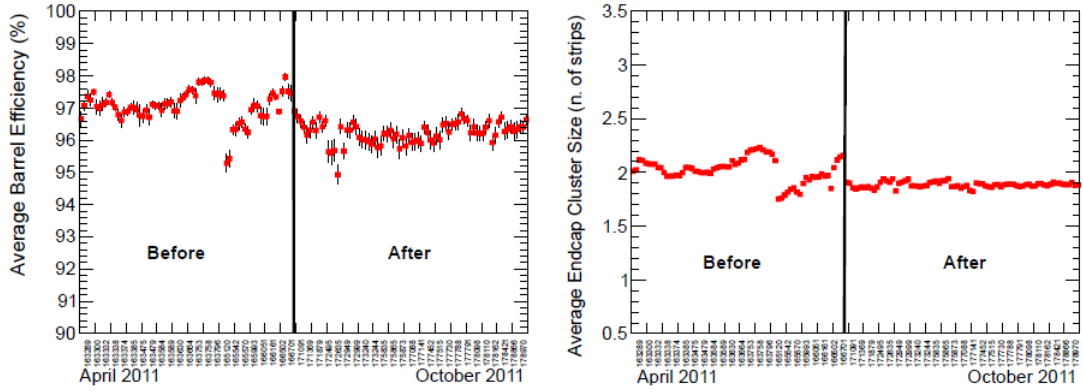


Figure 7.19: Left: Barrel efficiency (in %) as a function of the run number, i.e. as a function of time, for runs taken between April 2011 and October 2011. The two regions, before and after the automatic $HV_{eff}(P,T)$ correction, are shown in the plot. Right: Endcap cluster size (in number of strips), as a function of the run number, for the same run range between April and October 2011.

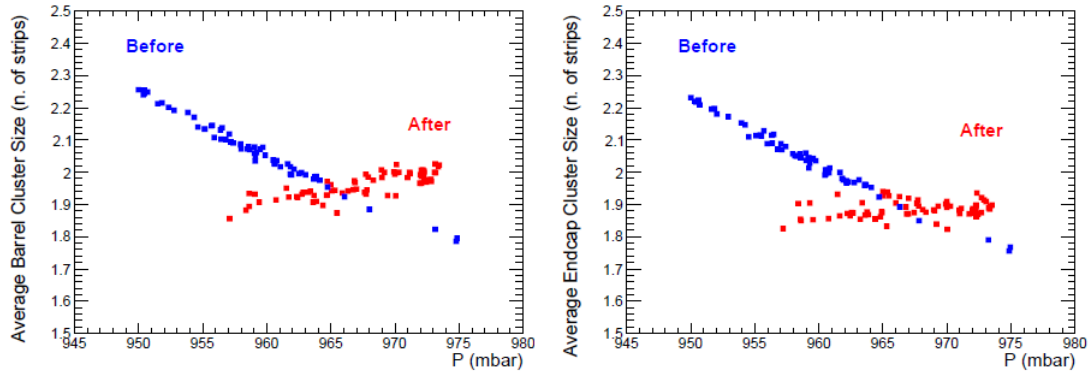


Figure 7.20: Average cluster size for the barrel (left) and for the endcap (right), in number of strips, as a function of the atmospheric pressure P (in mbar), for runs before (left, blue curve) or after (right, red curve) the automatic $HV_{eff}(P, T)$ correction. Preliminary results with 2011 data are shown.

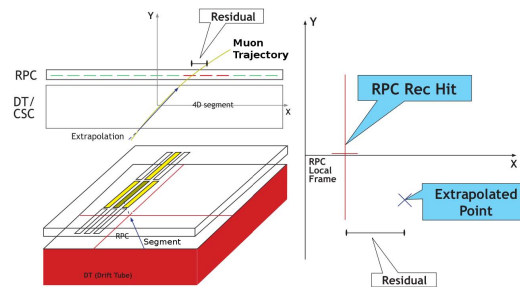


Figure 7.21: Explanation of extrapolation method for the muon trigger and efficiency measurement

beam fill, the intrinsic noise rate is measured in order to mask noisy strips where needed. Noise comparison is given in the Fig. 7.22, this comparison is for the both endcap and barrel systems. The average values, of about 0.1 Hz/cm^2 , well below the CMS requirements and is stable during the whole running period. It is shown in the Fig. 7.23, the noise rate map measure at chamber

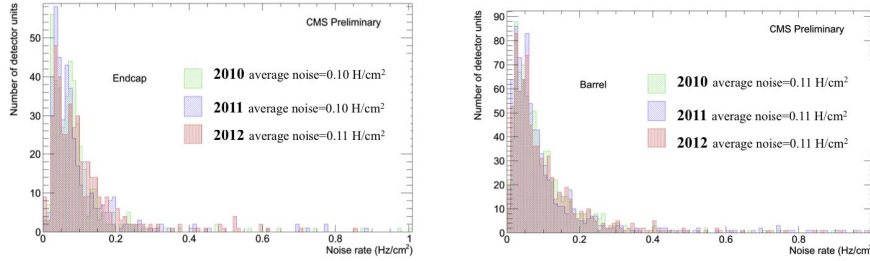


Figure 7.22: Distributions of the noise rate for barrel (left) and for the endcap (right) for the 3 years running 2010 - 2012.

level in the one barrel wheel and in one disk of endcap region at a luminosity $2.10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Thus in the barrel region, the highest rate found to $\approx 7 \text{ Hz/cm}^2$ in the outer most station RB4 and this rate is mainly due to the neutron background, and in the innermost stations (RB1), due to charged particles and punch through hadrons. In the endcap side, the highest rate measured was $\approx 12 \text{ Hz/cm}^2$ in the inner ring of disk 2 [125].

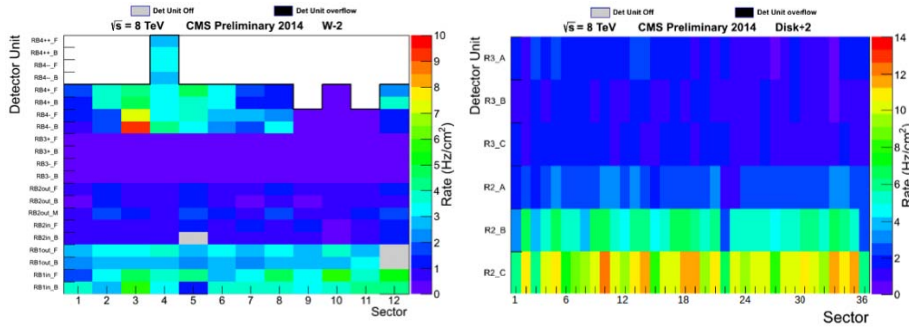


Figure 7.23: Measured noise rate map in one of the barrel wheel -2 (left) and rate map in the endcap Disk+2 (right)

7.6.5 Background Radiation

For stability and performance of the CMS muon system, background radiations are important consideration. There are many parameters which can affect the trigger performance, pattern recognition of muon tracks and overall performance of the system, such as, production of particles due to the interaction of beam with collimator, gas residual and with the components

of beam pipe. One of the most important impacts of the radiation level is: detector aging, high level of radiation can cause the aging effect.

In the Fig. 7.24, the average background rate as a function of the instantaneous luminosity during 2012 for all barrel wheels and background rate have linear dependence on the luminosity. As expected, the rates increase as the chambers are farther from the IP: wheel 0 is the closest one to the interaction point, +2 and -2 are the farthest.

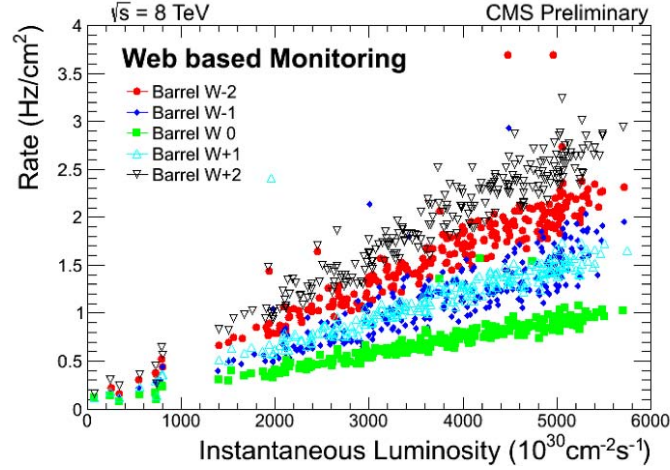


Figure 7.24: Measurement performed for background rate in barrel wheels as a function of the LHC luminosity in 2012 (wheel 0 is the closest one to the interaction point, +2 and -2 are the farthest).

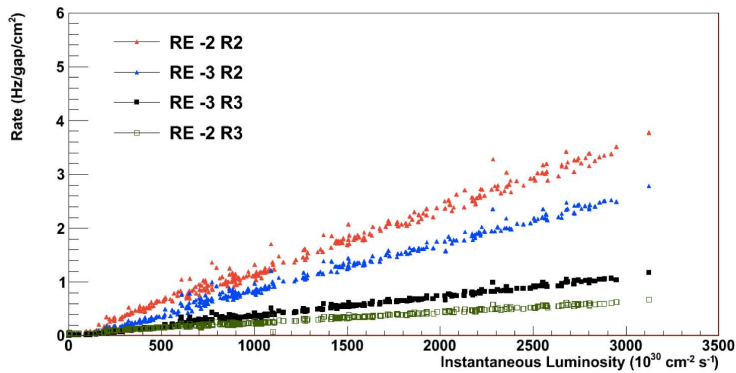


Figure 7.25: Background rate as function of instantaneous luminosity in the endcap station 2 and 3 of the negative disk 2 and 3.

7.7 Conclusion

The results have been described about the stability and uniformity of CMS RPCs during 2011 and 2012 data taking periods. HV scans have been performed at the beginning of 2011 and

again at the beginning of 2012. They have been extremely effective, allowing to select the optimal operating HV values for each individual RPC chamber and to obtain a high level of uniformity both in the barrel and in the endcap. A new method for determining the RPC hit efficiency is used by the CMS RPC Collaboration and automatic $HV_{eff}(P, T)$ corrections are in place since July 2011. Those efforts result in increased efficiency stability and increased cluster size stability as a function of pressure and time.

- RPC systems are operating extremely well delivering good triggers and data for physics.
- The contribution to the CMS downtime is very low (less than 1.5 %).
- The fraction of active channels is very high and stable (more than 98 %).
- After three years running of LHC with growing instantaneous luminosity and its six years from the start of construction of the RPC detectors, the performance and efficiency of the detector remains within the specification of collaboration both as a trigger detector and as a reconstruction system.
- Excellent synchronization and efficiency of the trigger system is obtained.
- The RPC performance is stable with no degradation observed.
- Background measurements are within expectation. No significant issues for running at nominal luminosity are observed.

Conclusion

The LHC high instantaneous and integrated luminosity is making it possible to measure the rare processes like tqZ . In this thesis, tqZ analysis has been presented by using CMS 8 TeV data collected during 2012 LHC running, corresponding to an integrated luminosity of 19.7 fb^{-1} . The main goal was to measure the production cross-section of single top quark in association with the Z boson. The measurement is performed in the full leptonic configuration of tqZ channel where both $Z \rightarrow \ell^+\ell^-$ and $t \rightarrow Wb \rightarrow \ell^\pm \nu_\ell b$ decay into leptons. These leptons have been selected after passing the tight selection criteria. This analysis is based on simple cut and count technique. This technique has been used for the extraction of signal events and to separate them from the dominant backgrounds like WZ and $t\bar{t}Z$. The Data Driven technique has been used for the estimation of contribution of the dominant background WZ and for fake rate calculation. For the calculation of cross-section different sources of systematic uncertainties have been taken into account. Systematics having effects on the cross-section are: Lepton Identification, Trigger, Jet Energy Correction and Jet Energy Resolution, Un-clustered MET, Pileup and luminosity. The SM predicted cross-section of times branching ratio of tqZ process is 0.00783 pb and the significance due to simulation is 0.79 ± 0.04 . The measured cross-section is $\sigma_{tqZ} = 0.018 \text{ (stat.)}_{-0.009}^{+0.011} \text{ (Syst.)}_{-0.004}^{+0.004} \text{ pb}$ with the observed significance for the inclusive cross-section is 1.8σ using background only hypothesis, while the expected significance is 0.81 having a one σ range of $[0.00-1.59]$ at the 68% CL. This is the first measurement of tqZ at the LHC energies, and the measured cross-section is in agreement within uncertainty with the expected NNLO prediction. The inclusive tqZ measured cross-section is in agreement with the SM prediction and with the BDT-based result [126].

In chapter 7, the results have been described about the stability and uniformity of CMS RPCs during 2012 data taking period. HV scans have been performed at the beginning of 2011 and again at the beginning of 2012. The HV scans were extremely effective, allowing to select the optimal operating HV values for each individual RPC chamber and to obtain a high level

of uniformity both in the barrel and in the endcap. Those efforts for calculating the the real working point of RPC chambers with the help of HV scan and automatic $HV_{eff}(P, T)$, result in increased efficiency stability and increased cluster size stability as a function of pressure and time. The operation of the CMS RPC muon system during 2012 data taking period of the LHC was outstanding. RPC systems are operating extremely well delivering good triggers and data for physics. The contribution to the CMS downtime is very low (less then 1.5 %). The fraction of active channels is very high and stable (more then 98 %). After three years running of LHC with growing instantaneous luminosity and its six years from the start of construction of the RPC detectors, the performance and efficiency of the detector remains within the specification of collaboration both as a trigger detector and as a reconstruction system. An excellent synchronization and efficiency of the trigger system is obtained. The RPC performance is stable with no degradation observed. The background measurements are within expectation. No significant issues for running at nominal luminosity are observed.

Appendix A

Datasets and Trigger

A.1 AOD Datasets

For the study of Standard Model tqZ process which is a rare decay, full 2012 dataset is used. The dataset corresponds to pp collision with integrated luminosity of 19.7 fb^{-1} collected by CMS experiment at 8 TeV. The tqZ process results in events having three leptons (electrons or muons) in the final state. Therefore DoubleMu, DoubleElectron and MuEG data streams are used in this analysis. Each of these datasets is associated with a special HLT path. Latest golden JSON file with the reconstruction tag "22JANRERECO" is being used. All datasets are filtered to have good lumi sections only.

Table A.1: **MuEG** Datasets expressed accordingly time period of data taking, used in the analysis

Datasets	Runs	Number of Events
/MuEG/Run2012A-22Jan2013-v1/AOD	190456 - 193621	2518137
/MuEG/Run2012B-22Jan2013-v1/AOD	193834 - 196531	14776453
/MuEG/Run2012C-22Jan2013-v1/AOD	198022 - 203742	20791905
/MuEG/Run2012D-22Jan2013-v1/AOD	203777 - 208686	21978229

A.2 Trigger

For the data samples given in above tables, events are required to pass one of the unprescaled double-electron, double-muon or muon-electron triggers. To avoid double counting of events, trigger path is required to be exclusive using the following criteria,

Table A.2: **Double Electron** Datasets with total number of events in each run period, used in the analysis

Datasets	Runs	Number of Events
/DoubleElectron/Run2012A-22Jan2013-v1/AOD	190456 - 193621	12964286
/DoubleElectron/Run2012B-22Jan2013-v1/AOD	193834 - 196531	23571931
/DoubleElectron/Run2012C-22Jan2013-v1/AOD	198022 - 203742	33843769
/DoubleElectron/Run2012D-22Jan2013-v1/AOD	203777 - 208686	34526899

Table A.3: **Double Mu** datasets for each run period collected by CMS experiment, which have been used in this analysis

Datasets	Runs	Number of Events
/DoubleMu/Run2012A-22Jan2013-v1/AOD	190456 - 193621	5636274
/DoubleMuParked/Run2012B-22Jan2013-v1/AOD	193834 - 196531	29308627
/DoubleMuParked/Run2012C-22Jan2013-v1/AOD	198022 - 203742	36820243
/DoubleMuParked/Run2012D-22Jan2013-v1/AOD	203777 - 208686	38006513

- accept all events from the DoubleMu primary dataset which have fired the above mentioned di-muon trigger paths
- accept all events from the DoubleElectron primary dataset, if they have fired one of the above di-electron paths and none of the di-muon paths
- accept all events from the MuEG primary dataset, if they have fired one of the above cross-flavor paths and neither of the di-muon nor di-electron paths

A.3 MC Datasets

In this Analysis, Summer12 signal (tqZ) and background Monte Carlo (MC) samples have been used for comparison with real data and background study. These simulated samples were generated by using Pythia (version 6), Powheg, Madgraph with tune "TuneZ2Star" and simulated samples were rescaled to total data integrated luminosity using NLO or higher order (when available) cross section. The complete list of MC simulated datasets which have been used in this analysis were generated by using the same pileup scheme "PU_S10". The simulated dataset with generated cross-section are given in Table A.5.

Table A.4: **Trigger** applied in the analysis

Process	HLT Path height
Double Electron	HLT_Ele17_CalIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_Ele8_CalIdT_CaloIsoVL_TrkIdVL_TrkIsoVL
Double Mu	HLT_Mu17_Mu8 HLT_Mu17_TkMu8
MuEG	HLT_Mu17_Ele8_CalIdT_CaloIsoVL_TrkIdVL_TrkIsoVL HLT_Mu8_Ele17_CalIdT_CaloIsoVL_TrkIdVL_TrkIsoVL

Table A.5: Simulated Datasets used in the analysis

Process	Dataset	$\sigma[\text{pb}]$ height
Signal (tqZ)	/TZJetsTo3LNUB_8TeV_TuneZ2Star_madgraph_tauola/[1]	0.00783
$t\bar{t}$	/TTJets_FullLeptMGDecays_8TeV-madgraph/[2]	234.
$t\bar{t}W$	/TTWJets_8TeV-madgraph/[1]	0.232
$t\bar{t}Z$	/TTZJets_8TeV-madgraph_v2/[1]	0.2057
WZ	/WZJetsTo3LNU_TuneZ2_8TeV-madgraph-tauola/[1]	1.058
$Z\gamma$	/ZGToLLG_8TeV-madgraph/[1]	132.6
ZZ	/ZZTo4e_8TeV-powheg-pythia6/[1]	0.07691
	/ZZTo4mu_8TeV-powheg-pythia6/[1]	0.07691
	/ZZTo2e2mu_8TeV-powheg-pythia6/[1]	0.1767
$Z + jets$	/DYJetsToLL_M-10To50filter_8TeV-madgraph/[1]	860.5
	/DYJetsToLL_M-50_TuneZ2Star_8TeV-madgraph-tarball/[1]	3532.8
	/ZbbToLL_massive_M-50_TuneZ2star_8TeV-madgraph-pythia6_tauola/[1]	94.1
$W\gamma^*$	/WGstarToLNU2E_TuneZ2star_8TeV-madgraph-tauola/[1]	5.873
	/WGstarToLNU2Mu_TuneZ2star_7TeV-madgraph-tauola/[1]	1.914
WW	/WW_TuneZ2star_8TeV_pythia6_tauola/[1]	5.817
[1]	Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	
	Summer12_DR53X-PU_S10_START53_V7A-v2/AODSIM	

Appendix B

Systematic Uncertainties Plots

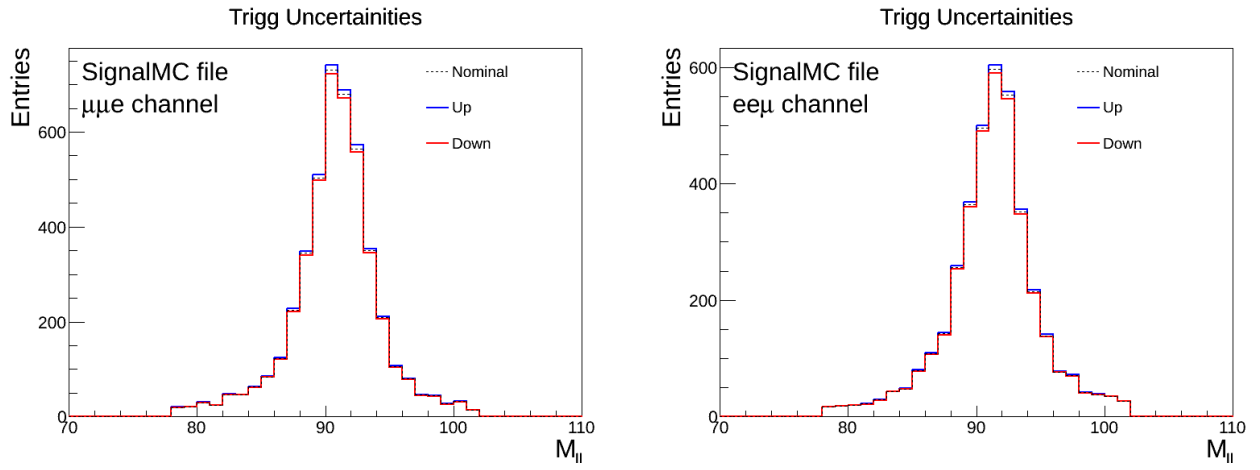


Figure B.1: Comparison of di-lepton invariant mass with and without trigger up/down systematic uncertainty in signal Monte Carlo. Left: distribution of di-lepton invariant mass in $\mu\mu e$ channel. Right: distribution of di-lepton invariant mass in $ee\mu$ channel.

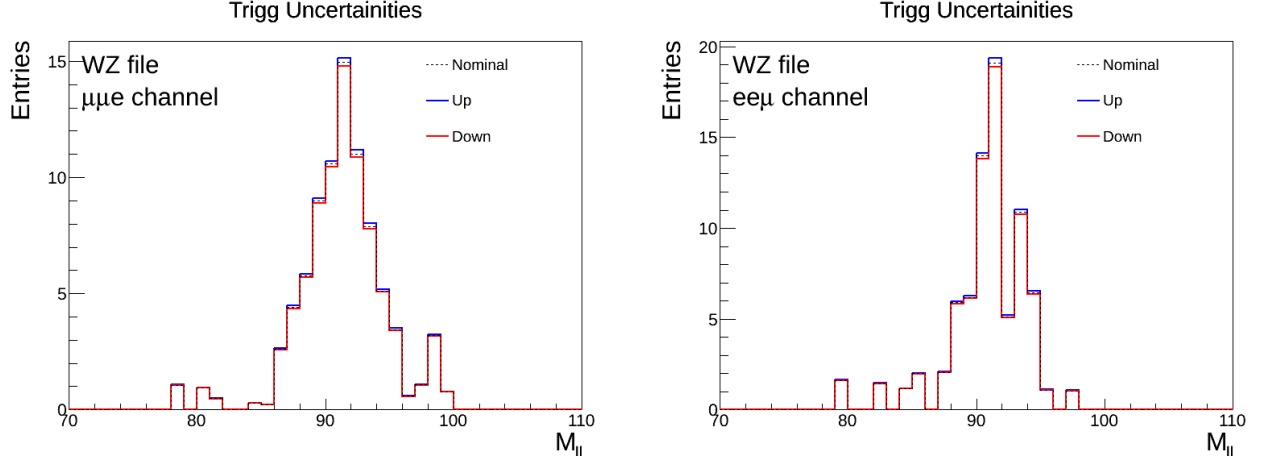


Figure B.2: Comparison of di-lepton invariant mass with and without trigger up/down systematic uncertainty in WZ Monte Carlo. Left: distribution of di-lepton invariant mass in $\mu\mu e$ channel. Right: distribution of di-lepton invariant mass in $ee\mu$ channel.

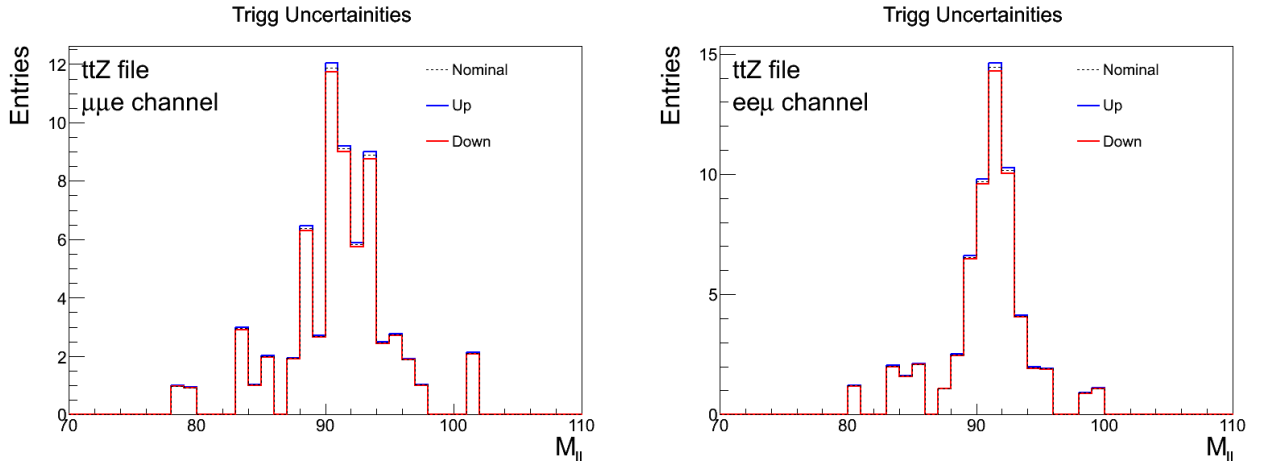


Figure B.3: Comparison of di-lepton invariant mass with and without trigger up/down systematic uncertainty in $t\bar{t}Z$ Monte Carlo. Left: distribution of di-lepton invariant mass in $\mu\mu e$ channel. Right: distribution of di-lepton invariant mass in $ee\mu$ channel.

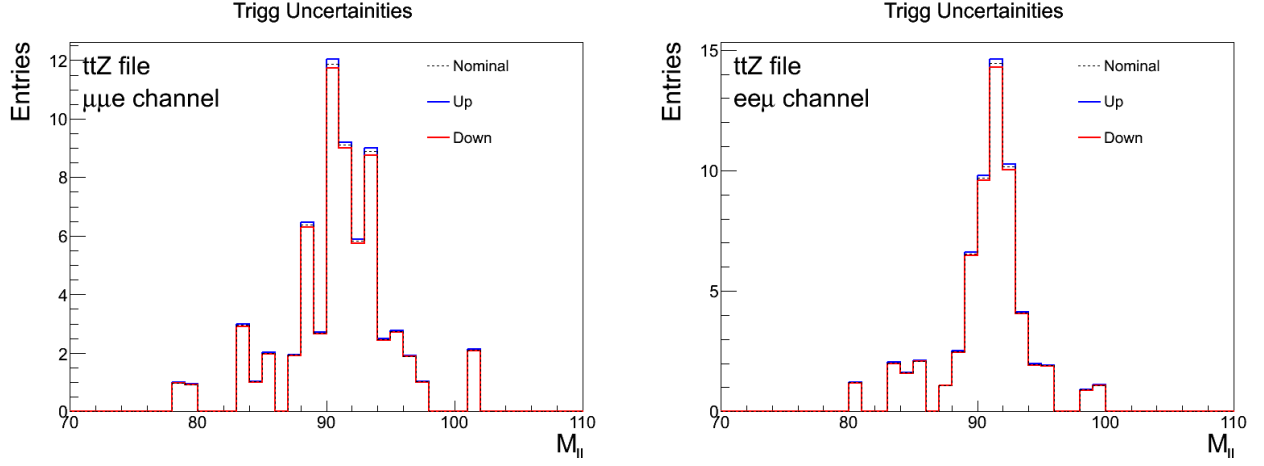


Figure B.4: Comparison of di-lepton invariant mass with and without trigger up/down systematic uncertainty in ttZ Monte Carlo. Left: distribution of di-lepton invariant mass in $\mu\mu e$ channel. Right: distribution of di-lepton invariant mass in $ee\mu$ channel.

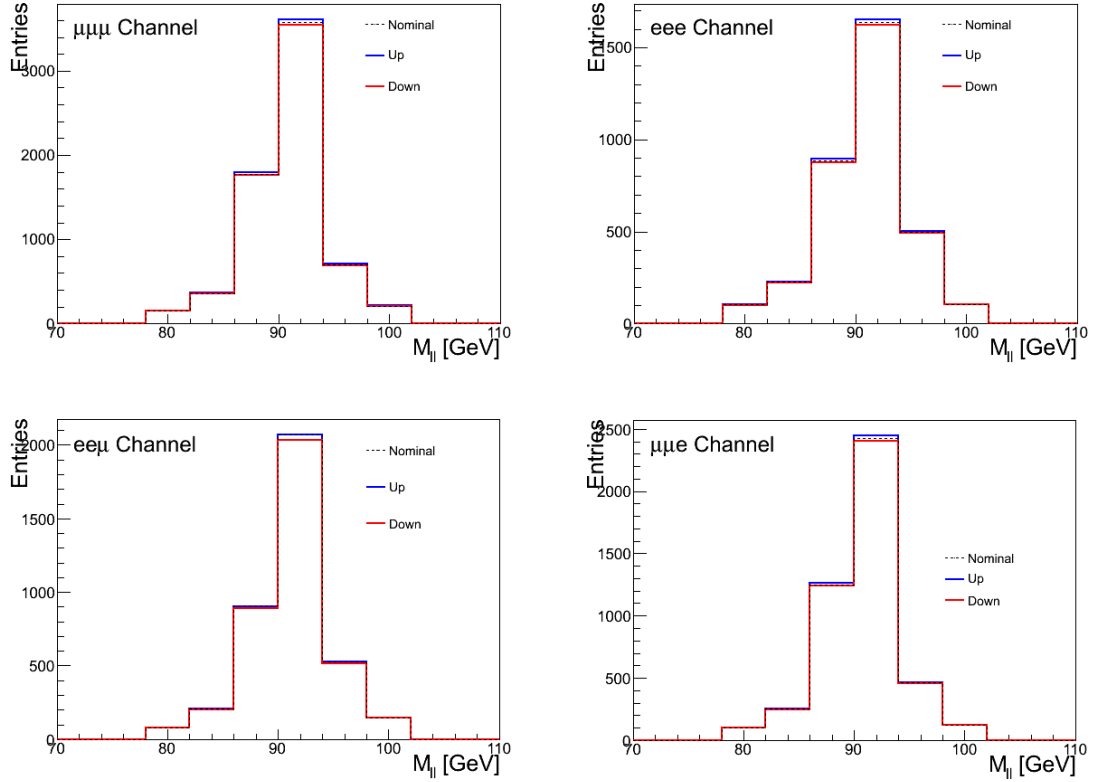


Figure B.5: Comparison of di-lepton invariant mass for different tri-lepton combinations with and without pileup up/down systematic uncertainty in signal Monte Carlo.

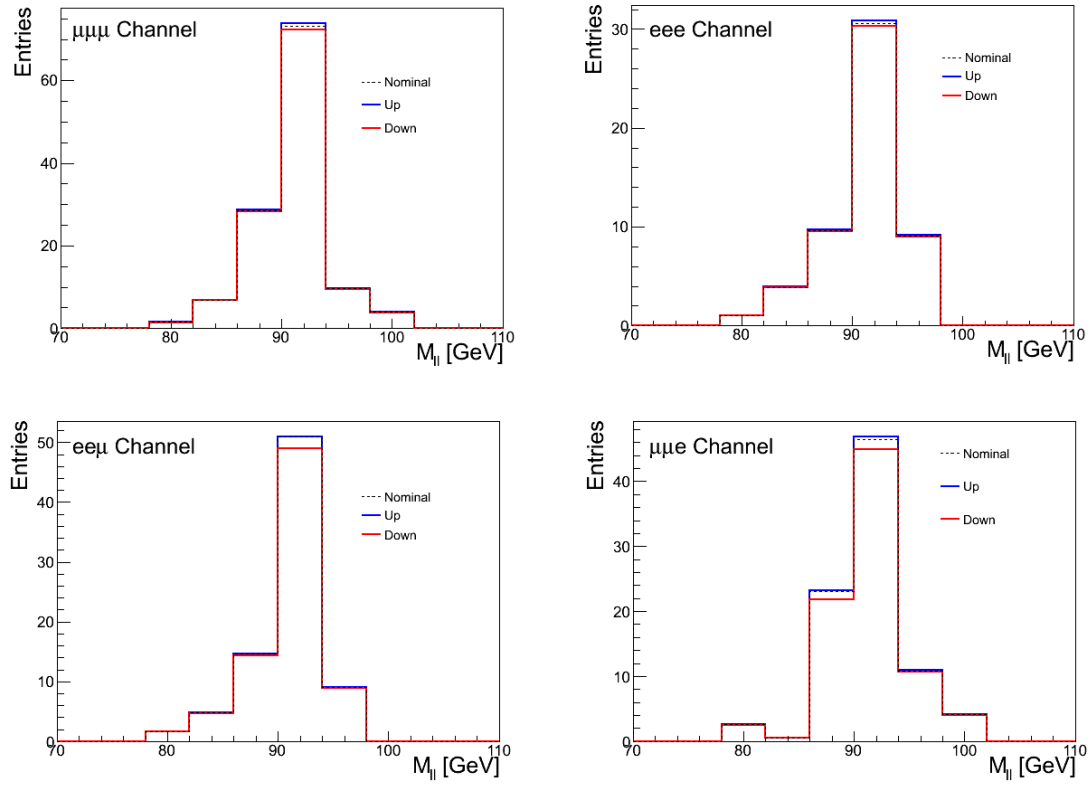


Figure B.6: Comparison of di-lepton invariant mass for different tri-lepton combinations with and without pileup up/down systematic uncertainty in WZ Monte Carlo.

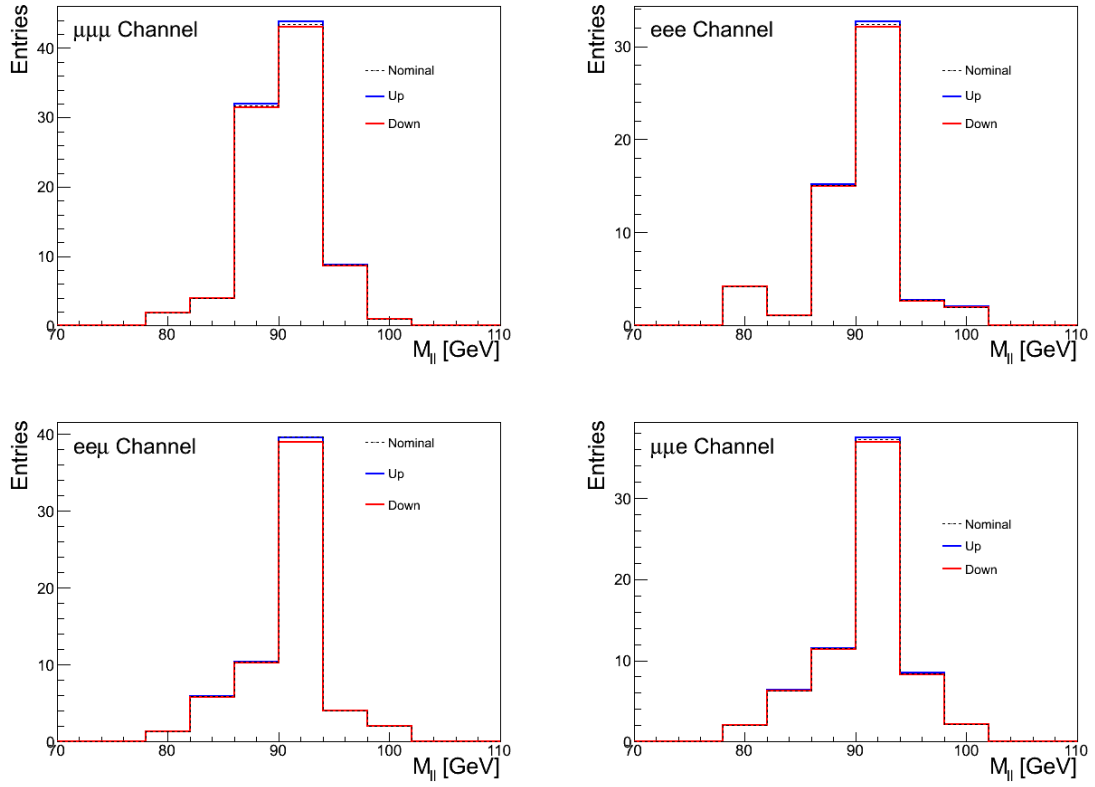


Figure B.7: Comparison of di-lepton invariant mass for different tri-lepton combinations with and without pileup up/down systematic uncertainty in $t\bar{t}Z$ Monte Carlo.

Appendix C

Lepton Isolation

C.1 Muon Isolation

In addition to the identification requirements, a further quality cut on isolation is performed to reduce contamination from muons that originate from hadronic processes. Recommended definition of isolation has been used for muons, which is shown in Eq. C.1. The purpose of isolation implementation in an analysis is that, muon should be an isolated particle in an event. It means that the energy flow in its vicinity is below a certain threshold, can effectively discriminate muons from the decays of W and Z boson from those produced in heavy-flavor decays and hadron decays in flight. The isolation for muons depends upon the p_T of all charged hadrons, photons transverse energy E_T , and the E_T of all neutral hadrons within a cone of radius $\Delta R < 0.4$ centered on the muon track direction, divided by the muon track p_T as shown in Eq. C.1. The energy of the neutral hadrons and photons are corrected for pile-up contamination by using an estimate of the total contribution of PU tracks.

$$I_{\text{rel}}^{\text{pf}} = \frac{1}{p_T^{(\mu)}} \left[\sum p_T^{(ch)} + \max \left(\sum p_T^{(nh)} + \sum p_T^{(\gamma)} - \Delta\beta, 0.0 \right) \right] \quad (\text{C.1})$$

$$\Delta\beta = \frac{1}{2} \sum p_T^{(ch,PU)} \quad (\text{C.2})$$

where $\sum p_T^{(ch,PU)}$ is the sum of transverse momenta of tracks associated to non-leading vertices.

C.2 Electron Isolation

Isolation refers to the amount of energy deposits surrounding a lepton, and it is a powerful quantity for discriminating against fake lepton signatures commonly found in jets. Electron isolation is computed by summing over the p_T of charged hadron, neutral hadron, and photon

collections generated using particle flow (PF) algorithm. We restrict the particles used in the isolation sum to be in the vicinity of the electron by imposing the following requirement:

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.3 \quad (\text{C.3})$$

The isolation sum needs to be computed from particles originating from the same hard scattering event as the electron. Because of pile-up, the energy sum could become contaminated with extraneous particles, which degrades the effectiveness of isolation. To mitigate the pile-up contamination from charged particles, we asked charged particles with their tracks originate at the primary vertex.

The expected energy density ρ , from neutral hadrons and photons is computed using an algorithm called FastJet. In this procedure, the average energy density from all jet activity is computed as a function of the number of pile-up vertices. To obtain the expected energy contribution, we have to multiply ρ with effective area A_{eff} . Where A_{eff} is the slope of the average isolation divided by ρ as a function of the number of pile-up vertices. Z has been used to calculate the effective area A_{eff} and are provided by the electron/photon Physics Object Group (POG) [127, 131].

Another effect to be accounted for, is the fact that the average energy present around an electron increases with its p_T . By placing a hard cut on the isolation energy, we would eliminate otherwise good electrons with high p_T . To avoid this, the isolation sum is divided by the electrons p_T . We call this relative isolation.

Putting everything together, the isolation for an electron is defined as

$$I_{\text{rel}}^{\text{pf}} = \frac{1}{p_T^{(e)}} \left[\sum p_T^{(ch)} + \max \left(\sum p_T^{(nh)} + \sum p_T^{(\gamma)} - \rho \times A_{\text{eff}}, 0.0 \right) \right] \quad (\text{C.4})$$

where $p_T^{(e)}$, $p_T^{(ch)}$, $p_T^{(nh)}$, and $p_T^{(\gamma)}$ are from the electron, charged hadrons, neutral hadrons, and photons respectively. The max statement is to ensure that the corrected neutral energy component does not drop below zero. At CMS experiment, we referee this as particle-flow isolation and requirement for this isolation is $I_{\text{rel}}^{\text{pf}} < 0.15$ for a cone size $\Delta R = 0.3$

Appendix D

MC Correction Factors

D.1 Pileup Re-weighting

Simulated Monte Carlo samples are often produced before or during a given data-taking period. It is to be expected, then, that the distribution of the average number of interactions per bunch crossing, obtained in MC will not necessarily match that from data. Therefore, to obtain a more accurate representation, an event weight is applied to fully reconstruct simulated events referred to as "pile-up re-weighting". The pile-up scenario simulated in MC simulation in general does not match with the pile-up conditions during 2012 data taking periods at the LHC. Simulated datasets have been generated before RunC and RunD of pp collision data were recorded. For this reason, simulation distributions are different from the actual ones. Simulated distributions are therefore re-weighted to make them in agreement with the pileup distribution in data. Pileup weights are calculated as a function of the expected additional interaction in simulated events because expected additional interaction has been used in Monte-Carlo event generation. In simulated events the expected additional interactions are accessed via method *PileupSummaryInfo::getTrueNumInteractions()*. In case of pp collision data, the distribution over this parameter is deduced from instantaneous Luminosity calculated per bunch crossing. Procedure of MC reweighting is known as *reweighting* and based on "true" number of additional interactions. Pileup re-weighting procedure is documented in detail in reference [132]. Number of reconstructed primary vertex distribution has been used to show the effects before and after pile-up re-weighting as shown in Fig. D.1. This Scale factor then applied to all distribution as a weight.

Therefore events from simulation are corrected event-by-event to match the measured distribution in data. The vertex multiplicity distribution is shown after applying the correction to

the simulation events. A good agreement between the data and the simulation can be observed.

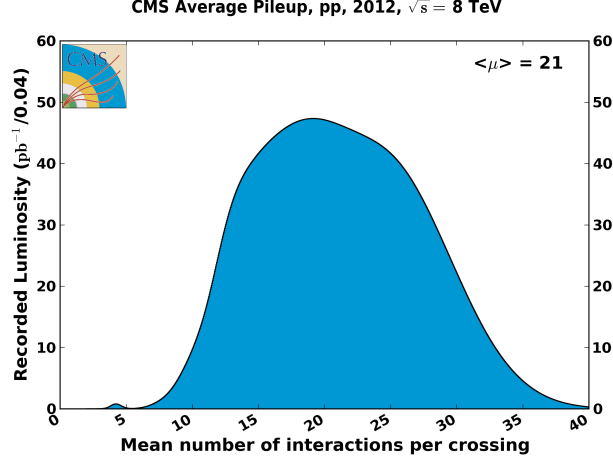


Figure D.1: No. of primary vertices reconstructed using simulation

D.2 b-tag Scale Factors

Identification efficiency of b-jet and the probability to identify a non-bet as a b-jet is not the same in data and MC simulation. Therefore to account for the difference in data and MC simulation, scale factors need to be applied to the simulation. The BTV POG [133] measures the b-tagging efficiency scale factors for b and light flavor jets. The scale factors depend in general on the jet flavor, the jet p_T and jet $|\eta|$.

$$\epsilon_f(i, j) = \frac{N_f^{b\text{-tagged}}(i, j)}{N_f^{Total}(i, j)} \quad (\text{D.1})$$

Where $N_f^{Total}(i, j)$ and $N_f^{b\text{-tagged}}(i, j)$ are the total number and the number of b-tagged jets, respectively, of flavor f in the (p_T, η) bin (i, j) . Jets flavor has been estimated using tool mentioned at [134] which determines the MC truth flavor of a jet. Tagging efficiencies depend on the event kinematics. Therefore, tagging efficiencies for each flavor, first computed from simulation and these efficiencies are dependent on the transverse momentum of jet and jets pseudo-rapidity shown in the Fig. D.2. After-wards MC simulated events have been weighted by the calculated SF values using one of the recommendations POG. After calculating the efficiency of tagger, events have been re-weighted by using event weight which depends upon the efficiencies and scale factors. The purpose of event re-weight is to predict the correct event yield in data by only changing the weight of the selected MC events.

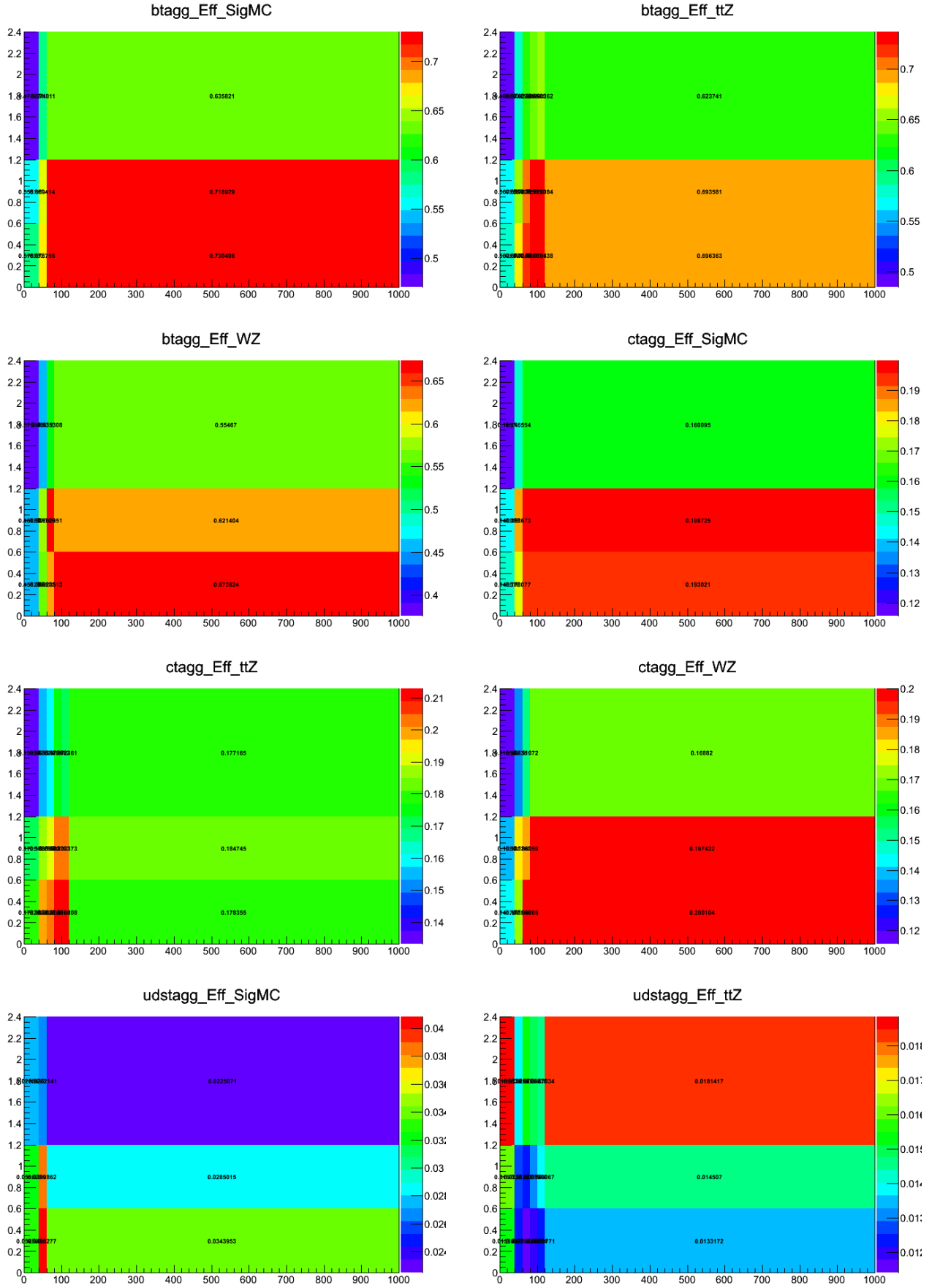


Figure D.2: b-tagging efficiency using signal MC and two dominant backgrounds, ttZ and WZ

The probability of a given configuration of jets in MC simulation and data is defined as

$$P(MC) = \prod_{i=\text{tagged}} \epsilon_i \prod_{j=\text{nottagged}} (1 - \epsilon_j) \quad (\text{D.2})$$

$$P(Data) = \prod_{i=\text{tagged}} SF_i \epsilon_i \prod_{j=\text{nottagged}} (1 - SF_j \epsilon_j) \quad (\text{D.3})$$

where ϵ_i is efficiency of b-tagging, SF_i are scale factors and functions of the jet flavor, p_T , and η . The event weight calculated as D.4,

$$w = \frac{P(Data)}{P(MC)} \quad (\text{D.4})$$

D.3 Lepton trigger Scale Factors

The trigger efficiency scale factors applied to correct the MC are given below in the Table D.3

Table D.1: Trigger efficiencies and data-to-MC scale factors are given in the table for four exclusive channels of tqZ .

Channel		Efficiency	Scale Factor (SF)
$\mu\mu\mu$	Data	0.979	$0.983^{+0.023}_{+0.022}$
	MC	0.995	
$\mu\mu e$	Data	0.844	$0.886^{+0.041}_{-0.042}$
	MC	0.952	
μee	Data	0.891	$0.987^{+0.034}_{-0.035}$
	MC	0.953	
eee	Data	0.957	$0.987^{+0.036}_{-0.036}$
	MC	0.970	

D.4 Lepton Identification and Isolation Scale Factors

Lepton efficiencies are estimated using a tag and probe method, following a simple cutcount based approach. In order to estimate the efficiency such that the measurement is uncorrelated from the di-lepton trigger efficiency, single lepton triggered data samples have been used to calculate the identification efficiencies. In Fig. D.3, total scale factors as a function of (η, p_T) of leptons are given.

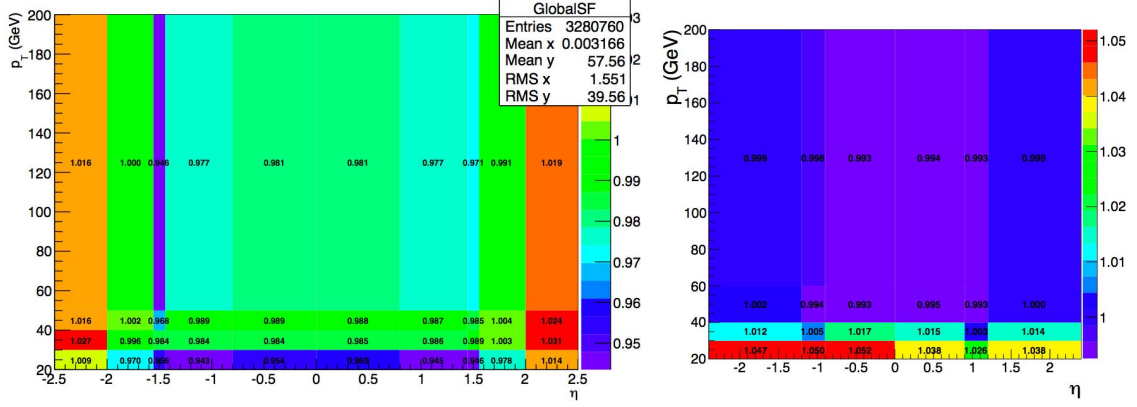


Figure D.3: Table shows the leptons Scale Factors as a functions of (η, p_T) , for muons (left) and electrons (right).

Table D.2: Muon Scale Factors.

$-\eta$	20-30 <i>GeV</i>	30-40 <i>GeV</i>	40-60 <i>GeV</i>	60-200 <i>GeV</i>	> 200 <i>GeV</i>
-2.4 to -1.2	1.047	1.012	1.002	0.999	0.999
-1.2 to -0.9	1.050	1.005	0.994	0.998	0.998
-0.9 to 0	1.052	1.017	0.993	0.993	0.993
0 to 0.9	1.038	1.015	0.995	0.994	0.994
0.9 to 1.2	1.026	1.003	0.993	0.993	0.993
1.2 to 2.4	1.038	1.014	1.000	0.999	0.999

Table D.3: Electron Scale Factors.

pt- eta	20-30 <i>GeV</i>	30-40 <i>GeV</i>	40-60 <i>GeV</i>	60-200 <i>GeV</i>	> 200 <i>GeV</i>
-2.5 to -2.0	1.009	1.027	1.016	1.016	1.016
-2.0 to -1.556	0.970	0.996	1.002	1.000	1.000
-1.556 to -1.442	0.956	0.984	0.968	0.946	0.946
-1.556 to -1.442	0.956	0.984	0.968	0.946	0.946
-1.442 to -0.8	0.943	0.984	0.989	0.977	0.977
-0.8 to 0	0.954	0.984	0.989	0.981	0.981
0 to 0.8	0.960	0.985	0.988	0.981	0.981
0.8 to 1.442	0.945	0.986	0.987	0.977	0.977
1.442 to 1.556	0.946	0.989	0.985	0.971	0.971
1.556 to 2	0.978	1.003	1.004	0.991	0.991
2 to 2.4	1.014	1.031	1.024	1.019	1.019

Bibliography

- [1] M. Gell-Mann, A Schematic Model of Baryons and Mesons, Phys. Lett. 8, 214 - 215, 1964.<http://inspirehep.net/record/11880?ln=en>.
- [2] G. Zweig, An SU(3) Model for Strong Interaction Symmetry and its Breaking, 1964, CERN Report No.8182/TH.401. <http://inspirehep.net/record/11881?ln=en>
- [3] J. Campbell et. al., Single Top Production in Association with a Z Boson at the LHC, 2013. <http://arxiv.org/abs/hep-ph/1302.3856v1>
- [4] Particle Data Group, Review of Particle Physics (RPP), Phys. Rev. D 86 (Jul, 2012) 010001. <http://journals.aps.org/prd/abstract/10.1103/PhysRevD.86.010001>
- [5] W. Wagner, Top Quark Physics in Hadron Collisions, Rept. Prog. Phys. 68, 2005. [arXiv: hep-ph/0507207](http://arxiv.org/abs/hep-ph/0507207)
- [6] M. Thomson, Modern Particle Physics, Cambridge University Press, 2013.
- [7] D. McMahon, Quantum Field Theory Demystified, McGraw-Hill, 2008.
- [8] B. R. Martin, G. Shaw, Particle Physics, Third Edition, Wiley Publisher, 2008.
- [9] D. H. Perkins, Introduction to High Energy Physics, Cambridge University Press, 2000.
- [10] E. A. Paschos, Electroweak Theory, Cambridge University Press, 2007.
- [11] P. W. Higgs, Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett., 1964.
- [12] F. Englert and R. Brout, Broken symmetry and the mass of gauge vector mesons, Phys. Rev. Lett., 1964.
- [13] S. Gasiorowicz and P. Langacker, Elementary Particles in Physics, <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.395.5166&rep=rep1&type=pdf>.

- [14] W. Greiner and B. Muller, Gauge Theory of Weak Interactions, Springer Verlag, 1993.
- [15] S. Weinberg, A Model of Lepton, Phys. Rev. Lett., 1967. http://physics.princeton.edu/~mcdonald/examples/EP/weinberg_prl_19_1264_67.pdf
- [16] The CMS Collaboration, Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC, Phys. Lett., B716: 30 - 61, 2012 <http://arxiv.org/abs/1207.7235>.
- [17] T. M. Nieuwenhuizen, Do non-relativistic neutrinos constitute the dark matter, EPL (Europhysics Letters), 2009. <http://iopscience.iop.org/article/10.1209/0295-5075/86/59001/meta>
- [18] R. A. Battye and Adam Moss, Evidence for Massive Neutrinos from Cosmic Microwave Background and Lensing Observations Phys. Rev. Lett., 2014. <http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.112.051303>
- [19] J. L. Rosner, The Standard Model and Beyond, hep-ph/0206176, 2002.
- [20] N. Cabibbo, L. Maiani, G. Parisi, and R. Petronzio, Bounds on the Fermions and Higgs Boson Masses in Grand Unified Theories, Nucl.Phys., 1979. <https://inspirehep.net/record/141517/>
- [21] The CDF experiment, Observation of Top Quark Production in $p\bar{p}$ Collisions, Phys. Rev. Lett. 74, 1995.
- [22] The D0 experiment, Observation of the Top Quark, Phys. Rev. Lett. 74, 1995.
- [23] S. W. Herb et al., Observation of a Dimuon Resonance at 9.5 GeV in 400 GeV Proton - Nucleus Collisions, Phys. Rev. Lett. 39, 252 - 255, 1977. <http://inspirehep.net/record/120368?ln=en>
- [24] W. Bernreuther, Top Quark Physics at the LHC, J.Phys.G, 2008. <http://arxiv.org/abs/0805.1333>
- [25] D. Dunser, Measurements of the top-quark mass and properties at CMS, J. Phys.: Conf. Ser. 623 012011, 2015. <http://iopscience.iop.org/article/10.1088/1742-6596/623/1/012011>

- [26] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO>
- [27] The D0 Collaboration, Observation of single top-quark production, Phys. Rev. Lett., 2009. <http://arxiv.org/abs/0903.0850v2> Aug 2009.
- [28] T. Aaltonen et al., First Observation of Electroweak Single Top Quark Production, Phys. Rev. Lett. 103, 2009. <http://arxiv.org/abs/0903.0885>
- [29] The D0 Collaboration, Observation of Single Top-Quark Production, Phys.Rev. Lett. 103, 2009. <http://arxiv.org/abs/0903.0850>
- [30] J. Agram et al., Probing Top Anomalous Couplings at the LHC with Trilepton Signatures in the Single Top Mode, Phys. Lett. B725, 2013 <http://arxiv.org/abs/1304.5551v2>
- [31] S. L. Glashow, J. Iliopoulos, and L. Maiani, Weak Interactions with Lepton-Hadron Symmetry, Phys. Rev. D, Feb, 1970. <http://journals.aps.org/prd/abstract/10.1103/PhysRevD.2.1285>
- [32] G. Degrand et al., Higgs Mass and Vacuum Stability in the Standard Model at NNLO, JHEP, 2012. <http://arxiv.org/abs/1205.6497>
- [33] G. Degrand et al., Higgs mass and vacuum stability in the Standard Model at NNLO, JHEP, 2012.
- [34] The CMS Collaboration, Measurement of the Top-quark Mass in $t\bar{t}$ Events with Lepton plus Jets Final States in pp Collisions at $\sqrt{s} = 8$ TeV, CMS PAS TOP-14-001, 2014. <http://cms.web.cern.ch/news/cms-presents-new-precise-measurement-top-quark-mass>
- [35] The ATLAS Collaboration, Measurement of Spin Correlation in $t\bar{t}$ Production from pp Collisions at $\sqrt{s} = 7$ TeV using the ATLAS Detector, ATLAS-CONF, 2011. <http://cds.cern.ch/record/1376409>
- [36] The CMS Collaboration, Measurement of Spin Correlations in $t\bar{t}$ Production, CMS PAS, 2012. CMS-PAS-TOP-12-004.
- [37] W. Bernreuther and Z. G. Si, Distributions and Correlations for Top Quark Pair Production and Decay at the Tevatron and LHC, hep-ph, 2010. <http://arxiv.org/abs/1003.3926> ATLASCONF-2011-117

- [38] T. M. P. Tait and C.-P. Yuan, Single Top Quark Production as a Window to Physics Beyond the Standard Model, Phys. Rev. D, 2000. <http://arxiv.org/abs/hep-ph/0007298>
- [39] Q. Hong Cao, Jose Wudka, and C.-P. Yuan, Search for New Physics via Single-Top Production at the LHC, Phys. Lett. B, 2007. <http://arxiv.org/abs/0704.2809>
- [40] T. M.P. Tait and C.P. Yuan, The Phenomenology of Single Top Quark Production at the Fermilab Tevatron, Phys.Rev.D, 2000, [arXiv:hep-ph/9710372](http://arxiv.org/abs/hep-ph/9710372).
- [41] J. Pumplin et al., New generation of parton distributions with uncertainties from global QCD analysis, JHEP, 2002. <http://arxiv.org/abs/hep-ph/0201195>
- [42] J. Campbell et. al., Single Top Production in Association with a Z Boson at the LHC, 2013. <http://arxiv.org/abs/hep-ph/1302.3856v1>
- [43] The CMS Collaboration, Measurement of Top Quark-Antiquark Pair Production in Association with a Z boson in pp Collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C74, 2014. <http://arxiv.org/abs/1406.7830>
- [44] Lyndon Evans and Philip Bryant, LHC Machine, J. Instrum. 3, S08001, 2008.
- [45] The LEP Design Report; CERN-LEP/84-01; June 1984 and CERN-AC/96-01 (LEP2); June 1996.
- [46] The CMS Collaboration, The Compact Muon Solenoid: Technical Proposal, CERN-LHCC-94-38 (1994).
- [47] The CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3, S08004 (2008). <http://stacks.iop.org/1748-0221/3/i=08/a=S08002>
- [48] The CMS Collaboration, CMS TDR - Technical Design Report: CMS - MAGNET
- [49] The CMS Collaboration, The CMS tracker system project: Technical Design Report, Technical Design Report CMS. CERN, Geneva, 1997. CERN-LHCC-98-006. CMS-TDR-005.
- [50] D. Barge et al., Study of Photon Conversion Rejection at CMS. Technical Report, 2009. CMS AN-2009/159.

- [51] The CMS Collaboration, The CMS electromagnetic calorimeter project: Technical Design Report, Technical Design Report CMS. CERN, Geneva, 1997. CERN-LHCC-97-033. CMS-TDR-004. <http://cdsweb.cern.ch/record/349375>
- [52] G. Gratta, et al., Crystal Calorimeters in Particle Physics, 1994. *Ann.Rev.Nucl.Part.Sci.* **44**(1994)453.
- [53] The CMS Collaboration, Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at 7 TeV, JINST, Vol 8, 2013. doi:10.1088/1748-0221/8/09/P09009.
- [54] The CMS Collaboration, The Hadron Calorimeter Project Technical Design Report, CERN/LHCC 97-31, CMS TDR 2, 20 June 1997
- [55] The CMS Collaboration, The Muon Project Technical Design Report, CERN/LHCC 97-32, CMS TDR 3, 15 December 1997
- [56] The CMS Collaboration, Concept of the First Level Global Trigger for the CMS Experiment at LHC, Nucl. Instr. Meth. A473/3, 2001.
- [57] The CMS Collaboration, The TriDAS project, technical design report. Volume 2: Data acquisition and high-level trigger technical design report, CERN-LHCC-2002-026
- [58] T. Sjostrand et al., PYTHIA 6.4 Physics and Manual, JHEP, 2006. <http://arxiv.org/abs/hep-ph/0603175>
- [59] B. Andersson, The Lund Model, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, 2005.
- [60] T. Stelzer and W.F. Long. Automatic Generation of Tree Level Helicity Amplitudes, hep-ph, 1994. <http://arxiv.org/abs/hep-ph/9401258>
- [61] V. Hirschi et al., Automation of One-Loop QCD Corrections, JHEP, 2011. <http://arxiv.org/abs/1103.0621>
- [62] P. Nason, A New Method for Combining NLO QCD with Shower Monte Carlo Algorithms, JHEP, 2004. <http://arxiv.org/abs/hep-ph/0409146>

- [63] S. Frixione, P. Nason, and C. Oleari, NLO QCD Computations with Parton Shower Simulations: the POWHEG Method, JHEP, 2007. <http://arxiv.org/abs/0709.2092>
- [64] S. Alioli, P. Nason, C. Oleari, and E. Re, General Framework for Implementing NLO Calculations in Sower Monte Carlo Programs: the POWHEG BOX, JHEP 06, 043, 2010.
- [65] D. Bourilkov, LHAPDF: PDF Use from the Tevatron to the LHC, <http://arxiv.org/abs/hep-ph/0605240v2>
- [66] P. Biallass et al., Parton Distribution Uncertainty Determination within CMSSW, CMS AN -2009/048.
- [67] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and Tim Stelzer, Madgraph 5: going beyond, JHEP, 2011. <http://arxiv.org/abs/1106.0522>
- [68] P. Zeiler Skands, Tuning Monte Carlo Generators: The Perugia Tunes, Phys.Rev, 2010. doi: 10.1103/PhysRevD.82.074018.
- [69] G.Corcella et al., HERWIG 6.5: An Event Generator for Hadron Emission Reactions with Interfering Gluons,hep-ph, 2002. <http://arxiv.org/abs/hep-ph/0011363>
- [70] Buckley et al., General-Purpose Event Generators for LHC Physics, Phys. Rept. 504, 145, 2011.
- [71] S. Agostinelli et al., Geant4: A Simulation Toolkit, Nucl. Instrum.Meth. A506, 2003. <http://inspirehep.net/record/593382?ln=en>
- [72] The CMS Collaboration, Fast Simulation of the CMS Detector at the LHC, CERN-CMS-CR-2010-297 (2010). <http://inspirehep.net/record/1398906>
- [73] The CMS Collaboration, Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and MET, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009. <http://inspirehep.net/record/925379>
- [74] The CMS Collaboration, Track Reconstruction Performance in CMS, Nucl.Phys.Proc.Suppl., 2008. arXiv:0812.5036
- [75] The CMS Collaboration, Description and Performance of Track and Primary-Vertex Reconstruction with the CMS Tracker, JINST, 2014. <http://dx.doi.org/10.1088/1748-0221/9/10/P10009>

- [76] The CMS Collaboration, Tracking and Primary Vertex Results in First 7 TeV Collisions, CMS-PAS-TRK-10-005, 2010.
- [77] W. Adam, R. Fruhwirth, A. Strandlie, and T. Todorov, Reconstruction of electrons with the Gaussian Sum Filter in the CMS tracker at LHC, CHEP03, 2003. <http://arxiv.org/abs/physics/0306087>
- [78] The CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, JINST, 2015. <http://arxiv.org/abs/1502.02701>
- [79] Salam et al. A practical Seedless Infrared-Safe Cone jet algorithm. JHEP, 05:086, 2007.
- [80] M. Cacciari, Gavin P. Salam, and Gregory Soyez. The Anti-k(t) jet clustering algorithm. JHEP, 0804:063, 2008.
- [81] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/CMSPublic/TWikiBTVMoriond2013>.
- [82] The CMS Collaboration, Identification of b-quark jets with the CMS experiment, 2013 JINST 8 P04013.
- [83] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/CMSPublic/WorkBookMetAnalysis>.
- [84] The CMS Collaboration, Performance of the CMS missing transverse momentum reconstruction in pp data at 8 TeV, JINST 8, 2015.
- [85] The CMS Collaboration, Performance of CMS Muon Reconstruction in pp Collision Events at $\sqrt{s} = 7$ TeV, JINST, 2012. doi:10.1088/1748-0221/7/10/P10002
- [86] The CMS Collaboration, The CMS Data Quality Monitoring Software: Experience and Future Prospects, Journal of Physics: Conference Series, 2014. <http://iopscience.iop.org/article/10.1088/1742-6596/513/3/032024>
- [87] CMS twiki, https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideHiggsAnalysisCombinedLimit#How_to_run_the_tool.
- [88] CMS Physis Validation Group, Estimating Systematic Errors due to Pileup Modeling, 2014.

- [89] The CMS Collaboration, Parton Distribution Uncertainty Determination with CMSSW, Technical Report CMS-AN-2009-048, CERN, Geneva, 2009.
- [90] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/CMS/TopMU0>.
- [91] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/CMS/TopEGM#Electron>.
- [92] CMS twiki, <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TopJME>.
- [93] The CMS Collaboration, Performance of b tagging at $\sqrt{s} = 8$ TeV, in multijet, $t\bar{t}$ and boosted topology events. CMS-PAS-BTV-13-001
- [94] Particle Data Group Collaboration, Review of Particle Physics, Chin.Phys., 2014.
- [95] The CMS Collaboration, Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS, JINST, 2011. <http://iopscience.iop.org/article/10.1088/1748-0221/6/11/P11002/meta>.
- [96] The CMS Collaboration, 8 TeV Jet Energy Corrections and Uncertainties based on 19.8 fb⁻¹ of Data in CMS, 2013. <https://cds.cern.ch/record/1627305/>
- [97] The CMS Collaboration, CMS Luminosity Based on Pixel Cluster Counting-Summer 2013 Update. CERN, CMS-PAS-LUM-13-001, 2013. <http://cds.cern.ch/record/1598864>.
- [98] Procedure for the LHC Higgs boson search combination in Summer 2011, ATL-PHYS-PUB-2011-11, 2011.
- [99] CMS twiki, <https://twiki.cern.ch/twiki/bin/viewauth/CMS/SWGuideHiggsAnalysisCombinedLimit>
- [100] F. Dulat and B. Mistlberger, Limit Setting Procedures and Theoretical Uncertainties in Higgs Boson Searches, JHEP, 2012. arXiv:1204.3851v2 [hep-ph], 2012
- [101] A. L. Read, Modified Frequentist Analysis of Search Results (The CL_s Method), in Proceedings of the First Workshop on Confidence Limits, CERN-OPEN-2000-205, 2000. <http://cds.cern.ch/record/451614/files/open-2000-205.pdf>
- [102] G. J. Feldman, R. D. Cousins, A Unified Approach to the Classical Statistical Analysis of Small Signals, HUTP-97/A096, 2008. arXiv:physics/9711021 [physics.data-an]

- [103] The ATLAS Collaboration, Procedure for the LHC Higgs boson search combination in summer 2011, 2011
- [104] A. L. Read, Presentation of Search Results: the CLs Technique, J. Phys. G: Nucl. Part. Phys., 28, 2002. <http://iopscience.iop.org/article/10.1088/0954-3899/28/10/313/pdf>
- [105] The CMS Collaboration, Statistical Methods in CMS Searches, 2011
- [106] T. R. Junk, Statistical Methods for Experimental Particle Physics, Fermilab, 2009. TRIUMF_{summer_institute}
- [107] T. Sjostrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 Physics and Manual, JHEP, 2006. <http://arxiv.org/abs/hep-ph/0603175>
- [108] CMS Analysis Note, Measurement of the WZ Production Cross-section with the Full 2011 Dataset, CMS AN AN-12-090, 2011.
- [109] W. Riegler, R. Veenhof, and C. Lippmann, Simulation of Resistive plate chambers, Nucl. Instr. Meth. A., 2002.
- [110] R. Santonico and R. Cardarelli, Progress in Resistive Plate Counters, Nucl. Instr. and Meth., 1988.
- [111] K. Bunkowski, Optimization, Synchronization, Calibration and Diagnostic of the RPC PAC Muon Trigger System for the CMS detector, CMS Thesis, 2009.
- [112] The CMS Collaboration, The Muon Project Technical Design Report, CERN/LHCC 97-32, CMS TDR 3, 15 December 1997
- [113] M. Abbrescia et al. Performance of Resistive Plate Chambers for the Muon Detection at CMS, Nucl. Phys. Proc. Suppl., 1999.
- [114] The CMS AN, The Detector Control Systems for the CMS Resistive Plate Chamber, CMS NOTE -2008/036, 2008.
- [115] R. Santonico and R. Cardarelli, Development of Resistive Plate Counters, Nuclear Instruments and Methods (377-380), 1981.

- [116] CAEN S.p.A. Costruzioni Apparecchiature Elettroniche Nucleari, http://www.caen.it/nuclear/easy_info.php
- [117] The CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3, S08004 (2008).
- [118] G. Polese, The Detector Control Systems for the CMS Resistive Plate Chamber at LHC, CMS Thesis, 2009 .
- [119] P. Verwilligen, Data-driven Determination of Z ($\nu\nu$) Background to New-Physics Searches with Jets and Missing Transverse Momentum at CMS, CERN-THESIS-2012-150, 2012.
- [120] The CMS Collaboration, The Detector Control Systems for the CMS Resistive Plate Chamber, Journal of Physics, Conference Series 219, 2010.
- [121] The CMS Collaboration, Uniformity and Stability of the CMS RPC Detector at the LHC, JINST, 2013. <http://iopscience.iop.org/article/10.1088/1748-0221/8/03/P03017>
- [122] The CMS Collaboration, CMS RPC Tracker Muon Reconstruction, JINST, 2014. <http://iopscience.iop.org/article/10.1088/1748-0221/9/10/C10027/meta>
- [123] The CMS Collaboration, CMS Reconstruction Improvement for the Muon Tracking by the RPC Chambers, JINST, 2013.
- [124] The CMS Collaboration, CMS RPC muon detector performance with 2010-2012 LHC data, JINST, 2014.
- [125] The CMS Collaboration, CMS RPC muon detector performance with 2010-2012 LHC data, JINST, 2014.
- [126] CMS twiki, <http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/T0P-12-039/index.html>.
- [127] CMS Physics Validation Group, Estimating Systematic Errors due to Pileup Modeling, 2014. <https://twiki.cern.ch/twiki/bin/viewauth/CMS/PileupSystematicErrors>. [Un-published. Online, accessed 2014].
- [128] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/CMS/TopMU0>.

- [129] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/CMS/TopEGM#Electron>.
- [130] CMS twiki, <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TopJME>.
- [131] The CMS Collaboration, Parton Distribution Uncertainty Determination with CMSSW, Technical Report CMS-AN-2009-048, CERN, Geneva, 2009.
- [132] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/CMS/PileupSystematicErrors> .
- [133] CMS twiki, <https://twiki.cern.ch/twiki/bin/view/CMS/BTagSFMethods>.
- [134] CMS twik, <https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideBTagMCTools> .