



**SEARCH FOR RESONANCE IN THE PHOTON+JET FINAL STATE AT
 $\sqrt{s} = 13$ TeV USING THE CMS DETECTOR AT LHC**

A THESIS

**Submitted to the
PANJAB UNIVERSITY, CHANDIGARH**

For the Award of

DOCTOR OF PHILOSOPHY

2023

in

FACULTY OF SCIENCE

BY

JYOTI BABBAR

GUIDE

Prof. VIPIN BHATNAGAR

Dr. SUSHIL SINGH CHAUHAN

**DEPARTMENT OF PHYSICS
PANJAB UNIVERSITY
CHANDIGARH, INDIA**



AUGUST 2023

DECLARATION

I declare that the thesis entitled **“SEARCH FOR RESONANCE IN THE PHOTON+JET FINAL STATE AT $\sqrt{s} = 13$ TeV USING THE CMS DETECTOR AT LHC”** has been prepared by me under the guidance of Prof. Vipin Bhatnagar, Professor, Department of Physics, Panjab University, Chandigarh and Dr. Sushil Singh Chauhan, Assistant Professor, Department of Physics, Panjab University, Chandigarh. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

Jyoti Babbar

Department of Physics,
Panjab University, Chandigarh

DATE:

CERTIFICATE

We certify that Jyoti Babbar has prepared her thesis entitled “**SEARCH FOR RESONANCE IN THE PHOTON+JET FINAL STATE AT $\sqrt{s} = 13$ TeV USING THE CMS DETECTOR AT LHC**” for the award of PhD degree of the Panjab University, Chandigarh, under our guidance. She has carried out the work at the Department of Physics, Panjab University, Chandigarh.

Prof. Vipin Bhatnagar

Professor
Department of Physics
Panjab University, Chandigarh

Dr. Sushil Singh Chauhan

Assistant Professor
Department of Physics
Panjab University, Chandigarh

DATE:

*Dedicated To My
Family
&
Friends*

Acknowledgement

First and foremost, I would like to give my sincerest gratitude to my supervisors Prof. Vipin Bhatnagar and Dr. Sushil Singh Chauhan, for their constant guidance, support, and encouragement. I am extremely grateful for their dedication and constant discussions on various aspects of the analysis and other tasks I was involved in. They were always willing to listen and offer assistance whenever needed.

I am grateful to Prof. J.B Singh, Prof. Manjit Kaur, Prof. Suman Bala Beri and Dr. Sunil Bansal for providing us adequate facilities in the PU EHEP lab. Many thanks to India-CMS Collaboration and PU EHEP group for conducting regular meetings to discuss our work and give valuable suggestions.

I am thankful to Prof. Ghan Shyam Singh Saini, Chairman, Department of Physics, Panjab University, for providing adequate facilities to work in the department.

This research would not have been possible without the financial support of the Department of Science and Technology (DST). I owe my sincere gratitude to the European Council for Nuclear Physics (CERN) for providing me the computing resources and hosting me at different points in time. I have thoroughly enjoyed going through all the intricacies of acquisition, retrieval, analysis, and presentation of experimental data.

I want to express my special thanks to Prof. Sunanda Banerjee for being such an inspiration to me with his attitude towards work.

I am so thankful to my amazing labmates in Panjab University, most especially Amandeep, Rajat and Sandeep Sharma, working with them was a real joy. They have made my time at the physics department much more enjoyable.

Above all, I want to thank my family for their constant love and encouragement these many years. I owe my thesis to them. I would like to show my earnest gratitude to my mother, Mrs. Manju Babbar and my husband, Mr. Harkawal Singh for motivating me and listening to my constant jibber-jabber over phone. I would also

like to thank my brother Mr. Anmol Babbar for being there through out this journey of PhD.

One page is not enough to thank everyone, I apologize to those whose names I could not mention but I express my deepest gratitude to everyone for their priceless support, encouragement and standing by me all the time.

Last, but not least I would like to thank my “Cup of Tea” to boost me enough to continue.

Date:

Jyoti Babbar

Abstract

The Standard Model, that describes the fundamental particles and their interactions, is a very solid and elegant theory, verified in many independent experiments. However there are still many reasons to believe it is incomplete. To name some: the theory does not incorporate gravity; it does not explain the asymmetry of matter and antimatter in the universe; similarity in three families of fermions. There are several models of new physics that predict the existence of resonances at the TeV scale, and therefore accessible at the proton-proton collisions of the LHC. The new resonance searches presented in this thesis are narrow resonances decaying to a photon and a jet. If such a resonance exists, the experimental signature will be a bump corresponding to the mass of the resonance over the smoothly falling invariant mass distribution of photon and jet.

In this thesis, proton-proton collision data collected by CMS experiment corresponding to an integrated luminosity of 138 fb^{-1} is used. The potential backgrounds are estimated using data-driven techniques and excess of events above the standard model background predictions are investigated. No evidence for the existence of new particles is observed relative to expectations from the standard model. Hence, upper limits on production cross-section times branching ratio and lower limits on the mass of excited quarks and Quantum Black Holes, predicted by the BSM models, are placed at a 95% confidence level.

The thesis also presents the installation of Gas Electron Multiplier (GEM) in CMS muon system, as an upgrade of CMS detector for HL-LHC. The GEM detectors are installed in the forward region of the muon system to improve the muon reconstruction and the trigger rate. The Panjab University participated in the assembly and testing of the GEM detectors for muon upgrade. A brief summary of the assembly procedure and testing setup is presented in this thesis.

Contents

List of Figures

List of Tables

1	Introduction and Motivation	1
1.1	The Standard Model	3
1.1.1	Elementary particles	3
1.1.2	The SM particle interactions	5
1.1.3	Limitations of SM	8
1.2	Beyond Standard Model	10
1.2.1	Compositeness model	10
1.2.2	Large Extra Dimension models	12
1.3	Previous Searches	15
1.4	Thesis Organization	16
2	Experimental Apparatus	23
2.1	Large Hadron Collider	23
2.1.1	Luminosity	25
2.1.2	Pileup	27

2.2	The CMS Detector	28
2.2.1	Co-ordinate system	29
2.2.2	Tracker	30
2.2.3	Electromagnetic Calorimeter	32
2.2.4	Hadronic Calorimeter	35
2.2.5	Magnet	38
2.2.6	Muon Detector	38
2.2.7	Trigger System	43
3	Gas Electron Multiplier Detector	49
3.1	Motivation for GEM upgrade in CMS	50
3.2	GEM Technology	52
3.3	Principle of GEM detector in CMS	53
3.4	Production of GE1/1	55
3.5	Assembly procedure of GE1/1	56
3.5.1	Preparation of Drift Board	56
3.5.2	Preparation of Readout Board	58
3.5.3	Preparation of Internal and External Frames	59
3.5.4	Preparation of Foils	61
3.6	Assembly of Chamber	62
3.7	Preparation of the final stack	65
3.8	Quality-Check Tests	69
3.8.1	QC2: Current Leakage Test	70
3.8.2	QC3 Gas Leakage Test	71
3.8.3	QC4 HV test with CO_2 gas	73
3.9	Further testing and validation	76

3.10 Summary	78
4 Event Simulation and Reconstruction	83
4.1 Types of processes in pp collisions	84
4.2 Parton Shower and Hadronization process	85
4.3 Event Generation and Simulation	87
4.3.1 Matrix Element	87
4.3.2 Event Generators	87
4.3.3 Detector Response	88
4.4 Data Flow	89
4.5 Physics Object Reconstruction	90
4.5.1 Primary Vertex	90
4.5.2 Track Reconstruction	91
4.5.3 Object Reconstruction	93
4.5.4 Photon Reconstruction	94
4.5.5 Jet Reconstruction	95
4.5.5.1 b-jet Reconstruction	98
5 Data and MC Analysis	107
5.1 Signal processes	109
5.1.1 Excited Quark Production	109
5.1.2 Quantum Black Holes Production	110
5.2 SM Background Processes	111
5.3 Data and Monte-Carlo Simulation Samples	113
5.4 Analysis Strategy	114
5.5 Signal Modelling	115
5.6 Signal Interpolation	117

6	Event Selection	123
6.1	Trigger Selection	123
6.2	Event Reweighting	125
6.2.1	Pileup-Reweighting	126
6.2.2	Luminosity Reweighting	127
6.3	Event Selection	127
6.3.1	Photon Selection	129
6.3.1.1	Isolation Variables	129
6.3.1.2	Shower Shape Variables	130
6.3.1.3	Cut-Based Identification Technique	131
6.3.2	Jet Selection	132
6.3.3	b-Jet Selection	136
6.3.3.1	b-jets in WideJet	138
6.3.4	Photon+Jet System	139
6.4	Optimization of Event Selection Criteria	153
6.4.1	Photon Identification Working Point	153
6.4.2	DeepJet Discriminator Working Point	154
6.4.3	$\Delta\eta$ and Mass Threshold	154
6.5	Selections summarized	157
6.6	Background Parameterization	159
6.6.1	Fisher-test	162
6.6.2	Goodness-of-fit test	163
6.7	Bias due to the choice of fit functions	167
6.8	Systematic Uncertainties	171
7	Results and Summary	179

CONTENTS

7.1	Limit Computation Method	179
7.2	Results	181
7.2.1	Local Significance	181
7.2.2	Exclusion Limits and Conclusion	182
7.3	Summary	188
7.3.1	Gas Electron Multiplier detector assembly and characterization	188
7.3.2	Search for resonances in the photon+ jet final state	189
7.4	Outlook	191
A	List of Samples	195
A.1	Data Samples	195
A.2	Signal samples for q^* resonances	197
A.3	Signal samples for b^* resonances	198
A.4	Signal samples for QBH resonances	199
B	Invariant mass of a system	200
C	Invariant Mass Binning	201
D	List of triggers used in the analysis	202
	List of Publications	203
	Reprints	209

List of Figures

1.1	An illustration of particle discoveries across different years	2
1.2	The SM particles, spin-1/2 particles known as fermions in purple(quarks) and green(leptons). The three columns represents three generations of the fermions. The spin-1 vector boson in orange color, and the Higgs scalar boson in yellow.	3
1.3	The production of excited quarks via gauge interactions (left) and via contact interactions (right).	12
1.4	An illustration of gravity escaping to other hidden world with extra dimensions, while other particles existing in our 3-dimensional spatial space.	13
2.1	A schematic diagram of the CERN accelerator complex [2].	24
2.2	Schematic layout of the LHC ring divided into eight octants. The positions of four experiments located is indicated by star, and the CMS is located at octant 5 (Point 5) [8].	26
2.3	Machine Parameters of the LHC	26
2.4	The LHC performance during Run-II with integrated luminosity on left for different taking years and cumulative integrated luminosity recorded by CMS for Run-II at center of mass energy 13 TeV.	27
2.5	The mean number of interactions per beam crossing for each data taking year.	28
2.6	The cross-sectional view of the CMS detector [9].	29
2.7	The right-handed coordinate system of CMS detector, also representing the coverage in η , ϕ and θ	30

2.8	A comparison of pixel detector in the tracker before and after Phase-I upgrade. The longitudinal view (left) shows the pixel layers after the upgrade in the upper half and before in the lower half. In the right, shows transverse view of the pixel detector with concentric barrel layers.	31
2.9	A layout of the tracker in r - z view, with different sensor modules of subsystems in tracker [12].	32
2.10	A schematic diagram of the ECAL detector [14].	34
2.11	The energy resolution of ECAL from $Z \rightarrow ee$ as a function of η for different years of Run-I and Run-II data taking [17].	34
2.12	The longitudinal view of CMS detector in r - η plane showing the positions of hadronic barrel (HB), hadronic endcap (HE), Hadronic outer (HO) and hadronic forward (HF) calorimeters in the HCAL [6].	35
2.13	The numbering scheme of 18 azimuthal wedges in HB of HCAL [6]. Wedge 1 is in $+x$ direction of LHC ring.	36
2.14	A longitudinal view of one quarter of HCAL detector in the $r - z$ plane representing the tower segmentation [19].	37
2.15	The magnetic field $ B $ (left) and field lines (right) in the longitudinal view of the CMS detector [26].	39
2.16	Longitudinal view of muon detector with its three subsystems: Drift Tubes (DTs) in yellow, Cathode Strip Chambers (CSCs) in green and Resistive Plate Chambers (RPCs) in blue [26].	40
2.17	A schematic layout of muon detector.	41
2.18	A schematic view of CSC chamber.	42
2.19	A cross-section view of RPC system.	43
3.1	A quadrant of the muon system, showing DT chambers (yellow), RPC (light blue), and CSC (green). The new GEM detector station, GE1/1 is indicated in red [3].	50
3.2	Simulations of L1 muon trigger rate at a luminosity of $2 \times 10^{34} \text{ cm}^2 \text{ sec}^{-1}$ as a function of p_T threshold [3].	51
3.3	A microscopic view of GEM foil, with holes and its sketch taken from [6].	52
3.4	A layout of GEM detector with single foil [7].	53
3.5	A schematic view of the GE1/1 detector with three foils placed at a gap of 3/1/2/1 mm in between drift and readout boards [9].	54

3.6	The drift board for a GE1/1 chamber coated with copper layer. . . .	57
3.7	HV divider circuit and HV pins connected to top and bottom of each foil to provide the power source.	58
3.8	Soldering the HV pins (left), preparing the SMD pads (middle), and soldering the SMD components (right).	58
3.9	The brass inserts placed at the respective position (on left) and clamping of these brass inserts using clamping hand (on right).	59
3.10	Removing the internal frames (left) and inserting brass inserts into the 3mm internal spacer (right).	60
3.11	The placement of O-ring in the external frame by pulling out from all four corners is presented.	60
3.12	Cleaning the GEM foil with a anti-static roll (left) and mounting the HV clip to the foils (right).	62
3.13	The figure shows mounting of 3mm spacers on plexiglass baseplate using guiding pins.	63
3.14	An illustration on how to stretch the foils in a sequence on top, and on bottom it shows the final picture after stretching as done in the lab for one of the chamber.	64
3.15	Cleaning of drift board with vacuum cleaner on left and with sticky roller on right.	66
3.16	Placement of aluminium bars and fixing it around the stack.	67
3.17	Figure a) Method describing the stretching, b) Stretching the foils. . .	67
3.18	Placing the a) external frame on stack b) readout board on GEM stack.	68
3.19	The process followed for Quality Assurance (QA) and Quality Check (QC) tests for the chambers at CERN site and other production sites all over the world.	70
3.20	A schematic overview of the QC3 gas leakage test setup.	72
3.21	Results of QC3 gas leakage test for all GE1/1 chambers assembled at the Panjab University site.	74
3.22	The data acquisition setup for QC4 test	75
3.23	The I-V characteristics results of QC4 test for the assembled GEM detectors at the Panjab University site.	76
3.24	The intrinsic noise rate as a function of monitored current for the assembled GEM detectors at the Panjab University site.	77

3.25	(a) GE1/1 shows the effective Gain as a function of the HV Divider Current for a subset of GE1/1 chamber, and (b) shows the response uniformity distribution. The 50% contours in response uniformity represent the gain fluctuations beyond which the detector time resolution starts degrading.	78
4.1	A sketch of pp collisions simulated by MC generator depicting hard-interaction, initial-state radiation, final-state radiation and underlying events. The source of figure is Ref. [2]	85
4.2	Representation of the color string between quark and anti-quark Lund String Model	86
4.3	An illustration of the difference between string hadronization (left) and cluster hadronization (right). The source of figure is Ref. [9] . . .	86
4.4	A recorded collision by the CMS detector during the 2016 data taking [22].	92
4.5	The workflow of the track reconstruction	92
4.6	Photons and electrons energy deposition in ECAL, with electron having a track in the tracker.	95
4.7	Sketch of the jets at different levels in the detector [30].	97
4.8	An illustration of b-hadron decay from the secondary vertex (SV) that is displaced from primary vertex (PV). The source of figure is Ref. [38]	99
5.1	The sketch depicts how a new resonance peak would appear over a smoothly falling SM background distribution.	108
5.2	The Feynman diagram of the excited quark production via s-channel (left) and t-channel (right) in the γ +jet state.	109
5.3	The resonance shapes of q^* at the reconstruction level radiating to γ +jet for three coupling multipliers $f = 1.0, 0.5$ and 0.1	110
5.4	The Feynman diagram of the QBH production and decaying to γ +jet state.	111
5.5	Invariant mass distributions of γ +jet state (normalised to unity) for QBH ADD ($n = 6$) and RS ($n = 1$) models for $M_{th} = 3$ TeV.	111
5.6	The Feynman diagrams of SM background processes contributing through different channels to the γ +jet signal state.	112

5.7	The Feynman diagrams of QCD multijet background processes that contributes to the signal state.	113
5.8	The Feynman diagrams of electroweak processes contributing to the γ +jet signal state.	113
5.9	The product of signal cross-section (σ) and branching fraction (B) for q^* , b^* and QBH signals with ADD (RS) model having $n = 6(1)$ extra dimensions.	115
5.10	The resonance shapes of q^* signal for mass 2 TeV and 5 TeV fitted with Gaussian and Crystall Ball function.	116
5.11	The mass resolution of q^* signal plotted and fitted as a function of resonance mass.	117
5.12	Generated and interpolated shapes for different q^* mass points. Shapes in dotted lines are interpolated and in solid lines are generated ones.	119
5.13	Comparison of generated and interpolated shapes at different q^* mass points	119
6.1	Relative trigger efficiencies for HLT_Photon175 (2016), HLT_Photon200 (2017-2018) triggers.	125
6.2	Absolute trigger efficiency for HLT_Photon175(2016), HLT_Photon200 (2017-2018) single photon triggers using jet triggerd dataset (top row) and using single muon triggerd dataset (bottom row) from the respective data taking periods.	126
6.3	Data-MC comparison showing the effect of pileup reweighting on MC events.	128
6.4	Data-MC comparison of photon identification and isolation variables after final selection for 2018 data-taking year.	133
6.5	The illustration of an event with final state radiation (FSR), and the wide-jet has included the FSR in it and hence improving the γ +jet invariant mass resolution.	135
6.6	The improvement in the invariant mass distribution with the construction of wide-jets with respect to AK4 jets of q^* signal of mass 2.0 TeV and 5.0 TeV on left and right, respectively. The wide-jets are constructed with $\Delta R = 1.1$	135

6.7	Data-MC comparison of Jet Particle Flow Identification variables after final selections applied for 2018 data taking year corresponding to luminosity 58.7fb^{-1}	137
6.8	DeepJet discriminator distribution before and after applying the b-tagging for 2018 dataset. The distributions are similar for 2016 and 2017 data-taking year also.	139
6.9	b-tag efficiency, and c and light quarks mistag rate as a function of p_T and η of wide-jets in $\Delta R = 1.1$ for 2016 dataset.	140
6.10	b-tag efficiency, and c and light quarks mistag rate as a function of p_T and η of wide-jets in $\Delta R = 1.1$ for 2017 dataset.	141
6.11	b-tag efficiency, and c and light quarks mistag rate as a function of p_T and η of wide-jets in $\Delta R = 1.1$ for 2018 dataset.	142
6.12	The invariant mass distribution $m_{\gamma+jet}$ without and with 760 GeV threshold applied to avoid the turn-on region for 2016, 2017 and 2018 respectively.	143
6.13	Data-MC comparison of p_T distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2016 data-taking year.	144
6.14	Data-MC comparison of p_T distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2017 data-taking year.	145
6.15	Data-MC comparison of p_T distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2018 data-taking year.	146
6.16	Data-MC comparison of η distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2016 data-taking year.	147
6.17	Data-MC comparison of η distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2017 data-taking year.	148
6.18	Data-MC comparison of η distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2018 data-taking year.	149
6.19	Data-MC comparison of ϕ distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2016 data-taking year.	150

6.20	Data-MC comparison of ϕ distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2017 data-taking year.	151
6.21	Data-MC comparison of ϕ distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2018 data-taking year.	152
6.22	Expected 95% CL upper limits on $\sigma \times B$ for q^* resonance mass. . . .	154
6.23	Efficiencies of various photon identification criteria as functions of photon p_T in barrel region for q^* signal $m_{\gamma+\text{jet}} = 5\text{TeV}$	155
6.24	Expected 95% CL upper limits on $\sigma \times B$ for b^* resonance mass. . . .	156
6.25	Mass turn-on efficiency curve for a) $ \Delta\eta < 1.5$, and b) $ \Delta\eta < 1.8$., with arrow indicating a mass threshold with 100% efficiency.	157
6.26	95% expected limits for two $\Delta\eta$ values with different jet p_T and mass threshold derived from mass turn-on curve.	157
6.27	The product of acceptance and efficiency for the signals q^* in the inclusive category and b^* in btag and 0- tag category for SM coupling $f = 1.0$ (left), and the QBH (ADD/RS) model in the inclusive category for different threshold mass M_{th} (right) for the years 2016, 2017, and 2018.	159
6.28	The F-test distributions for various background fit functions considered for q^* for full Run-II data.	164
6.29	The F-test distributions for various background fit functions considered for b^* for full Run-II data.	165
6.30	Toy distribution for the goodness-of-fit study using the χ^2 test statistic for q^* signal.	167
6.31	Toy distribution for the goodness-of-fit study using the χ^2 test statistic for b^* signal with 1-btag (left) and 0-btag(right) categories. . . .	167
6.32	Invariant mass distribution fitted with 4-parameter fit function for (a) q^* (top), (b) 1 tag b^* (bottom left) and (c) 0 tag b^* (bottom right) scenarios fitted with ROOT likelihood.	168
6.33	Gaussian fit to the pulls distribution by generating and fitting toys using the same function.	170
6.34	Pull distribution as a function of q^* , b^* and QBH (ADD and RS model) for Run-II mass corresponding to the four test functions with data.	171

6.35	Effect of photon and jet energy scale uncertainties on invariant mass of q^* for $M_{q^*} = 2.0$ TeV.	173
6.36	Effect of photon and jet energy resolution uncertainties on invariant mass of q^* for $M_{q^*} = 2.0$ TeV.	174
6.37	Effect of b-tag scale factor uncertainties on γ +jet distribution of b^* signal for $M_{b^*} = 2.0$ TeV.	175
6.38	The ratio of observed limits with and without systematic uncertainty to the statistical uncertainties for q^* signal.	175
7.1	The observed significance in data for q^* signal with coupling (a) $f = 1.0$, (b) $f = 0.5$ and (c) $f = 0.1$ as a function of the resonance mass for γ +jet resonances.	182
7.2	The observed significance in data for b^* signal with coupling (a) $f = 1.0$, (b) $f = 0.5$ and (c) $f = 0.1$ as a function of the resonance mass for γ + b-jet resonances.	183
7.3	The observed significance in data for QBH ADD and RS1 signal . . .	184
7.4	The expected and observed 95% C.L. upper limit on cross section and lower bound on the mass for $\gamma + jet$, that is q^* resonance for coupling $f=1.0$ (top left), and $f=0.5$ (top right), and $f=0.1$ (bottom).	185
7.5	The expected and observed 95% C.L. upper limit on cross section and lower bound on the mass for $\gamma + jet$, that is b^* resonance for coupling $f=1.0$ (top left), and $f=0.5$ (top right), and $f=0.1$ (bottom).	186
7.6	The expected and observed 95% C.L. upper limit on cross section and lower bound on the mass for $\gamma + jet$, that is for ADD($n=6$) and RS1 ($n=1$) models on left and right respectively.	187
7.7	The expected and observed 95% exclusion mass limit variation with the SM couplings for the excited q^* and b^* signal models.	187
B.1	The sketch depicts a particle X decaying to two particle state with energies E_1 and E_2 , and momentum p_1 and p_2 , respectively	200

List of Tables

1.1	The properties of the vector and scalar bosons in the SM	4
1.2	Branching Ratio of the decay states of the excited quarks	12
1.3	The size of extra dimension for the number of different dimensions . .	14
3.1	The main specifications and parameters for the GE1/1 design and its operation in CMS [8]	55
3.2	Results from QC4 HV test showing the value of measured resistance ($R_{\text{multimeter}}$) by multimeter, resistance (R_{IV}) by IV curve, and the maximum intrinsic noise rate.	75
6.1	b-tag DeepJet discriminator working points and their thresholds for 2016, 2017 and 2018 data and MC.	138
6.2	The correction factors applied to MC for q^*/QBH , 1-btag and 0-btag categories for 2016, 2017 and 2018.	142
6.3	Jet p_{T} and $ \Delta\eta $ optimization for Run-II with medium photon ID, tight jetID.	156
6.4	Cut flow table for different selections with respect to total events for data, signal, and all contributing backgrounds for 2016 data-taking year	159

6.5	Selection efficiency (in %) table for 2016 data taking year for q^* , b^* signals for coupling multiplier value $f = 1.0$, and QBH signal for ADD ($n = 6$) and RS1 ($n = 1$) model for two mass points.	160
6.6	Cut flow table for different selections with respect to total events for data, signal, and all contributing backgrounds for 2017 data-taking year	160
6.7	Selection efficiency (in %) table for 2017 data-taking year q^* , b^* signals for coupling multiplier value $f = 1.0$, and QBH signal for ADD ($n = 6$) and RS1 ($n = 1$) model for two mass points.	161
6.8	Cut flow table for different selections with respect to total events for data, signal, and all contributing backgrounds for 2018 data-taking year	161
6.9	Selection efficiency (in %) table for 2017 data-taking year q^* , b^* signals for coupling multiplier value $f = 1.0$, and QBH signal for ADD ($n = 6$) and RS1 ($n = 1$) model for two mass points.	161
6.10	Different functions tested for fitting mass distribution using F-test statistics	163
6.11	Effect of various systematic uncertainties on signal shape and normalization.	176
A.1	JSON files used to select certified runs and luminosity sections	195
A.2	List of dataset with corresponding run range used in the analysis . . .	196
A.3	List of q^* signal MC samples officially simulated and reconstructed at $\sqrt{s} = 13$ TeV, along with the number of generated events, cross-sections and coupling strengths. All the samples uses MINIAODSIM tier of the RunIISpring16MiniAODv2-PUSpring16RAWAODSIM-80X-mcRun2-asymptotic-2016-miniAODv2-v0-v* production.	197

A.4	List of b^* signal MC samples officially simulated and reconstructed at $\sqrt{s} = 13$ TeV, along with the number of generated events, cross-sections and coupling strengths. All the samples uses MINIAODSIM tier of the RunIISpring16MiniAODv2-PUSpring16RAWAODSIM-80X-mcRun2-asymptotic-2016-miniAODv2-v0-v* production.	198
A.5	List of QBH signal MC samples centrally simulated by CMS experiment and reconstructed at $\sqrt{s} = 13$ TeV, along with the number of generated events and cross-sections.	199
D.1	The HLT triggers used in the analysis with the objects and the p_T threshold	202

Chapter 1

Introduction and Motivation

For millennia, humans have attempted to comprehend the nature of matter and everything else in the universe. This inquisitive mind of scientists inspired them to deeply observe and study physical phenomena on the basis of their fundamental constituents. As a result, this led to the emergence of the field of *particle physics* in the 20th century which describes the behavior of particles at the shortest distant scales. Many scientists around the world devote their time to find new particles and understanding the law of particle interactions. For a start, John Dalton in the 19th century concluded that atoms are the elementary particles and everything is made up of atoms. However, towards the end of the century Dalton's theory was discarded and several other theories were brought forth, indicating that atoms are not fundamental but rather are constituted of more particles. The discovery of the first elementary particle started with discovery of “electrons” [1] by J.J Thomson through his experiments on cathode rays. Later in 1911, Rutherford through his scattering experiments [2] concluded that mass of the atom is concentrated in a small core, which we call the “nucleus”. This further led to the discovery of another elementary particle, “proton”. In 1932, the picture of the atom became clear when James Chadwick announced the discovery of charge-less “neutrons” [3]. Around that time in couple of decades, many new particles such as muons, pions, neutrinos were discovered. Fig. 1.1 depicts the discovery of several new particles in different years

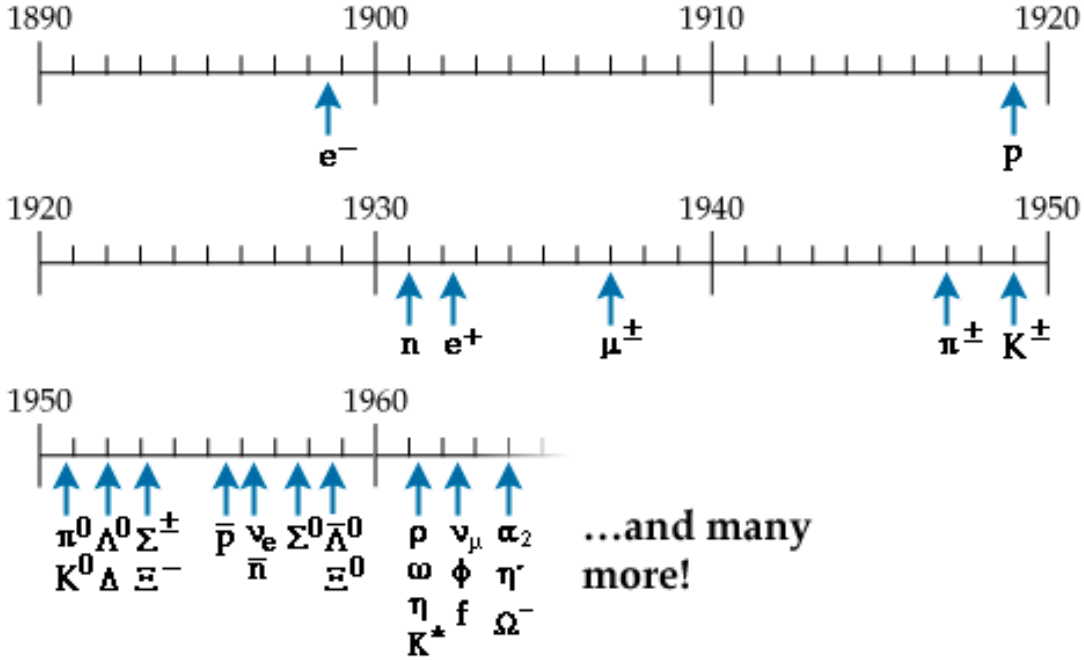


Figure 1.1: An illustration of particle discoveries across different years

starting with the discovery of electron. At this point, the scientists were caught up in determining the structure of all newly discovered particles. This problem was eventually solved in 1964, when Murray Gell-Mann [4] and George Zweig [5] proposed the “Quark Model” stating that quarks are the fundamental particles and all hadrons are made up of quarks. This model was further verified by numerous experiments after the discovery of various bound states of baryons and mesons. With tremendous effort by physicists to describe all elementary particles, a model was formulated, now known as the “Standard Model”. It is the greatest model developed gradually over a century of research work that successfully explains almost all the fundamental interactions. The standard model has been validated up by various experiments, and the agreement between the standard model predictions and the experimental observations is extraordinary [6].

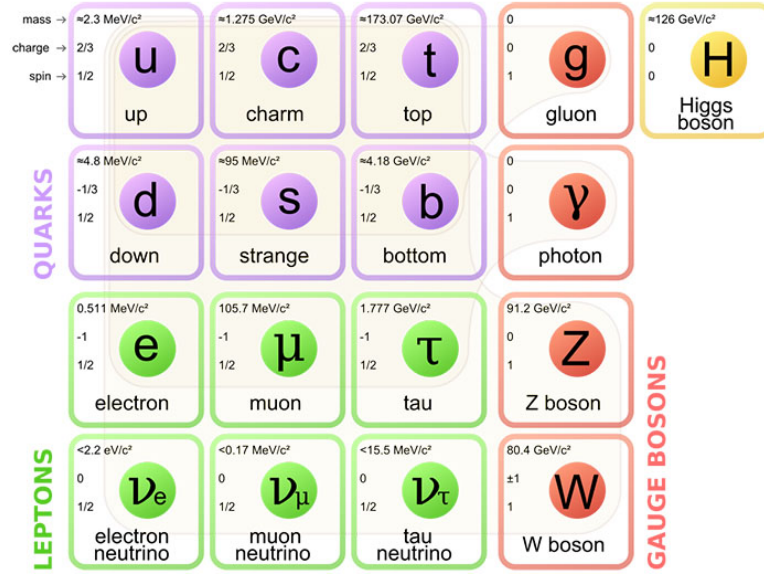


Figure 1.2: The SM particles, spin-1/2 particles known as fermions in purple(quarks) and green(leptons). The three columns represents three generations of the fermions. The spin-1 vector boson in orange color, and the Higgs scalar boson in yellow.

1.1 The Standard Model

The standard model (SM) is a robust theoretical framework that describes the properties of fundamental particles and their interactions through three fundamental forces: electromagnetic force, strong force, and the weak force, excluding gravity. Mathematically, the SM can be defined as a gauge invariant Quantum Field Theory (QFT) [7]. The QFT describes the particles as quantum fields, and the dynamics of these particles is represented by a Lagrangian term $\mathcal{L}$ [8]. In general, each fundamental particle is associated with a quantum field. The following section describes the particles and their interactions in the SM.

1.1.1 Elementary particles

The SM comprises of two types of elementary particles, fractional spin-1/2 particles known as fermions and integral spin-1 particles known as bosons.

The fermions are the basic building blocks of matter, and the bosons are

exchange mediators between these building blocks. There are in total 12 fermions divided in two categories: leptons and quarks each constituting three generations. The first generation of the leptons consists of electron (e) and its corresponding neutrino (ν_e), the second generation consists of (μ) and its neutrino (ν_μ), and finally the third generation consists of tau (τ) and its neutrino (ν_τ). Similarly, quarks come in three families, namely up (u) and down (d) quark comprising the first generation, charm (c) and strange (s) comprising second generation, and top (t) and bottom (b) quarks comprising the third generation. Within each generation of quarks, the former carries charge $+2/3$ while the latter carries charge $-1/3$. Each of these 12 fermions has further their “anti-particles”. The anti-particles possess the same mass as their particles but opposite quantum numbers. The first generation of quarks and leptons with lighter masses are more stable than the other two generations. Figure 1.2 depicts an overview of the SM particles.

There are two types of spin-1 bosons : vector bosons and scalar boson. The vector bosons are the force mediators in the SM : gluons (g) are the mediators of strong force, photons (γ) are the mediators of electromagnetic force and W/Z bosons are the mediators of weak force. Gluons and photons are massless and electrically neutral, whereas W and Z are heavy, with the W boson having an electrical charge of ± 1 and Z boson being a neutral particle. The only scalar boson, the Higgs boson has a large mass of 125.35 GeV and is responsible for providing the masses to all particles in the SM. The discovery of Higgs boson (H) was announced only a decade ago by the ATLAS and CMS Collaboration on 4th July, 2012 [9] [10], and the Nobel Prize for the discovery was awarded in 2013. The properties of the bosons listed in the SM are given in Table 1.1.

	Name	Symbol	Interaction	Charge	Mass (GeV)
Gauge Bosons	Gluon	g	Strong	0	–
	Photon	γ	Electromagnetic	0	–
	W bosons	$W^\pm$	Weak	± 1	80.37
	Z boson	Z	Weak	0	91.18
Scalar Boson	Higgs boson	H	–	0	125.25

Table 1.1: The properties of the vector and scalar bosons in the SM

1.1.2 The SM particle interactions

The SM is a non-abelian gauge theory described by symmetry groups of strong and electroweak interactions.

$$\underbrace{SU(3)_C}_{\text{Strong Interaction}} \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{\text{Electroweak Interaction}} \quad (1.1)$$

where $SU(3)_C$ is the gauge symmetry group of strong interactions, with “C” representing the color. The $SU(2)_L \otimes U(1)_Y$ is the unified gauge symmetry group of electromagnetic and weak interactions. Here “L” stands for left-handed interactions of SU(2) group, and “Y” stands for the weak hypercharge ($Y = B + S$ where B is the Baryon Quantum number and S is the Strangeness). A brief introduction of these interactions is given below:

- **Strong interactions** : The strong force is responsible for binding the quarks together to form nucleons and also binds nucleons to make nuclei. It is a very short ranged force acting up to a distance of 10^{-15} m. The theory that describes the strong interactions is called “Quantum Chromodynamics (QCD)” [11]. It explains the interactions between gluons and quarks and follows the $SU(3)_C$ gauge symmetry where C represents the color charge existing in the state red(r), green(g) and blue(b). Quarks can carry any one of the three color charges with their anti-particle carrying anti-color charge state, while gluons simultaneously carries color and anti-color charges. Gluons can have eight color charge states and they are: $R\bar{G}, R\bar{B}, G\bar{R}, B\bar{G}, G\bar{B}, B\bar{R}, \frac{1}{\sqrt{2}}(R\bar{R} - G\bar{G}), \frac{1}{\sqrt{6}}(R\bar{R} + G\bar{G} - 2B\bar{B})$. These color charge quantum numbers assigned to gluons make them self interacting particles. Furthermore, gluons can only be absorbed or emitted by colored particles.

Quarks hold together to form colorless particles known as hadrons. The hadrons are further categorized depending on the number of “valence quarks”, that determine the quantum numbers of hadrons. There are two types of hadrons : baryons and mesons. Baryons are made up of three valence quarks

for example, the protons are constituted of two up and one down quark, and the mesons are made up of two quarks as pions. Furthermore, hadrons can have an indefinite number of virtual quarks (also known as “sea quarks”), anti-quarks and gluons but they do not contribute to the quantum numbers of the hadrons. The coupling strength of the QCD interaction is dependent on the energy scale Q and is defined by

$$\alpha_s = \frac{12\pi}{(33 - 2n_f)\ln(\frac{Q^2}{\lambda^2})} \quad (1.2)$$

where Q is the momentum transferred, n_f refers to the number of quarks active in pair production, and λ is defined as the chromodynamic scale. When $\lambda_{QCD} \sim 200 \text{ MeV}$ i.e. QCD scale, the coupling constant increases such that it becomes impossible to isolate the quarks and gluons inside hadrons. Therefore, as a result of this phenomena, known as “confinement”, quarks and gluons are always observed in bound states. Additionally, when $Q^2 \rightarrow \infty$, the coupling strength between quarks decreases and vanishes asymptotically. This demonstrates that quarks exhibit asymptotic freedom, or the behavior of free particles at high energies.

- **Electromagnetic interactions** : The interactions between the charged particles are described by quantum electrodynamics (QED) [12] [13]. The mediator of this force are neutral massless photons, and unlike gluons they don't interact with themselves. The QED field theory is represented by symmetry group $U(1)_Y$.

The electromagnetic interactions has infinite range obeying inverse square law, similar to gravity. The strength of the electromagnetic interactions is given by coupling constant

$$g_e = \sqrt{4\pi\alpha} \quad (1.3)$$

where α being the fine structure constant and is defined as

$$\alpha = \frac{e^2}{\hbar c} \simeq \frac{1}{137} \quad (1.4)$$

where e is the unit charge and $\hbar$ is the reduced Planck constant defined as $\frac{h}{2\pi}$.

- **Electroweak interactions** : A theory was proposed by Glashow, Weinberg and Salam unifying the weak interactions with the electromagnetic interactions and calling it as “Electroweak Theory”. The Electroweak Theory [14] is defined by the symmetry group $SU(2)_L \otimes U(1)_Y$. Here L represents the left handedness and Y stands for weak hypercharge ($Y = 2(Q - I_3)$), with Q the charge and I_3 the weak isospin.

The symmetry group $SU(2)$ introduces three fields, two charged and one neutral, whereas the group $U(1)$ give rise to gauge field B_μ . These four fields thus generate four bosonic fields associated by $W^\pm$, Z^0 and photon. The gauge invariance of this symmetry group expects gauge bosons to be massless. However by experimental observations, masses of W and Z bosons are measured precisely to be 81.4 GeV and 91.2 GeV [6], respectively. To explain such heavy masses of bosons, a new mechanism called as “Higgs mechanism” was introduced.

The Higgs Mechanism: The gauge invariance of the symmetry group breaks if the mass term of gauge bosons is added to SM Lagrangian. However, it is well known experimentally that W and Z bosons are massive bosons. To serve this problem, the concept of Spontaneous Symmetry Breaking via Brout-Englert-Higgs(BEH) mechanism [15] [16] is included in SM. In the BEH mechanism, a new complex scalar field called Higgs field(ϕ) is introduced.

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

The potential due to this Higgs field has the form

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

The shape of $V_H(\Phi)$ is dependent on the parameters μ^2 and λ . For $\mu^2 < 0$ and $\lambda > 0$ there are infinite values possible for $V_H(\Phi)$ potential and hence the symmetry is broken.

$$|\phi|^2 = -\frac{\mu^2}{2\lambda} = \frac{v^2}{2} \quad (1.7)$$

To maintain the SM symmetry and to give a feasible solution to $SU(2)_L \otimes U(1)_Y$ symmetry breaking, it requires EW symmetry group to be broken as $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$ and this requirement guarantees charged Higgs field ϕ^+ to be zero which leads to the massless photon and Φ to be written as

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix} \quad (1.8)$$

and here h is the massive Higgs field associated with the Higgs Boson. This scalar field Φ when introduced in Lagrangian originates masses of the W and Z bosons, and for self-interacting Higgs boson as well.

1.1.3 Limitations of SM

- **Absence of gravity:** Gravity is one of the fundamental interactions but yet it is not included in the SM. It is the weakest force among the four fundamental forces. The SM to be called as a complete theory should also contain description of the gravitational force.
- **Matter-Antimatter asymmetry:** It is evidently known that the universe is almost entirely comprised of matter and not anti-matter [17]. But in principle, there is no possible reason to explain the dominance of matter over anti-matter. A promising solution is connected to charge parity (CP) violation, which can

explain how this unbalance could have eventually resulted to this structure of Universe that we see today.

- **Dark matter and dark energy:** The SM justifies only 5% of the energy present in the Universe, and the rest is still largely unknown. Cosmological observations hint at 26% of another kind of matter called “dark matter” and yet it is another challenge for it to be included in SM. In addition to dark matter, there is another mystery of dark energy contributing 68% of the Universe energy [18]. Observations implying the expanding of the universe can be explained by the presence of this dark energy.
- **The Hierarchy problem:** Another limitation of the SM is its inability to provide an answer to hierarchy problem [19]. The hierarchy problem leads to the question why gravity is such a weaker force than other forces, or why there is such a large difference between the Planck scale (10^{19} GeV) and the electroweak scale (10^2 GeV). One may define Planck’s scale using three fundamental constants as

$$m = \sqrt{\frac{\hbar c}{G}} \sim 1.22 \times 10^{19} \text{ GeV}/c^2 \quad (1.9)$$

where $\hbar$ is defined as reduced Planck constant, c is speed of light and G is the Newton’s Gravitational constant. The Planck scale represents the energy scale at which gravity is expected to become stronger.

- **Neutrino masses:** Neutrinos are the massless fermions existing in each family of leptons in the SM. However, there are experimental observations that they show oscillating behavior between different flavors [20]. This can be only possible if they have different masses assigned to different flavors. The masses of the neutrinos can be added to SM but it will bring up new theoretical questions of origin of these masses.
- **Existence of three families of fermions:** The SM can’t explain the existence of exactly three generations of the lepton and quark families among

fermions, as well as the mass-hierarchy between these families. This symmetry raises numerous questions and one possible explanation is that fermions are composed of some pseudo-fundamental particles with deeper substructure. These fundamental particles are not yet discovered.

1.2 Beyond Standard Model

In order to resolve the shortcomings of the SM, there are many Beyond Standard Model (BSM) theories [21], such as Grand Unified Theory (GUT) [22], Supersymmetry (SUSY) [23], Compositeness Model, existence of Large Extra Dimensions (LED) proposed. The work described in this thesis is based on the two such theoretical models, viz, Compositeness model and Large Extra Dimensions models.

1.2.1 Compositeness model

In the SM, we are familiar with the fact that quarks and leptons are the fundamental particles. However, the compositeness theoretical model [24–26] states that quarks and leptons are not fundamental but rather are made up of some smaller and undiscovered particles, hence they could exist in excited states. This is very similar to the composite state of the atoms. The model assumes excited quarks to be spin 1/2 particles with SM quarks existing in left handed doublets and right handed singlets, while the excited state exists in left- and right-handed doublets.

$$\begin{aligned} \text{SM quarks : } & \begin{pmatrix} u \\ d \end{pmatrix}_L, u_R, d_R \\ \text{Excited quarks : } & \begin{pmatrix} u^* \\ d^* \end{pmatrix}_L, \begin{pmatrix} u^* \\ d^* \end{pmatrix}_R \end{aligned}$$

There are many models predicting the nature of the hypothetical particles constituting the quarks and leptons. One such model is given by Pati and Salam and in their model they named these hypothetical particles as “preons” [27]. The preons are subjected to a new force that becomes very strong at a new scale, Λ known

as compositeness scale. The interactive process by which the excited fermions are produced depends on this scale Λ . If the collision energy falls below Λ then the excited fermions are produced via four-fermion Contact Interaction (CI). In CI, four fermions interact at a single vertex in contrast to the exchange of SM bosons. The Lagrangian term for CI is given by :

$$\mathcal{L}_{\text{CI}} = \frac{1}{\Lambda^2} \frac{g^{*2}}{2} j^\mu j_\mu \quad (1.10)$$

with $j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta'_L \bar{f}_L^* \gamma_\mu f_L^* + \eta''_L \bar{f}_L^* \gamma_\mu L_L + h.c + (L \rightarrow R)$

where f_L is the left handed SM fermionic field; f_L^* is the excited fermionic field and g^* is the coupling constant. The parameters $\eta_L, \eta'_L, \eta''_L$ are all assigned value 1 and $\eta_R, \eta'_R, \eta''_R$ are set to 0.

However, if the collision energy is greater than Λ , then excited fermions are produced via gauge interactions. In gauge interactions, two excited fermions or two SM fermions are coupled via a boson and the Lagrangian for such gauge interactions is given by

$$\mathcal{L}_{\text{eff}} = \frac{1}{2\Lambda} \bar{f}^* \sigma^{\mu\nu} \left[g_s f_s \frac{\lambda_a}{2} F_{\mu\nu}^a + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] f + \text{h.c.}, \quad (1.11)$$

where $F_{\mu\nu}^a$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field tensor strength corresponding to the SU(3), SU(2) and U(1) gauge fields. For the respective gauge fields, g_s , g and g' are gauge coupling constants; f_s , f and f' are the coupling multiplier parameters and are assumed to be equal to unity. The other higher dimensional operators in the effective Lagrangian can be integrated by changing the f 's parameters to form factors as $f_s(q^2)$, $f(q^2)$ and $f'(q^2)$.

This thesis represents the study of light flavor excited quarks (u^*, d^*) produced by gauge interactions and heavy flavor excited quarks (b^*) produced by gauge and contact interactions. The Feynman diagram for both production processes is shown in the Fig 1.3.

The excited quarks (q^*) return to the ground state by radiating a gluon, photon or heavy bosons W and Z . The Table. 1.2 shows the possible decay modes and the

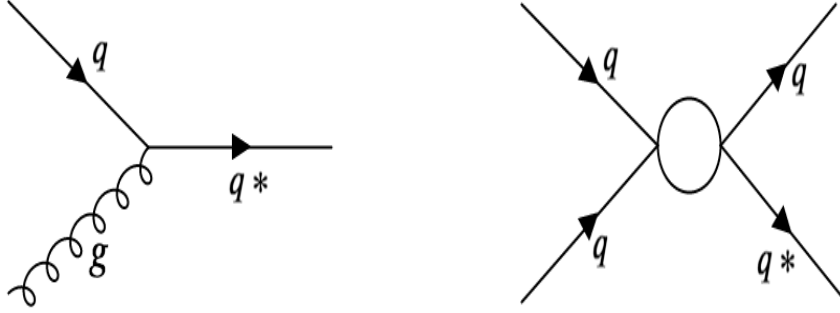


Figure 1.3: The production of excited quarks via gauge interactions (left) and via contact interactions (right).

branching ratios of the excited quarks to different states. In this thesis, the final state of photon and jet from excited quark is considered.

Signal Modes	Branching Ratio %
$q^* \rightarrow qg$	~ 83
$q^* \rightarrow qW$	~ 10
$q^* \rightarrow qZ$	~ 5
$q^* \rightarrow q\gamma$	~ 2

Table 1.2: Branching Ratio of the decay states of the excited quarks

1.2.2 Large Extra Dimension models

To address the possible solution to the hierarchy problem, there are theories implying gravity shares the same strength as other three forces, but since it is weaker in our 3+1 dimensional world, it is stronger in some extra dimensional space and is diluting into those dimensions. The skeptical figure of how gravity escapes to other dimensions is shown in Fig.1.4. But the question arises that if extra dimensions exist then why have they not been observed yet? The extra dimensions are compact in size (as large as 1 millimeter), having the geometry of a circle with a small radius. The space traversed by the extra dimensions is called “bulk”. Particles with small wavelengths can only probe such compact dimensions. With the wavelength of the particle being inversely proportional to the energy, the dimensions are hidden where

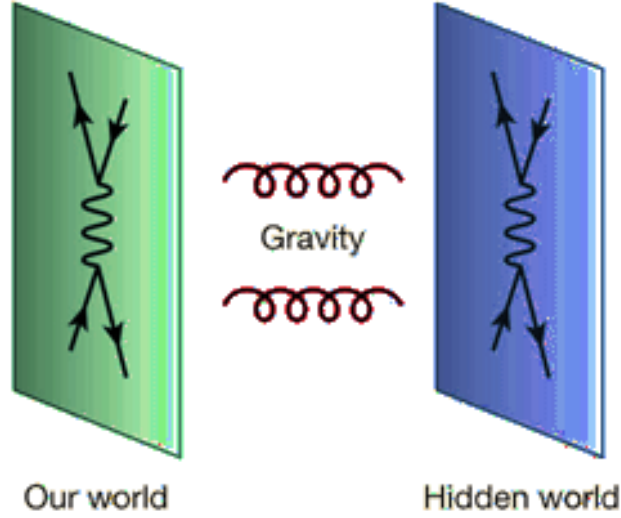


Figure 1.4: An illustration of gravity escaping to other hidden world with extra dimensions, while other particles existing in our 3-dimensional spatial space.

energy scale is smaller than size of the corresponding extra dimensions.

To understand it better, let us consider Newton's law in $4+n$ dimensions with the assumption that extra dimensions are compactified in a sphere of radius L . The interaction force between two masses m_1 and m_2 separated at distance r shows inversely proportional behavior with r as $r^{-(2+n)}$

$$F(r) \sim \frac{G_N^{4+n} m_1 \cdot m_2}{r^{(n+2)}} = \frac{1}{M_{pl(4+n)}^{n+2}} \cdot \frac{m_1 \cdot m_2}{r^{(n+2)}} \quad (1.12)$$

At distances less than L , the gravitational effect can be observed in all $3+n$ dimensions. But when r exceeds L , the gravitational effect shows r^{-2} inversely proportional behavior with no extra dimensional space to spread out.

$$F(r) \sim \frac{1}{M_{pl(4+n)}^{n+2}} \cdot \frac{m_1 \cdot m_2}{r^2 \cdot L^n} \quad (1.13)$$

Comparing this last expression with 4D Newton's law:

$$F(r) \sim \frac{1}{M_{pl(4)}^{n+2}} \cdot \frac{m_1 \cdot m_2}{r^2} \quad (1.14)$$

we see

$$M_{pl(4)}^2 \sim M_{pl(4+n)}^{n+2} L^n = M_{pl(4+n)}^{n+2} V_n \quad (1.15)$$

where V_n represents the volume of the extra dimensions. If we consider the fundamental scale $M_{pl(4+n)} \sim 1 \text{ TeV}$ and the 4D Planck scale $M_{pl(4)}^2$ to be $\sim 10^{19} \text{ GeV}$ then the size of extra dimension is

$$L \sim \left(\frac{M_{pl(4)}^2}{M_{pl(4+n)}^{n+2}} \right)^{\frac{1}{n}} \sim 10^{\frac{32}{n}} \text{ TeV}^{-1} \sim 10^{\frac{30-19n}{n}} m \quad (1.16)$$

Hence, the size of extra dimensions for the number of dimensions $n = 1, 2, 3 \dots 7$ are defined in Table 1.3.

Extra dimensions (n)	~ Size of extra dimensions (L)
1	10^{11} m
2	0.1 mm
3	1 nm
4	1 pm
5	100 fm
6	10 fm
7	1 fm

Table 1.3: The size of extra dimension for the number of different dimensions

The existence of the large extra dimensions predicted by various models may lower the Planck scale such that it could become accessible at the LHC energies [28] and Quantum Black Holes could be produced at the pp collisions. As the mass and radius of the ordinary black holes approached quantum gravity scale, the black holes are named as “Quantum Black Holes” (QBHs). They don’t have semi-classical spacetimes and does not follows black hole thermodynamics. The QBHs in many aspects show resemblance to the strong resonances coupling and decay to only few of the SM particles. The QBHs formation and decay takes place over a small spacetime region, and then only hadronization occurs next.

There exist several models of extra dimensions with the potential to solve a few problems of the SM. The most influential models include those by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [29] and by Randall and Sundrum (RS) [30] aiming

to solve the hierarchy problem with extra dimensions. The ADD model proposes flat, large extra dimensions compactified on a circle, and the RS model proposes a single, warped extra dimension. In this thesis, the search for QBHs resonances as predicted by the ADD model with six extra dimensions ($n=6$) and RS model with one extra dimension ($n=1$) is reported using photon and jet final state.

1.3 Previous Searches

Many large accelerators are probing for the physics beyond the standard model and for new particles. Previous searches for resonances of excited quarks and QBHs includes results from many collider experiments but no evidence has been found yet. In this case, experiments provide a mass limit for the resonances stating that below this mass the particle does not exist. The CDF collaboration searched for excited quarks in the $\gamma + jet$ and dijet channel in $p\bar{p}$ at $\sqrt{s} = 1.8$ TeV and excluded the mass range $80 < M_{q^*} < 540$ GeV [31], $200 < M_{q^*} < 520$ GeV, and $580 < M_{q^*} < 760$ GeV [32] respectively. The DØ experiment has excluded the mass of excited quarks upto 775 GeV in the dijet decay channel [33]. The CMS and ATLAS detectors at the LHC have excluded excited quarks below mass 5.5 TeV and 5.3 TeV in the $\gamma + jet$ channel at 95% CL corresponding to luminosity $36.7 fb^{-1}$ at $\sqrt{s} = 13$ TeV. The CMS has excluded the excited quarks in dijet channel below mass 6.3 TeV corresponding to integrated luminosity $137 fb^{-1}$ [34] and ATLAS has excluded in the same channel below mass 6.7 TeV corresponding to luminosity $139 fb^{-1}$ at 95% CL.

The searches for heavy flavor quarks are also performed by CMS and ATLAS experiments. The ATLAS excluded b^* in the tW channel upto mass 870 GeV at $\sqrt{s} = 7$ TeV [35]. In the tW final state, the CMS Collaboration excluded b^* below mass 1.53 TeV for vector like couplings at 95% CL at $\sqrt{s} = 8$ TeV [36]. In Run-II data collection at $\sqrt{s} = 13$ TeV the excited b quark is excluded at 95% CL upto mass 1.8 TeV in the $\gamma + jet$ channel corresponding to luminosity $36.7 fb^{-1}$ [37] and upto 4.0 TeV in the dijet channel corresponding to $138 fb^{-1}$ luminosity for full Run-II.

For the QBHs model, the ATLAS and CMS performed searches in the $\gamma + jet$, diphoton and dijet final states. The CMS and ATLAS have excluded the ADD QBH with 6 extra dimensions in the dijet state upto 8.2 TeV [38] and 8.9 TeV [39] respectively, at $\sqrt{s} = 13$ TeV. At the same energy, the ADD with 6 extra dimensions is excluded below mass 5.6 TeV in the $e\mu$ state, 5.2 TeV in $e\tau$ and 5.0 TeV in $\mu\tau$ final state [40]. However, ATLAS has excluded the ADD with 6 extra dimensions upto 7.1 TeV in $\gamma + jet$ channel [41]. The RS model with 1 extra dimension is excluded below mass 4.4 TeV in the $\gamma + jet$ channel at $\sqrt{s} = 13$ TeV [41].

1.4 Thesis Organization

The thesis covers two major aspects, one is physics analysis of pp collision data collected by the CMS detector and other is GEM detector hardware work as a part of CMS detector upgrade.

The physics analysis aims to search for new resonances in the $\gamma + jet$ final state using data and Monte-Carlo simulations. Precisely, the new resonances here includes the search for excited state of light (u^*, d^*) and heavy flavor (b^*) quarks, and search for Quantum Black Holes (QBHs) of the ADD model (n=6) and RS model (n=1).

The detector hardware part includes the assembly and testing of new sub-detector Gas Electron Multiplier (GEM) in the muon subsystem of CMS detector during long shutdown-2 (LS2) i.e from year 2018-2021. The outline is as follows:

- The ongoing Chapter is based on the basic understanding of particle physics. The shortcomings of the SM are discussed, with many theoretical models existing to overcome these limitations. A brief introduction of the new resonance signals defined by different models is also described in this Chapter.
- Chapter 2 is dedicated to the experimental setup of the studies discussed in this thesis, i.e Large Hadron Collider and the CMS detector. The CMS detector

is one of the general purpose detector of the LHC. A brief introduction of the CMS and its subdetectors is given in this chapter.

- Chapter 3 presents the GEM detector hardware work being performed at the Panjab University, Chandigarh for the CMS detector upgrade to be done during the LS2. The assembly and testing of the GEM detectors done at Panjab University are described in detail in this chapter.
- Chapter 4 gives a brief overview of the reconstruction of the particles from pp collision data interacting with the subdetectors of the CMS detector. Different event generators used in the simulation studies and various event reconstruction algorithm used to reconstruct the primary vertex of interaction, the outgoing particles and their kinematics are focussed here in this chapter.
- Chapter 5 gives a description of the physics analysis for resonance searches of excited quarks (q^* , b^*) and QBHs from ADD model ($n=6$) and RS model ($n=1$). An overview of analysis strategy with signal modeling is given in this chapter.
- Chapter 6 describes the event selection criteria, background modelling and the possible systematic and statistical uncertainties.
- Chapter 7 presents the results of the physics analysis, and also summarizes the hardware work and physics analysis performed in the thesis. The future outlook of the work is also described in this chapter.

Bibliography

- [1] J. Thomson, “Xl. cathode rays”, *Philosophical Magazine Letter* **87** (2007), no. 5, 303–326, doi:10.1080/09500830701306165.
- [2] E. Rutherford, “The scattering of alpha and beta particles by matter and the structure of the atom”, *Phil. Mag. Ser. 6* **21** (1911) 669–688, doi:10.1080/14786440508637080.
- [3] J. Chadwick, “Possible Existence of a Neutron”, *Nature* **129** (1932) 312, doi:10.1038/129312a0.
- [4] M. Gell-Mann, “A Schematic Model of Baryons and Mesons”, *Phys. Lett.* **8** (1964) 214–215, doi:10.1016/S0031-9163(64)92001-3.
- [5] G. Zweig, “An SU(3) model for strong interaction symmetry and its breaking. Version 2”, pp. 22–101. 2, 1964.
- [6] Particle Data Group Collaboration, “Review of Particle Physics”, *Phys. Rev. D* **98** (2018), no. 3, 030001, doi:10.1103/PhysRevD.98.030001.
- [7] M. E. Peskin and D. V. Schroeder, “An Introduction to quantum field theory”. Addison-Wesley, Reading, USA, 1995. ISBN 978-0-201-50397-5.
- [8] M. Srednicki, “Quantum Field Theory”. Cambridge University Press, 1, 2007. ISBN 978-0-521-86449-7, 978-0-511-26720-8.
- [9] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys.*

- Lett. B* **716** (2012) 1–29, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [10] CMS Collaboration, “Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30–61, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [11] T.Muta, “Foundations of Quantum Chromodynamics: An Introduction to Perturbative Methods in Gauge Theories.”. World Scientific lecture notes in physics, 2010.
- [12] R. P. Feynman, “QED: The Strange Theory of Light and Matter”. 1986. ISBN 978-0-691-02417-2.
- [13] P. A. M. Dirac, “Quantum theory of emission and absorption of radiation”, *Proc. Roy. Soc. Lond. A* **114** (1927) 243, doi:10.1098/rspa.1927.0039.
- [14] S. L. Glashow, “Partial-symmetries of weak interactions”, *Nuclear Physics* **22** (1961), no. 4, 579–588, doi:https://doi.org/10.1016/0029-5582(61)90469-2.
- [15] P. W. Higgs., “Broken symmetries and the masses of gauge bosons”, *Phys. Rev. Lett.* **13** (1964) 508–509, doi:doi:10.1103/PhysRevLett.13.508.
- [16] F. Englert and R. Brout, “Broken symmetry and the mass of gauge vector mesons”, *Phys. Rev. Lett.* **13** (1964) 321–323, doi:10.1103/PhysRevLett.13.321.
- [17] U. Sarkar, “Particle and Astroparticle Physics (1st ed.)”. CRC Press, 2007.
- [18] Planck Collaboration, “Planck 2013 results. I. Overview of products and scientific results”, *Astron. Astrophys.* **571** (2014) A1, doi:10.1051/0004-6361/201321529, arXiv:1303.5062.
- [19] F. Quevedo, S. Krippendorff, and O. Schlotterer, “Cambridge Lectures on Supersymmetry and Extra Dimensions”, arXiv:1011.1491.

-
- [20] Super-Kamiokande Collaboration, “Evidence for oscillation of atmospheric neutrinos”, *Phys. Rev. Lett.* **81** (1998) 1562–1567, doi:10.1103/PhysRevLett.81.1562, arXiv:hep-ex/9807003.
- [21] J. D. Lykken, “Beyond the Standard Model”, 5, 2010. arXiv:1005.1676.
- [22] H. Georgi and S. L. Glashow, “Unity of All Elementary Particle Forces”, *Phys. Rev. Lett.* **32** (1974) 438–441, doi:10.1103/PhysRevLett.32.438.
- [23] I. J. R. Aitchison, “Supersymmetry and the MSSM: An Elementary introduction”, arXiv:hep-ph/0505105.
- [24] U. Baur, I. Hinchliffe, and D. Zeppenfeld, “Excited quark production at hadron colliders”, *Int. J. Mod. Phys. A* **2** (1987) 1285, doi:10.1142/S0217751X87000661.
- [25] W. Buchmuller, “Composite quarks and leptons”, *Acta Phys. Austriaca Suppl.* **27** (1985) 517, doi:10.1007/978-3-7091-8830-9_8.
- [26] U. Baur, M. Spira, and P. M. Zerwas, “Excited quark and lepton production at hadron colliders”, *Phys. Rev. D* **42** (1990) 815, doi:10.1103/PhysRevD.42.815.
- [27] I. A. D’Souza and C. S. Kalman, “Preons: models of leptons, quarks and gauge bosons as composite objects”. World Scientific, 1992. doi:10.1142/1700.
- [28] D. M. Gingrich, “Quantum black holes with charge, colour, and spin at the LHC”, *J. Phys. G* **37** (2010) 105008, doi:10.1088/0954-3899/37/10/105008, arXiv:0912.0826.
- [29] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, “The hierarchy problem and new dimensions at a millimeter”, *Phys. Lett. B* **429** (1998) 263, doi:10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315.

-
- [30] L. Randall and R. Sundrum, “A large mass hierarchy from a small extra dimension”, *Phys. Rev. Lett.* **83** (1999) 3370, doi:10.1103/PhysRevLett.83.3370, arXiv:hep-ph/9905221.
- [31] CDF Collaboration, “Search for excited quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV”, *Phys.Rev.Lett.* **72** (1994) 3004–3008, doi:10.1103/PhysRevLett.72.3004.
- [32] CDF Collaboration, “Search for new particles decaying to dijets at CDF”, *Phys.Rev.* **D55** (1997) 5263–5268, doi:10.1103/PhysRevD.55.R5263, arXiv:hep-ex/9702004.
- [33] D0 Collaboration, “Search for new particles in the two jet decay channel with the D0 detector”, *Phys.Rev.* **D69** (2004) 111101, doi:10.1103/PhysRevD.69.111101, arXiv:hep-ex/0308033.
- [34] CMS Collaboration, “Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **05** (2020) 033, doi:10.1007/JHEP05(2020)033, arXiv:1911.03947.
- [35] ATLAS Collaboration, “Search for single b^* -quark production with the ATLAS detector at $\sqrt{s} = 7$ TeV”, *Phys. Lett.* **B721** (2013) 171–189, doi:10.1016/j.physletb.2013.03.016, arXiv:1301.1583.
- [36] CMS Collaboration, “Search for the production of an excited bottom quark decaying to tW in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **01** (2016) 166, doi:10.1007/JHEP01(2016)166, arXiv:1509.08141.
- [37] CMS Collaboration, “Search for excited quarks of light and heavy flavor in $\gamma +$ jet final states in proton–proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **781** (2018) 390, doi:10.1016/j.physletb.2018.04.007, arXiv:1711.04652.
- [38] CMS Collaboration, “Search for new physics in dijet angular distributions using proton–proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark

- matter and other models”, *Eur. Phys. J. C* **78** (2018), no. 9, 789,
doi:10.1140/epjc/s10052-018-6242-x, arXiv:1803.08030. [Erratum:
Eur.Phys.J.C 82, 379 (2022)].
- [39] ATLAS Collaboration, “Search for new phenomena in dijet events using 37
 fb^{-1} of pp collision data collected at $\sqrt{s}=13$ TeV with the ATLAS detector”,
Phys. Rev. D **96** (2017), no. 5, 052004, doi:10.1103/PhysRevD.96.052004,
arXiv:1703.09127.
- [40] CMS Collaboration, “Search for heavy resonances and quantum black holes in
 $e\mu$, $e\tau$, and $\mu\tau$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”,
JHEP **05** (2023) 227, doi:10.1007/JHEP05(2023)227, arXiv:2205.06709.
- [41] ATLAS Collaboration, “Search for new phenomena in high-mass final states
with a photon and a jet from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS
detector”, *Eur. Phys. J. C* **102** (2018) 041,
doi:10.1140/epjc/s10052-018-5553-2, arXiv:1709.10440.

Chapter 2

Experimental Apparatus

The data analyzed and presented in this thesis is obtained from pp collisions recorded by the Compact Muon Solenoid Experiment (CMS) situated at the Large Hadron Collider (LHC). The LHC is the world's largest and most powerful particle accelerator ever built. In this chapter, a brief description of the LHC and its operations, detailed description of the CMS detector and its sub-detectors are given.

2.1 Large Hadron Collider

The Large Hadron Collider (LHC) [1] is the largest hadron collider built by the European Council for Nuclear Research (CERN) and operated at the France-Switzerland Border near Geneva. It is a large ring with circumference of 26.7 km, located ~ 100 m underground and is used to produce pp and heavy ion collisions. The collider is capable of generating the pp collision upto center-of-mass energy ($\sqrt{s}$) of 14 TeV, which is the highest ever reached by any collider. The LHC started operating in 2009 with pp beam colliding at $\sqrt{s} = 7$ TeV. In the year 2012, $\sqrt{s}$ increased to 8 TeV. This data taking period from 2009-2012 is called Run-I of the LHC. Later, at the end of year 2012 the LHC went into Long Shutdown for maintenance and upgrades, and the collisions again started in the year 2015 at $\sqrt{s} = 13$ TeV. During the Run-II of the LHC, the data is collected in between the years 2015-2018.

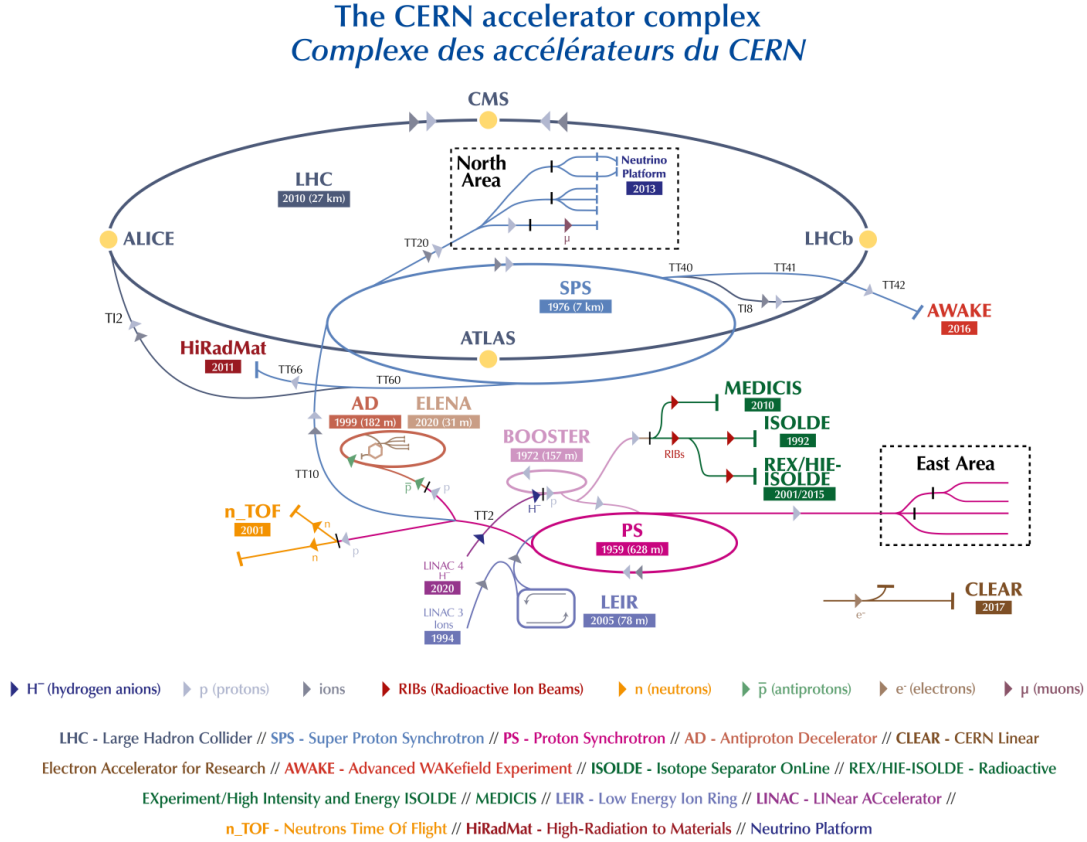


Figure 2.1: A schematic diagram of the CERN accelerator complex [2].

In order to achieve the desired energy and before entering the LHC tunnel, the protons are accelerated at successive stages at CERN, as shown in Fig. 2.1. It starts with stripping out the hydrogen atoms of their electrons and accelerating the protons of energy of about 100 keV to an energy of 50 MeV in a Linear Accelerator (LINAC2). The protons are then subsequently injected into circular Proton Synchrotron Booster (PSB) where their energy is increased upto 2 GeV. In the next step, the further acceleration is done by Proton Synchrotron (PS) where they are grouped into bunches separated by 25 ns and accelerated upto the energy of 25 GeV. At the next stage of acceleration, the protons are injected into Super Proton Synchrotron (SPS) where protons energy reaches 450 GeV. The protons are then finally injected in bunches with $N_b \sim 10^{11}$ protons into the LHC where the beam energy is accelerated to 6.5 TeV per beam [3].

In the LHC ring, the proton beams circulate in two high vacuum pipes in opposite directions, that collide at four interaction points. A magnetic field strength of 8T is required to bend the beams in circular motion that is generated by 1232 superconducting dipole magnets, while an additional number of 392 quadrupole magnets are required to focus the beam. These quadrupole magnets are placed before each interaction point to squeeze the beams and increase the density of protons. To maintain the temperature of 1.9K of the dipole magnets, approximately 96 tonnes of super-fluid Helium is used.

The four interaction points of collision are analyzed by four detectors : ALICE (A Large Ion Collider Experiment) [4], ATLAS (A Toroidal LHC Apparatus) [5], CMS (Compact Muon Solenoid) [6] and LHCb (LHC beauty) [7]. The ALICE and LHCb experiments study heavy ion and b-quark physics, and are located in the octant 2 (Point 2) and octant 8 (Point 8), respectively. The ATLAS and CMS experiments are two general purpose detectors designed for the precision measurements of the SM and beyond standard model (BSM) searches. These general purpose detectors are located at the opposite sides to each other: ATLAS in octant 1 (Point 1) and CMS in octant 5 (Point 5). The protons, after being injected into the LHC ring are accelerated by the force provided by Radio Frequency (RF) cavities. The current layout of the LHC is shown in Fig. 2.2.

2.1.1 Luminosity

A key parameter of the LHC is instantaneous luminosity, $\mathcal{L}$, of collisions depends on many beam parameters

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F \quad (2.1)$$

where, N_b is the number of protons in each bunch, n_b is the number of bunches in each beam, f_{rev} is the collision frequency, γ is the lorentz factor, F is the geometry reduction factor, ϵ_n is the transverse emittance and β^* is the betatron function at the interaction point. The values of these parameters that can be achieved by the LHC and is achieved in different years is shown in Fig. 2.3.

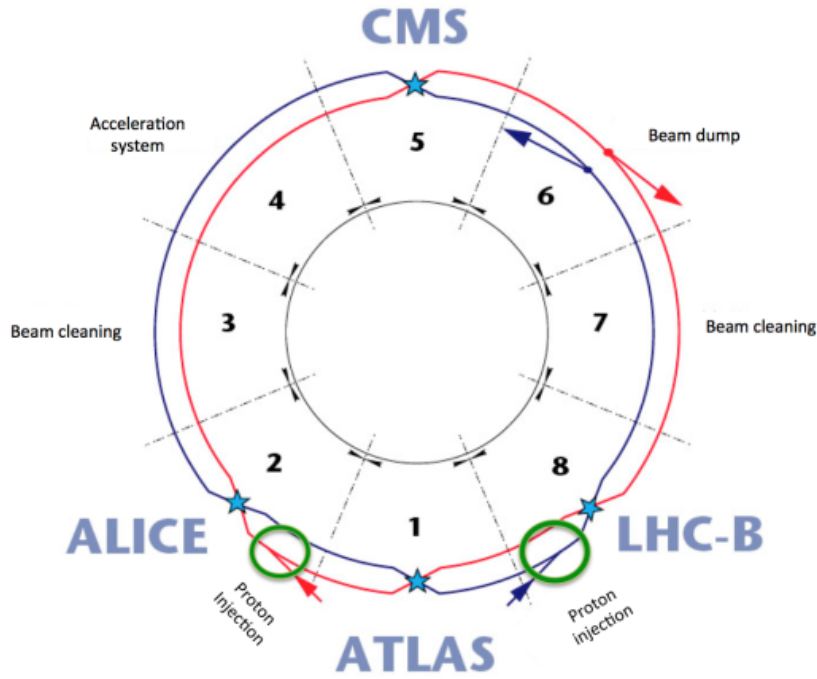


Figure 2.2: Schematic layout of the LHC ring divided into eight octants. The positions of four experiments located is indicated by star, and the CMS is located at octant 5 (Point 5) [8].

Parameter	Design	2012	2016	2017	2018
beam energy [TeV]	7	4	6.5	6.5	6.5
bunch spacing [ns]	25	50	25	25	25
β^* CMS/ATLAS [cm]	55	60	40	40 / 30	30 - 25
crossing angle [μ rad]	285	290	370 / 280	300 - 240	320 - 260
bunch population N [10^{11} ppb]	1.15	1.65	1.1	1.15	1.15
normalized emittance ϵ [μ m]	3.75	2.5	2.2	2.2	2.0
number of bunches per ring k	2808	1374	2220	2556	2556
peak luminosity L [10^{34} cm $^{-2}$ s $^{-1}$]	1	0.75	1.4	2.05	2.01
peak average event pile-up μ	~ 20	~ 35	~ 50	~ 55	~ 60
peak stored energy [MJ]	360	145	270	320	340

Figure 2.3: Machine Parameters of the LHC

The total number of events (N) that could be produced for a physics process

having a cross section value σ is given by the eq.,

$$N = \sigma \int \mathcal{L} dt = \mathcal{L}_{int} \quad (2.2)$$

where $\mathcal{L}_{int}$ is the integrated luminosity, calculated by integrating the instantaneous luminosity over a period of time. Since N depends on luminosity and σ , high luminosity values are needed to study the processes of low production cross section.

The integrated luminosity recorded each data taking year and the cumulative integrated luminosity recorded by the CMS is shown in Fig. 2.4 left and right, respectively.

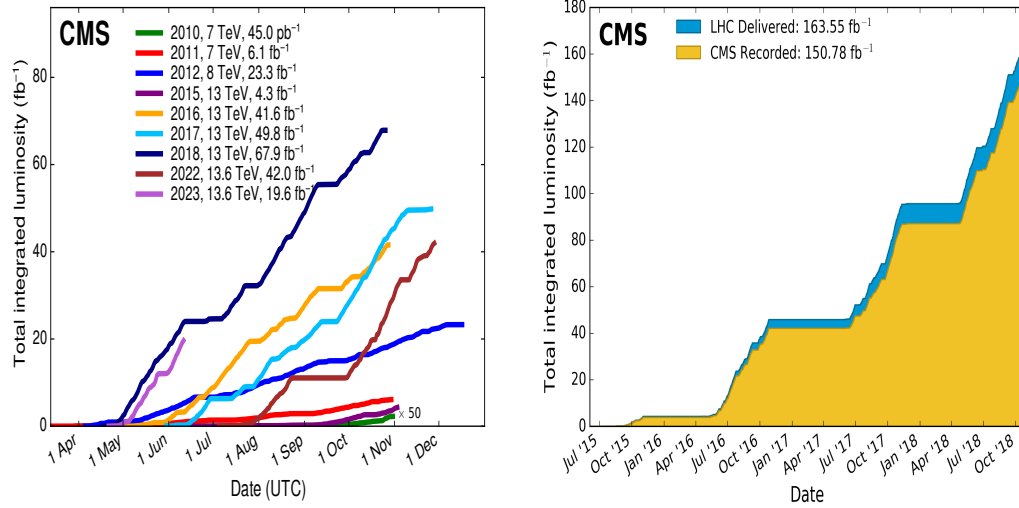


Figure 2.4: The LHC performance during Run-II with integrated luminosity on left for different taking years and cumulative integrated luminosity recorded by CMS for Run-II at center of mass energy 13 TeV.

2.1.2 Pileup

Since there are approximately 10^{11} protons in each bunch circulating in beam pipe, there can be many pp interactions in each bunch crossing. These additional inelastic pp interactions, aside from the interaction with hardest momentum transfer in the same bunch crossing, are called *pileup* (PU) events. Fig. 2.5 depicts the average

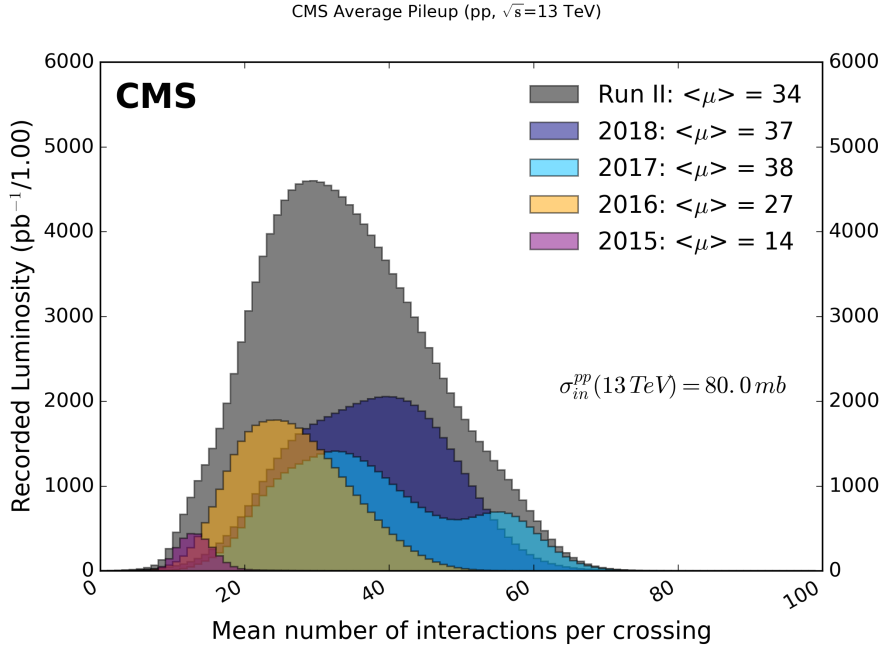


Figure 2.5: The mean number of interactions per beam crossing for each data taking year.

number of pileup observed by the CMS in data taking year 2015-2018 with an average of 34 interactions for Run-II. The figure clearly indicates an increase in the number of pileup interactions between 2015 (a mean of 13) and 2018 (a mean of 37 interactions).

2.2 The CMS Detector

The CMS detector [6] is one of the general purpose detector built at the LHC to explore the physics at the TeV scale for different final state signatures. It is a cylindrical detector with a diameter of 15 m, length of 21 m and weighing about 14000 tonnes. The central feature of the detector is a large superconducting solenoid that provides a magnetic field of roughly 3.8 T. The detector is composed of concentric layers of subdetectors with silicon tracker as the innermost layer closest to the interaction point. The tracker is surrounded by two calorimeters: electromagnetic calorimeter (ECAL) and hadron calorimeter (HCAL). These three subdetectors tracker, ECAL and HCAL are embedded inside the solenoid, while the muon system, outermost

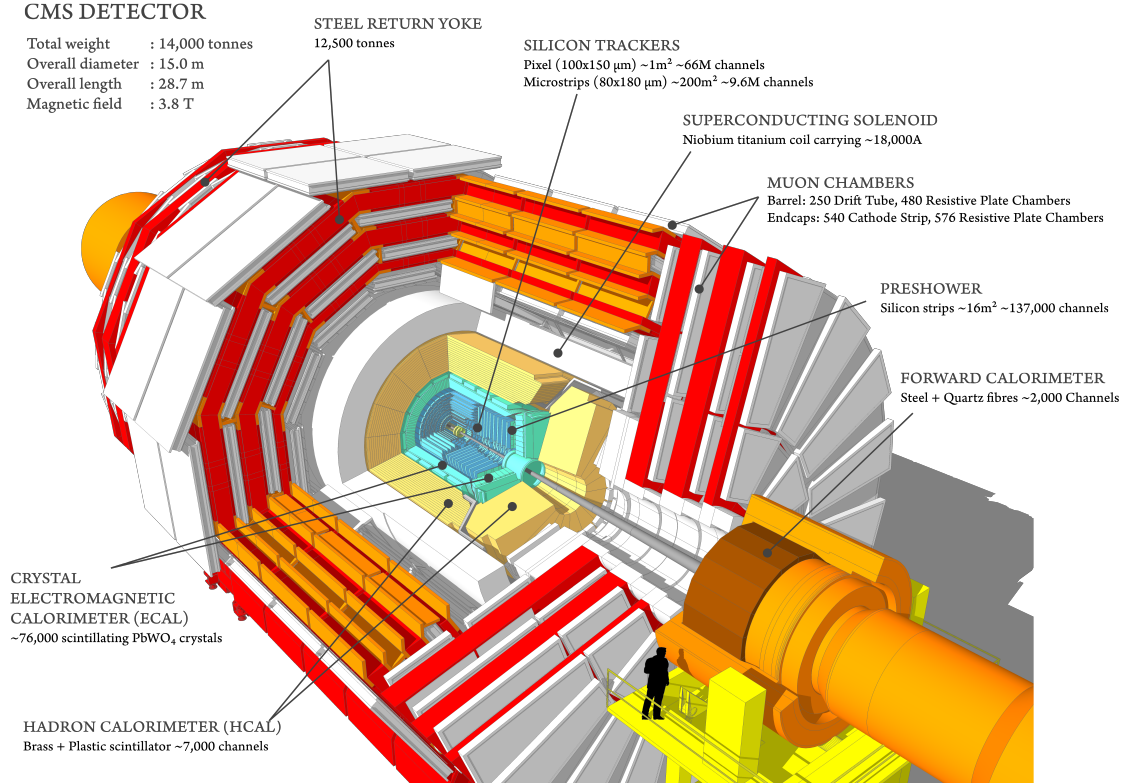


Figure 2.6: The cross-sectional view of the CMS detector [9].

layer, is located outside the solenoid. Fig. 2.6 shows the overall view of the CMS detector with its subsystems.

2.2.1 Co-ordinate system

The CMS detector uses right-handed Cartesian coordinate system as shown in Fig. 2.7 with origin defined as the nominal interaction point. The x -axis points towards the center of LHC ring, the z -direction pointing in the anticlockwise beam direction, y -axis is perpendicular to x - z plane pointing vertically upwards, and r is the radial distance from the beam-line. Given the cylindrical structure of detector, the azimuthal angle ϕ is measured in x - y plane and polar angle θ is measured with respect to x - z plane. A variable called pseudorapidity η , is most commonly used variable in hadron colliders since the difference in pseudorapidity of two particles is

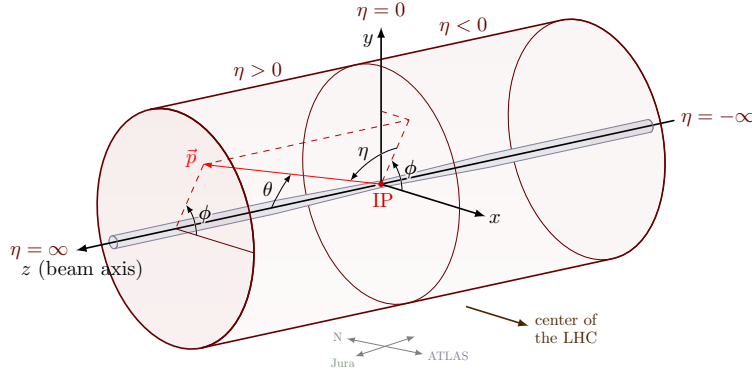


Figure 2.7: The right-handed coordinate system of CMS detector, also representing the coverage in η , ϕ and θ .

invariant under Lorentz boosts along the z-axis. It is defined by eq 2.3.

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right) \quad (2.3)$$

2.2.2 Tracker

The tracker [10] is the innermost sub-detector of the CMS surrounding the interaction point. The tracker is designed for robust and efficient reconstruction of the trajectories of the charged particles. Due to the large magnetic field of the CMS, the charged particles bend their path and leave a track behind for precise measurement of the trajectory path and their momenta. The tracker is constituted of several layers of silicon detectors made of silicon sensors, which provide coverage upto $|\eta| = 2.5$. The choice of the silicon sensors is made due to the good radiation hardness, high granularity and fast response time of the material. The tracker is composed of two subsystems: pixel detector which is a few cm away from the collision point, and the outer silicon strip detector.

Pixel detector: The pixel detector, being closest to the collision point ($r \leq 10$ cm) receives a large flux of particles. It is responsible for high precision measurements of the charged particle tracks, along with the reconstruction of secondary vertices. The pixel detector, prior to the Phase-I upgrade of the tracker in 2017/2018,

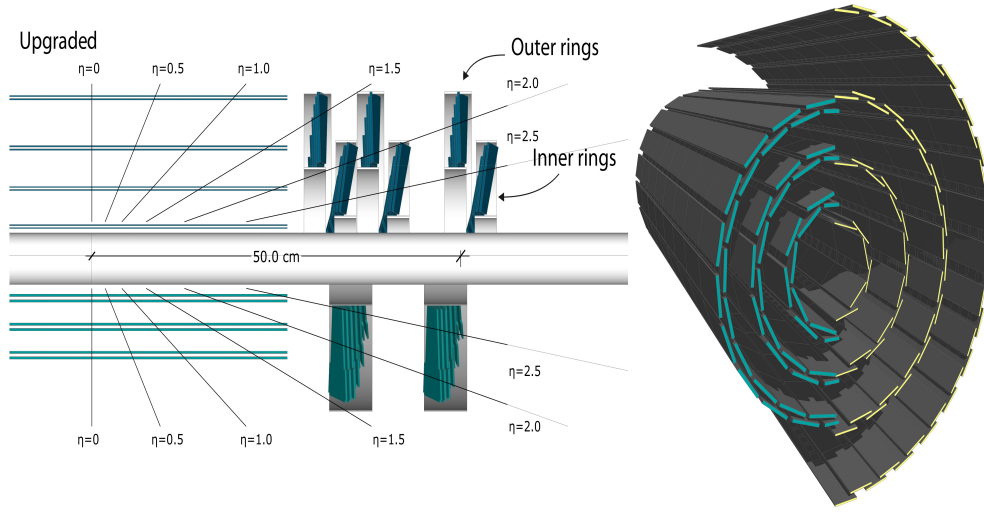


Figure 2.8: A comparison of pixel detector in the tracker before and after Phase-I upgrade. The longitudinal view (left) shows the pixel layers after the upgrade in the upper half and before in the lower half. In the right, shows transverse view of the pixel detector with concentric barrel layers.

consisted of three concentric layers in the barrel (referred to as BPIX) present at $r = 4.4, 7.3$, and 10.2 cm and two disks at each endcap in the forward regions (referred to as FPIX) placed at $z = \pm 34.5$ and ± 46.5 cm. However, in order to cope with the high luminosity and to achieve efficient tracking, the tracker was upgraded to four layers in the barrel and three disks in each endcap [11]. Furthermore, the nearest BPIX layer is moved closer to the interaction point, i.e. from 4.4 cm to 2.9 cm. After the upgrade, the position of all four layers is at $r = 2.9, 6.8, 10.9$ and 16.0 cm. The layout view of the pixel silicon tracker is shown in Fig. 2.8.

The pixel detector is made up of 1856 silicon sensor modules, with 1184 modules used in barrel layers (BPIX) and 672 modules used in endcap disks (FPIX). These modules further consist of a sensor with 160×416 number of pixels connected to 16 readout chips. In total, 124 million pixels (79 million in four barrel layers and 45 million in six endcap disks) are used in the detector.

Strip detector: The strip detector surrounding the pixel detector is composed of ten coaxial barrel layers, three small and nine large disks in each endcap. The strip detector consists of 15148 modules, divided into four subsystems: Tracker

Inner Barrel (TIB), Tracker Inner Disks (TID), Tracker EndCaps (TEC) and the Tracker Outer Barrel (TOB). The TIB is made up of 4 layers of silicon strips having thickness of $340\text{ }\mu\text{m}$, and the TID on each endcap consists of 3 disks covering the radial distance $20 < r < 55\text{ cm}$, same as TIB. The position of TIB and TID is such that strips in TIB are parallel to beam line and disks in TID are radial. The TOB consists of six layers of strips covering $55 < r < 116\text{ cm}$. In each endcap, there are 9 disks in TEC modules covering the forward region $124 < |z| < 280\text{ cm}$, and radial distance coverage between $20 < r < 116\text{ cm}$. The silicon sensors used in TOB has a thickness of $500\text{ }\mu\text{m}$, while in TEC thickness varies in range of 320 to $500\text{ }\mu\text{m}$ depending on the position of disks from the centre. A layout of the tracking system with all modules is shown in Fig. 2.9.

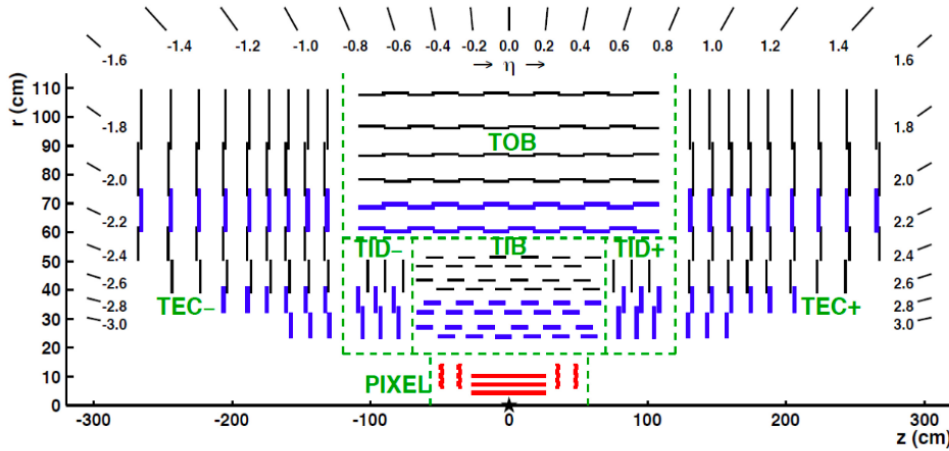


Figure 2.9: A layout of the tracker in r - z view, with different sensor modules of subsystems in tracker [12].

2.2.3 Electromagnetic Calorimeter

The Electromagnetic Calorimeter (ECAL) [13] is a hermite and homogenous detector made up of finely granuled lead tungstate (PbWO_4) crystals. The electromagnetic particles, mainly electrons, positrons, and photons interact with the PbWO_4 crystals and emit a scintillating light proportional to the energy of incident particle. The light signal is collected by the photodetectors to measure the incident's

particle energy. The electrons or positrons upon interaction with the material, radiate bremsstrahlung photons, whereas the photons interact via pair production, and hence generating a shower of particles. The process of radiating photons and pair production keeps going until the electron or photon energies fall below the process thresholds.

The choice of PbWO_4 crystals to construct ECAL is driven by high density of material (8.28 g/cm^3), short radiation length ($X_0 = 0.89 \text{ cm}$) and small Moliere radius (2.2 cm) making it a compact calorimeter to be well fitted within CMS solenoid magnet. Another important factor to consider PbWO_4 crystals is that they are radiation hard, hence more suitable to cope up with the high exposure of ionizing particles. The scintillating decay time of the crystal is also similar to the LHC bunch crossing time (25 ns) and therefore has a fast response time.

The ECAL is made up of a total of 75848 trapezoidal crystals, with the barrel system (EB) consisting of large number of 61200 crystals and two endcap systems (EE) each consisting of 7324 crystals. The length of crystals in barrel is 23 cm , with a frontal area cross-section of $22 \times 22 \text{ mm}^2$ and rear area cross-section of $26 \times 26 \text{ mm}^2$ ensuring a coverage upto the pseudorapidity region $|\eta| < 1.479$. In the endcap, the crystal length is 22 cm with dimensions $28.62 \times 28.62 \text{ mm}^2$ in the front area and $30 \times 30 \text{ mm}^2$ in the rear area covering upto the region $1.479 < |\eta| < 3.0$. The front of each endcap is covered by the electromagnetic preshower (ES) detectors in the region $1.653 < |\eta| < 2.6$. The preshower detector is a sampling calorimeter made of lead absorber plates and silicon strip sensors providing better spatial resolution than crystals. This design helps in distinguishing single photons from boosted π^0 decay to $\gamma\gamma$. A schematic view of the ECAL detector is shown in Fig. 2.10.

The energy resolution of the ECAL is dependent on the energy of incoming electrons and photons as :

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{S}{E}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2 \quad (2.4)$$

The S stands for stochastic term which arises from photon-electron statistics

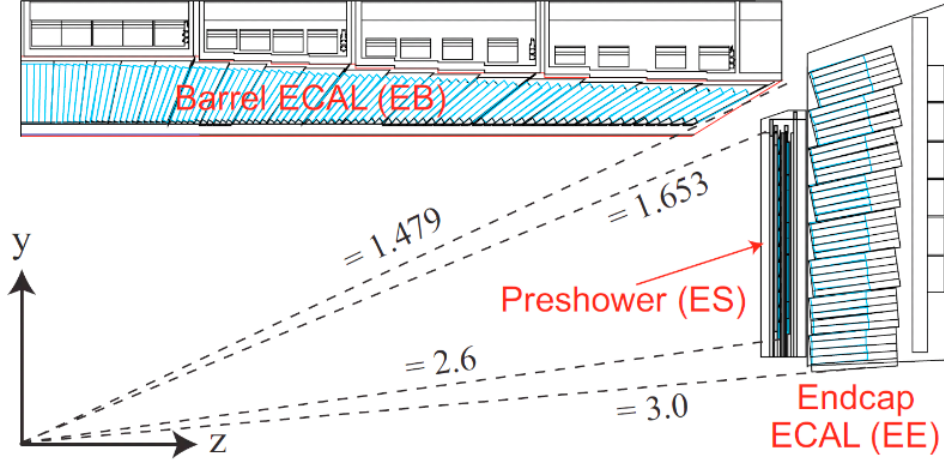


Figure 2.10: A schematic diagram of the ECAL detector [14].

from the scintillation process, while the noise term (N) is due to the electronic noises. The constant term (C) depends on detector non-uniformity response and calibration uncertainties. The energy resolution varies around 2% for barrel and it increases upto 5% in endcap as depicted in the Fig. 2.11 for different years of Run-II data taking [15, 16].

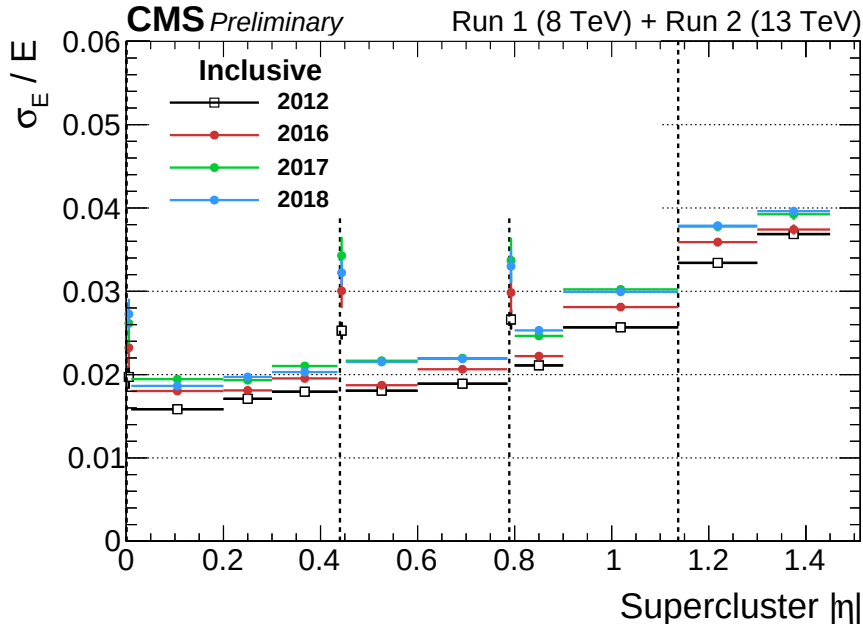


Figure 2.11: The energy resolution of ECAL from $Z \rightarrow ee$ as a function of η for different years of Run-I and Run-II data taking [17].

2.2.4 Hadronic Calorimeter

The hadronic calorimeter (HCAL) is a sampling calorimeter designed to measure the energy of charged and neutral hadrons. It is made of alternating layers of brass absorber plates and tiles of plastic scintillators, with light from scintillators collected by wavelength shifting (WLS) fibres for readout system. The mean free path transversed by hadron before undergoing a nuclear interaction is defined by the hadronic interaction length, λ_l . The depth of HCAL varies between 5.8 and $10.6 \lambda_l$ depending on η [18]. The absorber thickness of HB depends on polar angle θ , varying as $1/\sin\theta$, and hence resulting a thickness of $10.6 \lambda_l$ at $|\eta| = 1.3$.

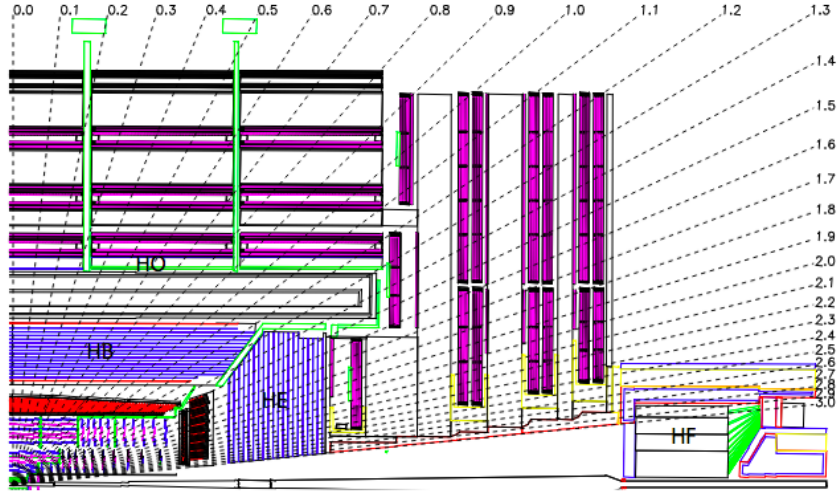


Figure 2.12: The longitudinal view of CMS detector in r - η plane showing the positions of hadronic barrel (HB), hadronic endcap (HE), Hadronic outer (HO) and hadronic forward (HF) calorimeters in the HCAL [6].

The CMS HCAL consists of four different subsystems: hadronic barrels (HB), hadronic endcaps (HE), hadronic outer (HO), and hadronic forward (HF) calorimeters, as shown in Fig. 2.12. The HB is categorized in two half-barrels (HB+ and HB-) aligned in the beam direction (z axis) covering the pseudorapidity region $|\eta| < 1.4$. Each half barrel is made up of 18 azimuthal wedges each subtending an angle of 20° in ϕ , as shown in Fig. 2.13. These wedges are constructed of brass absorber plates bolted together in a staggered geometry. In order to provide structural support, the innermost and outermost layers of absorber plate is made of stainless

steel. Each wedge in transverse plane is divided into 4 segments, i.e $18 \times 4 = 72$ sectors in ϕ , denoted as $i\phi$ and in longitudinal plane is divided into a total of 16 sectors for each barrel, denoted as $i\eta$. This provides a segmentation of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for each scintillation tile. Moreover, each channel of $i\eta - i\phi$ is known as a *tower*. The tower segmentation is shown in Fig. 2.14.

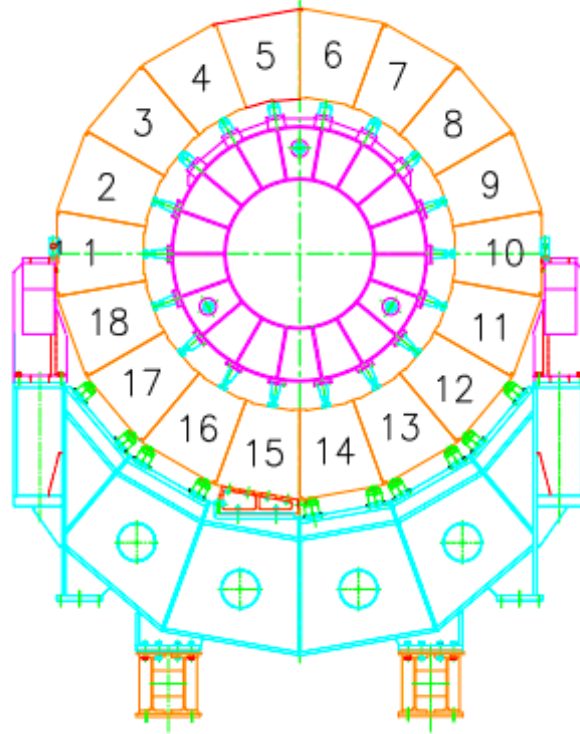


Figure 2.13: The numbering scheme of 18 azimuthal wedges in HB of HCAL [6].
Wedge 1 is in $+x$ direction of LHC ring.

The HE in the endcap has 18 fold symmetry in ϕ and covers the pseudorapidity region $1.3 < |\eta| < 3.0$. The sampling structure of brass absorber and plastic scintillating layer is similar to HB. In the region $1.3 < |\eta| < 1.6$, each $\Delta\eta \times \Delta\phi$ tower covers an area of 0.087×0.087 with a segmentation of 5° in ϕ . The granularity of HE in this region is same as that of HB. However, in the region $1.6 < |\eta| < 3.0$, the granularity is $\Delta\eta \times \Delta\phi = 0.017 \times 0.017$ where ϕ segmentation is of 10° .

The HO covering the pseudorapidity region $|\eta| < 1.4$ (same as barrel) is installed outside the solenoid. Since the absorbing thickness of HB is not enough to

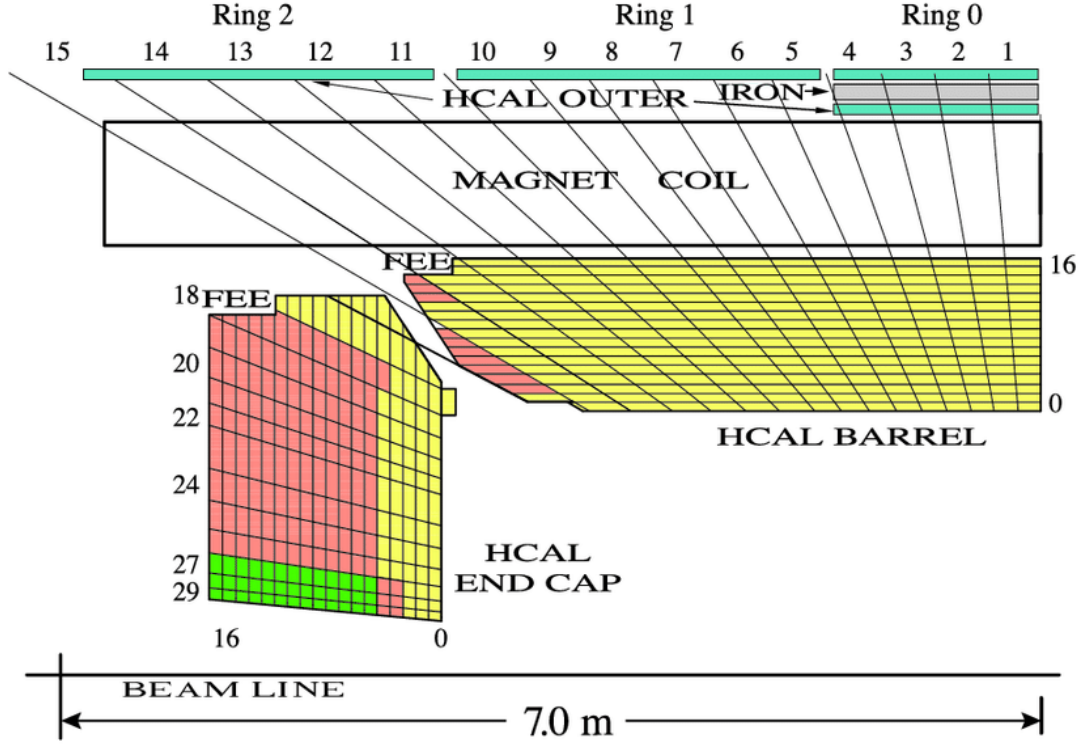


Figure 2.14: A longitudinal view of one quarter of HCAL detector in the $r-z$ plane representing the tower segmentation [19].

fully contain the hadronic shower, HO serves as *tailcatcher* by providing an extra layer of absorber in the same region [20]. The HO is divided into five rings (identified by the numbers $\pm 2, \pm 1, 0$) along the beam direction, each having 12 sectors in ϕ . The central ring 0 consists of two layers of scintillators separated by steel absorber, while the other rings at ± 1 and ± 2 have only a single layer of scintillator. The solenoid coil in front of HO also acts as an additional absorber layer.

The forward region $3.0 < |\eta| < 5.0$ is covered by the HF which is placed at distance of 11.5 cm from the collision point on both the sides [21]. The HF is Cherenkov-light based calorimeter that uses steel as the absorbing material instead of brass and the quartz fibres as the scintillating material. The quartz fibres serves as more suitable choice to the high particle flux environment in the forward region.

Till the starting of year 2017, the HB, HE and HO used hybrid photodiodes (HPD) as their photodetectors. However, during the Phase-I upgrade,

the HPDs were replaced by more efficient and compact Silicon Photomultipliers (SiPMs) [22], [23]. The SiPMs offers better signal-to-noise ratio and low operating volatages as compared to HPDs. The energy resolution of combined HCAL and ECAL is measured to be

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{84.7\%}{E}\right)^2 + (7.4\%)^2 \quad (2.5)$$

where 84.7% represents the stochastic term and 7.4% represents the constant term [19].

2.2.5 Magnet

The superconducting solenoid system in CMS [24] [25] is the largest ever built solenoid. It is the central system in the CMS detector around which the detector is built. The magnet provides a homogeneous field of strength $B = 3.8$ Tesla. The magnetic field is 100000 times stronger than the Earth's magnetic field, which bends the path of the charged particles from the collisions. This bending is necessary for the high resolution on measurement of particles' momenta. The length of the solenoid is 13m with a diameter of 5.9m large enough to contain the tracker and calorimeter. The magnetic flux from the solenoid is returned via a steel iron yoke that weights 10000 tonnes (Fig. [?]). The iron yoke makes most of the contribution to the large mass of the CMS.

2.2.6 Muon Detector

The core feature of the CMS detector, as name suggests, is the muon subsystem designed to precisely identify the muons and measure their kinematics. The motivation behind having a specific muon system is that muons are involved in many SM processes and are predicted as decay particle in the new searches as well. Muons are the least ionizing particles, have a relatively long lifetime, and as a result traverse without interacting with the material of the detector. Therefore, the muon subsys-

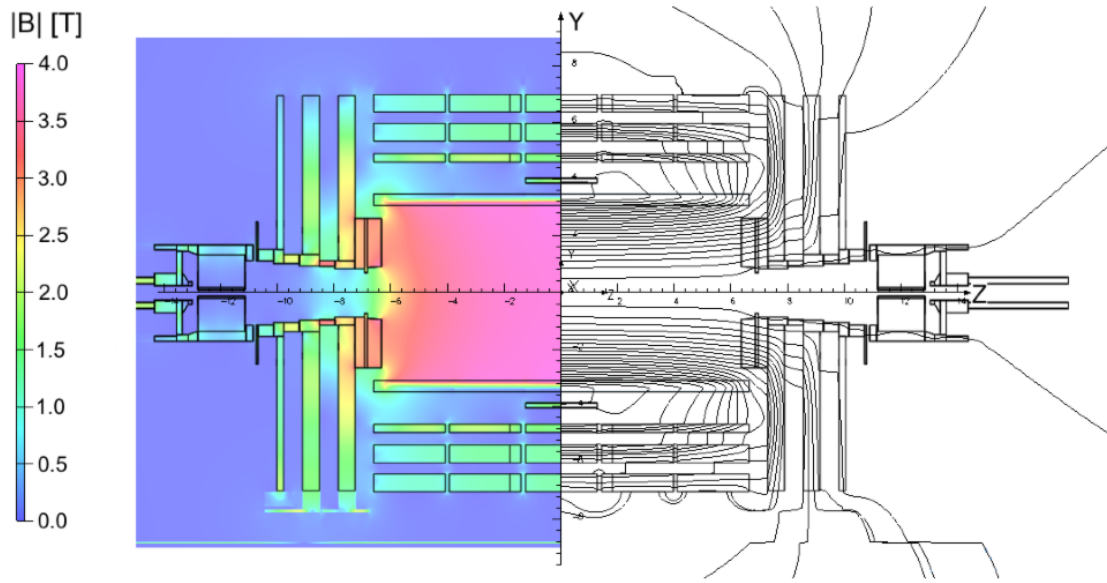


Figure 2.15: The magnetic field $|B|$ (left) and field lines (right) in the longitudinal view of the CMS detector [26].

tem is the outermost layer installed outside the solenoid and embedded in return yoke. Like most subdetectors, the muon system consists of one barrel and two end-caps. It is composed of three different type of gas-ionization detectors : Drift Tubes (DT), Cathode Strips Chambers (CSC) and Resistive Plate Chambers (RPC). During Long Shutdown 2 (LS2) period, which started in 2019, another subsystem of the muon detector was planned to be installed in the forward region $1.5 < |\eta| < 2.4$. This subsystem, called Gas Electron Multipliers (GEM) is also a gaseous detector, similar to other muon subsystems. The primary purpose of these GEM detectors will be to provide a good L1 trigger rate and improved muon reconstruction at high luminosity rates. A detailed description of the GEM detectors is given in Chapter 3.

Drift Tube Chambers: The DTs installed in the barrel region covering $|\eta| < 1.2$ are arranged in five identical wheels. Each wheel is further divided into twelve azimuthal sectors with four layers per sector. These layers are MB1, MB2, MB3 and MB4 as shown in Fig. 2.18. The DT is a rectangular cell of size $13 \times 42 \text{ mm}^2$ with electrodes on top and bottom, cathode strips on sides and an anode wire in

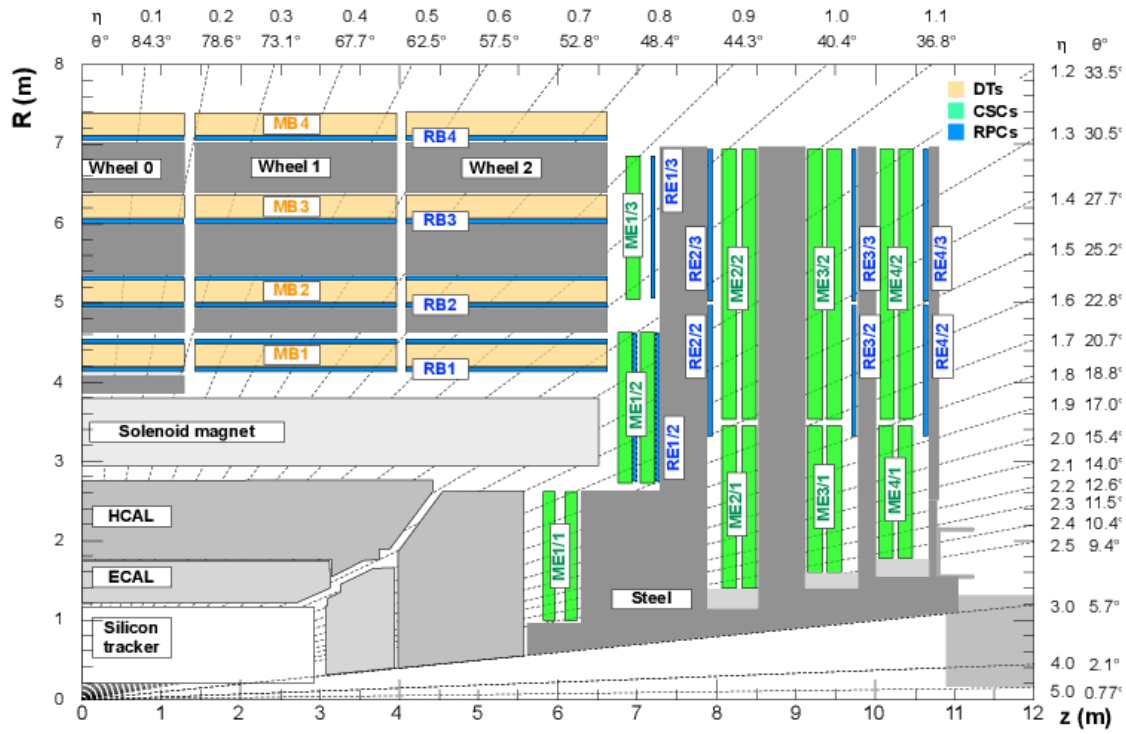


Figure 2.16: Longitudinal view of muon detector with its three subsystems: Drift Tubes (DTs) in yellow, Cathode Strip Chambers (CSCs) in green and Resistive Plate Chambers (RPCs) in blue [26].

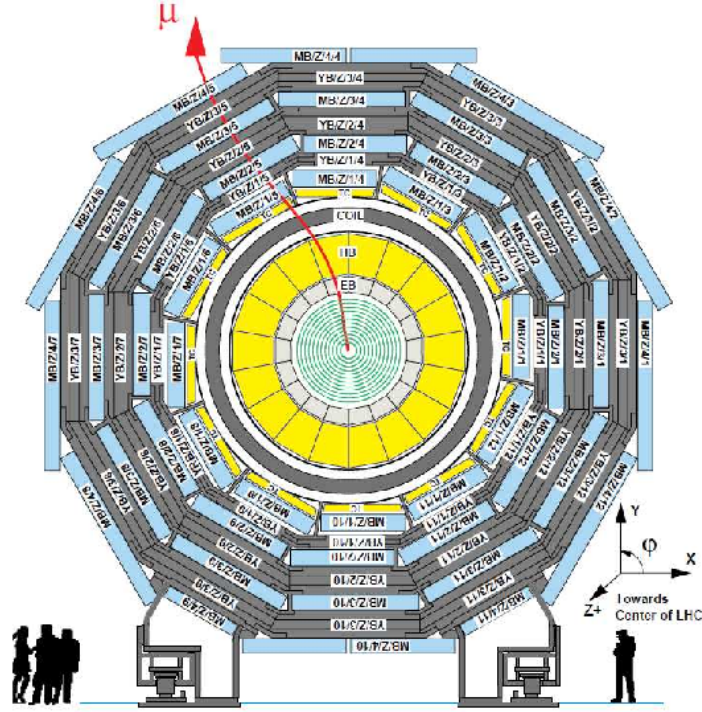


Figure 2.17: A schematic layout of muon detector.

between. The cell is filled with a gaseous mixture of Ar and CO_2 in the composition of 85% and 15%, respectively. As muon passes through the chamber, it ionizes the gas producing an electron avalanche. The current induced through this avalanche gives the estimation of drift time and position of the muon hit in the chamber. The DTs have an excellent spatial resolution of $100\ \mu\text{m}$ [27].

Cathode Strips Chambers: CSC cover the barrel pseudorapidity region $0.9 < |\eta| < 2.4$, overlapping with the DTs in the region $0.9 < |\eta| < 1.2$. In the endcaps, the particle flux is high and magnetic field is also non-uniform. Hence, a sub-detector with fast response time, radiation hard should be installed in this region making CSCs a better choice than DTs. The CSCs are designed in trapezoidal shapes with seven panels, having six gaps filled with gaseous mixture $\text{Ar}:\text{CO}_2:\text{CF}_4$ in the proportion 30%:50%:20%. The cathode strips on panel are arranged in radial direction, while the anode wires are azimuthally placed (perpendicular to cathode

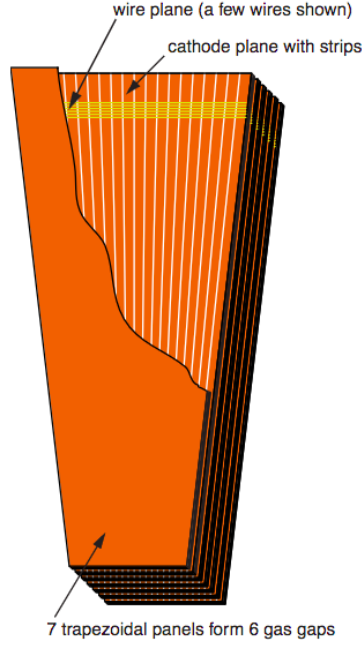


Figure 2.18: A schematic view of CSC chamber.

wires). This structure allows the precise measurements in r - ϕ and η direction, with a spatial resolution of 40-150 μm [28] [26].

Resistive Plate Chambers: The RPCs are installed in the region $|\eta| < 1.9$ covering both barrel and endcap. There are in total 1056 PC's, 480 in barrel and 576 in endcap, installed in the muon system. Rocks are double-gap gaseous chamber with two resistive plates separated by 2 mm spacers and volume filled with mixture of $C_2H_2F_4(95\%)/iC_4H_{10}(5\%)$. A layout of module is shown in Fig. 2.19. As muons traverse through the chamber, it ionizes the gas and electron starts drifting due to high electric field and signal is captured by readout strips. Although, RPCs have coarser spatial resolution (few cm), but they provide excellent time resolution of 1 ns i.e less than LHC bunch crossing of 25 ns [29]. This makes the RPCs an independent and suitable triggering system. However, the rate capability of RPCs does not allow them to be used in the very-forward region for High-Luminosity LHC (HL-LHC), where the background rates will be higher. Thus, Micro-pattern detectors are proposed to be installed in this region, and more details on this is given in the next chapter.

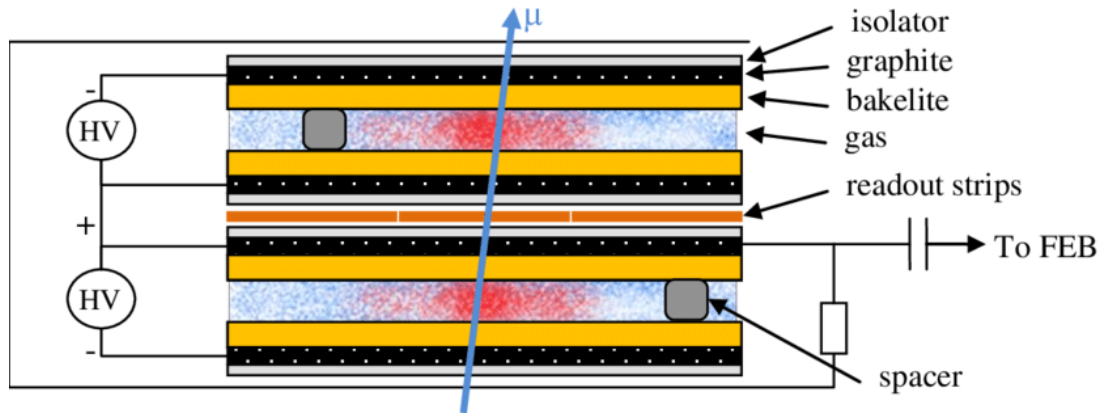


Figure 2.19: A cross-section view of RPC system.

2.2.7 Trigger System

The LHC produce bunches at the rate of 40 MHz with bunch spacing of 25 ns generating a billion of pp interactions in a second. Since storing each event with all the detector information is one of the major limitation for all high energy experiments. Moreover, only a small fraction of events are of physics interest. Hence, CMS comes up with a trigger system [30] to store only the interesting pp collision data. The event rate is reduced from 40 MHz to 1 kHz using two tier trigger system.

- Level-1 trigger (L1) is a hardware system which performs logical operations based on information from calorimeters and muon detectors.
- High Level Trigger (HLT) is a software based trigger that filters data based on reconstructed physics objects

L1 trigger reduces the event rate to 100 kHz from 40 MHz with a fixed latency of about 4 μ s. In order to be quick, only the information from calorimeters and muons chambers is utilised to accept or reject the event. Since the track reconstruction takes time, it is not included in this decision making process by the L1 trigger. Coarsely segmented information from the calorimeters and muon system is fed to the trigger system, while the full event detail is kept in buffer until a decision is made by the L1 trigger system. The loose selection criteria for electrons, photons, tau, jets, and energy sums from the energy deposits in calorimeters and hits in muon chambers

are defined, and based on this the decision is made by the trigger. Events passing the L1 trigger are further slimmed down by HLT to rate 1 kHz. Tracker information is considered by this software based HLT trigger to facilitate the difference between electrons, photons, muons, and hadronic jets. After all the selections in a HLT path are passed, the event is stored as offline data for further physics analysis.

To improve the L1 trigger rate and muon reconstruction, new detectors i.e GEM detectors as a part of CMS upgrade are installed in the muon chamber in forward region. In the following chapter, the assembly and testing of these GEM detector at the Panjab University site is discussed.

Bibliography

- [1] L. Evans and P. Bryant, “LHC Machine”, *JINST* **3** (2008) S08001, doi:10.1088/1748-0221/3/08/S08001.
- [2] C. Lefèvre, “The CERN accelerator complex. Complexe des accélérateurs du CERN”, Dec, 2008. CERN.
- [3] M. Benedikt et al., “LHC Design Report. 3. The LHC injector chain”, doi:10.5170/CERN-2004-003-V-3.
- [4] ALICE Collaboration, “The ALICE experiment at the CERN LHC”, *JINST* **3** (2008) S08002, doi:10.1088/1748-0221/3/08/S08002.
- [5] ATLAS Collaboration, “The ATLAS Experiment at the CERN Large Hadron Collider”, *JINST* **3** (2008) S08003, doi:10.1088/1748-0221/3/08/S08003.
- [6] CMS Collaboration, “The CMS Experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [7] LHCb Collaboration, “The LHCb Detector at the LHC”, *JINST* **3** (2008) S08005, doi:10.1088/1748-0221/3/08/S08005.
- [8] A. P. Singh, P. C. Bhat, N. V. Mokhov, and S. Beri, “Beam-induced radiation in the compact muon solenoid tracker at the Large Hadron Collider”, *Pramana* **74** (2010) 719–729, doi:10.1007/s12043-010-0093-9.
- [9] CMS Collaboration, “A New Boson with a Mass of 125 GeV Observed with the CMS Experiment at the Large Hadron Collider”, *Science* **338** (2012) 1569–1575, doi:10.1126/science.1230816.

-
- [10] CMS Collaboration, “The CMS tracker system project: Technical Design Report”. Technical design report. CMS. CERN, Geneva, 1997.
- [11] CMS Collaboration, “CMS Technical Design Report for the Pixel Detector Upgrade”, doi:10.2172/1151650.
- [12] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014), no. 10, P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
- [13] CMS Collaboration, “The CMS electromagnetic calorimeter project: Technical Design Report”. Technical design report. CMS. CERN, Geneva, 1997.
- [14] CMS Collaboration, “The CMS ECAL performance with examples”, *JINST* **9** (2014) C02008, doi:10.1088/1748-0221/9/02/C02008.
- [15] CMS Collaboration, “Energy Calibration and Resolution of the CMS Electromagnetic Calorimeter in pp Collisions at $\sqrt{s} = 7$ TeV”, *JINST* **8** (2013) P09009, doi:10.1088/1748-0221/8/09/P09009, arXiv:1306.2016.
- [16] P. Adzic et al., “Energy resolution of the barrel of the CMS electromagnetic calorimeter”, *JINST* **2** (2007) P04004, doi:10.1088/1748-0221/2/04/P04004.
- [17] CMS Collaboration, “The ultimate CMS ECAL calibration and performance for the legacy reprocessing of LHC Run 2 data”, *PoS* (2023) 643, doi:10.22323/1.414.0643.
- [18] CMS Collaboration, “CMS Physics: Technical Design Report Volume 1: Detector Performance and Software”. Technical design report. CMS. CERN, Geneva, 2006.
- [19] CMS Collaboration, “Performance of the CMS hadron calorimeter with cosmic ray muons and LHC beam data”, *Journal of Instrumentation* **5** (mar, 2010) T03012–T03012, doi:10.1088/1748-0221/5/03/t03012.

-
- [20] B. S. Acharya et al., “The CMS Outer Hadron Calorimeter”, technical report, CERN, Geneva, 2006.
- [21] CMS HF Calorimeter Collaboration, “CMS hadronic forward calorimeter”, *Nucl. Phys. B Proc. Suppl.* **61** (1998) 41–46, doi:10.1016/S0920-5632(97)00536-7.
- [22] CMS Collaboration, “CMS Technical Design Report for the Phase 1 Upgrade of the Hadron Calorimeter”, doi:10.2172/1151651.
- [23] CMS Collaboration, “Phase I Upgrade of the CMS Hadron Calorimeter”, *Nucl. Part. Phys. Proc.* **273-275** (2016) 1002–1007, doi:10.1016/j.nuclphysbps.2015.09.157.
- [24] CMS Collaboration, “The CMS magnet project: Technical Design Report”. Technical design report. CMS. CERN, Geneva, 1997. doi:10.17181/CERN.6ZU0.V4T9.
- [25] CMS Collaboration, “Precise Mapping of the Magnetic Field in the CMS Barrel Yoke using Cosmic Rays”, *JINST* **5** (2010) T03021, doi:10.1088/1748-0221/5/03/T03021, arXiv:0910.5530.
- [26] CMS Collaboration, “The Performance of the CMS Muon Detector in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV at the LHC”, *JINST* **8** (2013) P11002, doi:10.1088/1748-0221/8/11/P11002, arXiv:1306.6905.
- [27] CMS Collaboration, “Performance of the CMS Drift Tube Chambers with Cosmic Rays”, *JINST* **5** (2010) T03015, doi:10.1088/1748-0221/5/03/T03015, arXiv:0911.4855.
- [28] CMS Collaboration, “Performance of the CMS Cathode Strip Chambers with Cosmic Rays”, *JINST* **5** (2010) T03018, doi:10.1088/1748-0221/5/03/T03018, arXiv:0911.4992.
- [29] CMS Collaboration, J. G. Layter, “The CMS muon project: Technical Design Report”. Technical design report. CMS. CERN, Geneva, 1997.

- [30] CMS Collaboration, “The CMS trigger system”, *Journal of Instrumentation* **12** (jan, 2017) P01020–P01020, doi:10.1088/1748-0221/12/01/p01020.

Chapter 3

Gas Electron Multiplier Detector

The upgrade of LHC to High-Luminosity LHC (HL-LHC) will achieve a center-of-mass energy of 14 TeV and an instantaneous luminosity of $5 \times 10^{-34} \text{ cm}^{-2}\text{s}^{-1}$. This luminosity is approximately 5 times of current delivered instantaneous luminosity during Run-II. However, the current design of the CMS is not fully capable of handling such a massive increase in luminosity and background rates. Hence, to take full advantage of the increased event rates and show limited downsides due to detector aging, the CMS design needs an upgrade for better performance during HL-LHC operation. These upgrades are planned during long shutdown LS2 and LS3 in 2019-2021 and 2024-2026, respectively. According to the current scenario, LS2 is over and Run3 data-taking has started. One of the upgrades that will be instrumented in the CMS detector is installation of a new detector in the muon system, called Gas Electron Multipliers (GEMs).

The CMS muon system consists of three types of gaseous detectors : Cathode Strip Chambers (CSCs), Resistive Plate Chambers (RPCs) and Drift Tubes (DTs) [1]. The details of these sub-systems are already discussed in Chapter 2. The DTs provide the pseudorapidity coverage upto $|\eta| < 1.2$, while CSC covers the range $0.9 < |\eta| < 2.4$. The RPCs with better time resolution provide coverage both to DTs and CSCs in the η region $|\eta| < 1.6$. Furthermore in the forward region $1.6 < |\eta| < 2.4$, the background event rate is large and also lack redundancy and is

only covered by CSCs. Therefore, to preserve L1 trigger performance, improve reconstruction capabilities, and for precise momentum measurements, GEM (GE1/1) detectors [2] are installed in this region to complement CSCs. In the name GE1/1, G stands for GEM; E stands for Endcap; the first “1” corresponds to first muon station, and second “1” is for first ring of muon station. The Fig. 3.1 shows the quadrant view of CMS with position of GE1/1 (illustrated in red color) installed in the endcap.

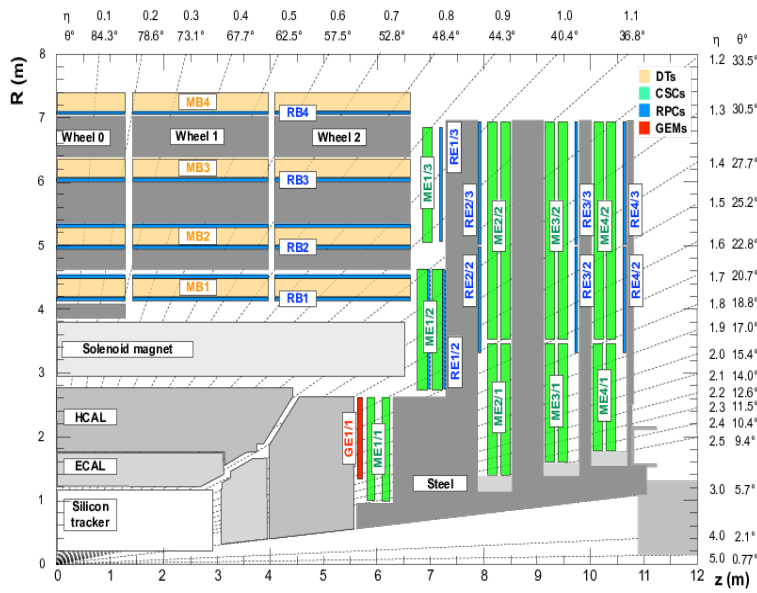


Figure 3.1: A quadrant of the muon system, showing DT chambers (yellow), RPC (light blue), and CSC (green). The new GEM detector station, GE1/1 is indicated in red [3].

3.1 Motivation for GEM upgrade in CMS

In the initial proposal of the CMS, RPCs were to be installed beyond $|\eta| > 1.6$ but later, this proposal was not executed due to concerns that RPCs would not be able to cope up with the higher background rates of the HL-LHC. In order to rectify this, a new proposal for GEM detectors was made to complement CSCs in the same region where RPCs were planned to be installed. The GEM detectors are very robust and will help improve the performance of CMS muon system and CMS

detector for HL-LHC.

In the first muon station, the bending of muon tracks due to the magnetic field lines is large as compared to the other stations. With the installation of GE1/1 chambers in this region, the determination of bending angle will be more accurate and hence, will result in a more precise measurement of muon's direction. Thus, the L1 standalone muon trigger momentum resolution will also be improved [4]. For example, a single muon trigger will allow L1 trigger threshold at 12-14 GeV to be fully efficient at 18-19 GeV by installing GE1/1 chambers. Fig. 3.2 shows the L1 trigger rate for single-muon studied on simulations for $\sqrt{s} = 14$ TeV before and after installing GE1/1 chambers. The figure shows improved L1 trigger rate for a p_T threshold after installing GE1/1 chambers and therefore will be beneficial for broad spectrum of studies from Beyond Standard Model (BSM) searches to the Higgs sector measurements.

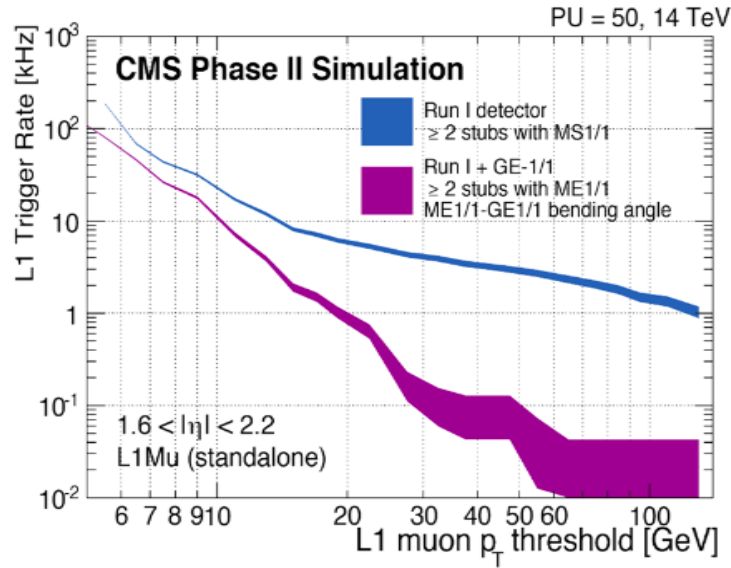


Figure 3.2: Simulations of L1 muon trigger rate at a luminosity of $2 \times 10^{34} \text{ cm}^2 \text{ sec}^{-1}$ as a function of p_T threshold [3].

Other advantages of installing GE1/1 detector are :

- expected to provide a time resolution of 8-10 ns
- angular resolution of $300 \mu\text{rad}$ on $\Delta\Phi = \Phi_{GE1/1} - \Phi_{ME1/1}$

- rate capability of 10 kHz cm^{-2} or better

3.2 GEM Technology

The GEM detectors belong to the Micro Pattern Gas Detectors (MPGDs) family, relying on the microscopic structures to generate electron avalanches [5]. The key element of the detector is GEM foil, that is a $50 \mu\text{m}$ thick polyimide sheet coated with a $5 \mu\text{m}$ thick conducting layer of copper on top and bottom of sheet. Microscopic holes are chemically etched throughout the sheet using photolithography technology. The holes have an hour-glass geometry with an outer diameter of $70 \mu\text{m}$ and inner diameter of $50 \mu\text{m}$, as shown in Fig 3.3.

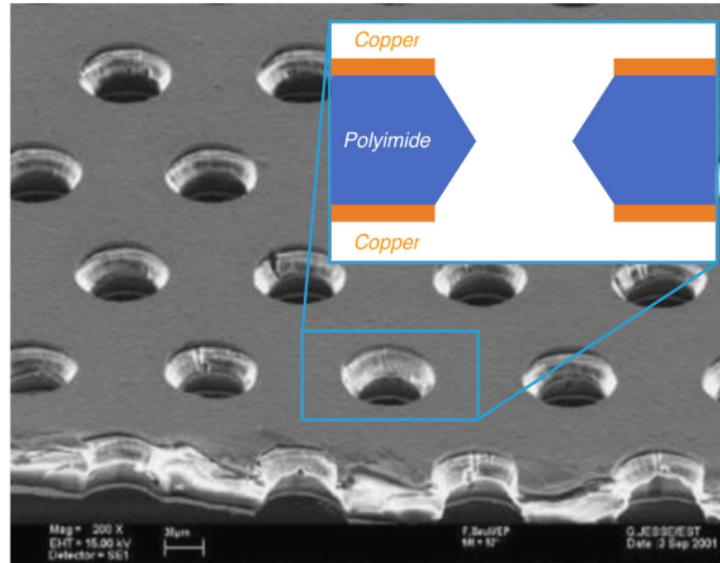


Figure 3.3: A microscopic view of GEM foil, with holes and its sketch taken from [6].

The GE1/1 chamber is a triple-GEM detector i.e. it consists of three layers of foil separated by a few mm with volume filled with a gas. The holes etched in the GEM foils work as a proportional counter with a high voltage applied across the conducting copper layers and further, creating a potential difference of around 300-500 V. This potential difference across two layers makes an electric dipole with an electric field upto 100 kV. To understand the working principle, consider a single-

GEM detector where a foil is placed in between cathode and anode at a gap. In a case when a particle such as a muon enters the chamber, it ionizes the gas and create ion-electron pair. The electron drifts towards the foil following the electric field and ions move to cathode. Once electron reaches the hole in the foil, there they acquire enough energy to produce secondary electron-ion pairs. This is called amplification region with a potential gain of 10^3 provided by a single foil. These secondaries then reaches the anode travelling through induction field. A measurable signal is further induced on the anode with readout strips to identify the signal in the form of collected charge. A layout of the GEM detector having single foil is shown in Fig 3.4.

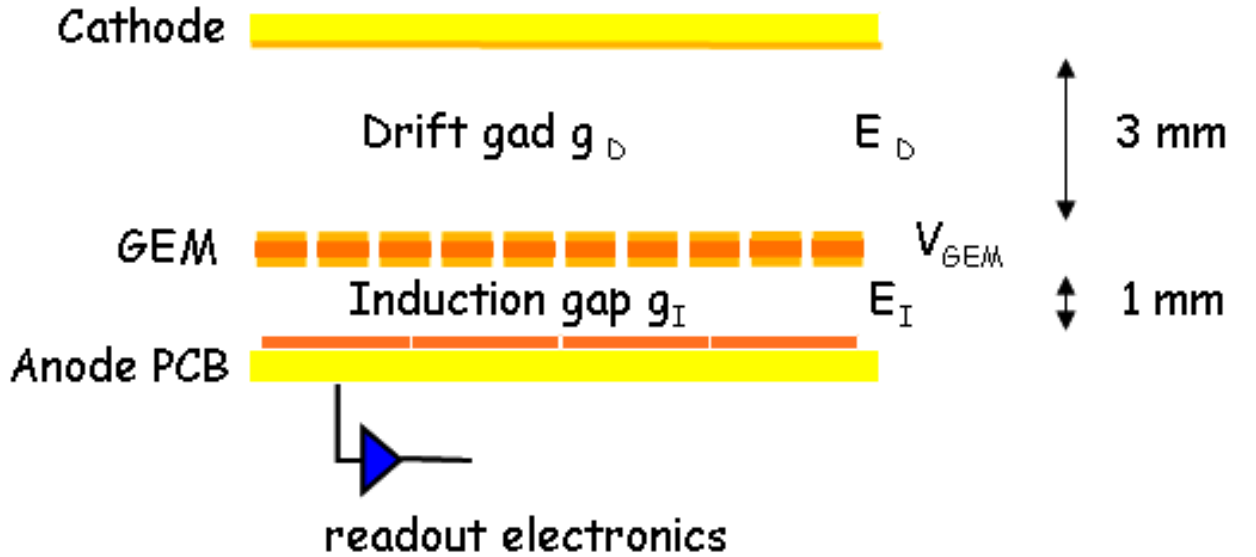


Figure 3.4: A layout of GEM detector with single foil [7].

3.3 Principle of GEM detector in CMS

The GE1/1 detector is trapezoidal in shape, with a drift and readout board and three foils stacked in between. The module configuration is such that the drift board is on top, the readout board is at bottom, and the three foils in between are separated at a gap of 3/1/2/1 mm. The distance between drift and first foil is called drift gap, between foils is called transfer gap to be 1 and 2, and between

the third foil and the readout board is called induction gap. A schematic overview of the same is shown in Fig 3.5. Such configuration of the chamber ensures better time resolution. Due to mechanical constraints of GE1/1 station, two versions of detector are deployed to provide maximum detection coverage: one is long GE1/1-L with a length of 128 cm and other is short GE1/1-S with a length of 113.5 cm. The gas composition is chosen in the ratio 70:30 to optimize the gain from the chamber while considering environmental effects as well. All the important specifications and related parameters are listed in Table 3.1 for the GE1/1 design and its operation in CMS. More details for CMS GEM detector can be found in Ref. [8].

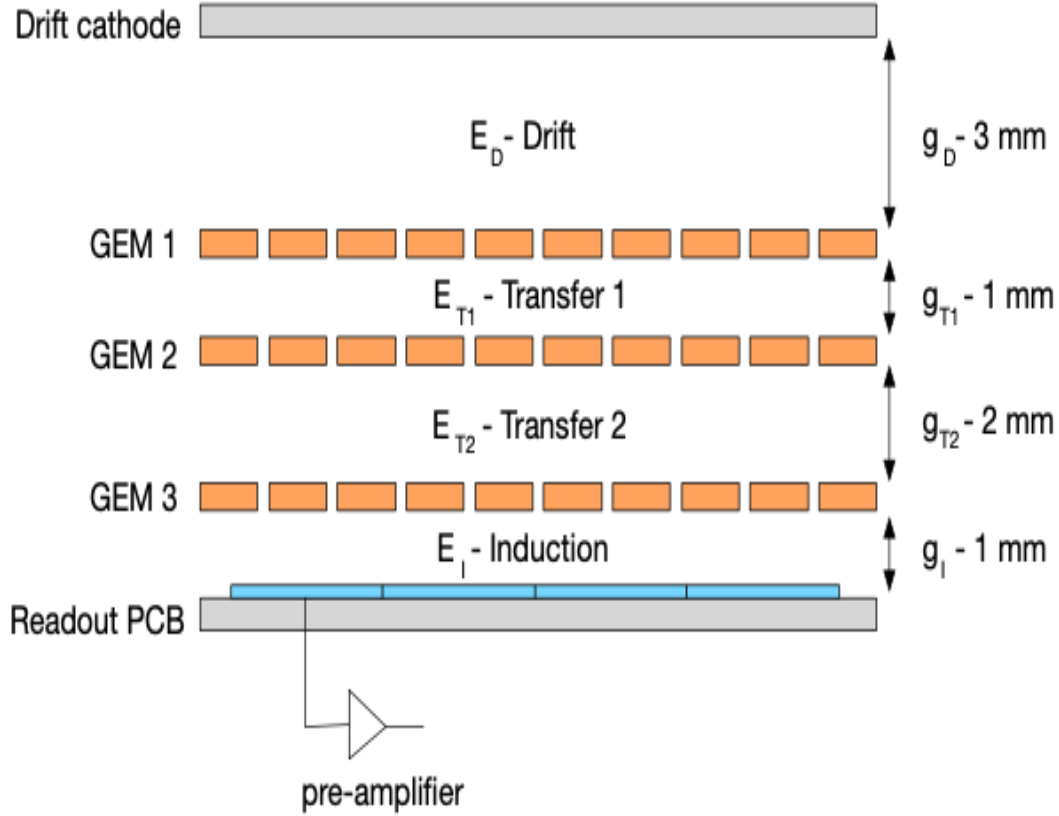


Figure 3.5: A schematic view of the GE1/1 detector with three foils placed at a gap of 3/1/2/1 mm in between drift and readout boards [9].

Table 3.1: The main specifications and parameters for the GE1/1 design and its operation in CMS [8]

Specification/Parameter	GE1/1
Detector Technology	Triple-GEM; Micro Pattern gaseous detector
Total number of single chambers	144
Total number of super chambers	72
Chamber shape	Trapezoidal; opening angle 10.15°
Active area overlap in adjacent chambers	2.6 mrad = 5.7 readout strip pitches
Short chamber dimensions	L: 106.1 cm (center line) W: (23.1 - 42.0 cm) T: 0.7 cm
Long chamber dimensions	L: 120.9 cm (center line) W: (23.1 - 44.6 cm) T: 0.7 cm
Total chamber thickness	T: 3.5 cm
Active readout area	0.345 m^2 (short ch.); 0.409 m^2 (long ch.)
Active chamber volume	2.6 litres (short ch.); 3 litres (long ch.)
Radial distance from beam line	130.2 cm (at inner edge of active readout area)
Geometric acceptance in η	$1.61 < \eta < 2.18$ (short ch.); $1.55 < \eta < 2.18$ (long ch.)
Signal readout structure	Truly radial readout strips
Readout strip chambers	463 μrad angular pitch
Number of η - partitions in readout	8
η partition length at the center (short ch.)	101.81, 102.06, 119.57, 140.57, 140.57, 166.55, 166.14 mm
η partition length at the center (long ch.)	113.22, 113.07, 134.56, 161.07, 161.07, 195.05, 194.2 mm
Number of readout strips per η -partition	384
Number of readout strips per chamber	3072
Counting gas mixtures	Ar/CO ₂ (70/30%)
Nominal operational gas flow	5 litres per hour
Number of gas inlets per chamber	1
Number of gas outlets per chamber	1
Nominal HV applied to drift electrode	-3242 V
Nominal operational effective gas gain	2×10^4
Number of HV sectors per foil (top)	40 (short ch.), 47 (long ch.)

3.4 Production of GE1/1

In GE1/1 muon system, two GE1/1 detectors are combined to form a *superchamber*. Each superchamber cover 10° in ϕ , and so a total of 36 superchambers are required in each endcap to provide full azimuthal coverage. Therefore, it constitutes a sum of 144 GE1/1 detectors to built this new sub-system. The CMS-GEM collaboration worked together for the production and testing of these 144 GE1/1 detectors. Among many institutes who were given responsibility for it, Panjab University was one of them. In Physics Department, Panjab University we fabricated a total of

eight detectors, with some quality-check test performed on them. In this chapter, a detailed description of fabrication of GEM and test performed on them, of which I was part of, will be discussed.

3.5 Assembly procedure of GE1/1

The GEM technology relies to a great extent on the foil's production and the gain of the signal in the chamber. A microscopic external dust particle can create a false signal, disrupt the operation and damage the detector. Hence, to avoid any kind of contamination source, the GE1/1 detector assembly is performed in a class 100 clean room. This clean room allows utmost of only 100 particles smaller than $0.5 \mu\text{m}$ per cubic foot and is incorporated in Panjab University for the GEM detector assembly. There should be a maximum four people at a time in clean room wearing anti-static coats, shoe covers, head covers, and face masks maintained for the assembly room. More technical details on the assembly procedure can be found in Ref [8], [10], [11]. The assembly of a detector is done in two steps: one is Pre-assembly, which is done in a separate laboratory where drift board, readout board and frames are prepared, and other is the assembly of foil stack and all the steps upto closing the detector which is done in the clean room environment. The pre-assembly is done in another lab since soldering iron, lubricating shafts are not allowed in the clean room. Once the drift board, readout board, and external and internal frames are ready, assembly is performed in clean room the next day. The steps followed to assemble the detector are mentioned below:

3.5.1 Preparation of Drift Board

The drift board is the trapezoidal shape drift electrode coated with the copper layer. On the top of this drift board, the stack of the three foils and readout board is placed. The gap between the drift board and first foil is filled with gas volume after assembly is completed. The mechanical design of the drift board is shown in

Fig 3.6. This board also accommodates a High Voltage (HV) divider to provide the voltages to top and bottom of each foil.

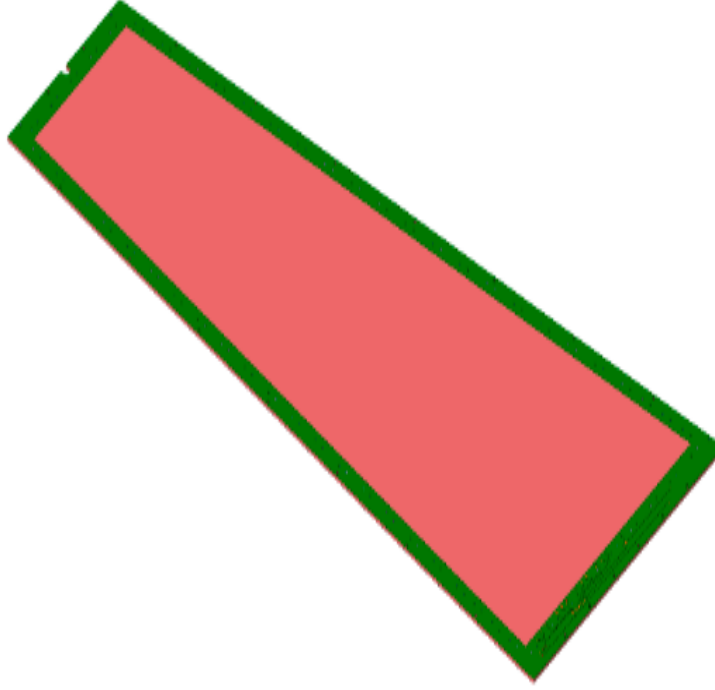


Figure 3.6: The drift board for a GE1/1 chamber coated with copper layer.

The preparation of drift board includes the mounting of pull-outs and placement of HV divider. The pull outs are made of stainless steel and serve the purpose of providing mechanical stretch to the foils (this will be explained later in Section 3.6). The pull-outs are placed at the dedicated holes on the board and tightened up using a torque screw driver with constant torque of 1.2 Nm. This is done throughout the board except on one side of trapezoid shape where HV divider and other surface mounted (SMD) components are to be positioned, as shown in Fig 3.7. The SMD components include a 10 M Ω resistor, a RC circuit component of 100 k Ω and 300 μ F mounted using soldering iron on the board at their respective positions. Similarly, the HV pins are also positioned at the dedicated place and soldered using the soldering iron. Once the soldering of HV pins and SMD components is done, the complete board is cleaned using a tissue paper and ethanol to avoid any contamination. Later, the remaining pull-outs are also mounted on this trapezoidal side of

board where electrical components are positioned.

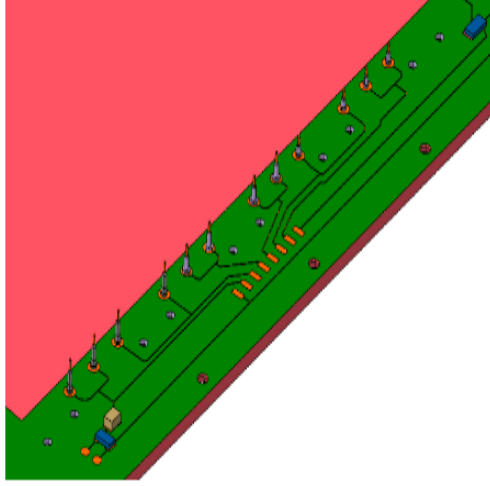


Figure 3.7: HV divider circuit and HV pins connected to top and bottom of each foil to provide the power source.

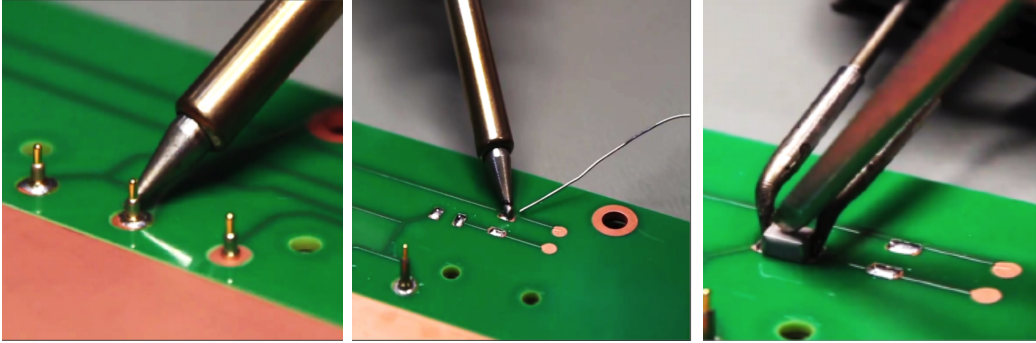


Figure 3.8: Soldering the HV pins (left), preparing the SMD pads (middle), and soldering the SMD components (right).

3.5.2 Preparation of Readout Board

The readout board is a trapezoidal shape board, similar to the shape of drift board and foils. The top of the board has 24 panasonic connectors to read the signal representing $(8 \times 3) i\eta \times i\phi$ sectors. The diagonal opposite side of the trapezoidal base of board has two holes for gas inlet and outlet plugs. To initiate the preparation, the table on which the board is to be placed is cleansed with a clean tissue paper and ethanol. Further, dust is removed from both sides of board using a vacuum

cleaner and also cleaning it a tissue and ethanol. The brass inserts are clamped in the dedicated holes in the flanges of board (as shown in Fig. 3.9) using the clamping hand. The gas connectors are inserted in the inlets using a epoxy glue. This is done by mixing two parts of epoxy glue on a clean metallic surface, and applying glue in the shape of ring between the body and threaded part of connector.

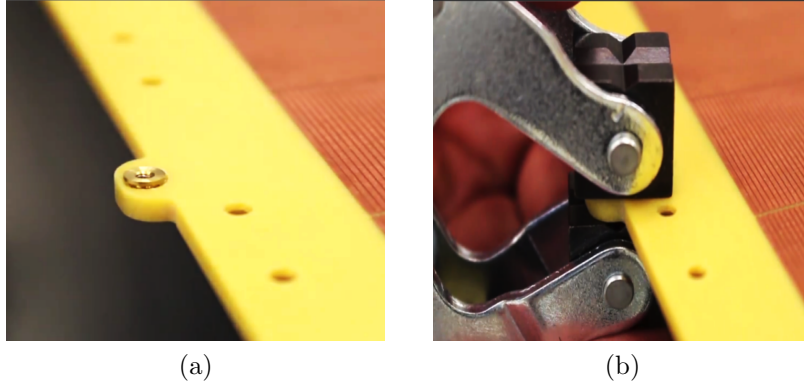


Figure 3.9: The brass inserts placed at the respective position (on left) and clamping of these brass inserts using clamping hand (on right).

3.5.3 Preparation of Internal and External Frames

The preparation of internal frames is an essential step as these frames define the space between drift board, GEM foils and readout board. The frame consists of spacers having thickness 3 mm, 1 mm, 2 mm and 1 mm to define the gap. The internal frames are provided in a support system, and to take them out from the support a very gentle pressure is applied by holding the support system gently and applying a tape over it (as shown in Fig 3.10). These can be easily broken, and hence need extra care to handle. Brass inserts are inserted in these frames using a FR4 baseplate. The baseplate is taped on a table to fix its position and frame is placed over it to match the hole of baseplate with the frame. When the holes are aligned, brass insert is gently pushed into the hole using a hammer. The procedure is shown in the Fig 3.10. Once it is done for all frames, a further check is done to make sure no brass insert piece is loose.

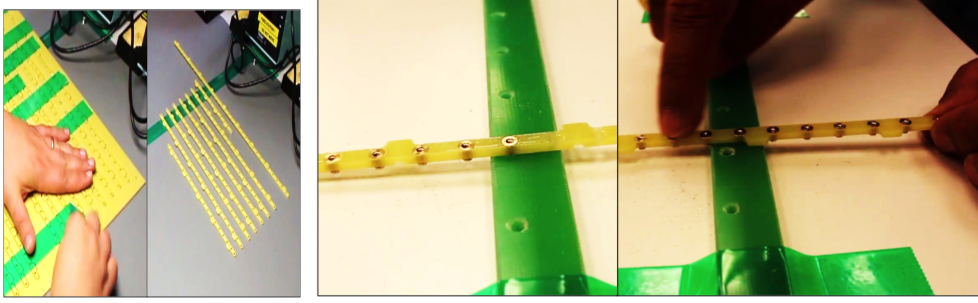


Figure 3.10: Removing the internal frames (left) and inserting brass inserts into the 3mm internal spacer (right).

The external frame is trapezoidal shape frame designed to make the GE1/1 chamber gas-tight; to avoid any gas leakage from the chamber. It is made up of halogen-free glass-epoxy material. Inside this frame, there is a groove to insert a O-ring that compresses between drift and readout board to ensure no leakage and any deformation to the chamber of any kind. These O-rings are first checked to observe any cut on it, and then cleaned in an ultrasonic bath to remove any dust. Later, the O-ring is fitted to the dedicated groove by pulling it from four sides and gently placing it in the frame, as shown in Fig. 3.11. It should perfectly fit in the groove.

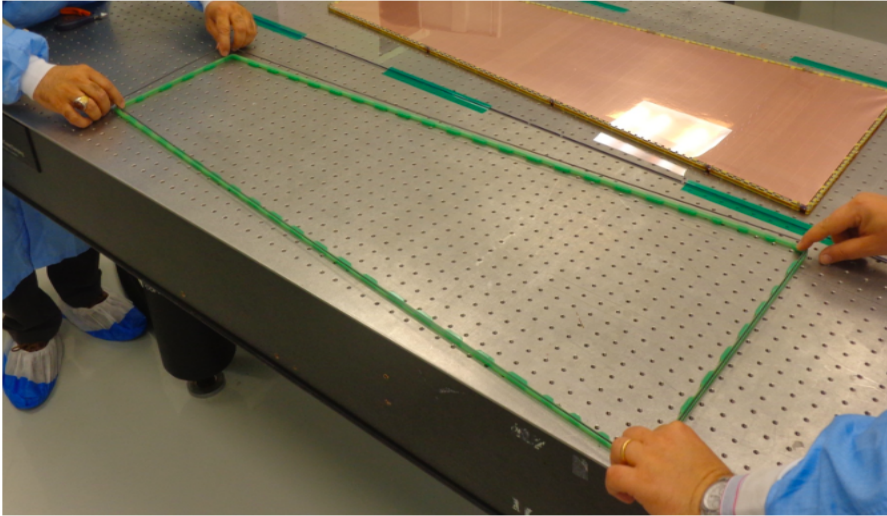


Figure 3.11: The placement of O-ring in the external frame by pulling out from all four corners is presented.

3.5.4 Preparation of Foils

After the preparation of drift board, readout-board, internal and external frames they are brought to the clean room. The GEM foils and their outer frame in the shape of foil are also placed in the clean room. Everything in the room should be cleaned to avoid any dust sticking to the foils and entering the chamber, and a relative humidity of 40% and an average ambient temperature of 22° should also be maintained. The steps are mentioned below for the preparation of foils.

- The outer foil frame is placed on the clean working table, and then foils are attached to this frame only using the dead area of foils with the help of kapton tape.
- This is done for all three foils, and for extra precaution one extra foil is also cleaned in case it is needed.
- All three frames are then aligned in a vertical position against the wall and a sticky roller is gently rolled over the foil to clean any dust particles on the foil, as shown in Fig. 3.12. This is done for both sides of the foils. The sticky roller is also frequently cleaned on a sticky pad.
- Further, to test the GEM-foils, HV clips are placed such that HV pins are in contact with top and bottom of the foils, as shown in Fig 3.12.
- Using a Mega-ohmmeter (Megger) a constant voltage of 550 V is applied to the foil for several minutes. If the resistance of the foil reaches 20 G Ω , the foils are marked as good to be used in the chamber.
- To define the foils as foil-1, foil-2 and foil-3, the spare HV pads for the other foils are cut down using a sharp blade, i.e. for selecting a foil as foil-1, the HV pads for foil-2 and foil-3 on the same foils are removed.

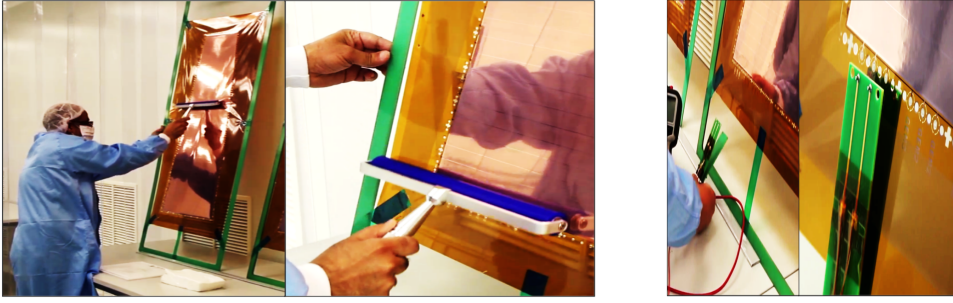


Figure 3.12: Cleaning the GEM foil with a anti-static roll (left) and mounting the HV clip to the foils (right).

3.6 Assembly of Chamber

To assemble the chamber, we need to first have the stack of three foils with the discussed gap between them. The process of preparing the stack is discussed below in steps:

- A plexiglass baseplate is placed and fixed on the working table using tape. Later, it is cleaned by a clean tissue paper and ethanol. The guiding pins are placed over the dedicated positions.
- The pre-assembled internal frames or spacers of 3 mm are cleaned using sticky roller. It is further checked that no brass inserts should be missed or pulled out till this stage.
- The 3 mm spacers are then placed over the plexiglass using the guiding pins, as shown in Fig 3.13.
- The frame holding GEM foil-1 is now placed on the top of these spacers with the help of guiding pins and later is detached by cutting the tape holding frame and foil using a sharp blade.
- The foil laying over the spacers is stretched on the opposite sides simultaneously throughout the foil and fixed using a kapton tape on the dead end of foil. The pressure applied to stretch should be similar such that foil should not be deformed.

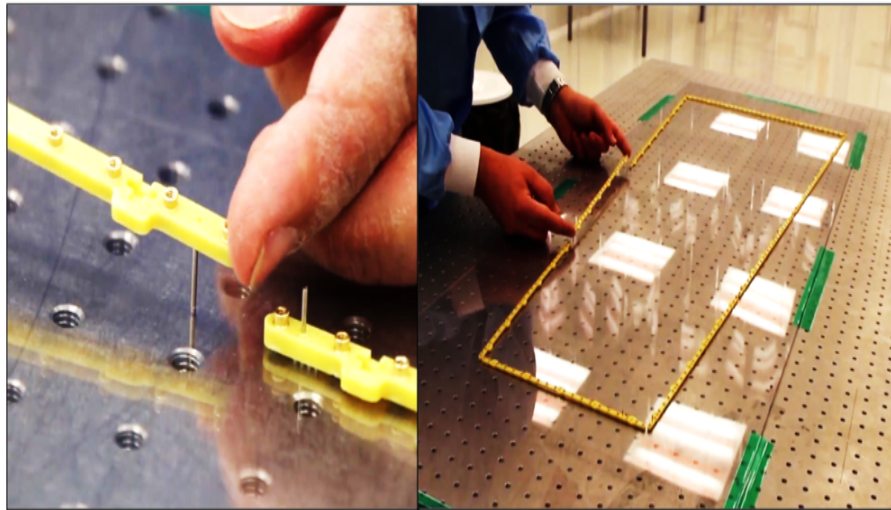


Figure 3.13: The figure shows mounting of 3 mm spacers on plexiglass baseplate using guiding pins.

- A layout for order of stretching and a picture after stretching from the lab is shown in Fig. 3.14.
- The GEM foil-1 is again tested by applying 550 V to the top and bottom of foil pads using a Megger. The impedance of the foil should again reach 20 G Ω .
- Now, the spacers of 1 mm thickness are cleaned using sticky roller and placed over the foil-1 using guiding pins. These spacers work as the first transfer gap.
- The outer frame holding foils is detached from the foil by removing the tape, and the foil is tested using Megger with impedance of foil reaching 20 G Ω . The foils are stretched on all sides and fixed using kapton tape on dead end of foil.
- Similarly, for third foil, spacers of 2 mm are cleaned and placed on the top of second foil using guiding pins, and further M2.5 metallic nuts are fitted to the dedicated position of spacers.
- The following step is to place the last foil on these spacers and detach the frame holding it.
- Again, these foils are stretched on all sides, fixed using tape, and then tested by applying 550 V with impedance reaching 20 G Ω .

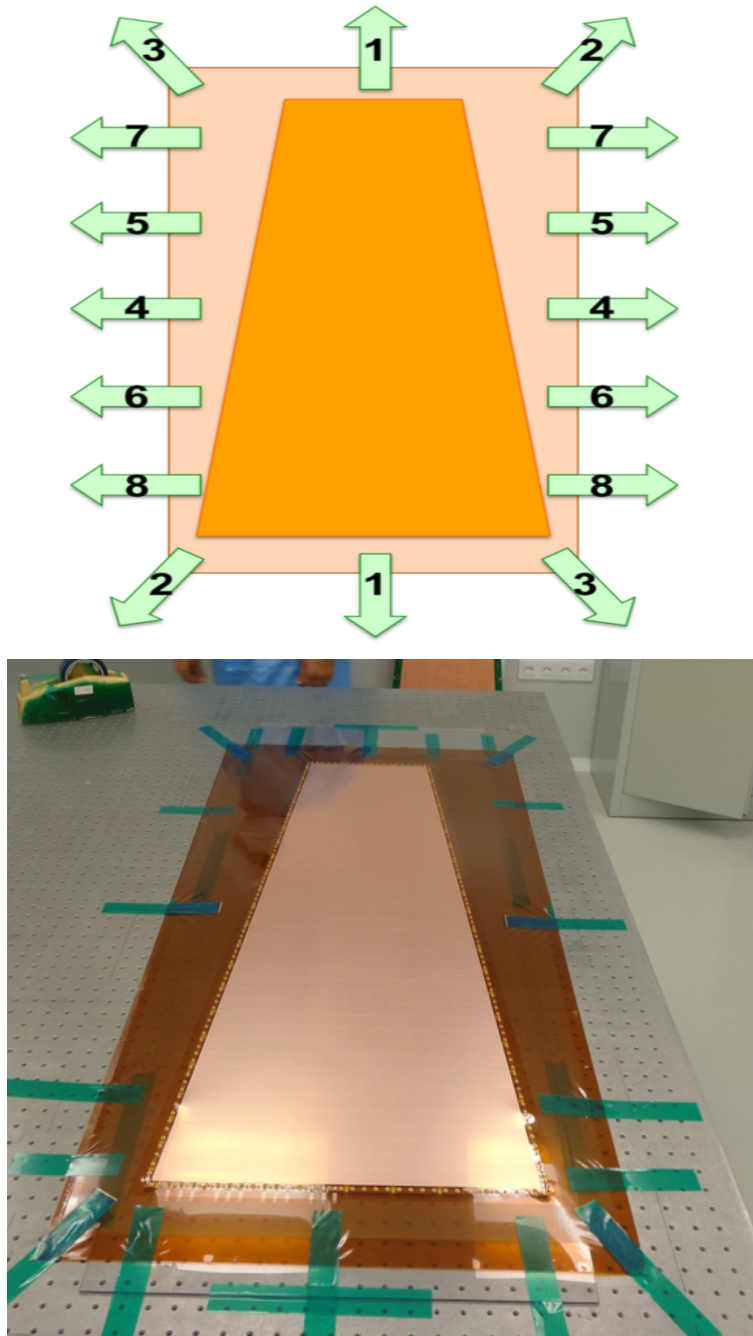


Figure 3.14: An illustration on how to stretch the foils in a sequence on top, and on bottom it shows the final picture after stretching as done in the lab for one of the chamber.

- The last 1 mm spacers are placed on the third foil to form induction gap.

Further on this stack of foils prepared, a clean plexiglass is positioned on the top of it. To hold the plexiglass with stack of foil, long M2 screws and washers are placed at the each edge of spacers and corners of trapezoid. Also, M2×6 screws are positioned on plexiglass cover in the dedicated area to hold the internal frames together.

3.7 Preparation of the final stack

At this stage, the GEM stack of foils is prepared with plexiglass plate at bottom and top. The plexiglass with few steps are to be replaced with drift and readout boards. The steps followed are :

- Finalizing the stack with drift board
 - The dead end area around the GEM stack for each foil is removed keeping the plexiglass cover as reference. The quality of cut should be perfect such that no extra foil or dead end is laying outside the trapezoidal area. The stack is further cleaned using a vacuum cleaner.
 - The drift board surrounded by pull-outs is placed on another table and cleaned using vacuum cleaner without touching the active area. The active area of the board is cleaned with the help of static roller. The same is shown in Fig 3.15.
 - The stack is placed next to the drift board, and very carefully without plexiglass baseplate is lifted and positioned on the top of drift board. The guiding pins are then removed from the stack using tweezers.
 - At another table, a aluminium material assembly jig of trapezoidal shape is positioned and fixed with screws, as shown in Fig. 3.16. This is done to ensure the position of drift board is settled at a fixed place while doing the final stretching of stack, as recommended by CMS.



Figure 3.15: Cleaning of drift board with vacuum cleaner on left and with sticky roller on right.

- The plexiglass on the top is left as it is, so that the foils and stack remain covered.

• Stretching of Foils

- The foils in the stack are stretched in a way in opposite direction simultaneously as shown in Fig. 3.17, to avoid any wrinkle on the foils. This step is performed by two individuals standing on opposite sides and inserting M2.8×8 screws in the tangential position of aluminium bars and tightening on all the sides. These screws should be cleaned first in an ultrasonic bath, similar to O-ring.
- The plexiglass cover is removed and the foil on top is cleaned with a static roller.
- The foils are tested again using Megger by applying 550 V on all three foils, and impedance of foils should reach 20 GΩ.
- This test is later performed for drift and transfer gaps. For the gaps, the impedance should reach 100 GΩ after a voltage of 550 V is applied for few

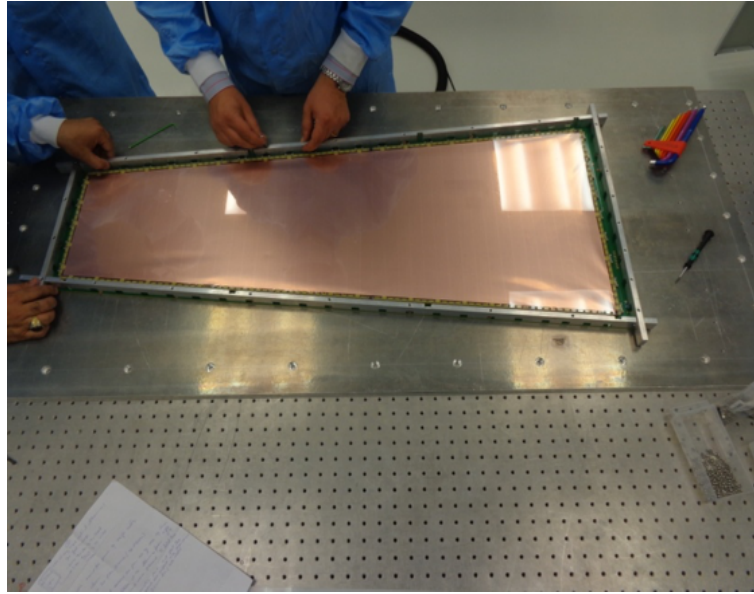


Figure 3.16: Placement of aluminium bars and fixing it around the stack.

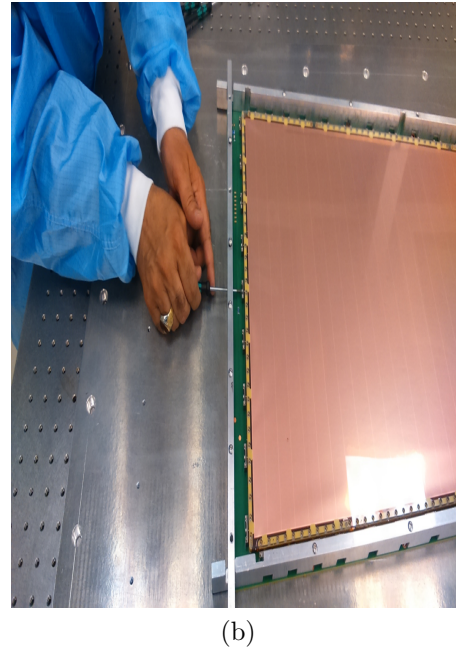
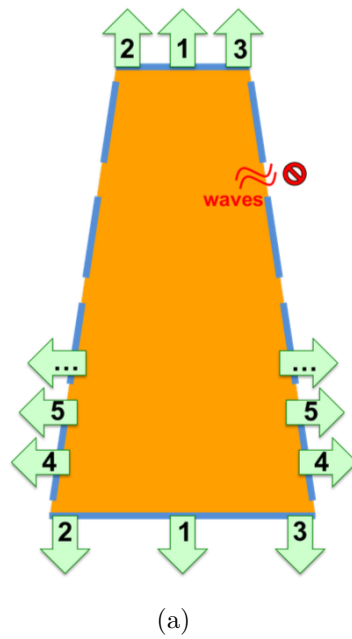


Figure 3.17: Figure a) Method describing the stretching, b) Stretching the foils.

seconds.

- After this test, the final stretching of foils is done using a electronic screw-driver by applying a torque of 9 Nm, and slightly higher around 15 Nm at the corners.

- **Closing of Chamber**

- The external frame is placed on the stack lying between the aluminium bars, as shown in Fig. 3.18. The stack is again cleaned with static roller.
- The readout board is cleaned using a vacuum cleaner first, and static roller on the active area. It is then positioned on the top of GEM stack, as shown in Fig 3.18.

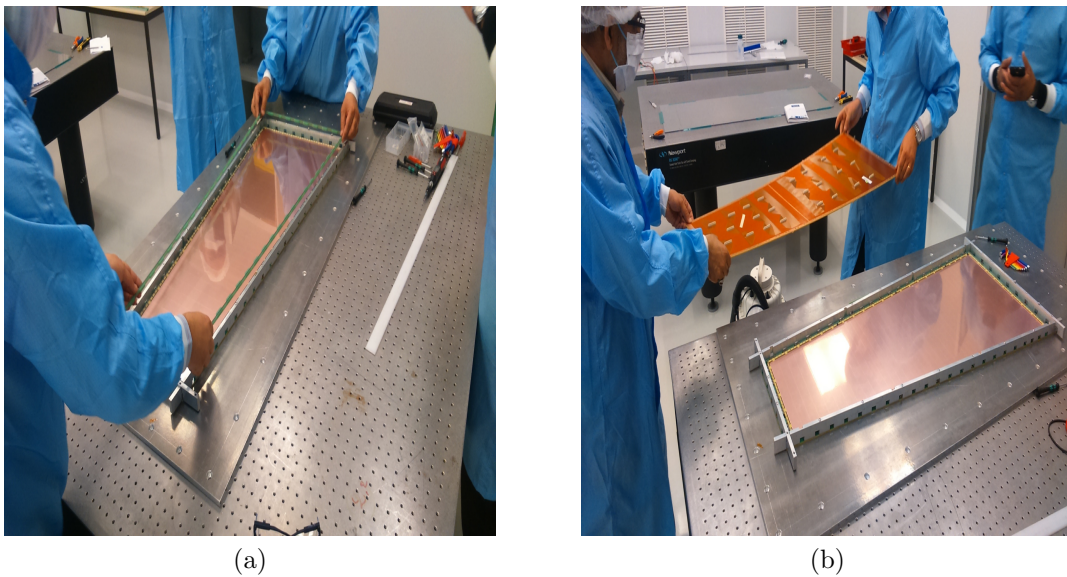


Figure 3.18: Placing the a) external frame on stack b) readout board on GEM stack.

- The polyamide washers and $M3$ screws are placed in the dedicated holes on the readout board and tightened using a torque screw driver with a constant torque of 1.2 Nm applied.
- The chamber is now ready and closed with everything in place. The aluminium bars are removed to access the chamber.
- The complete stack is again checked with Megger by applying voltage of 550 V .
- To further check the induction gap, Panasonic-to-LEMO connectors are connected to readout sectors and a voltage of 550 V is applied between

signal pad of connector and GEM foil-3. If the impedance reaches $100\text{ G}\Omega$ instantly, the gap is marked good. This is done for all the readout sectors one by one.

- With the foils and gaps marked good, the chamber is ready for other quality check tests.

3.8 Quality-Check Tests

To assure the performance of the foils and chamber, specific Quality Assurance (QA) or Quality Check (QC) tests established by the GEM Collaboration at CMS need to be qualified. These tests determine the production quality and accuracy of the assembled chamber. The QC tests are aimed to find if there is any mechanical or electrical issue with the chamber that could later be a source of problem after the installation in CMS muon system. To be part of CMS muon system, the chambers must pass these QC tests. The collaboration has defined many tests to be performed in a particular order, where few of them are done at CERN site only and other are performed at the production site only.

Fig 3.19 shows the complete process of the QCs tests performed at CERN site and other production site located in different countries of the GEM collaboration. To list them here, the steps are :

- Production and the QC tests of assembly components at the CERN site.
- Shipping these components to other production site for assembly and few QC tests.
- From the other production sites, shipping the assembled chambers to CERN site.
- Assembly of superchambers from the GE1/1 chambers received, and performing QCs test before installing in CMS muon system.

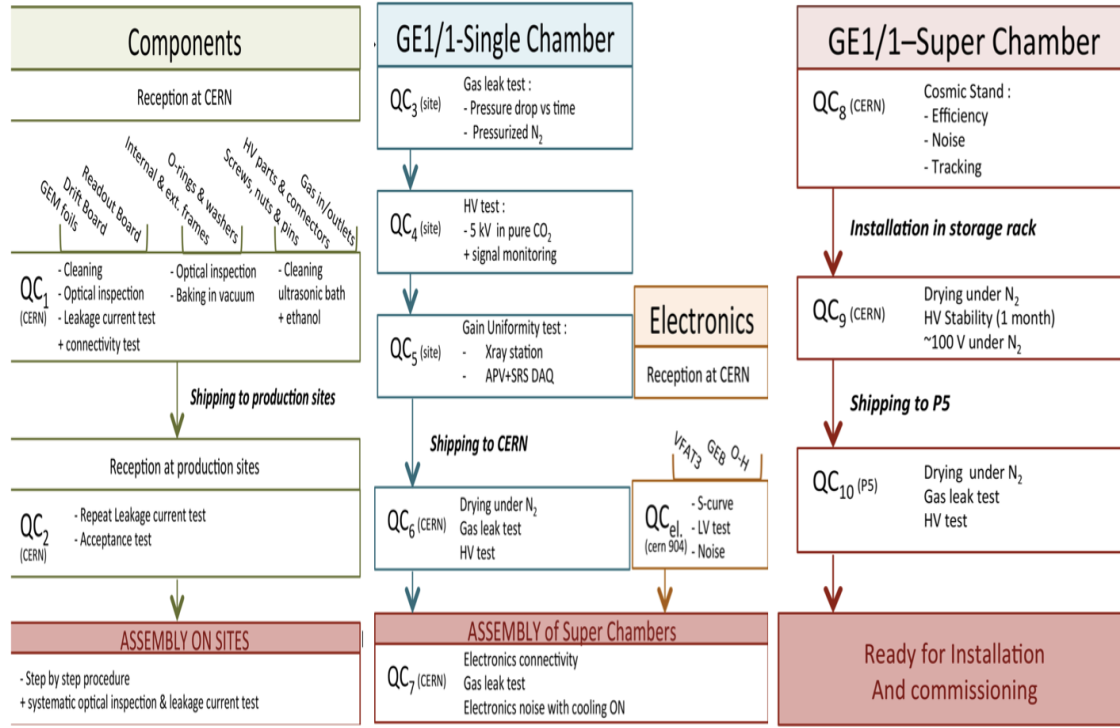


Figure 3.19: The process followed for Quality Assurance (QA) and Quality Check (QC) tests for the chambers at CERN site and other production sites all over the world.

At the Panjab University production site, a total of 8 chambers were assembled with 3 QCs tests performed besides the physical inspection of the foils. The corresponding 3 tests are :

- QC2: Foils Current Leakage test
- QC3: Gas Leakage test
- QC4: HV test

3.8.1 QC2: Current Leakage Test

The QC2 current leakage test determine the quality of GEM foils by determining the leakage current flowing on the surface of GEM holes. When a voltage is applied to the foil, the current flows from the top to bottom of the foil as polyamide (kapton) provides a conductive surface. This current is called *leakage current*. Hence, it is

very important to perform this test before, during and after the assembly of GE1/1 chamber. The presence of dust particles or any other deposit on the foil can act as a bridge between the top and bottom surface and can result in increased leakage current flowing through the surface.

After the GE1/1 chamber is assembled in the clean room, the QC2 test is performed by measuring the impedance of the foils using Megger. The relative humidity of the room should be monitored and maintained to be 40% at the vicinity of chamber. With the help of Megger, a voltage of 550 V is applied to HV pads at the drift board for a foil by connecting the negative pin to the top electrode and positive pin to the bottom electrode. For example, to determine this test for foil-1, the negative pin of Megger is connected to top electrode of foil and positive pin connected to bottom electrode of foil. The impedance is measured, and number of sparks are counted after 30 seconds and then, after 10 minutes. The impedance should reach $20\text{ G}\Omega$, while the count of sparks should be zero after 10 minutes. Similarly, this is done for other foils and gaps. For gaps, the impedance should reach $100\text{ G}\Omega$ with no sparks observed after 10 minutes.

The eight detectors assembled by Panjab University were named by CERN as “GE1/1-X-S-INDIA-00YY” where YY stands for ‘02’, ‘07’, ‘09’, ‘10’, ‘15’, ‘16’, ‘17’. All detectors passed the QC2 current leakage test and hence, taken out of the clean room to proceed with the next QCs test.

3.8.2 QC3 Gas Leakage Test

The next test to determine the quality of assembled chamber after the QC2 test is QC3 Gas leakage test. Since, the drift and readout boards with stack in between are enclosed using a lot of screws, they also become the source of external openings. The possible reasons for any such opening could be if any screw got loosened, or got much tightened that it broke, or O-ring used in external frame is not fitted properly. Any such cause could become the source of contamination through very slight openings and further, could deteriorate the performance and lifetime of the

assembled chambers. Hence, the gas leakage test is performed to examine any such opening if present.

A schematic overview of the test setup is shown in Fig 3.20. The gas input inlet is connected to a CO_2 gas pipeline with a pressure regulator and having the maximum output pressure limit of 50 mbar. The gas inlet flow meter along with manual valve allows to control the input gas flow rate, while output flow meter allows to monitor the output gas flow rate and thus, determining the gas leakage through the detector. The input and output valves are also added in the system to isolate the detector from the rest of gas system. A digital pressure transducer is also connected in the system to measure over-pressure inside the gas system only or gas+detector combined. Before introducing the detector to the gas system, the system itself is calibrated first as shown in Fig 3.20 bottom. The system is calibrated in the following steps:

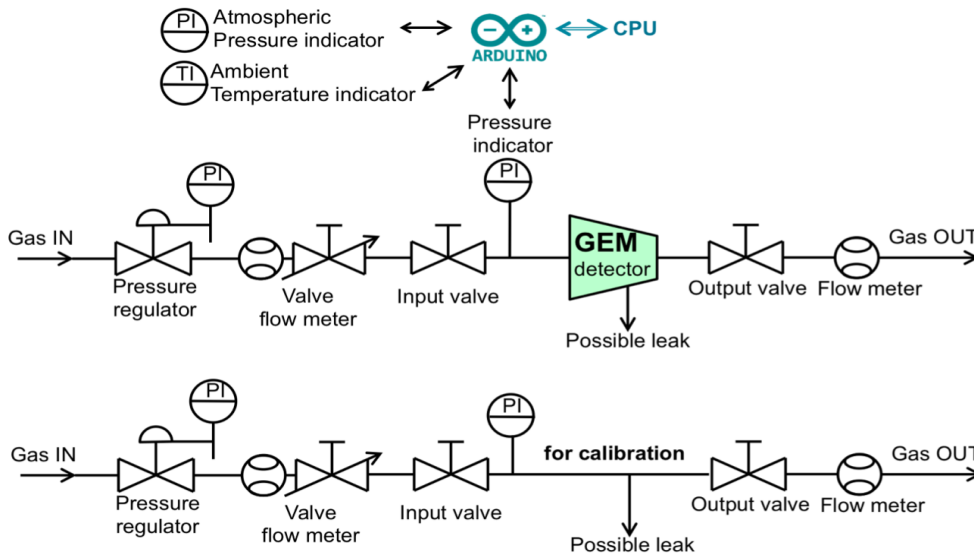


Figure 3.20: A schematic overview of the QC3 gas leakage test setup.

- The gas system are connected together with no detector, as shown in Fig. 3.20 (bottom).
- The input and output valve of the system are opened and CO_2 is allowed to

enter the system by adjusting manual valve at a flow rate of 5 L per hour. The output flow rate should be instantly visible in the output flow meter.

- The over-pressure is set to 25 mbar and output valve is closed to begin ramping up the pressure in the system. As soon as pressure reaches 25 mbar, input valve is also closed.
- Now the data acquisition (DAQ) system monitors the pressure drop inside the system as a function of time. The DAQ records over-pressure drop, and other environmental conditions such as temperature and atmospheric pressure at a interval of one minute.
- The system is qualified or marked good if the pressure drop does not exceed 1 mbar in 1 hour.

After the system validation, the gas leak in the detector is examined with the same setup but now with GE1/1 detector in between the input and output valve. The detector is acceptable and marked good for this test if the pressure drop inside the detector does not go beyond 7 mbar per hour. The Fig 3.21 shows the result of all assembled detectors at the Panjab University site, and all of them successfully passed the QC3 gas leakage test.

3.8.3 QC4 HV test with CO_2 gas

The QC4 high voltage test aims to identify any possible malfunctioning, any defects in HV circuit and to observe intrinsic noise rate (which is signal not produced by ionizing particle). To perform this test, the detector is flushed with CO_2 gas at a flow rate of 5 L per hour for 5 hours. The test setup consists of HV power supply with a user control for current limit (I_{set}), the steps of ramping up and down the voltage, setting maximum voltage and trip time. Negative voltage V_{set} is provided by this programmable power supply. A pre-amplifier (ORTEC) is connected to the bottom electrode of third GEM foil through decoupled RC circuit already set-up on the drift

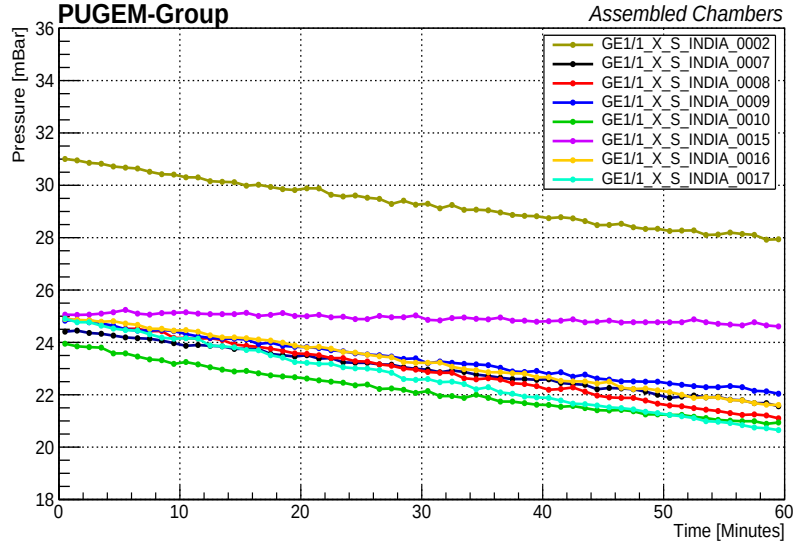


Figure 3.21: Results of QC3 gas leakage test for all GE1/1 chambers assembled at the Panjab University site.

board. The output from the pre-amplifier is sent to amplifier+shaper (ORTEC 474 model), and afterwards sent to discriminator. The output from discriminator is then sent to dual timer and scaler to determine the intrinsic noise rate. The schematic overview of the setup is shown in Fig. 3.22.

The resistance of the HV circuit (i.e HV divider and all HV filters) is measured using the digital multimeter. Additionally, the threshold of the discriminator and the scaler clock are set to -140 mV and 60 s, respectively. To initiate the measurements, the current limit I_{set} is set according to the target value adding 5 μ A and the corresponding V_{set} is switched on. After 5 minutes when operating current and voltage are stable, the actual voltage V_{mon} and current I_{mon} are recorded. The numbers of counts (i.e noise rate) is also recorded after 60 s and saved in the DAQ system. These steps are repeated at a gap of 100 V till maximum voltage of 4.9 kV is reached. For the recorded values of V_{mon} , I_{mon} and noise rate, two curves are plotted i) I-V characteristic curve ii) noise rate versus I_{mon} curve. The reciprocal of I-V characteristic curve slope indicate the value of total resistance of the system. This resistance value is compared with the value measured from the digital multimeter. These two values should not differ from each other by more than 2% for the detector

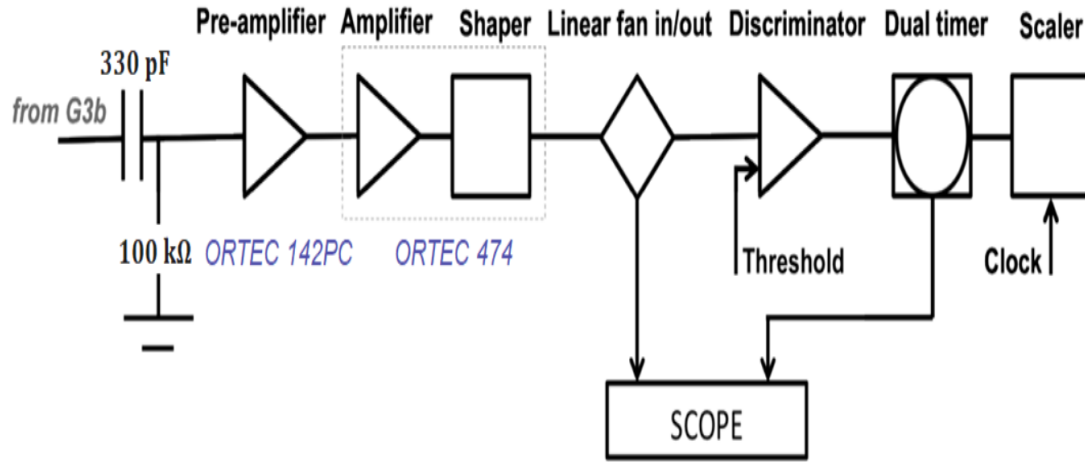


Figure 3.22: The data acquisition setup for QC4 test

to pass this test. Further, the noise rate should not exceed 15 Hz at the high voltage of 4.9 kV to qualify the test. All the detectors assembled at Panjab University successfully passed this HV test, and the curves for I-V characteristic curve and noise rate versus I_{mon} curve are shown in Fig 3.23 and Fig 3.24 respectively. The results of this test are shown in Table 3.2.

Table 3.2: Results from QC4 HV test showing the value of measured resistance ($R_{multimeter}$) by multimeter, resistance (R_{IV}) by IV curve, and the maximum intrinsic noise rate.

Chamber ID	Resistance by multimeter (R)(M Ω)	Resistance by I-V curve (R_{IV}) (M Ω)	Intrinsic noise rate(Hz)
GE1/1.X.S.INDIA.0002	4.67	4.69	11.88
GE1/1.X.S.INDIA.0007	5.00	5.01	3.50
GE1/1.X.S.INDIA.0008	5.00	5.02	6.57
GE1/1.X.S.INDIA.0009	5.00	5.01	5.62
GE1/1.X.S.INDIA.0010	4.97	5.02	5.72
GE1/1.X.S.INDIA.0015	4.96	5.01	11.30
GE1/1.X.S.INDIA.0016	4.97	5.02	8.58
GE1/1.X.S.INDIA.0017	5.00	5.02	8.25

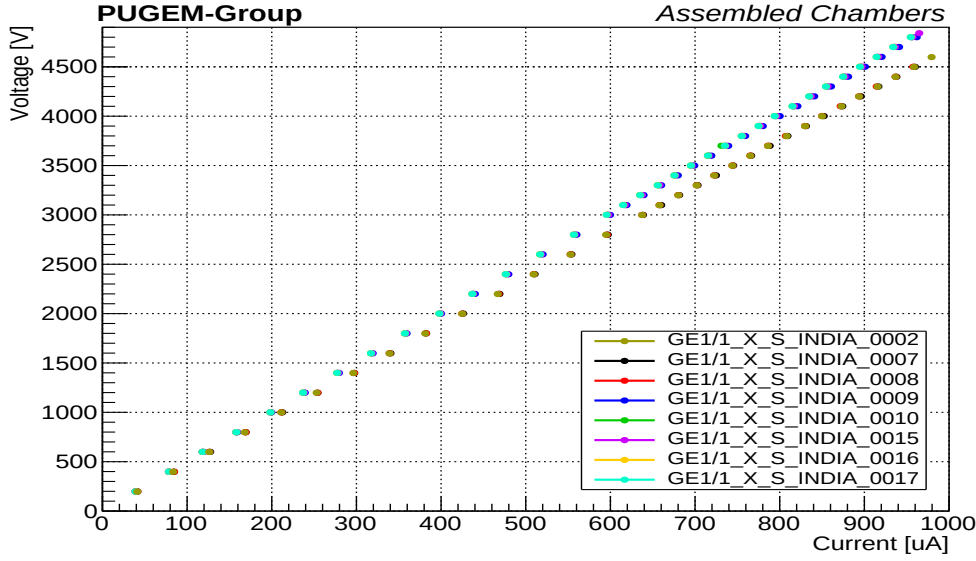


Figure 3.23: The I-V characteristics results of QC4 test for the assembled GEM detectors at the Panjab University site.

3.9 Further testing and validation

Following the QC4 HV test, another test QC5 is performed in two stages. First stage is to measure the effective gas gain as a function of high voltage applied through voltage divider, and other is to determine the uniformity of the detector response through readout electronics consisting of APV25 front-end ASICs. These measurements are done in a closed radiation box with AMPTEK miniX X-ray source installed inside it. This test is performed to examine if due to any factors such as non-uniform GEM holes, over-stretching of foils, or defects on readout board could effect the uniform gains through out the active area of detector.

The effective gas gain measurement of the detector is done in the gas mixture of $Ar:CO_2$ in ratio 70:30 by comparing the induced primary current in drift gap with the amplified current at the readout board. To perform this test, the detector is irradiated with X-ray electron gun incident on a silver target with two peaks at 22 and 25 keV. The X-ray photons are absorbed by copper atoms on the drift electrode of detector, and which further emits photons of 8 keV energy. These photons are then converted by photoelectric effect in detector active gas volume. The gain is

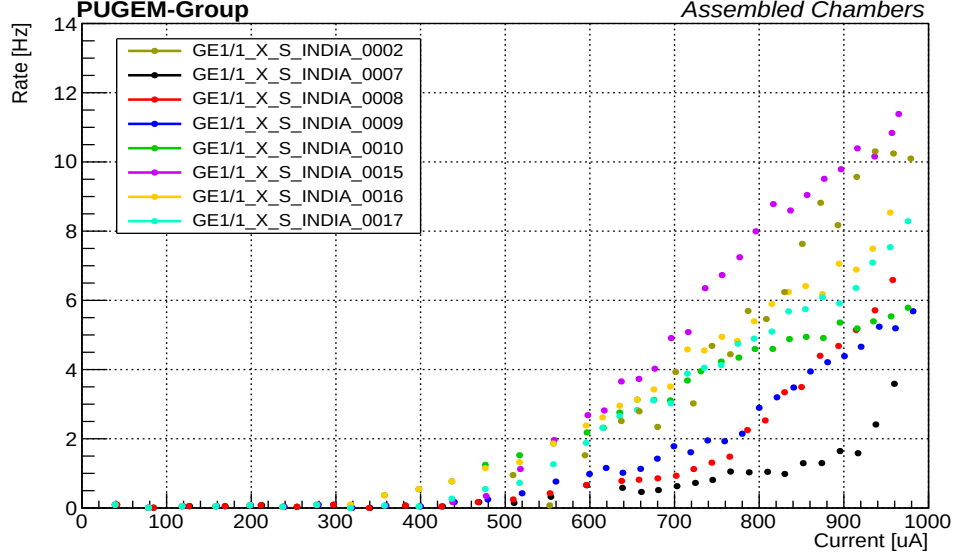


Figure 3.24: The intrinsic noise rate as a function of monitored current for the assembled GEM detectors at the Panjab University site.

calculated by using the eq.:

$$G = \frac{I_a}{R \times N_p \times q_e} \quad (3.1)$$

where I_a is the amplified current at the readout, R is the X-ray photon interactions rate, N_p is the number of primary electrons induced by incident photoelectrons, and q_e is the elementary charge.

The second stage of this test is estimating the uniformity of gas gain throughout the detector. Therefore, each η sector is divided into 96 slices, i.e. total of 768 slices and further each slice consists of 4 strips. The cluster charge collected in terms of ADC is fitted to extract the position of copper fluorescence peak. This is done for each η sector for each GE1/1 chamber. The mean position of the copper fluorescence peak spectrum for each η sector is utilized to generate a distribution of peak position for the GE1/1 detector. Further, a gaussian fitting is done on this generated distribution to get the mean (μ) and standard deviation (σ). The response uniformity is defined as

$$R.U = \frac{\sigma}{\mu} \times 100 \quad (3.2)$$

For ideal cases, the response uniformity $R.U$ should not exceed beyond 30% for stable operation of the detector. Fig. 3.25 shows the uniformity response for all chambers to be within 30%.

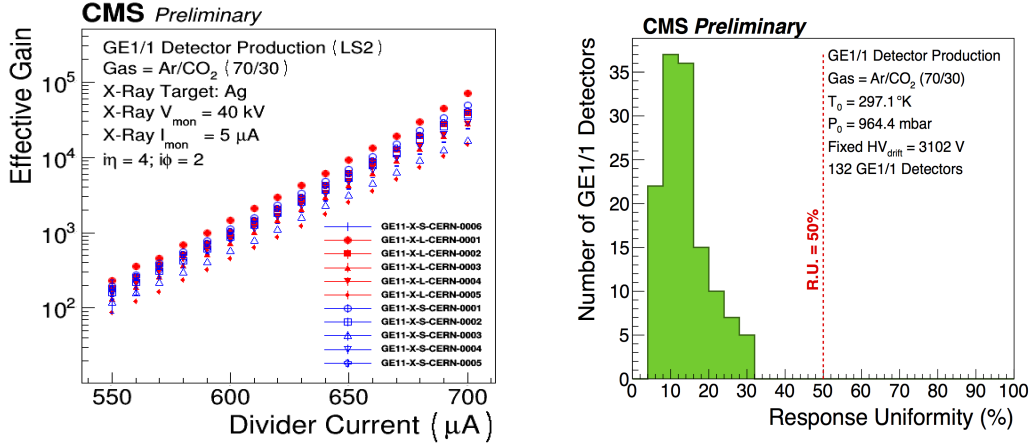


Figure 3.25: (a) GE1/1 shows the effective Gain as a function of the HV Divider Current for a subset of GE1/1 chamber, and (b) shows the response uniformity distribution. The 50% contours in response uniformity represent the gain fluctuations beyond which the detector time resolution starts degrading.

After the detectors successfully pass all QC tests, the detectors are sent to CERN site for further more QC tests and superchambers assembly before installation in CMS detector. At CERN, QC6 and QC7 tests are performed to ensure HV stability and proper readout electronics. In these tests, GEM Electronic Board (GEB) is mounted onto the chamber along with Optohybrids that can communicate with VFAT3 chips designed for GE1/1 detectors. When detectors passes these tests, they are further assembled to make a superchamber using two detectors at a time. The QC8 test is performed on the superchambers assembled with a cosmic muon stand for the final validation of all the performance studies and electronics before installing it in the CMS detector.

3.10 Summary

During the LS2 period as a part of HL-LHC upgrade, a total of 144 GE1/1 detectors were installed in the CMS muon system. The Panjab University site assembled 8

such detectors and performed quality check tests QC2, QC3 and QC4 at the site. These 8 detectors were successfully shipped to CERN site for further QCs tests and superchamber assembly. All the detectors are now part of CMS muon endcap system and are taking data. More details on the assembly and testing of the GE1/1 detectors can be found in several published papers and conference proceedings [12], [13], [11].

In the next chapter, the simulation of events through various event generators and reconstruction of the physics objects is discussed.

Bibliography

- [1] CMS Collaboration, J. G. Layter, “The CMS muon project: Technical Design Report”. Technical design report. CMS. CERN, Geneva, 1997.
- [2] F. Sauli, “GEM: A new concept for electron amplification in gas detectors”, *Nucl. Instrum. Meth. A* **386** (1997) 531–534, doi:10.1016/S0168-9002(96)01172-2.
- [3] CMS GEM Collaboration, “Physics motivations and expected performance of the CMS muon system upgrade with triple-GEM detectors”, *PoS* (2015) 225, doi:10.22323/1.234.0225.
- [4] CMS Collaboration, “CMS Technical Design Report for the Level-1 Trigger Upgrade”, technical report, 2013.
- [5] F. Sauli, “Gaseous Radiation Detectors: Fundamentals and Applications”. Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology. Cambridge University Press, 2023. doi:10.1017/9781009291200.
- [6] G. Mocellin, “Performance of the GE1/1 detectors for the upgrade of the CMS muon forward system”. PhD thesis, Rheinisch-Westfälischen Technischen Hochschule (RWTH) Aachen, RWTH Aachen U., 2021. doi:10.18154/RWTH-2021-07066.
- [7] R. Antunes Nobrega, “Development of the Experiment Control System and Performance Study of the Muon Chambers for the LHCb Experiment”. PhD thesis, Rome U., 2010.

-
- [8] CMS GEM Collaboration, “CMS Technical Design Report for the Muon Endcap GEM Upgrade”, technical report, Jun, 2015.
 - [9] CMS Collaboration, “Benchmarking LHC background particle simulation with the CMS triple-GEM detector”, *JINST* **16** (2021), no. 12, P12026, doi:10.1088/1748-0221/16/12/P12026, arXiv:2107.03621.
 - [10] CMS Collaboration, “The Phase-2 Upgrade of the CMS Muon Detectors”, technical report, CERN, Geneva, 2017.
 - [11] CMS Muon Collaboration, “Layout and Assembly Technique of the GEM Chambers for the Upgrade of the CMS First Muon Endcap Station”, *Nucl. Instrum. Meth. A* **918** (2019) 67–75, doi:10.1016/j.nima.2018.11.061, arXiv:1812.00411.
 - [12] CMS Collaboration, “Production and quality control of the new chambers with GEM technology in the CMS muon system”, technical report, CERN, Geneva, 2019. doi:10.1016/j.nima.2018.11.035.
 - [13] CMS Collaboration, “Upgrade of the CMS muon spectrometer in the forward region with the GEM technology”, technical report, CERN, Geneva, 2019. doi:10.22323/1.340.0132.

Chapter 4

Event Simulation and Reconstruction

The simulation in any experiment is equally important as the data collection by the experiment. The accuracy of event simulation is a paramount for the successful analysis of the experimental data. Hence, Monte-Carlo (MC) [1] simulations are extremely important for any high energy particle accelerator based experiments. These methods are implemented in many generator programs to simulate the signal and background events, and their topology. At the CMS experiment, events are generated in two step process using an event generator based on a model defined for SM and BSM processes. For the complete simulation of the event, all the details of the pp collisions are provided to replicate the data as closely as possible. The events generated are passed through CMS detector reconstruction using the CMSSW software framework to emulate the response of the generated particle interactions with detector material. In this chapter, various processes involved in pp collisions, event generators with detector response and the event reconstruction of the objects are discussed.

4.1 Types of processes in pp collisions

In pp collisions, various processes contribute to the total cross-section due to parton-parton elastic and inelastic collisions. The inelastic collisions where momentum transfers take place have the potential for many new particle discoveries and physics measurement studies. These processes are described below in brief.

- **Hard Interaction:** It is defined as the process where the momentum transfer among the partons is the highest and the outgoing particles have the largest momentum among all other processes in the same event. These interactions are the physics processes of interest.
- **Initial State Radiation and Final State Radiation:** The emission of a SM boson (typically gluons, photon or a Z boson) from the partons prior to interacting is called Initial State Radiation (ISR). On the other hand, if a SM boson is radiated from partons after the hard interaction takes place then the radiation is called Final State Radiation (FSR). These radiations result in the formation of jets near the interacting partons and also takes away the small energy of the parent partons.
- **Soft Interactions:** In these processes, the momentum transfer is small. These can be directly from pp collisions, or can be between the outgoing particles from hard interactions.
- **Multiple Parton Interactions:** The interactions where due to large parton densities there are significant number of parton-parton interactions in a pp collisions, such processes are known as Multiple Parton Interactions (MPI). The momentum transfer is minimum in these interactions, and hence these interactions produce low p_T particles.

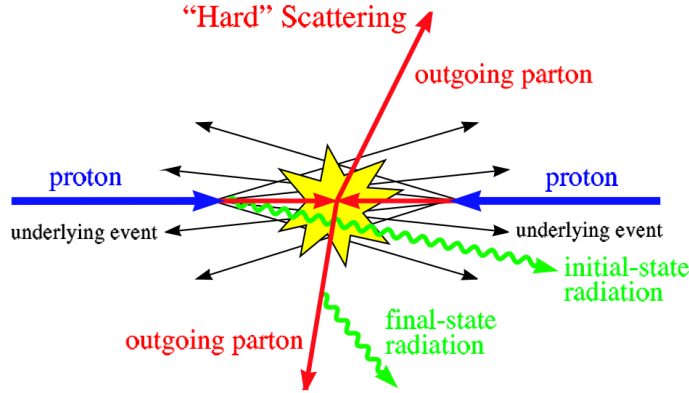


Figure 4.1: A sketch of pp collisions simulated by MC generator depicting hard-interaction, initial-state radiation, final-state radiation and underlying events. The source of figure is Ref. [2]

4.2 Parton Shower and Hadronization process

In order to fully simulate the event in pp collisions, all the interactions besides the hard process should also be simulated with the help of various event generators. In particular, parton showering and the hadronization processes. The initial interacting partons from pp collisions and the partons produced further from hard interaction can result in dozens of additional partons in the same event creating a shower of the particles. This showering of particles is known as parton shower [3] [4]. However, when the events reach the non-perturbative regime ($\alpha_s \sim 1$) the parton showering comes to an end. At this stage, free colored partons further group together to produce color neutral states called as hadrons and are stable enough that they can be detected by the CMS detector. This process is called hadronization. The hadronization processes are well described by the following two widely used models :

- **String Model:** The most famous string model is the “Lund String Model” [5] [6]. In QCD, at large distances linear confinement is expected i.e., linear behavior of color potential between quarks ($q\bar{q}$). This can be anticipated as a *string* with q and $\bar{q}$ at the ends of the string. As the partons move apart from each other, they can be imagined as a stretched color flux tube. The quarks

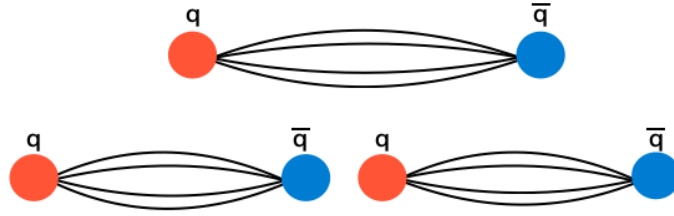


Figure 4.2: Representation of the color string between quark and anti-quark Lund String Model

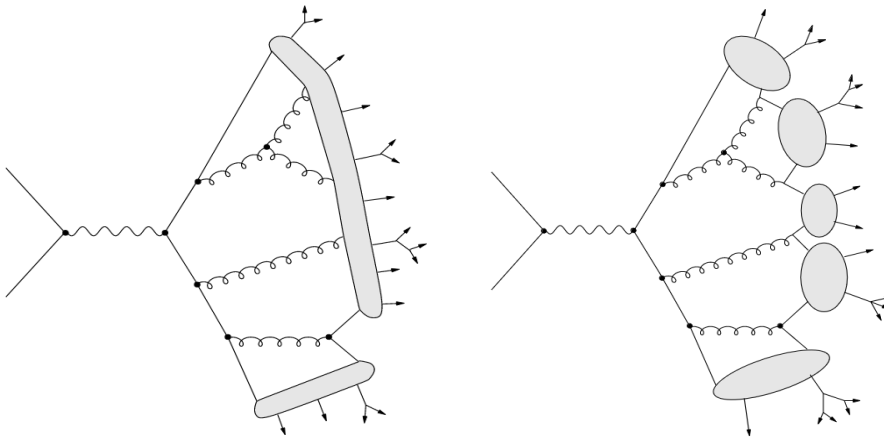


Figure 4.3: An illustration of the difference between string hadronization (left) and cluster hadronization (right). The source of figure is Ref. [9]

along the string keep on experiencing force till it breaks to create a new $q\bar{q}$ pair, but it only happens if quarks energy allows it. The illustration of same is shown in Fig. 4.2. This process continues till any of the strings have sufficient energy to produce more hadrons.

- **Cluster Model:** It is based on the preconfinement property of the shower [7], [8]. Here clusters is referred to as color singlet ($q\bar{q}$) combinations of partons. The main idea behind this model is to force gluons into $q\bar{q}$ pairs at shower cutoff scale via non-perturbative splitting. The physical picture to show the difference between cluster hadronization and string hadronization is given in Fig. 4.3.

4.3 Event Generation and Simulation

In order to have the apple to apple comparison of simulated events with data, the event generation process is divided into smaller steps. The foremost task of event generation is to calculate the production cross-section of physics process of interest over whole phase space. With this being done, the next step is to generate the events with the calculated cross-section and provide the four momentum information of all the particles produced for that process. These steps are discussed in more detail below.

4.3.1 Matrix Element

The MC generators simulate all possible processes and also calculate the cross-section of those processes. The cross-sections are calculated with the help of Matrix Element (ME) at different accuracy levels. For a given Feynman process, the ME computes the differential and integrated cross section at a fixed order of α_s (coupling constant of strong interactions) describing the interactions of partons. The ME computes predictions at leading order (LO), next-to-leading order (NLO) and for even higher order cases as next-to-next-to-leading order (NNLO). The higher the order included, the more accurate the cross-section and realistic topology of the generated events.

4.3.2 Event Generators

CMS uses general purpose event generators for simulating the high energy collisions. The event simulations starts with ME calculation at a chosen order. Generally MADGRAPH5_aMC@NLO [10] and POWHEG [11] serve this purpose with the parton showering simulated by PYTHIA8, HERWIG [12] and SHERPA [13] generators. The PYTHIA8 and MADGRAPH5_aMC@NLO event generators are used to simulate the signal and background events in this analysis, and a brief description of these generators is given below :

- **PYTHIA** : PYTHIA8 is a general purpose event generator widely used for the LHC physics studies. The program includes all the processes or the event generation starting from the hard interaction, following the hadronization models and all the possible decays. The processes are mainly $2 \rightarrow 1$, $2 \rightarrow 2$, and $2 \rightarrow 3$ with the ME calculations upto LO precision. PYTHIA8 relies on p_T based parton showering for ISR, FSR and also MPI. It includes highly developed simulations of MPI, along with the hadronization using Lund String Model.
- **MADGRAPH** : MADGRAPH5_aMC@NLO [14] [15] generator computes the matrix elements for higher multiplicities i.e. $2 \rightarrow n$ processes. However, the MADGRAPH5_aMC@NLO does not incorporate parton showering, hadronization and multi-partonic interactions. Thus, it is most commonly interfaced with PYTHIA8 to include such processes in an event. The aMC@NLO refers to the order at which ME are calculated, which is next-to leading order. MADGRAPH also generates the Feynman diagrams of the processes with the user's input parameters such as mass, coupling, initial and final state particles provided. Since, this generator is interfaced with other for parton showering a CKKW, MLM matching is done to avoid the double counting of events [16].

4.3.3 Detector Response

The last step of the event generation is to simulate the detector responses in the event using the GEANT4 (GEometry ANd Tracking) [17–19] software. This is done to translate the event from the generator level with a defined model to the detector level. In this step, the effects of the detector geometry, responses to the interaction with the detector material and magnetic field, and the effect of electronic readout is eventually induced to the event. It is a crucial step for simulation in order to compare it with the observed data from the detector collected by the experiment.

4.4 Data Flow

There are $\sim 10^{11}$ protons in each bunch of proton beam, and with every bunch crossing in 25 ns, there are billions of events to store for physics analysis. Storage of such numerous events requires a lot of computing resources. Therefore, to minimize resources only interesting events for physics are saved and are also categorized into different datasets based on the physics object. These datasets are saved in different data formats depending on the degree of detail of the event stored. The data formats are:

- **RAW** : The events passed by the HLT trigger system (as discussed in Chapter 2) are stored as the “RAW” event. The raw events are classified into primary datasets and stores detector level information, L1 triggers and HLT trigger results. The event size is large, approximately 1.5 MB per event, in the raw format.
- **RECO** : The RECO events are the reconstructed events derived from the raw data. These events contain object level information such as hits in silicon tracker, primary and secondary vertex information and reconstructed energy clusters. They also have the information of reconstructed physics objects stored as electrons, photons, muons, jets, and missing transverse energy. The size of a event in the reco format is reduced to ~ 250 kB.
- **AOD** : Analysis Object Data (AOD) is derived from the RECO events to provide information of physics data in a compact format. The AOD data format of events contains enough information for the physics analysis of objects such as electrons, photons, muons, taus, jets and missing transverse energy. But only the limited tracking information of a event is allowed in the AOD format. This limited information from tracker reduces the size of a event to ~ 50 kB, which is approximately five times smaller than RECO format. The events from AOD format are further classified to MiniAOD and NanoAOD formats with various kinematic selection applied on the physics object. These

selection reduces the event size further, and make it easy for the analysts to use these data formats.

- **FEVT** : FEVT stands for Full Event data, and as the name suggests it contains the complete information of an event. It has the RAW plus RECO event details, and stored for simplicity for later access if needed.

4.5 Physics Object Reconstruction

The CMS detector takes the snapshot of an event and stores the detailed information of the collision using high-speed electronics. This information is then used to reconstruct the physics objects such as electrons, photons, muons, taus and hadrons. Many objects leave a signal in more than one sub-detector, and these signals are processed to reconstruct the object. Starting with the very basic information is the track of the particle from the tracker and muon system, and then leading to the energy clusters in the calorimeters. These information are then linked to reconstruct the particle. In the following sections, the reconstruction of the tracks and objects is discussed in detail.

4.5.1 Primary Vertex

Primary vertex is defined as the most energetic hard scattering vertex associated with tracks from the pp collision. Despite this hard interaction vertex, there are multiple inelastic pp interactions vertices within a bunch crossing which are referred to as “pileup vertices”. In order to determine the position of the primary vertex and all other pileup vertices, the reconstruction is done in three steps. In the first step, tracks are selected with different criteria imposed on track quality and distance from the center of the most luminous region of pp collision (also known as beam spot). In this step, no selection on track p_T is applied. In the following step, tracks are clustered using deterministic annealing (DA) algorithm [20] which relies on the transverse impact parameter. From these two steps, a set of primary vertices

candidates are acquired. In the last step, these vertex candidates with a minimum of two associated tracks are fitted with an adaptive vertex fitter (AVF) [21]. The vertex candidate with largest p_T^2 sum of associated tracks is considered as primary vertex (PV) for that event, and all other vertices are named as pileup vertices. In an event there should be atleast one good PV for the event to be considerable for physics analysis. The conditions for a PV to be acceptable are : its position should be within $|z| < 24$ cm of the beam spot, radial position to be within 2 cm of the interaction point and number of degrees of freedom should be greater than four.

4.5.2 Track Reconstruction

The charged particles produced from the pp collisions pass through the silicon tracker and leave a hit behind in the pixel and strip tracker layers following a helical trajectory. The hit information of these particles through the tracker layers is exploited to determine their position and momentum in the detector. This process is referred to as *track reconstruction*. A recorded collision image by the CMS detector is shown in Fig. 4.4, to illustrate how difficult it is to reconstruct the millions of tracks. The reconstruction of tracks is done using multiple iterations, and the method is called as *iterative tracking*. The basic idea behind iterative tracking is to first search for track fits of particles with high p_T and then, with more iterations search for low p_T and displaced tracks. The process of iterations is described below, and workflow is demonstrated in Fig. 4.5.

- **Seed Generation** : In this step, a seed is defined as a starting point to find out the particle trajectory. These seeds are collection of particle hits in two or three detector layers, and provide an estimate of initial track parameters and associated uncertainties with it. However, a lot more information is needed to determine the trajectory of the particle. The seed generation starts from the inside of the tracker, and then moves towards the outermost region of the tracker. The various parameters contributing to the seed generation are the number of the detector layers where hits are observed, the minimum p_T of the

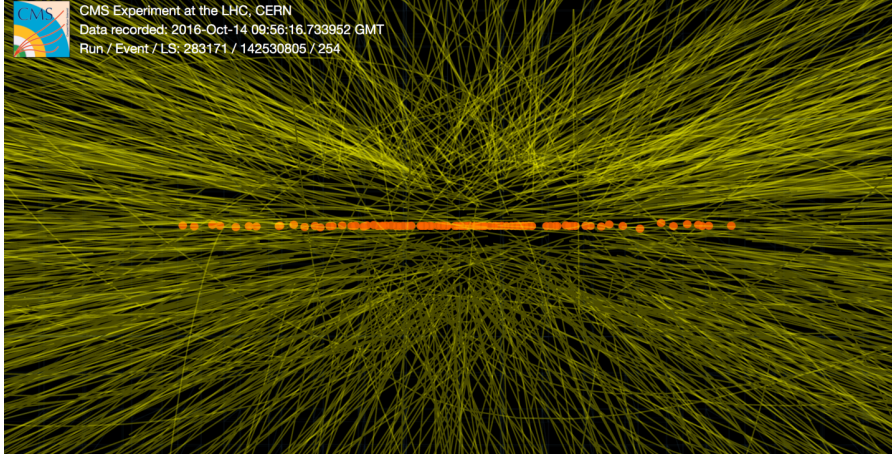


Figure 4.4: A recorded collision by the CMS detector during the 2016 data taking [22].

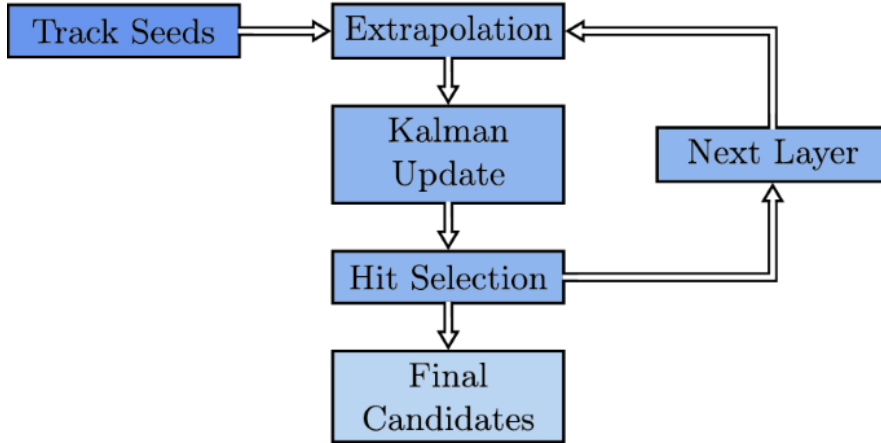


Figure 4.5: The workflow of the track reconstruction

particle and how far is the production point of the particle from the beam spot.

- **Track Finding** : The second step is the track finding, which is implemented using Combinatorial Track Finder (CTF) based on Kalman Filter method [23]. This process starts with the track parameters of the trajectory seed and then construct the track parameters by adding the information of hits from each successive layers and updating the parameters with each added layer. The extrapolated trajectory is considered acceptable based on a χ^2 test, i.e. $\chi^2 < 30$ for one degree of freedom (dof). The hit and trajectory uncertainties are taken into account for χ^2 calculations.

- **Track Fitting** : This is done using the Kalman Filter by performing a fit starting from the innermost hits. The fit is done in an iterative way through all hits, updating the parameters at each sequential fit. The hit position uncertainty is also re-evaluated for each hit using the parameters values. For the precise measurements, the Runge Kutta method is used to extrapolate the trajectory with each added hit.

For particles such as charged pions when crossing the tracker volume, they interact with the tracker material and with a definite energy loss in the tracker, entire trajectory of the particle is not reconstructed. These circumstances lead to fake tracks i.e. the tracks which are not associated with a charged particle. In order to reject these fake tracks and improve the track quality, the selections are applied on the χ^2 of the fit and on the track impact parameters [24] w.r.t beam spot. The χ^2 selection is applied after the track fitting step of fitting and iteration through all hits.

4.5.3 Object Reconstruction

The Particle Flow (PF) reconstruction algorithm [25] [26] is widely used in the CMS to reconstruct and identify the particles and jets originating from the pp collisions at the LHC. For this purpose, the information collected from various sub-detectors is used. The PF candidates are classified into a list of electrons, photons, muons, charged and neutral hadrons, with each of these particles leaving a compatible signature in the detector to identify it. Photons and electrons deposit most of their energy in ECAL, while hadrons may initiate showers in ECAL but deposit energy in HCAL. Muons on the other hand transverse the detector and produce hits in the muon sub-detectors and also in the tracker (Global muons).

4.5.4 Photon Reconstruction

Photons and electrons interact in a similar manner in ECAL as discussed in Section 2.2.3, and deposit almost their entire energy in ECAL clusters. Although before reaching the ECAL, the photons and electrons transverse through tracker and interact with the tracker material which leads to the conversion of photons into electron-positron pair, and electrons radiating bremsstrahlung photons with photons again converting to electron-positron pairs. This creates a shower of particles that deposit energy in the form of clusters in ECAL. To reconstruct the energy of photons and electrons from these clusters, a seed cluster having higher transverse energy (E_T) and the neighboring clusters having energy above the threshold electronic noise (typically ~ 80 MeV in barrel and ~ 300 MeV in endcap) are selected. Here, E_T is defined as $E_T = \sqrt{m^2 + p_T^2}$, where m is the mass of the object and p_T is the transverse momentum of the object. The group of clusters within a certain window is called supercluster (SC), that captures the primary photon's or electron's energy. The cluster combining process makes use of two algorithms. The first algorithm is named as “mustache algorithm” [27] and it is useful to determine the low energy deposits in ECAL. The clustering starts with the seed cluster, with the addition of nearby clusters. The name of this algorithm is derived from the distribution spread of the energy in η - ϕ direction. The distribution of $\Delta\eta = \eta_{seedcluster} - \eta_{cluster}$ Vs $\Delta\phi = \phi_{seedcluster} - \phi_{cluster}$ is slightly bend because of the effect of CMS solenoidal magnetic field. The second algorithm is known as “refined” algorithm. This algorithm uses SC's from mustache algorithm and is also capable of creating its own SC. The superclustering process in this algorithm utilizes the information from tracker to extrapolate bremsstrahlung tangents and also the conversion tracks of electron-positron pair to decide if it should belong to SC or not.

The seed for an electron's reconstruction and the estimation of its tracking parameters are determined by a tracking algorithm that is based on Gaussian Sum Filter (GSF) [28], and for a photon candidate, it is determined with the cluster with $E_T > 10$ GeV provided it is not linked to any GSF track. The ECAL clusters, seed,

- **Calorimeter Jets:** The Calorimeter Jets (CaloJets) use solely calorimeter information, i.e. the energy deposits in the ECAL cells and tower based HCAL information. To avoid the electronic noise in the energy measurements, thresholds are applied on individual cell's energy.
- **Jet-Plus-Track (JPT) Jets:** The JPT jets use the tracker information along with the calorimeter information. In this algorithm, the CaloJets are first reconstructed, and then charged particle based track information is linked to each jet based on the η - ϕ phase space. Using the tracker information improves the jet energy resolution of reconstructed jets.
- **Particle Flow (PF) Jets :** In the PF approach, all the subdetectors information is used to reconstruct the jets. This is the most widely used reconstruction method as it ensures better momentum and spatial resolution and also mitigates the pileup effect with respect to the other two methods.

There are two types of jet clustering algorithms: cone algorithm and sequential clustering algorithm [31]. The sequential algorithm is the preferred one as it is collinear and infrared safe which provides better precision with the theoretical predictions. The algorithm uses the PF candidates and the parameters : distance d_{ij} between the particles or pseudojets i and j , and distance d_{iB} between particle i and beam to begin the reconstruction of the jets. The clustering of particles starts by finding the smallest distance among d_{ij} and d_{iB} . If d_{ij} is the minimum, then i and j particles are combined together, and the algorithm starts at the first step. However, if d_{iB} is the minimum then i particle is considered as the jet and is removed from the list of particles and again the algorithm repeats the first step of calculating the minimum distance. The process keeps on repeating until all the PF candidates are clustered into the jets.

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}, \quad (4.1a)$$

$$d_{iB} = k_{ti}^{2p}, \quad (4.1b)$$

The jets are further classified into two categories based on the pileup reduction techniques to avoid the pileup contribution from the vertices other than primary vertices. The two categories are charged hadron subtraction (CHS) and pileup per particle identification (PUPPI). The AK4 jets with CHS technique applied are used as jets in this analysis where energy contribution from charged hadrons coming from the pileup vertices are subtracted from the reconstructed jet energy. Despite applying all such techniques, the reconstructed jets need calibration of energy and momenta to account the non-uniform response of the calorimeter, inefficiencies of object reconstruction, UE activity and pileup contributions. Hence, it leads to further application of jet energy corrections (JECs) [35] for the precise measurements of jet energies. The corrections are applied in the following steps:

- **L1 corrections** : These corrections are applied to account for the pileup contribution in the jets. It is determined as a function of p_T and η of jet, pileup density and area of the jet [36], [37].
- **L2L3 corrections** : After the pileup offset corrections (L1) are applied, the simulated corrections are applied by comparing the reconstructed jets with the generator level jets to account for difference due to the detector response.
- **L2L3 residual corrections** : After the above two mentioned corrections are applied to data and simulations, additional p_T dependent residual corrections are applied only to data to account for different jet response in data and simulations.

4.5.5.1 b-jet Reconstruction

Jets originating from the bottom quarks are called b-jets and the identification of b-jets is referred to as b-tagging. B-hadrons having a relatively large lifetime (10^{-12} s) decay few millimeters away from the PV, and the displaced track can form a secondary vertex (SV). The displacement of track indicated by a variable called, impact parameter (IP), is a significant variable to distinguish between PV and SV.

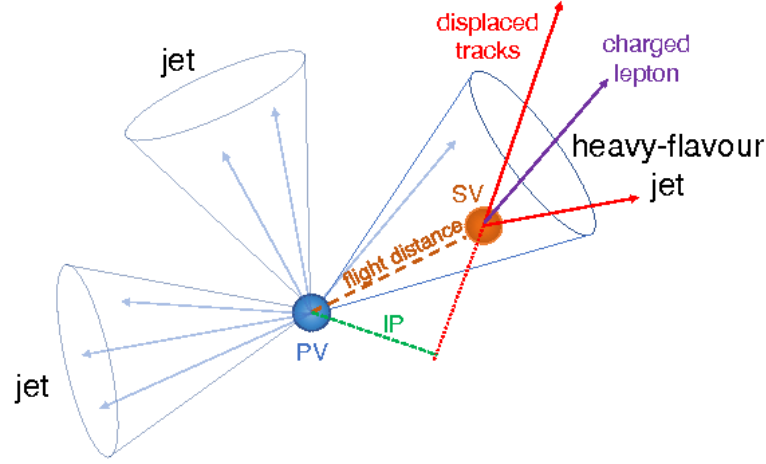


Figure 4.8: An illustration of b-hadron decay from the secondary vertex (SV) that is displaced from primary vertex (PV). The source of figure is Ref. [38]

The tracks associated with the SV have large value of IP, while other associated with PV are symmetrically distributed around zero. Figure. 4.8 shows b-hadron decay, associated PV, SV and the displaced track. Additionally, b-quark have large mass and hence the decay products carry large transverse momentum and are highly fragmented.

Several distinctive properties of b-jet are provided in the form of input variables to a tagger to tag the b-jets. The IP variable have the merit of excellent resolution of pixel layers in the tracker is measured very precisely, with its significance (S_{IP}) defined as the ratio of measured IP value to its associated uncertainty. The S_{IP} holds a great discriminating power to identify the decay products coming from b-jet and non b-jet. The reconstruction of SV is also a challenging task with pileup events. Hence, the tagging algorithm efficiency depends on the reconstruction efficiency of SV. Within CMS, two different algorithms are used to reconstruct SV i.e. Adaptive Vertex Reconstruction (AVR) algorithm [39] and Inclusive Vertex Finding (IVF) algorithm [38]. The latter one is used for Run-II data having better efficiency than the former.

In the present analysis work, a deep neural network based *DeepJet* [40] tagger is used for b-tagging. It is a multi-classifier flavor tagger, and therefore it is also for c-tagging and *uds* tagging. The tagger exploits 650 input variables associated with

the jet such as jet kinematics, number of tracks in jet, impact parameter value and its significance, number of SV in the event and list of other variables associated with SV. Among all the available taggers, *DeepJet* tagger has the better efficiency of b/c tagging and less misidentification probability.

However, there are other reconstruction methods and algorithm used by CMS for other physics objects such as muons, taus and missing transverse energy which are not described here. The details for those can be found in the References [41] and [42].

The physics analysis performed for the new resonance searches with all the details of event selections and statistical interpretation is discussed in the following Chapters.

Bibliography

- [1] N. Metropolis and S. Ulam, “The Monte Carlo Method”, *Journal of the American Statistical Association* **44** (1949), no. 247, 335–341, doi:10.1080/01621459.1949.10483310. PMID: 18139350.
- [2] B. Hippolyte, “Bulk matter physics and its future at the large hadron collider”, *The European Physical Journal C* **62** (feb, 2009) 237–242, doi:10.1140/epjc/s10052-009-0910-9.
- [3] Z. Nagy and D. E. Soper, “What is a parton shower?”, *Phys. Rev. D* **98** (2018), no. 1, 014034, doi:10.1103/PhysRevD.98.014034, arXiv:1705.08093.
- [4] S. Höche, “Introduction to parton-shower event generators”, in *Theoretical Advanced Study Institute in Elementary Particle Physics: Journeys Through the Precision Frontier: Amplitudes for Colliders*, pp. 235–295. 2015. arXiv:1411.4085. doi:10.1142/9789814678766_0005.
- [5] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjostrand, “Parton Fragmentation and String Dynamics”, *Phys. Rept.* **97** (1983) 31–145, doi:10.1016/0370-1573(83)90080-7.
- [6] T. Sjöstrand, S. Mrenna, and P. Skands, “PYTHIA 6.4 physics and manual”, *Journal of High Energy Physics* **2006** (may, 2006) 026–026, doi:10.1088/1126-6708/2006/05/026.

-
- [7] A. Buckley et al., “General-purpose event generators for LHC physics”, *Phys. Rept.* **504** (2011) 145–233, doi:10.1016/j.physrep.2011.03.005, arXiv:1101.2599.
- [8] D. Amati and G. Veneziano, “Preconfinement as a Property of Perturbative QCD”, *Phys. Lett. B* **83** (1979) 87–92, doi:10.1016/0370-2693(79)90896-7.
- [9] B. R. Webber, “Fragmentation and hadronization”, *Int. J. Mod. Phys. A* **15S1** (2000) 577–606, doi:10.1142/S0217751X00005334, arXiv:hep-ph/9912292.
- [10] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *Journal of High Energy Physics* **2014** (2014), no. 7, 79, doi:10.1007/JHEP07(2014)079.
- [11] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *Journal of High Energy Physics* **2007** (nov, 2007) 070–070, doi:10.1088/1126-6708/2007/11/070.
- [12] M. Bähr et al., “Herwig++ physics and manual”, *The European Physical Journal C* **58** (2008) 639–707, doi:10.1140/epjc/s10052-008-0798-9.
- [13] T. Gleisberg et al., “Event generation with SHERPA 1.1”, *JHEP* **02** (2009) 007, doi:10.1088/1126-6708/2009/02/007, arXiv:0811.4622.
- [14] J. Alwall et al., “Madgraph 5 : Going beyond”, *Journal of High Energy Physics* **2011** (2011), no. 6, 128, doi:10.1007/JHEP06(2011)128.
- [15] F. Maltoni and T. Stelzer, “MadEvent: automatic event generation with MadGraph”, *Journal of High Energy Physics* **2003** (feb, 2003) 027–027, doi:10.1088/1126-6708/2003/02/027.

-
- [16] S. Hoeche et al., “Matching parton showers and matrix elements”, pp. 288–289. 2005. [arXiv:hep-ph/0602031](#).
[doi:10.5170/CERN-2005-014.288](#).
- [17] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250–303, [doi:10.1016/S0168-9002\(03\)01368-8](#).
- [18] J. Allison et al., “Recent developments in Geant4”, *Nucl. Instrum. Meth. A* **835** (2016) 186–225, [doi:10.1016/j.nima.2016.06.125](#).
- [19] J. Allison et al., “Geant4 developments and applications”, *IEEE Trans. Nucl. Sci.* **53** (2006) 270, [doi:10.1109/TNS.2006.869826](#).
- [20] L. Angelini et al., “Deterministic annealing as a jet clustering algorithm in hadronic collisions”, *Phys. Lett. B* **601** (2004) 56–63,
[doi:10.1016/j.physletb.2004.09.024](#), [arXiv:hep-ph/0407214](#).
- [21] R. Fruhwirth, W. Waltenberger, and P. Vanlaer, “Adaptive vertex fitting”, *J. Phys. G* **34** (2007) N343, [doi:10.1088/0954-3899/34/12/N01](#).
- [22] CMS Collaboration, “Collisions recorded by the CMS detector on 14 Oct 2016 during the high pile-up fill”, 2016.
- [23] P. Billoir and S. Qian, “Simultaneous pattern recognition and track fitting by the Kalman filtering method”, *Nucl. Instrum. Meth. A* **294** (1990) 219–228,
[doi:10.1016/0168-9002\(90\)91835-Y](#).
- [24] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014), no. 10, P10009, [doi:10.1088/1748-0221/9/10/P10009](#), [arXiv:1405.6569](#).
- [25] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *Journal of Instrumentation* **12** (oct, 2017) P10003–P10003, [doi:10.1088/1748-0221/12/10/p10003](#).

-
- [26] CMS Collaboration, “Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and MET”, technical report, CERN, Geneva, 2009.
- [27] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021), no. 05, P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [28] W. Adam, R. Frühwirth, A. Strandlie, and T. Todor, “Reconstruction of Electrons with the Gaussian-Sum Filter in the CMS Tracker at the LHC”, technical report, CERN, Geneva, Jan, 2005.
- [29] CMS Collaboration, “Jet Performance in pp Collisions at 7 TeV”, technical report, CERN, Geneva, 2010.
- [30] T. Carli, K. Rabbertz, and S. Schumann, “Studies of Quantum Chromodynamics at the LHC”, pp. 139–194. 2015. arXiv:1506.03239. doi:10.1007/978-3-319-15001-7_5.
- [31] G. P. Salam, “Towards Jetography”, *Eur. Phys. J. C* **67** (2010) 637–686, doi:10.1140/epjc/s10052-010-1314-6, arXiv:0906.1833.
- [32] S. D. Ellis and D. E. Soper, “Successive combination jet algorithm for hadron collisions”, *Phys. Rev. D* **48** (1993) 3160–3166, doi:10.1103/PhysRevD.48.3160, arXiv:hep-ph/9305266.
- [33] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, “Better jet clustering algorithms”, *JHEP* **08** (1997) 001, doi:10.1088/1126-6708/1997/08/001, arXiv:hep-ph/9707323.
- [34] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_t jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [35] CMS Collaboration, “Plans for Jet Energy Corrections at CMS”, technical report, CERN, Geneva, 2008.

-
- [36] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet User Manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [37] M. Cacciari, G. P. Salam, and G. Soyez, “The Catchment Area of Jets”, *JHEP* **04** (2008) 005, doi:10.1088/1126-6708/2008/04/005, arXiv:0802.1188.
- [38] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018), no. 05, P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [39] W. Waltenberger, R. Frühwirth, and P. Vanlaer, “Adaptive vertex fitting”, *Journal of Physics G: Nuclear and Particle Physics* **34** (nov, 2007) N343–N356, doi:10.1088/0954-3899/34/12/n01.
- [40] CMS Collaboration, “Jet Flavour Classification Using DeepJet”, *JINST* (2020) doi:10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.
- [41] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s}=13$ TeV”, *Journal of Instrumentation* **13** (jun, 2018) P06015–P06015, doi:10.1088/1748-0221/13/06/p06015.
- [42] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13\text{TeV}$ using the CMS detector”, *Journal of Instrumentation* **14** (jul, 2019) P07004–P07004, doi:10.1088/1748-0221/14/07/p07004.

Chapter 5

Data and MC Analysis

After the long awaited discovery of the Higgs boson [1], [2] in 2012, many collider experiments are extensively searching for new particles manifested by several beyond standard model (BSM) theories [3], [4], [5], [6]. As discussed in Chapter 1, this thesis explores two BSM models : Compositeness Model [7] and Large Extra Dimensions Model [8], [9]. The composite model of fermions states the possibility of sub-structure of quark and leptons, with an observed similar pattern among all three families of fermions. Further, the extra dimensions model predicts that the gravitational force propagates to other extra dimensions, and is more powerful there than the other three fundamental forces. The scientists, Arkani-Hamed, Dimopoulos, and Dvali (ADD) and Randall-Sundrum (RS) described in their theoretical work the existence of extra dimensions. The ADD assumed $n = 6$ flat extra dimensions, while RS assumed $n = 1$ warped extra dimension where n is the number of dimensions other than the 3+1 dimensional space known to us. The model also assumed that the fundamental Planck scale (M_D) can be as low as TeV in the $4 + n$ space-time dimensions and within the reach of LHC energy. It is also assumed that the Quantum Black Holes (QBHs) are produced just above this Planck scale with very unlikely occurrence of QBHs decaying thermally. Here, the QBHs differ from semi-classical black holes, as the latter undergo thermal decay at the Hawking temperature and are described by black hole thermodynamics.

This chapter describes the search for excited state of light flavor quarks (q^*), heavy flavor quarks (b^*), and the QBH by ADD ($n = 6$) and RS ($n = 1$) models. The existence of q^* , b^* or QBH is confirmed if a peak, called as resonance peak, is observed over a smooth continuous falling invariant mass distribution of the final state particles reconstructed over large set of events. A simplified sketch of resonance peak over the invariant mass distribution of a resonant particle X is shown in Fig 5.1. The decay signature for the searches considered in this analysis is one very high energy photon and one high energy jet, and is performed using the data collected by the CMS experiment corresponding to an integrated luminosity of 138 fb^{-1} .

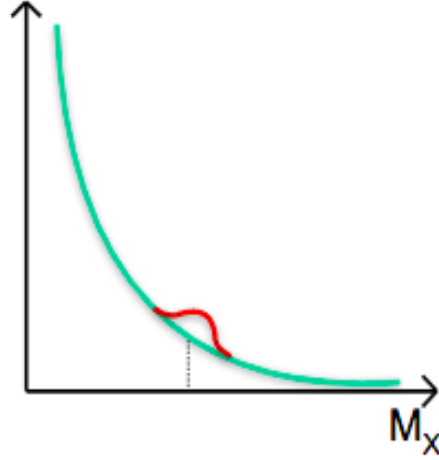


Figure 5.1: The sketch depicts how a new resonance peak would appear over a smoothly falling SM background distribution.

This chapter is organized as follows : The signal and background processes are discussed in Section 5.1 and Section 5.2 respectively, the samples analysed for signal, data and background simulations are given in Section 5.3, the analysis strategy is described in Section 5.4 with the signal modeling and interpolation method defined in Section 5.5 and 5.6, respectively.

5.1 Signal processes

The underlying signal process can be represented as $pp \rightarrow \text{BSM particles} \rightarrow \gamma + \text{jet}$, here BSM particle can be q^* , b^* and the QBH. In case of b^* , the associated jet is a heavy flavor jet. The production phenomenon of these signal processes are discussed in detail below:

5.1.1 Excited Quark Production

The excited light flavor quarks ($q^* = u^*, d^*$) and heavy flavor quarks (b^*) could be produced via qg fusion, $q\bar{q}$ annihilation, and gg fusion. The most dominant process of excited quark production is qg fusion via s-channel, where quark absorbs gluon and then further radiate a boson to reach the ground state. The Feynman diagram of these fusion processes via s-channel and t-channel are shown in Fig 5.2 in left and right respectively.

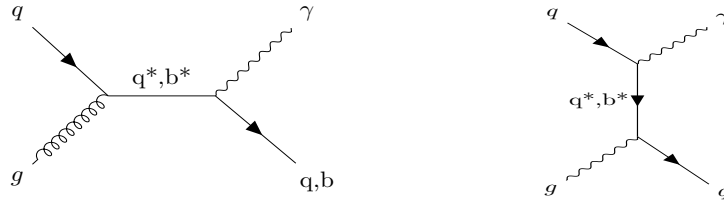


Figure 5.2: The Feynman diagram of the excited quark production via s-channel (left) and t-channel (right) in the $\gamma + \text{jet}$ state.

The Lagrangian term for the excited quark interaction with gauge bosons is described in eq.1.11 in Chapter 1, with all the variables and model parameters defined. Among all model parameters, one of the important parameter is coupling multiplier that indicates the strength of coupling of SM boson with the excited quarks. In this analysis, three different coupling multiplier $f = 1.0, 0.5$ and 0.1 are considered for both q^* and b^* signals. The width of resonance shape is directly proportional to the resonance mass and square of coupling multiplier value, as defined in the eq. 5.1. The higher value of coupling multiplier results in the wider shape of signal. This is

depicted from Fig 5.3, where the resonance shapes of q^* signal for resonance mass $M_{q^*} = 5.0 \text{ TeV}$ for three coupling multipliers $f = 1.0, 0.5$ and 0.1 is plotted.

$$\Gamma(q^*) \sim 0.04 f^2 M_{q^*} \quad (5.1)$$

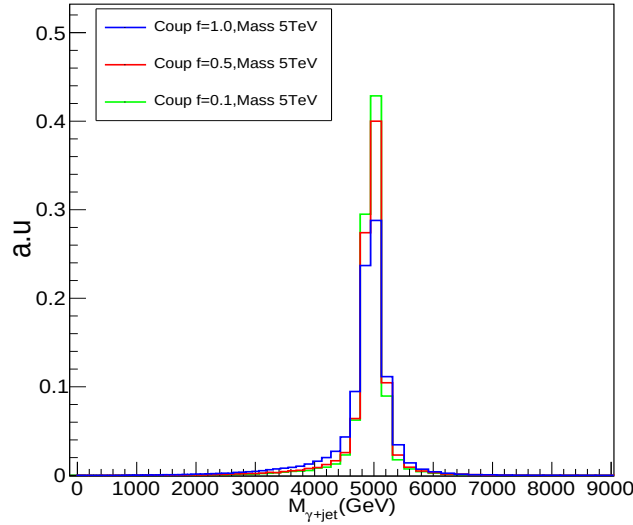


Figure 5.3: The resonance shapes of q^* at the reconstruction level radiating to γ +jet for three coupling multipliers $f = 1.0, 0.5$ and 0.1 .

5.1.2 Quantum Black Holes Production

Various models predict that the existence of extra dimensions can lower the fundamental Planck scale such that it could be accessible at the LHC energies and hence leading to the abundant QBHs production. However, the QBHs production must conserve the electric charge, QCD color and the angular momentum inherited from two partons during pp collision.

In these models, the threshold mass (M_{th}) of a QBH is assumed to be equal to the Planck scale M_D , and the maximum allowed mass is set to be either $3M_D$ or LHC center-of-mass energy $\sqrt{s} = 13 \text{ TeV}$, whichever is smaller. The QBH produced decay on an average to two particles, and the γ +jet final state is the sub-leading decay process with dijet being the leading one. The Feynman diagram of the process

decaying to γ +jet is shown in Fig 5.4. With QBHs produced between M_{th} and the maximum mass, the invariant masses of QBH production resembles to a resonance shape due to continuous falling spectrum above M_{th} and a similar falling distribution on lower mass tail due to experimental and detector effects. The resonance shape of QBH signals for ADD and RS model is shown in Fig 5.5.

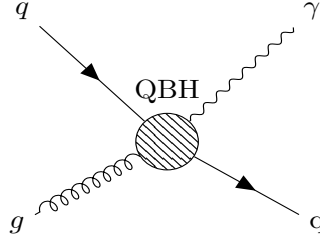


Figure 5.4: The Feynman diagram of the QBH production and decaying to γ +jet state.

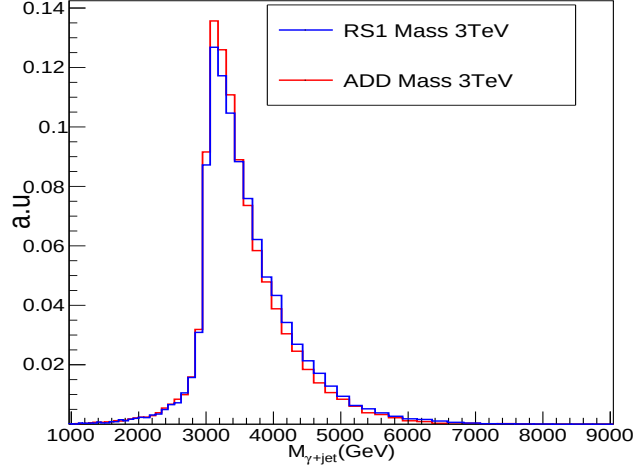


Figure 5.5: Invariant mass distributions of γ +jet state (normalised to unity) for QBH ADD ($n = 6$) and RS ($n = 1$) models for $M_{th} = 3 \text{ TeV}$.

5.2 SM Background Processes

Several SM processes produced in the pp collisions shows signature to γ +jet final state and as a result mimic the signal state. These processes contribute as the back-

ground source to the resonance signal signature. The most dominant contribution comes from the SM γ +jet processes, while QCD multijet processes contributes as a second leading background. A very small contribution comes from electroweak processes. The details of these background processes and how they mimic the signal state are described below:

- **SM γ +jet Background:** A significant and irreducible contribution comes from SM γ +jet production. These processes make a contribution via quark-gluon compton scattering($qg \rightarrow q\gamma$), quark anti-quark annihilation($q\bar{q} \rightarrow g\gamma$) and gluon-gluon fusion($gg \rightarrow g\gamma$). The quark-gluon compton scattering processes has the large cross-section over the other two processes. The Feynman diagrams of these processes are shown in Fig 5.6.

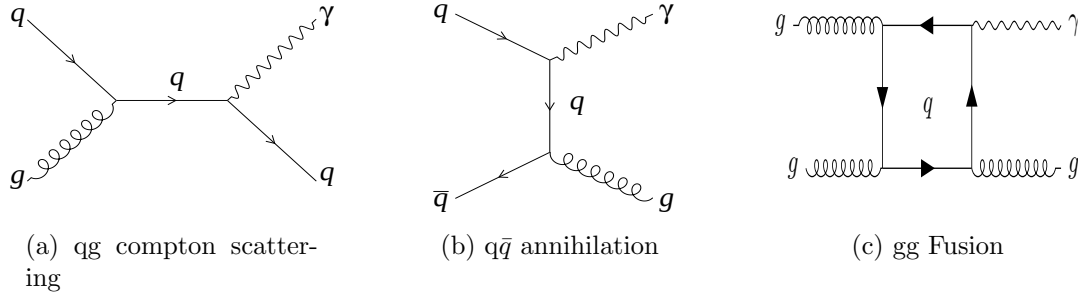


Figure 5.6: The Feynman diagrams of SM background processes contributing through different channels to the γ +jet signal state.

- **QCD multijet Background:** The QCD dijet or multijet production state in the pp hard scattering has the largest cross-section in the SM processes, and are background sources for many analyses channels. However, in our case this process can contribute as background when jets have large electromagnetic fraction and are mis-reconstructed as photons. For example, when jet fragments into highly energetic π^0 or η and further π^0/η decays into two overlapping photons, which are reconstructed as a single photon. The Feynman diagrams of the contributing QCD processes are shown in Fig 5.7. Despite being the largest cross-section process, the probability of jet fragmenting to

π^0 being not large ($\sim 10^4 - 10^5$), and hence the multijet production processes become our second largest contributing background.

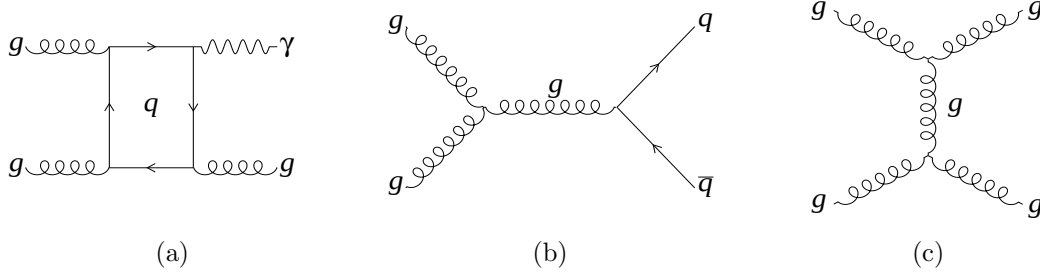


Figure 5.7: The Feynman diagrams of QCD multijet background processes that contributes to the signal state.

- **Electroweak Background:** A small contribution from electroweak (W/Z +jet) processes has been also observed to the γ +jet channel. These processes can mimic the signal when the heavy boson W or Z decay leptonically, and lepton is either lost or not reconstructed leading to missing transverse energy. The Feynman diagrams of these processes is shown in Fig 5.8.

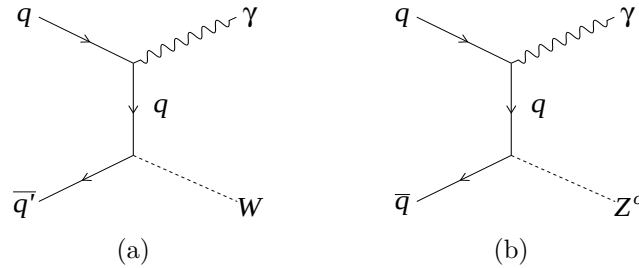


Figure 5.8: The Feynman diagrams of electroweak processes contributing to the γ +jet signal state.

5.3 Data and Monte-Carlo Simulation Samples

- **Data Samples:** The data used in the analysis is collected by the CMS at the $\sqrt{s} = 13$ TeV during the Run-II period in year 2016 (36.7 fb^{-1}), 2017 (41.7 fb^{-1}), and 2018 (59.4 fb^{-1}) corresponding to a total integrated luminosity of

138 fb^{-1} . The data sets are photon triggered, with atleast one photon in each event. A list of dataset is given in the Appendix A (Table A.2) for different years corresponding to different campaigns for data taking conditions.

- **Monte-Carlo Simulations** :The signals and background samples are simulated using Monte-Carlo (MC) technique and processed through GEANT4 for full CMS detector simulation. The q^* and b^* signal are simulated for three coupling multipliers $f = 1.0, 0.5$ and 0.1 using the PYTHIA 8.212 generator upto the leading-order (LO) precision. The signals are generated for mass point 1.0 TeV to 7.0 TeV at the intervals of 1 TeV and 0.5 TeV for q^* and b^* , respectively, with the list of these samples provided in Appendix A, Table A.3 and A.4.

The QBH samples for ADD model and RS model are generated with QBH generator v3.0 using CTEQ6L PDFs. The signals are generated for mass point 3.0 to 8.5 TeV for ADD model and upto 7.0 TeV for RS model. The list of samples is given in Appendix A, Table. A.5.

Figure 5.9 shows the product of cross-sections and branching ratio of the benchmark signal models for the γ +jet final state, as a function of the resonance mass at $\sqrt{s} = 13 \text{ TeV}$.

The SM γ +jet, W+jets, and DrellYan Z+jets background sample are simulated using MADGRAPH5_aMC@NLO generator version 2.2.2 (2.4.2) for 2016 (2017-2018). The QCD multijet background is simulated using PYTHIA generator at LO precision. Hadronization and parton showering of all the simulated samples is performed using PYTHIA generator version 8.205 and 8.230 using CUETP8M1 and CP5 tunes for 2016 and 2017-2018, respectively.

5.4 Analysis Strategy

In resonances searches at high energy colliders, the invariant mass of a system holds great significance. The invariant mass distribution of the final state particles for

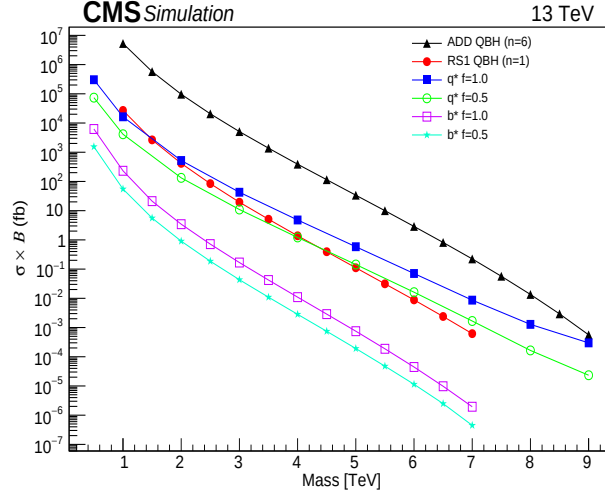


Figure 5.9: The product of signal cross-section (σ) and branching fraction (B) for q^* , b^* and QBH signals with ADD (RS) model having $n = 6(1)$ extra dimensions.

a resonant particle is reconstructed, using the formula described in Appendix B. If the distribution is a smoothly falling distribution, it corresponds to events from SM processes decaying to the same final state particles. However, if an excess is observed over this smoothly falling distribution it indicates the presence of resonant particle. In this analysis, the background estimation is performed using the data driven technique of fitting the invariant mass distribution of the γ +jet state with a smooth parameterization. This same strategy was used when Higgs particle was discovered in 2012, and a resonance peak at 125 GeV led to the discovery of Higgs boson - a major missing piece of SM. In the absence of any such significant deviation from SM expectations, the results are presented in terms of the upper-limit of signal cross section and lower limit on possible signal mass.

5.5 Signal Modelling

The signal q^* , b^* , QBH with ADD ($n = 6$) and RS ($n = 1$) models are the narrow resonances with width of signal narrower than the experimental mass resolution. The peak of these signals resembles to a gaussian peak, but the tails on both side of the shape is dominated by initial- and final-state radiation. Thus, a combination of

two functions is required to describe and fit the shape. This is achieved by adding a Crystal Ball function [10] to the Gaussian function, where Crystal Ball (CB) function is defined by the form:

$$CB(x, \delta, n, \mu, \sigma) = N_{CB} \cdot \begin{cases} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) & \text{for } \frac{x-\mu}{\sigma} \geq -\delta \\ \left(\frac{n}{|\delta|}\right)^n \cdot \exp\left(-\frac{|\delta|^2}{2}\right) \cdot \left(\frac{n}{|\delta|} - |\delta| - \frac{x-\mu}{\sigma}\right)^{-n} & \text{for } \frac{x-\mu}{\sigma} \leq -\delta \end{cases} \quad (5.2)$$

where N is the normalization; σ and μ are width and mean of the resonance shape; and δ and n are the parameters determining the left and right-side tail of the shapes.

An illustration of the signal shape fitted with the Gaussian+ CB function is represented in Fig 5.10.

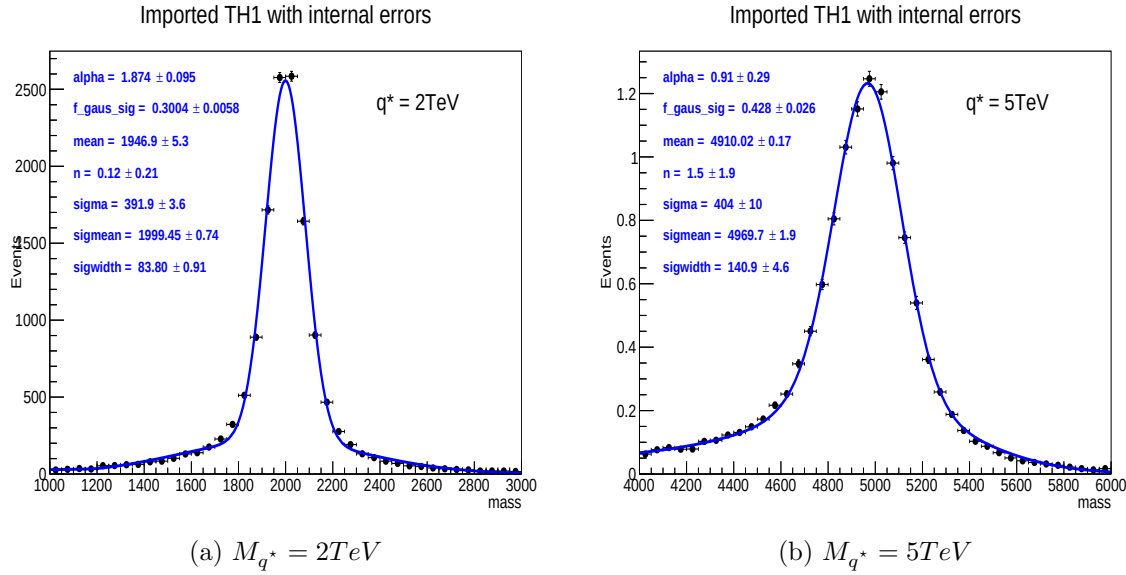


Figure 5.10: The resonance shapes of q^* signal for mass 2 TeV and 5 TeV fitted with Gaussian and Crystall Ball function.

The narrow resonances of q^* , b^* , and QBH models can be observed over falling continuous mass spectrum. However, to observe these narrow resonances the bin width of the signal spectrum should complement the mass resolution of signals. An additional factor to consider is that resonance width of signal increases as we move towards higher resonance masses. Thus, to maintain the analysis sensitivity

to excesses, a variable binning is preferred with bin width increasing with increasing masses. The variable binning is derived from the expected mass resolution for signal using the equation:

$$\frac{\sigma}{Mean} = A + \frac{B}{M_{Res}} \quad (5.3)$$

Here, $\frac{\sigma}{Mean}$ is the mass resolution with σ defined as resonance width and Mean is the resonance mean obtained from the fitting of resonance mass M_{Res} . This functional form is plotted for mass resolution on y axis, as a function of M_{Res} of q^* signal on x-axis. This graph is fitted to obtain the parameters A and B as shown in Fig 5.11. These parameters A and B are then used to obtain the variable binning, and the binning used for mass distribution is given in Appendix. C.

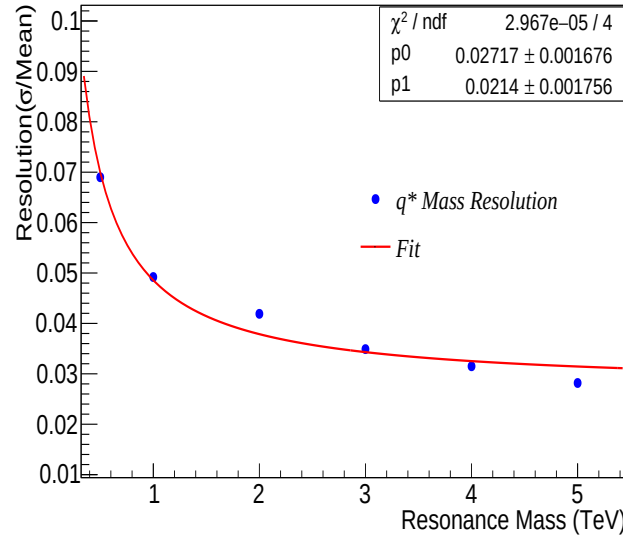


Figure 5.11: The mass resolution of q^* signal plotted and fitted as a function of resonance mass.

5.6 Signal Interpolation

For signal searches, a whole range of mass values is explored for the potential signal. But due to certain computing limitations only few mass points could be generated

using the MC generator and then finally reconstructed. The shapes of intermediate signal masses are obtained using the interpolation technique by utilizing the information from two nearby mass points. The signals b^* and QBH for ADD ($n = 6$) and RS ($n = 1$) models are generated at a gap of 0.5 TeV, while q^* signal generated at a gap is 1.0 TeV. The intermediate mass points are interpolated at a gap of 100 GeV, using generated mass points. In order to interpolate a mass point M lying in between mass point M_X and M_Y , probability distribution $\text{Prob}(A) = \frac{M_{\gamma+jet}}{M_{Res}}$ is build, where $M_{\gamma+jet}$ is invariant mass distribution of mass point M , and M_{Res} is the resonance mass value. Similar distributions from generated points M_X and M_Y are also obtained and further utilized to get the interpolated shape for intermediate mass point M using the relation

$$\text{Prob}_M(A) = \text{Prob}_X(A) + [\text{Prob}_Y(A) - \text{Prob}_X(A)] \cdot \frac{M - M_X}{M_Y - M_X} \quad (5.4)$$

At the next step, this probability distribution is transformed to obtain the final γ +jet distribution shape using ROOT framework for interpolation. Figure 5.12 depicts the generated (solid) and interpolated (dotted) shapes for different resonance masses. However to validate the procedure, the shapes for already generated mass points is also interpolated, and then is compared with an actual generated mass points. Such a validation for $M_{q^*} = 2.0$ and 4.0 TeV is shown in Fig 5.13.

In the next chapter, event selection criteria for the physics analysis is described in detail.

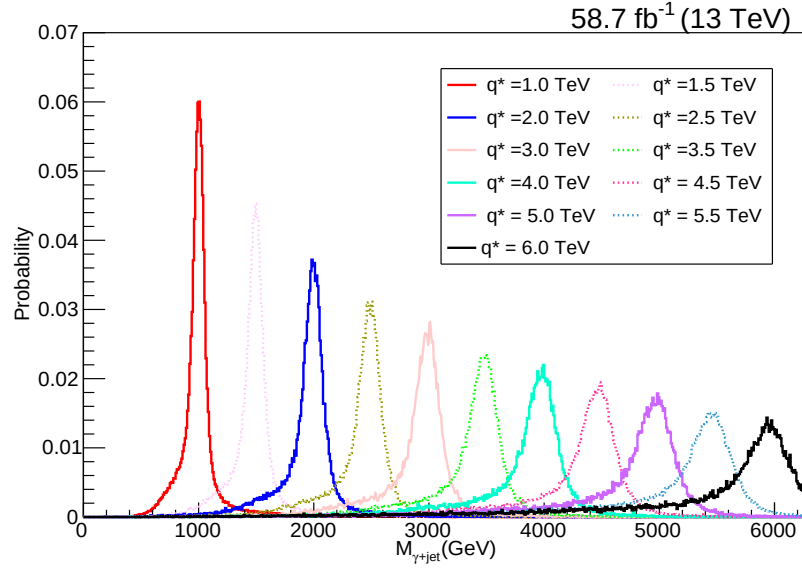


Figure 5.12: Generated and interpolated shapes for different q^* mass points. Shapes in dotted lines are interpolated and in solid lines are generated ones.

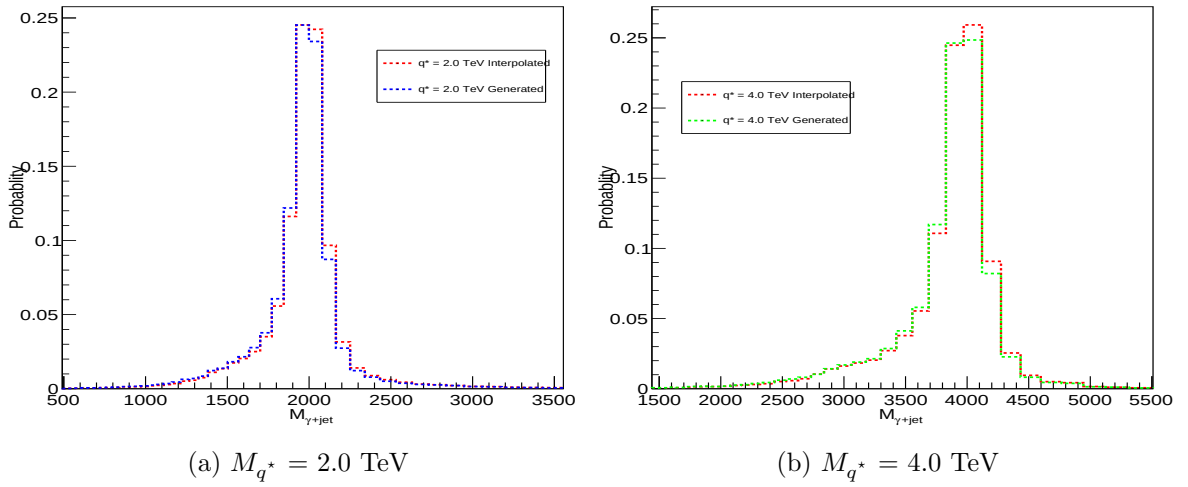


Figure 5.13: Comparison of generated and interpolated shapes at different q^* mass points

Bibliography

- [1] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1–29, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [2] CMS Collaboration, “Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30–61, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [3] D. London and J. L. Rosner, “Extra Gauge Bosons in E(6)”, *Phys. Rev. D* **34** (1986) 1530, doi:10.1103/PhysRevD.34.1530.
- [4] J. C. Baez and J. Huerta, “The Algebra of Grand Unified Theories”, *Bull. Am. Math. Soc.* **47** (2010) 483–552, doi:10.1090/S0273-0979-10-01294-2, arXiv:0904.1556.
- [5] R. Davis, D. S. Harmer, and K. C. Hoffman, “Search for neutrinos from the sun”, *Phys. Rev. Lett.* **20** (May, 1968) 1205–1209, doi:10.1103/PhysRevLett.20.1205.
- [6] S. P. MARTIN, “A SUPERSYMMETRY PRIMER”, in *Perspectives on Supersymmetry*, pp. 1–98. WORLD SCIENTIFIC, jul, 1998. doi:10.1142/9789812839657_0001.
- [7] W. Buchmuller, “Composite quarks and leptons”, *Acta Phys. Austriaca Suppl.* **27** (1985) 517, doi:10.1007/978-3-7091-8830-9_8.

-
- [8] L. Randall and R. Sundrum, “A large mass hierarchy from a small extra dimension”, *Phys. Rev. Lett.* **83** (1999) 3370,
doi:10.1103/PhysRevLett.83.3370, arXiv:hep-ph/9905221.
- [9] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, “The hierarchy problem and new dimensions at a millimeter”, *Phys. Lett. B* **429** (1998) 263,
doi:10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315.
- [10] S. Das, “A simple alternative to the Crystal Ball function”,
arXiv:1603.08591.

Chapter 6

Event Selections

The final state of the analysis is a high p_T photon and high p_T jet. The reconstruction of photons and jets is described in Chapter 4, with the signal and background processes defined in Chapter 5. The event selection applied to data and MC events for improved signal efficiency and background rejection is discussed in this chapter. The chapter is organized as: the HLT selection and event reweighting in simulations explained in Section 6.1 and 6.2, respectively. The Section 6.3 explains the details of selections applied, with the optimization studies discussed in Section 6.4. The sources of systematic uncertainties are described in Section 6.8.

6.1 Trigger Selection

As described in the Chapter 4, all the events produced by the LHC are not the interesting events and trigger is applied on the data to store only the useful events. The online selection to store and to reject the events for offline analysis is made by High Level Trigger (HLT). The decision is based on sequence of various selection on kinematic and identification of physics objects reconstructed. In this analysis, the HLT trigger path is a photon trigger with a kinematic selection on the transverse momentum of photon being applied. For 2016 data analysis, events passing HLT_Photon175 trigger path are selected. This is the lowest unprescaled trigger ap-

plied on 2016 photon dataset. For 2017 and 2018, events that passes HLT_Photon200 trigger path are selected. Here, the suffix 175 and 200 in trigger names represents the kinematic threshold on the photon's transverse momentum. The efficiencies of these HLT triggers are measured to observe if there is any difference in the online and offline versions of the object identification and kinematic selection. The efficiency of the trigger used in the analysis is calculated on different datasets utilizing a few reference triggers. Different datasets are : photon triggered dataset, jet-triggered dataset and muon-triggered dataset with the reference trigger corresponding to same object as the dataset. The efficiency measured on the same photon dataset is called relative trigger efficiency and the one measured on orthogonal jet-triggered and muon-triggered dataset is called absolute efficiency. The details of the trigger used in the analysis is given in Appendix. D.

$$\epsilon = \frac{N_{events}(\text{passing analysis trigger}) + N_{events}(\text{passing reference triggers})}{N_{events}(\text{passing reference triggers})} \quad (6.1)$$

- Relative Trigger Efficiency :** The relative trigger efficiency is calculated on photon-triggered data sets with reference triggers HLT_Photon75, HLT_Photon90 and HLT_Photon120. The events that passes any of these reference triggers in an event are considered as denominator events. In addition to these events, those passing the analysis trigger HLT_Photon175 (HLT_Photon200) for 2016 (2017-2018) are considered as numerator events. As a result, the efficiency is simply measured from the eq 6.1 and is found to be around 100% for photon $p_T^\gamma > 240$ GeV. The Fig 6.1 shows the relative trigger efficiency curve as a function of p_T^γ for 2016 (left), 2017 (middle) and 2018 (right).
- Absolute Trigger Efficiency:** The absolute trigger efficiency is calculated using jet-triggered and muon-triggered dataset with each event having atleast one jet and one muon, respectively. The muon dataset is completely orthogonal dataset to photon dataset in terms of reconstruction in the CMS detector. The reference triggers for jet-triggered dataset are low jet momentum thresh-

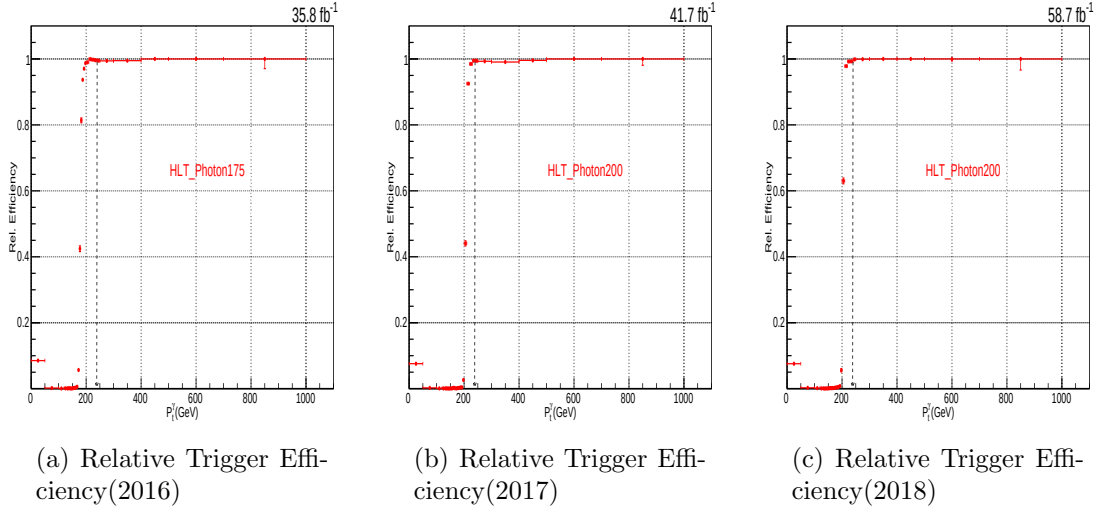


Figure 6.1: Relative trigger efficiencies for HLT_Photon175 (2016), HLT_Photon200 (2017-2018) triggers.

old triggers : HLT_PFJet60, HLT_PFJet90 and HLT_PFJet120 triggers, while for muon-triggered dataset it is a single muon trigger, HLT_Muon50. The efficiency evaluated on jet-triggered dataset is around 99% at $p_T^\gamma \geq 240$ GeV. Similarly, on muon-triggered dataset it is found to be around 97–98% and as shown in the Fig 6.2 as function of p_T^γ . The inefficiency of the trigger measured as 2.5% on muon-dataset will be considered as the systematics. It is further discussed in Section 6.8.

6.2 Event Reweighting

The idea behind generating MC simulated events is to model the expected signal and background events, and have a comparison study with the data. The events observed in data must be validated with the MC background events. Although, there is always some sort of mismodeling between data and MC due to several reasons. To account for this mismodeling, event reweighting is done to MC events for a fair comparison between them. Two different kind of reweighting factors used in this analysis are described below:

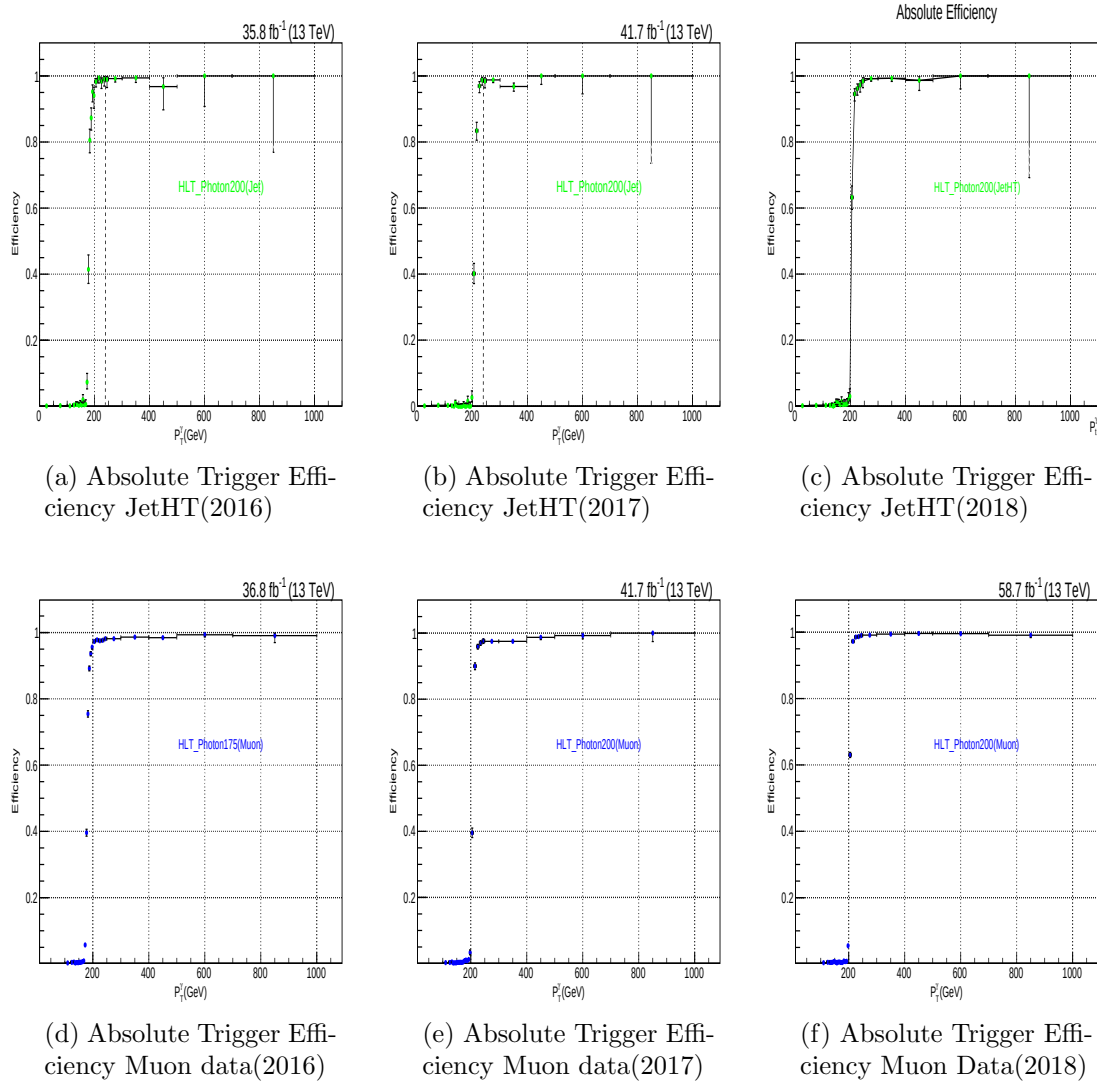


Figure 6.2: Absolute trigger efficiency for HLT_Photon175(2016), HLT_Photon200 (2017-2018) single photon triggers using jet triggerd dataset (top row) and using single muon triggerd dataset (bottom row) from the respective data taking periods.

6.2.1 Pileup-Reweighting

The pileup distribution in data does not exactly match the same distribution simulated in MC samples, due to varying beam conditions and luminosity. To match this distribution, a pileup weight as function of number of primary vertices is applied to the MC. This weight is calculated by taking the ratio of number of primary vertices distribution in data and MC. The distribution shown in the Fig. 6.3 represents

sents the pileup distribution between data and MC for different data-taking years 2016(upper), 2017(middle) and 2018(bottom). The left column represents the actual distribution of pileup in data and MC, and on the right side, it represents the agreement after the mismatched is accounted in MC by applying the pileup weight on event by event basis depending on number of vertices present in that particular event.

6.2.2 Luminosity Reweighting

The events in MC samples for a process are generated for pp collision at $\sqrt{s} = 13$ TeV. However, the events in MC should reflect the actual data collected by the detector. To account for this difference in number of events, the events in MC are weighted by applying a weight that corresponds to those recorded by the detector. This depends on the production cross section of particular process and luminosity. This weight is called luminosity weight or luminosity normalization and is calculated as::

$$\text{Luminosity Weight} = \frac{(\text{Luminosity of data recorded}) \times \sigma}{N_{\text{events in the MC sample}}} \quad (6.2)$$

where σ is the cross-section of the MC process.

6.3 Event Selection

The resonance search of the signals consists of one photon and one jet produced directly from the new resonant particle and carrying large momentum. Various SM processes could become the background source for signal signature that decays to photons and jets, as discussed in Section 5.2. Thus, a very appropriate and precised selection criteria is required to identify the signal events, and as well as reduce the background contribution. The event selection starts with identification of potential photon and jet candidates, and later selection cuts applied on them to minimize the background processes. The event selection criteria is discussed in the below section for a detailed overview.

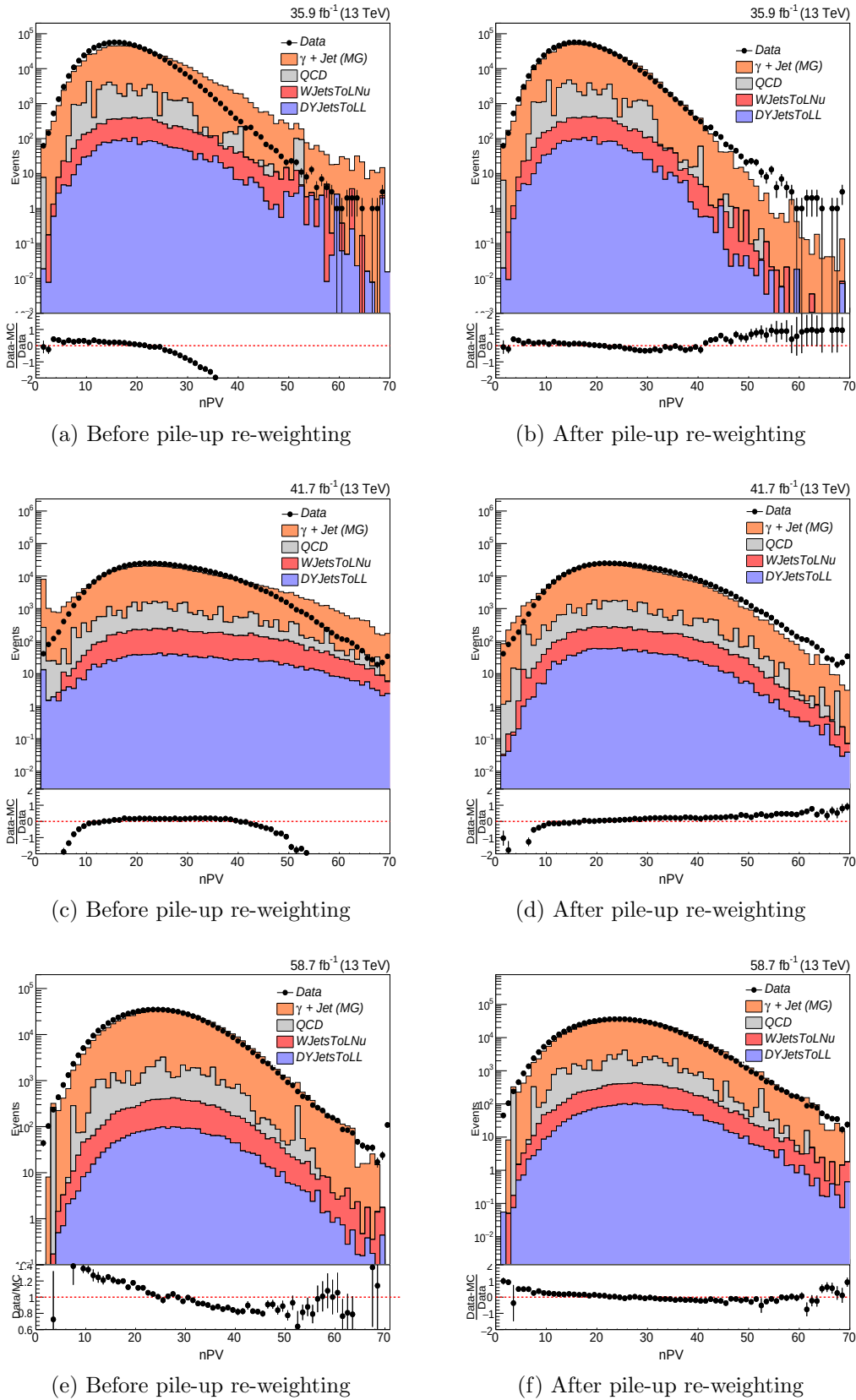


Figure 6.3: Data-MC comparison showing the effect of pileup reweighting on MC events.

6.3.1 Photon Selection

The reconstruction and identification of the well isolated photon is crucial for many physics analyses, and therefore CMS has defined two criteria : cut-based and multivariate technique based identification to reduce the background and enhance the signal efficiency [1]. The two criteria are different in their approach of exploiting the isolation variables. In the cut-based strategy, the selections are applied on various isolation variables, while in multivariate technique, a Boosted Decision Tree (BDT) [2] approach is implemented where a single variable is built using many input variables. The BDT strategy provides improved significance for those analysis where signal yield is small. Moreover, in this analysis the cut-based strategy is used.

The main source of background to the prompt photons (photons from hard interactions) are hadronic jets that have large electromagnetic fraction and are misreconstructed as photons. For example, high energy π^0 and η mesonic jets decaying to two nearly collinear photons are as a single photon object making it a background event. To reduce such significantly contributing background events with these misreconstructed photons, isolation variables and shower shape variables are defined with their description below :

6.3.1.1 Isolation Variables

The most efficient way to reduce the background sources is to construct the isolation variables by using the isolation energy sum of the particles around the reconstructed photon. To do so, a cone of $\Delta R = 0.3$ is built around the photon in $\eta - \phi$ plane along the photon direction. Inside this cone, the transverse momenta of charged hadrons, neutral hadrons and photons are summed and defined as isolation variables. These variables are named as: I_{ch} for charged hadrons, I_n for neutral hadrons and I_{ph} for photons. Since the spread of incoming prompt photon in the calorimeter is energy dependent, the threshold applied on these isolation variables is also energy dependent.

Additionally, the contribution from pileup and underlying events in the isola-

tion cones are required to be corrected. This contribution is estimated by variable ρ which refers to the median of the transverse energy density per unit area (E_T/area). In order to evaluate the correction, the ρ variable is multiplied with effective area A_{eff} , i.e the area in the isolation cone weighted by a factor that accounts for the distribution of pileup energy in the η regions of an object.

The corrected isolation variables after the pileup correction is :

$$Iso^{corrected} = maximum(Iso^{original} - \rho \times A_{eff}, 0) \quad (6.3)$$

6.3.1.2 Shower Shape Variables

The shower shape of the incident particle in the ECAL is another discriminating criteria to reject the background events. The shower shape of photons from the hadronic jets are expected to be wider in comparison to the single isolated photon. This is particularly seen in η direction of the cluster. Two variables constructed to describe the shower shape of photon are : Hadronic to electromagnetic energy ratio (H/E) and $\sigma_{i\eta i\eta}$.

- **H/E** : The H/E is defined as the ratio of the hadronic energy to the electromagnetic energy of the photon in a cone of $\Delta R = 0.15$ along the photon direction. The prompt photons deposit almost all of their energy in ECAL with a small leakage to the HCAL, while this is not the case for hadronic jets. For low energy prompt photons, the contribution to the hadronic energy comes from HCAL noise and pileup, while for high energy photons, it comes from the leakage of photons through the intermodule gaps. This ratio should be very small for prompt photons, but the value can be large for backgrounds.
- **$\sigma_{i\eta i\eta}$** : This variable is defined as the log-energy weighted distribution along the η direction, calculated in 5×5 crystal array around the crystal having

maximum energy in supercluster (SC).

$$\sigma_{i\eta i\eta}^2 = \frac{\sum_{5 \times 5} (\eta_i - \bar{\eta})^2 w_i}{\sum w_i}, \quad (6.4)$$

$$\text{where } \bar{\eta} = \frac{\sum w_i \eta_i}{\sum w_i} \text{ and } w_i = \max \left[0, 4.7 + \log \left(\frac{E_i}{E_{5 \times 5}} \right) \right]$$

where, η_i is the pseudorapidity of the i^{th} crystal, $\bar{\eta}$ is the mean position of pseudorapidity. The weight factor w_i is non-zero when $\ln(\frac{E_i}{E_{5 \times 5}}) > 4.7$, i.e the energy of i^{th} crystal (E_i) is greater than 0.9% of energy of deposited in 5×5 crystal around the SC. Hence only in this condition, crystal makes contribution to the shower shape. This distribution is generally observed to be wider for endcap prompt photons compare to those in barrel.

There is another important variable R_9 , which is defined as the energy sum of the 3×3 crystal array centered around the most energetic crystal in the SC divided by the energy of the SC. This variable is used to distinguish photons and electrons that undergo a conversion in the ECAL from those that do not. Showers of photons and electrons that convert before reaching calorimeter are wider in shape, and have lower R_9 value than the unconverted photons and electrons.

6.3.1.3 Cut-Based Identification Technique

The “medium” working point with 80% efficiency for signal like events is used in this analysis. As mentioned in the previous section, in cut-based approach thresholds are applied on the energy sum isolation variables and shower shape variables. The thresholds on these variables for medium working point are :

- Single tower H/E < 0.02197.
- $\sigma_{i\eta i\eta} < 0.01015$.
- I_{ph} (ρ corrected Particle Flow Photon Isolation) < $2.08 + 0.004017 \times p_T^\gamma$.
- I_{ch} (ρ corrected Particle Flow Charged Hadron Isolation) < 1.141.

- $I_{neutral}$ (ρ corrected Particle Flow Neutral Hadron Isolation) $< 1.189 + 0.01512 \times p_T^\gamma + 0.00002259 \times (p_T^\gamma)^2$.
- A conversion safe electron veto condition is also applied to minimize the contribution from misidentified electrons. The veto removes the photon candidate if its supercluster is matched to an electron with all hits in the tracker, and is not matched to reconstructed conversion vertex ($\gamma \rightarrow e^- e^+$).

The data-MC comparison of all these isolation and identification variables for photons are shown in Fig. 6.4.

Further, the photons that passes the cut-based criteria with medium working point are required to pass the kinematic selection for more efficient background rejection. A p_T threshold of 240 GeV and $|\eta| < 1.4$ is applied on the isolated photons passing the criteria, with the p_T threshold derived from the trigger efficiency. The photons only in the barrel region of the detector i.e. $|\eta| < 1.4$ are selected, since the signal production from hard scattering leads to the photons and jets that are back to back. Additionally, endcap region contributes large to the background events and also has poor energy resolution.

6.3.2 Jet Selection

The jets considered in this analysis are particle flow (PF) jets reconstructed using anti- k_T algorithm with $\Delta R = 0.4$, also known as AK4 jets, and are discussed previously in Chapter 4. These jets are essentially required to pass identification criteria to avoid the contributions from electronic noise and pileup events. The identification criteria for jets, named as PF JetID criteria, is based on the energy contribution from neutral hadrons, neutral electromagnetic (EM) particles, charged hadrons and charged EM candidates that are clustered inside the jet. In this analysis, jets passing the “tight” working point of PF JetID are analysed, with the criteria for 2016 (2017/2018) defined as:

- Neutral Hadron Fraction $< 0.99(0.90)$

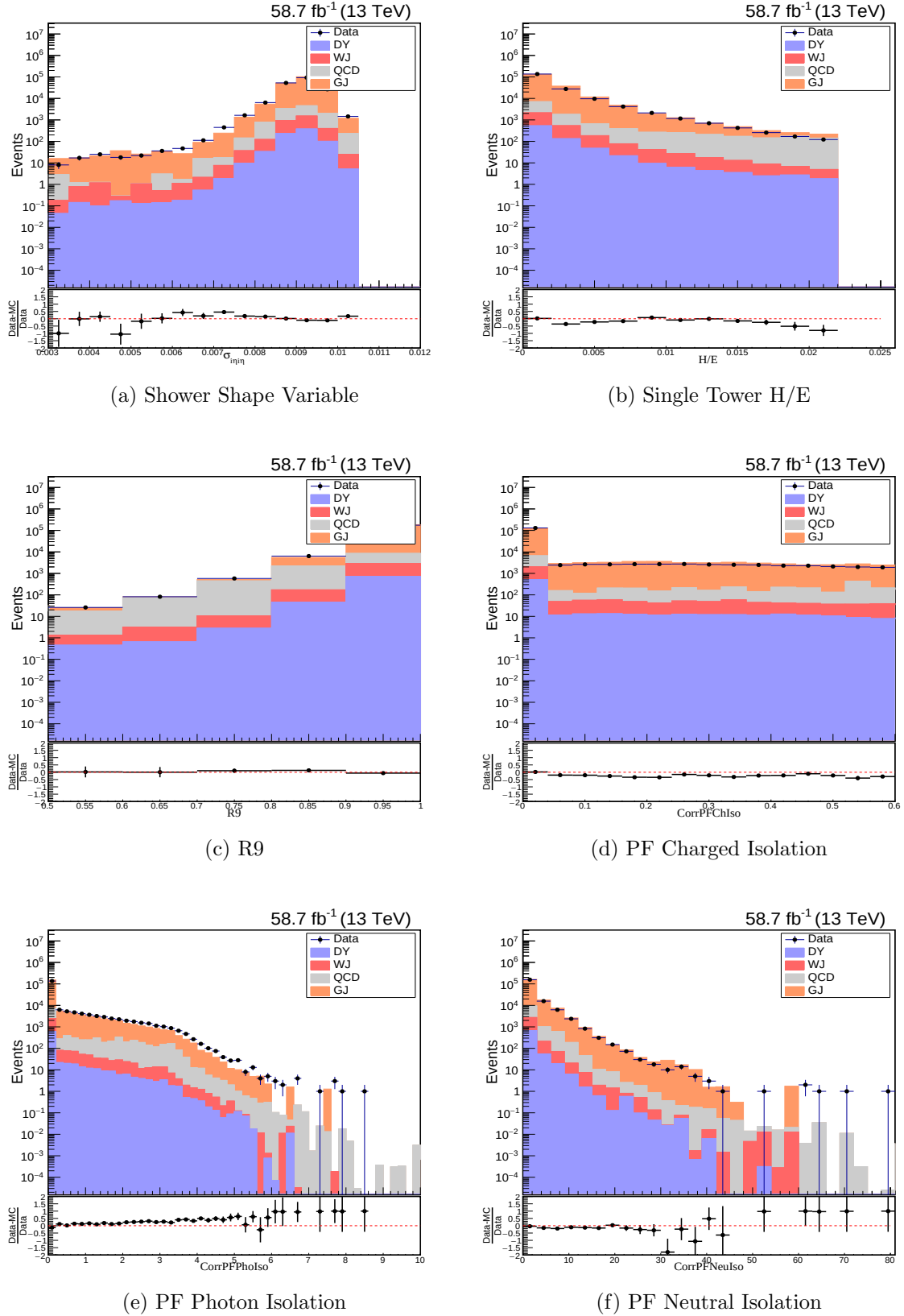


Figure 6.4: Data-MC comparison of photon identification and isolation variables after final selection for 2018 data-taking year.

- Neutral EM fraction $< 0.99(0.90)$
- Charged EM fraction $< 0.99(0.99)$
- Charged Hadron Fraction $< 0(0)$
- Number of Constituents $> 1(1)$
- Charged Multiplicity $> 0(0)$

The tight identification criteria is observed to have an efficiency of 99% to identify the AK4 jets. The jets passing the criteria are imposed with a pre-selection on their transverse momentum $p_T > 30 \text{ GeV}$ and tracker coverage selection of $|\eta| < 2.4$ to remove contribution from pileup jets.

In order to avoid the momentum loss due to the final state radiation, and consequently to improve the γ +jet mass resolution, “wide” jets are constructed using the AK4 jets that passes the above identification and pre-selection criteria. The procedure followed is described below :

- Primarily, a leading and a subleading jet in an event are considered as “seeds” to start the construction of wide-jet. They are named as wj_1 and wj_2 .
- For each AK4 jet j_i , $\Delta R_{i1,2}$ is calculated between this AK4 jet j_i and two seeds wj_1 and wj_2 to determine if it is closer to wj_1 or wj_2 .
- A cone of radius $\Delta R < 1.1$ is built around each wj_1 and wj_2 . A skeptical description of the wide jet is shown in Fig 6.5.
- If $\Delta R_{i1} < \Delta R_{i2}$ and $\Delta R_{i1} < 1.1$, the jets j_i are merged by vectorial sum with the seed wide jet wj_1 .
- If $\Delta R_{i2} < \Delta R_{i1}$ and $\Delta R_{i2} < 1.1$, the jets j_i are merged by vectorial sum with the seed wide jet wj_2 .
- The wj_1 and wj_2 along with the other jets j_i merged are the final two wide jets.

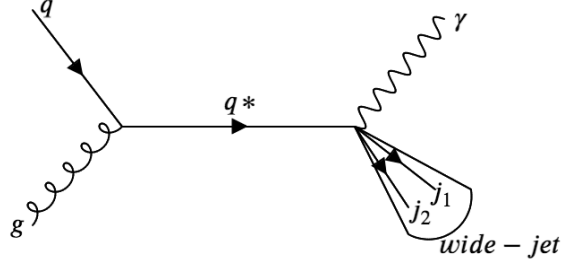


Figure 6.5: The illustration of an event with final state radiation (FSR), and the wide-jet has included the FSR in it and hence improving the γ +jet invariant mass resolution.

- Among these two wide jets constructed, the leading wide-jet with $p_T > 170$ GeV is considered as the final jet candidate. The selection $p_T > 170$ GeV is based on the signal topology of high p_T jet with further optimization studies on the selection discussed later in this chapter in Section 6.4.3.
- The construction of wide-jet improves the mass resolution by 3–4% with respect to AK4 jets, as shown in Fig 6.6. The same study is also performed for two different ΔR values of 1.3 and 1.5. The mass resolution was not effected by increasing the cone size.

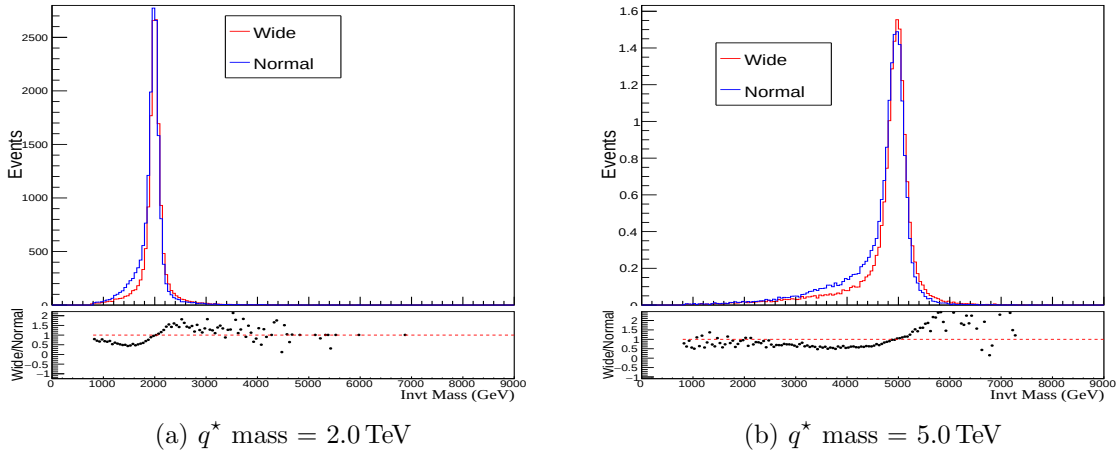


Figure 6.6: The improvement in the invariant mass distribution with the construction of wide-jets with respect to AK4 jets of q^* signal of mass 2.0 TeV and 5.0 TeV on left and right, respectively. The wide-jets are constructed with $\Delta R = 1.1$.

The identification and isolation variables comparison of MC and Data for year 2018 is shown in Fig 6.7. The distributions shows good agreement.

6.3.3 b-Jet Selection

Since the search for excited bottom quarks (b^*) requires one jet to be a b-quark jet, various deep neural network (DNN) based tagger [3] are developed by CMS to tag a jet as b-jet. Among all, the “DeepJet” tagger [4] is the most efficient tagger that is used in this analysis. In order to develop this tagger, approximately 650 input variables divided into four categories : global jet variables, charged PF candidate features, neutral PF candidate features, and secondary vertices based variables associated with the jet are used. The complete list of variables can be found in Ref. [4].

The tagger operate at three different working points “loose”, “medium” and “tight” having b-jet identification efficiency of 90%, 80%, 60% and with a misidentification probability of light-flavor jets to be 10%, 1% and 0.1% [3], respectively. The performance studies of the tagger is done on simulation samples, with PF reconstructed AK4 jets. The discriminator value shows a continuous output in the range 0 to 1, where the highest value indicate the probability of jet arising from b-quark. The three working points are defined based on the threshold applied on the discriminator value. The Table 6.1 shows the same threshold values for all data-taking years 2016, 2017 and 2018 for all working points. This analysis considers the “medium” working point with 80% efficiency to tag the jets as b-jets. The optimization studies for the working point is discussed later in Section 6.4.2.

The algorithm shows different behavior in data and simulations for reconstructed jets, and to account for this discrepancy a scale factor (SF) is applied to simulations. This SF is provided by the CMS experiment centrally for all years and is p_T , η and jet-flavor dependent.

Furthermore, the b-jets and b-tagged jets are not same. The b-jets are identified using the truth flavor of jets saved in the simulations, while the b-tagged jet are

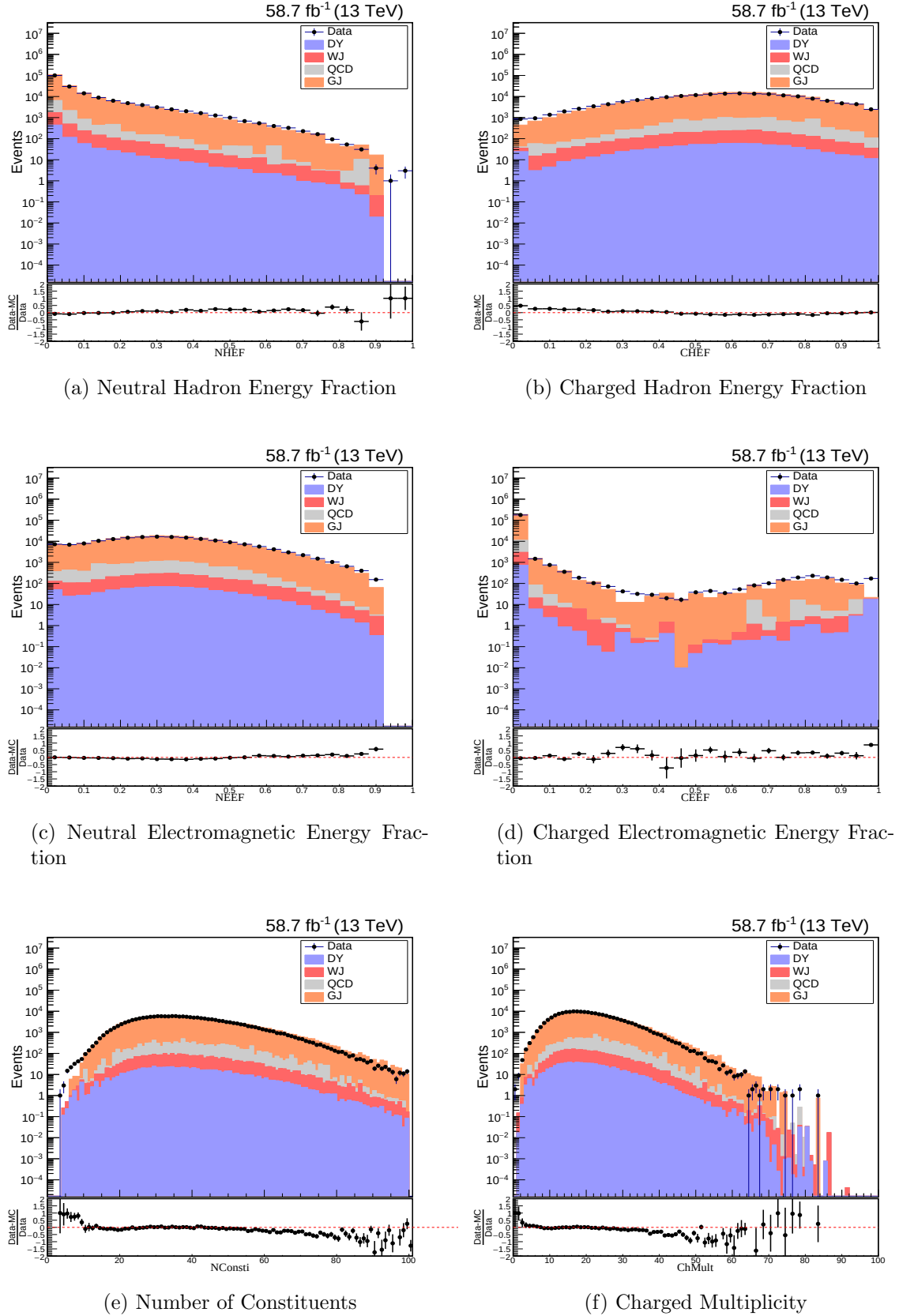


Figure 6.7: Data-MC comparison of Jet Particle Flow Identification variables after final selections applied for 2018 data taking year corresponding to luminosity 58.7fb⁻¹.

WP name	WP Discr Cut		
	2016	2017	2018
Loose	0.0614	0.0521	0.0494
Medium	0.3093	0.3033	0.2770
Tight	0.7221	0.7489	0.7264

Table 6.1: b-tag DeepJet discriminator working points and their thresholds for 2016, 2017 and 2018 data and MC.

those jets that are tagged by the discriminator. The tagger is not fully efficient to tag the b-quark jets as b-jets, and to overcome this difference two categories have been considered for b-jets. These categories are :

- 1-btag category : Jets passing the discriminator * SF
- 0-btag category : Jets passing the discriminator * (1-SF) + Jets failing the discriminator

where, SF is the factor for b-jets applied to the jets passing the discriminator. The factor (1-SF) is applied to those same jets but are categorized in 0-btag category in addition to the jets failing the discriminator. The Fig 6.8 shows the distribution of DeepJet discriminator for a) no-Tag condition applied, b) jets falling in 0-btag category and c) jets falling under 1-btag category. The sharp cut at around 0.27 is due to the discriminator condition applied for 2018, which from the Table 6.1 is 0.2770 for medium working point.

6.3.3.1 b-jets in WideJet

The wide-jet in case of excited b-quark (b^*) signal is constructed with a condition that atleast one of the jet in a wide jet should pass the discriminator condition. The SF applied to leading wide b-tagged jet categorized further into 1-btag and 0-btag is calculated on all the AK4 jets constituting the wide-jet. If there are n AK4 jets in a wide jets, then events falling in 1-btag category are weighted by $W_{btag} = 1 - ((1 - SF_1) \times (1 - SF_2) \times (1 - SF_3) \dots \times (1 - SF_n))$, and the same events

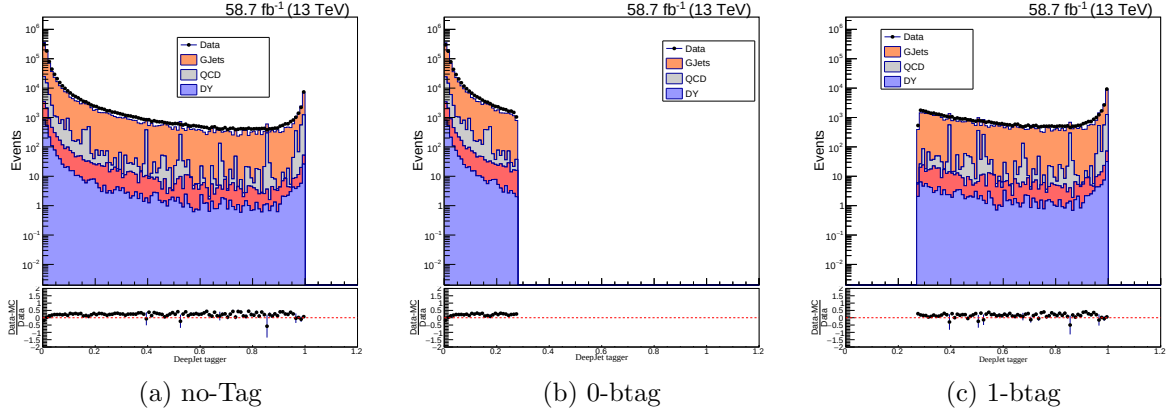


Figure 6.8: DeepJet discriminator distribution before and after applying the b-tagging for 2018 dataset. The distributions are similar for 2016 and 2017 data-taking year also.

in 0-btag category are weighted by $(1 - W_{btag})$. Here, SF_i corresponds to the SF for i^{th} AK4 jet.

The SFs are calculated by the CMS group for jet p_T ranging from 20 to 2000 GeV, and $|\eta| < 2.4$. The Fig 6.9, 6.10, and 6.11 shows the efficiency of b-tagging as a function of p_T and η of jets for signal simulations of year 2016, 2017, and 2018 respectively. The mistagging probability of c-flavor and light flavor (u,d,s) quarks are also shown in the same figure.

6.3.4 Photon+Jet System

The leading photon and leading wide-jet with the kinematic selections described in above sections are further analysed as the final candidate. To reduce the background contribution from events where photon is very close to the wide-jet, a selection on $\Delta R(\text{photon, wide-jet}) > 1.1$ is applied. However, to further enhance the signal efficiency and reduce the contribution from t-channel backgrounds a cut on angular separation between photon and jet is also applied i.e. $|\Delta\eta(\gamma, \text{jet})| < 1.5$. This selection has the most impact on the multijet background and reduces it upto $\sim 35\%$. The invariant mass of the $\gamma + \text{jet}$ system (i.e. $m_{\gamma + \text{jet}}$) is then reconstructed with the events that passes all the above selection criteria. As discussed in analysis strategy

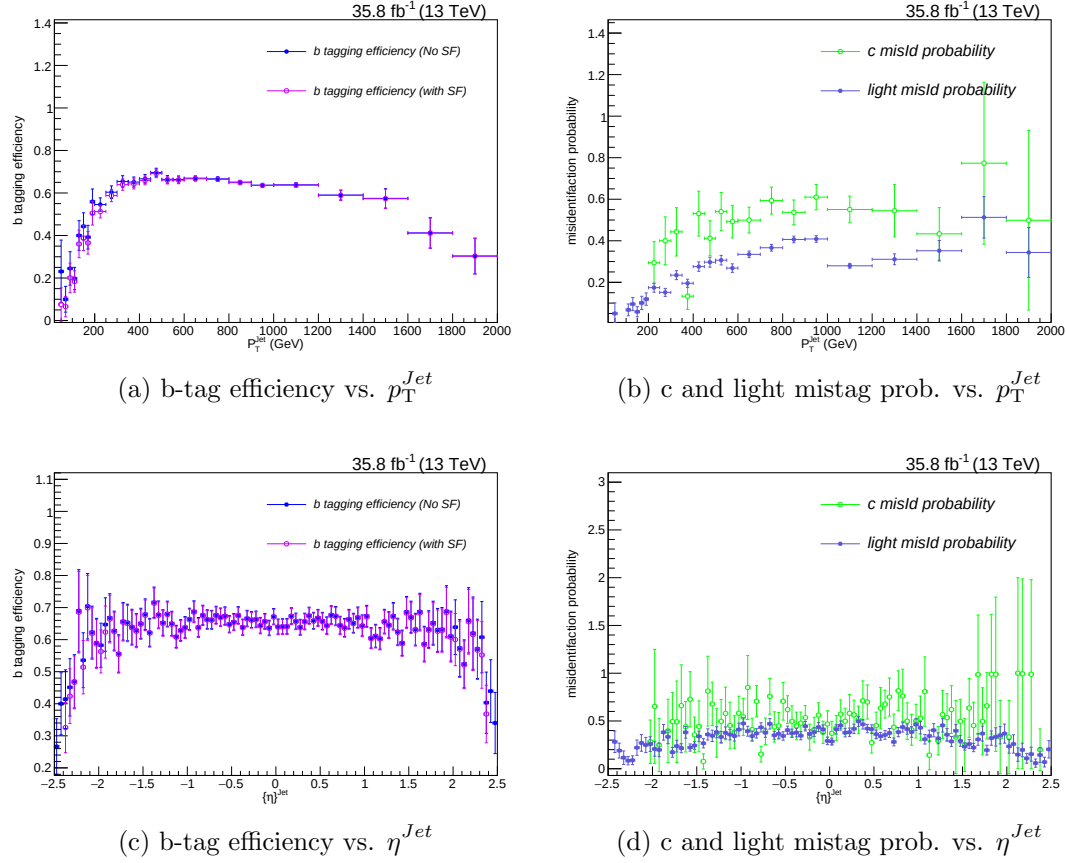


Figure 6.9: b-tagging efficiency, and c and light quarks mistag rate as a function of p_T and η of wide-jets in $\Delta R = 1.1$ for 2016 dataset.

in Section 5.4, the invariant mass distribution is the most significant distribution in this study and is fitted with a polynomial function for background estimation. Moreover, due to various kinematic selections applied there is a turn-on region in the mass distribution (as shown in Fig 6.12 for 2016, 2017 and 2018 data-taking years), and it is slightly difficult to parameterize such distribution. Hence, a mass threshold of 760 GeV is applied on $m_{\gamma+jet}$ to avoid this turn-on region. The optimization studies for the mass threshold selection is discussed later in this chapter.

After the full event selection, the MC backgrounds are scaled by a fixed correction factor to account for missing higher orders which are present in data. The MC are generated with LO or fixed order calculation, and they do not fully account for all higher order contribution despite predicting shapes quite accurately. The MC are

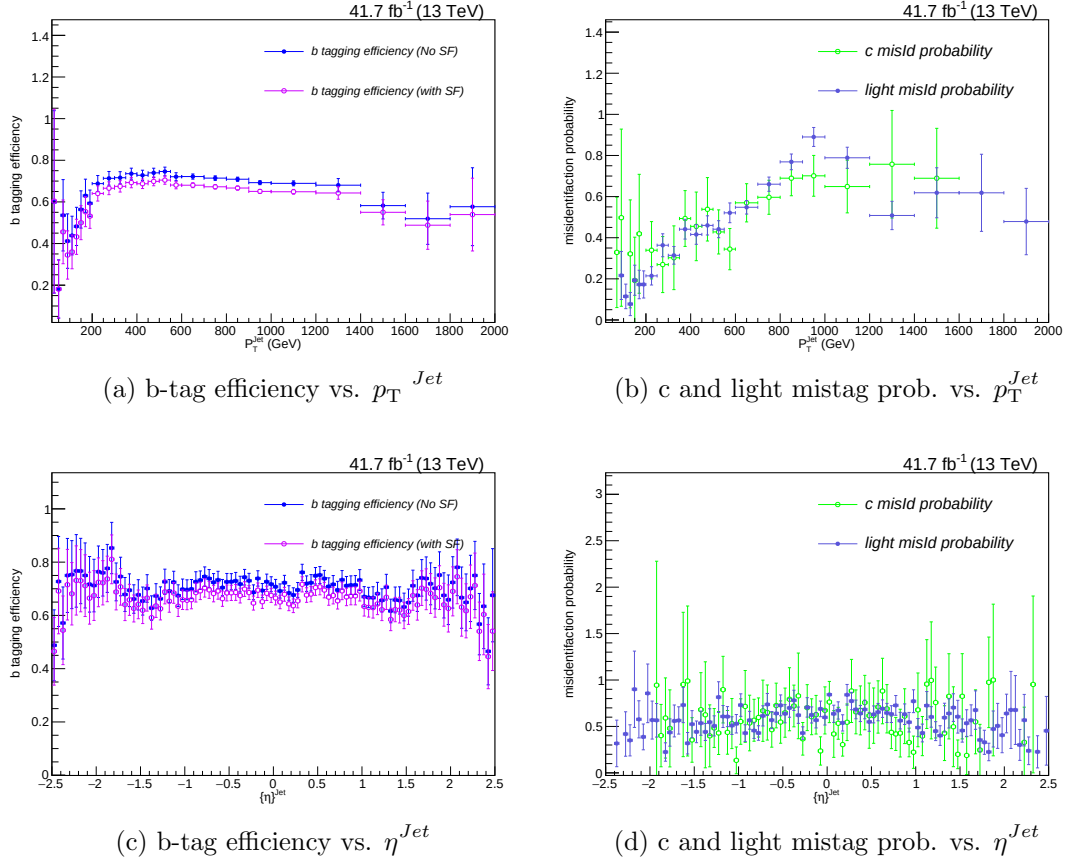


Figure 6.10: b-tag efficiency, and c and light quarks mistag rate as a function of p_T and η of wide-jets in $\Delta R = 1.1$ for 2017 dataset.

normalized with a single correction factor (without changing any shape of the MC) for the shape comparison of MC predicted background with the data. It should be noted that this is done for Data vs MC comparison while for final observed limits data will be used for evaluating background. To estimate the overall correction factor we used photon p_T spectrum as photons are well reconstructed compared to jets. We fit the ratio of data/MC with a zero order polynomial to obtain the correction factor and applied it to MC background. These correction factor are mentioned in Table 6.2 for 2016, 2017 and 2018.

The data-to-MC agreement for photon and jet kinematic variables p_T , η , and ϕ are shown in Fig 6.13– 6.21 for the three data-taking periods. A good agreement is observed between data and simulations in these distributions as indicated by the

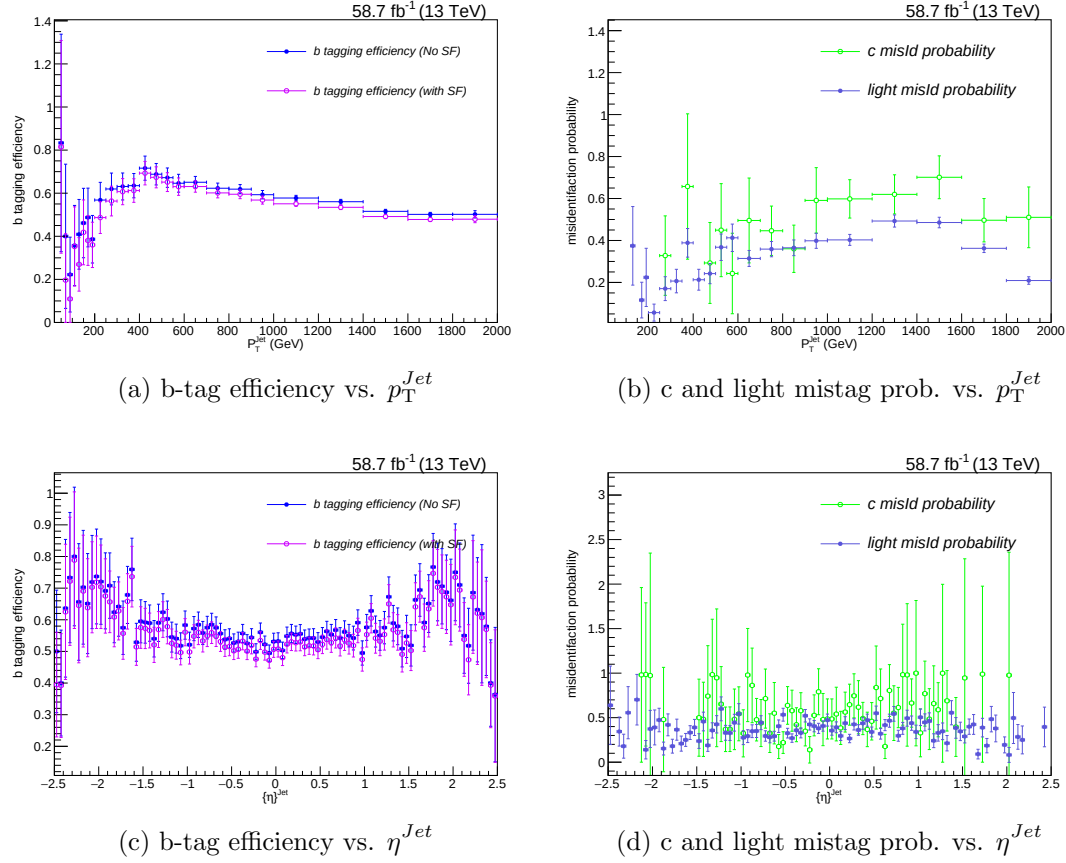


Figure 6.11: b-tag efficiency, and c and light quarks mistag rate as a function of p_T and η of wide-jets in $\Delta R = 1.1$ for 2018 dataset.

Categories	Correction Factor		
	2016	2017	2018
q^*/QBH	1.30	1.27	1.25
1-btag	1.39	1.45	1.42
0-btag	1.29	1.25	1.23

Table 6.2: The correction factors applied to MC for q^*/QBH , 1-btag and 0-btag categories for 2016, 2017 and 2018.

bottom panel of the plots.

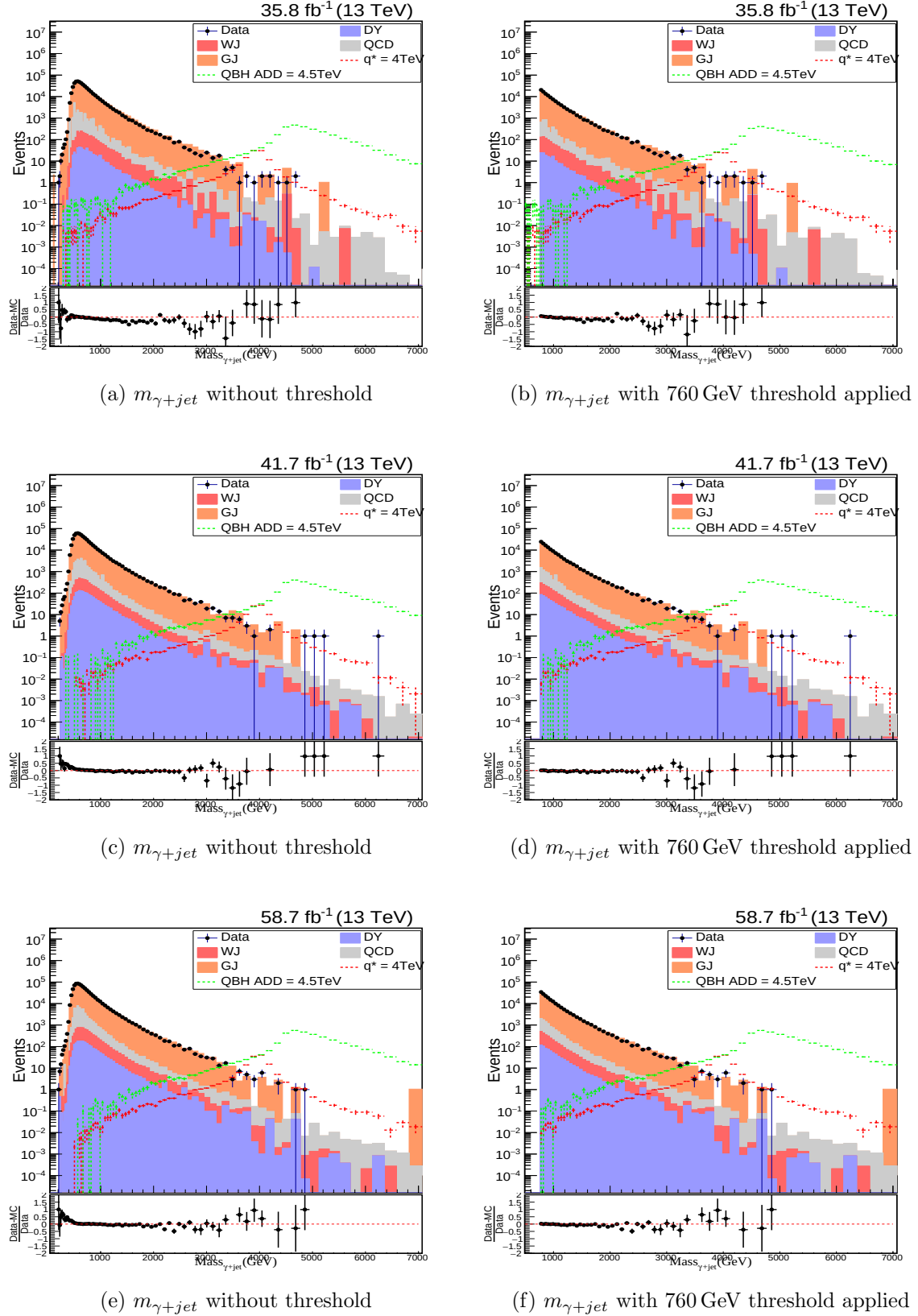


Figure 6.12: The invariant mass distribution $m_{\gamma+jet}$ without and with 760 GeV threshold applied to avoid the turn-on region for 2016, 2017 and 2018 respectively.

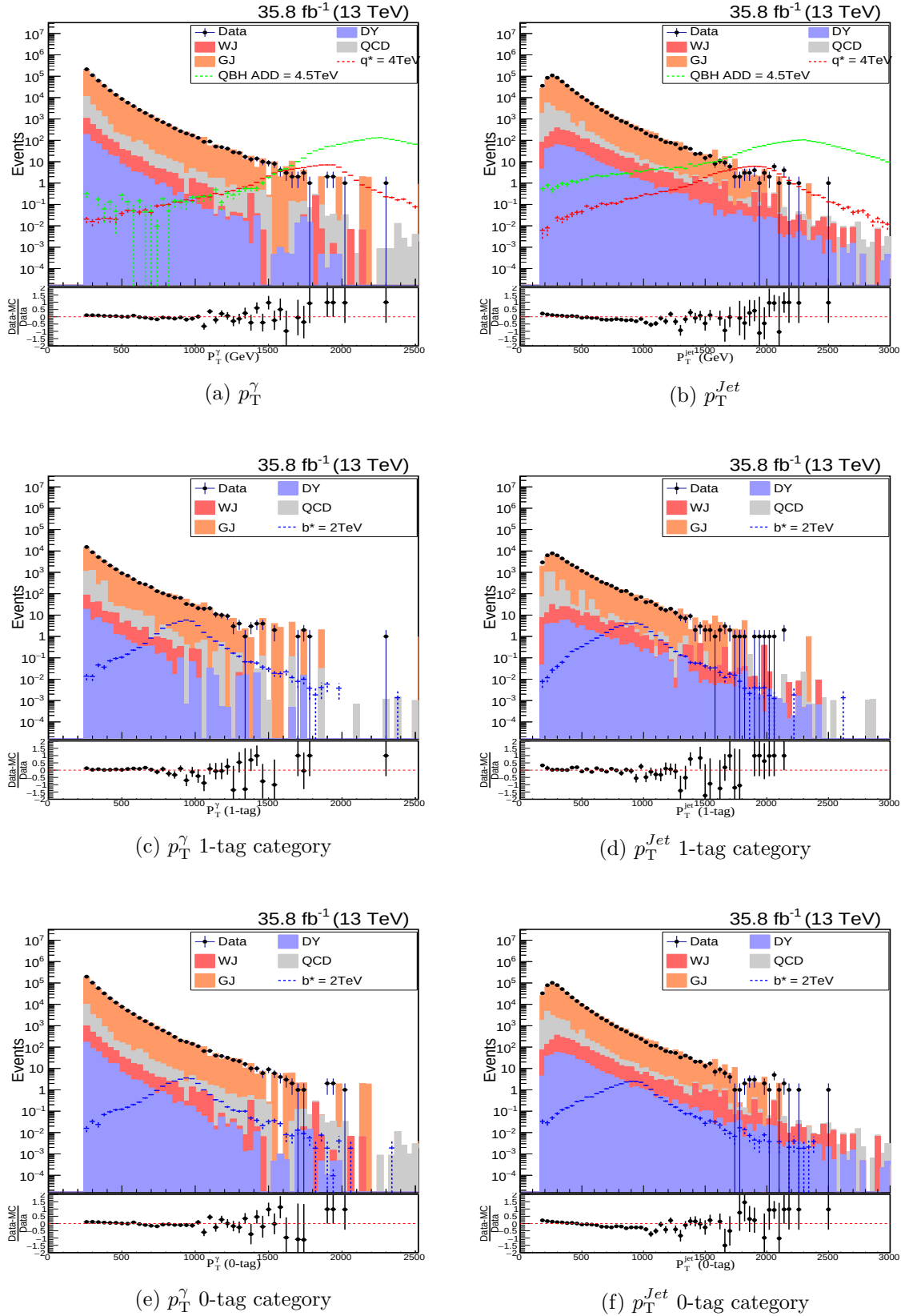


Figure 6.13: Data-MC comparison of p_T distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2016 data-taking year.

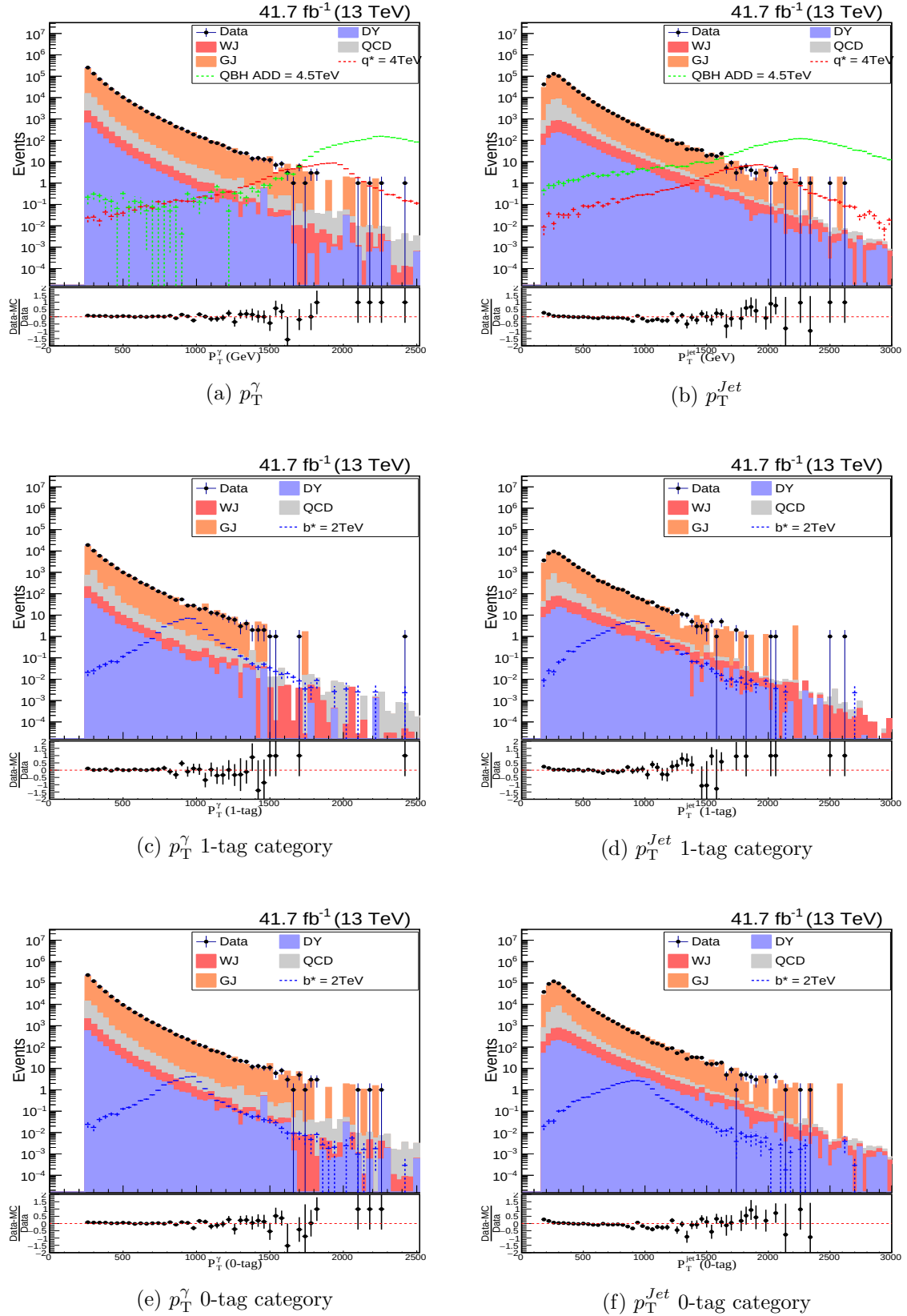


Figure 6.14: Data-MC comparison of p_T distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2017 data-taking year.

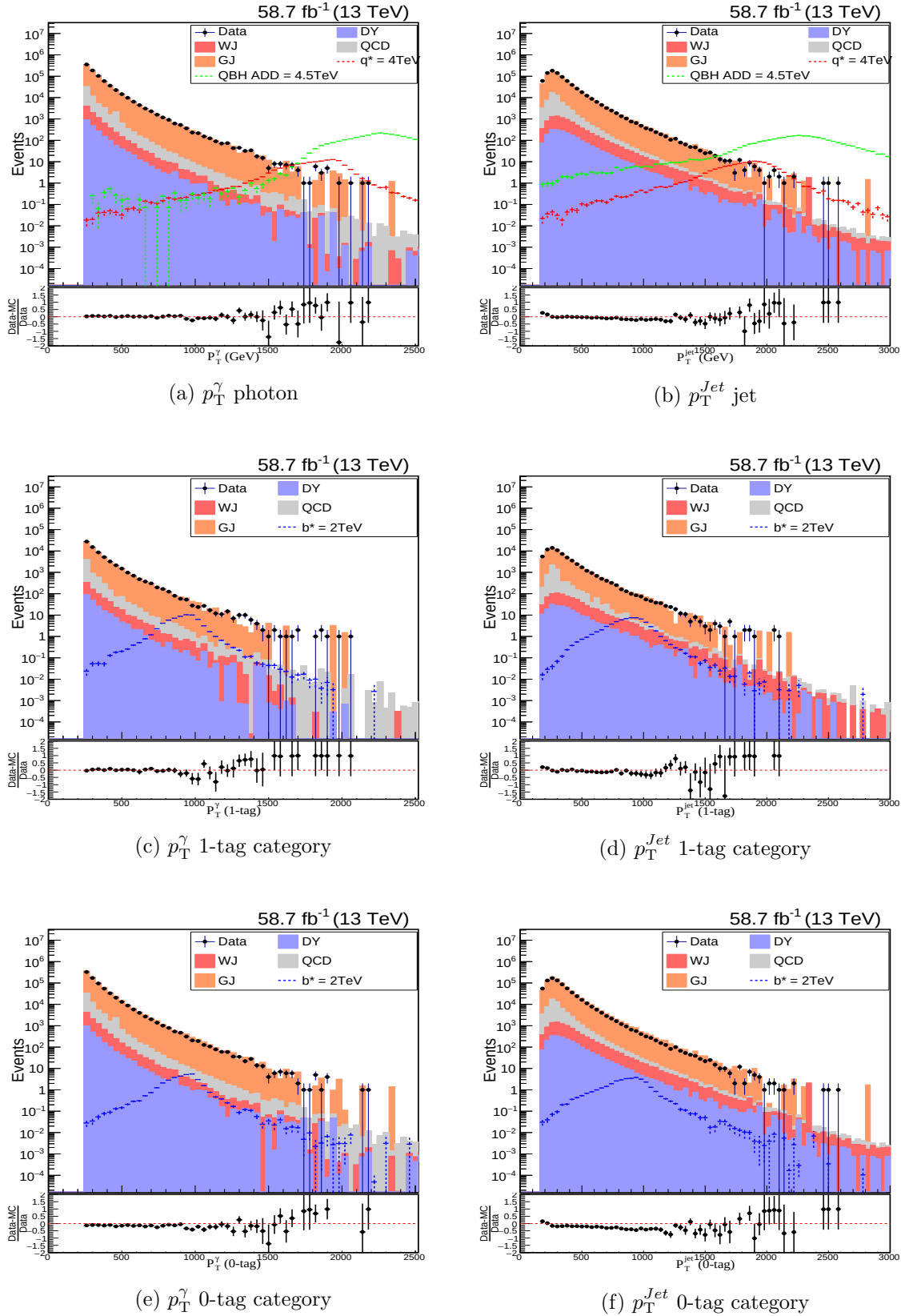


Figure 6.15: Data-MC comparison of p_T distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2018 data-taking year.

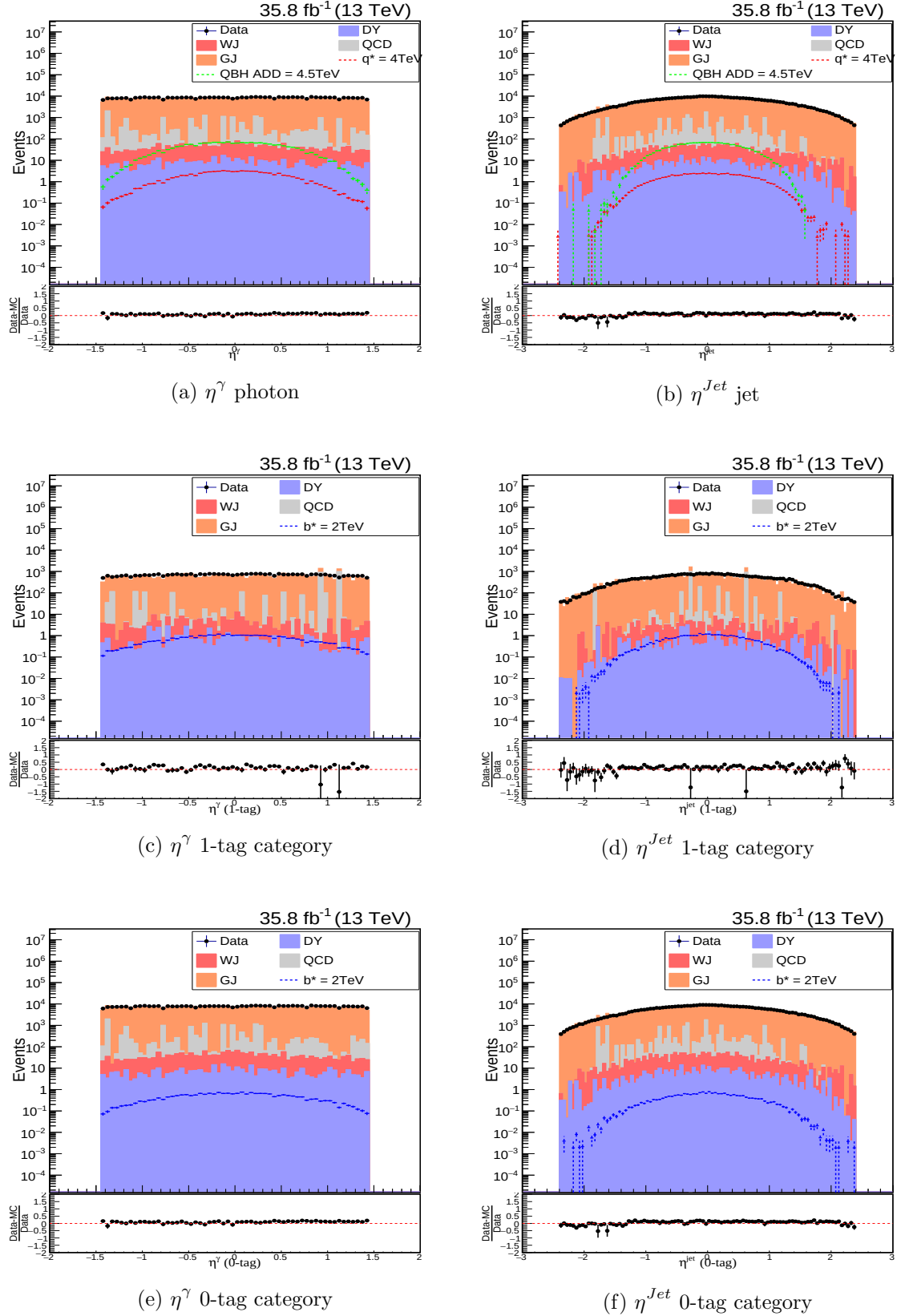


Figure 6.16: Data-MC comparison of η distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2016 data-taking year.

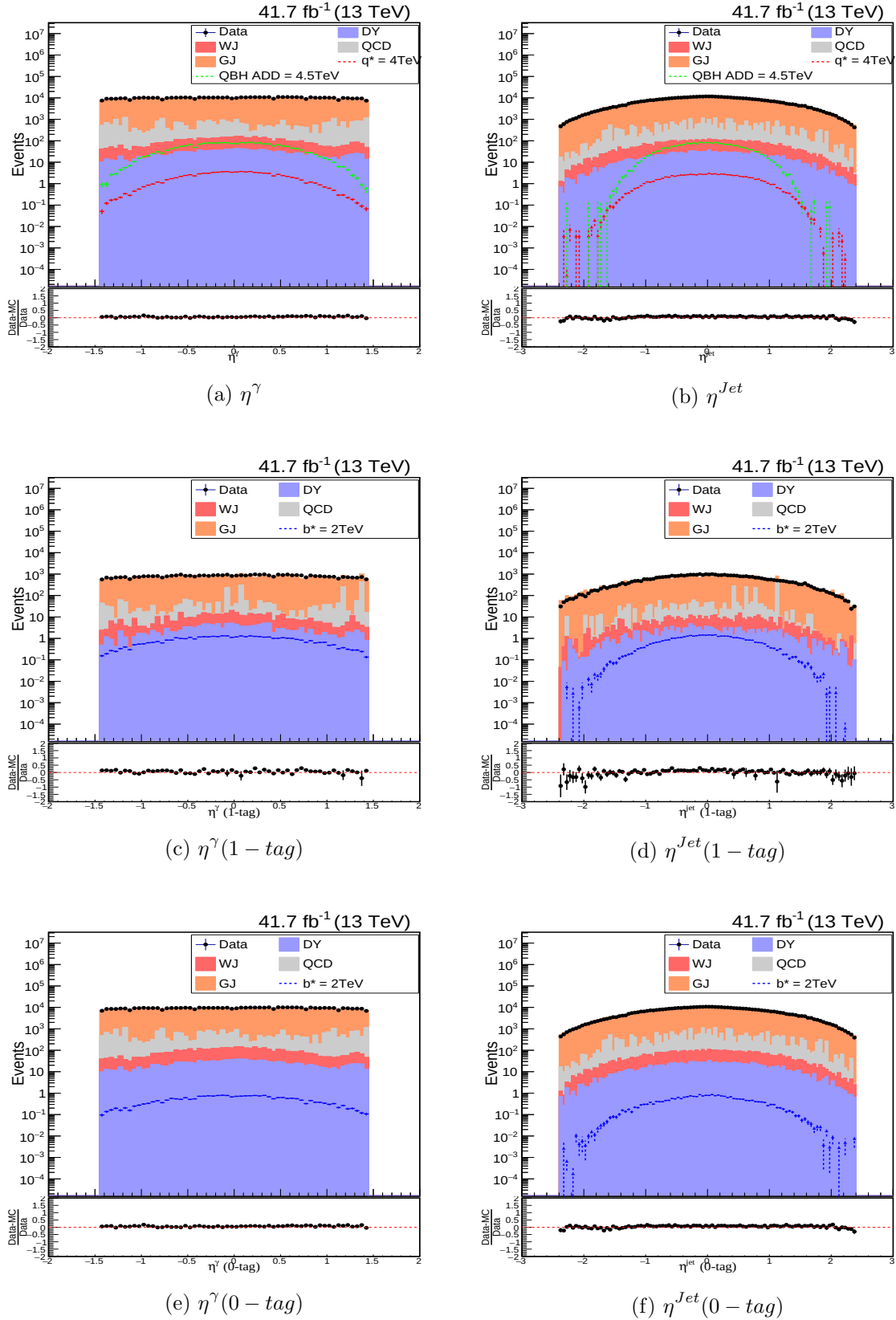


Figure 6.17: Data-MC comparison of η distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2017 data-taking year.

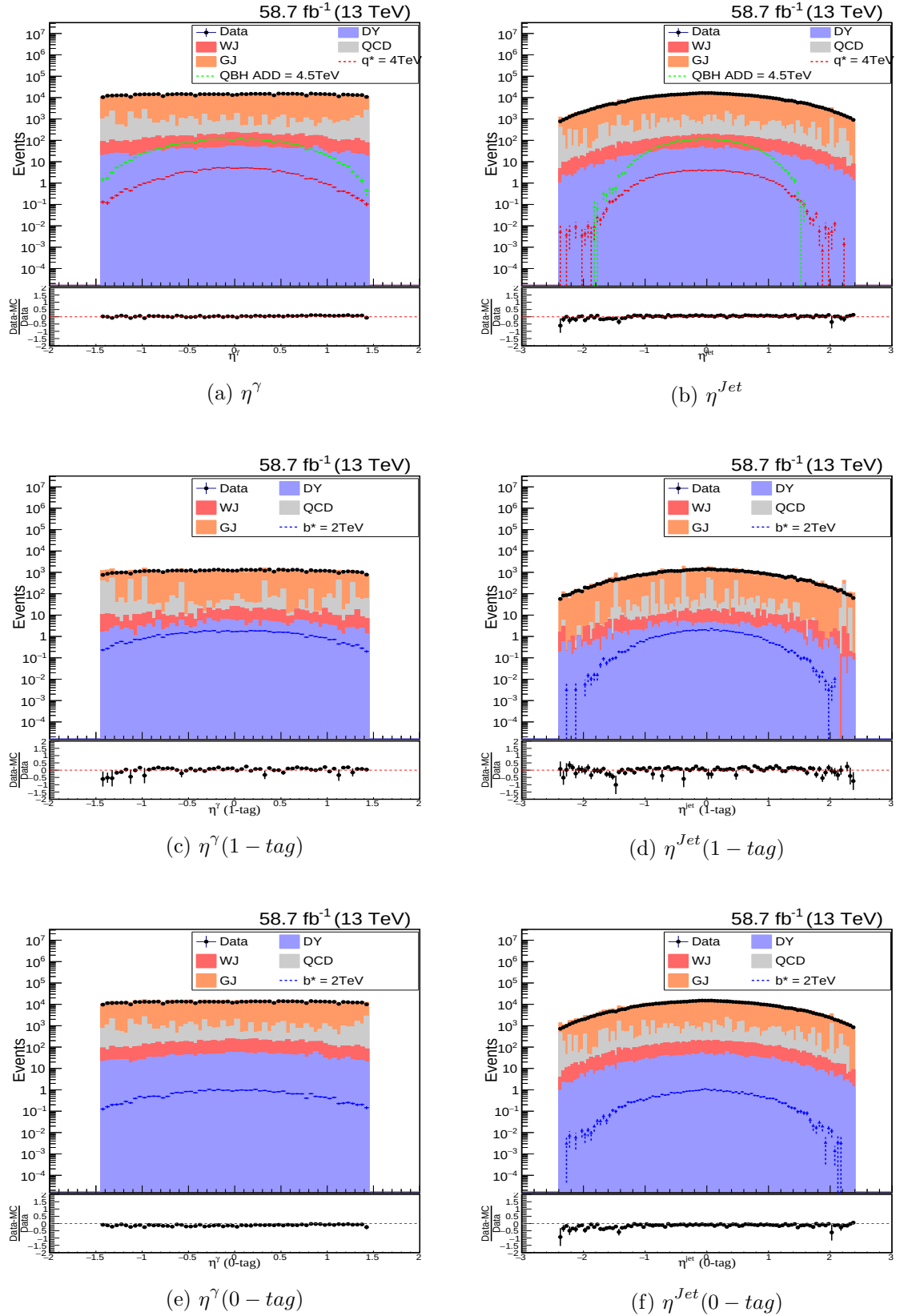


Figure 6.18: Data-MC comparison of η distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2018 data-taking year.

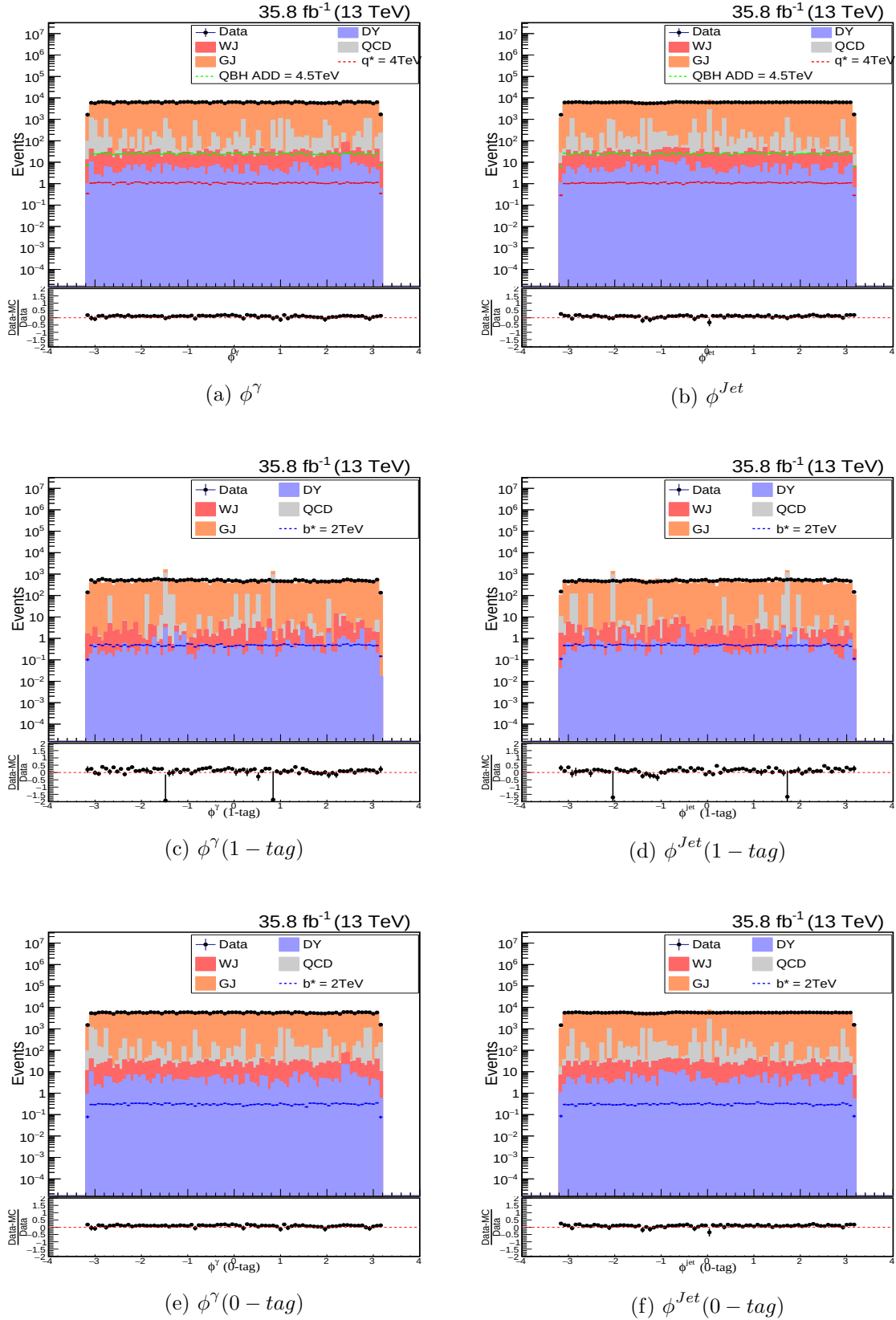


Figure 6.19: Data-MC comparison of ϕ distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2016 data-taking year.

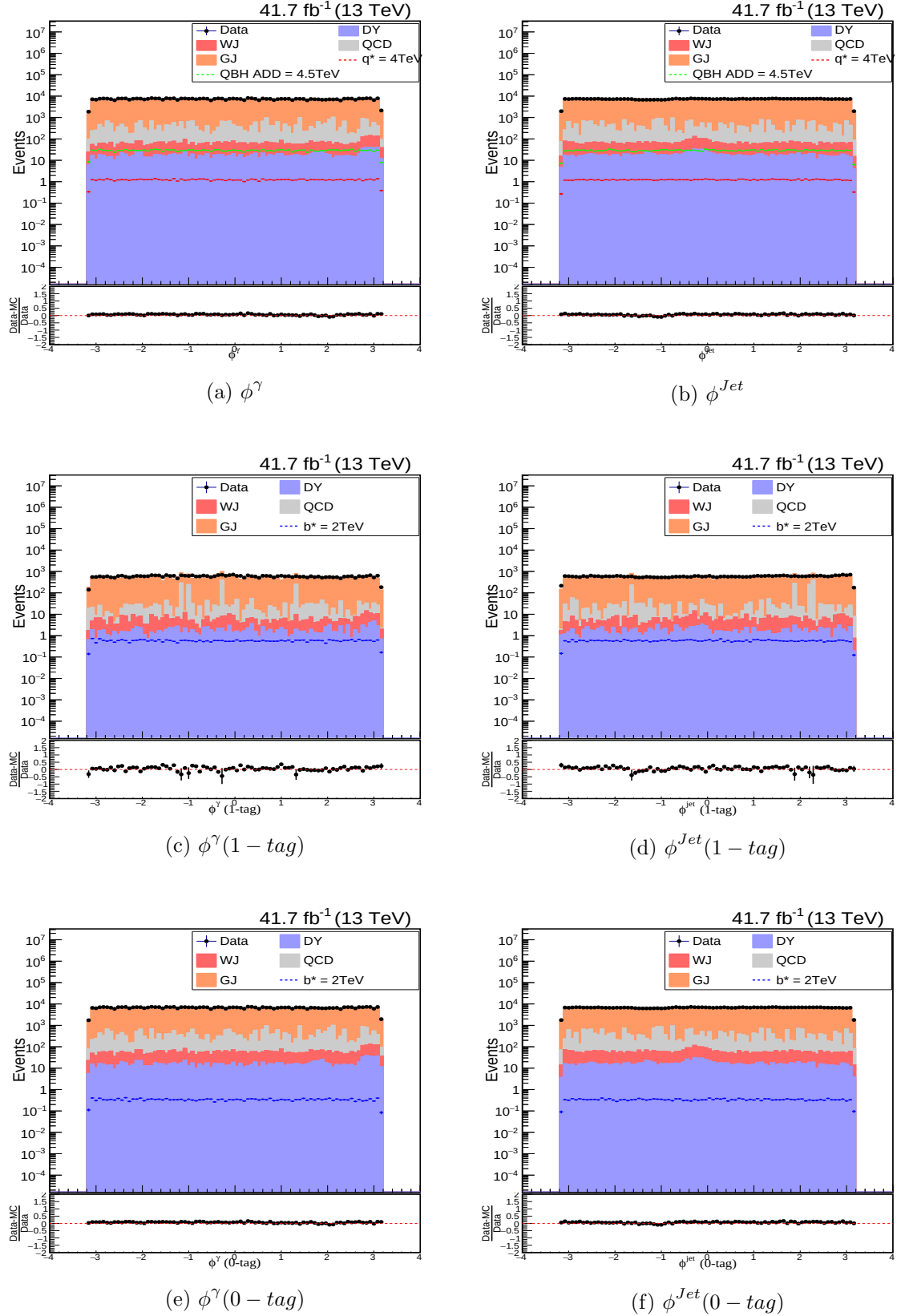


Figure 6.20: Data-MC comparison of ϕ distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2017 data-taking year.

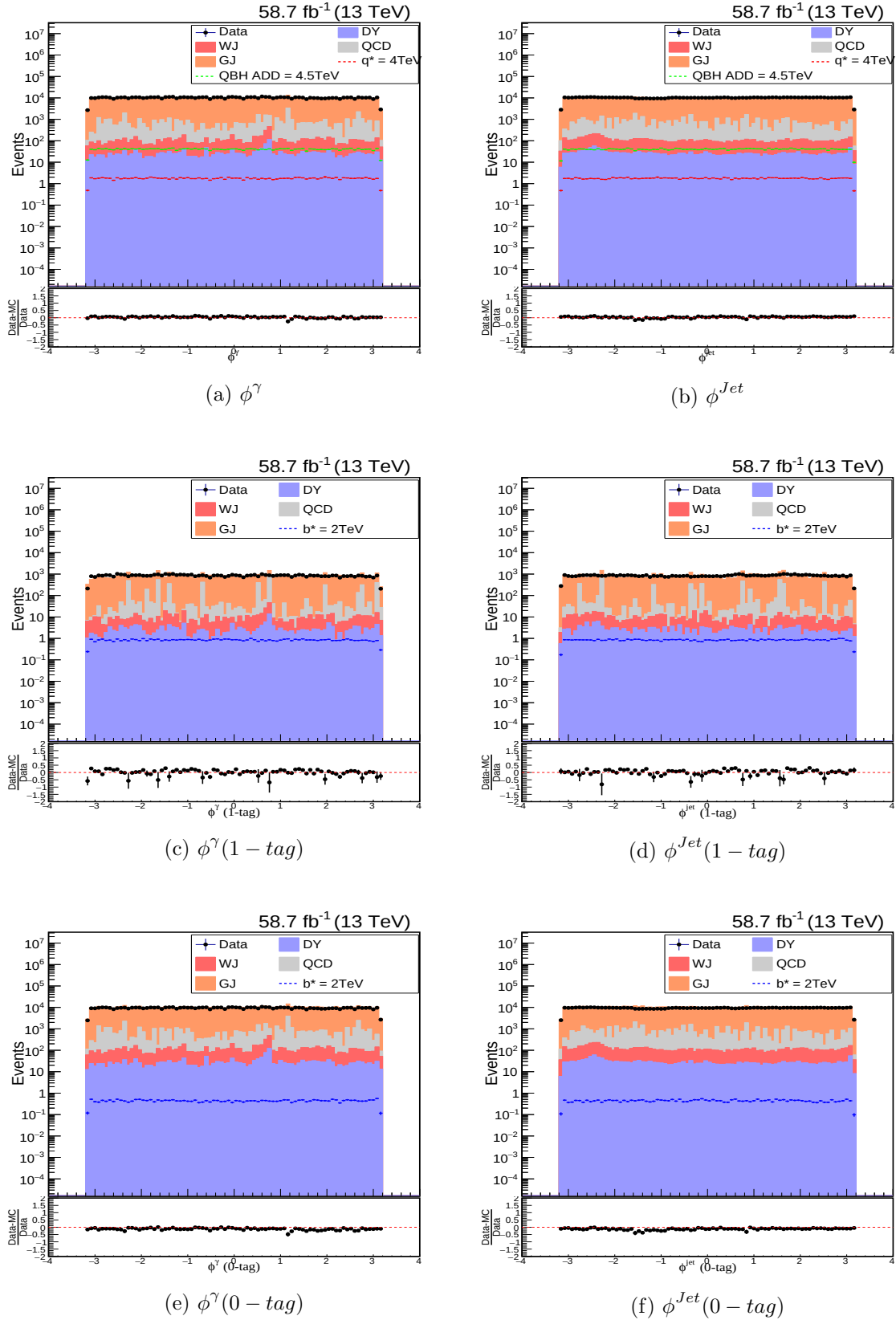


Figure 6.21: Data-MC comparison of ϕ distributions of leading photons and wide-jets in three categories: no-tag, 1-tag and 0-tag for 2018 data-taking year.

6.4 Optimization of Event Selection Criteria

To obtain the best possible results on the upper limit of the product of cross section and branching fraction, and on lower limit of signal mass, optimization studies are performed to finalize the selections for photon and jet, and on γ +jet system as well. These studies are performed using MC simulations since data is blinded following the analysis strategy. The optimization is done for the below mentioned selections :

- Photon identification working point
- DeepJet discriminator working point
- Wide-jet p_T
- $|\Delta\eta|(\text{photon, wide-jet})$
- Mass threshold on γ +jet system

6.4.1 Photon Identification Working Point

For photon identification (ID) selection, three working points (WP) “loose”, “medium” and “tight” with respective efficiencies of 90%, 80%, and 70% are considered for the optimization studies. The optimization studies tells that a loose WP is very slightly better at higher mass region in terms of upper limit of cross section, as shown in Fig 6.22. However, it is also true that mass limit are almost same. The flatness of signal efficiency with loose and medium ID as a function of photon p_T is also observed and shown in Fig 6.23. The medium is more or less flat and also since the expected limit does not differ much for loose and medium WPs, the medium WP is finalised. This also make sure that fake backgrounds do not sneak-in much in selected phase space for this analysis.

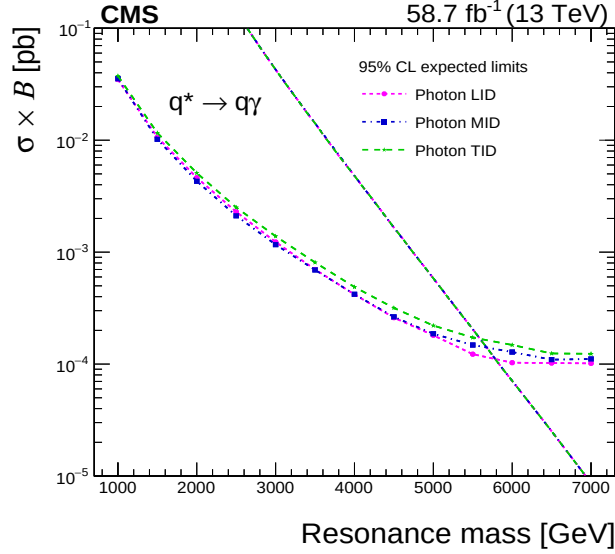


Figure 6.22: Expected 95% CL upper limits on $\sigma \times B$ for q^* resonance mass.

6.4.2 DeepJet Discriminator Working Point

Similar to the case of Photon ID, the optimization is performed for three WPs of DeepJet tagger to provide best performance in the b-jet selection. Fig 6.24 depicts the upper cross section limits, as a function of b^* resonance mass for all three WPs. The “tight” WP provides the best expected cross-section upper limits, but it also restricts the number of b-tagged jets selected. Hence to avoid the limited statistics, “medium” WP has been chosen as the final selection for the analysis, as excluded mass limit is same for both WPs.

6.4.3 $\Delta\eta$ and Mass Threshold

To further suppress the background contribution, $\Delta\eta$ between photon and wide-jet is applied since the background from t-channel processes are mostly in forward and backward directions. The $\Delta\eta$ selections ensures reduction in background events, while maintaining signal events efficiency. An optimization studies for $\Delta\eta$ cut is done considering four different $\Delta\eta$ values i.e $|\Delta\eta| < 1.5$, $|\Delta\eta| < 1.8$, $|\Delta\eta| < 2.0$ and with no $|\Delta\eta|$ applied. Additionally, corresponding to these $|\Delta\eta|$ values, a jet

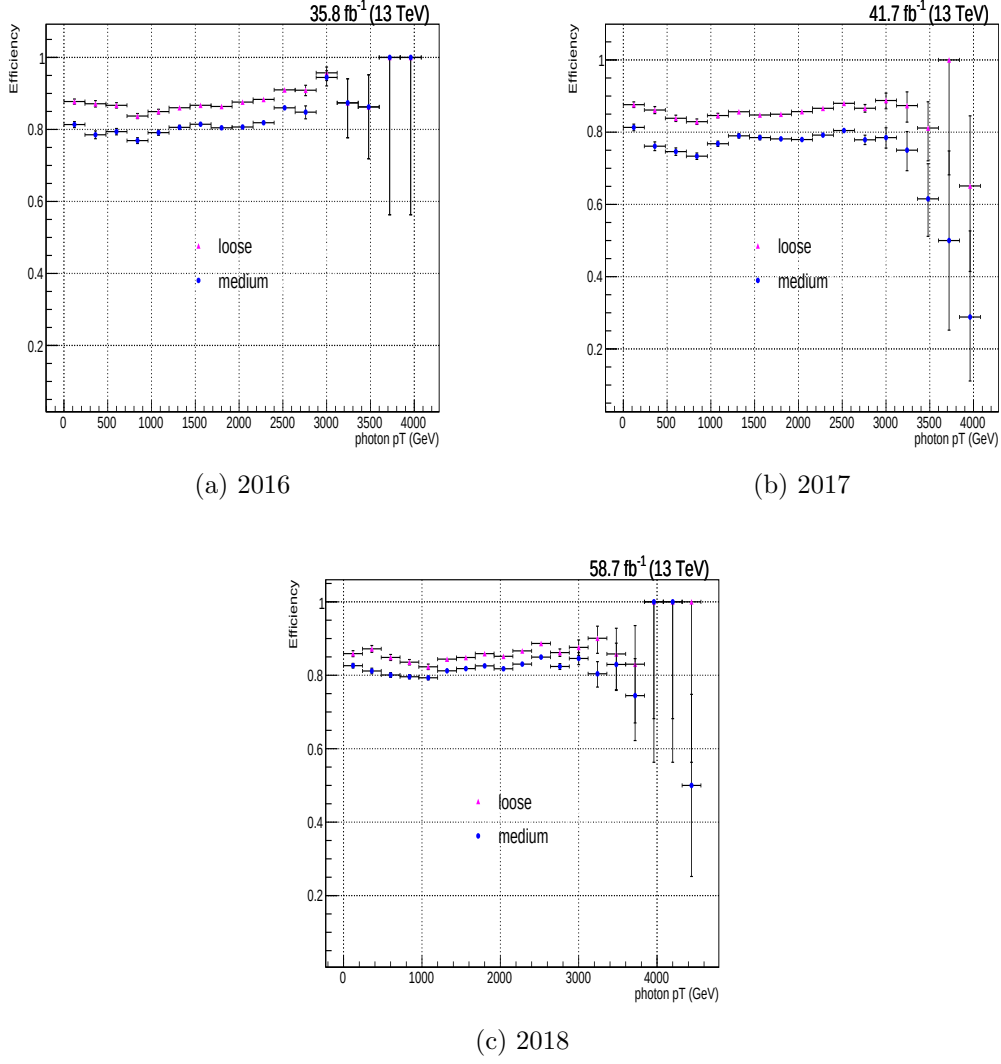


Figure 6.23: Efficiencies of various photon identification criteria as functions of photon p_T in barrel region for q^* signal $m_{\gamma+\text{jet}} = 5\text{TeV}$.

p_T selection is also optimized. As discussed in Section 6.3.4, the mass turn-on region in $m_{\gamma+\text{jet}}$ should not be considered to avoid the complexity in parameterizing the fit for $m_{\gamma+\text{jet}}$. The mass turn-on points are driven from the signal efficiency for a $|\Delta\eta|$ and jet p_T selection as a function of invariant mass (shown in Fig 6.25). As a result, there are different mass thresholds corresponding to a $\Delta\eta$ and jet p_T cut, determined as the point where signal efficiency reaches 100%.

The best 95% expected limits are determined with different $\Delta\eta$ values and

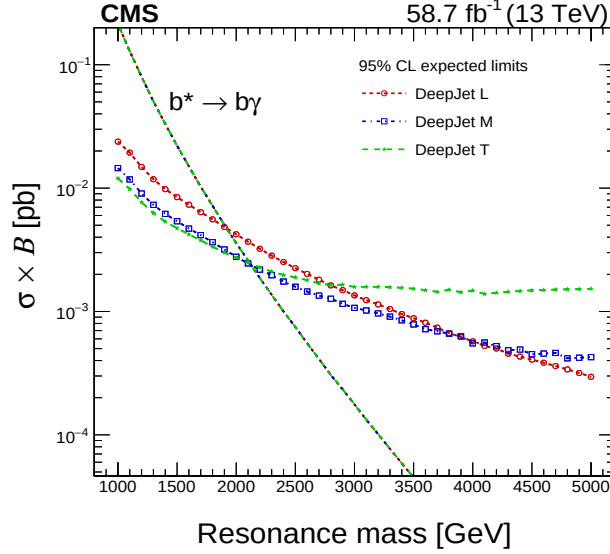


Figure 6.24: Expected 95% CL upper limits on $\sigma \times B$ for b^* resonance mass.

their corresponding jet p_T and mass thresholds. The limits are shown in fig 6.26 for jet p_T 170 and 210 GeV. From the Table 6.3, the selections jet $p_T > 170$ GeV, $|\Delta\eta| < 1.5$ and mass threshold of 760 GeV and the other combination of selection jet $p_T > 210$ GeV, $|\Delta\eta| < 1.5$ and mass threshold of 800 GeV shows best expected limits of 6.0 TeV. The former selections offering wider phase-space is chosen as the final one for this analysis. It also promise more events which further help to constrained the fit at higher masses to evaluate the background shape from data.

Jet p_T (GeV)	$ \Delta\eta $ and $m_{\gamma+\text{jet}}$ (GeV) selection	Exp. Mass Limit (TeV)
> 170	$ \Delta\eta < 1.5, m_{\gamma+\text{jet}} > 760$	6.0
> 170	$ \Delta\eta < 1.8, m_{\gamma+\text{jet}} > 800$	5.92
> 170	$ \Delta\eta < 2.0, m_{\gamma+\text{jet}} > 800$	5.95
> 170	No $ \Delta\eta , m_{\gamma+\text{jet}} > 1213$	5.94
> 210	$ \Delta\eta < 1.5, m_{\gamma+\text{jet}} > 800$	6.0
> 210	$ \Delta\eta < 1.8, m_{\gamma+\text{jet}} > 881$	6.0
> 210	$ \Delta\eta < 2.0, m_{\gamma+\text{jet}} > 924$	5.96
> 210	No $ \Delta\eta , m_{\gamma+\text{jet}} > 1381$	5.94

Table 6.3: Jet p_T and $|\Delta\eta|$ optimization for Run-II with medium photon ID, tight jetID.

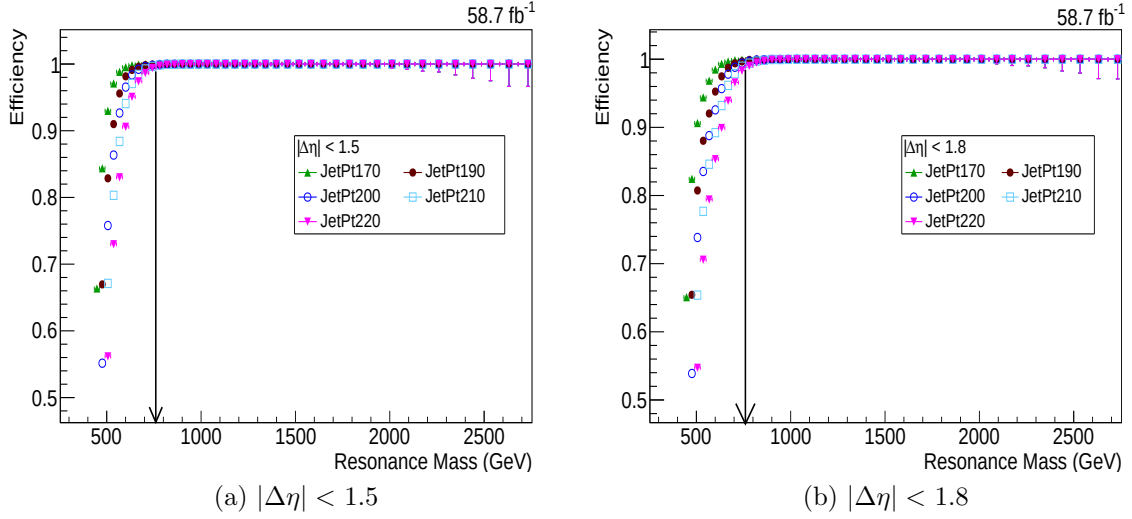


Figure 6.25: Mass turn-on efficiency curve for a) $|\Delta\eta| < 1.5$, and b) $|\Delta\eta| < 1.8$, with arrow indicating a mass threshold with 100% efficiency.

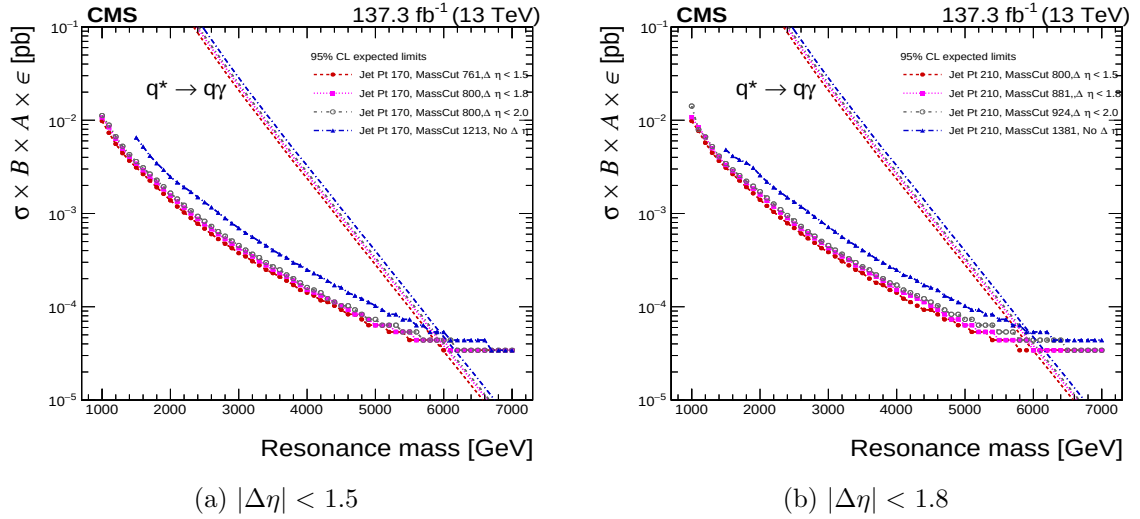


Figure 6.26: 95% expected limits for two $\Delta\eta$ values with different jet p_T and mass threshold derived from mass turn-on curve.

6.5 Selections summarized

The analysis is divided into two different categories based on selections applied: inclusive for q^*/QBH and exclusive categories for b^* signal searches. The exclusive category for b^* search is defined because of additional b-tagging condition applied. The selections applied in a sequence are summarized as:

- HLT trigger HLT_Photon175 and HLT_Photon200 are applied on data-taking year 2016 and 2017/2018 respectively.
- Photon passing identification with medium working point with $p_T^\gamma > 240$ GeV and $|\eta| < 1.4$
- AK4 jets passing identification criteria with tight working point
- Wide-jet constructed from AK4 jets with $\Delta R < 1.1$
- Leading wide-jet with $p_T > 170$ GeV and $|\eta| < 2.4$
- For b-tagging, “DeepJet” medium working point applied on b^* signal search only.
- $|\Delta\eta(\gamma, \text{wide-jet})| < 1.5$
- Minimum mass threshold of 760 GeV applied

With all the selections applied, the efficiencies of the signals are calculated at different mass points as the ratio of events passing all the kinematic selections to the initially generated events within detector acceptance. The product of the acceptance and efficiency for q^*/b^* and QBH (ADD/RS) signals is shown in the Fig 6.27 on left and right, respectively. As indicated from the 6.27a, the efficiency of the b^* for 1-btag category starts decreasing as moving towards higher mass points. This is primarily due to the tagger lower efficiency at higher jet p_T [4]. Similarly in case of QBH signal for ADD model, the efficiency starts reducing for masses $M_{th} > 5$ TeV due to photon identification criteria.

The cut flow table for data and backgrounds is presented in Table 6.4, 6.6, 6.8 for year 2016, 2017, and 2018 respectively. The cumulative efficiency of signals after each selection is presented in tabular form as well in Table 6.5, 6.7, and 6.9 for all three data-taking periods.

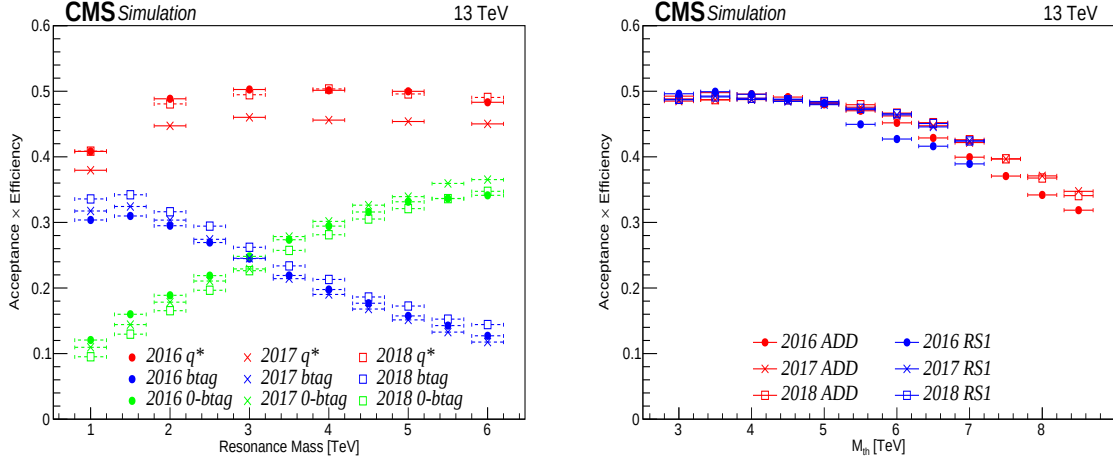


Figure 6.27: The product of acceptance and efficiency for the signals q^* in the inclusive category and b^* in btag and 0- tag category for SM coupling $f = 1.0$ (left), and the QBH (ADD/RS) model in the inclusive category for different threshold mass M_{th} (right) for the years 2016, 2017, and 2018.

Cuts	q^* 2.0 TeV	PhotonJet Bkg	DiJet Bkg	DrellYan Bkg	WJets	Total Bkg	Data
Total	18735.1	1.5756e+09	2.8707e+10	9.4650e+06	8.5543e+07	3.0376e+10	2.0578e+08
HLT	18735.1	1.5756e+09	2.8707e+10	9.4650e+06	8.5543e+07	3.0376e+10	3.6568e+07
MetFilters	18735.1	1.5756e+09	2.8707e+10	9.4650e+06	8.5543e+07	3.0376e+10	3.5206e+07
medium Photon ID	13718.9	6.8835e+08	6.9883e+07	7.4113e+05	3.2667e+06	7.6172e+08	3.4619e+06
$P_T^\gamma > 240$ GeV & $ \eta^\gamma < 1.4442$	12451.1	5.8026e+05	2.1578e+05	1138.30	3801.12	8.0064e+05	6.6247e+05
QCD Overlap Removal	12451.1	5.8005e+05	48780.02	1138.30	3801.12	6.3333e+05	6.6247e+05
Tight Jet ID	12446.7	5.7970e+05	47790.56	1138.30	3801.12	6.3200e+05	6.5766e+05
$P_T^{Jet} > 170$ GeV	12413.6	546334.13	45879.19	1115.94	3688.48	596609.54	6.0067e+05
$ \eta^{Jet} < 2.4$	12170.7	528064.34	44615.97	1107.63	3635.82	577028.12	5.8651e+05
$\Delta R > 1.1$	12166.3	505015.24	26671.63	537.11	2355.37	534201.72	5.8617e+05
$ \Delta\eta < 1.5$	8927.19	421256.38	18413.88	442.89	1975.07	441773.88	4.8597e+05
Mass > 760 GeV	8905.3	106366.91	3476.75	170.93	773.04	110708.12	110808

Table 6.4: Cut flow table for different selections with respect to total events for data, signal, and all contributing backgrounds for 2016 data-taking year

6.6 Background Parameterization

Following the discussion in Section 5.4, the background estimation is done using data by fitting the γ +jet invariant mass distribution with a smooth polynomial function. Since a mass threshold of 760 GeV is applied on the mass distribution to avoid the turn on region, it is expected to be a smoothly falling distribution. We consider numerous functions that are followed by many earlier searches also [5–9], to perform the data-driven background estimation. However, these functions should

Signal Resonances	q^*		b^*		ADD ($n = 6$)		RS($n = 1$)	
Cuts	2000	5000	2000	5000	2000	5000	2000	5000
Total	100	100	100	100	100	100	100	100
medium PhotonID	72.71	73.33	73.99	73.91	73.53	71.52	74.16	72.82
$P_T^\gamma > 240$ GeV & $ \eta^\gamma < 1.4442$	55.00	65.59	67.55	67.63	67.56	65.52	63.69	65.28
Tight JetID	54.95	65.57	67.51	67.62	67.54	65.51	63.66	65.25
$P_T^{Jet} > 170$ GeV	54.33	65.39	67.44	67.56	67.49	65.43	63.44	65.17
$ \eta^{Jet} < 2.4$	52.25	64.11	66.83	67.28	67.35	65.35	62.84	65.14
DeepJetM	—	—	37.85	25.53	—	—	—	—
$\Delta R > 1.1$	52.24	64.09	66.80	67.25	67.30	65.29	62.81	65.10
$ \Delta\eta < 1.5$	40.81	47.03	48.17	47.94	47.77	45.94	48.28	46.91
Mass > 760 GeV	39.11	46.91	48.13	47.93	47.76	45.91	47.23	46.91

Table 6.5: Selection efficiency (in %) table for 2016 data taking year for q^* , b^* signals for coupling multiplier value $f = 1.0$, and QBH signal for ADD ($n = 6$) and RS1 ($n = 1$) model for two mass points.

Cuts	q^* 2.0 TeV	PhotonJet Bkg	DiJet Bkg	DrellYan Bkg	WJets	Total Bkg	Data
Total	21773.0	1.6149E+09	2.8140E+10	1.4624E+07	1.0094E+08	2.9871E+10	1.08367E+08
HLT	21773.0	1.6149E+09	2.8140E+10	1.4624E+07	1.0094E+08	2.9871E+10	2.2851E+07
MetFilters	21773.0	1.6149E+09	2.8140E+10	1.4624E+07	1.0094E+08	2.9871E+10	2.28358E+07
medium Photon ID	15715.10	6.675E+08	6.7210E+07	6.9202E+05	2.3197E+06	7.3772E+08	2.2307E+06
$P_T^\gamma > 240$ GeV & $ \eta^\gamma < 1.4442$	14552.70	6.5023E+05	215171.93	1849.11	4908.41	8.7217E+05	7.7572E+05
QCD Overlap Removal	14552.70	6.5001E+05	51487.56	1849.11	4908.41	7.0826E+05	7.7572E+05
Tight Jet ID	14507.3	649274.98	50785.50	1848.24	4896.57	7.0680E+05	773780
$P_T^{Jet} > 170$ GeV	14443.5	614641.68	46616.27	1781.06	4660.11	667698.86	717084
$ \eta^{Jet} < 2.4$	14086.2	598619.58	44787.99	1750.59	4568.21	649726.60	706295
$\Delta R > 1.1$	14081.8	598323.20	44777.08	1749.63	4565.14	649414.83	705939
$\Delta\eta < 1.5$	10364.1	500756.18	29052.51	1491.05	3893.92	535193.19	584468
Mass > 760 GeV	10327.1	125524.23	6066.82	544.54	1304.27	133439.70	133440

Table 6.6: Cut flow table for different selections with respect to total events for data, signal, and all contributing backgrounds for 2017 data-taking year

qualify some quality check tests to assure that they represent the background shape in data. The functions are listed below:

1. $F_1 = \frac{P_0(1-m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3} \ln(m/\sqrt{s})}$
2. $F_2 = \frac{P_0(1+m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3} \log(m/\sqrt{s}) + P_4 \log^2(m/\sqrt{s})}$
3. $F_3 = \frac{P_0}{(P_1+P_2.m/\sqrt{s}+(m/\sqrt{s})^2)^{P_3}}$
4. $F_4 = P_0 \exp[P_1(m/\sqrt{s})^{P_2} + P_1(1-m/\sqrt{s})^{P_3}]$
5. $F_5 = \frac{P_0(1-m/\sqrt{s})^{P_1}(1+P_4(m/\sqrt{s})+P_5(m/\sqrt{s})^2)}{(m/\sqrt{s})^{P_2+P_3} \log(m/\sqrt{s})}$

Signal Resonances	q^*		b^*		ADD ($n = 6$)		RS($n = 1$)	
Cuts	2000	5000	2000	5000	3000	5000	2000	5000
Total	100	100	100	100	100	100	100	100
medium PhotonID	71.50	72.18	72.78	72.20	72.22	71.91	72.54	72.79
$P_T^\gamma > 240$ GeV & $ \eta^\gamma < 1.4442$	56.29	66.70	68.47	68.18	68.26	68.18	64.22	67.14
Tight JetID	56.14	66.62	68.42	68.15	68.23	68.15	64.16	67.10
$P_T^{Jet} > 170$ GeV	55.47	66.33	68.25	68.05	64.16	68.08	63.88	67.03
$ \eta^{Jet} < 2.4$	52.91	64.69	67.43	67.58	67.92	67.91	63.14	66.96
DeepJetM	–	–	39.99	25.82	–	–	–	–
$\Delta R > 1.1$	52.90	64.67	67.41	67.55	67.87	67.86	63.10	66.93
$ \Delta\eta < 1.5$	41.85	47.60	48.83	48.37	48.14	47.75	47.48	48.45
Mass > 760 GeV	40.26	47.43	48.80	48.35	48.13	47.74	47.72	48.44

Table 6.7: Selection efficiency (in %) table for 2017 data-taking year q^* , b^* signals for coupling multiplier value $f = 1.0$, and QBH signal for ADD ($n = 6$) and RS1 ($n = 1$) model for two mass points.

Cuts	q^* 2.0 TeV	PhotonJet Bkg	DiJet Bkg	DrellYan Bkg	WJets	Total Bkg	Data
Total	30656.6	2.1536e+09	3.1113e+11	1.5870e+07	1.3570e+08	3.1344e+11	1.3125e+09
HLT	30656.6	2.1536e+09	3.1113e+11	1.5870e+07	1.3570e+08	3.1344e+11	4.1960e+07
MetFilters	30656.6	2.1536e+09	3.1113e+11	1.5870e+07	1.3570e+08	3.1344e+11	4.0666e+07
medium Photon ID	22156.7	8.6953e+08	7.6863e+07	5.7873e+05	2.3473e+06	9.4932e+08	3.8061e+06
$P_T^\gamma > 240$ GeV & $ \eta^\gamma < 1.4442$	20458.2	9.1987e+05	286570.54	2617.20	8272.70	1.2173e+06	1.1059e+06
QCD Overlap Removal	20458.2	9.1961e+05	78501.65	2617.20	8272.70	1.0090e+06	1.1059e+06
Tight Jet ID	20428.0	918384.34	78153.14	2613.40	8244.40	1.0074e+06	1.1037e+06
$P_T^{Jet} > 170$ GeV	20330.7	869142.05	73115.49	2503.60	7880.80	952642.46	1.0190E+06
$ \eta^{Jet} < 2.4$	19832.7	846924.48	70309.23	2457.60	7719.80	927411.38	988592
$\Delta R > 1.1$	19827.5	846538.29	70308.73	2456.20	7715.10	927016.61	977027
$\Delta\eta < 1.5$	14528.5	710197.28	48774.17	2087.90	6542.60	767602.38	809675
Mass > 760 GeV	14486.9	172357.21	7919.00	727.28	2178.80	183182.79	183215

Table 6.8: Cut flow table for different selections with respect to total events for data, signal, and all contributing backgrounds for 2018 data-taking year

Signal Resonances	q^*		b^*		ADD ($n = 6$)		RS($n = 1$)	
Cuts	2000	5000	2000	5000	3000	5000	2000	5000
Total	100	100	100	100	100	100	100	100
medium PhotonID	71.56	72.27	72.39	73.17	72.90	72.63	72.54	72.79
$P_T^\gamma > 240$ GeV & $ \eta^\gamma < 1.4442$	56.32	66.73	68.08	69.09	68.73	66.97	64.22	67.14
Tight JetID	56.18	66.64	68.03	69.06	68.69	66.93	64.16	67.10
$P_T^{Jet} > 170$ GeV	55.56	66.32	67.85	68.97	68.60	66.84	63.88	67.03
$ \eta^{Jet} < 2.4$	53.09	64.69	66.99	68.56	68.39	66.77	63.14	66.96
DeepJetM	–	–	41.64	28.20	–	–	–	–
$\Delta R > 1.1$	53.08	64.68	66.97	68.52	68.35	66.74	63.10	66.93
$ \Delta\eta < 1.5$	41.89	47.42	48.53	49.30	48.49	48.32	47.78	48.45
Mass > 760 GeV	40.36	47.26	48.49	49.28	48.48	48.32	47.72	48.44

Table 6.9: Selection efficiency (in %) table for 2017 data-taking year q^* , b^* signals for coupling multiplier value $f = 1.0$, and QBH signal for ADD ($n = 6$) and RS1 ($n = 1$) model for two mass points.

where P_0 , P_1 , P_2 , P_3 and P_4 are the parameters of the function, m is the invariant mass of γ +jet distribution and $\sqrt{s}$ is the center-of-mass energy. To perform the quality check of fit functions, two test-statistics approaches used are discussed below in detail.

6.6.1 Fisher-test

The polynomial degree of the functions for signal fitting is decided on the basis of Fisher-test [10], also known as F-test. To start with this test, two models m_1 and m_2 (or functions) with parameters n_1 and n_2 respectively are examined, where $n_1 < n_2$ and model m_1 is nested within model m_2 . If the F-test statistic value for such case has the p -value significance [11] greater than 0.05, then it is interpreted that model m_1 is describing the distribution better than m_2 and is considered for further study in the analysis. However, if that is not the case then another model m_3 with higher degree than m_2 is taken to perform the same test again with respect to model m_2 .

The F-test statistics is constructed as

$$F = \frac{-2\log(\lambda_1/\lambda_2)/(n_2 - n_1)}{-2\log\lambda_2/(N_{bins} - n_2)}, \quad (6.5)$$

where N_{bins} is the number of mass bins and $-2\log(\lambda_i)$ is the “saturated model” goodness-of-fit test statistics that follows χ^2 distribution having $N_{bins} - n_i$ degrees of freedom.

In this statistic-test, a null hypothesis is considered that model m_1 (with n_1 parameters) better describes the mass distribution than model m_2 (with n_2 parameters). This null hypothesis is rejected if F-value obtained from data is greater than the critical value of F-distribution with p -value = 0.05. To obtain the F-distribution, the γ +jet invariant mass distribution from background MC simulation is fitted with model m_1 to get the best fit parameters. Afterwards, these parameters are used to generate a large number of toy datasets. The F-value is calculated for each toy-dataset and the F-distribution is obtained. The number of degree of freedom for this F-distribution is $n_2 - n_1$, $N_{bins} - n_2$. The list of the functions for different families

is given in the Table 6.10, and the corresponding F-value with the F-distribution is shown in Fig 6.28, 6.29 for q^* and b^* signals respectively.

Number of Parameters	F1
4	$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1+m/\sqrt{s})^{P_1}}{m/\sqrt{s}^{P_2+P_3\log(m/\sqrt{s})}}$
5	$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1+m/\sqrt{s})^{P_1}}{m/\sqrt{s}^{P_2+P_3\log(m/\sqrt{s})+P_4\log^2(m/\sqrt{s})}}$
6	$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1+m/\sqrt{s})^{P_1}}{m/\sqrt{s}^{P_2+P_3\log(m/\sqrt{s})+P_4\log^2(m/\sqrt{s})+P_5\log^3(m/\sqrt{s})}}$
—	F2
3	$\frac{d\sigma}{dm_{jj}} = \frac{P_0}{(P_1+m/\sqrt{s})^{P_2}}$
4	$\frac{d\sigma}{dm_{jj}} = \frac{P_0}{(P_1+P_2.m/\sqrt{s}+(m/\sqrt{s})^2)^{P_3}}$
5	$\frac{d\sigma}{dm_{jj}} = \frac{P_0}{(P_1+P_2.m/\sqrt{s}+P_3.(m/\sqrt{s})^2)^{P_4}}$
—	F3
4	$\frac{d\sigma}{dm_{jj}} = P_0 \exp[P_1(m/\sqrt{s})^{P_2} + P_1(1-m/\sqrt{s})^{P_3}]$
5	$\frac{d\sigma}{dm_{jj}} = P_0 \exp[P_1(m/\sqrt{s})^{P_2} + P_3(1-m/\sqrt{s})^{P_4}]$
—	F4
6	$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}(1+P_4x+P_5x^2)}{x^{P_2+P_3\log(x)}}$
7	$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}(1+P_4x+P_5x^2+P_6x^3)}{x^{P_2+P_3\log(x)}}$

Table 6.10: Different functions tested for fitting mass distribution using F-test statistics

6.6.2 Goodness-of-fit test

In order to evaluate if the γ +jet distribution can be characterized by the functions F1-F5 defined in Section 6.6, the Goodness-of-Fit (GOF) statistic is performed that is based on modified χ^2 test-statistic. It is defined as

$$\chi^2 = \sum_{i=1}^{n_b} \left(\frac{x_i - b_i}{\sigma_{x_i}} \right)^2, \quad (6.6)$$

where, x_i is the data yield in the i^{th} bin with total of n_b bins, b_i is the total number of expected events multiplied by the integral of fit in the i^{th} bin, σ_{x_i} is the

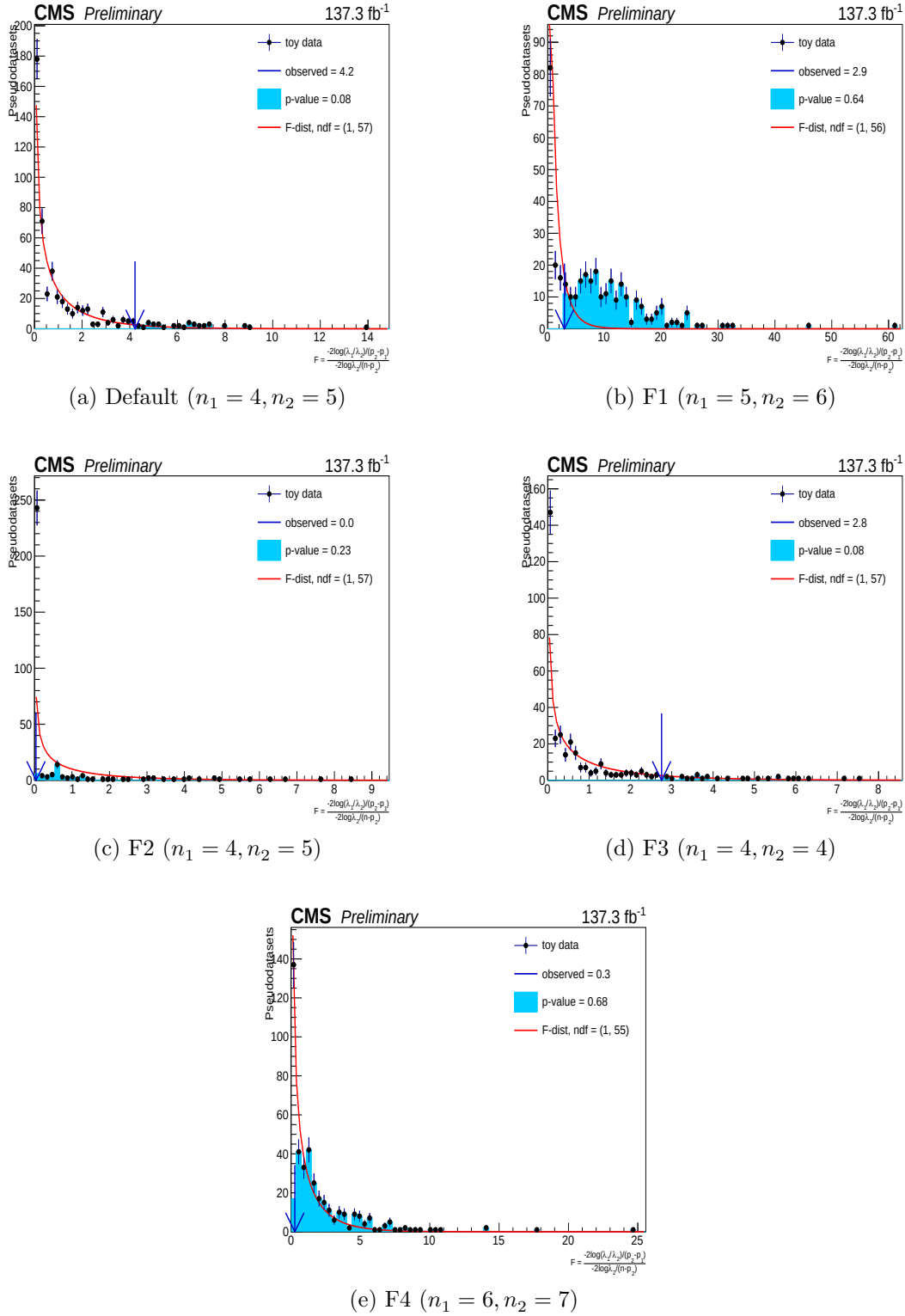


Figure 6.28: The F-test distributions for various background fit functions considered for q^* for full Run-II data.

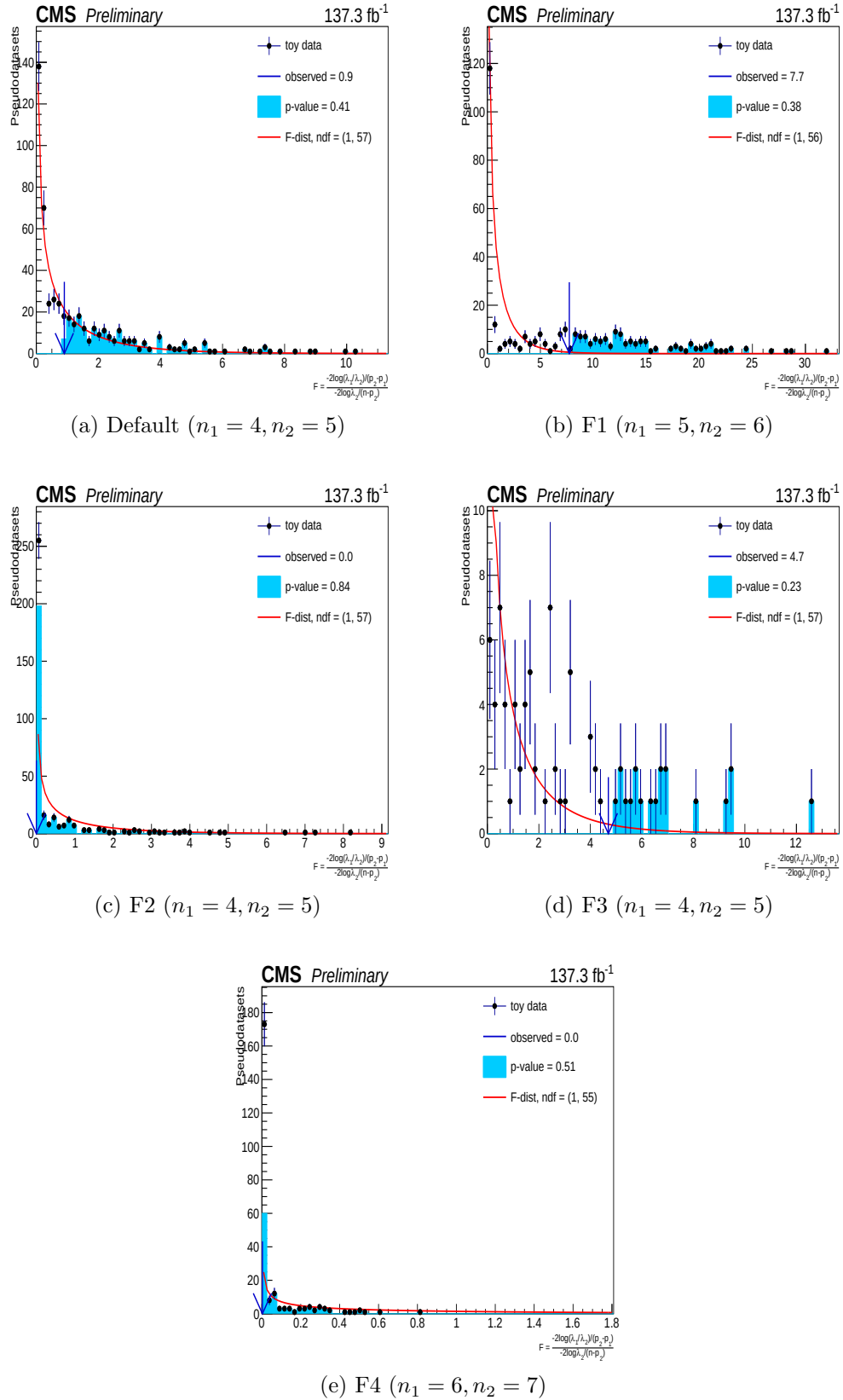


Figure 6.29: The F-test distributions for various background fit functions considered for b^* for full Run-II data.

uncertainty defined as

$$\sigma_{x_i} = \begin{cases} D_c^{-1}(\alpha/2, x_i + 1), & \text{if } b_i > x_i \\ D^{-1}(\alpha/2, x_i), & \text{if } b_i < x_i \end{cases} \quad (6.7)$$

where $\alpha = 1 - 0.687$ and $D^{-1}(\alpha/2, x_i)$ is the inverse of the cumulative distribution function of lower tail of gamma distribution, described as

$$D(\alpha/2, x_i) = \int_{-\infty}^{\alpha/2} \frac{1}{\Gamma(x_i)} z^{x_i-1} e^{-z} dz, \quad (6.8)$$

and, $D_c^{-1}(\alpha/2, x_i + 1)$ is the inverse of the cumulative distribution function (upper tail) of the gamma distribution,

$$D_c(\alpha/2, x_i + 1) = \int_{\alpha/2}^{+\infty} \frac{1}{\Gamma(x_i + 1)} z^{x_i} e^{-z} dz. \quad (6.9)$$

In order to perform this test, we generated 1000 toy-datasets using the best-fit model parameters from the fit performed on data. These toy-datasets are fitted using maximum likelihood approach and the test-statistic value is saved to have a distribution of χ^2 value. A p -value significance is calculated by taking the ratio of number of toys having the test statistic value greater than the same value from the data to the total number of toys, and if this p -value is greater than 0.05 then it indicates a reasonable agreement between the data and model defined by functions. The same distribution of test-statistic value for the data and toys is shown in Fig 6.30 and 6.31 for both inclusive and exclusive categories.

From the results of the F-test and GOF test, it is evident that all the functions fit and describe the mass distribution in data reasonably good, however only one of the function is chosen for background estimation i.e F1 defined as

$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3 \ln(m/\sqrt{s})}} \quad (6.10)$$

and, other functions F2-F5 are used as alternate functions for the bias studies, discussed in the following Section 6.7. The function F1 will now be referred as

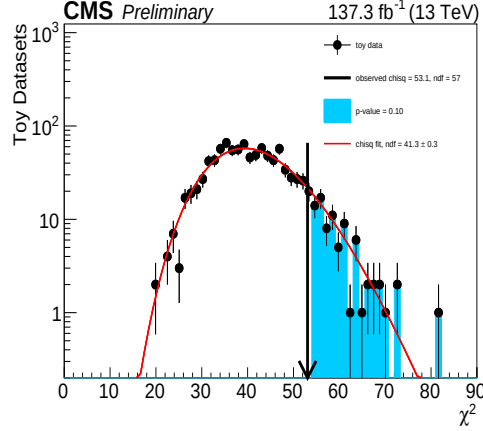


Figure 6.30: Toy distribution for the goodness-of-fit study using the χ^2 test statistic for q^* signal.

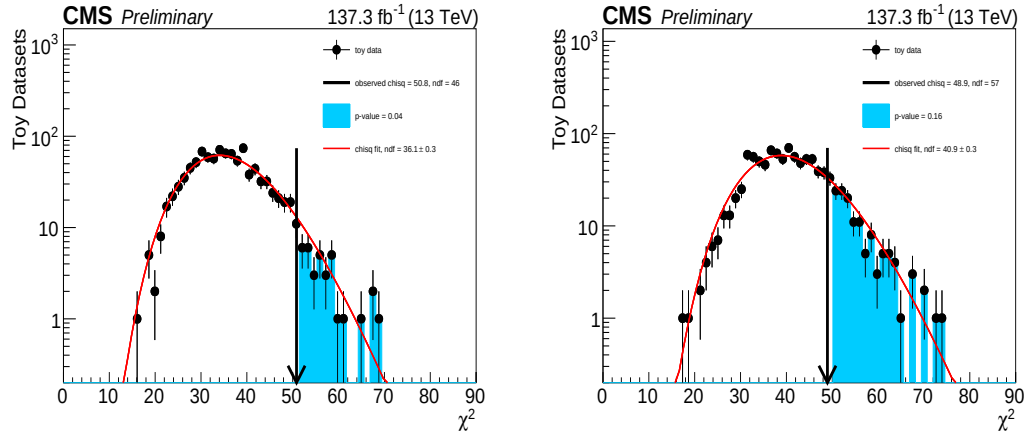


Figure 6.31: Toy distribution for the goodness-of-fit study using the χ^2 test statistic for b^* signal with 1-btag (left) and 0-btag(right) categories.

default function in the upcoming sections.

The mass distribution of q^*/QBH signals and b^* for both categories 1-tag and 0-tag fitted with the function eq 6.10 is shown in Fig. 6.32.

6.7 Bias due to the choice of fit functions

The fit function chosen for background estimation for both the exclusive and inclusive categories is defined in eq. 6.10. The alternative functions F2-F5 also rea-

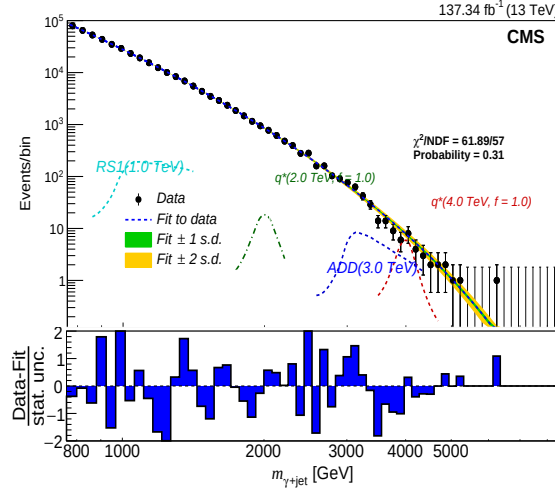
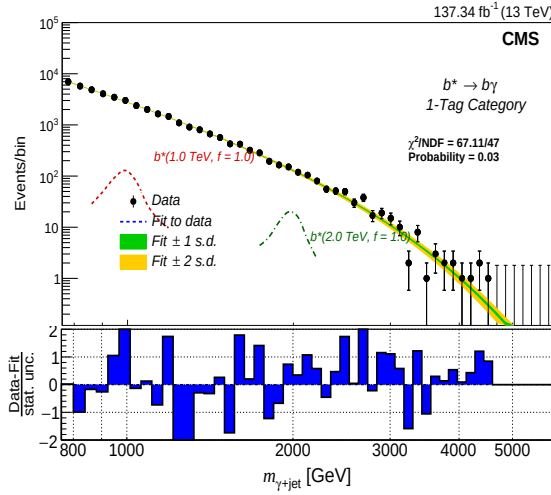
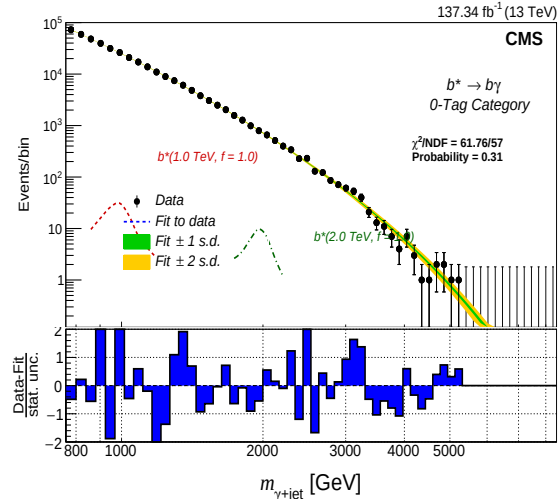
(a) $q^* \rightarrow q\gamma$ (b) $b^* \rightarrow b\gamma$ (c) $b^* \rightarrow b\gamma$

Figure 6.32: Invariant mass distribution fitted with 4-parameter fit function for (a) q^* (top), (b) 1 tag b^* (bottom left) and (c) 0 tag b^* (bottom right) scenarios fitted with ROOT likelihood.

sonably fit the distribution for both the categories, as assured by F-test and GOF test. Despite qualifying these test-statistics, there are uncertainties associated with the choice of the functional form and should be taken care of by performing bias studies with the alternative functions. If any significant bias due to the chosen function is observed, it is considered as the systematic uncertainty. The procedure of

performing this bias studies is as follows :

- An underlying distribution $g(m_{\gamma+jet})$ is obtained from the invariant mass distribution $m_{\gamma+jet}$ (inclusive) and $m_{\gamma+b-jet}$ (exclusive) categories of data.
- A signal having input mass m and signal strength $\mu = 1$ is injected to perform the signal plus background (S+B) fit on the distribution $g(m_{\gamma+jet})$ using the default function.
- From the S+B fit, the best fit parameters are obtained and are further used to generate 500 toys corresponding to each function F2-F5.
- These toy datasets for each alternate function are then fitted with the default function using the maximum likelihood approach to obtain a distribution $\hat{f}_i(m_{\gamma j})$, for each alternative function where $i = 1, 2, 3, 4$.
- The signal strength $\hat{\mu}_i$ is evaluated from $\hat{f}_i(m_{\gamma j})$ distributions and compared with the injected signal strength $\mu = 1$ for all input masses m , and a pull distribution is constructed

$$p_i^j = \frac{\hat{\mu}_i^j - \mu}{\sigma_{\mu_i^j}} \quad (6.11)$$

where $\sigma_{\mu_i^j}$ is uncertainty associated with the calculated signal strength from alternative functions.

- The pull distribution for each input mass and alternative function is fitted with a Gaussian function to get the predicted value of signal strength μ .
- For the ideal case, the mean and rms value of the pull distribution should be 0 and 1, respectively representing a normal distribution. However, any deviation from 0 mean value is the indication of the bias due to the choice of the function.

The pull distribution for two mass points $M_{q^*} = 1.0$ and 2.0 TeV of q^* signal when same function is used for generating and fitting the toys is presented in Fig 6.33. The mean of distribution is observed to be close to zero for both masses.

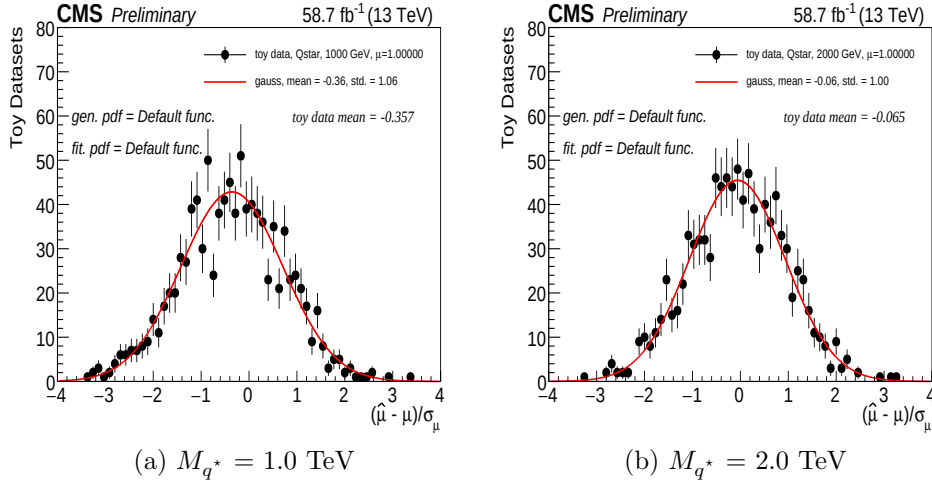


Figure 6.33: Gaussian fit to the pulls distribution by generating and fitting toys using the same function.

The bias for any background parameterization following the relation,

$$b^j = |\text{median}(p_i^j)| < 0.5 \quad (6.12)$$

is acceptable, where p_i^j is the mean of Gaussian distribution for the i^{th} toy and j^{th} mass point. Any deviation of median of pulls from 0.5 is an indication of significant bias. Fig 6.34 shows the pull distributions for few mass points of the alternative functions, where it is clear that value of b^j is within the range of -0.5 and 0.5. Similar studies is performed by considering a different signal strength of $\mu = 0$, and in that case as well the bias is in the acceptable range having median less than 0.5.

To evaluate the impact of bias on the signal cross-section, the bias uncertainty is added in quadrature with the total uncertainty which has maximum contribution from background fit. In such case, if the bias uncertainty is about one-half of the fit uncertainty, then the total uncertainty will be:

$$\sigma^{tot} = \sqrt{\sigma_{fit}^2 + 0.5\sigma_{fit}^2} \sim 1.1\sigma_{fit} \quad (6.13)$$

Hence, the bias uncertainty contributes only 10% of the fit uncertainty and

can be neglected.

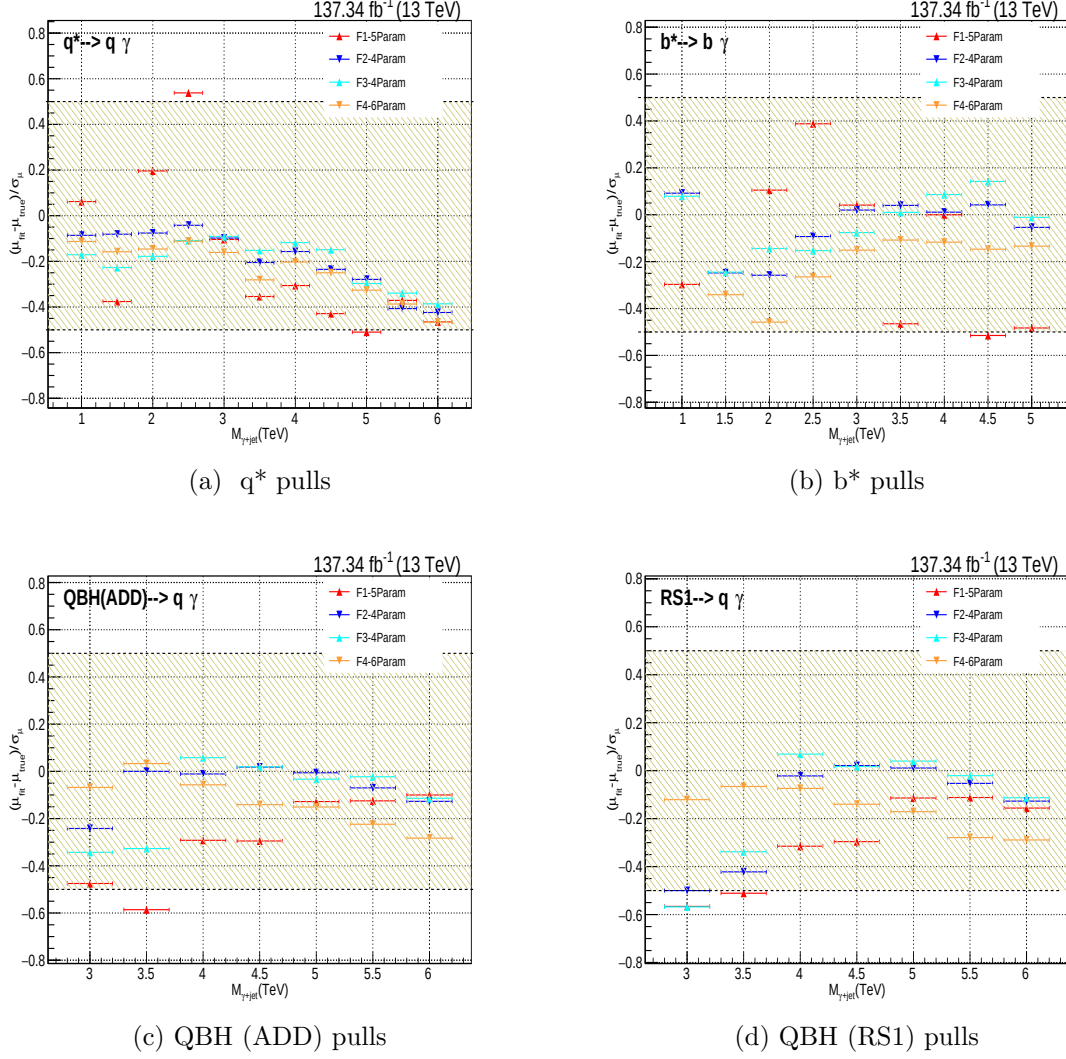


Figure 6.34: Pull distribution as a function of q^* , b^* and QBH (ADD and RS model) for Run-II mass corresponding to the four test functions with data.

6.8 Systematic Uncertainties

All the systematic sources of uncertainties that affect the analysis and their impact on measurements are discussed in this section. The sources of these uncertainties are analysis dependent, for example, the background estimation method, the re-

construction and identification techniques used for the physics objects, any kind of corrections applied to them. The uncertainties are either implemented as normalization variations or as the shape variations due to that source on the signal and background simulations. The list of the most dominant uncertainties sources are described as:

- **Background Shape Uncertainties** : The shape of estimated background from data for the invariant mass distribution depends on the analytical function used to fit the distribution. The choice of the function is motivated by the test determining the fit-quality, and the possible bias due to the chosen function is also evaluated as discussed in previous section. However, there could be shape difference between the data and background due to the analytical function which is accounted by uncertainties on the parameters of the function. To begin with, a signal+ background fit is performed to evaluate the initial values of the parameters and with improving fit techniques the final values of the parameters and associated uncertainties are considered. These parameters values are assigned as the nuisance parameters with uniform priors.
- **Luminosity** : The uncertainties associated due to the luminosity measurement by CMS for individual data-taking years during Run-II for are 1.2%, 2.3% and 2.5% for 2016, 2017 and 2018 respectively [12], [13], [14]. The combined correlated uncertainty of 1.6% across different years is taken for this analysis. This uncertainty is considered as normalization uncertainty impacting event yield.
- **Pileup** : The ability to model the average number of interactions in a LHC bunch crossing is the basis of this source. The impact of this uncertainty is evaluated by varying the total inelastic cross-section value of 69 mb by $\pm 5\%$. Its effect is evaluated to be 1% on the signal yield.
- **Photon and Jet Energy Scale** : The uncertainty associated with the photon and jet energy scale (PES and JES) is because of the non-uniform and non-linear response of the calorimeters which is translated to the measured energy

of the photons and jets. These uncertainties are evaluated on the simulated signal at different resonance masses by shifting the energy scale applied by ± 1 standard deviation at the reconstruction level. The PES and JES, both uncertainty translate a effect of 1% on the mean of γ +jet signal resonance shape. The effect due to the PES and JES systematics on the q^* signal for $M_{q^*} = 2.0 \text{ TeV}$ is shown in the left and right of Fig 6.35, respectively.

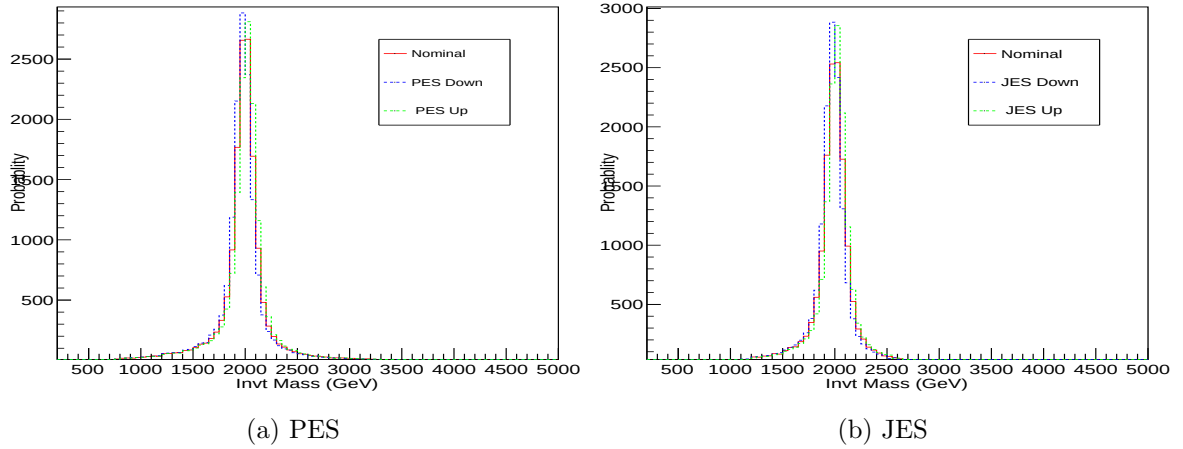


Figure 6.35: Effect of photon and jet energy scale uncertainties on invariant mass of q^* for $M_{q^*} = 2.0 \text{ TeV}$.

- Photon and Jet Energy Resolution :** The uncertainty associated with photon and jet energy resolution (PER and JER) is due to the different energy measurements in data and simulations. This can impact the resolution of γ +jet signal resolution expected in data. The PER and JER propagate a effect of 0.4–1.2% and 0.6–2.0%, respectively on the width (or mass resolution) of signal shapes as shown in Fig 6.36. This impact is computed for different resonance masses, with smaller effect observed at lower masses and large effect (upper end of range) observed at higher masses.
- Signal Shape Interpolation :** The mean of the interpolated and generated mass distribution of resonant shapes differ by $\sim 1\%$, and this effect is considered as the systematic uncertainty associated with the interpolation method.

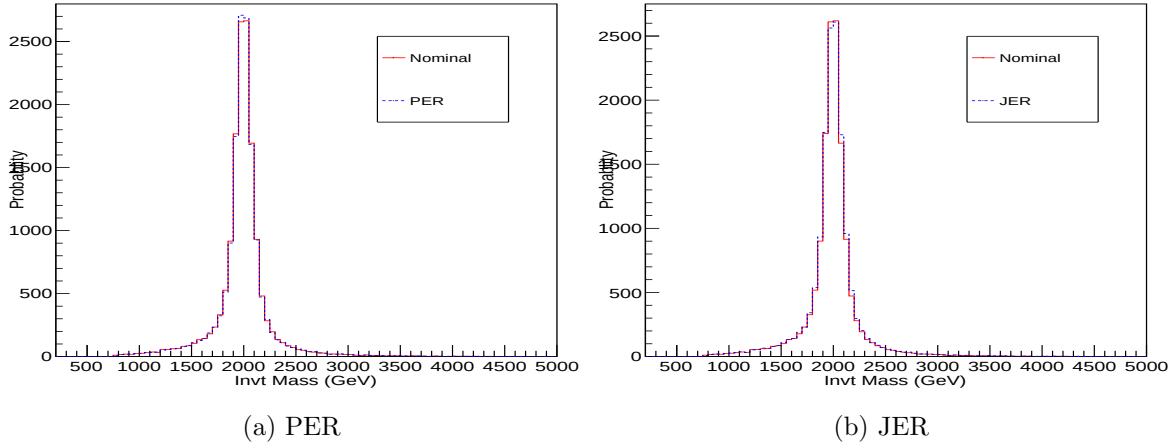


Figure 6.36: Effect of photon and jet energy resolution uncertainties on invariant mass of q^* for $M_{q^*} = 2.0$ TeV.

- **b-tag SF uncertainty** : In order to account for the difference in b-tagging efficiency between data and MC simulations, event-by-event b-tagging scale factors (BSF) are applied to background and signal simulations. The uncertainty associated with these scale factors is obtained by varying the scale factors up and down with the errors on them. The impact of these variations is computed and observed to be 0.2–3.0% on the mean of resonance signal, and 7.9–14.3% on the signal yield. The Fig 6.37 shows the effect of BSF variation up and down on the resonance shape of b^* signal for $M_{b^*} = 2.0$ TeV.
- **HLT Trigger Efficiency** : The determination of trigger efficiency by orthogonal muon data-set is estimated to be 97.5% and consequently, a 2.5% systematic uncertainty is considered for the photon trigger inefficiency.
- **Photon Identification** : Due to less statistics of high p_T photons, the efficiency of photon identification at the high p_T is difficult to measure and hence, a conservative value of 10% is assigned to account for the identification inefficiency.

The dominant contributor to the systematics is the uncertainties with the background parameters, while other sources does not contribute much to the total un-

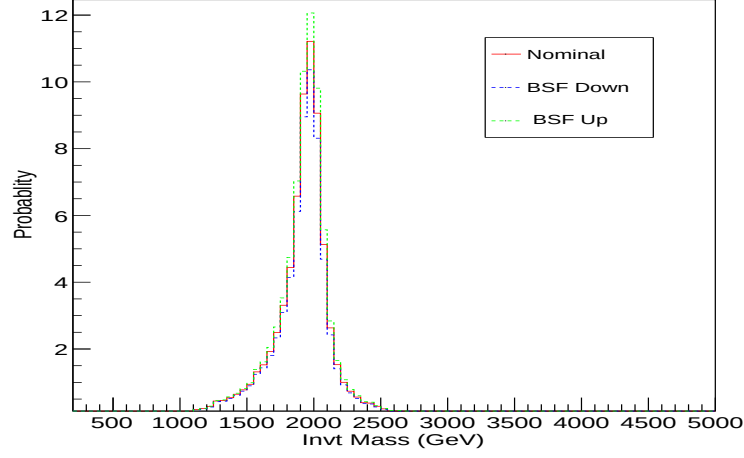


Figure 6.37: Effect of b-tag scale factor uncertainties on γ +jet distribution of b^* signal for $M_{b^*} = 2.0$ TeV.

certainty. The Fig 6.38 shows the ratio of the observed limits calculated with and without systematic uncertainty to the statistical uncertainties for q^* signal.

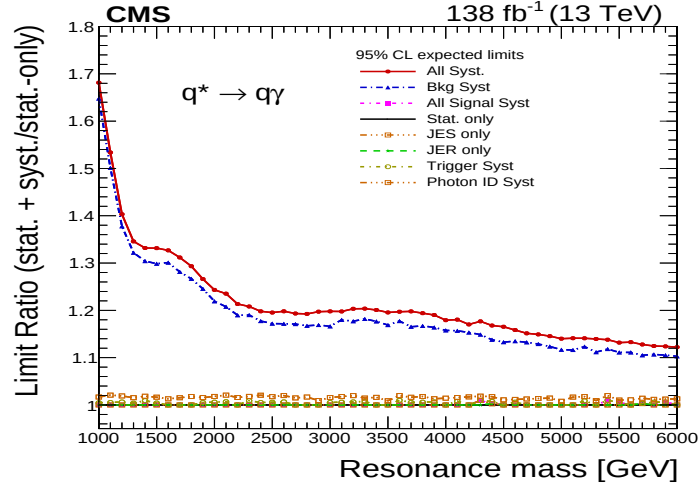


Figure 6.38: The ratio of observed limits with and without systematic uncertainty to the statistical uncertainties for q^* signal.

The Table 6.11 summarizes all the systematics sources and their impact on signal shape and yields. Further, the results of the analysis for all signal resonances with limits computation method are discussed in next chapter.

Source of Systematic	Type	Impact of systematic	Applied to $q^*/b^*/\text{QBH}$
Luminosity	Normalization	1.6%	All
Jet Energy Scale	Shape (mean)	$\sim 1.0\%$	All
Jet Energy Resolution	Shape (width)	0.6-1.9%	All
Photon Energy Scale	Shape (mean)	$\sim 1.0\%$	All
Photon Energy Resolution	Shape (width)	0.4-1.2%	All
Pileup	Normaliation	0.1%	All
High pT Photon ID inefficiency	Normalization	$\sim 10.0\%$	All
HLT Trigger inefficiency	Normalization	2.5%	All
Signal Shape interpolation	Shape (mean)	$<1.0\%$	All
b-tag SF uncertainty	Shape (mean)	0.2-3.0%	Only b^*
b-tag SF uncertainty	Normalization	7.9-14.3%	Only b^*

Table 6.11: Effect of various systematic uncertainties on signal shape and normalization.

Bibliography

- [1] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [2] Y. Coadou, “Boosted decision trees”, doi:10.1142/9789811234033_0002, arXiv:2206.09645.
- [3] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018), no. 05, P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [4] CMS Collaboration, “Jet Flavour Classification Using DeepJet”, *JINST* (2020) doi:10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.
- [5] CDF Collaboration, “Search for new particles decaying into dijets in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. D* **79** (2009) 112002, doi:10.1103/PhysRevD.79.112002, arXiv:0812.4036.
- [6] CMS Collaboration, “Search for excited quarks in the γ +jet final state in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Phys. Lett. B* **738** (2014) 274, doi:10.1016/j.physletb.2014.09.048, arXiv:1406.5171.
- [7] CMS Collaboration, “Search for narrow resonances decaying to dijets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **116** (2016) 071801, doi:10.1103/PhysRevLett.116.071801, arXiv:1512.01224.

-
- [8] ATLAS Collaboration, “Search for new phenomena with photon+jet events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **03** (2016) 041, doi:10.1007/JHEP03(2016)041, arXiv:1512.05910.
- [9] CMS Collaboration, “Search for excited quarks of light and heavy flavor in γ +jet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **781** (2018) 390, doi:10.1016/j.physletb.2018.04.007, arXiv:1711.04652.
- [10] R. A. Fisher, “On the interpretation of χ^2 from contingency tables, and the calculation of p”, *J. Roy. Stat. Soc.* **85** (1922) 87, doi:10.2307/2340521.
- [11] E. Gross and O. Vitells, “Trial factors for the look elsewhere effect in high energy physics”, *Eur. Phys. J. C* **70** (2010) 525–530, doi:10.1140/epjc/s10052-010-1470-8, arXiv:1005.1891.
- [12] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [13] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [14] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

Chapter 7

Results and Summary

In this thesis, the work presented is based on participation in Gas Electron Multiplier (GEM) detector R&D work, and is described in detail in Chapter 3 with assembly and testing procedure. Subsequently, the thesis also presents the search analysis based on two models utilizing the data from the CMS experiment. The models considered and event selections are described in Chapter 5 and Chapter 6, with the limit computation method and results presented in this chapter in Section 7.1 and 7.2, respectively. Later, in Section 7.3, the summary of the thesis is given, followed by future outlook in Section 7.4.

7.1 Limit Computation Method

The invariant mass spectrum of the γ +jet system is examined for the presence of resonances over the SM smooth falling background. If there is no significant excess observed in data, exclusion limits are set on the parameters of signal model using the modified frequentist approach [1]. This statistical approach is embedded by CMS statistical group in a framework, known as “Higgs Combine Tool”, and is widely used by CMS search analyses. In this approach, a binned likelihood function is constructed as the product of Poisson probabilities in each bin to observe events.

The functions takes the form :

$$\mathcal{L}(data|\mu, \theta) = \prod_{i=1}^{n_b} Poisson(x_i | s_i(\mu, \theta) + b_i(\theta)).p(\theta|\bar{\theta}, \delta\theta), \quad (7.1)$$

where i is the bin number; x_i , s_i and b_i are data, signal and background yield respectively in the i^{th} bin, θ represents nuisance parameters associated with each source of systematics uncertainty, μ indicates the signal strength that is the parameter of interest in this study. To calculate the exclusion limits, a test-statistic is built and is expressed as function of logarithmic value of profile likelihood ratio [1]. For a given value of signal strength μ , the test-statistic is defined as:

$$\tilde{q}_\mu = -2 \log \frac{\mathcal{L}(data|\mu, \hat{\theta}_\mu)}{\mathcal{L}(data|\hat{\mu}, \hat{\theta}_{\hat{\mu}})}, 0 \leq \hat{\mu} \leq \mu. \quad (7.2)$$

Here, numerator represents the maximum likelihood calculated for a value of nuisance parameter that maximizes it for a fixed signal strength value, and denominator represents maximum likelihood value when both signal strength and nuisance parameters are floating. The interpretation of absence or presence of signal is done by comparing the test-statistic value from the observed data ($\tilde{q}_\mu^{obs}$) with the same distribution from background-only (B) and signal plus background (S+B) hypotheses. The $\tilde{q}_\mu$ test-statistics distribution is constructed by generating a number of pseudo-datasets using the respective B and S+B hypotheses.

The exclusion limits for the signal are calculated for a confidence level (CL) as :

$$CL_s = \frac{CL_{s+b}}{CL_b} = \frac{P(q_\mu \geq q_\mu^{obs} | \mu.s + b)}{P(q_\mu \geq q_\mu^{obs} | b)} = \alpha \quad (7.3)$$

where CL_{s+b} and CL_b indicate the probability to observe the test statistic value (q_μ) as equal or larger than the $\tilde{q}_\mu^{obs}$ for respective S+B and B-only hypothesis. Additionally, any effect due to statistical fluctuations in background is accounted in this ratio. More details on this method can be studied in Refs [2], [3].

For a signal to be excluded at 95% confidence level, we scan over different

values of q_μ for varying μ until $\alpha = 0.05$ is achieved.

7.2 Results

The results for new resonance search decaying to γ +jet final state is presented in this section. The search for any excesses observed in data is described in terms of local significances and in the absence of such excesses exclusion limits are set on the parameters of signal model using the above detailed limit setting procedure.

7.2.1 Local Significance

In case of observing an excess of events in data, a local significance (S) is calculated and reported as the number of standard deviations (σ) from the SM expectation. A local significance of 5σ if observed indicates the discovery of new particle as per the standard adopted in experimental high energy physics. It is calculated by the following relation:

$$S = \sqrt{(-2 \ln \frac{\mathcal{L}_b}{\mathcal{L}_{s+b}})} \quad (7.4)$$

where $\mathcal{L}_b$ and $\mathcal{L}_{s+b}$ are the maximum likelihood for B and S+B hypotheses. It should be noted that significances are calculated only for upward fluctuations i.e positive signal strengths. The results for any possible significance for $q^\star$ and $b^\star$ for all three couplings as a function of resonance mass are reported in Figure 7.1, 7.2. For the QBH signals with ADD ($n = 6$) and RS1 ($n = 1$) models, the significances are reported in Figure 7.3, as a function of threshold mass. The most significant excess of 2σ for $q^\star$ signal is observed at mass of 3 TeV, while for $b^\star$ signal a significant excess of 1.8σ is observed at 2.5 TeV. This observation is similar for all three coupling strengths. In case of QBH signals, the most significant excess of 0.7σ for ADD ($n = 6$) model and 1.8σ for RS1 ($n = 1$) model is seen at threshold mass of 2.1 and 3.0 TeV, respectively. These excesses are not enough to claim any discovery or hint

of new particles, and could arise also due fluctuation in background spectrum.

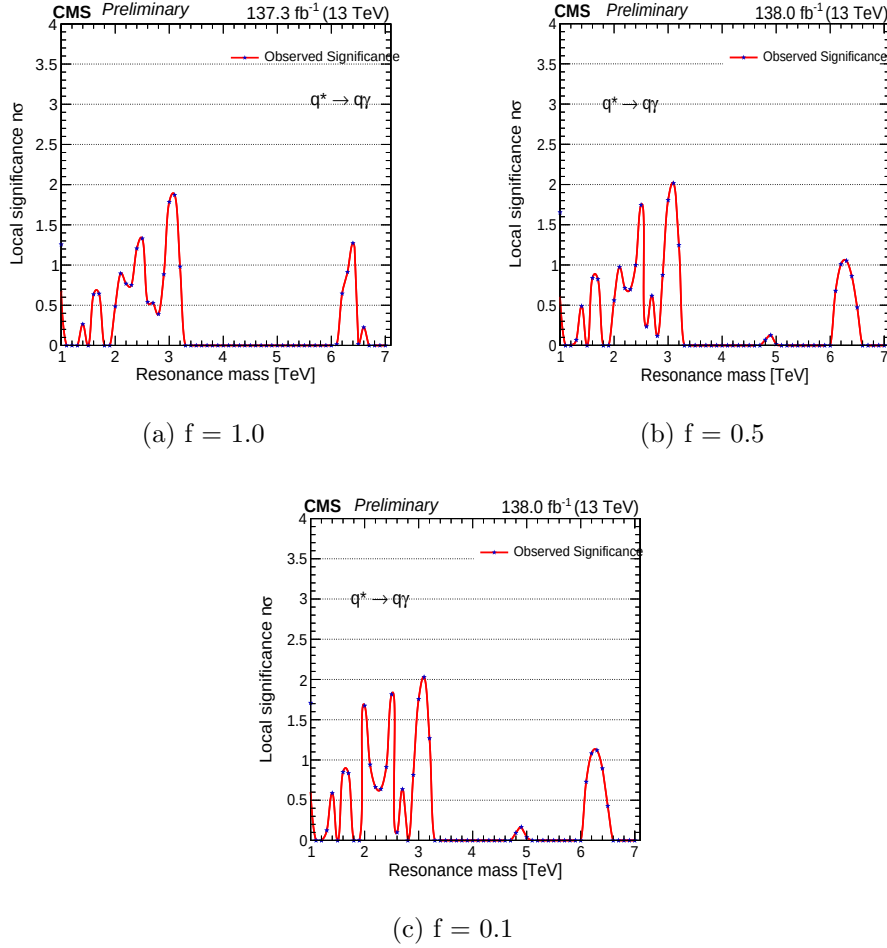


Figure 7.1: The observed significance in data for q^* signal with coupling (a) $f = 1.0$, (b) $f = 0.5$ and (c) $f = 0.1$ as a function of the resonance mass for γ +jet resonances.

7.2.2 Exclusion Limits and Conclusion

Since no significant excess in data is observed over the background expectations, 95% CL exclusion upper limit on signal cross-section and lower mass limit are set. The exclusion limits are set on q^* signal, QBH ADD ($n = 6$) and RS1 ($n = 1$) by calculating the likelihood value for the mass range of 1.0–7.0 TeV, 2.0–9.0 TeV, and 2.0–7.0 TeV respectively. However, for b^* the likelihoods are calculated independently for 1-btag and 0-btag categories in the range 1.0–7.0 TeV and then are combined to evaluate the exclusion limits on b^* signal. b-tagging efficiency de-

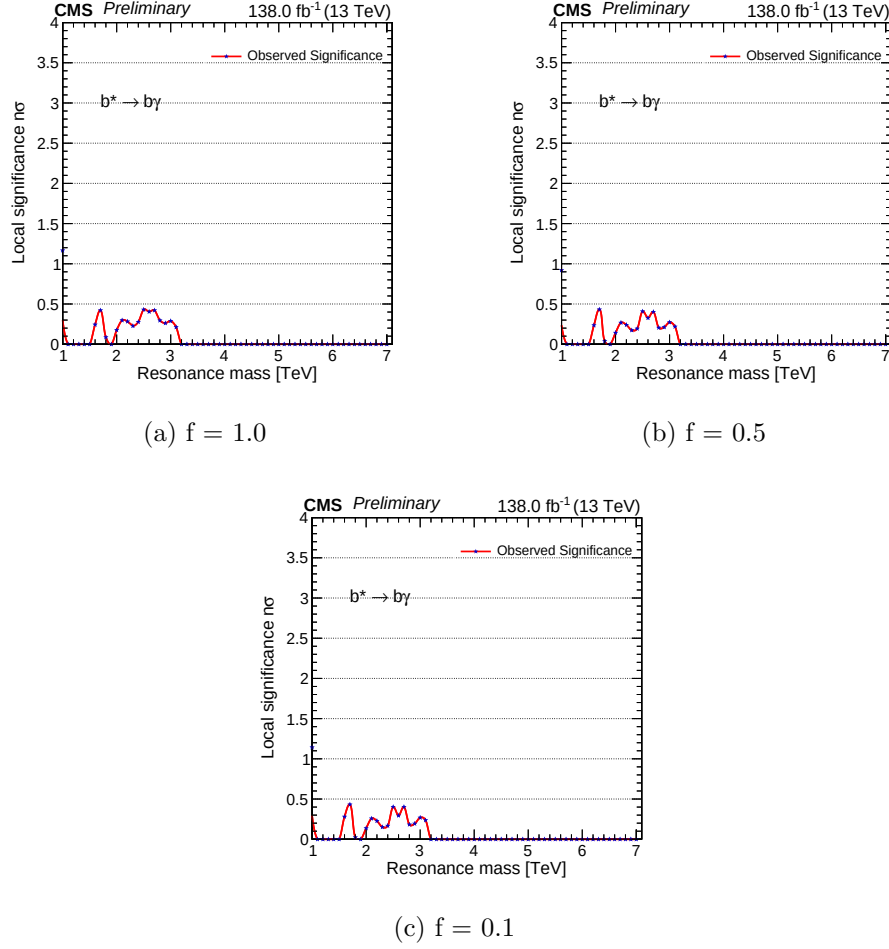


Figure 7.2: The observed significance in data for b^* signal with coupling (a) $f = 1.0$, (b) $f = 0.5$ and (c) $f = 0.1$ as a function of the resonance mass for $\gamma + b$ -jet resonances.

creases with increasing mass due to low tracking efficiency of CMS detector for high p_T . So some of the b -jets may not be identified and may go into the 0-btag category. This results into a loss of statistical power and make the final results sensitive to the efficiency of tagging a jet correctly. The two categories are combined together to avoid loss due to these effects. Figure 7.4 and Figure 7.5 shows the upper exclusion limits presented in terms of $\sigma \times B$ on q^* and b^* signal for three coupling multiplier values of $f = 1.0, 0.5$ and 0.1 .

The observed (expected) lower mass bound on q^* is found to be 6.0 (6.0), 5.4 (5.2) and 2.4 (2.8) TeV for coupling multipliers $f = 1.0, 0.5$ and 0.1 respectively. For

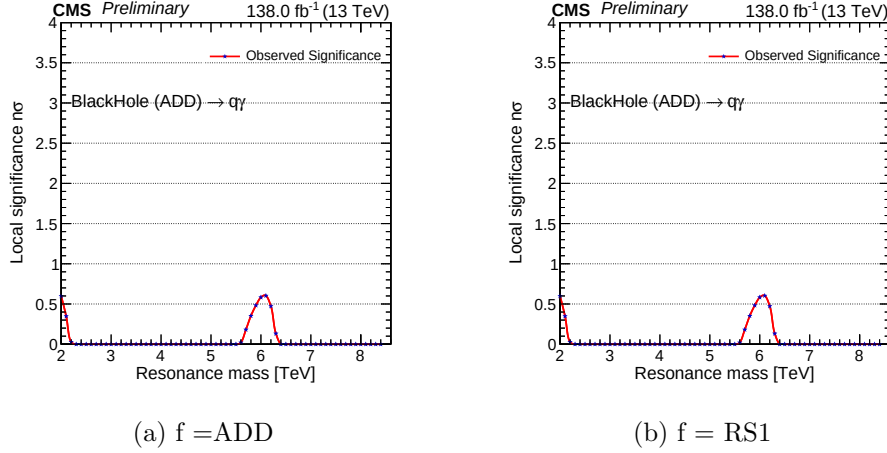


Figure 7.3: The observed significance in data for QBH ADD and RS1 signal

b^* signal, the limits are presented for coupling $f = 1.0$ for both gauge and contact interactions. The observed (expected) lower mass bound on b^* is estimated to be 2.15 (2.30) and 1.6 (1.7) TeV for couplings $f = 1.0$ and 0.5. However, the analysis could not reach the sensitivity for coupling $f = 0.1$. The results on b^* signal with coupling multiplier $f = 1.0$ are also presented for the combined process following gauge and contact interactions. In this case, the upper cross-section limit curve for gauge processes is used with a combined theory line cross-section from both processes. The limits are found to be 3.8 TeV as shown in Figure 7.5(a).

Additionally, for QBH signal a lower limit of 7.5(5.2) TeV is observed with expected limit of 7.5 TeV (5.2 TeV) on mass parameter for ADD (RS1) model, as shown in Figure 7.6. These limits are obtained for full Run-II luminosity of 138 fb^{-1} of data.

The two-dimensional representation of the excluded mass region for excited quarks (q^* and b^*) as a function of the coupling strength f , with the assumption $q^* = \Lambda$, is shown in Figure 7.7. The exclusion of the excited quark mass, as a function of q^*/Λ , is also presented in the same figure on the right hand axis. The excluded q^* region could also be interpreted in terms of the q^*/Λ ratio; this interpretation is based on the fact that the detector resolution effects dominate

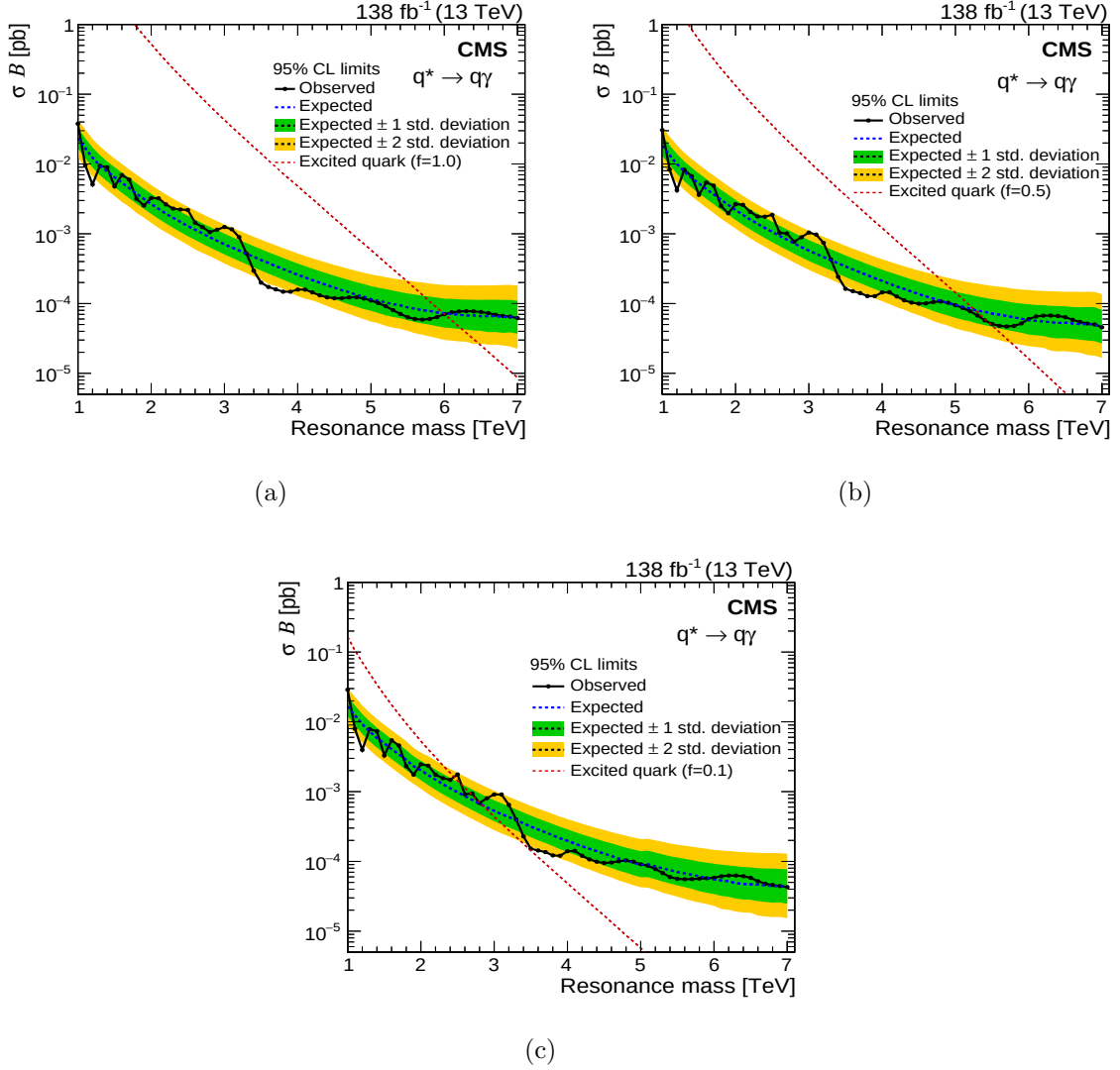


Figure 7.4: The expected and observed 95% C.L. upper limit on cross section and lower bound on the mass for $\gamma + jet$, that is q^* resonance for coupling $f=1.0$ (top left), and $f=0.5$ (top right), and $f=0.1$ (bottom).

compared to the change in the signal intrinsic width ($\Gamma_{q^*} \sim 0.04 f^2 q^*$) [4] arising from the change in the coupling strength f . Consequently, the variation of f effectively changes the production cross section in a similar way to the variations in q^*/Λ , since both appear as multiplicative factors in the cross section calculation.

The lower mass limits on q^* improved to 6.0 TeV from 5.5 TeV, and on b^* signal to 2.3 TeV from 1.8 TeV with respect to latest results published in the same channel [5]. For the ADD (RS1) model, the lower mass limits improved from 7.1

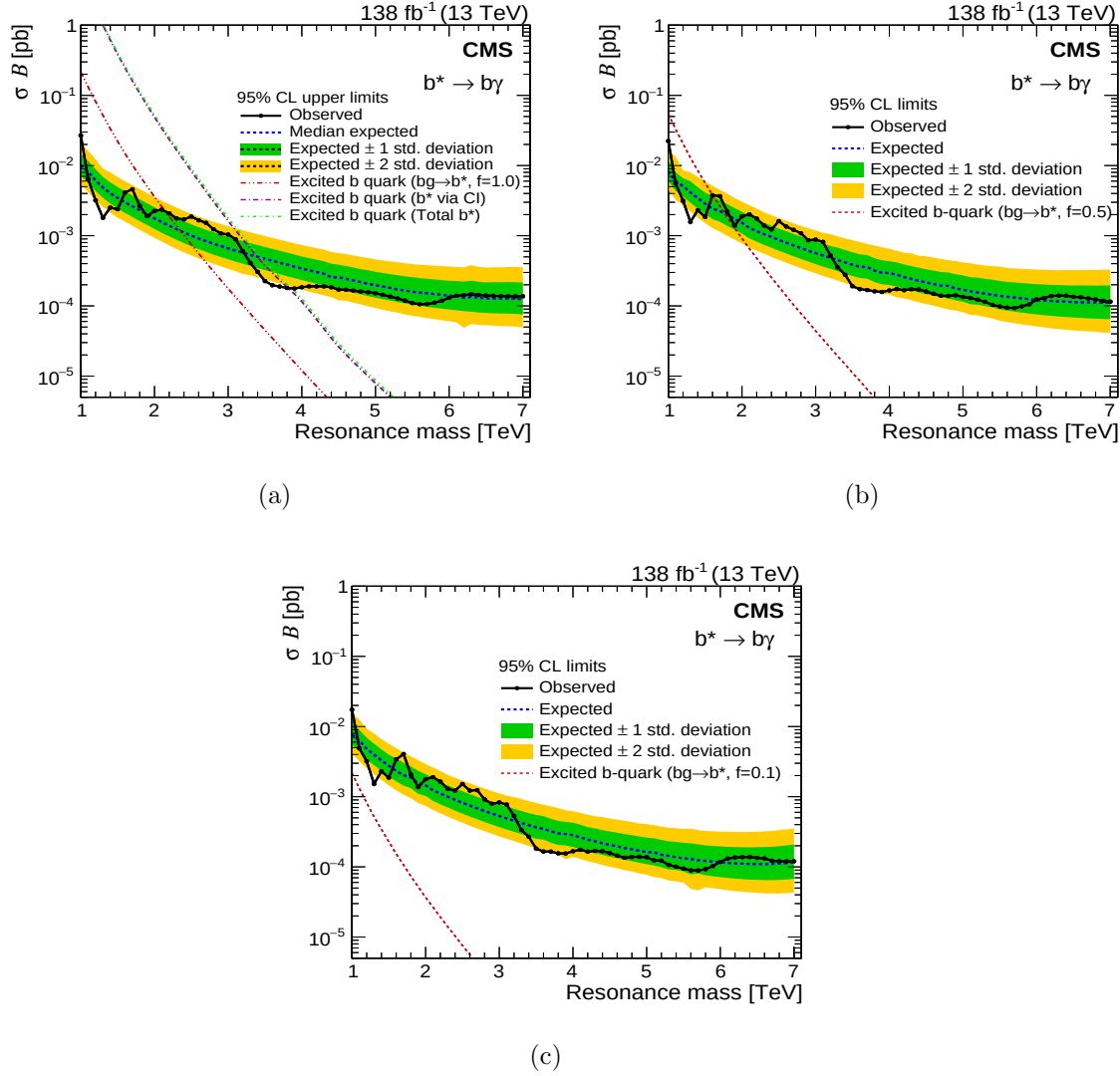


Figure 7.5: The expected and observed 95% C.L. upper limit on cross section and lower bound on the mass for $\gamma + jet$, that is b^* resonance for coupling $f=1.0$ (top left), and $f=0.5$ (top right), and $f=0.1$ (bottom).

(4.4) TeV to 7.5 (5.2) TeV in the same channel compared to the latest results reported in Ref. [6].

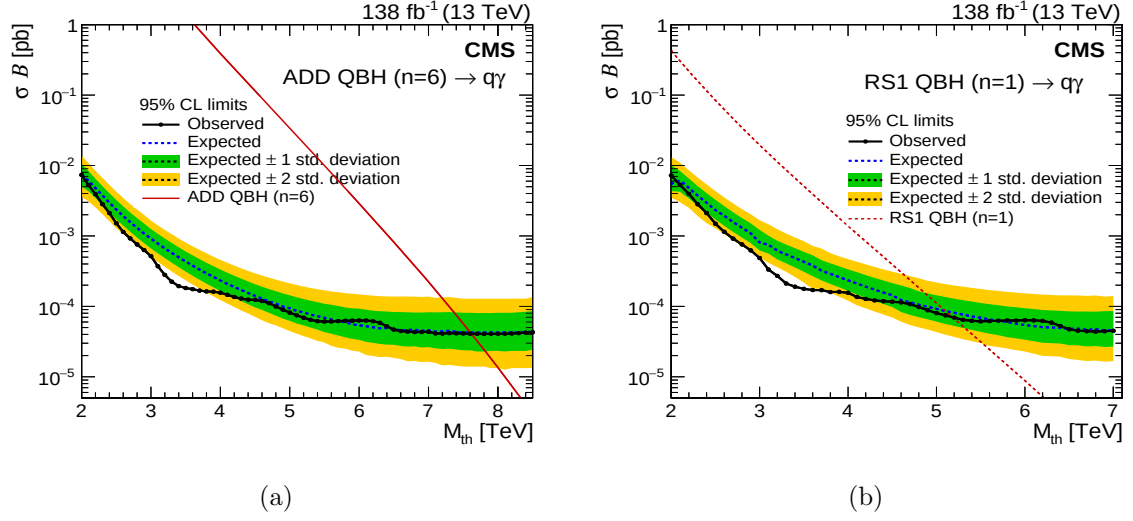


Figure 7.6: The expected and observed 95% C.L. upper limit on cross section and lower bound on the mass for $\gamma + jet$, that is for ADD(n=6) and RS1 (n=1) models on left and right respectively.

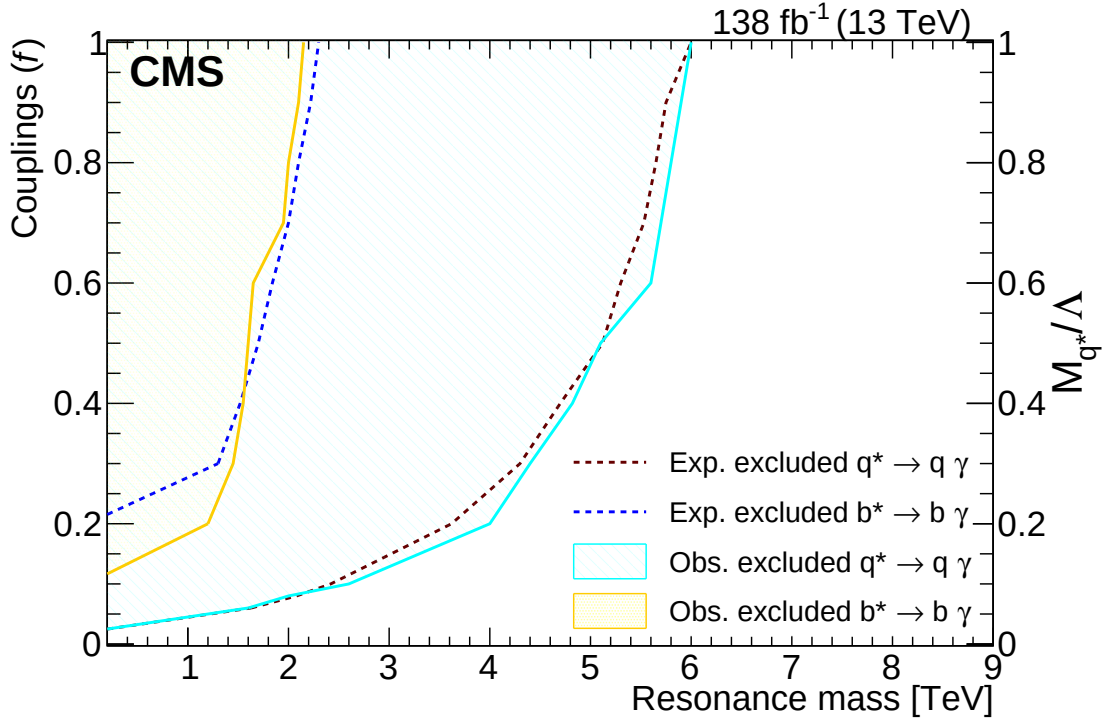


Figure 7.7: The expected and observed 95% exclusion mass limit variation with the SM couplings for the excited q^* and b^* signal models.

7.3 Summary

The CMS detector is designed to perform precise measurements of the SM physics and to search for the new physics signatures not defined in SM. The work presented in this Thesis is categorized into two tasks : hardware participation and physics analysis performed. The hardware participation involves the assembly and testing of GEM detectors at the Panjab University for HL-LHC. Following this, the other task is based on physics analysis for the search of new resonant particle decaying to the photon and jet state. A brief summary of these two tasks is given below.

7.3.1 Gas Electron Multiplier detector assembly and characterization

During the Run-II period, the LHC delivered an instantaneous luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. After the upgrade of LHC to HL-LHC, the beams are expected to collide at increased centre-of-mass energy of 14 TeV and deliver five times more luminosity than delivered during Run-II i.e. $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. To withstand such increased luminosity and improved reconstruction efficiency, the CMS detector needs upgrades involving pixel detector, hadron calorimeter, muon detectors and data acquisition.

The muon system of CMS detector consists of drift tubes (DTs) in barrel region ($|\eta| < 1.2$), cathode strip chambers (CSCs) installed in endcap ($1.0 < |\eta| < 2.4$), and resistive plate chambers (RPCs) in both barrel and endcap region ($|\eta| < 1.6$). The RPCs could not be installed beyond $|\eta| < 1.6$ because of their incapability to handle large background rates. Hence, to maintain the L1 trigger rate and increase the reconstruction efficiency for the HL-LHC, new detectors based on GEM technology are to be installed in the region $1.6 < |\eta| < 2.2$. These new detectors are gaseous detectors with a high spatial resolution of $\sim 100 \mu\text{m}$ and good time resolution of $\sim 8 \text{ ns}$.

A total of 144 GEM chambers (GE1/1) are installed in endcaps assembled at

CERN and various production sites. One of the production site is Panjab University that assembled a total of eight chambers. The assembly is performed in two steps: preparation of drift board and readout board done in a lab, and the assembly of detector in a class 100 clean room. The assembly is performed in clean room to avoid any contamination of foils and eventually the detector due to dust and moisture. During the preparation of drift and readout boards, all the required components are cleaned and are mounted on the board, for example pull outs, high-voltage (HV) divider, gas nozzles. In the clean room for stack assembly, the foils are cleaned, and the foils are stacked with spacers in between. Finally, the chamber is closed and assembly is completed. To test the quality of assembled chambers, few quality checks established by CMS collaboration are performed. The tests performed at the Panjab university are : QC2 to check the quality of foils by determining the impedance of the foils and the gap between foils, QC3 to identify any possible leakage due to various components used during assembly, QC4 to calculate the intrinsic noise ratio and depict the current vs voltage characteristic curve, QC5 to evaluate the effective gain and uniformity for all sectors of the chamber.

All the eight chambers assembled at the Panjab University, Chandigarh passed these tests, and were shipped to CERN. Few more quality checks were performed at CERN site, and later these assembled detectors were installed in the CMS endcap. Now these detectors assembled by Panjab University are a part of Run-III data taking.

7.3.2 Search for resonances in the photon+ jet final state

In this thesis, a search for new resonances in the photon and jet final state is performed using pp collision data collected by CMS detector at $\sqrt{s}=13$ TeV corresponding to integrated luminosity of 138 fb^{-1} . The study is motivated by two different theoretical models i.e. compositeness model and large extra dimension model for beyond SM studies. The compositeness model states that fermions are composite particles, and are made up of more fundamental particles that are not yet part of

SM. Through this study, the search for excited state of light flavor quarks (q^*) and heavy-flavor quarks (b^*) radiating a photon and jet to reach its ground state is being performed. Three coupling multiplier values of $f = 1.0, 0.5$, and 0.1 based on the coupling of excited quarks to SM are considered. If a resonance is discovered, this would imply that quarks are not fundamental particles.

Moreover, the other model i.e. large extra dimensions model attempts to resolve the hierarchy problem through the existence of large extra dimensions. The models proposed by Arkani-Hamed, Dimopoulos, and Dvali (ADD), and the Randall-Sundrum (RS) are considered in this search analysis, with $n = 6$ and $n = 1$ extra dimensions, respectively. These models lower the Planck's scale such that it could be accessible at the LHC and eventually, the production of Quantum Black Holes (QBHs) is a possibility at the LHC. Considering these models by ADD ($n = 6$) and RS ($n = 1$), the search for QBHs decaying to photon and jet final state is presented in this thesis.

The signal topology is selecting a high p_T photon and a high p_T jet with photon in the barrel region and jet in $|\eta| < 2.4$ region of the detector. The selection criteria imposed on the photon and jet are optimized using MC simulations for signal and background. The optimization is based on best 95% CL expected upper cross-section limits evaluated using a framework based on asymptotic approximation developed by CMS. The invariant mass distribution of photon and jet final state ($m_{\gamma+jet}$) in data is kept blinded until all the selections are finalised through optimization studies. The background is estimated from data by fitting smoothly falling $m_{\gamma+jet}$ distribution with a polynomial function. The functional form is chosen through p -value significance of Goodness-of-Fit (GOF) test and Fisher test. The GOF test determines the quality of fit, and Fisher test determines the order of the polynomial function. However, to account for any possible bias due to the choice of functional form a bias study using alternative functions is performed. The bias studies gives no indication of any possible bias, and only the statistical uncertainty of the fit is considered in this analysis.

No resonant excess over the smoothly falling distribution is found, and hence 95% CL exclusion limits are set on the signal cross-section and mass. The details of the method are described in Section 7.3b. The observed lower mass bound set on q^* signal for coupling multiplier $f = 1.0, 0.5$, and 0.1 are $6.0, 5.4$ and 2.4 TeV, respectively. For b^* signal, the observed lower mass bounds set for coupling multiplier $f = 1.0$ and 0.5 are 2.15 and 1.6 TeV respectively. The analysis could not reach the expected sensitivity to set the exclusion limits on b^* signal for coupling value $f = 0.1$. The lower mass bounds on b^* signal combining the gauge and contact interactions cross-sections is found to be 3.8 TeV. For the QBHs production predicted by ADD ($n = 6$) and RS ($n = 1$) models, the observed lower mass limits are set to be 7.5 and 5.2 TeV, respectively. These lower mass limits found are the most stringent to date among those obtained in this channel.

7.4 Outlook

The LHC is world's largest particle detector and many research scientists are working day and night for its operations and performing analysis study. With such great inspiration, it has the potential to achieve many more milestones. At the time of writing this thesis, Run3 has already started and soon in early 2024 the LHC will go for LS3 for HL-LHC upgrades. During the LS2, a total of 144 GE1/1 detectors based on GEM technology were installed in CMS muon endcap station. Out of these detectors, eight were assembled in the Panjab University site. Further in LS3, the LHC will undergo several other upgrades such as some part of ECAL and HCAL will be replaced by Highly-Granular Calorimeter (HGCAL) that will provide excellent energy resolution of electrons, photons and hadrons. Another essential upgrade will be installation of GE2/1 and ME0 detectors in muon endcap region to withstand high-luminosity background rates. The muon endcap region with the installation of GE1/1, GE2/1 and ME0 will provide redundancy and higher trigger rate. This will increase the efficiency of muons with lower momentum threshold, and hence better prospects for discovery of beyond SM phenomena. Panjab University will also be a

part of GE2/1 assembly and testing.

The HL-LHC foresee many new particles discovery predicted by various theoretical models. Various deep neural network based taggers are under development for improved efficiency of signal selection or background rejection. Besides this, increased instantaneous luminosity, increased $\sqrt{s}$ to 14 TeV and improved energy resolution due to HGCAL, there is a great potential to find excited quarks and QBHs in the photon and jet channel.

Bibliography

- [1] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727.
- [2] A. L. Read, “Presentation of search results: The CL(s) technique”, *J. Phys. G* **28** (2002) 2693–2704, doi:10.1088/0954-3899/28/10/313.
- [3] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [4] U. Baur, I. Hinchliffe, and D. Zeppenfeld, “Excited Quark Production at Hadron Colliders”, *Int. J. Mod. Phys. A* **2** (1987) 1285, doi:10.1142/S0217751X87000661.
- [5] CMS Collaboration, “Search for excited quarks of light and heavy flavor in γ +jet final states in proton–proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **781** (2018) 390, doi:10.1016/j.physletb.2018.04.007, arXiv:1711.04652.
- [6] ATLAS Collaboration, “Search for new phenomena in high-mass final states with a photon and a jet from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **78** (2018), no. 2, 102, doi:10.1140/epjc/s10052-018-5553-2, arXiv:1709.10440.

Appendix A

List of Samples

A.1 Data Samples

The table A.1 lists the JavaScript Object Notation (JSON) files for the 2016, 2017 and 2018 data-taking years containing a list of good runs, while table A.2 lists the data samples for these years with the respective run ranges and corresponding luminosity for each era.

JSON Files
Cert_271036-284044_13TeV_23Sep2016ReReco_Collisions16_JSON.txt
Cert_294927-306462_13TeV_EOY2017ReReco_Collisions17_JSON.txt
Cert_314472-325175_13TeV_17SeptEarlyReReco2018ABC_PromptEraD_Collisions18_JSON.txt

Table A.1: JSON files used to select certified runs and luminosity sections

Data Samples	Run Range	Luminosity (fb^{-1})
/SinglePhoton/Run2016B-17Jul2018_ver2-v2/MINIAOD	273150 - 275376	5.788
/SinglePhoton/Run2016C-17Jul2018-v1/MINIAOD	275656 - 276283	2.573
/SinglePhoton/Run2016D-17Jul2018-v1/MINIAOD	276315 - 276811	4.248
/SinglePhoton/Run2016E-17Jul2018-v1/MINIAOD	276831 - 277420	4.025
/SinglePhoton/Run2016F-17Jul2018-v1/MINIAOD	277932 - 278808	3.104
/SinglePhoton/Run2016G-17Jul2018-v1/MINIAOD	278820 - 280385	7.575
/SinglePhoton/Run2016H-17Jul2018_ver2-v1/MINIAOD	281613 - 284044	8.650
/SinglePhoton/Run2016H-17Jul2018_ver3-v1/MINIAOD	284036 - 284044	0.215
Total	273150 - 284044	36.3
/SinglePhoton/Run2017B-31Mar2018-v1/MINIAOD	297046 - 299329	4.763
/SinglePhoton/Run2017C-31Mar2018-v1/MINIAOD	299368 - 302029	9.748
/SinglePhoton/Run2017D-31Mar2018-v1/MINIAOD	302030 - 303434	4.323
/SinglePhoton/Run2017E-31Mar2018-v1/MINIAOD	303824 - 304797	9.385
/SinglePhoton/Run2017F-31Mar2018-v1/MINIAOD	305040 - 306462	13.567
Total	297046 - 306462	41.78
/EGamma/Run2018A-17Sep2018-v2/MINIAOD	315252 - 316995	13.704
/EGamma/Run2018B-17Sep2018-v2/MINIAOD	317080 - 319310	7.060
/EGamma/Run2018C-17Sep2018-v2/MINIAOD	319337 - 320065	6.894
/EGamma/Run2018D-22Jan2019-v2/MINIAOD	320673 - 325175	31.741
Total	315252 - 325175	59.40
Run II		138

Table A.2: List of dataset with corresponding run range used in the analysis

A.2 Signal samples for q^* resonances

The table lists the simulated samples for q^* signals for three coupling multiplier values $f = 1.0, 0.5$ and 0.1 simulated with PYTHIA8, with their respective cross-section values and number of events generated and analysed.

Sample Name	Events	Cross section (pb) $\sigma \times B$	Couplings
/QstarToGJ_M-500.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	299,760	3.033×10^2	1.0
/QstarToGJ_M-1000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	297,576	1.632×10^1	1.0
/QstarToGJ_M-2000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	99,499	5.213×10^{-1}	1.0
/QstarToGJ_M-3000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	74,879	4.272×10^{-2}	1.0
/QstarToGJ_M-4000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	73,482	4.8×10^{-3}	1.0
/QstarToGJ_M-5000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v3	74,918	5.835×10^{-4}	1.0
/QstarToGJ_M-6000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	75,000	7.076×10^{-5}	1.0
/QstarToGJ_M-7000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	50,000	8.66×10^{-6}	1.0
/QstarToGJ_M-8000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v3	49,814	1.283×10^{-6}	1.0
/QstarToGJ_M-9000.f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	50,000	2.985×10^{-7}	1.0
/QstarToGJ_M-500.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	300,000	7.378×10^1	0.5
/QstarToGJ_M-1000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	99,723	4.129	0.5
/QstarToGJ_M-2000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	100,000	1.328×10^{-1}	0.5
/QstarToGJ_M-3000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	75,000	1.095×10^{-2}	0.5
/QstarToGJ_M-4000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	72,900	1.212×10^{-3}	0.5
/QstarToGJ_M-5000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	70,632	1.437×10^{-4}	0.5
/QstarToGJ_M-6000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	74,776	1.62×10^{-5}	0.5
/QstarToGJ_M-7000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	49,520	1.672×10^{-6}	0.5
/QstarToGJ_M-8000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v3	49,427	1.647×10^{-7}	0.5
/QstarToGJ_M-9000.f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	50,000	2.329×10^{-8}	0.5
/QstarToGJ_M-500.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v3	99,681	2.955	0.1
/QstarToGJ_M-1000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v3	99,254	1.655×10^{-1}	0.1
/QstarToGJ_M-2000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v2	75,000	5.315×10^{-3}	0.1
/QstarToGJ_M-3000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v2	75,000	4.356×10^{-4}	0.1
/QstarToGJ_M-4000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	72,312	4.861×10^{-5}	0.1
/QstarToGJ_M-5000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v2	75,000	5.715×10^{-6}	0.1
/QstarToGJ_M-6000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v2	49,942	6.241×10^{-7}	0.1
/QstarToGJ_M-7000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v2	47,660	5.973×10^{-8}	0.1
/QstarToGJ_M-8000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v2	49,650	4.515×10^{-9}	0.1
/QstarToGJ_M-9000.f-0p1_TuneCUETP8M1_13TeV-pythia8 *v2	49,814	2.655×10^{-10}	0.1

Table A.3: List of q^* signal MC samples officially simulated and reconstructed at $\sqrt{s} = 13$ TeV, along with the number of generated events, cross-sections and coupling strengths. All the samples uses MINIAODSIM tier of the RunIISpring16MiniAODv2-PUSpring16RAWAODSIM-80X-mcRun2-asymptotic-2016-miniAODv2-v0-v* production.

A.3 Signal samples for $b^\star$ resonances

The table below lists the simulated samples for $b^\star$ signals for three coupling multiplier values $f = 1.0, 0.5$ and 0.1 simulated with PYTHIA8, with their respective cross-section values and number of events generated and analysed.

Sample Name	Events	Cross section (pb) $\sigma \times B$	Couplings
/BstarToGJ_M-500-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	100,000	6.236	1.0
/BstarToGJ_M-1000-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v3	99,736	2.148×10^{-1}	1.0
/BstarToGJ_M-1500-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	73,990	2.204×10^{-2}	1.0
/BstarToGJ_M-2000-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	75,000	3.585×10^{-3}	1.0
/BstarToGJ_M-2500-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v3	75,000	7.488×10^{-4}	1.0
/BstarToGJ_M-3000-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	73,170	1.766×10^{-4}	1.0
/BstarToGJ_M-3500-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	50,000	4.517×10^{-5}	1.0
/BstarToGJ_M-4000-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	48,100	1.202×10^{-5}	1.0
/BstarToGJ_M-4500-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v3	50,000	3.289×10^{-6}	1.0
/BstarToGJ_M-5000-f-1p0_TuneCUETP8M1_13TeV-pythia8 *v2	49,608	9.216×10^{-7}	1.0
/BstarToGJ_M-500-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	99,544	1.574	0.5
/BstarToGJ_M-1000-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	100,000	5.438×10^{-2}	0.5
/BstarToGJ_M-1500-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v2	74,536	5.666×10^{-3}	0.5
/BstarToGJ_M-2000-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	74,404	9.162×10^{-4}	0.5
/BstarToGJ_M-2500-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	71,454	1.884×10^{-4}	0.5
/BstarToGJ_M-3000-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	72,730	4.393×10^{-5}	0.5
/BstarToGJ_M-3500-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	49,150	1.112×10^{-5}	0.5
/BstarToGJ_M-4000-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	50,000	2.909×10^{-6}	0.5
/BstarToGJ_M-4500-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	50,000	7.705×10^{-7}	0.5
/BstarToGJ_M-5000-f-0p5_TuneCUETP8M1_13TeV-pythia8 *v1	50,000	2.027×10^{-7}	0.5
/BstarToGJ_M-500-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	99,033	6.357×10^{-2}	0.1
/BstarToGJ_M-1000-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	99,040	2.175×10^{-3}	0.1
/BstarToGJ_M-1500-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	75,000	2.278×10^{-4}	0.1
/BstarToGJ_M-2000-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	73,936	3.674×10^{-5}	0.1
/BstarToGJ_M-2500-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	75,000	7.595×10^{-6}	0.1
/BstarToGJ_M-3000-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	74,911	1.768×10^{-6}	0.1
/BstarToGJ_M-3500-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	50,000	4.454×10^{-7}	0.1
/BstarToGJ_M-4000-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	50,000	1.155×10^{-7}	0.1
/BstarToGJ_M-4500-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v2	46,590	3.031×10^{-8}	0.1
/BstarToGJ_M-5000-f-0p1_TuneCUETP8M1_13TeV-pythia8 *v1	49,388	7.703×10^{-9}	0.1

Table A.4: List of $b^\star$ signal MC samples officially simulated and reconstructed at $\sqrt{s} = 13$ TeV, along with the number of generated events, cross-sections and coupling strengths. All the samples uses MINIAODSIM tier of the RunIISpring16MiniAODv2-PUSpring16RAWAODSIM-80X-mcRun2-asymptotic-2016-miniAODv2-v0-v* production.

A.4 Signal samples for QBH resonances

The table below lists the simulated samples of QBH signals for ADD ($n = 6$) and RS ($n = 1$) model simulated with PYTHIA8, with their respective cross-section values and number of events generated and analysed.

Sample Name	Events	Cross Section(fb) $\sigma \times B$
/QBHToGJ_M-3000_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	5085.91
/QBHToGJ_M-3500_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	1379.65
/QBHToGJ_M-4000_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	389.37
/QBHToGJ_M-4500_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	114.86
/QBHToGJ_M-5000_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	33.86
/QBHToGJ_M-5500_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	10.00
/QBHToGJ_M-6000_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	2.88
/QBHToGJ_M-6500_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	0.817
/QBHToGJ_M-7000_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	0.223
/QBHToGJ_M-7500_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	5.69×10^{-2}
/QBHToGJ_M-8000_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	1.35×10^{-2}
/QBHToGJ_M-8500_ADD_n6_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	2.93×10^{-3}
/QBHToGJ_M-1000_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	26971.1
/QBHToGJ_M-1500_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	2647.46
/QBHToGJ_M-2000_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	425.69
/QBHToGJ_M-2500_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	84.27
/QBHToGJ_M-3000_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	19.49
/QBHToGJ_M-3500_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	5.09
/QBHToGJ_M-4000_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	1.38
/QBHToGJ_M-4500_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	3.93×10^{-1}
/QBHToGJ_M-5000_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	100K	1.11×10^{-1}
/QBHToGJ_M-5500_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	3.14×10^{-2}
/QBHToGJ_M-6000_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	8.838×10^{-3}
/QBHToGJ_M-6500_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	2.388×10^{-3}
/QBHToGJ_M-7000_RS1_n1_TuneCP5_13TeV-QBHv3p0_pythia8/	50K	6.174×10^{-4}

Table A.5: List of QBH signal MC samples centrally simulated by CMS experiment and reconstructed at $\sqrt{s} = 13$ TeV, along with the number of generated events and cross-sections.

Appendix B

Invariant mass of a system

Suppose, a particle X with rest mass M is decaying to two particles with energies E_1 and E_2 and carrying the momentum p_1 and p_2 . The rest mass or the invariant mass M of the particle X in natural units (where $\hbar = c = 1$) can be calculated by :

$$M = \sqrt{(E_1 + E_2)^2 - (p_1 + p_2)^2} \quad (\text{B.1})$$

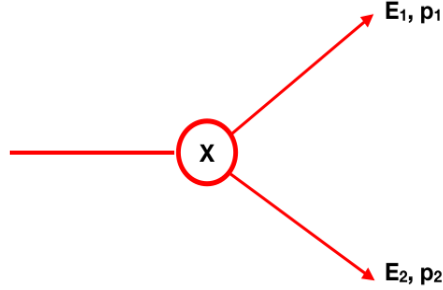


Figure B.1: The sketch depicts a particle X decaying to two particle state with energies E_1 and E_2 , and momentum p_1 and p_2 , respectively .

In this analysis, the new resonance particle X is decaying to the photon and jet state. The invariant mass of X is calculated using the above formula through the values the energy and momentum of a photon and a jet.

Appendix C

Invariant Mass Binning

The variable binning for the mass distribution of γ +jet system is derived based on the mass resolution. The method is described in the Chapter 5, and the variable binning used in the analysis is mentioned below:

```
nMassBin[120] = {1, 15, 29, 44, 59, 74, 90, 107, 124, 142, 160, 179, 199, 219, 240, 262, 284, 307,  
331, 356, 381, 407, 434, 462, 491, 521, 552, 584, 617, 651, 686, 723, 760, 800, 840, 881, 924, 968,  
1014, 1061, 1110, 1161, 1213, 1267, 1323, 1381, 1441, 1503, 1567, 1633, 1701, 1772, 1845, 1921, 1999,  
2080, 2164, 2251, 2341, 2434, 2530, 2629, 2732, 2838, 2948, 3061, 3178, 3299, 3425, 3555, 3689, 3828,  
3972, 4121, 4275, 4434, 4598, 4768, 4944, 5126, 5314, 5509, 5710, 5918, 6133, 6356, 6586, 6824, 7070,  
7325, 7588, 7860, 8142, 8433, 8734, 9046, 9368, 9701, 10046, 10403, 10772, 11153, 11547, 11955, 12377,  
12813, 13264, 13731, 14214}
```

Appendix D

List of triggers used in the analysis

The table lists the trigger used in the analysis, with the analysis trigger being HLT_Photon200 and HLT_Photon175 and the remaining are the reference trigger used for the efficiency studies of the analysis triggers.

Table D.1: The HLT triggers used in the analysis with the objects and the p_T threshold

Objects	Trigger Name	Kinematic object with threshold on p_T
Photon Triggers	HLT_Photon200	photons with $p_T \geq 200$ GeV
	HLT_Photon175	photons with $p_T \geq 175$ GeV
	HLT_Photon120	photons with $p_T \geq 120$ GeV
	HLT_Photon90	photons with $p_T \geq 90$ GeV
	HLT_Photon75	photons with $p_T \geq 75$ GeV
Jet Triggers	HLT_PFJet120	jets with $p_T \geq 120$ GeV
	HLT_PFJet90	jets with $p_T \geq 90$ GeV
	HLT_PFJet60	jets with $p_T \geq 60$ GeV
Muon Trigger	HLT_Mu50	muons with $p_T \geq 50$ GeV

Publications/Conferences

Publications and CMS Public Notes with Direct Contribution

1. CMS Collaboration, “Search for resonances in events with photon and jet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV,” **Submitted to JHEP**, [arXiv:2305.07998].
2. J. Babbar *et al.*, “Search for resonance production in events with a photon and jet with the CMS experiment,” **CMS PAS-EXO-20-012**, Nov, 2022.
3. J. Babbar, V. Bhatnagar, S. Chauhan *et al.* “Quality control of mass-produced GEM detectors for the CMS GE1/1 muon upgrade,” Nucl. Instrum. Meth. A **1034** (2022), 166716 doi:10.1016/j.nima.2022.166716 [arXiv:2203.12037]
4. J. Babbar, V. Bhatnagar, S. Chauhan *et al.* “Fabrication and Characterization of Gaseous Detector for the identification of High Energy Particles,” IOP Conf. Ser. Mater. Sci. Eng. **1033**, 012055 (2021) doi:10.1088/1757-899X/1033/1/012055
5. J. Babbar *et al.*, “Quark Gluon Discrimination using DeepJet,” **CMS AN-2022/106** Internal Note, July, 2022.
6. J. Babbar *et al.*, “Search for Resonance in Photon+Jet Final State at $\sqrt{s} = 13$ TeV,” **CMS AN-19-267** *Internal Note*, June, 2021.

* CMS PAS - CMS Public Analysis Summary

* CMS AN - CMS Analysis Note

Papers presented in Conferences, Workshops, Symposiums

1. J. Babbar *et al.*, “ARDUINO BASED QUALITY CHECK SETUP FOR GEM DETECTOR,” **Chandigarh Science Congress (CHASCON-2018)**, February 12th - 14th 2018, Panjab University, India.
2. J. Babbar *et al.*, “Discrimination of Quark and Gluon Jets,” **Chandigarh Science Congress (CHASCON-2020)**, Dec 17th - 19th 2020, Panjab University, India.
3. J. Babbar *et al.*, “Search for New Resonance in Photon and Jet final State using CMS Data,” **LHCP2021: 9th Edition of the Large Hadron Collider Physics Conference**, Jun 7th - 12th 2021, Paris.
4. J. Babbar *et al.*, “Search for New Resonance in Photon and Jet final State using CMS Data,” **Lomonosov 2021: 20th Lomonosov Conference on Elementary Particle Physics**, Aug 19th - 25th 2021, Moscow State University, Moscow (Russian Federation).
5. J. Babbar *et al.*, “Search for New Resonance in the photon and jet final state using CMS data,” **DISCRETE 2022**, Nov 7-11, 2022, in Baden-Baden, Germany.
6. J. Babbar *et al.*, “Discrimination of quark and gluon jets at 13 TeV in the CMS experiment,” **XXV DAE-BRNS HIGH ENERGY PHYSICS SYMPOSIUM 2022**, Dec 12th - 16th 2022, IISER, Mohali, India.

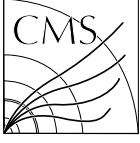
Publications as co-author with CMS Collaboration

1. CMS Collaboration, “Detector Control System for the GE1/1 slice test” *JINST*, 15(05):P05023, 2020.
2. CMS Collaboration, “Interstrip capacitances of the readout board used in large triple-GEM detectors for the CMS Muon Upgrade”. *JINST*, 15(12):P12019, 2020.
3. CMS Collaboration, “Performance of prototype GE1 / 1 chambers for the CMS muon spectrometer upgrade”. *Nucl. Instrum. Meth. A*, 972:164104, 2020.
4. CMS Collaboration, “Triple-GEM discharge probability studies at CHARM: simulations and experimental results”. *JINST*, 15(10):P10013, 2020.
5. CMS Collaboration, “Two years’ test of a temperature sensing system based on fibre Bragg grating technology for the CMS GE1/1 detectors”. *J. Phys. Conf. Ser.*, 1561(1):012006, 2020.
6. CMS Collaboration, “Benchmarking LHC background particle simulation with the CMS triple-GEM detector”. *JINST*, 16(12):P12026, 2021.
7. CMS Collaboration, “Performance of a triple-GEM demonstrator in pp collisions at the CMS detector”. *JINST*, 16(11):P11014, 2021.
8. CMS Collaboration, “Quality control of mass-produced GEM detectors for the CMS GE1/1 muon upgrade”. *Nucl. Instrum. Meth. A*, 1034:166716, 2022.
9. CMS Collaboration, “Observation of four top quark production in proton-proton collisions at $\sqrt{s} = 13$ TeV”. [arXiv:2305.13439].
10. CMS Collaboration, “Search for the lepton-flavor violating decay of the Higgs boson and additional Higgs bosons in the $e\mu$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”. 5 2023.

11. CMS Collaboration, “A portrait of the Higgs boson by the CMS experiment ten years after the discovery”. *Nature*, 607(7917):60–68, 2022.
12. CMS Collaboration, “First measurement of the top quark pair production cross section in proton-proton collisions at $\sqrt{s} = 13.6$ TeV,” [arXiv:2303.10680].
13. CMS Collaboration, “Measurement of inclusive and differential cross sections for single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *JHEP*, 07:046, 2023.
14. CMS Collaboration, “Measurement of the $B_S^0 \rightarrow \mu^+ \mu^-$ decay properties and search for the $B^0 \rightarrow \mu^+ \mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *Phys. Lett. B*, 842:137955, 2023.
15. CMS Collaboration, “Measurement of the differential $t\bar{t}$ production cross section as a function of the jet mass and extraction of the top quark mass in hadronic decays of boosted top quarks”. *Eur. Phys. J. C*, 83(7):560, 2023.
16. CMS Collaboration, “Measurement of the Higgs boson inclusive and differential fiducial production cross sections in the diphoton decay channel with pp collisions at $\sqrt{s} = 13$ TeV”. *JHEP*, 07:091, 2023.
17. CMS Collaboration, “Measurements of the azimuthal anisotropy of prompt and nonprompt charmonia in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”. [arXiv:2305.16928]
18. CMS Collaboration, “Performance of the local reconstruction algorithms for the CMS hadron calorimeter with Run 2 data”. [arXiv:2306.10355].
19. CMS Collaboration, “Probing Heavy Majorana Neutrinos and the Weinberg Operator through Vector Boson Fusion Processes in Proton-Proton Collisions at $s=13$ TeV”. *Phys. Rev. Lett.*, 131(1):011803, 2023.

20. CMS Collaboration, “Search for a heavy composite Majorana neutrino in events with dilepton signatures from proton-proton collisions at $\sqrt{s}=13$ TeV”. *Phys. Lett. B*, 843:137803, 2023.
 21. CMS Collaboration, “Search for CP violation in $t\bar{t}H$ and tH production in multilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *JHEP*, 07:092, 2023.
 22. CMS Collaboration, “Search for long-lived particles decaying to a pair of muons in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *JHEP*, 05:228, 2023.
 23. CMS Collaboration, “Search for nonresonant Higgs boson pair production in the four leptons plus two jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *JHEP*, 06:130, 2023.
 24. CMS Collaboration, “Search for top squark pair production in a final state with at least one hadronically decaying tau lepton in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *JHEP*, 07:110, 2023.
 25. CMS Collaboration, “Search for top squarks in the four-body decay mode with single lepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”. *JHEP*, 06:060, 2023.
-

Selected
Reprints



CERN-EP-2023-064
2023/05/16

CMS-EXO-20-012

Search for resonances in events with photon and jet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Abstract

A search for resonances in events with the γ +jet final state has been performed using proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC. The total data analyzed correspond to an integrated luminosity of 138 fb^{-1} . Models of excited quarks and quantum black holes are considered. The invariant mass spectrum of the γ +jet system is examined for the presence of resonances over the standard model continuum background. The data exhibit no statistically significant deviations from the expected standard model background. Exclusion limits at 95% confidence level on the resonance mass and other parameters are set. Excited light-flavor quarks (excited bottom quarks) are excluded up to a mass of 6.0 (3.8) TeV. Quantum black hole production is excluded for masses up to 7.5 (5.2) TeV in the Arkani-Hamed–Dimopoulos–Dvali (Randall–Sundrum) model. These lower mass bounds are the most stringent to date among those obtained in the γ +jet final state.

Submitted to the Journal of High Energy Physics

arXiv:2305.07998v1 [hep-ex] 13 May 2023

1 Introduction

Various theoretical proposals of beyond the standard model (BSM) physics predict the production of new resonances at hadron collider experiments. In the last decade, experiments at the CERN LHC have searched extensively for signatures of such phenomena to help understand some of the unresolved questions concerning features of the standard model (SM) of particle physics, for example the existence of only three fermion families and the hierarchy problem [1]. A variety of models have been proposed to address these questions, some of which predict new resonances producing a γ +jet final state. Models of compositeness [2–4] address the existence of three fermion families, and other models address the origin of the hierarchy problem by predicting the existence of extra dimensions [5, 6].

The composite models postulate that the quarks and leptons are composed of more fundamental particles, known as “preons” [7]. These preons experience a new force that becomes very strong at the compositeness scale (Λ), when forming the quark and lepton composite states. This paper considers the excited states of composite quarks produced via gauge-mediated interactions with the dominant process $qg \rightarrow q^*$, and decaying to SM particles. It is assumed that the compositeness scale Λ is equal to the mass of the excited quark M_{q^*} .

The interactions between excited quarks, SM quarks, and the gauge bosons can be described by an effective Lagrangian [8]

$$\mathcal{L}_{\text{eff}} = \frac{1}{2\Lambda} \bar{q}^* \sigma^{\mu\nu} \left[g_s f_s \frac{\lambda_a}{2} F_{\mu\nu}^a + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right] q + \text{h.c.}, \quad (1)$$

where $\bar{q}^*$ is the right-handed excited quark field; $F_{\mu\nu}^a$, $W_{\mu\nu}$, and $B_{\mu\nu}$ are the field strength tensors associated with the SU(3), SU(2), and U(1) gauge fields, respectively; λ_a , τ , and Y are the corresponding Lie algebra generators; g_s , g , and g' are the gauge couplings; σ is the Pauli spin matrix; and f_s , f , and f' are coupling strengths between the excited quark and SM quarks. An assumption is also made that f_s , f , and f' have identical values and henceforth these coupling strengths will be collectively referred to as f .

In this paper we consider excited light-flavor quarks and bottom quarks (q^* and b^* , respectively) radiating a photon and thus resulting in the γ +jet final state. The corresponding Feynman diagram for the production and decay of the q^* , b^* signals through gauge mediation is shown in Fig. 1 (left). Additionally, an interpretation for b^* production from contact interactions (CI) [4] is also considered for the search of excited bottom quarks. Similar searches for excited quarks have been performed previously by the CMS [9–13] and ATLAS [14–17] Collaborations at the LHC and at other high-energy particle colliders [18–20] and have reported no evidence of a signal. Lately, the ATLAS and CMS experiments have set exclusion limits of 5.3 [15] and 5.5 TeV [13] on the mass of q^* in the γ +jet channel with data corresponding to 36 and 37 fb $^{-1}$ of integrated luminosity, respectively, collected at $\sqrt{s} = 13$ TeV.

In addition, we also consider the models of Arkani-Hamed, Dimopoulos, and Dvali (ADD) [5], and Randall–Sundrum (RS1) [6], which have extra spatial dimensions. The basic assumption of these models is that the fundamental gravitational scale (M_D) can be as low as 1 TeV, while the size of the extra dimensions can be as large as 1 millimeter, assuming the extra dimensions are only accessible to gravity and not to the SM fields. The ADD model assumes $(4 + n)$ dimensions with $n = 6$ flat compact extra dimensions, and RS1 considers $n = 1$ extra dimension with a warped metric. As a consequence, the models predict the production of microscopic black holes [21], which can be either semi-classical black holes or quantum black holes (QBHs) [22, 23]. In this model, the threshold mass M_{th} for production of a QBH at the LHC is assumed to be M_D , and the maximum mass limit is set to the smaller of either $3M_D$

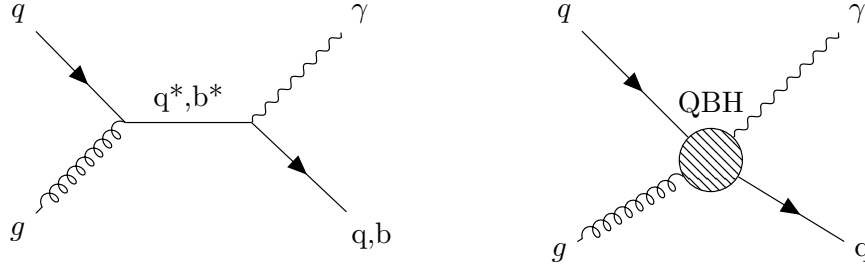


Figure 1: Illustrative Feynman diagrams for $qg \rightarrow \gamma + \text{jet}$ resonance signal models of q^*, b^* (left), and QBH production (right).

or $\sqrt{s} = 13$ TeV. A QBH with a mass in this range will decay preferentially to a few-particle state, rather than undergo thermal decay. The QBH production occurs with a continuous QBH mass spectrum, falling rapidly from M_{th} toward the maximum mass limit; however, because of radiation and experimental effects on the low-mass side of the mass spectrum, the signal shape resembles a resonance-like structure, as shown in Fig. 2. Previous searches for QBHs performed at $\sqrt{s} = 13$ TeV by the CMS and ATLAS experiments are reported in Refs. [10, 12, 15, 24–27]. This paper also reports the first search by the CMS experiment for QBHs in the $\gamma + \text{jet}$ final state (as shown in the Feynman diagram of Fig. 1 (right)). The ATLAS Collaboration has excluded QBH production in the $\gamma + \text{jet}$ channel with mass up to 7.1 (4.4) TeV in the ADD (RS1) model using 13 TeV data corresponding to 37 fb^{-1} of integrated luminosity [15].

The main background to this analysis are $\gamma + \text{jet}$ production, quantum chromodynamics (QCD) multijet production, and $W/Z + \gamma$ processes of the SM. The $\gamma + \text{jet}$ background is an irreducible background, and is the largest contributing. Despite its large cross section, the QCD multijet background is only the second largest, contributing when one of the jets fragments decays into an high energy π^0 decaying into two overlapping photons that are reconstructed as a single photon in the detector. Electroweak processes contribute to the background via the production of $W/Z + \gamma$, with the heavy boson decaying to a pair of jets, in the scenario where just one jet passes the selections or where one jet is reconstructed and the second jet is either merged with the first or escapes detection.

This search for excited quarks and QBHs is performed using proton-proton (pp) collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment, corresponding to an integrated luminosity of 138 fb^{-1} . The analysis strategy consists of searching for a resonance-like excess in the $\gamma + \text{jet}$ invariant mass, above the expected SM background.

This paper is organized as follows: Section 2 provides a brief description of the CMS detector. The triggers used for data selection are discussed in Section 3. In Section 4, the data sets and simulation samples used in this analysis are described. The event reconstruction and selection criteria are detailed in Section 5. The background estimation and systematic uncertainties are discussed in Sections 6 and 7, respectively. The results and their interpretation are presented in Section 8, followed by a summary given in Section 9. Tabulated results are provided in the HEPData record for this analysis [28].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. The muon detection system consists of a gas-ionization detector installed outside the solenoid and embedded in the steel flux-return yoke.

In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The energy resolution of the remaining barrel photons is about 1.3% up to $|\eta| = 1$, changing to about 2.5% at $|\eta| = 1.4$. In the endcaps, the energy resolution is about 2.5% for unconverted or late-converting photons, and between 3 and 4% for the other ones [29]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [30]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [31].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about $4\ \mu\text{s}$ [32]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [33].

3 Trigger selection

Events used in this analysis must pass a HLT single-photon trigger, which requires the photon transverse momentum p_T greater than 175 GeV in 2016, and greater than 200 GeV in 2017–2018. The higher p_T threshold in 2017–2018 is set to optimize available bandwidth and storage of events for offline analysis. The trigger also requires that the fraction of energy associated with the photon deposited in the HCAL is less than 15% of that deposited in the ECAL ($H/E < 0.15$). The efficiency of single-photon triggers is calculated using the single-photon data set with a low- p_T requirement and is found to be 99%. To calculate the possible bias on single-photon trigger due to any systematic detector effects, the efficiency is also calculated using jet- and muon-triggered independent data sets. The trigger efficiency with the independent data sets is found to be about 97–98% and the trigger inefficiency is taken as an estimate of systematic uncertainty.

4 Simulated data samples

The signal and background samples are obtained from event generators using Monte Carlo (MC) simulations. The signal samples for q^* and b^* are generated at leading order (LO) with the PYTHIA 8.205 (8.230) event generator [34] for 2016 (2017/2018) using coupling values $f = 1.0$, 0.5, and 0.1 and different resonance masses. The generated events are processed through the full CMS detector simulation based on GEANT4 [35]. Additional pp interactions in the same and nearby proton bunch crossings, referred to as pileup, are also simulated and a weight is applied to simulated events to reproduce the same pileup distribution as measured in data. The simulation uses the CUETP8M1 and CP5 underlying event tunes [36, 37] for 2016 and 2017–

2018 data sets, respectively, and renormalization (μ_R) and factorization scale (μ_F) corresponding to $\mu_R = \mu_F = \mu = p_T$ for the hard-scattered partons. The samples with the CUETP8M1 tune use the NNPDF3.0 LO [38] parton distribution functions (PDFs), while simulated samples generated with the CP5 tune use the NNPDF3.1 next-to-next-LO [39] PDFs. For b^* signals, only events with M_{b^*} within $\pm 20\%$ of the input M_{b^*} are considered in order to avoid sizable off-shell nonresonant contributions, which are otherwise present for high- M_{b^*} scenarios with coupling parameters $f = 0.5$ and 1.0 but do not contribute to the search sensitivity. The signals for intermediate mass values are extracted with an interpolation technique at intervals of 0.1 TeV.

The QBH signal events in the ADD ($n = 6$) and the RS1 ($n = 1$) models are generated with the QBH generator [40] version v3.0 using CTEQ6L [41] PDFs. The signals are generated for masses ranging from 3.0 to 8.5 TeV for the ADD model and from 2.0 to 7.0 TeV for the RS1 model at intervals of 0.5 TeV. The γ +jet mass distribution for QBH is similar between the RS1 and ADD models; therefore, the RS1 simulated sample is used for the ADD model for $M_{\text{th}} < 3$ TeV. The resonance shapes for q^* , b^* , and QBH for the ADD ($n = 6$) and RS1 ($n = 1$) models for a mass of 4 TeV are shown in Fig. 2.

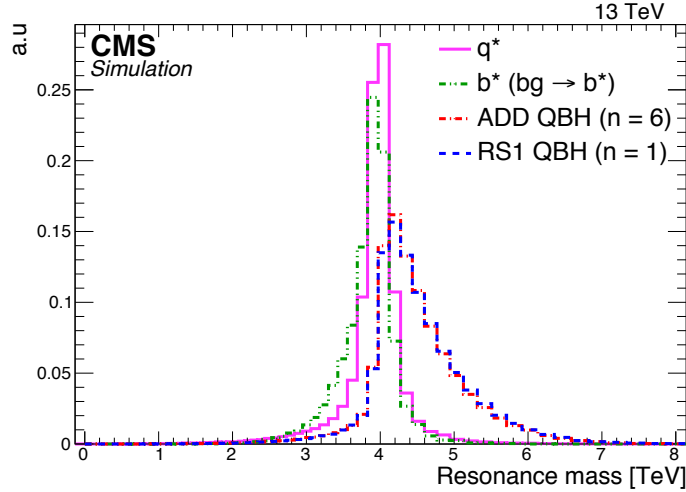


Figure 2: Distributions of reconstructed γ +jet invariant mass for the q^* and b^* signal models with resonance mass of 4 TeV, and for QBH from the ADD and RS1 models with $M_{\text{th}} = 4$ TeV.

Figure 3 shows the product of the cross section (σ) and branching fraction $\mathcal{B}$ for the production at $\sqrt{s} = 13$ TeV of the photon and jet final state as a function of the resonance mass, for excited quark models, or the threshold mass, for QBH models.

The γ +jet, Drell–Yan, and W +jet background are simulated using the MADGRAPH5_aMC@NLO version 2.2.2 (2.4.2) generators for 2016 (2017–2018) [42] at LO in QCD with the MLM matching scheme [43] between jets produced via matrix element calculations and from parton showers. The QCD multijet background simulation is obtained at LO with the PYTHIA generator using version 8.205 (8.230) for 2016 (2017–2018). Hadronization and parton showering of all simulated samples are performed using the PYTHIA program versions 8.205 and 8.230 with the CUETP8M1 and CP5 tunes, respectively.

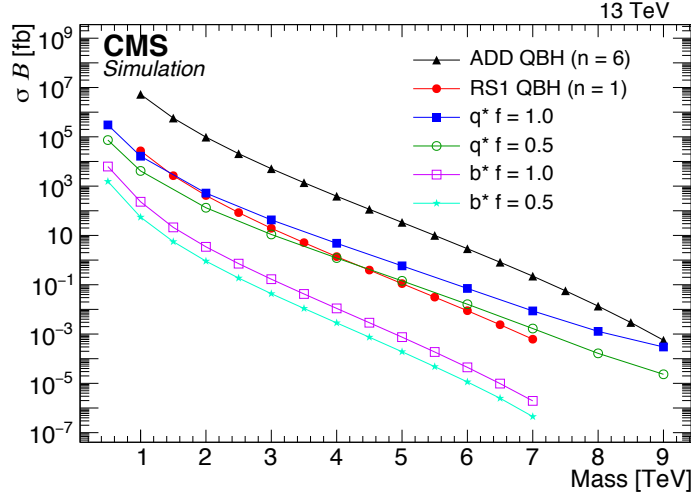


Figure 3: The product of the cross section and branching fraction, $\sigma\mathcal{B}$, as a function of the resonance mass of q^* or b^* signals (M_{q^*} or M_{b^*}) or the threshold mass of QBH signal models (M_{th}).

5 Event reconstruction and selection

The particle-flow (PF) algorithm [44] reconstructs and identifies photons, electrons, muons, charged and neutron hadrons (called PF candidates), with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL detector. The clusters of energy deposited in the ECAL are combined together within a defined geometric area to form a supercluster around the seed cluster [45]. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with their origin from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker with the matched ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are reconstructed from PF candidates using the infrared- and collinear-safe anti- k_T algorithm [46, 47] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole p_T spectrum and detector acceptance. Pileup interactions can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle level jets on average. In situ measurements of the momentum balance in dijet, γ +jet, Z+jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [30].

The primary vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [48].

Candidate events are required to have at least one photon with transverse momentum $p_T^\gamma > 240$ GeV in the barrel region ($|\eta^\gamma| < 1.44$) of the detector. At the p_T^γ threshold of 240 GeV, the trigger is more than 95% efficient. The photon with the highest p_T is selected as the candidate photon in the event. To reject jets misreconstructed as photons, candidate photons are required to satisfy identification and isolation requirements [45] having a selection efficiency of 80% on signal-like events. The requirements placed on the identification and isolation variables are the following:

- The ratio H/E of the energy deposited in the single HCAL tower behind the ECAL supercluster seed crystal over the total supercluster energy in ECAL within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.15$ centered around the supercluster must be less than 0.021.
- The transverse η spread of the shower shape ($\sigma_{i\eta i\eta}$) [45] must be less than 0.01. This variable differentiates between prompt photons and photons from π^0 decays.
- The p_T sum of the charged hadrons within a cone of radius $\Delta R = 0.3$ around the photon must be less than 1.14 GeV.
- The p_T sum of the neutral hadrons within a cone of $\Delta R = 0.3$ around the photon must be less than $1.19 \text{ GeV} + 0.015 p_T^\gamma + 2.26 \times 10^{-5} (p_T^\gamma)^2 / \text{GeV}$.
- The p_T sum of additional photons within a cone of $\Delta R = 0.3$ around the photon candidate must be less than $2.08 \text{ GeV} + 0.0040 p_T^\gamma$.
- An electron veto must also be applied to remove photon candidates in the cases where the candidate's supercluster is matched to a reconstructed electron's track that has no missing hits in the innermost tracker layers.

The observed difference between data and MC simulation in the efficiency for photon identification and isolation is accounted for by applying a data-to-simulation scale factor, as a function of p_T and η [45].

Each candidate event is also required to have at least one jet that passes identification criteria in order to remove spurious jets arising from detector noise [49]. Among the selected jets, a list of jets having at least $p_T^{\text{jet}} > 30$ GeV and $|\eta^{\text{jet}}| < 3.0$ is made in decreasing order of p_T . Setting a minimum value for p_T^{jet} reduces the number of pileup jets in the selected events.

The jets passing all the above criteria and calibrated as discussed above are clustered to form wide jets. The clustering captures final-state radiation and improves the γ +jet invariant mass resolution. To construct wide jets, the highest p_T jet is used as a seed jet, and other jets are merged with it if they are within $\Delta R < 1.1$. The jets are merged by adding the four momenta of jets. The resultant jet is stored as a wide jet and the constituent jets are removed from the jet list. The procedure is repeated with the remaining highest p_T jet as a seed jet to form the next wide jet. These clustered wide jets are ordered in p_T and the highest one is used as the final jet candidate to study signal-like characteristics, such as the invariant mass of the photon and jet. The use of wide jets improves the mass resolution in the q^*/b^* signal by 1.0–1.3% over the entire mass range considered in this analysis. The leading wide jet is required to have $p_T(\text{wide jet}) > 170$ GeV with $|\eta(\text{wide jet})| < 2.4$. The final selected photon and wide-jet candidates are required to be separated by $\Delta R > 1.1$ and to be back-to-back in the azimuthal angle ϕ .

A large reduction in the number of QCD multijet events is achieved by the requirements on photon isolation. To suppress this background further, an additional requirement of $|\Delta\eta| < 1.5$ is imposed on the photon and wide-jet system. This requirement mainly reduces QCD

dijet events produced by t -channel processes, which have a relatively large spread in $\Delta\eta$. If a leading wide-jet (or photon) candidate fails any of the selections described above, the event is discarded. The events selected are assigned to the "inclusive category" for the q^* and QBH signal searches.

The b^* signal search separates the data sets into two categories based on the identification of jets originating from b quarks (b jets). The identification of b jets is performed using the neural network-based DEEPJET tagger [50, 51] at an operating point with 75% b quark efficiency and 1% light quarks misidentification probability. b tag category (events with at least 1 b tagged jet) and 0- b tag category (events without any b tagged jet). The sensitivity of the b^* signal search is improved by combining the results of the 0- b tag category and of the b tag category. This is done to mitigate the effect of a slightly reduced acceptance of the b tag category at higher masses.

The wide-jet, in the case of a b^* , is constructed with the same process described previously, but with an additional requirement that at least one of the constituent jets within $\Delta R < 1.1$ must pass the b tag discriminator selection and fall into the b tag category. This jet will be referred to as a b -tagged jet. In a wide-jet, there could be one, or more b -tagged jets and also light jets. The simulated distributions in both b tag and 0- b tag categories are weighted using scale factors (SF) that account for differences between data and simulation in the b tagging efficiencies.

To avoid the turn-on region in the photon + wide-jet invariant mass distribution that arises due to the various kinematic selections, only events with $m_{\gamma+\text{jet}} > 0.76$ TeV are considered, where γ +jet denotes the photon and wide-jet system. The products of acceptance and efficiency for the q^*/b^* and QBH (ADD/RS1) signals are shown in Fig. 4 for the years 2016, 2017, and 2018. For the ADD and RS1 signals with mass $M_{\text{th}} > 5$ TeV, the reduction in the product of acceptance and efficiency mainly comes from the application of photon isolation criteria. In the following sections, we will refer to wide-jets simply as jets.

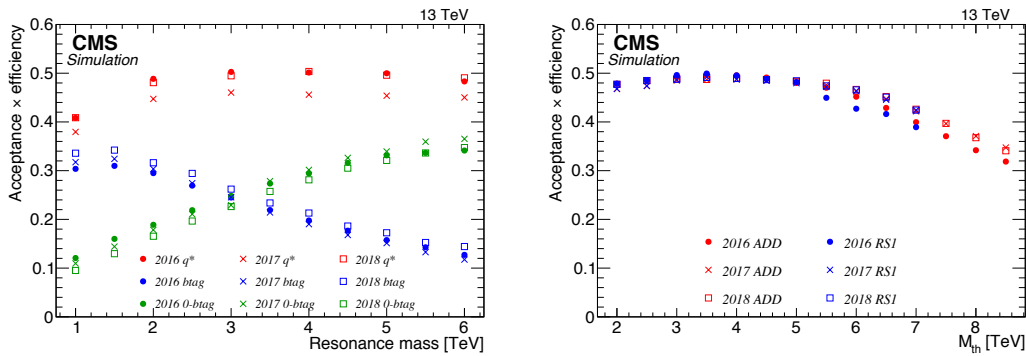


Figure 4: The product of acceptance and efficiency for the q^* signal in the inclusive category and the b^* signal in the b tag and 0- b tag categories, for SM coupling $f = 1.0$ and for different resonance values (left), and the signal for the QBH (ADD/RS1) model in the inclusive category, for different M_{th} values (right), for the years 2016, 2017, and 2018.

6 Signal and background modeling

The background is estimated directly from data. However, MC-simulated background samples are used to perform optimization studies for the event selection and validation of various data distributions.

To extract the background from data, the γ +jet mass spectrum is parameterized with the following empirical functional form

$$\frac{d\sigma}{dm} = \frac{P_0(1 - m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3\ln(m/\sqrt{s})}}, \quad (2)$$

where P_0 , P_1 , P_2 , and P_3 are the fit parameters, and $\sqrt{s} = 13$ TeV. The search uses the signal plus background fit method, where the mass spectrum is fitted with this functional form and the signal template is obtained from simulation. The parameters P_0 , P_1 , P_2 , and P_3 in this functional form are kept floating. This same functional form has also been used in a number of earlier searches [9, 11, 13, 14, 20] to describe the SM background distribution. The fitting range for the q^* , b^* , and RS1 signal is $0.76 < m_{\gamma+\text{jet}} < 8.40$ TeV while for the ADD signal interpretation, where a better signal sensitivity is reached, it is extended up to 9.4 TeV.

The invariant mass distributions for the γ +jet and γ +b jet channels, after all selections, are shown in Figs. 5 and 6, respectively. The bin size of the mass distribution is varied to match the γ +jet mass resolution, which is approximately 4.5% at 1 TeV and 3.3% at 6 TeV.

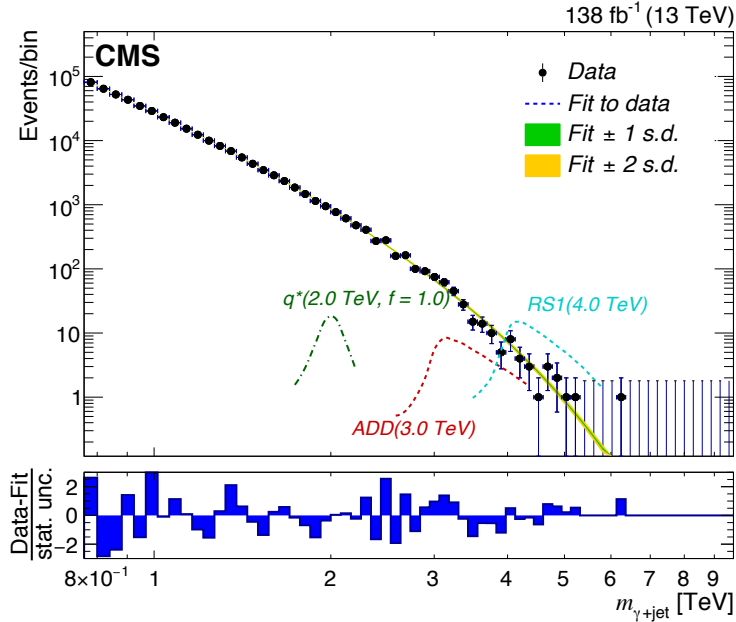


Figure 5: Fit to the γ +jet invariant mass distribution in data with Eq. (2) for the “inclusive” category of q^* and QBH after all selections. Simulations of the q^* signal with a 2 TeV mass and coupling $f = 1.0$, the QBH ADD signal with $M_{\text{th}} = 3$ TeV, and the QBH RS1 signal with $M_{\text{th}} = 4$ TeV are also shown. The lower panel shows the difference between the data yield and the background prediction divided by the statistical uncertainty of the data. The green (inner) and yellow (outer) bands, respectively, represent the 68 and 95% confidence level statistical uncertainties in the fit.

Alternative polynomial functions with 4 and 5 parameters are also considered, to evaluate any possible bias due to the chosen functional form shown in Eq. (2). The choice of the background function is made on the basis of the results of the Fisher test [52]. The procedure used to evaluate the possible bias is the following: pseudo-experiment data distributions are generated for a given alternative function that is fitted to the invariant mass distribution of the SM background and injecting the signal of cross section corresponding to a value of 95% confidence

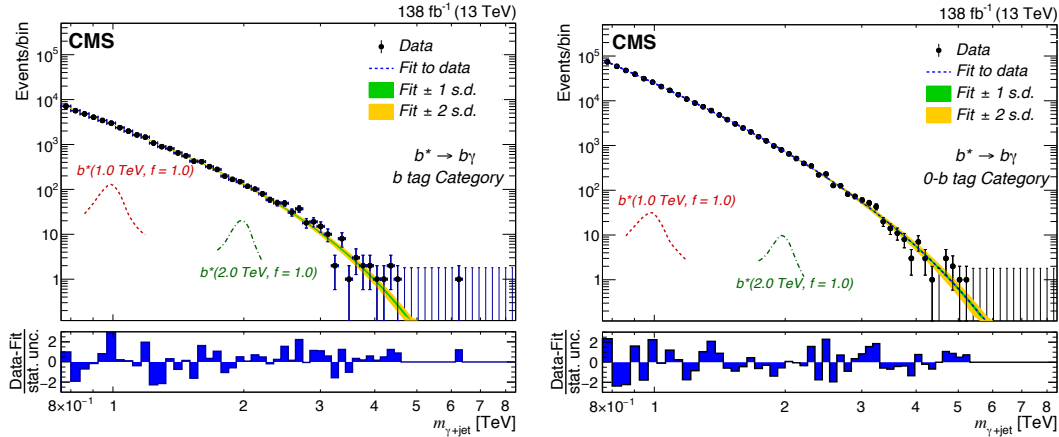


Figure 6: Fits to the γ +jet invariant mass distributions in data with Eq. (2) for the b^* selection for the b tag category (left) and 0- b tag category (right). Simulations of b^* signals are shown for mass values of 1.0 and 2.0 TeV and for $f = 1.0$. The lower panel shows the difference between the data yield and background prediction divided by the statistical uncertainty of the data. The green (inner) and yellow (outer) bands, respectively, represent the 68 and 95% confidence level statistical uncertainties in the fit.

level (CL) expected limit to it. These pseudo-experiment mass distributions are then fitted with the functional form shown in Eq. (2) using the maximum log likelihood approach to obtain the fitted signal cross section. The possible bias due to the choice of the function is estimated by constructing pull distributions for each mass hypothesis and for each alternative fit function, where the pull is the difference between the injected and extracted signal cross section divided by statistical uncertainty of extracted signal cross section. The pull distributions are found to have a mean bias of less than one half standard deviation for the normalized Gaussian form. A bias of this magnitude is considered acceptable since it contributes $\sim 11\%$ to the total uncertainty when added in quadrature with the statistical uncertainty and has a negligible effect on the sensitivity to signal.

To test the goodness-of-fit for the function used for the alternate fit functions and for the function described in Eq. (2), two different test statistics, the log-likelihood ratio and χ^2 , are used. The test is performed by generating 1000 pseudo-datasets from the best fit model parameters, and each pseudo-dataset is refitted with a maximum log likelihood fit. The estimated p -value [53] for the test statistic is found to be greater than 5% for all the alternative fit functions.

7 Systematic uncertainties

The systematic uncertainties due to various sources can affect both the normalization and the shape of the mass distribution. The dominant source of uncertainty comes from the parametrization of the background fit to data. The background uncertainties are considered as floating nuisance parameters, while the uncertainties in the signal predictions are implemented either as log-normal or Gaussian constraints on the nuisance parameters.

The signal yield and shape are affected by the uncertainties related to the energy or momentum measurements for the reconstructed photons and jets.

To evaluate the effect of uncertainties in wide jets, the jet-related uncertainties are first applied

to the constituent jets. The jet energy scale and jet energy resolution effects are measured by applying the respective ± 1 standard deviation uncertainties in the four-momenta of the constituent jets and reconstructing the mass of the γ +jet system. The effects of the jet energy scale and resolution on the mean and width of the signal shape are found to be in the range 1.0–2.0%.

The photon energy scale and photon energy resolution are measured with $Z \rightarrow e^+e^-$ events, with the electrons reconstructed as photons, using the procedure described in Ref. [45]. The uncertainties in the photon energy scale and photon energy resolution translate into a variation of 1.0–1.5% in the signal mean and width. The uncertainty associated with the photon identification inefficiency due to the extrapolation at very high p_T is taken to be about 10%, which covers all related systematic effects in the procedure used in its measurement.

The b^* signal shape mean and yield have 0.2–3.0% and 7.9–14.3% uncertainties, respectively, obtained by varying the b tagging SF within its ± 1 standard deviation uncertainty. The other sub-dominant uncertainties for the b^* signal shape and normalization are found to be of the order of 1.0–2.0%, as in the case of q^* .

To account for the uncertainty in the HLT inefficiency as discussed in Section 3, a 2.5% systematic uncertainty is used.

The uncertainties associated with the integrated luminosity measurement [54–56] and pileup are also considered. The integrated luminosities of the 2016, 2017, and 2018 data-taking periods are individually known with uncertainties in the 1.2–2.5% range, while the total 2016–2018 integrated luminosity has an uncertainty of 1.6%, used in this paper. The uncertainty due to pileup is calculated by varying the inelastic cross section of 69.4 mb [57] by $\pm 5\%$ and its impact is estimated to be $\sim 0.1\%$ on the signal yield. The uncertainty in the signal shapes due to interpolation for intermediate masses is considered to be $\sim 1\%$, evaluated by comparing the interpolated mass shape with the corresponding generated mass point.

The statistical interpretation considers the systematic uncertainties to be fully correlated among different data-taking years, except for the integrated luminosity uncertainty, which is partially correlated between the years. The effect of uncorrelated systematic uncertainties is also studied by taking the respective uncertainties for each data set separately and obtaining the results again. The results obtained are found to be similar to the case when fully correlated systematic uncertainties are considered for all years.

The details of systematic uncertainties and their relative effects on the shape and normalization are listed in Table 1.

Table 1: Systematic uncertainties in the signal yields for the mass range analyzed.

Source	Type	Uncertainty	Applied to ($q^*/b^*/QBH$)
Integrated luminosity	Normalization	1.6%	All
Jet energy scale	Shape (mean)	$\sim 1.0\%$	All
Jet energy resolution	Shape (width)	0.6–1.9%	All
Photon energy scale	Shape (mean)	$\sim 1.0\%$	All
Photon energy resolution	Shape (width)	0.4–1.2%	All
Pileup	Normalization	0.1%	All
High- p_T photon efficiency	Normalization	$\sim 10.0\%$	All
HLT efficiency	Normalization	2.5%	All
Signal shape interpolation	Shape (mean)	$\sim 1.0\%$	All
b tag SF uncertainty	Shape (mean)	0.2–3.0%	Only b^*
b tag SF uncertainty	Normalization	7.9–14.3%	Only b^*

8 Results and interpretation

The observed mass spectrum is found to be consistent with the background-only prediction. We set limits on potential signals by using a CL_s approach [58, 59] based on an asymptotic approximation [60, 61] of the multibin counting experiment likelihood, taken to be a product of Poisson distributions corresponding to individual bins:

$$\mathcal{L}(\text{data}|\mu, \theta) = \prod_{i=1}^{n_{\text{bin}}} \text{P}(x_i | s_i(\mu, \theta) + b_i(\theta)) C(\theta), \quad (3)$$

where P stands for the Poisson probability to observe x_i data events in the i^{th} bin, C represents a constraint term for the nuisance parameters (θ) associated with the systematic uncertainties, μ is the signal strength (parameter of interest), $s_i(\mu, \theta)$ the corresponding signal yield, $b_i(\theta)$ the corresponding background yield, and the product runs over the number of bins (n_{bin}). The systematic uncertainties are considered as nuisance parameters with log-normal constraints on the integrated luminosity and trigger efficiency, and Gaussian constraints on the energy scales and resolutions for the photon and jet. The observed and expected limits are computed and shown in Figs. 7–9 in terms of the product of the cross-section and the branching fraction, $\sigma\mathcal{B}$.

The observed (expected) lower limits on M_{q^*} are found to be 6.0 (6.0), 5.4 (5.2) and 2.4 (2.8) TeV for the coupling strength $f = 1.0, 0.5$, and 0.1 , respectively.

For the b^* resonance search with the process $bg \rightarrow b^* \rightarrow b\gamma$, the observed (expected) lower bounds are 2.2 (2.3) and 1.6 (1.7) TeV for a coupling strength of $f = 1.0$ and 0.5 , respectively. For $f = 0.1$, the analysis did not have sufficient sensitivity to set a mass limit. For b^* production via CI, several processes contribute, with the dominant one being $q\bar{q} \rightarrow \bar{b}b^*$ (or $b\bar{b}^*$) $\rightarrow \bar{b}b\gamma$. Using the same exclusion limit for the $bg \rightarrow b^*$ signal with $f = 1.0$, the observed lower bound on the b^* mass is 3.8 TeV when combining both the processes (b^* produced via gauge interaction and the resonant component of b^* via CI) in the total signal cross section, as shown in Fig. 8 (upper left).

For the QBH search with the ADD (RS1) model with $n = 6$ (1) extra dimensions, the observed lower bound is set to 7.5 (5.2) TeV and the expected exclusion limits are estimated to have the same values. In comparison to q^* , the limits are weaker for b^* resonances and QBH resonances at higher masses.

The two-dimensional representation of the excluded mass region for excited quarks (q^* and b^*) as a function of the coupling strength f , with the assumption $M_{q^*} = \Lambda$, is shown in Fig. 10. The exclusion of the excited quark mass, as a function of M_{q^*}/Λ , is also presented in the same figure on the right hand axis. The excluded M_{q^*} region could also be interpreted in terms of the M_{q^*}/Λ ratio; this interpretation is based on the fact that the detector resolution effects dominate compared to the change in the signal intrinsic width ($\Gamma_{q^*} \sim 0.03f^2M_{q^*}$) [4] arising from the change in the coupling strength f . Consequently, the variation of f effectively changes the production cross section in a similar way to the variations in M_{q^*}/Λ , since both appear as multiplicative factors in the cross section calculation.

9 Summary

A search for resonances in the γ +jet final state has been performed using proton-proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1} . The results are compared with standard model extensions postulating excited quarks, excited b quarks, and quantum black holes.

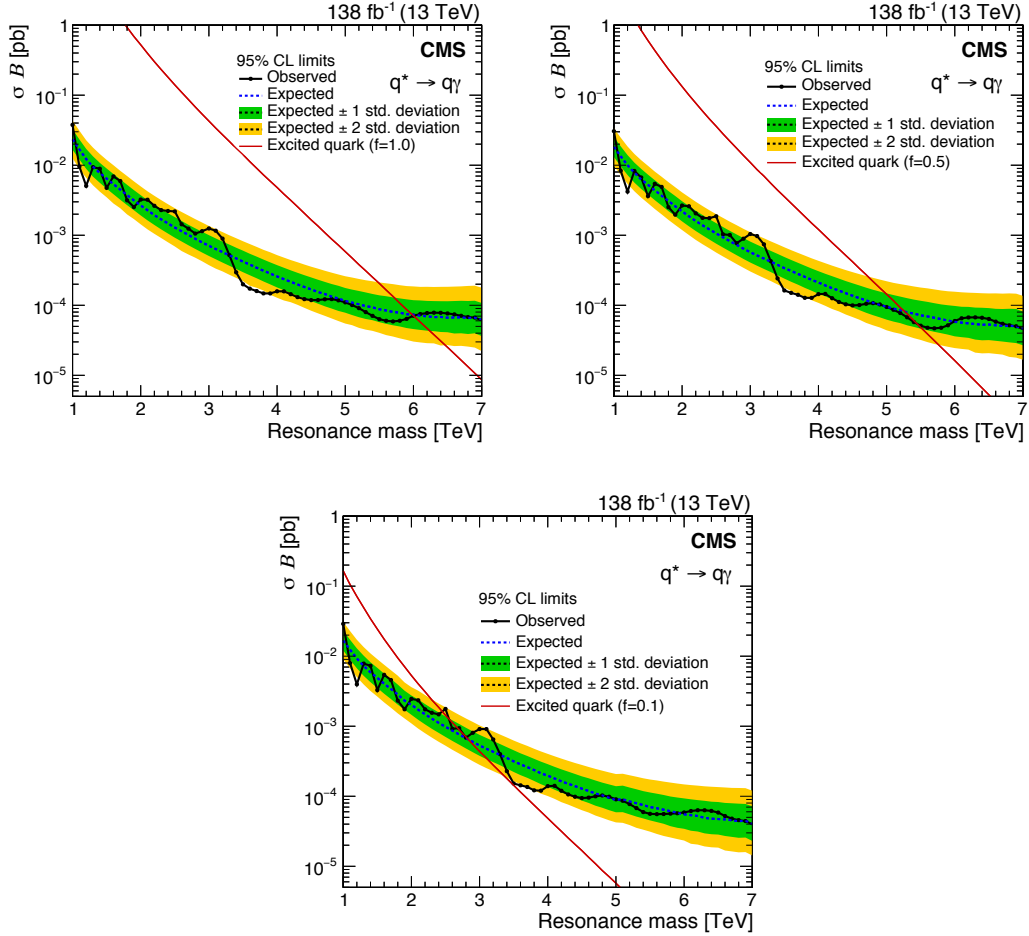


Figure 7: The expected (dashed) and observed (solid) 95% CL upper limits on the product of the cross section and branching fraction, as functions of q^* mass, for coupling strength $f = 1.0$ (upper left), $f = 0.5$ (upper right), and $f = 0.1$ (lower). The green (inner) and yellow (outer) bands correspond to 1 and 2 standard deviation uncertainties in the expected limit, respectively. The limits are compared with the theoretical predictions for q^* production for the corresponding coupling strengths.

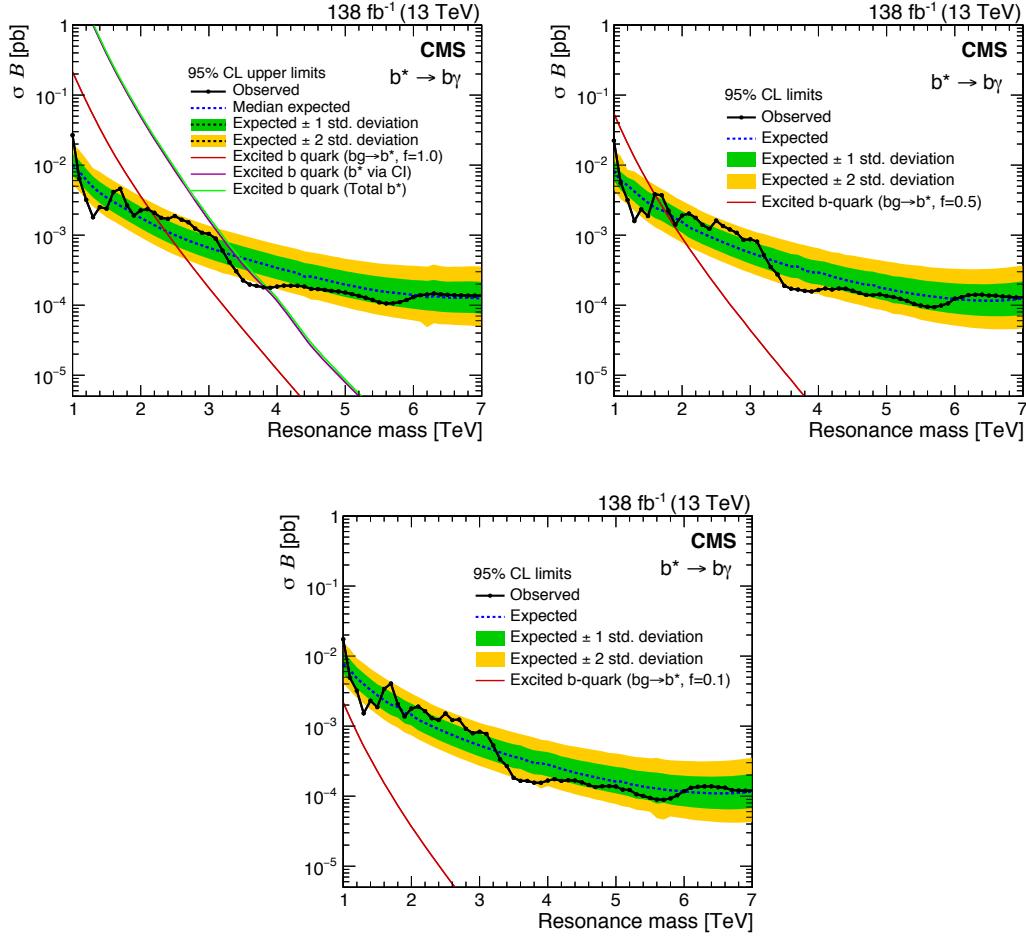


Figure 8: The expected (dashed) and observed (solid) 95% CL upper limits on the product of the cross section and branching fraction, as functions of b^* mass, for coupling strength $f = 1.0$ (upper left), $f = 0.5$ (upper right), and $f = 0.1$ (lower). The green (inner) and yellow (outer) bands correspond to 1 and 2 standard deviation uncertainties in the expected limit, respectively. The limits are compared with the theoretical predictions for b^* production for the corresponding coupling strengths. For coupling $f = 1.0$, the limits are compared for b^* production by gauge interactions (red), contact interactions (violet), and total b^* signal by the addition of these two production modes.

For the coupling strength $f = 1.0$, the observed (expected) lower mass bounds on the excited light-flavor quarks and excited bottom quarks from gauge interactions are estimated to be 6.0 (6.0) and 2.2 (2.3) TeV, respectively. For the same coupling strength, the observed lower mass bounds on the excited bottom quarks extends to 3.8 TeV, when the production mode from contact interactions is also considered. For quantum black hole production, observed exclusion limits are estimated to be 7.5 and 5.2 TeV for the Arkani-Hamed–Dimopoulos–Dvali and the Randall–Sundrum models with 6 and 1 extra dimensions, respectively. These lower mass bounds are the most stringent to date among those obtained in the γ -jet final state.

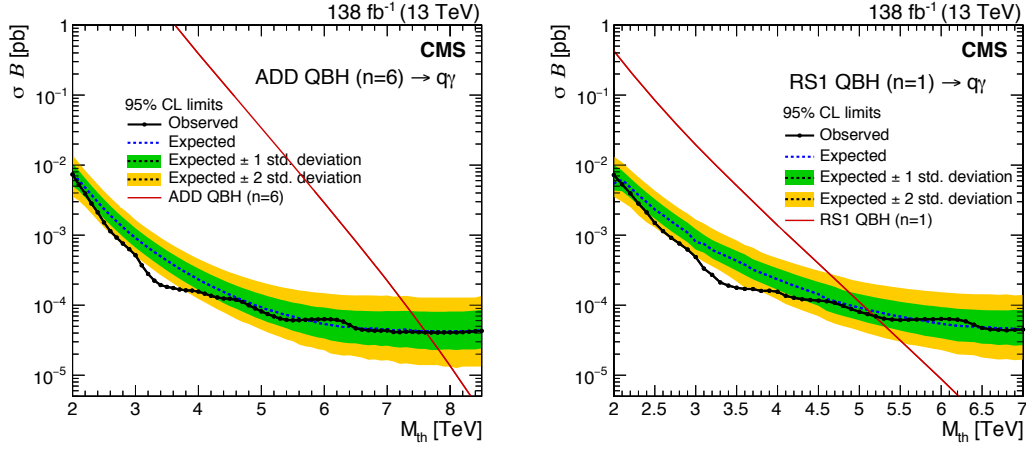


Figure 9: The expected (dashed) and observed (solid) 95% CL upper limit on the product of the cross section and branching fraction as a function of the minimum black hole mass for the ADD ($n = 6$) and RS1 ($n = 1$) models on the left and right, respectively. The green (inner) and yellow (outer) bands correspond to 1 and 2 standard deviation uncertainties in the expected limit. The limits are compared with the theoretical predictions for QBH production for ADD ($n = 6$) and RS1 ($n = 1$) models.

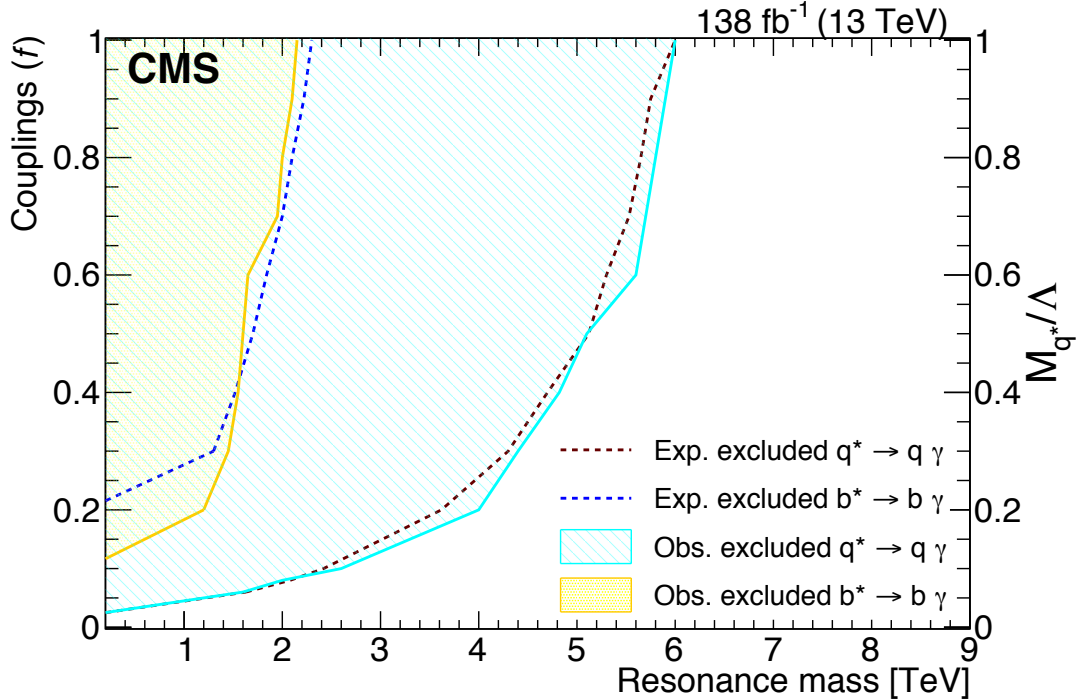


Figure 10: The expected and observed 95% CL exclusion mass limit variation with the SM couplings for the excited q^* and b^* signal models.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other

CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] M. Shaposhnikov and A. Shkerin, “Gravity, scale invariance and the hierarchy problem”, *JHEP* **10** (2018) 024, doi:10.1007/JHEP10(2018)024, arXiv:1804.06376.
- [2] W. Buchmuller, “Composite quarks and leptons”, *Acta Phys. Austriaca Suppl.* **27** (1985) 517, doi:10.1007/978-3-7091-8830-9_8.
- [3] U. Baur, I. Hinchliffe, and D. Zeppenfeld, “Excited quark production at hadron colliders”, *Int. J. Mod. Phys. A* **2** (1987) 1285, doi:10.1142/S0217751X87000661.
- [4] U. Baur, M. Spira, and P. M. Zerwas, “Excited quark and lepton production at hadron colliders”, *Phys. Rev. D* **42** (1990) 815, doi:10.1103/PhysRevD.42.815.
- [5] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, “The hierarchy problem and new dimensions at a millimeter”, *Phys. Lett. B* **429** (1998) 263, doi:10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315.
- [6] L. Randall and R. Sundrum, “A large mass hierarchy from a small extra dimension”, *Phys. Rev. Lett.* **83** (1999) 3370, doi:10.1103/PhysRevLett.83.3370, arXiv:hep-ph/9905221.
- [7] I. A. D’Souza and C. S. Kalman, “Preons: models of leptons, quarks and gauge bosons as composite objects”. World Scientific, 1992. doi:10.1142/1700.
- [8] S. Bhattacharya, S. S. Chauhan, B. C. Choudhary, and D. Choudhury, “Quark excitations through the prism of direct photon plus jet at the LHC”, *Phys. Rev. D* **80** (2009) 015014, doi:10.1103/PhysRevD.80.015014, arXiv:0901.3927.
- [9] CMS Collaboration, “Search for excited quarks in the γ +jet final state in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Phys. Lett. B* **738** (2014) 274, doi:10.1016/j.physletb.2014.09.048, arXiv:1406.5171.
- [10] CMS Collaboration, “Search for resonances and quantum black holes using dijet mass spectra in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Phys. Rev. D* **91** (2015) 052009, doi:10.1103/PhysRevD.91.052009, arXiv:1501.04198.
- [11] CMS Collaboration, “Search for narrow resonances decaying to dijets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **116** (2016) 071801, doi:10.1103/PhysRevLett.116.071801, arXiv:1512.01224.
- [12] CMS Collaboration, “Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **05** (2020) 033, doi:10.1007/JHEP05(2020)033, arXiv:1911.03947.
- [13] CMS Collaboration, “Search for excited quarks of light and heavy flavor in γ +jet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **781** (2018) 390, doi:10.1016/j.physletb.2018.04.007, arXiv:1711.04652.
- [14] ATLAS Collaboration, “Search for new phenomena with photon+jet events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **03** (2016) 041, doi:10.1007/JHEP03(2016)041, arXiv:1512.05910.
- [15] ATLAS Collaboration, “Search for new phenomena in high-mass final states with a photon and a jet from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **78** (2018) 102, doi:10.1140/epjc/s10052-018-5553-2, arXiv:1709.10440.

- [16] ATLAS Collaboration, “Search for resonances in the mass distribution of jet pairs with one or two jets identified as b-jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Rev. D* **98** (2018) 032016, doi:10.1103/PhysRevD.98.032016, arXiv:1805.09299.
- [17] ATLAS Collaboration, “Search for new resonances in mass distributions of jet pairs using 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *JHEP* **03** (2020) 145, doi:10.1007/JHEP03(2020)145, arXiv:1910.08447.
- [18] CDF Collaboration, “Search for excited quarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV”, *Phys. Rev. Lett.* **72** (1994) 3004, doi:10.1103/PhysRevLett.72.3004.
- [19] CDF Collaboration, “Search for new particles decaying to dijets at CDF”, *Phys. Rev. D* **55** (1997) 5263, doi:10.1103/PhysRevD.55.R5263, arXiv:hep-ex/9702004.
- [20] CDF Collaboration, “Search for new particles decaying into dijets in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV”, *Phys. Rev. D* **79** (2009) 112002, doi:10.1103/PhysRevD.79.112002, arXiv:0812.4036.
- [21] S. Dimopoulos and G. L. Landsberg, “Black holes at the LHC”, *Phys. Rev. Lett.* **87** (2001) 161602, doi:10.1103/PhysRevLett.87.161602, arXiv:hep-ph/0106295.
- [22] X. Calmet, W. Gong, and S. D. H. Hsu, “Colorful quantum black holes at the LHC”, *Phys. Lett. B* **668** (2008) 20, doi:10.1016/j.physletb.2008.08.011, arXiv:0806.4605.
- [23] P. Meade and L. Randall, “Black holes and quantum gravity at the LHC”, *JHEP* **05** (2008) 003, doi:10.1088/1126-6708/2008/05/003, arXiv:0708.3017.
- [24] CMS Collaboration, “Search for black holes in high-multiplicity final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **774** (2017) 279, doi:10.1016/j.physletb.2017.09.053, arXiv:1705.01403.
- [25] CMS Collaboration, “Search for new physics with dijet angular distributions in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2017) 013, doi:10.1007/JHEP07(2017)013, arXiv:1703.09986.
- [26] CMS Collaboration, “Search for new physics in dijet angular distributions using proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on dark matter and other models”, *Eur. Phys. J. C* **78** (2018) 789, doi:10.1140/epjc/s10052-018-6242-x, arXiv:1803.08030. [Erratum: doi:10.1140/epjc/s10052-022-10278-0].
- [27] ATLAS Collaboration, “Search for new phenomena in dijet events using 37 fb^{-1} of pp collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Rev. D* **96** (2017) 052004, doi:10.1103/PhysRevD.96.052004, arXiv:1703.09127.
- [28] “HEPData record for this analysis”, 2023. <https://www.hepdata.net/record/139903>.
- [29] CMS Collaboration, “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P08010, doi:10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.
- [30] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

-
- [31] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [32] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [33] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [34] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [35] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [36] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [37] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [38] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [39] NNPDF Collaboration, “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [40] D. M. Gingrich, “Quantum black holes with charge, colour, and spin at the LHC”, *J. Phys. G* **37** (2010) 105008, doi:10.1088/0954-3899/37/10/105008, arXiv:0912.0826.
- [41] J. Pumplin et al., “New generation of parton distributions with uncertainties from global QCD analysis”, *JHEP* **07** (2002) 012, doi:10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.
- [42] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [43] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [44] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [45] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.

- [46] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [47] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [48] CMS Collaboration, “Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid”, CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, 2015.
- [49] CMS Collaboration, “Jet algorithms performance in 13 TeV data”, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017.
- [50] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [51] E. Bols et al., “Jet flavour classification using DeepJet”, *JINST* **15** (2020) P12012, doi:10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.
- [52] R. A. Fisher, “On the interpretation of χ^2 from contingency tables, and the calculation of p ”, *J. Roy. Stat. Soc.* **85** (1922) 87, doi:10.2307/2340521.
- [53] E. Gross and O. Vitells, “Trial factors for the look elsewhere effect in high energy physics”, *Eur. Phys. J. C* **70** (2010) 525, doi:10.1140/epjc/s10052-010-1470-8, arXiv:1005.1891.
- [54] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [55] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [56] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [57] CMS Collaboration, “Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.
- [58] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [59] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [60] LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011.
- [61] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].



Quality control of mass-produced GEM detectors for the CMS GE1/1 muon upgrade[☆]

M. Abbas¹⁴, M. Abbrescia^{19,20}, H. Abdalla^{8,10}, A. Abdelalim^{8,11,a}, S. AbuZeid^{8,9}, A. Agapitos⁴, A. Ahmad³⁴, A. Ahmed¹⁷, W. Ahmed³⁴, C. Aimè^{26,27}, C. Aruta^{19,20}, I. Asghar³⁴, P. Aspell³⁸, C. Avila⁶, J. Babbar¹⁶, Y. Ban⁴, R. Band⁴⁰, S. Bansal¹⁶, L. Benussi²³, T. Beyrouthy³², V. Bhatnagar¹⁶, M. Bianco³⁸, S. Bianco²³, K. Black⁴³, L. Borgonovi^{21,22}, O. Bouhali³⁹, A. Braghieri^{26,27}, S. Braibant^{21,22}, S.D. Butalla^{44,*}, S. Calzaferri^{26,27}, M. Caponero²³, J. Carlson⁴², F. Cassese^{24,25}, N. Cavallo^{24,25}, S.S. Chauhan¹⁶, S. Colafranceschi²³, A. Colaleo^{19,20}, J. Collins⁴⁴, A. Conde Garcia³⁸, M. Dalchenko³⁹, A. De Iorio^{24,25}, G. De Lentdecker¹, D. Dell'Olio^{19,20}, G. De Robertis^{19,20}, W. Dharmaratna³⁷, S. Dildick^{39,b}, B. Dorney¹, R. Erbacher⁴⁰, F. Fabozzi^{24,25}, F. Fallavollita³⁸, A. Ferraro^{26,27}, D. Fiorina^{26,27}, E. Fontanesi^{21,22}, M. Franco^{19,20}, C. Galloni⁴³, P. Giacomelli^{21,22}, S. Gigli^{26,27}, J. Gilmore³⁹, M. Gola¹⁷, M. Gruchala³⁸, A. Gutierrez⁴¹, T. Hakkarainen¹², J. Hauser⁴², K. Hoepfner¹³, M. Hohlmann⁴⁴, H. Hoorani³⁴, T. Huang³⁹, P. Iaydjiev³, A. Irshad¹, A. Iorio^{24,25}, F. Ivone¹³, W. Jang³¹, J. Jaramillo⁷, A. Juodagalvis³³, E. Juska³⁹, B. Kailasapathy^{35,36}, T. Kamon³⁹, Y. Kang³¹, P. Karchin⁴¹, A. Kaur¹⁶, H. Kaur¹⁶, H. Keller¹³, H. Kim³⁹, J. Kim³⁰, S. Kim³¹, B. Ko³¹, A. Kumar¹⁷, S. Kumar¹⁶, N. Lacalamita^{19,20}, J.S.H. Lee³¹, A. Levin⁴, Q. Li⁴, F. Licciulli^{19,20}, L. Lista^{24,25}, K. Liyanage³⁷, F. Loddo^{19,20}, M. Luhach¹⁶, M. Maggi^{19,20}, Y. Maghrbi³², N. Majumdar¹⁸, K. Malagalage³⁵, S. Malhotra³⁹, S. Martiradonna^{19,20}, C. McLean⁴⁰, J. Merlin^{31,*}, M. Misheva³, G. Mocellin^{13,c}, L. Moureaux¹, A. Muhammad³⁴, S. Muhammad³⁴, S. Mukhopadhyay¹⁸, M. Naimuddin¹⁷, S. Nuzzo^{19,20}, R. Oliveira³⁸, P. Paolucci^{24,25}, I.C. Park³¹, L. Passamonti²³, G. Passeggio^{24,25}, A. Peck⁴², A. Pellicchia^{19,20}, N. Perera³⁷, L. Petre¹, H. Petrow¹², D. Piccolo²³, D. Pierluigi²³, M. Rahmani⁴⁴, F. Ramirez⁷, A. Ranieri^{19,20}, G. Rashevski³, B. Regnery⁴⁰, M. Ressegotti^{26,27,d}, C. Riccardi^{26,27}, M. Rodozov³, E. Romano^{26,27}, C. Roskas², B. Rossi^{24,25}, P. Rout¹⁸, J.D. Ruiz⁷, A. Russo²³, A. Safonov³⁹, A.K. Sahota¹⁶, D. Saltzberg⁴², G. Saviano²³, A. Shah¹⁷, A. Sharma³⁸, R. Sharma¹⁷, T. Sheokand¹⁶, M. Shopova³, F.M. Simone^{19,20}, J. Singh¹⁶, U. Sonnadara³⁵, A. Stamerra^{19,20}, E. Starling¹, B. Stone⁴², J. Sturdy⁴¹, G. Sultanov³, Z. Szillasi¹⁵, D. Teague⁴³, D. Teyssier¹⁵, T. Tuuva¹², M. Tytgat², I. Vai^{28,27}, N. Vanegas⁷, R. Venditti^{19,20,*}, P. Verwilligen^{19,20}, W. Vetens⁴³, A.K. Virdi¹⁶, P. Vitulo^{26,27}, A. Wajid³⁴, D. Wang⁴, K. Wang⁴, I.J. Watson³¹, N. Wickramage³⁷, D.D.C. Wickramaratna³⁵, S. Yang³¹, U. Yang³⁰, Y. Yang¹, J. Yongho²⁹, I. Yoon³⁰, Z. You⁵, I. Yu²⁹, S. Zaleski¹³

¹ Université Libre de Bruxelles, Bruxelles, Belgium

² Ghent University, Ghent, Belgium

³ Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

[☆] Manuscript prepared by S.D. Butalla (FIT), M. Hohlmann (FIT), J. Merlin (UoS), R. Venditti (Bari) on behalf of the CMS Muon GEM Collaboration.

* Corresponding authors.

E-mail addresses: stephen.butalla@cern.ch (S.D. Butalla), jeremie.alexandre.merlin@cern.ch (J. Merlin), rosamaria.venditti@cern.ch (R. Venditti).

^a Also at Zewail City of Science and Technology, Cairo, Egypt.

^b Now at Rice University, Houston, USA.

^c Now at UC Davis, Davis, USA.

^d Now at INFN Sezione di Genova, Genova, Italy.

- ⁴ Peking University, Beijing, China
⁵ Sun Yat-Sen University, Guangzhou, China
⁶ University de Los Andes, Bogota, Colombia
⁷ Universidad de Antioquia, Medellin, Colombia
⁸ Academy of Scientific Research and Technology - ENHEP, Cairo, Egypt
⁹ Ain Shams University, Cairo, Egypt
¹⁰ Cairo University, Cairo, Egypt
¹¹ Helwan University, Cairo, Egypt
¹² Lappeenranta University of Technology, Lappeenranta, Finland
¹³ RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
¹⁴ Karlsruhe Institute of Technology, Karlsruhe, Germany
¹⁵ Institute for Nuclear Research ATOMKI, Debrecen, Hungary
¹⁶ Panjab University, Chandigarh, India
¹⁷ Delhi University, Delhi, India
¹⁸ Saha Institute of Nuclear Physics, Kolkata, India
¹⁹ Politecnico di Bari, Università di Bari, Bari, Italy
²⁰ INFN Sezione di Bari, Bari, Italy
²¹ Università di Bologna, Bologna, Italy
²² INFN Sezione di Bologna, Bologna, Italy
²³ Laboratori Nazionali di Frascati INFN, Frascati, Italy
²⁴ Università di Napoli, Napoli, Italy
²⁵ INFN Sezione di Napoli, Napoli, Italy
²⁶ Università di Pavia, Pavia, Italy
²⁷ INFN Sezione di Pavia, Pavia, Italy
²⁸ Università di Bergamo, Pavia, Italy
²⁹ Korea University, Seoul, Republic of Korea
³⁰ Seoul National University, Seoul, Republic of Korea
³¹ University of Seoul, Seoul, Republic of Korea
³² College of Engineering and Technology, American University of the Middle East, Dasman, Kuwait
³³ Vilnius University, Vilnius, Lithuania
³⁴ National Center for Physics, Islamabad, Pakistan
³⁵ University of Colombo, Colombo, Sri Lanka
³⁶ Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
³⁷ University of Ruhuna, Matara, Sri Lanka
³⁸ CERN, Geneva, Switzerland
³⁹ Texas A&M University, College Station, USA
⁴⁰ University of California, Davis, USA
⁴¹ Wayne State University, Detroit, USA
⁴² University of California, Los Angeles, USA
⁴³ University of Wisconsin, Madison, USA
⁴⁴ Florida Institute of Technology, Melbourne, USA

ARTICLE INFO

Keywords:

Gas electron multiplier
 Gaseous detector
 Muon system
 CMS upgrade

ABSTRACT

The series of upgrades to the Large Hadron Collider, culminating in the High Luminosity Large Hadron Collider, will enable a significant expansion of the physics program of the CMS experiment. However, the accelerator upgrades will also make the experimental conditions more challenging, with implications for detector operations, triggering, and data analysis. The luminosity of the proton–proton collisions is expected to exceed $2\text{--}3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for Run 3 (starting in 2022), and it will be at least $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ when the High Luminosity Large Hadron Collider is completed for Run 4. These conditions will affect muon triggering, identification, and measurement, which are critical capabilities of the experiment. To address these challenges, additional muon detectors are being installed in the CMS endcaps, based on Gas Electron Multiplier technology. For this purpose, 161 large triple-Gas Electron Multiplier detectors have been constructed and tested. Installation of these devices began in 2019 with the GE1/1 station and will be followed by two additional stations, GE2/1 and ME0, to be installed in 2023 and 2026, respectively. The assembly and quality control of the GE1/1 detectors were distributed across several production sites around the world. We motivate and discuss the quality control procedures that were developed to standardize the performance of the detectors, and we present the final results of the production. Out of 161 detectors produced, 156 detectors passed all tests, and 144 detectors are now installed in the CMS experiment. The various visual inspections, gas tightness tests, intrinsic noise rate characterizations, and effective gas gain and response uniformity tests allowed the project to achieve this high success rate.

1. Introduction

The muon system [1] of the CMS experiment installed at the Large Hadron Collider (LHC) at CERN currently exploits three different gaseous detector technologies commensurate with the background rates in each detector region: Resistive Plate Chambers (RPCs) [2] in the barrel and endcaps, Cathode Strip Chambers (CSCs) [3] in the endcaps, and Drift Tubes (DTs) [4] in the barrel. The system provided information for muon triggering, reconstruction, and identification with excellent

performance during Run 1 [5] and Run 2 [6] data-taking. After the upgrade of the LHC injector chain during the second long shutdown (LS2) of the LHC, the instantaneous luminosity of the colliding beams will regularly exceed $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which is twice the original design luminosity [7]. Under these conditions, each proton–proton bunch crossing will experience up to 100 pileup (PU) interactions, meaning that during each bunch crossing at the interaction point, up to 50 proton–proton collisions will occur. This increased pileup, along with an increase of the integrated radiation dose, consequently leads to a degradation of the current detector performance. In this scenario, the muon reconstruction in the forward region of the CMS

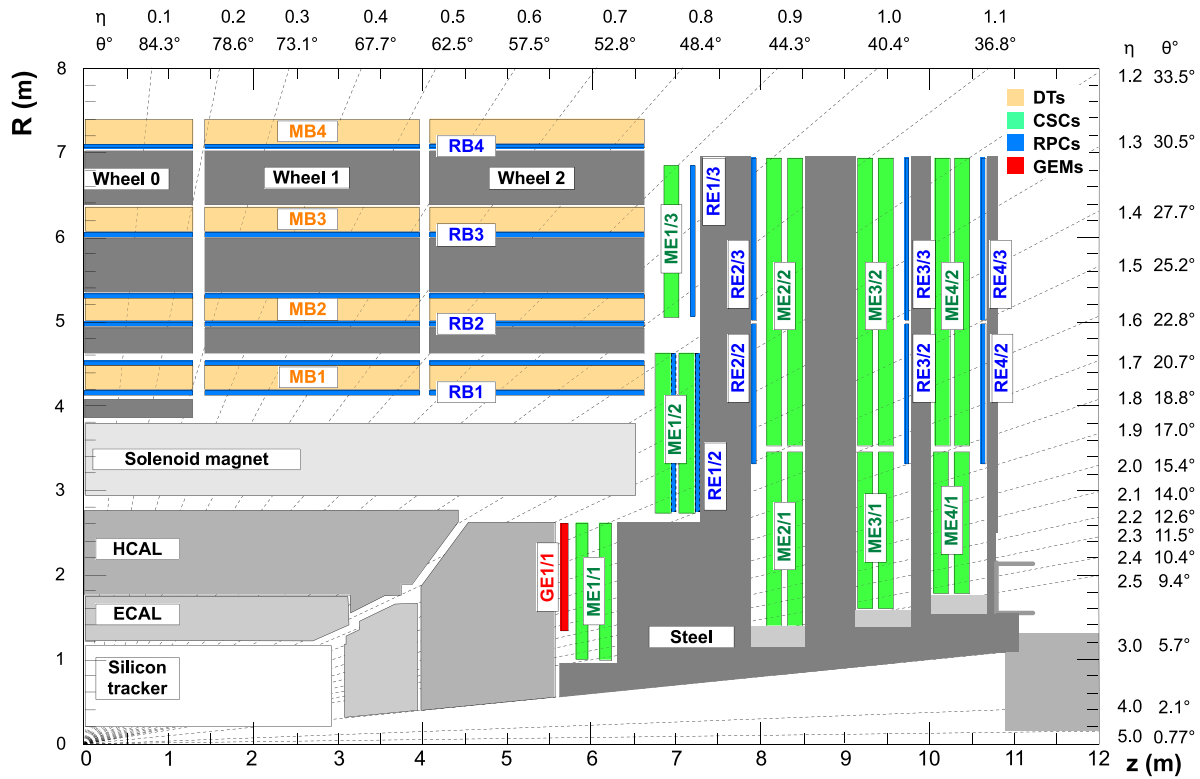


Fig. 1. A quadrant of the CMS detector, showing the different types of chambers used in the muon system [7]. The original system consisted of the DT chambers (yellow) in the barrel region, together with the RPCs (light blue) and CSCs (green) in the endcap regions. The new GEM detector station GE1/1 is indicated in red.

muon system will become particularly challenging, especially for the Level-1 (L1) Trigger. The smaller track bending in the magnetic field surrounding the endcap detectors relative to the track bending in the barrel, combined with multiple scattering of muons in the yoke, leads to muon momentum mis-measurements by the L1 trigger. This factor contributes to an increase of the overall muon L1 trigger rate in the forward region and, together with the general increase in background rates, will lead to a situation where the L1 rates in the pseudorapidity region $|\eta| \geq 1.6$ can no longer be controlled by the CSC detectors alone. This effect will be further exacerbated in the High Luminosity LHC (HL-LHC) scenario, where 200 PU interactions per bunch-crossing are expected.

As a consequence, a general upgrade [8] of the present muon system has been carefully designed and planned by the CMS collaboration. Here we focus on the first new muon endcap station (GE1/1) [9], which is based on Gas Electron Multiplier (GEM) detector technology [10] and was installed in front of the first CSC station (ME1/1) before Run 3 (Fig. 1). Simulation studies [9] have shown that this new station will improve the muon L1 trigger performance in the forward region. It is expected to keep the L1 trigger rates under control in the high-radiation environment of Run 3.

This paper is organized as follows: An overview of the GE1/1 station is presented in Section 2, while the quality control procedures and detector performance results are discussed in Section 3. The selection of the detector working point is described in Section 4, and Section 5 provides a summary and conclusions of the GE1/1 construction and quality control process, and perspectives for the next two GEM stations to be built.

2. Overview of the GE1/1 station

The GE1/1 station provides full coverage in the azimuthal coordinate, ϕ , while instrumenting the pseudorapidity region $1.55 < |\eta| < 2.18$, as shown in Fig. 1. A triple-GEM chamber (also simply referred to as “a detector”), consists of three GEM foils separated by spacers and held

between an anode readout board and a cathode drift board. The choice of the triple-GEM technology is driven by the excellent performance of these detectors: triple-GEM detectors exhibit a rate capability well above the required ~ 10 kHz/cm², a time resolution of ~ 8 ns or better, and a spatial resolution of ~ 200 μ m, which make them well suited for the purposes of the CMS Muon System Upgrade [9].

In the GE1/1 station, a pair of triple-GEM chambers is combined to form a “superchamber” (SC) that provides two measurements of the muon hit position per muon track. As each superchamber covers a $\sim 10^\circ$ sector, 36 superchambers are installed in each endcap. Short and long chambers alternate in ϕ to maximize the pseudorapidity coverage. A total of 144 (plus 17 spare) triple-GEM detectors were constructed and instrumented with electronics for installation.

An exploded view of a GE1/1 detector is shown in Fig. 2. A detailed description of the chamber design can be found in Ref. [9]. Three GEM foils, i.e. copper-clad polyimide foils perforated with a high density of microscopic holes (140 μ m pitch and 70 μ m hole diameter), are stacked between an unsegmented drift cathode and a segmented readout anode.

The induced electrical signal produced by the particles that hit the detector is picked up by the anode readout board, which is segmented into 384 radial readout strips with a pitch of 461 μ rad. These readout strips are grouped into three main sectors along the azimuthal coordinate and eight sectors along the η coordinate, thus resulting in a total of 24 readout sectors. Each of these 24 readout sectors are assigned a two-coordinate designation, (i_η, i_ϕ) , with $i_\eta = 8$ at the narrow end (closest to the beamline), and $i_\eta = 1$ at the wide end, and from $i_\phi = 1$ to $i_\phi = 3$ from left to right (see Fig. 3).

While operating in CMS, each sector is read out by one VFAT3 chip, which is an Application Specific Integrated Circuit (ASIC), adapted for gaseous detector readout [11]. The voltage is provided to the GEM foils through the drift board, a single, contiguous drift cathode that routes a total of seven potentials (drift electrode plus two sides of each of the three GEM foils) to the various GEM electrodes and to the drift cathode.

Assembly and gas sealing of the detector are entirely mechanical. A brief overview of the construction process is shown in Fig. 4. The

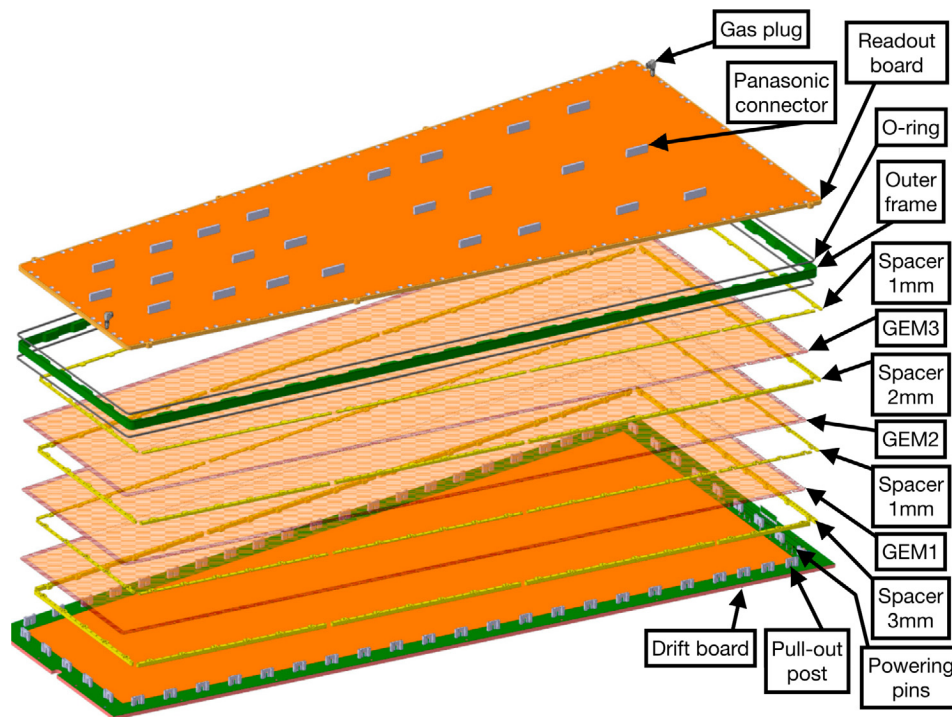


Fig. 2. Exploded view of the mechanical design of a triple-GEM detector.

stack of three GEM foils is first completed outside of the drift board, as shown in Figs. 4(a) and 4(b). Fig. 4(c) displays the transferring of the GEM stack to the drift board. The GEM foils are then tensioned by the stretching screws (Fig. 4(d)), after which the resistances of the GEM foils and gaps are tested (Fig. 4(e)). Finally, the chamber is closed by fixing the readout board to the drift board, as shown in Fig. 4(f). For a comprehensive and detailed description of the assembly techniques, see Ref. [12]. No glue is applied during assembly, which makes it possible to open a detector again for repairs if needed while also minimizing any remaining risk from potential gas contamination due to epoxy glue outgassing, which may be present even with glues generally accepted for chamber construction because glue production batches and mixing of epoxy components by the operator may still vary to some extent and may cause outgassing. The three GEM foils are sandwiched at their edges between four thin frames. Square stainless steel nuts are embedded into the frames every few centimeters to host stainless steel screws that are inserted into small “pull-out” posts, which are located within the gas volume. When the pull-out screws are tightened manually, the GEM foils in the stack are tensioned against the posts. A large outer glass-epoxy frame is placed around the tensioned GEM stack and around the pull-outs providing the enclosure of the gas volume. The standard gas mixture for operating and testing this triple-GEM detector is Ar/CO₂ (70:30).

3. Quality control process and performance of GE1/1 detectors

Several institutions from six countries participated in the assembly and quality control process of the GE1/1 detectors. These institutions are located in Switzerland (CERN), Italy (INFN Bari and Frascati), Belgium (U. Ghent), India (U. Delhi, BARC, Punjab U., Saha Inst. of Nuclear Physics), Pakistan (National Centre for Physics), and USA (Florida Inst. of Technology). An additional satellite site in Germany (RWTH Aachen U.) performed quality control tests on a subset of the chambers produced in Belgium. This distributed production model was adopted by the collaboration to ensure timely mass production with built-in redundancy.

Before becoming a production site, each institution had to follow a two-year certification program organized by the GEM Collaboration.

This program is designed to ensure that all GE1/1 chambers are produced in suitable conditions using the same infrastructure, and that the same procedures for construction and quality control testing are performed. All steps of the certification program are reviewed by the collaboration, culminating in a final certification after an on-site visit. The entire process is supported by a set of technical documents that describe the composition of the test setups and provide guidance for the local management of the production [13].

To ensure proper and robust operation of the chambers within their performance specifications once installed in CMS, a detailed Quality Control (QC) procedure [12–14] is employed in all the production sites, which are equipped with the same laboratory infrastructure and instrumentation. This protocol aims to carefully assess the detector performance at each step. If measurements are found that are incompatible with predefined standards, the detector undergoes further adjustment until it fulfills those requirements. The results of all QC tests are systematically reviewed by the production community and the final validation of the chambers is submitted to the GEM collaboration every two months during dedicated reviews.

The first group of tests is performed on the components before the assembly. The second set of tests are completed on a single chamber while the third set of tests are performed after superchamber assembly. Single-chamber assembly and QC tests are done at the different production sites, while the assembly and the QC tests on the SC are only performed centrally at CERN. The detailed step-by-step description of the QC process performed at the production sites and the results obtained for single chambers are the focus of this paper. The five main steps that comprise this component and single-chamber QC are listed in Table 1, and are discussed in detail below.

3.1. QC step 1 — Initial inspection of the chamber components

The quality control procedure starts with the initial inspection of the components that will form the main structure of the chamber, i.e. the printed circuit boards (PCBs) that host the drift and readout electrodes, the internal frames, and the external frame with its embedded Viton O-rings. While the mechanical dimensions of all components are



(a) The readout board of the GE1/1.

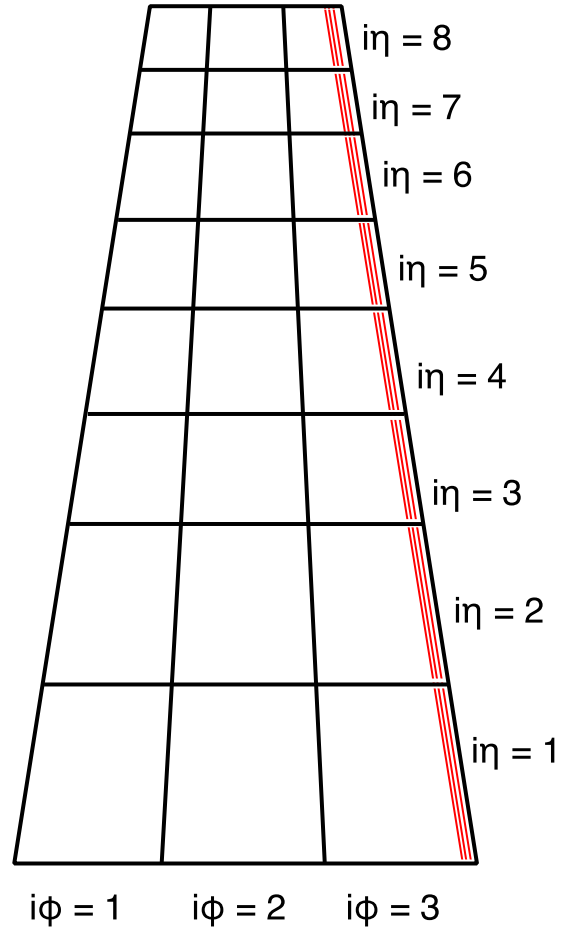
(b) The local coordinate system, showing the local pseudo-rapidity coordinate, denoted by $i\eta$, and the local azimuthal coordinate, denoted by $i\phi$. Some readout strips (red lines) are pictured to indicate their orientation on the readout board. Note: readout strips not drawn to scale.

Fig. 3. The readout board and the partitioning scheme of the readout sectors.

Table 1
Quality control steps for GE1/1 chamber components and assembly.

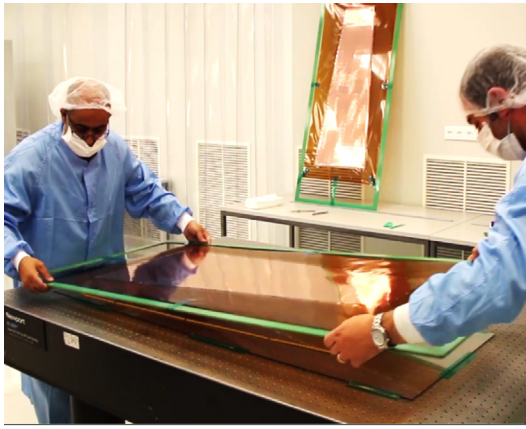
QC step	QC procedure
1	Initial inspection of the chamber components
2a	Electrical cleaning of the GEM foils and resistance check
2b	Long-term monitoring of the GEM foil leakage current
3	Leak test of closed detector volume
4	Linearity test of high voltage divider and intrinsic noise rate measurement
5a	Effective gas gain measurement
5b	Response uniformity measurement

carefully verified using a precision caliper, an additional systematic visual inspection of the materials helps to identify potential defects, such as mechanical degradation, scratches and cracks, and the presence of any residues of chemicals used during manufacturing or other contaminants. Components outside the specifications or showing defects are discarded from the production materials or returned to the factory for rectification.

Particular attention is paid to the planarity of the drift and readout PCBs, which directly impacts the electric field uniformity, and consequently the overall detector performance. To determine the planarity, the boards are placed on a flat marble table, and then gaps between PCBs and the table are measured with precision calipers. Boards with deviations from flatness above 3 mm from the center are rejected. The readout boards undergo an additional electrical test to ensure the integrity of all readout paths. The setup for this test, based on an ARDUINO microprocessor, automatically measures the continuity of the signals between the internal strips and the external connectors and also identifies any short circuits between neighboring strips. For more information on the chamber components and their quality control, see Ref. [12].

3.2. QC step 2a — Electrical cleaning of the GEM foils and resistance check

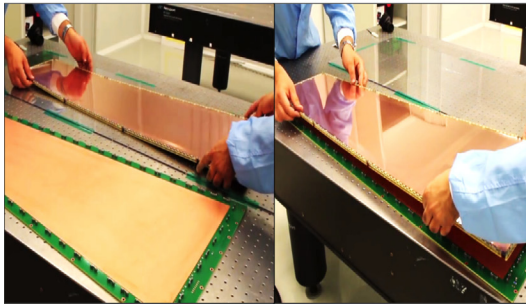
The GEM foil is the core component of the amplification structure of the detector. Because of its microscopic nature, the qualification of the GEM foils is not done optically, but electrically. The presence of dust, chemical contaminants, or mechanical defects creates a low



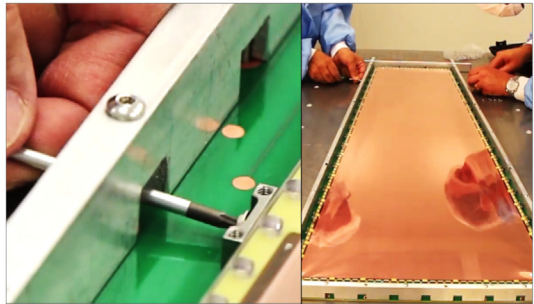
(a) Placing the first GEM foil in the stack.



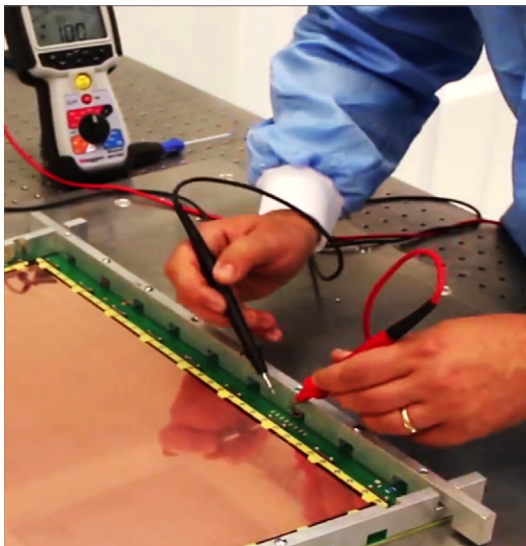
(b) Securing the GEM stack.



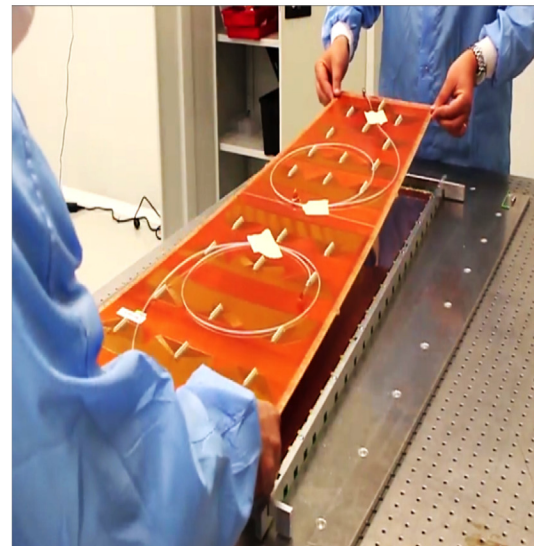
(c) Transferring the stack to the drift board.



(d) Stretching the GEM foils.



(e) Resistance testing of all GEM foils and gaps.



(f) Closing the chamber with the readout board.

Fig. 4. Various steps of the assembly process of a CMS GE1/1 GEM detector.

resistance bridge between the two electrodes of the GEM foil as shown in Fig. 5. For healthy foils, the total resistance should be greater than 20 G Ω in environments with relative humidity below 50%. In the extreme scenario of a short-circuit between the GEM electrodes, the measured resistance of the foil is equal to 10 M Ω – the value of the protection resistors that are soldered directly onto the GEM foils – or lower in case of multiple short-circuits.

The resistance across the foil is measured in a cleanroom environment (ISO 7/class 10,000 or better) using a handheld Giga-Ohm insulation meter (Megger MIT485). The meter applies 550 V across the foil and measures the corresponding leakage current to derive the foil

resistance (see Fig. 6 for a schematic representation of this test, and Fig. 7 for a photo of the procedure being performed).

The same procedure is repeated multiple times during the various steps of the detector assembly to detect any foils that might have developed short-circuits because of the manipulations required for testing, transport, and assembly. In this case, the voltage is applied on dedicated pads present on the assembly table or on the drift PCB on which the GEM stack is mounted, as shown in Fig. 8. This voltage is applied to the pads on the GEM foil via spring-loaded pins which are in turn soldered to the HV circuit on the drift PCB.

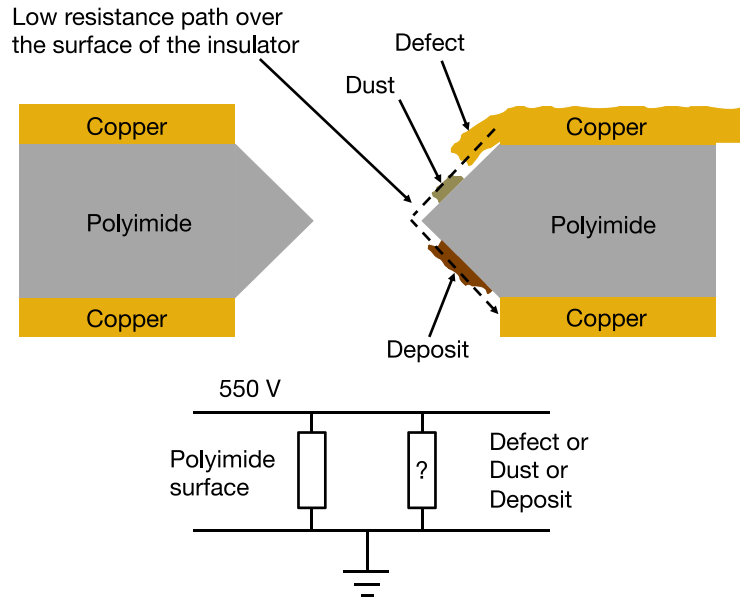


Fig. 5. Schematic representation of the cross-section of a GEM foil at the location of a hole. As shown on the right of the figure, defects in the copper, deposits, and dust can affect the resistance of the GEM foil.

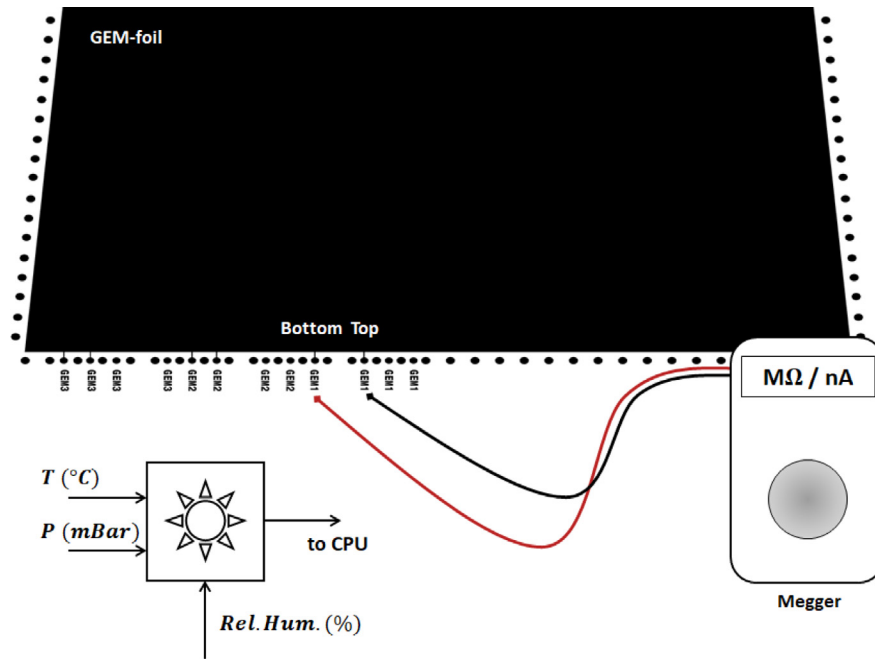


Fig. 6. Resistance test setup of a single GEM foil with a Megger Giga-Ohmmeter.

The same technique is also used as needed during production, testing, or operation of a chamber, to clean the GEM foils in case of contamination, defects, or dust particles trapped inside the GEM holes. The current injected by the Giga-Ohmmeter flows primarily through contaminated areas with low impedance, resulting in the evaporation or burning of the impurity. In dry environments, it is also possible to clean the inside surfaces of a damaged hole responsible for a short-circuit between the GEM electrodes.

3.3. QC step 2b — Long-term monitoring of the GEM foil leakage current

3.3.1. Motivations

While the impedance check helps to identify major problems with a GEM foil, it might not be sufficiently sensitive to minor issues or

hidden defects that can affect the long-term stability of the chamber. Specifically, some GEM foils could reach their nominal voltages with high impedances, while simultaneously experiencing discharges at high frequency (e.g., several per hour). These discharges can seriously and permanently damage the GEM foils, and they can also prevent stable operation of the detector, once in continuous run mode. Consequently, it is essential to monitor the leakage current and discharge rate of all the GEM foils for several hours before the detectors are assembled.

3.3.2. Selection criteria

The total leakage current of a GEM foil mainly depends on the resistivity of the biconical holes of the polyimide layer between the two copper layers of the foil. This resistivity can vary with the ambient humidity or because of contaminants. For a precise measurement of

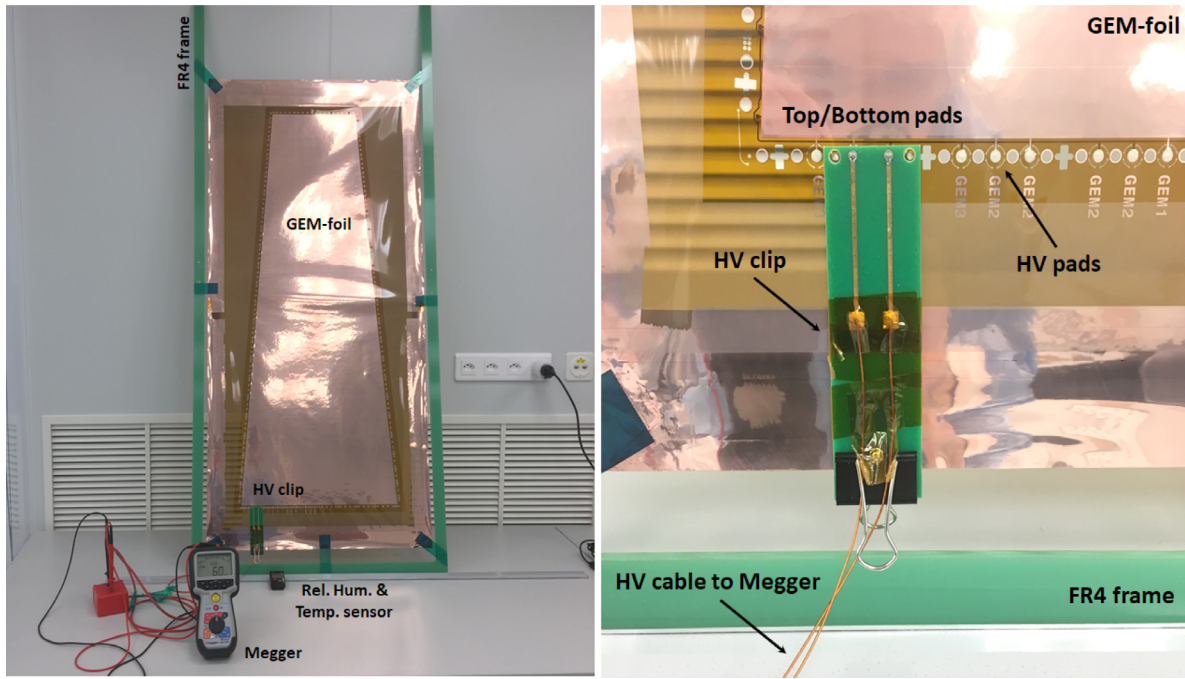


Fig. 7. Typical setup for the electrical resistance test of a GE1/1 GEM foil.

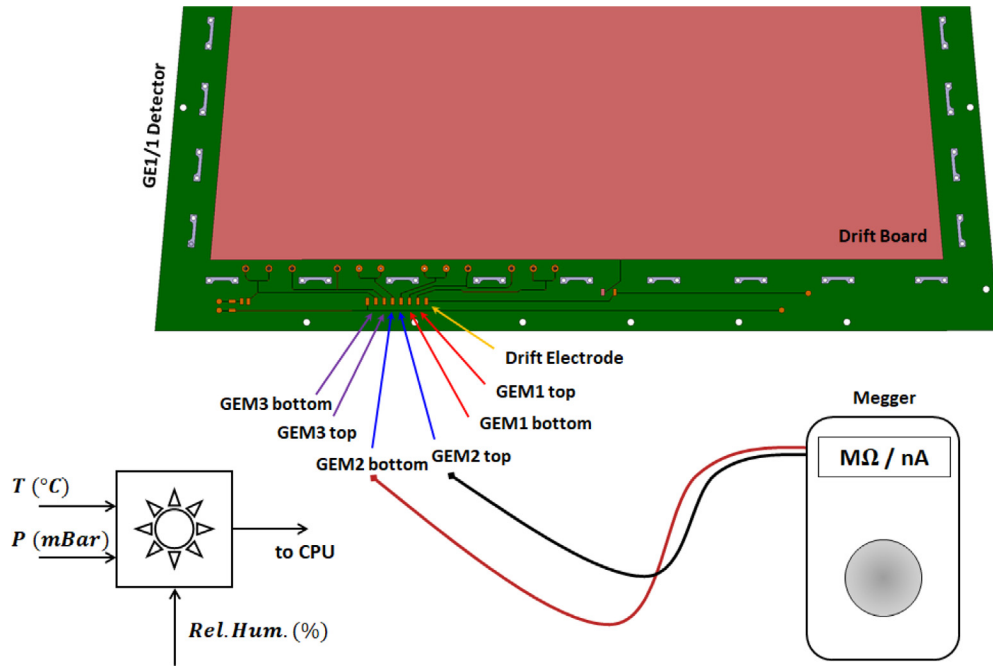


Fig. 8. Resistance test setup of a GEM stack during assembly.

the leakage current, the foil needs to be operated at the maximum stable voltage, i.e. just below the breakdown voltage of the gas. As the Paschen curves in Fig. 9 indicate that the breakdown voltage in pure nitrogen is close to 660 V for a GEM foil where the two copper layers are separated by 50 μm , an appropriate voltage for testing GEM foil stability is 600 V in pure nitrogen. In such conditions, and with a relative gas humidity below 10%, we require that the leakage current of a GE1/1-sized foil not exceed 1 nA, with a maximum discharge rate below 3 discharges per 5 h.

3.3.3. Test setup and procedure

Before performing this quality control step, both sides of the foils are mechanically cleaned using an anti-static silicone roller to remove dust and contaminants. The GEM foils are enclosed in a plexiglass box filled with pure nitrogen flowing at a rate of 30–40 L/h. The box, which can accommodate up to 8 foils, is placed in a cleanroom and covered to prevent ambient light from reaching the foils. This is done because electrons can be released from the GEM copper as a consequence of a photoelectric effect induced by UV photons emitted from fluorescent lighting. We observed that when the foils operate at the maximum

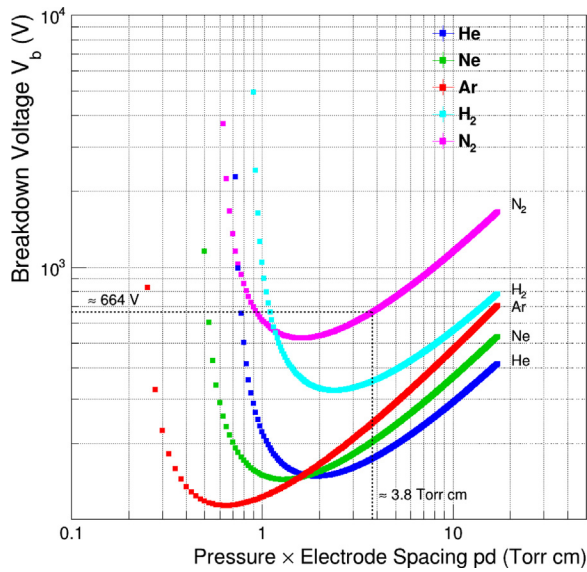


Fig. 9. Paschen curves for electrical breakdown voltages of parallel plates in different gas mixtures [15] at standard temperature. For GEM foils surrounded by gas at atmospheric pressure and room temperature, the pressure $\times$ spacing value is 3.8 Torr $\times$ cm.

voltage of 600 V, these photo-electrons can get sufficiently amplified by the GEM to generate a leakage current of the order of 2–3 nA, which can bias the test results for the intrinsic leakage current measurement.

The foils are powered by an 8-channel CAEN R1471HETD power supply, which has a current monitoring resolution down to 50 pA. The power supply is controlled by a LabView interface that is programmed to run the test automatically. A picture of the QC2b test setup is shown in Fig. 10.

The test procedure consists of three main steps: the initial ramp-up phase, a power cycling phase, and the final stability phase. During the ramp-up phase, the voltage is increased from 0 to 500 V in steps of 100 V, and then from 500 V to 600 V in smaller steps, typically in increments of 50 V. After a desired voltage is reached, it is maintained for 15 s before moving to the next step. During the cycling phase, the voltage is quickly ramped up and down between 600 V and 100 V within ten seconds in order to stress the foil and to lift potential solid contaminants off the foil via the oscillating electric field. During the stability phase, the foil is maintained at the maximum voltage of 600 V for 6–8 h. This final step is designed to verify the long-term behavior and the stability of the foil during continuous operation. At any phase of the test, if the leakage current exceeds a limit of 20 μ A (a typical magnitude of a discharge current), the system trips and automatically restarts at the same phase. If the system records more than three trips in the same phase, it automatically goes back to the previous phase. Three phase failures result in aborting the test and automatic rejection of the foil from chamber production.

3.3.4. Typical results

Fig. 11 shows typical QC2b data for a “good” GEM foil, that is fully validated and approved for detector assembly. All three phases are completed and it is demonstrated that the foil can safely operate long-term at 600 V without high voltage (HV) trips and with an average leakage current below 0.5 nA.

Conversely, Fig. 12 shows the typical QC2b data of a “bad” GEM foil that suffers from instabilities. The plot shows multiple trips that force the system to go back from the stability phase to the cycling phase. The repetition of the trips and the measurement of a high leakage current prematurely abort the test. Such a foil would require an additional, in-depth cleaning at the manufacturer’s facility before going back through the entire QC protocol from the beginning.

Over the course of the GE1/1 detector mass production, on average, about one to two foils per batch of 15 foils were rejected by the QC2 tests and sent back to the manufacturer. After additional, in-depth cleaning at the manufacturer’s facility, those foils were tested again and most of them could be validated for assembly. Overall, only one foil out of 485 had to be completely rejected without any possibility for recovery.

3.4. QC step 3 — Leak test of closed detector volume

3.4.1. Motivations

Detector gas-tightness is crucial to avoid gas leaks and to reduce the possibility of contamination by external pollutants. The presence of undesired gas molecules, e.g. those found in air, particularly oxygen and other electronegative elements, can deteriorate the charge amplification and electron transfer process, which will affect the detector performance during operation. Additionally, dust particles could enter the gas volume and jeopardize the foil integrity. Such effects can have a significant impact on the HV stability and the long-term behavior of the chamber. Given the design of the GE1/1 detectors, where a large number of screws are employed, the leak test is the first verification performed after the assembly.

3.4.2. Selection criteria

To maintain high gas purity, the maximum acceptable leak rate for a single detector is set to 1% of the total incoming gas flow rate. For GE1/1, this rate is initially set to 2.5 L/h with a maximum internal over-pressure of 25 mbar. Directly measuring a leak rate as little as 0.025 L/h is challenging and would require a specific and expensive tooling, which is not necessarily available at all production sites. The leak rate, however, can also be derived from the measurement of the internal pressure loss when the chamber input and output are both closed. Such a measurement is much easier and more reliable with standard laboratory equipment.

Assuming that the detector volume remains constant during the test, the time evolution of the internal pressure can be expressed as a simple exponential:

$$P_{\text{int}} = P_0 e^{-t/\tau} \quad (1)$$

where P_0 is the initial over-pressure and τ is the time constant of the system that depends on the leak point dimensions. From the ideal gas law, $PV = nRT$, with P being the absolute pressure inside the detector volume V , we can then derive the quantity of gas n lost after a given time t :

$$n = \frac{V}{RT} (P_{\text{atm}} + P_{\text{int}}(t)). \quad (2)$$

Substituting P_{int} from Eq. (1) in Eq. (2) and differentiating with respect to time, we find

$$\frac{dn}{dt} = \frac{VP_0}{RT} \left(\frac{-1}{\tau} \right) e^{-t/\tau}. \quad (3)$$

Consequently, we can calculate the detector leak rate from the measurement of the pressure-loss time constant τ . Fig. 13 shows the gas leak rate as a function of the time constant for different values of internal over-pressure P_0 during operation. Fig. 14 shows the gas leak rate as a function of the internal over-pressure for different time constants τ . To ensure that the leak rate will remain below 1% of the total incoming flow rate, the time constant for each GE1/1 chamber should be greater than 3.04 h.

3.4.3. Test setup and procedure

The leak test aims to quantify the gas leak rate of a GE1/1 detector by monitoring the drop of the internal over-pressure as a function of time. A pressure sensor connected to an ARDUINO-Mega micro-controller allows the monitoring of the over-pressure in the detector and the gas system. The ambient temperature and pressure are also

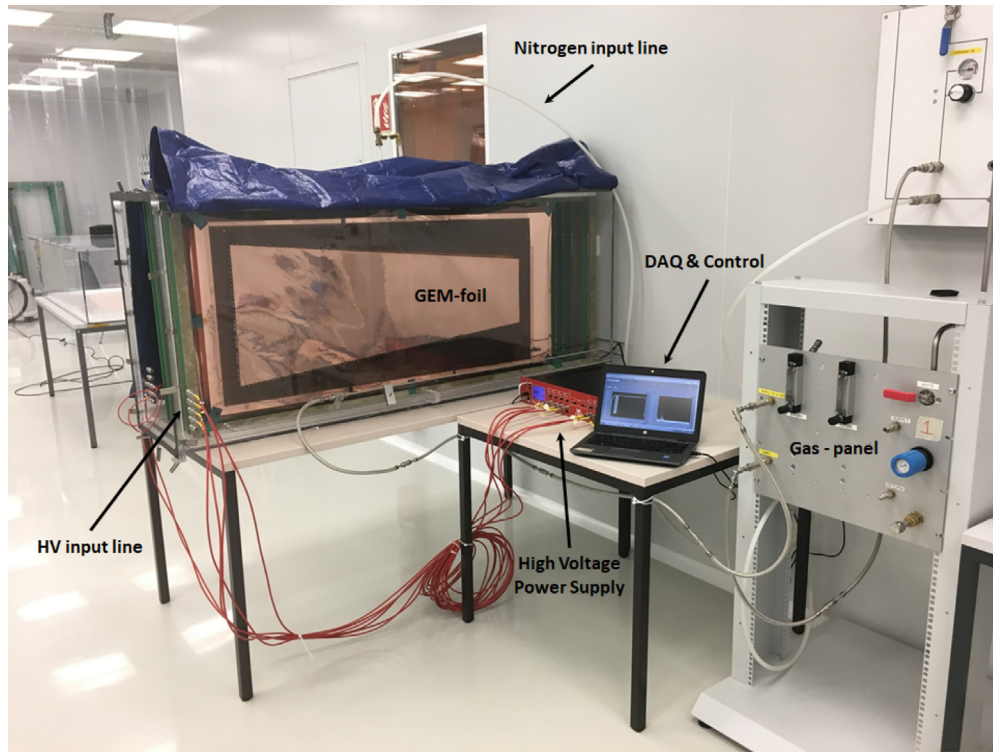


Fig. 10. Test setup for the long-term measurement of leakage currents in the GE1/1 GEM foils.

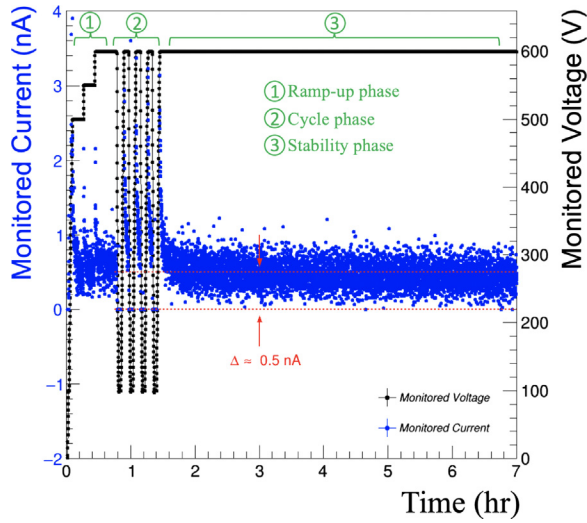


Fig. 11. Typical leakage current behavior in a validated GEM foil.

monitored via sensors connected to the ARDUINO board during this quality control procedure. The top schematic in Fig. 15 shows a basic diagram of the data acquisition (DAQ) and gas system setup for this test. Before the leak test is conducted, the DAQ system is calibrated to ensure accurate measurement of the leak rate (see the bottom diagram of Fig. 15). We first check the manufacturer's calibration of the pressure transducers by connecting it to a closed-off stainless steel cylinder of similar volume as a detector. We ensure that the gas system itself does not have any leak by connecting the inflow and outflow systems together and thus by-passing the detector, as shown at the bottom of Fig. 15. With the outflow valve closed, the system is pressurized to 25 mbar and the internal pressure is monitored over one hour. If the pressure decreases more than 1 mbar over the course of the hour,

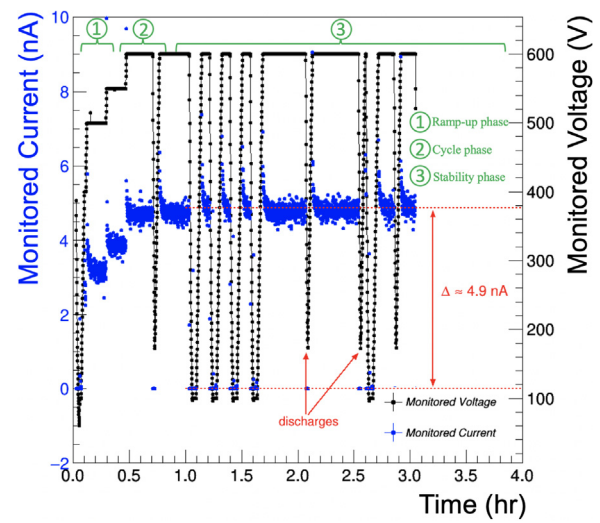


Fig. 12. Typical leakage current behavior in a rejected GEM foil.

the system is checked for leaks and the procedure is repeated. After calibration of the system, a chamber is connected to the gas system with its outflow gas line plugged. The chamber is then pressurized to about 25 mbar, and the over-pressure is monitored every minute over the course of one hour.

3.4.4. Typical results

The pressure drop is modeled by the function $P(t) = P_0 e^{-t/\tau}$ discussed above, where P_0 is a constant representing the initial over-pressure of the detector (set to about 25 mbar at all the production sites and for each detector) and the time constant τ quantifies how fast the over-pressure inside the detector decreases as a function of time.

Results of the leak tests for two different chambers measured at two different sites (serial numbers: GE1/1-X-L-CERN-0018 and

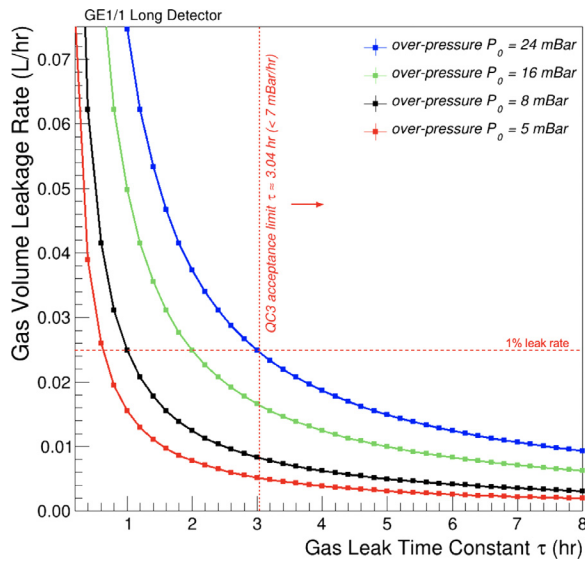


Fig. 13. Calculations of the gas leak rate as a function of the time constant measured during QC Step 3 for the GE1/1 chambers.

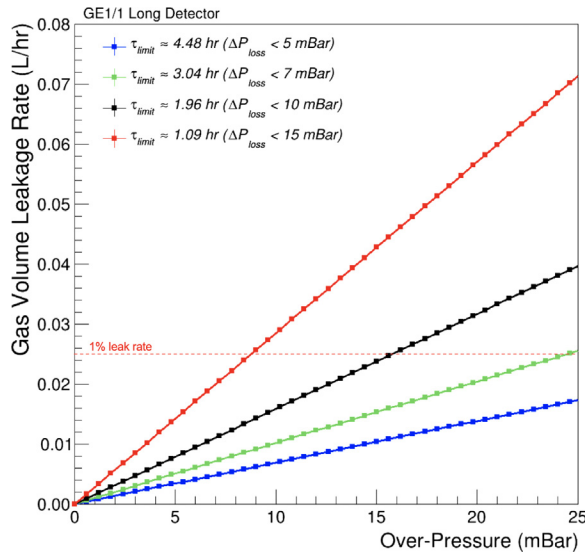


Fig. 14. Calculations of the gas leak rate in GE1/1 chambers as a function of the internal over-pressure.

GE1/1-X-S-FIT-0004) are displayed in Fig. 16. The expected exponential behavior is exhibited by GE1/1-X-L-CERN-0018 (green data points with a blue fitted exponential curve), and shows a time constant of $\tau = (21.6 \pm 0.14)$ hr, which is well above the acceptance criterion for a gas-tight chamber ($\tau \geq 3.04$ hr). In some cases, we observe chambers that initially do not follow an exponential leak profile. This can be attributed due to the bulging of the readout and drift PCBs after the initial pressurization of the chamber to 25 mbar. Once the PCBs return from the deformed shape to their planar shape, the gas volume returns to its nominal, constant shape, and the gas escaping from the closed chamber exhibits the theoretically predicted exponential leak behavior. Consequently, the time constant determined from the fit for GE1/1-X-S-FIT-0004 (black data points with a red fitted exponential curve) has the first few points excluded. Note that this chamber exhibits a time constant of $\tau = (33.27 \pm 0.41)$ hr, which is also well above the acceptance criterion. Out of the 161 fully assembled chambers, 158 chambers could be tested in this QC step; three chambers were eliminated due to failures in earlier QC steps and were not tested for

leak tightness. As shown in Fig. 17, all 158 GE1/1 detectors are found to be gas-tight except two built with a pre-series internal frame. These two detectors with excessive leak rates are not installed in CMS.

3.5. QC step 4 — Linearity test of the HV divider

3.5.1. Motivation

The goal of this test is to check the on-detector circuitry that distributes the high voltage to the detector electrodes. The proper functioning of this circuitry is important for the operational stability of the GE1/1 detector with respect to the applied HV, both for guaranteeing a stable effective gas gain and for avoiding discharges that could damage the surface of the GEM foils or the readout electronics. This need is particularly crucial for GE1/1 detectors because of the large size of the GEM foils. Even with the foils being segmented into 40 HV sectors (with the sensitive sector areas ranging from dozens to a hundred cm^2), the foils still have large total capacitances – on the order of tens of nF – and store considerable charge.

During the detector production and test phase, a simple ceramic voltage divider, directly soldered onto the drift board, is used to divide the voltage from a single high voltage input line [9]. This ceramic divider comprises a small network of ohmic resistors (see the bottom of Fig. 18 for the circuit diagram) with resistances R_i (see the top right of Fig. 18 for the values of the resistors). This HV divider has an equivalent resistance of $R_{\text{divider}} = 4.7$ M Ω . The current I_d through this network produces voltage drops $V_i = R_i \times I_d$ across the various resistors that are used to create the appropriate electric potentials needed to power the different electrodes i of the detector. A custom low-pass protection filter (with equivalent resistance $R_{\text{filter}} = 0.3$ M Ω) connects the detector to the power supply to eliminate the high frequency noise (see the top of Fig. 18 for the circuit diagram). The total equivalent resistance of the ceramic divider and low-pass filter is 5.0 M Ω . The HV stability is quantified by monitoring two quantities: the deviation of the measured total resistance of the powering circuit with respect to the one predicted by Ohm's law, and the noise induced on the bottom of the third GEM foil in a gas with high ionization energy.

3.5.2. Selection criterion

For each HV step, the current through the powering circuit is recorded, as shown in Fig. 19. The measured resistance of the powering circuit R_m is then obtained by computing the average of all the values recorded in each step. This value is compared with the nominal resistance R_n of the powering circuit measured with a standard multimeter (at a few volts) before soldering the divider onto the detector, and the resistance deviation is computed. The deviation of the resistance of the powering circuit with respect to Ohm's law, labeled D_R in the following discussion, is defined in Eq. (4) as the relative deviation of the measured resistance, R_m , with respect to the nominal value, R_n :

$$D_R = \frac{R_m - R_n}{R_n}. \quad (4)$$

The value of the resistance deviation includes the tolerances on the resistors in the HV divider and HV filters used for biasing the GE1/1 detector. Ten resistors are employed in total in this powering circuit, each of them rated with a 1% tolerance. Summing all of the involved tolerances in quadrature shows that a deviation D_R of up to 3% can be tolerated. Consequently, GE1/1 detectors exhibiting resistance deviation greater than this value are rejected or undergo further investigation.

3.5.3. Test setup

A commercial power supply able to provide up to 1 mA current with 1 μA monitoring resolution is used to ramp the HV applied to the filter and divider (connected to the detector) up to 5 kV in steps of 100 V, and also used to monitor the current. The detector is flushed with pure CO_2 gas with a flow rate of 5 L/h.

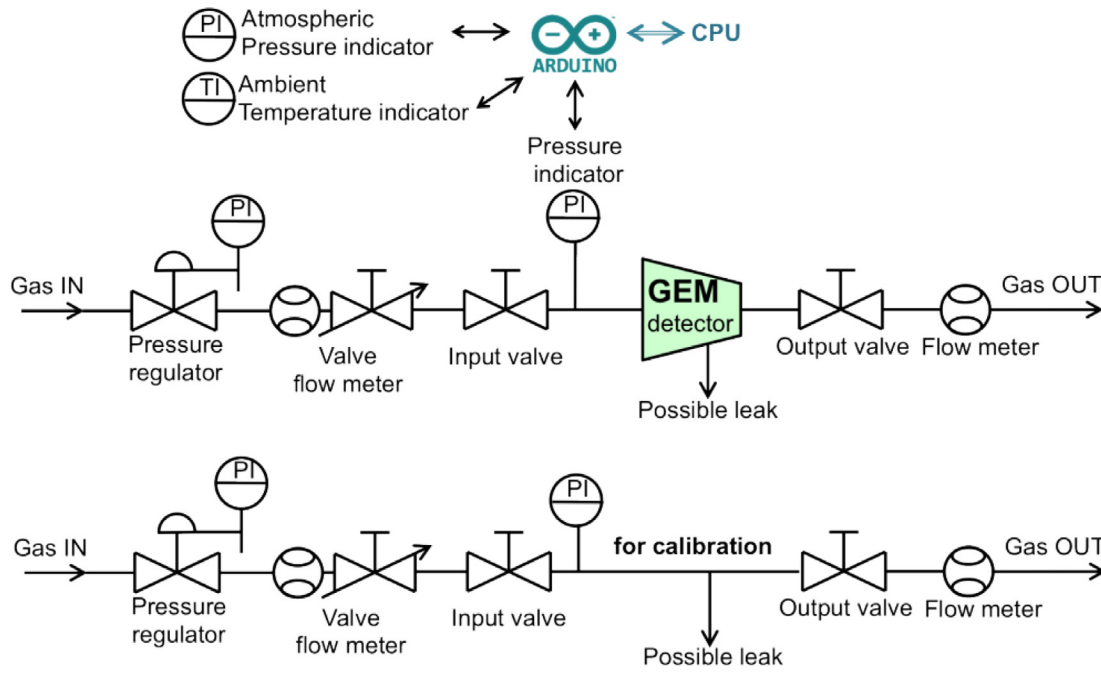


Fig. 15. Diagram of the ARDUINO DAQ and the gas system for the leak test (top diagram) and for calibration (bottom diagram).

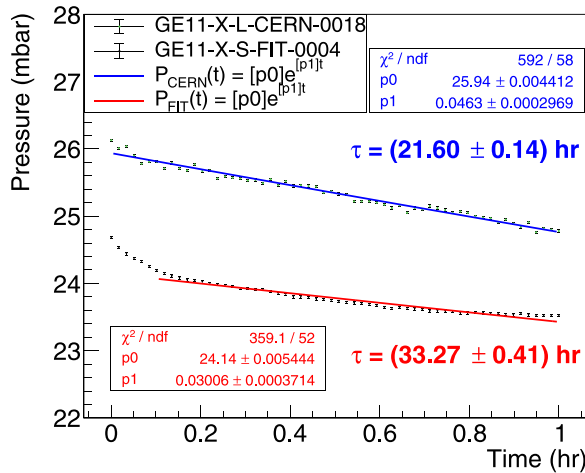


Fig. 16. Examples of the measured gas leak rate for closed GE1/1 chambers over one hour (serial numbers: GE1/1-X-L-CERN-0018 and GE11-X-S-FIT-0004). Both chambers display time constants that are well above the acceptance criterion for a gas-tight chamber ($\tau \geq 3.04 \text{ h}$).

3.5.4. Results

To characterize the biasing circuit, the slope from the linear fit on the points of a plot of the applied voltage as a function of divider current is obtained (see Fig. 19), and then the resistance deviation is computed using Eq. (4). The distribution of the resistance deviations for all of the GE1/1 detectors is displayed in Fig. 20. The HV biasing circuits for all detectors were found to have a resistance deviation D_R better than the 3% tolerance.

3.6. QC step 4 — Intrinsic noise rate measurement

3.6.1. Motivation

Micro-pattern gaseous detectors are known to suffer from spurious discharges, particularly when operating at very high counting rates or at exceptionally high gas gains. These glow discharges – which are not induced by the direct detection of any ionizing particles, but

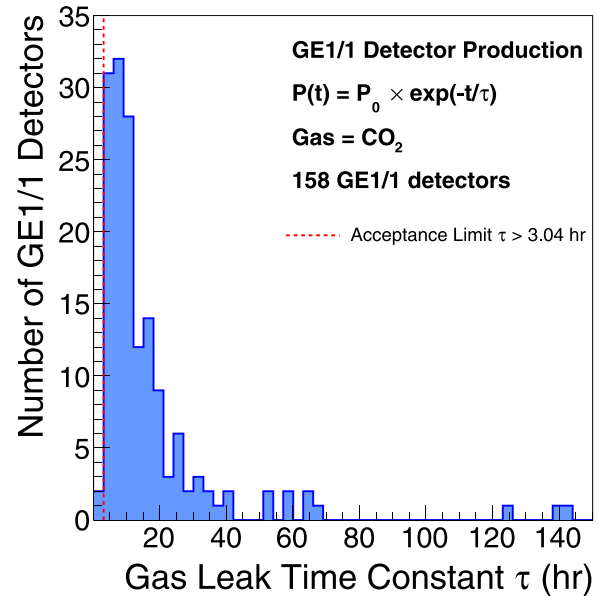


Fig. 17. Gas leak time constants of all the GE1/1 detectors. The threshold for acceptance is also shown. Results for 158 GE1/1 detectors out of 161 produced are shown. Out of these, 156 detectors are accepted and two are rejected.

rather from imperfections in the electrodes or from design flaws of the detector – can produce spurious signals and must therefore be reduced to an acceptably low rate. At high counting rates, other effects, such as statistical avalanche overlapping, the cathode excitation effect, and electron jets contribute to the spurious noise rate [16]. The test described in this section is designed to quantify the intrinsic noise rate of the detectors due to those spurious signals originating from the detector design flaws and electrode imperfections. To perform this measurement, the detectors are put into a safe mode by flushing them with a gas that has a high ionization energy, such as pure CO_2 , which suppresses signals from cosmic rays. The rate of spurious signals as a function of the applied high voltage is then observed. This procedure

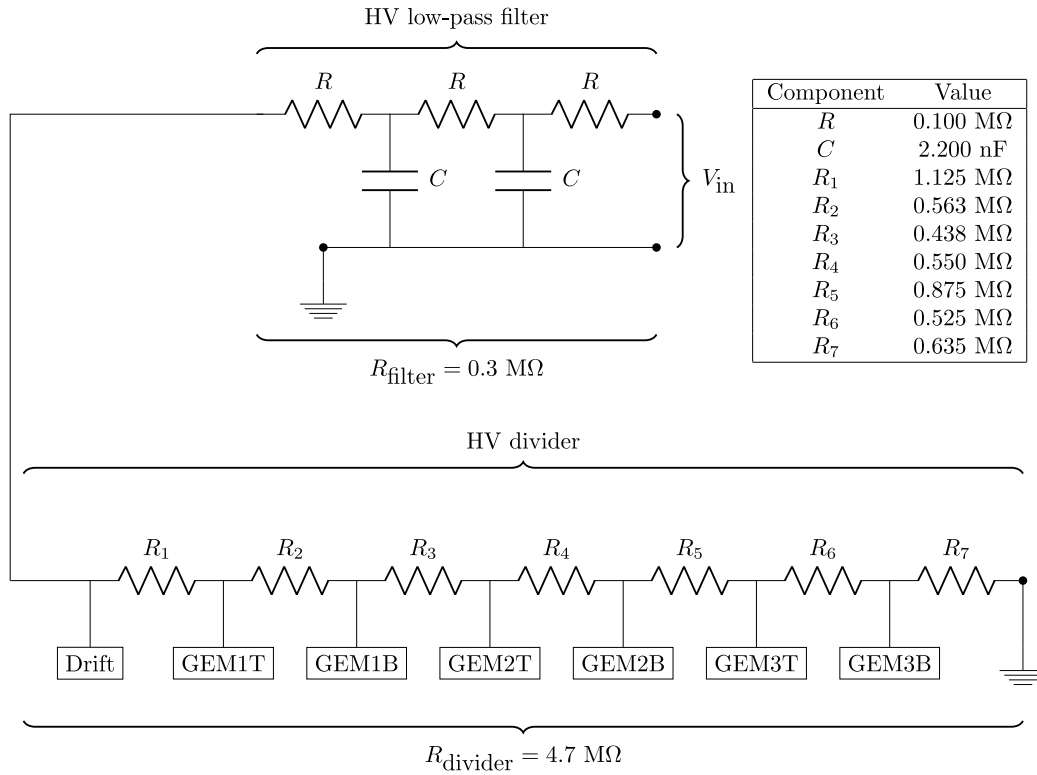


Fig. 18. The circuit diagram for the HV filter (top) and the ceramic HV divider (bottom).

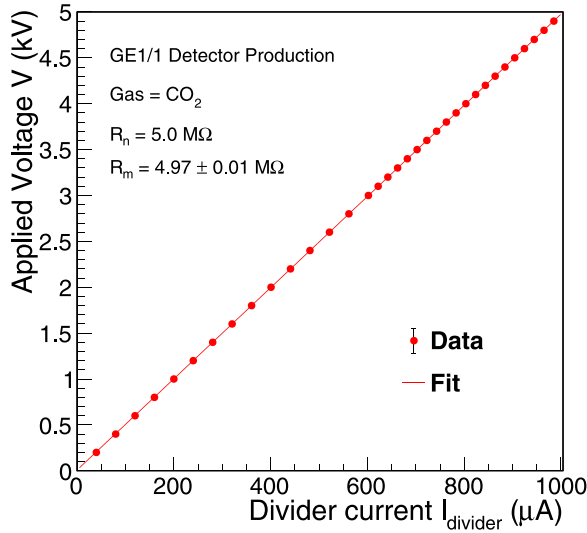


Fig. 19. High voltage vs. divider current curve for a GE1/1 detector (GE11-X-S-CERN-0012), measured in pure CO₂. Error bars are smaller than the markers. A linear fit of the measured data points is shown. The slope from the fit is taken as the measured resistance R_m .

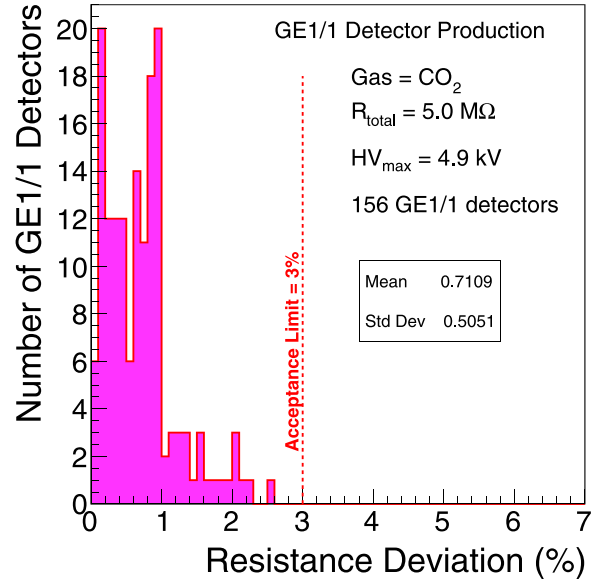


Fig. 20. Deviation of the measured resistance, D_R , for the high voltage powering circuit connected to the detector, with respect to its nominal value for all 156 GE1/1 detectors (the two missing detectors did not pass the previous QC test). The 3% threshold for accepting a detector is also shown.

serves to disentangle effects related to the detection of actual radiation from those induced solely by the application of high voltage.

Fig. 21 shows the number of spurious signals recorded by each strip in the eta sector next to the narrow base of the trapezoid for a prototype of the GE1/1 detector. In this reference measurement, the detector is operated with Ar/CO₂ (70:30) with an average effective gas gain of only ~ 300 to reduce the detection efficiency for cosmic ray muons to a few percent. It is found that the discharges that create the spurious signals here are induced mainly in strips near the screws used to stretch the GEM foils. Similar results are found for the eta partition next to

the long base of the trapezoid while measurements performed in the remaining sectors showed no substantial contribution to the spurious signal rate. We conclude that the origin of the spurious signals in the GE1/1 detectors under these conditions is a coronal discharge from the active area of the GEM along the internal frame (which holds the GEM foils inside the gas volume) to ground through the anode strips where the signal is read out.

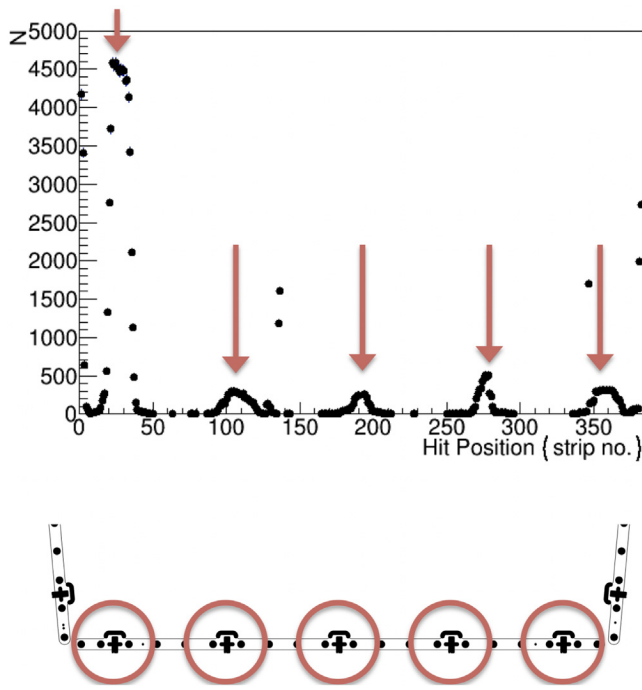


Fig. 21. Number of intrinsic noise signals recorded by each strip in the eighth *in* partition (next to the short base of the trapezoid) for a prototype GE1/1 detector (serial number GE1/1-VII-L-CERN-0001). The layout in the bottom part of the picture shows the location of the stretching screws along the internal frame in this partition that the intrinsic noise signals correlate to.

3.6.2. Selection criteria

The rate of intrinsic noise signals produced by coronal discharges across the full 3500–4000 cm² surface area of a normally operating GE1/1 detector is found to not exceed $\mathcal{O}(10^{-2})$ Hz/cm². Consequently, the detector is accepted if the intrinsic noise rate for the full detector does not exceed 100 Hz. This value is negligible when compared to the 4.5 kHz/cm² background rate [9] expected in the CMS experiment during standard operating conditions.

3.6.3. Test setup

A grounding plate is attached to the backside of the detector readout board and connected to the ground pad of the drift PCB to reduce environmental RF noise pick-up. The readout sectors are grounded via Panasonic-to-LEMO adapters with 50 Ω termination. To measure the intrinsic noise rate, signals are read from the contiguous bottom of the third GEM foil through a decoupling CR differentiator circuit soldered onto the drift board of the GE1/1 detector. The signals are then processed with a readout chain (Fig. 22) that comprises a charge-sensitive preamplifier, an amplifier, and a discriminator with the threshold set to suppress the environmental noise (140 mV). The resulting digital pulses go through a dual timer and then to a counting unit for the rate measurement. A linear fan-in fan-out module is placed between the shaper and the discriminator to allow simultaneous monitoring of the intrinsic noise signals on the scope.

3.6.4. Results

The rate of intrinsic noise signals induced on the bottom of the third GEM foil is measured as a function of applied HV for each detector as shown in Fig. 23. The maximum measured value of the intrinsic noise rate at 4.9 kV is taken as a final result. All GE1/1 detectors show a noise rate that is well below the 100 Hz acceptance threshold, as displayed in Fig. 24.

3.7. QC step 5 — Effective gas gain measurement

3.7.1. Motivations

The effective gas gain is a crucial parameter for operating a gaseous detector in proportional mode. It is a combination of two main components: the amplification factor given by each GEM foil and the transparency factor which depends on the fraction of the electrons that get lost because they recombine with the gas ions or attach to gas molecules or get absorbed by one of the GEM electrodes. It governs the detection performance such as efficiency and time resolution, which are key parameters for successfully reconstructing detector hits associated with charged particles that traverse the active detector volume.

The effective gas gain is determined experimentally by comparing the primary current induced in the drift gap by an incident, ionizing radiation quantum, with the output current provided by the amplification structure of the detector, i.e. the three GEM foils, with the signal induced on the readout electrode. The effective gas gain primarily depends on the operating gas and the electric field configuration inside the detector. For a triple-GEM detector, the effective gas gain is also a function of the electron multiplication factor in the GEM holes and the electron transparency of the GEM foils.

3.7.2. Selection criteria

To successfully detect muon hits used by the CMS trigger and offline reconstruction, a time resolution below 8 ns and at least a 97% detection efficiency are necessary. Previous test beam campaigns showed that such performance can be obtained using GE1/1 detectors operating with an effective gas gain around 2×10^4 . The gain of all detectors should fall within $\pm 37\%$ of this nominal effective gas gain value to ensure a detection system with sufficiently uniform gain [17]. The typical HV range for obtaining such gain values is 3290–3390 V applied on the drift electrode for GE1/1 detectors. Previous studies [18] show that this operational regime is far from the breakdown voltage that would trigger discharges towards the readout electrode with non-negligible probability.

3.7.3. Test setup and procedure

The effective gas gain of a GE1/1 detector is measured in the central readout sector as a function of the current through the HV divider. To perform the test, we use an X-ray generator with an emission cone size of 120 degrees that makes it possible to irradiate the entirety of the chamber simultaneously. The X-ray generator uses an electron gun with electrons incident on a silver target. The X-rays emitted from the silver consist mainly of K_α and K_β emission lines, centered on energies of 22.5 and 25 keV, on top of a Bremsstrahlung continuum. The X-ray photons are absorbed by the copper atoms that constitute the drift electrode which in turn emit 8 keV photons by fluorescence. These 8 keV photons are then converted to electrons via the photoelectric effect in the gas atoms in the detector volume — in particular in the drift gap. The primary current induced in the drift gap is given by the product of the rate R of electrons converted from the photoelectric effect from the incident photons, multiplied by the elementary charge e and the number of primary electrons N_p produced by the incident photoelectron in the Ar/CO₂ (70:30) gas mixture. To measure the rate of incident photoelectrons, the readout electrode in the sector under test is connected to the signal processing chain in Fig. 25.

The current I_{RO} induced on the readout electrode is measured separately with a pico-ammeter connected to the sector under test (Fig. 25). For each measurement, the thermal noise current and noise rate are also measured and treated as pedestals to be subtracted from the readout current and the photoelectron rate, respectively, that are measured when irradiating the detector with the X-ray beam. The effective gas gain G is given by:

$$G = \frac{I_{RO}}{R \cdot e \cdot N_p} \quad (5)$$

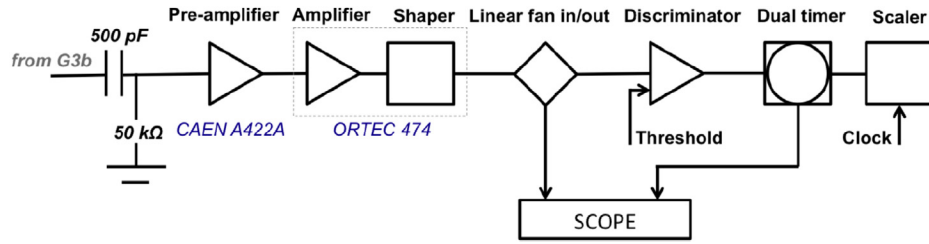


Fig. 22. The signal processing chain for the measurement of the rate of intrinsic noise signals coming from the bottom of the third GEM foil. Since the pre-amplifier and amplifier are among the most critical components of this processing chain, we indicate the specific models in the schematic. The measurement is performed on the contiguous bottom electrode of GEM3 (G3b) of a GE1/1 detector operated with pure CO_2 .

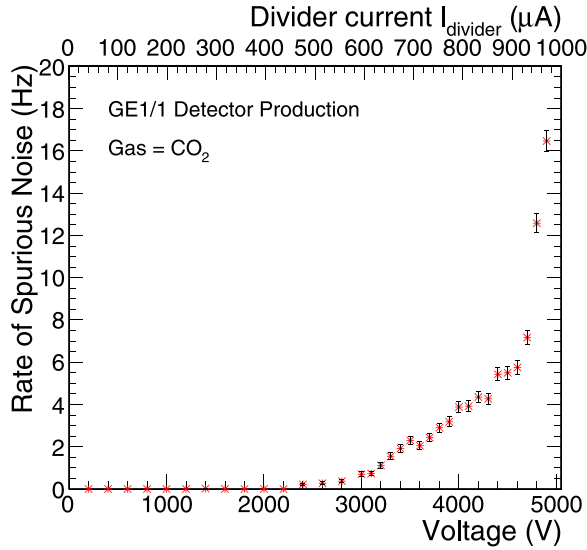


Fig. 23. Measured intrinsic noise rate of a GE1/1 detector (GE11-X-S-CERN-0012) when operated in pure CO_2 and at a signal threshold of 140 mV.

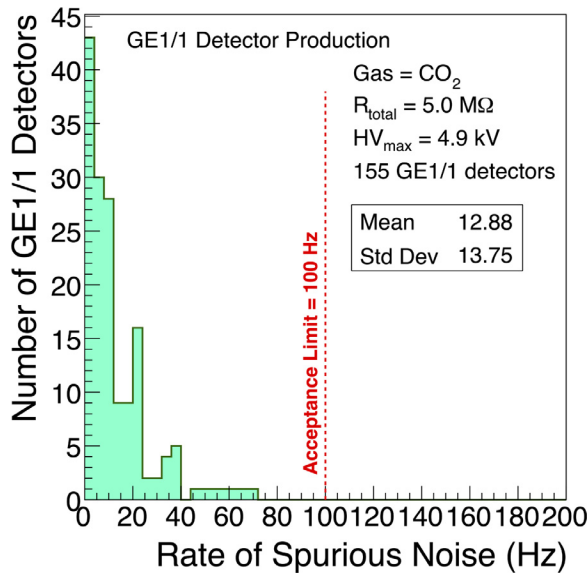


Fig. 24. Intrinsic noise rates for 155 GE1/1 detectors operated with pure CO_2 and a signal threshold of 140 mV out of 156 that passed the previous QC test. (Results for the one missing detector have been lost.)

For determining the experimental error on the gain values, Poissonian uncertainty is assumed on the number of recorded photoelectrons

for the determination of R . For the determination of the readout current, a sample of 300 measurements is taken and the standard deviation of the mean is taken as the uncertainty on I_{RO} .

3.7.4. Measuring the number of primary electrons

A dedicated calibration procedure is performed to measure the mean number of primary electrons N_p created by an incident X-ray photon in a GE1/1 detector filled with the Ar/CO_2 (70:30) gas mixture. The energy spectrum of the resulting photoelectrons is recorded by a GE1/1 detector with a multi channel analyzer for several detector operating points, each corresponding to a particular value of the effective gas gain. The peak position of each energy spectrum, which is extracted with a fit procedure assuming a Gaussian model for the peaks and a polynomial distribution for the underlying continuum, is taken as the measured value of the amplified charge recorded by the GE1/1 detector for an incident photoelectron from copper fluorescence with an energy of 8 keV. By assuming that the effective gas gain of the operating detector is precisely known, the number of primary electrons can be obtained. The mean number of primary electron induced by an 8 keV X-ray photon in an Ar/CO_2 (70:30) gas mixture in the GE1/1 detector is found to be $N_p = 346 \pm 3$ from this measurement.

As a cross-check, this procedure is performed with two more X-ray sources (^{55}Fe , ^{109}Cd) with the same detector under the same conditions. These same X-ray sources are then used to measure the effective gain calibration curve of the detector. It is found that the resulting respective gain curves, obtained with the same detector under irradiation by different sources, agree with each other within the uncertainties.

3.7.5. Typical results

Examples of typical effective gas gain curves for GE1/1 production detectors, measured as a function of the HV applied to the drift electrode and the current in the HV divider, are shown in Fig. 26. The blue and red curves refer to GE1/1 detectors produced and tested at different production sites. The difference in the measured effective gain is due to the different environmental conditions at the two production sites. Given the dependence of the effective gas gain on the exponential of the Townsend coefficient, which in turn depends on the ratio between environmental temperature and pressure, the gain curves are normalized to a predefined reference pressure and temperature. The reference values correspond to the average pressure and temperature at the location of the GE1/1 station in the CMS apparatus observed over one year, with $P_0 = 964$ mbar and $T_0 = 297$ K. Rather than correcting the gain values, the value of the applied drift voltage V_{drift} (or the current running through the divider), for a given production site X , is corrected by the relation

$$V_{\text{drift}}^{\text{corr}} = V_{\text{drift}} \cdot \frac{T_X}{P_X} \cdot \frac{P_0}{T_0} \quad (6)$$

The impact of the normalization procedure is clearly evident in Fig. 27, where the two curves are shown after applying the pressure and temperature correction. While this particular correction was used during the QC process described here, we note that an empirical correction was developed subsequently to improve the description of the gain dependence on environmental temperature and pressure [19].

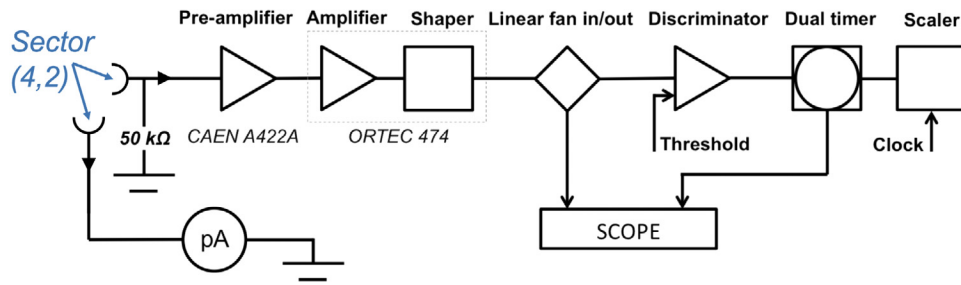


Fig. 25. Signal processing chain for the measurement of the rate of converted photoelectrons in the drift gap. The most critical modules are highlighted and their specifications are available on the manufacturer's website. The measurement is performed in the central readout sector ($i\eta = 4$, $i\phi = 2$) of a GE1/1 detector; see the CMS local coordinate system (Fig. 3).

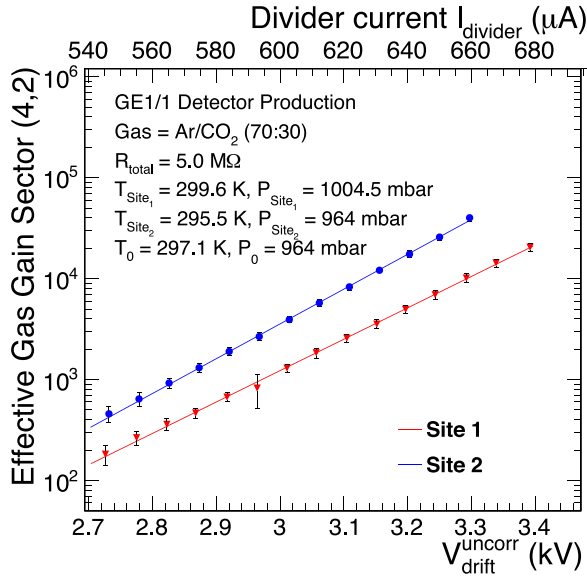


Fig. 26. The effective gas gain of two GE1/1 detectors built and tested at CERN (GE11-X-S-CERN-0012, red curve) and in Italy (GE11-X-S-BARI-0011, blue curve) as a function of drift voltage and HV divider current before pressure and temperature corrections.

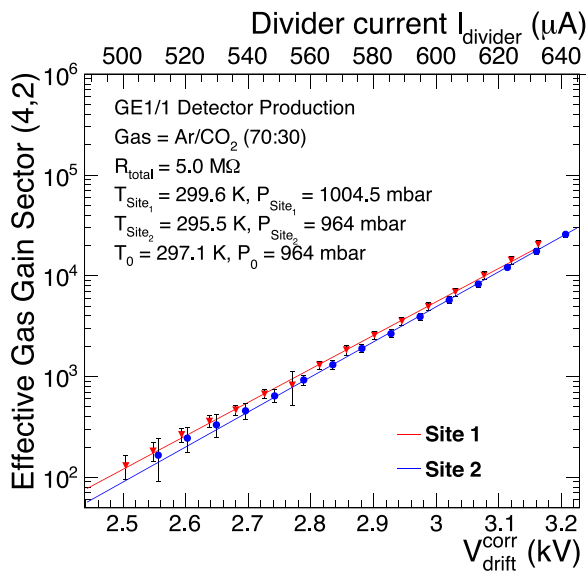


Fig. 27. The effective gas gain of two GE1/1 detectors built and tested at CERN (GE11-X-S-CERN-0012, red curve) and in Italy (GE11-X-S-BARI-0011, blue curve) after pressure and temperature corrections (see Eq. (6)) are applied to drift voltage and HV divider current.

3.8. QC step 5b — Response uniformity measurement

3.8.1. Motivations

The gain measurement performed in a central readout sector of each GE1/1 detector sets the absolute gain scale of the detector as a function of HV. To find the gain across the entire detector and to quantify its variation, the relative response is measured for all readout strips.

3.8.2. Test setup

The drift electrode is irradiated with a wide X-ray beam from the X-ray generator described in Section 3.7.3. The charge induced on the readout strips is amplified by analog pipeline voltage 25 (APV25) analog readout chips [20], digitized by analog-to-digital converters (ADCs), and recorded by front-end concentrator cards (FECs), which are components of the RD51 Scalable Readout System (SRS) [21]. Fig. 28 gives a schematic of this test setup.

During data taking, one would ideally want to trigger on the signal from the contiguous bottom electrode of the third GEM foil, which is the mirror image of the signals collected on all the readout strips. However, because of the large capacitance of this electrode relative to the anode strips, the electronic noise is typically too high to reliably trigger the APV system, in particular for the lower range of the energy distribution of the interacting particles. Consequently, the APV25 is operated in random trigger mode. Given the rate from the X-ray gun, which is on the order of several MHz over the entire chamber, and the size of the APV25 acquisition time window (up to 750 μ s), it is basically guaranteed that at least one event is recorded for each random trigger.

As the APV25 ASICs were initially designed for detection of minimum-ionizing particles with silicon-based detectors [20], the amplifiers tend to saturate when operating with X-rays in gaseous detectors at full nominal gain. This saturation typically prevents the proper reconstruction of the collected charge and diminishes the data quality. To overcome this issue, the GEM chambers under test are operated at a reduced gas gain (typically between 500 and 600), below the saturation level. Fig. 29 demonstrates that at lower operating voltages, i.e. at lower total effective gains, the response uniformity measured across all readout sectors of the chamber is very similar to that measured at higher voltages and gains. This is an important result as it allows flexibility when setting the operating point of the chamber. A broad range of drift voltages can be used without compromising the uniform response of the detector.

In the data analysis, the readout of the GE1/1 detector is divided into 768 slices with each slice comprising four readout strips that are adjacent in the $i\phi$ coordinate. For each detector slice, the position of the main peak in the spectrum – the copper fluorescence photopeak – is determined from fitting a Cauchy distribution to the ADC spectrum of the total measured strip-cluster charges. Here, the total charge in each X-ray conversion is obtained by summing the ADC counts over the strips in the strip cluster. To model the background, a fifth-order polynomial is fit to the data. Fig. 30 shows a typical example of this strip-cluster charge ADC spectrum for one slice of a production GE1/1 detector.

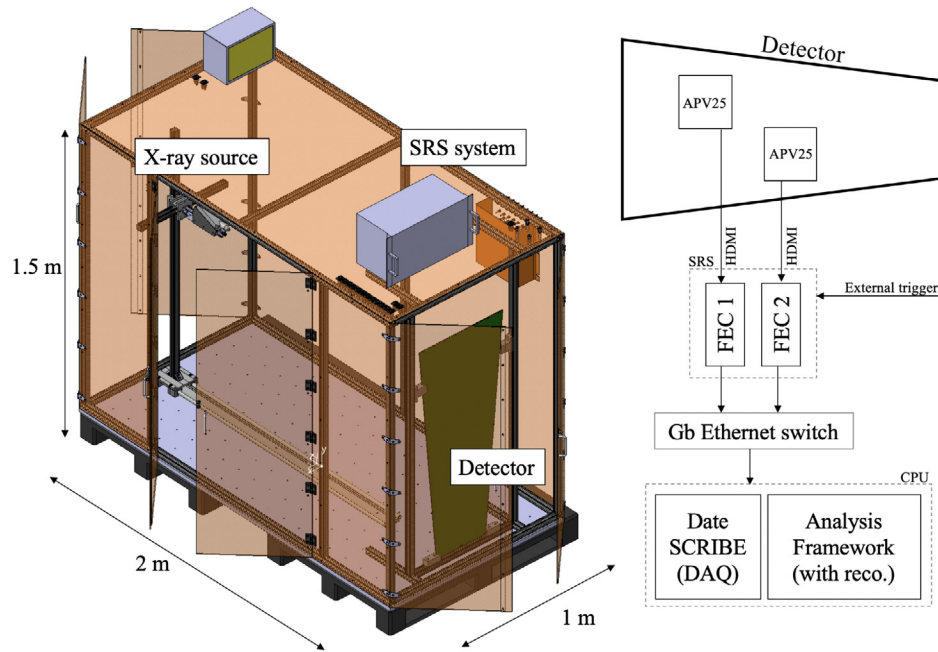


Fig. 28. Schematic overview of the X-ray station for the QC5 response uniformity test (left). Typical data flow in the SRS DAQ from the front-end APV25 to the analysis framework (right).

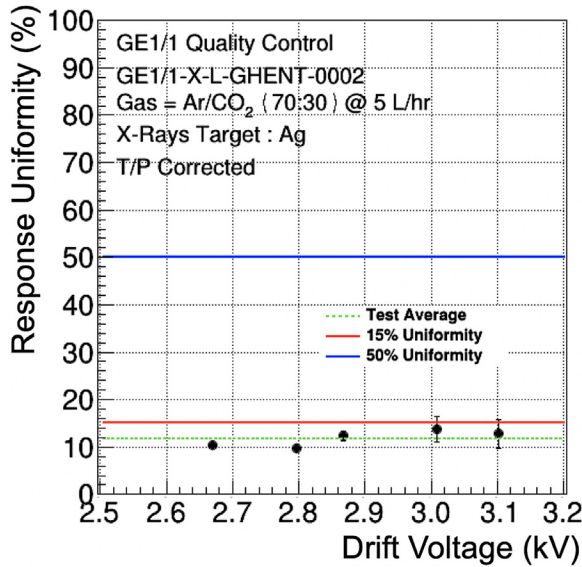


Fig. 29. Gas gain uniformity as a function of the HV applied to a GE1/1 chamber. The results shown are for GE1/1-X-L-GHENT-0002.

3.8.3. Selection criteria

As discussed in Section 3.7, the effective gas gain is a combination of the amplification factor given by each GEM foil and the transparency factor. The uniformity of the amplification factor is mostly driven by the consistency of the GEM hole geometry across the foil since the applied voltage is usually constant. Past measurements [22] show that the main variations in the GEM geometry are the thickness of the polyimide layer and the inner and outer diameters of the biconical holes. From the manufacturer's specifications, the polyimide thickness is typically $(50.0 \pm 0.1) \mu\text{m}$. The corresponding uncertainty on the electric field propagates into a gain variation of 2.4% for a single GEM and 4.2% for a triple-GEM stack [22]. Similarly, the effect of the uncertainty on the hole diameter can be translated in terms of

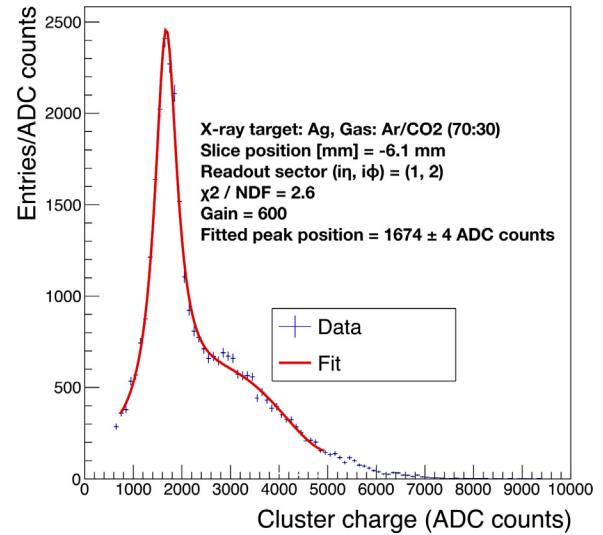


Fig. 30. X-ray spectrum measured within one 4-strip slice of a GE1/1 production detector (serial number GE1/1-X-S-BARI-0007) in ADC units. The spectrum is dominated by the copper fluorescence peak that occurs when irradiating the GEM detector and its various Cu components with X-rays from an X-ray tube with Ag or Au anode. The data are fit to a Cauchy function (peak) plus a fifth-order polynomial for the underlying continuum.

gain variations. Based on the measurements shown in Fig. 31 [22], we estimate that with a typical outer GEM hole diameter of $(70.0 \pm 5.0) \mu\text{m}$, the corresponding gain uncertainty is on the order of 15% for a single foil, and 26% for a triple-GEM stack.

The transparency factor is mostly affected by the variations of the electric field across the detector volume. While the input voltage is unique for each entire electrode, the variation of the gaps between the electrodes impacts the electric field uniformity. In the particular case of the GE1/1 detector, the gaps between the foils are defined by the thickness of the internal frame pieces and the foil stretching applied from the periphery of the GEM stack. The corresponding variation

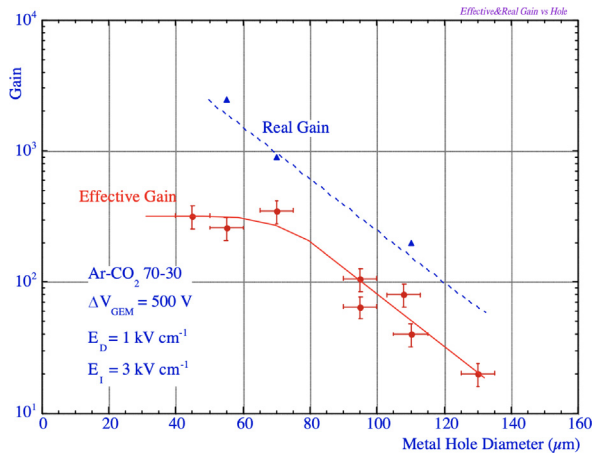


Fig. 31. Real and effective gas gains of a single-GEM detector as a function of the outer hole diameter (reproduced from [22]). The real gain is the absolute multiplication factor, which neglects losses of the secondary electrons to the bottom of the GEM foils and electron-ion recombination. The effective gain, which considers these losses, is the more relevant measure of gain.

Table 2

Parameters contributing to the uncertainty in uniformity response.

Uncertainty	Description	Contribution (%)
$\sigma_{\text{thickness}}$	Gap size between the GEM foils	1
σ_{diameter}	Diameter of holes in the GEM foil	4.2
$\sigma_{\text{drift-bend}}$	Bending of the drift PCB	25
$\sigma_{\text{RO-bend}}$	Bending of the RO PCB	7.5

of the gap sizes is below 1% and introduces only negligible gain variations. However, the drift and readout boards are large PCBs with uneven copper deposits on one side, and both are subject to significant mechanical tensions when they are fixed to the foil pull-outs. As a result, those boards can slightly bend, causing variations in gap thickness, especially near the center of the trapezoid. In addition, the boards can bulge in the center due to the applied gas pressure. Consequently, the typical dimension and variation of the drift gap is (3.0 ± 0.6) mm and (1.0 ± 0.4) mm for the readout gap. The corresponding relative errors on the electric fields are 20% for the drift field and 40% for the induction field in the readout gap. Figs. 32 and 33 show the influence of these electric field variations on the effective gain. From these values, we estimate the gain variations arising from the deformations of the PCBs to be 7.5% on the drift side and 25% on the induction side. The impact of the various effects are summarized in Table 2.

Combining the uncertainties for each parameter discussed above in quadrature yields the total expected relative uncertainty on the effective gain within a GE1/1 chamber:

$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{thickness}}^2 + \sigma_{\text{diameter}}^2 + \sigma_{\text{drift-bend}}^2 + \sigma_{\text{RO-bend}}^2} = 37.1\% \quad (7)$$

Thus, a maximum gain variation of 37% is taken as the upper threshold on the allowed response variation across a GE1/1 detector.

3.8.4. Results

The position of the copper fluorescence photopeak in the ADC spectrum of the total strip-cluster charges is a good measure of the local gain across the chamber. A typical distribution of the fitted positions of these photopeaks across all 768 slices in a chamber is plotted in Fig. 34. This distribution is fitted with a Gaussian to extract the mean (μ) and the standard deviation (σ) of the distribution.

The standard deviation is a measure of the response uniformity of the detector. Specifically, the relative response uniformity of a GE1/1 detector, quoted as a percent, is defined as $\frac{\sigma}{\mu} \cdot 100\%$, which characterizes the gain variation across the whole detector area. Fig. 35 shows two

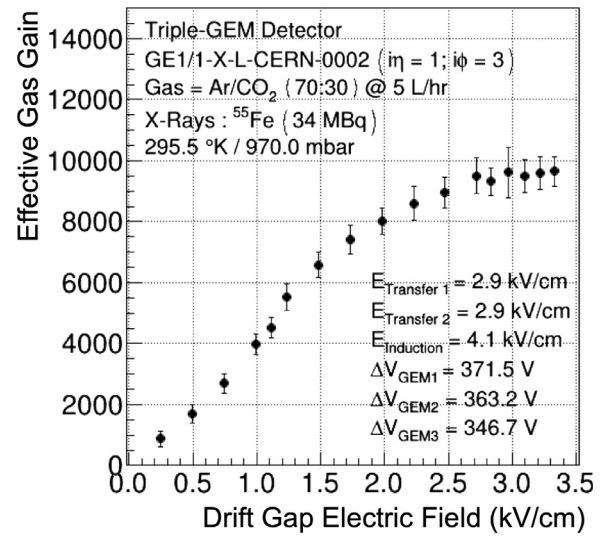


Fig. 32. Effective gas gain as a function of the electric field in the drift gap. The results are shown for detector GE1/1-X-L-CERN-0002.

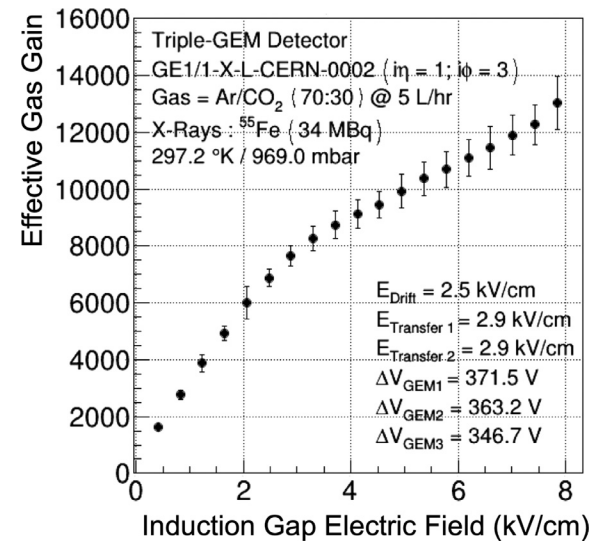


Fig. 33. Effective gas gain as a function of the electric field in the induction gap. The results are shown for detector GE1/1-X-L-CERN-0002.

examples for the absolute azimuthal gain variations across a chamber for each $i\eta$ sector, and Fig. 36 gives an example of the relative gain variation across a chamber. In general, we observe a continuous, “u”-shaped curve that peaks at the edges of the detector and attains a minimum at the center of the detector (Fig. 35, bottom). This phenomenon can be attributed to the bending of the readout and drift electrodes previously discussed. We also observe chambers with less variation along the azimuthal direction ($i\phi$), e.g. Fig. 35 (top), which results from more planar drift and readout PCBs. As Fig. 37 shows, all tested GE1/1 detectors exhibit gain variations below 30%. This value is well below the threshold (37%) that was described in the previous section and consequently all detectors pass this final QC step.

4. Choice of the operational working point

By combining the detector response uniformity with the gain measurement in the reference readout sector, we can infer the gas gain of each detector slice for each HV operating point. The average detector gain, i.e. the mean of the gain values for all 768 strip slices in the

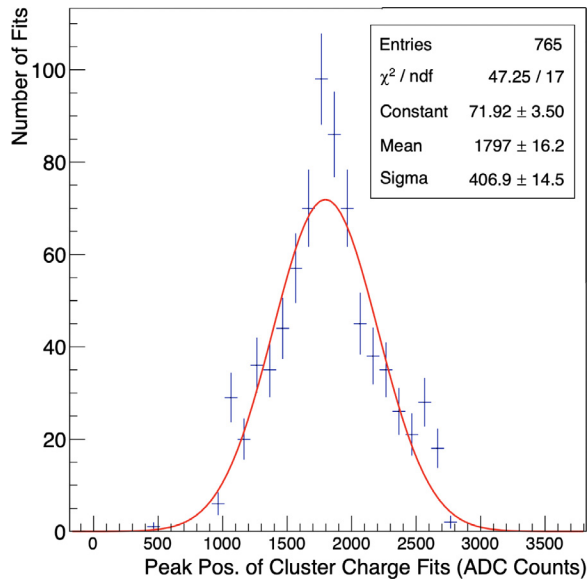


Fig. 34. Example of the aggregated ADC spectra of strip-cluster charge across one entire long chamber (serial number GE11-X-L-PAKISTAN-0005). The peak positions of strip-cluster charges obtained from the fits as shown in Fig. 30 are histogrammed for all slices here, where one slice corresponds to four strips. The standard deviation obtained from the Gaussian fit, shown relative to the mean of that Gaussian, is taken as an overall measure of the gain uniformity for the chamber; for this particular chamber $\sigma/\mu = 22.6\%$.

detector, at a fixed drift voltage of 3102 V, is plotted in yellow for all short (Fig. 38) and long (Fig. 39) detectors initially installed in the GE1/1 station.

It is important to choose HV working points that guarantee uniform behavior of the SCs in terms of gain and, consequently, uniform efficiency and time resolution across the GE1/1 system. During operation in CMS, the two detectors in a SC are powered together by the same power supply, i.e. the corresponding electrodes of the two GE1/1 detectors in one SC are connected in parallel and supplied by the same output channel of the HV supply. While gain variations between SCs can be compensated by adjusting the HV working points of the SCs, gain variations between two detectors in the same SC cannot be compensated by individual HV adjustments. To minimize the impact of this constraint, the detectors are sorted by increasing value of the gain and then neighboring chambers in this sorted list are paired into a SC. This ensures that the two detectors in each SC have similar gain performance.

Finally, for each SC, the HV operation point that ensures a SC gain of 10^4 averaged over the two chambers, is computed from the QC data. The corresponding gas gain distributions, obtained after this optimization procedure, are shown in blue in Figs. 38 and 39, for short and long detectors, respectively. As seen in the yellow histograms in Figs. 38 and 39, the distribution of the average effective gas gain before the pairing procedure is quite spread out. The width of these distributions, as quantified by the RMS, is found to be 2822 for long SCs and 3122 for short SCs. After the pairing procedure, the width of the distribution of the average effective gas gain is strongly reduced. A Gaussian fit of the blue histograms in Figs. 39 and 38 is performed and the sigma values obtained from the fits are found to be 290 ± 29 for long SCs and 619 ± 83 for short SCs.

5. Summary, conclusions, and perspectives

In total, 161 GE1/1 detectors were assembled and subjected to stringent quality control tests at several production sites. Of these, three were rejected in the QC2 HV test and two in the QC3 leakage test,

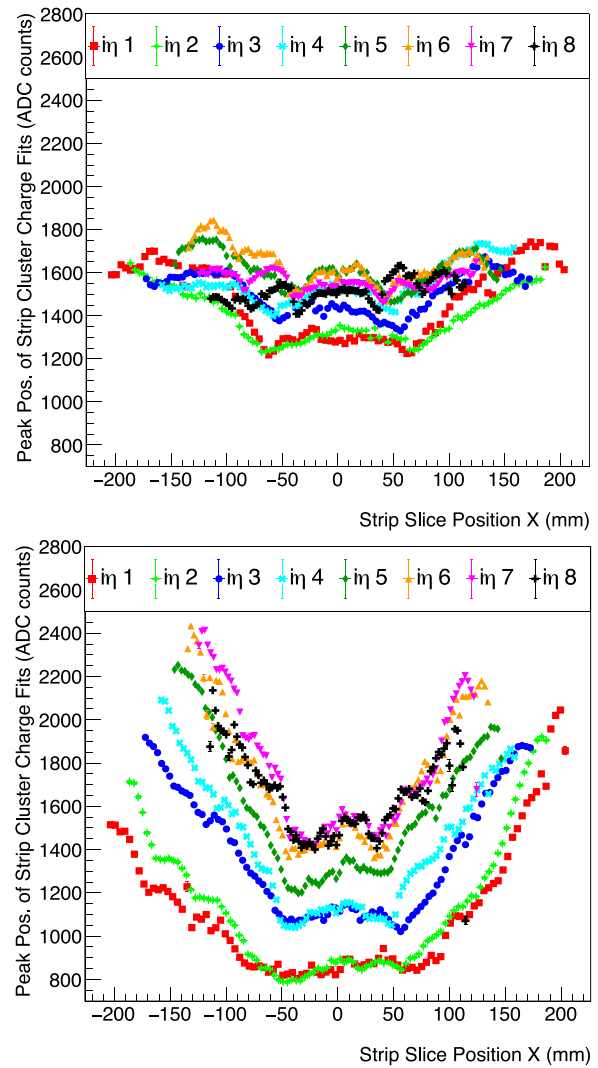


Fig. 35. Example of the gain variation across two GE1/1 chamber (serial numbers: GE11-X-L-GHENT-0003 [top] and GE11-X-L-GHENT-0023 [bottom]). The fitted peak position of the distribution of all strip cluster charges (Fig. 30) within slices of four strips is plotted as a function of the center of the strip slice position across the eight in sectors. The response uniformity, $\sigma/\mu \cdot 100\%$, for GE11-X-L-GHENT-0003 is $(6.6 \pm 0.3)\%$, and the response uniformity for GE11-X-L-GHENT-0023 is $(24.9 \pm 0.9)\%$. The systematic difference in gain variation between these two detectors is primarily due to a difference in the planarity of the drift and readout boards.

while 156 were successfully validated following all the quality control processes described in this paper. Subsequently, 144 detectors have been installed in the CMS muon endcaps with 12 detectors being kept as spares. The five rejected chambers are also kept as one can recuperate components as needed due to the assembly technique without the use of glue.

The QC procedure succeeds in ensuring robust performance and comparable results for detectors assembled and tested at different production sites. This is a great success for the distributed-sites production model, which has established a widespread community of GEM technology experts in CMS. The high success rate is indicative of the quality and pre-testing of the components, which is described in [12].

A few lessons have been learned that now inform the construction and testing of the detectors for the other two stations, GE2/1 and ME0. For example, the intrinsic noise can be reduced by slightly modifying the shape of the inner frames and the T-nuts. Also, a central pillar is now introduced into modules that provides a rigid connection between drift and readout PCBs which reduces the deformation of the

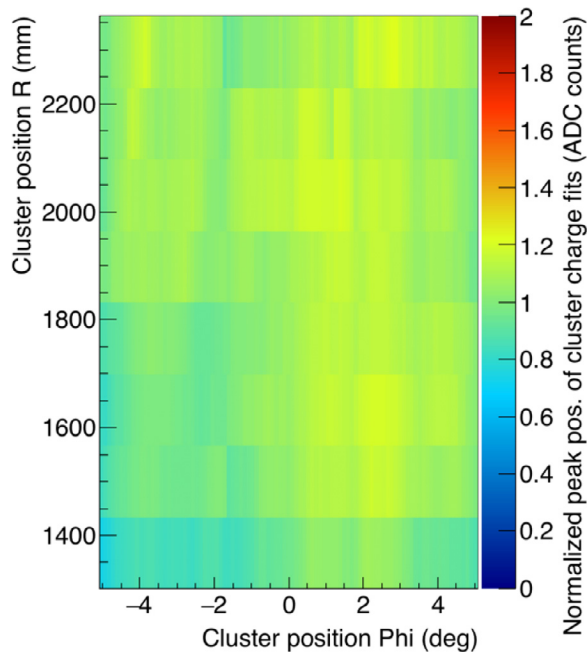


Fig. 36. Example of the gain variation across a GE1/1 chamber (serial number GE11-X-S-INDIA-0009) normalized to the chamber average. Note that the coordinates are plotted in radial distance from the beamline in the CMS experiment (y-axis) and angular distance from the centerline of the chamber ($i\phi$). The horizontal binning corresponds to slices of four strips while the vertical binning corresponds to the eight $i\eta$ sectors.

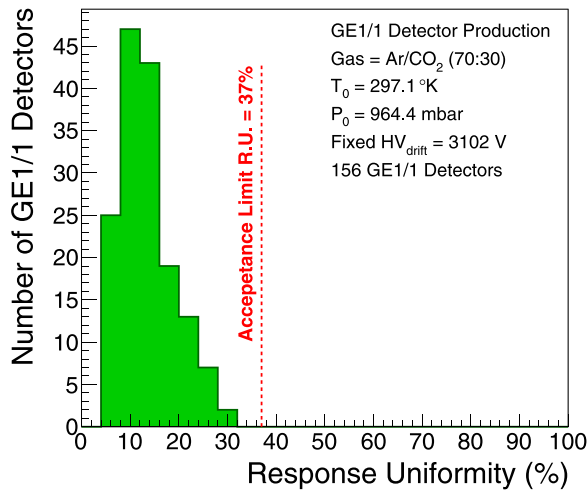


Fig. 37. Relative response uniformity of all 156 GE1/1 detectors as determined by σ/mean obtained from the respective distributions of the type shown in Fig. 34.

pressurized detector, which leads to a more uniform response across the detector. This community is now ready to produce new modules for the two additional muon stations based on GEM technology, i.e. GE2/1 and ME0 [8], which are currently slated to be installed in CMS in 2023 and 2026, respectively, to further enhance the muon system during Runs 4 and 5 at the HL-LHC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

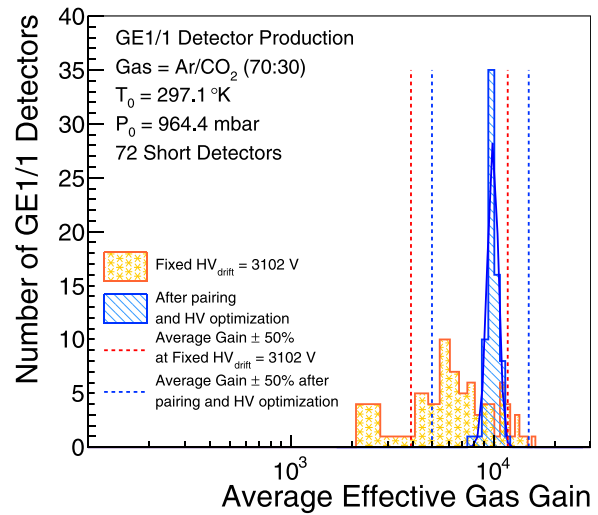


Fig. 38. Average effective gas gain distribution for short GE1/1 detectors before (yellow) and after (blue) the procedure for pairing detectors into superchambers is applied. The dashed lines represent the $\pm 50\%$ range of the gain around the average before (orange) and after (blue) the pairing procedure. The gain is normalized to the pressure and temperature expected at the GE1/1 station in the CMS experiment. Results are shown for all 72 short GE1/1 detectors initially installed in CMS.

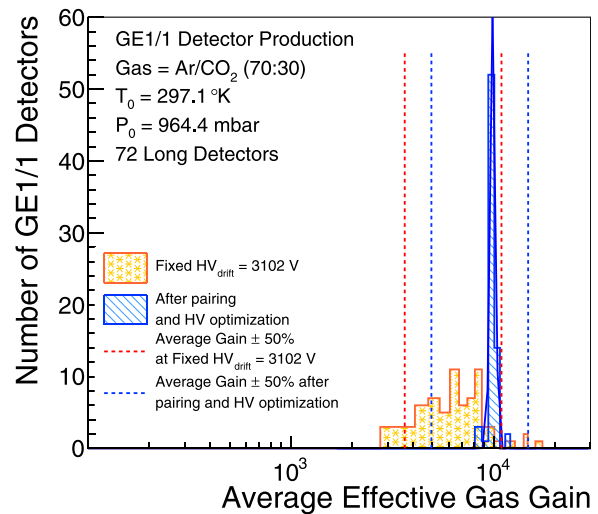


Fig. 39. Average effective gas gain distribution for long GE1/1 detectors before (yellow) and after (blue) the procedure for pairing detectors into superchambers is applied. The dashed lines represent the $\pm 50\%$ range of the gain around the average before (orange) and after (blue) the pairing procedure. The gain is normalized to the pressure and temperature expected at the GE1/1 station in the CMS experiment. Results are shown for all 72 long GE1/1 detectors initially installed in CMS.

Acknowledgments

We gratefully acknowledge support from FRS-FNRS (Belgium), FWO-Flanders (Belgium), BSF-MES (Bulgaria), MOST and NSFC (China), BMBF (Germany), CSIR (India), DAE (India), DST (India), UGC (India), INFN (Italy), NRF (Korea), MoSTR (Sri Lanka), DOE (USA), and NSF (USA).

References

- [1] CMS Collaboration, G.L. Bayatian, et al., The CMS Muon Project, Tech. Design Rep. CERN-LHCC-97-032, CMS-TDR-3, 1997, URL <http://cds.cern.ch/record/343814>.

- [2] R. Santonico, R. Cardarelli, Development of resistive plate counters, Nucl. Instrum. Methods 187 (1981) 377–380, [http://dx.doi.org/10.1016/0029-554X\(81\)90363-3](http://dx.doi.org/10.1016/0029-554X(81)90363-3).
- [3] CMS Collaboration, J. Hauser, Cathode strip chambers for the CMS endcap muon system, Nucl. Instrum. Methods A 384 (1996) 207–210, [http://dx.doi.org/10.1016/S0168-9002\(96\)00905-9](http://dx.doi.org/10.1016/S0168-9002(96)00905-9).
- [4] G. Abbiendi, et al., The CMS muon barrel drift tubes system commissioning, Nucl. Instrum. Methods A 598 (2009) 192–195, <http://dx.doi.org/10.1016/j.nima.2008.08.100>.
- [5] CMS Collaboration, S. Chatrchyan, et al., The performance of the CMS muon detector in proton-proton collisions at $\sqrt{s}=7$ TeV at the LHC, JINST 8 (2013) P11002, <http://dx.doi.org/10.1088/1748-0221/8/11/P11002>, arXiv:1306.6905.
- [6] CMS Collaboration, A. Sirunyan, et al., CMS Collaboration Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, JINST 13 (06) (2018) P06015, <http://dx.doi.org/10.1088/1748-0221/13/06/P06015>, arXiv:1804.04528.
- [7] CMS Collaboration, V. Khachatryan, et al., in: D. Contardo, M. Klute, J. Mans, L. Silvestri, J. Butler (Eds.), Technical Proposal for the Phase-II Upgrade of the CMS Detector, Tech. Rep. CERN-LHCC-2015-010, LHCC-P-008, CMS-TDR-15-02, 2015, URL <http://cds.cern.ch/record/2020886>.
- [8] CMS Collaboration, A.M. Sirunyan, et al., in: T. Hebbeker, A. Korytov (Eds.), The Phase-2 Upgrade of the CMS Muon Detectors, Tech. Design Rep. CERN-LHCC-2017-012, CMS-TDR-016, 2017, URL <https://cds.cern.ch/record/2283189>.
- [9] CMS Collaboration, M.A. Akl, et al., in: A. Colaleo, A. Safonov, A. Sharma, M. Tytgat (Eds.), CMS Technical Design Report for the Muon Endcap GEM Upgrade, Tech. Design Rep. CERN-LHCC-2015-012, CMS-TDR-013, 2015, URL <http://cds.cern.ch/record/2021453>.
- [10] F. Sauli, GEM: A New concept for electron amplification in gas detectors, Nucl. Instrum. Methods A 386 (1997) 531–534, [http://dx.doi.org/10.1016/S0168-9002\(96\)01172-2](http://dx.doi.org/10.1016/S0168-9002(96)01172-2).
- [11] P. Aspell, V. Avati, W. Bialas, J. Kaspar, J. Kopal, J. Petajajarvi, E. Radicioni, J. Rouet, W. Snoeys, P. Vichoudis, The VFAT production test platform for the TOTEM experiment, in: Electronics for Particle Physics. Proceedings, Topical Workshop, TWEPP-08, Naxos, Greece, 15-19 September 2008, 2008, pp. 544–548, URL <http://doc.cern.ch/yellowrep/2008/2008-008/p544.pdf>.
- [12] D. Abbaneo, et al., CMS Muon Collaboration, Layout and assembly technique of the GEM chambers for the upgrade of the CMS first muon endcap station, Nucl. Instrum. Methods A 918 (2019) 67–75, <http://dx.doi.org/10.1016/j.nima.2018.11.061>, arXiv:1812.00411.
- [13] M. Bianco, J.A. Merlin, B. Dorney, GE11 Quality Control Instructions, Tech. Rep., 2016.
- [14] M. Abbas, M. Bianco, M. Gola, J.A. Merlin, R.D. Oliveira, A. Shah, CMS Collaboration, Technical Assembly Manual for GE1/1 Chambers, Tech. Rep., 2017.
- [15] M.A. Lieberman, A.J. Lichtenberg, Principles of Plasma Discharges and Materials Processing, second ed., Wiley-Interscience, Hoboken, NJ, USA, 2005.
- [16] V. Peskov, P. Fonte, Research on Discharges in Micropattern and Small Gap Gaseous Detectors, Tech. Rep., 2009, arXiv:0911.0463. URL <https://cds.cern.ch/record/1216915> This report was written in the framework of the RD51 collaboration.
- [17] CMS GEM Collaboration, Performance of prototype GE1/1 chambers for the CMS muon spectrometer upgrade, Nucl. Instrum. Methods Phys. Res. A 972 (2020) 164104, <http://dx.doi.org/10.1016/j.nima.2020.164104>, URL <https://www.sciencedirect.com/science/article/pii/S0168900220305155>.
- [18] S. Bachmann, A. Bressan, M. Capeáns, M. Deutel, S. Kappler, B. Ketzer, A. Polouektov, L. Ropelewski, F. Sauli, E. Schulte, L. Shekhtman, A. Sokolov, Discharge studies and prevention in the gas electron multiplier (GEM), Nucl. Instrum. Methods Phys. Res. A 479 (2) (2002) 294–308, [http://dx.doi.org/10.1016/S0168-9002\(01\)00931-7](http://dx.doi.org/10.1016/S0168-9002(01)00931-7), URL <https://www.sciencedirect.com/science/article/pii/S0168900201009317>.
- [19] G. Mocellin, Performance of the GE1/1 Detectors for the Upgrade of the CMS Muon Forward System (Dissertation), RWTH Aachen University, Aachen, 2021, <http://dx.doi.org/10.18154/RWTH-2021-07066>, URL <https://publications.rwth-aachen.de/record/822893> Available on publication server at RWTH Aachen University.
- [20] M. French, et al., Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker, in: T. Ohsugi, Y. Unno, H. Sadrozinski, I. Nakano (Eds.), Nucl. Instrum. Methods A 466 (2001) 359–365, [http://dx.doi.org/10.1016/S0168-9002\(01\)00589-7](http://dx.doi.org/10.1016/S0168-9002(01)00589-7).
- [21] S. Martoiu, H. Muller, A. Tarazona, J. Toledo, Development of the scalable readout system for micro-pattern gas detectors and other applications, J. Instrum. 8 (03) (2013) C03015, <http://dx.doi.org/10.1088/1748-0221/8/03/C03015>.
- [22] S. Bachmann, A. Bressan, L. Ropelewski, F. Sauli, A. Sharma, D. Mörmann, Charge amplification and transfer processes in the gas electron multiplier, Nucl. Instrum. Methods Phys. Res. A 438 (1999) [http://dx.doi.org/10.1016/S0168-9002\(99\)00820-7](http://dx.doi.org/10.1016/S0168-9002(99)00820-7).

Fabrication and Characterization of Gaseous Detector for the identification of High Energy Particles.

J.Babbar¹ S.Bansal² S.B.Beri¹ V.Bhatnagar¹ S.Chauhan¹
R.Gupta¹ A.Kaur¹ H.kaur¹ S.Kumar¹ P.Kumari¹ M.Meena¹
J.B.Singh¹ A.K.Virdi¹

Department of Physics, Panjab University, Chandigarh, India

² UIET, Panjab University Chandigarh, India

E-mail: meenaluhach91@gmail.com

Abstract There is a vast range of gases which get ionized, produce electron-ion pairs, on the passage of high energy charged particles. Such gases are extensively used in experiments such as LHC, Belle-II, RHIC, DAFNE, etc which produce high energy particles. Panjab University established a detector assembly and characterization laboratory dedicated to gaseous detectors such as Resistive Plate Chamber (RPC) and Gas Electron Multiplier (GEM) for the LHC experiment. Here, we present the recent work on the fabrication and characterizations of the GEM detector at Panjab University.

1. Introduction

Gaseous detectors generally have two electrodes separated by the gas medium in which primary charged particles interact and produced electron-ion pairs. The GEM detector is one of the most important Micro-Pattern Gaseous Detector (MPGD) first introduced in 1997 by F. Sauli [1] at the European Organization for Nuclear Research (CERN). It records the ionization produced by charged particles in the gaseous medium consists of three GEM foils embedded between the drift board (acting as the cathode) and the readout board (acting as the anode) [2]. The GEM detector abundantly used in High-Energy Physics (HEP) experiments like CMS [3], LHCb [4], TOTEM [5], COMPASS [6] at Large Hadron Collider (LHC), Belle II [7], etc, and in medical diagnostics [8] as well as in astronomy due to their high rate detection [9] capability up to 100 MHz/cm² with efficiency above 97%, an excellent spatial resolution of ~ 340 μ m, an excellent time resolutions [10] of ~ 8 ns. In most of the experiments to achieve high gain a high voltage supposed to apply across the detector which leads to an electrical breakdown problem. This problem can be avoided by using multi-layer GEM foils placed at a relative distance of a few mm in a suitable gas mixture. In this case, amplification is shared over different gem foils [11], with a relatively low voltage on each GEM foil. Panjab University has been collaborated with CMS [12] and build high-energy physics laboratory to assemble and test [13] triple-GEM detectors (referred to GE1/1 detector) that are installed in the 1st ring in 1st muon station in both end-caps of the CMS detector. The GEM foils and other components of production chambers are delivered from CERN.



2. Description and working principle the GEM detector

The GEM detector works in a gas medium in which gas ionization takes place due to the acceleration of electrons under the influence of the electric field. Since among noble gas Argon (Ar) is having high specific ionization and is less expensive. It can cause avalanche creation beyond the limits which leads to sparks and cause permanent damage to the detector. There is a need for a small amount of quenching gas which can be used to reduce the spark probability and to stop fake avalanche due to the emission of UV photons. The Carbon-dioxide (CO₂) has the properties of electro-negativity, it attracts electrons and attached to its molecules. A lot of studies have been performed on the selection of gas mixture to be used for this detector [14]. The gas mixtures of Ar and CO₂ are used in proportions of 70:30. Basically, a triple GEM gaseous detector is made by a drift cathode, three GEM foils, and the Printed Circuit Board (PCB) anode (or readout board). Readout board has two gas connectors located at two diagonal corners, one for gas inlet and another one for gas outlet. GEM foils are made of Kapton of 50 μ m each coated with a copper layer of 5 μ m on each side. The Kapton is a good insulator which remains stable in a very wide range of temperature. Each foil has equally spaced small holes perforated by chemical etching in a hexagonal pattern with 50 μ m internal and 70 μ m outer diameter and a pitch of 140 μ m as shown in Figure 1 (Left) where the signal gets amplified as shown in Figure 1 (right). The cms triple GEM production chamber has a 3/1/2/1 mm (drift/transfer1/transfer2/induction) gas gap configuration as shown in Figure 2 which is enclosed between two electrodes with an electric field applied between them. The primary electrons produced ionization in the gap between the cathode and the first GEM foil (drift gap). In transfer region electron-ion pairs are attracted by electric field applied on GEM foil where they get multiplied in the hole. After crossing the last GEM foil they drift to the anode in the induction gap where the signal is registered by the readout strips.

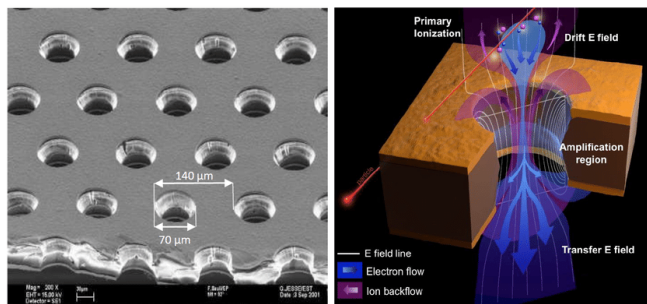


Figure 1. Left: Scanning Electron Microscope (SEM) picture of a GEM foil

Right : schematic view of the electric field lines (white), electron flow (blue), and ion flow (purple) through a bi-conical GEM hole

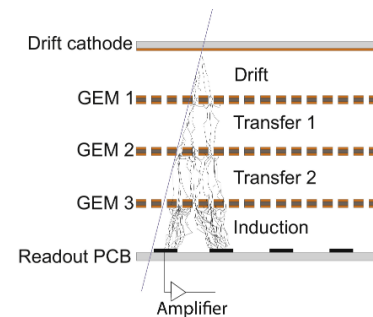


Figure 2. Sketch of a Triple-GEM chamber. Free electrons coming from ionization processes undergo three stages of amplifications.

3. Assembly and quality control testing

After receiving a kit of the different parts of the production chamber from CERN, they inspected very carefully for any possible damages that happened during transport. After that next step is the assembly of the different parts of the GE1/1 detector. Many quality control(QC) test have been performed during and after the assembly such as current leakage in foil, gas leak rate of the detector, noise, effective gas gain, etc.

3.1. Pre-assembly and assembly

3.1.1. Pre-assembly : The drift board and readout are cleaned using a vacuum cleaner. All the screws and pull-outs are cleaned with an ultrasonic bath to remove any dust. Then the drift board is prepared by placing high voltage pins as shown in Figure 3 (Left), mounting resistor and capacitor as shown in Figure 3 (Middle), and pull-outs as shown in Figure 3 (Right). Spacers are prepared by fixing the brass-inserts using pressure and are used for creating gap between the foils. Readout board screwed gently with the gas connector on the readout board as shown in Figure 4 (Left).

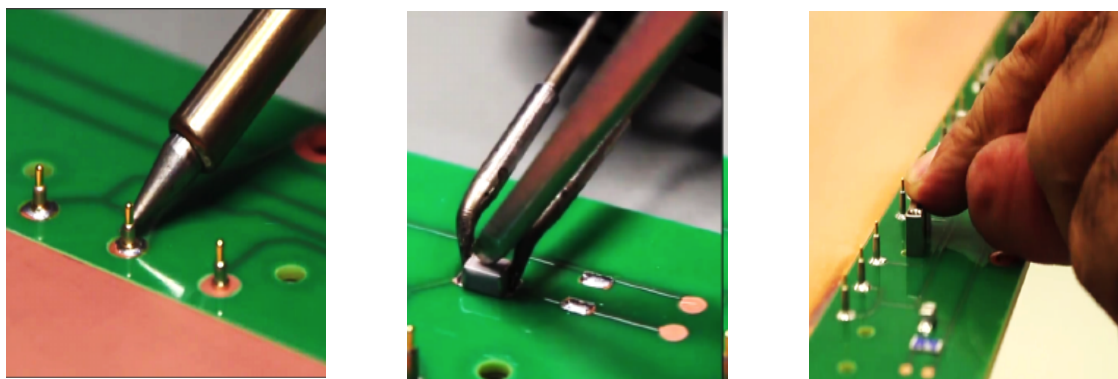


Figure 3. Left: Soldering of the HV pins, Middle : Soldering of the SMD components, Right: Mounting of the pull-outs

3.1.2. Assembly: A class 100 clean room is built at PU site for the assembly. All foils are stretched in the frames and cleaned gently by using an anti-static sticky roller over the foils on both sides in order to remove the dust particles as shown in Figure 4 (middle). Then foils are tested with the MegaOhm/insulation meter by applying 550V voltage to foil by putting a negative pin on the top and positive pin on bottom high voltage (HV) pads of the foils for several minutes. The foil is accepted if the resistance of foil reaches 10 G after few seconds with relative humidity less than 40%. During assembly first cleaned plexiglass is placed then 3 mm clean spacer is inserted on the guiding pins. After that GEM1 foil is placed then 1 mm spacer as shown in Figure 4 (Right). Then in a similar way, GEM2 foil, 2 mm spacer, GEM foil3, 1 mm spacer are placed to form a stack called GEM foil stack as shown in Figure 5 (Left). Plexiglass is placed on the top of the GEM foil stack using guiding pins and then uses screws to the protect GEM stack. Then the excess amounts of Kapton foils are removed using a sharp blade and detached stack from bottom plexiglass and placed it on the drift board. The chamber moved to the assembly jig and clamp the drift board to the assembly table using aluminum bars as shown in Figure 5 (Middle). After placing all the screws in place, the plexiglass and aluminum bar is removed. After that, the GEM foils and all gaps are tested at 550V and the foils are discharged after the test. To test the induction gap, the Panasonic-to-Lemo adapters are connected to one of the readout sectors and 550 V applied between GEM3 bottom and signal pad of the Panasonic-to-Lemo adapter, keeping the chamber in a vertical position as shown in Figure 5 (Right). The impedance should immediately reach 100 G . All QCs results reported in this paper are obtained from a GEM detector having the ID “GE1/1.X.S.INDIA-00YY”(where ‘YY’ stand for ‘02’, ‘07’, ‘08’, ‘09’, ‘10’, ‘15’, ‘16’, ‘17’).



Figure 4. Left: Fixing the gas connector onto the readout board, Middle : Cleaning of the GEM foil with the anti-static roller, Right : Placing the internal frame after testing.

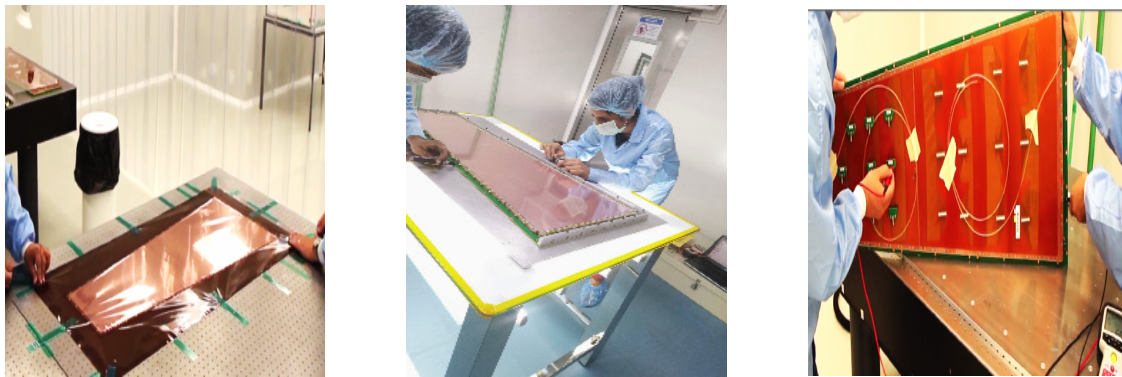


Figure 5. Left : Assembled GEM stack, Middle : Finalizing the stretching of the stack, Right : Assemble detector and testing the induction gap

3.2. Quality control testing

3.2.1. Post-assembly QC2 test: To check again GEM foils after assembly if they are clean or not by measuring the leakage current of the GEM foils and gas gap. The leakage current is that current which flows from the top surface of the foil to the bottom due to the surface conductivity. Due to deposition of some contaminants on the surface of foil in the form of moisture or dust particles will increase this leakage. The detector is accepted if the impedance of each foil and gap is above 10 G Ω and 100 G Ω respectively and the number of sparks are zero after every minute over a period of 10 minutes. Similarly, an impedance also measured over all 24 Panasonic connectors and it should be greater than 100 G Ω . If impedance does not fulfill these criteria then there might be some short circuit and in that case, the detectors have to be reopened and fixed the issue in the clean-room. All the 8 detectors assembled at the Panjab University site qualified the QC2-Leakage current test.

3.2.2. QC3 Gas leak test: If the first test goes fine, then we proceed for the QC3 test which is Gas leak test to identify the gas leak rate of the detector by monitoring the drop of the internal over-pressure as a function of the time. A typical QC3 system has 2 flow-meters, a micro-controller based Arduino chip having 3 sensors for atmospheric pressure, internal gas pressure, and temperature measurements stand prepared at the Panjab University is shown in Figure 6 (Left). The detector is connected in between the inlet and outlet of the calibrated gas system

and filled with CO₂ at the rate of 5 L/h. The chambers cannot sustain internal over-pressure higher than 40-50 hPa. All chambers, except our first production chamber, were tested with an initial over-pressure of 25 hPa, and its internal pressure is monitored for 1 hour. The internal gas pressure is parametrized by $P(t) = P \exp(-t/\tau)$, where P is the initial internal over-pressure [15]. The QC3 acceptance limit is $\tau \geq 3.04$ hour, corresponding to a maximum acceptable gas leak rate of about 7 hPa/hr. All the detectors successfully passed the QC3 gas leak test because gas leak reduction rate is less than 7 hPa/hr as shown in Figure 6 (Right).

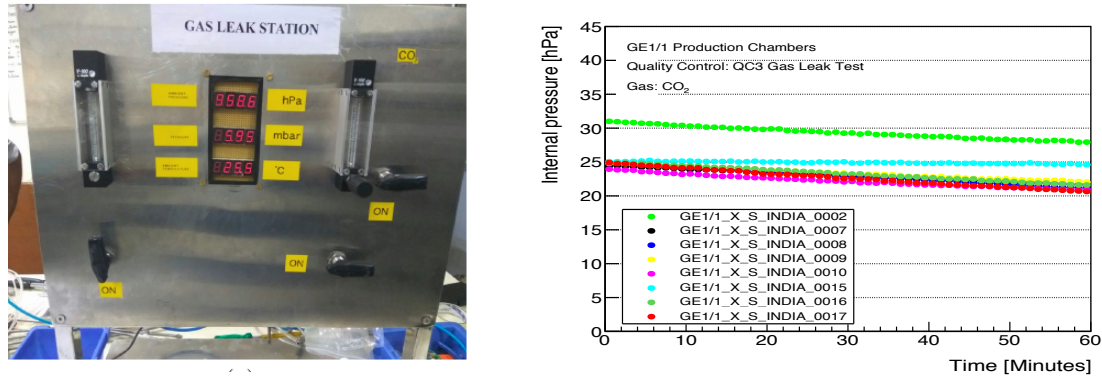


Figure 6. Left : Front view of QC3 Gas Leak Test Stand, Right : Results from the QC3 Gas Leak Test on the GE1/1 detectors assembled at Panjab University.

3.2.3. QC4 High Voltage) test: After the QC3 test, the QC4 test is performed which is a high voltage test to determine the voltage vs. current curve of the detector and to identify possible malfunctions, defects in the HV circuit, and intrinsic noise rate in GEM detector. The detector is shielded from the background noise with a ground shielding placed on the top of the readout board. The GE1/1 detector under this test is first flushed with pure CO₂ gas at least for 5 hours at the rate of 5 L/h. The high voltage (VSET) is provided by programmable HV power supply (CAEN SY5527) which allows the user to control the current limit (ISET), the steps to ramp up and down the voltage, the maximum voltage, and the trip time. A high voltage low pass filter was placed between the power supply and detector to reduce the electronics noise (by rejecting the high frequency noise from the power supply) so that a stable voltage can be provided to the electrodes [16]. The signal generated at the anode is processed using charged sensitive pre-amplifier connected to the bottom electrode of the third GEM foil through a decoupling RC circuit. Further to amplify and record the signal obtained from readout strips signal sent to timing filter amplifier (TFA). The output of TFA is fed into the discriminator to convert it into a rectangular digital pulse which further passes through a dual timer which generates a veto signal to avoid the fake counts. Finally, the resulting digital pulse sent to a scaler and counter unit for the rate measurement.

The discriminator threshold and the scaler clock are set to -140 mV and 60 s respectively. The total resistance ($R_{\text{multimeter}}$) of the HV circuit (divider plus HV filters) is measured using a multimeter and is used to calculate the current in the divider for every high voltage points. The current limit ISET of the power supply is set according to the expected target value plus 5

A, and the corresponding high voltage VSET is switched on. After the operating current and voltage get stable, the values of actual voltage V_{on} , the current I_{on} , and the intrinsic noise rate of the detector are recorded. The intrinsic noise rate is defined as the rate of signals not arising due to ionization of the gas. The number of counts are measured using the scaler unit

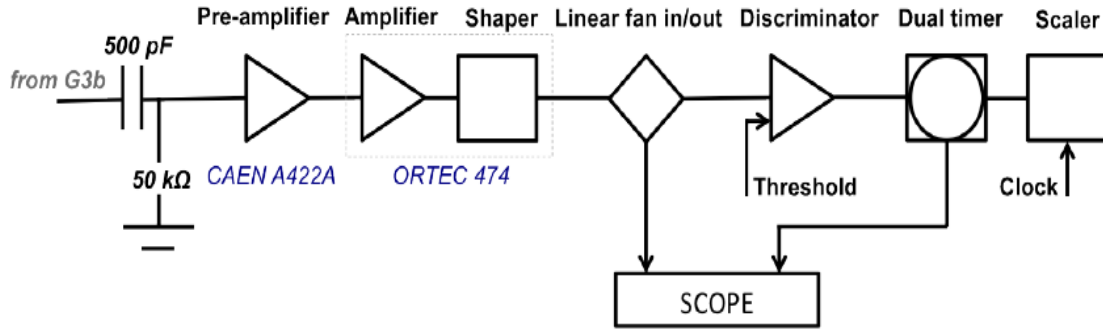


Figure 7. QC4 HV test experimental setup.

for interval of 60 s. These steps are repeated until the voltage reaches 4900 V on the detector. The detector is ramped up to 3000 V in the step of 200 V and up to 4900 V in the step of 100 V. The I-V curve is plotted, which must be a linear, and is fitted by a straight line to determine a resistance (“fitted resistance”). The reciprocal of its slope gives the resistance (R_{IV}) of the HV distribution system. This calculated resistance R_{IV} is then compared with the value of measured resistance $R_{multimeter}$. The detector is said to pass the test if the deviation in the resistance between $R_{multimeter}$ and R_{IV} is $\leq 2\%$ because the deviation greater than 2% indicates a loss of linearity. The maximum intrinsic noise rate should be ≤ 100 Hz at the value of current $\sim 999 \mu A$ and this rate is below 10^{-2} Hz/cm², which is a negligible value with respect to the 4.5 kHz/cm² background rate expected in CMS in standard operating conditions. Table 1 shows the value of measured resistance ($R_{multimeter}$) by multimeter, resistance (R_{IV}) by IV curve, and the maximum intrinsic noise rate (at the value of current $\sim 999 \mu A$) for all the detectors assembled at Panjab University. Figure 8 (Left) shows the monitored voltage (V_{on}) as a function of the monitored current (I_{on}) and Figure 8 (Right) shows intrinsic noise rate as a function of monitored current for different GE1/1 production chambers assembled at Panjab University site. All the detectors successfully passed the QC4 HV test as deviation in resistance is $< 2\%$ and maximum intrinsic noise rate is 11.88 Hz which is very less than 100 Hz. Some data points of 8 chambers are overlapped, as the I-V relation of each chamber is similar to each other.

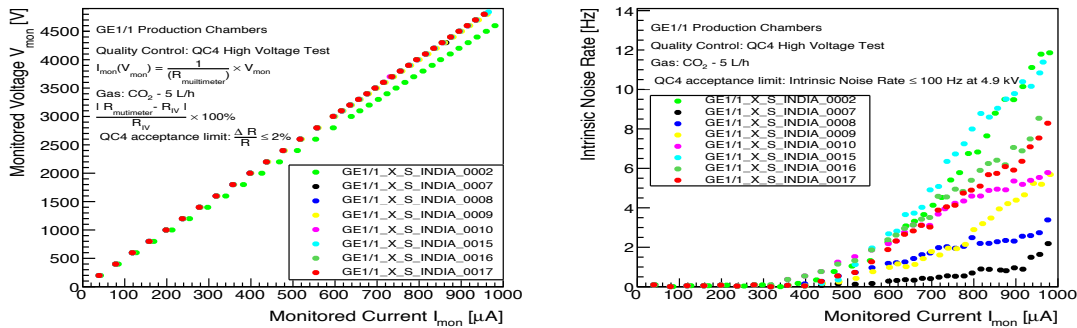


Figure 8. Left : Results from QC4 HV test, Right : Intrinsic Noise Rate as a function of monitored current for different assembled GE1/1 production chambers.

Table 1. Results from QC4 HV test showing the value of measured resistance ($R_{\text{multimeter}}$) by multimeter, resistance (R_{IV}) by IV curve, and the maximum intrinsic noise rate (at the value of current $\sim 999 \text{ A}$) for all the detectors assembled at Panjab University.

Detector ID	Resistance by Multimeter (R_{IV})(M)	Resistance by I-V curve ($R_{\text{multimeter}}$) (M)	Intrinsic Noise Rate(HZ)
GE1/1_X_S.INDIA.0002	4.67	4.69	11.88
GE1/1_X_S.INDIA.0007	5.00	5.01	3.50
GE1/1_X_S.INDIA.0008	5.00	5.02	6.57
GE1/1_X_S.INDIA.0009	5.00	5.01	5.62
GE1/1_X_S.INDIA.0010	4.97	5.02	5.72
GE1/1_X_S.INDIA.0015	4.96	5.01	11.30
GE1/1_X_S.INDIA.0016	4.97	5.02	8.58
GE1/1_X_S.INDIA.0017	5.00	5.02	8.25

4. Conclusion

All the QCs test have been performed at Panjab University and the results are consistent as recommended by the CMS GEM collaboration. In total, 8 production chambers have been assembled and tested at PU site and shipped to CERN, Geneva and successfully installed in the CMS detector. In future, Panjab university group will be receiving more kits of GEM detector for assembly and testing.

Acknowledgments

We would like to acknowledge the funding agency Council of Scientific and Industrial Research (CSIR), Department of Science and Technology (DST), and University Grants Commission (UGC) for providing the financial support to accomplish this work. We would also like to acknowledge the CMS GEM collaboration to provide the GEM detector, helps us to gain expertise in QC testing as well as to calibrate QCs set-ups.

References

- [1] F. Sauli 2016 The gas electron multiplier (GEM): operating principles and applications *Nucl. Instrum. Meth. A* **805** p 2.
- [2] Mohit Gola, Shivali Malhotra, Aashaq Shah, Asar Ahmed, Ashok Kumar and Md. Naimuddin 2020 Performance of the triple GEM detector built using commercially manufactured GEM foils in India *Nucl. Instrum. Meth. A* 951 162967
- [3] CMS Collaboration 2015 *CMS Technical Design Report for the Muon Endcap GEM Upgrade* CMS-TDR-013
- [4] A. Cardini, B. Bencivenni and P. De Simone 2012 *The operational experience of the triple-GEM detectors of the LHCb muon system: summary of 2 years of data taking* IEEE Nucl. Sci. Symp. Med. Imag. Conf. Rec. pp 759–762
- [5] G. Anelli et al. 2008 The TOTEM experiment at the CERN Large Hadron Collider *JINST* **3** S08007
- [6] COMPASS collaboration 2007 The COMPASS experiment at CERN *Nucl. Instrum. Meth. A* **577** pp 455–518
- [7] Z. Dolezal and S. Uno 2010 *Belle II Technical Design Report*
- [8] M. Bucciantonio and F. Sauli 2015 Proton computed tomography *Mod. Phys. Lett. A* **30** 1540024
- [9] Bachmann S., Kappler B., Ketzner B., Muller T., Ropelewski L., Sauli F. and Schulte E. 2002 *Nucl. Instrum. Meth. A* **478** pp 104–108
- [10] R. Alon et al. 2008 Time resolution of a Thick Gas Electron Multiplier (THGEM) - based detector *Journal of Instrumentation* **3** p 11001
- [11] F. Sauli 1997 GEM: a new concept for electron amplification in gas detectors *Nucl. Instrum. Meth. A* **386** p 531

- [12] CMS Muon Group Performance of prototype GE1/1 chambers for the CMS muon spectrometer upgrade (*Preprint* 1903.02186)
- [13] Manisha, A. Kaur, M. Meena, P. Kumari, R. Gupta, J. S. Shahi, S. Bansal, V. Bhatnagar and J. B. Singh 2017 *Proc. of the DAE Symp. on Nuclear Physics Quality control testing of GEM detector* vol 62
- [14] A. Buzulutskov et al. 1999 GEM operation in pure noble gases and the avalanche con nement *Nucl. Instrum. Meth. A* **433** p 471
- [15] Rosamaria Venditti 2020 *Production Quality Control and Performance of GE1/1 Detectors for the CMS Upgrade* J. Phys.: Conf. Ser. **1498** 012055
- [16] A. Ahmed, M. Gola, A. Kumar and Md. Naimuddin. 2020 Development and quali cation of triple-GEM detector built with large size single mask foils produced in India *JINST* **15**



Certificate of Attendance

We hereby confirm that

Jyoti Babbar

of

Panjab University, Chandigarh, India

has attended the conference *DISCRETE 2022*, Nov 7-11, 2022, in Baden-Baden, Germany,
and gave the presentation

Search for New Resonance in the photon and jet final state using CMS data
on behalf of the CMS collaboration.

Ulrich Nierste

(for the Local Organising Committee)



INDIAN INSTITUTE OF SCIENCE EDUCATION AND RESEARCH MOHALI
(Established by the Ministry of Education, Govt. of India)
Knowledge City, Sector 81, S. A. S. Nagar, Manauli PO 140306, Punjab, India

Certificate

On behalf of the local organizing committee, this is to certify that

Jyoti Babbar (Panjab University, Chandigarh)

presented a talk titled

Discrimination of quark and gluon jets at 13TeV in the CMS experiment [Abstract ID 260]

at the **XXV DAE-BRNS High Energy Physics Symposium 2022.**

The XXV DAE-BRNS high energy physics symposium (*silver jubilee edition*) was held from 12-16 December 2022 at Indian Institute of Science Education and Research Mohali, Punjab, India. The symposium is a premier event held every two years, supported by the Board of Research in Nuclear Sciences (BRNS), Department of Atomic Energy (DAE), India. The deliberations, from both experimental and theoretical perspectives, covered a variety of topics in Astroparticle Physics, Cosmology, Dark matter, Flavor physics, Higgs, Heavy-ion, LHC physics, Neutrino, Societal applications and related areas.

Dr. Ambresh Shivaji, Convener,
XXV DAE-BRNS HEP Symposium,
Indian Institute of Science Education and Research Mohali,
Sector 81, Knowledge City, SAS Nagar,
Punjab-140306, India

