



Gas Detectors Performance in CMS and Excited Muon Search Feasibility Study at 14 TeV

The thesis Submitted In Partial Fulfillment of the Requirements for the Master
Degree in Science (Nuclear Physics)

By

Walaa Mohamed Mohamed Abdelaziz Elmetenawee

B.Sc. in physics, Faculty of Science, Helwan University

Under Supervision of

Prof. Mohamed Nabil Yasein

Professor, Physics Department, Faculty of Science, Helwan University.

Dr. Ayman Mohamed Mahrous

Assistant Professor, Physics Department, Faculty of Science, Helwan University.

Dr. Ahmed Ali Abdelalim

Lecturer, Physics Department, Faculty of Science, Helwan University.

Submitted to

Physics Department, Faculty of Science, Helwan University

2015



Acknowledgments

Foremost, I would like to express my sincere gratitude to my supervisors Prof. M.N.Yassen , Ass.Prof Ayman Mahrous and Dr Ahmed Abdelalim for the continuous support of my Master study and research, for their patience, motivation, enthusiasm, and immense knowledge. Their guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my Master study. Last but not the least; I would like to thank all my family for supporting me spiritually throughout my life.

Abstract

Within the Standard Model (SM) of particle physics, quarks and leptons are understood to be the fundamental particles and their existence have been verified experimentally. A search for substructure of quarks or study of quark compositeness is carried out assuming a detector configuration such that of CMS detector at LHC, using $300 fb^{-1}$ of integrated luminosity at a center-of-mass energy $\sqrt{s} = 14 TeV$. The discovery of excited muons (μ^*) would be a first indication of lepton compositeness. In the current study, μ^* is assumed to be produced via four-fermions contact interactions in association with a muon (μ) and to decay via the gauge mediated process $\mu^* \rightarrow \mu\gamma$, yielding a final state with two muons and one photon. Monte Carlo (MC) samples are produced via MadGraph5 and PYTHIA 8 event generators. To simulate the detector response, GEANT4 which interfaced to CMS software was used for full simulation and Delphes was used for fast simulation, assuming the CMS detector configuration. Objects and event selections are optimized in order to maximize the signal to SM background ratio.

**Keywords: LHC; CMS; Simulation; Generation; Lepton
Compositeness**

Contents

Acknowledgments	iii
Abstract	v
List of Figures	xv
List of Tables	xvii
1 General Review	1
1.1 Introduction	1
1.2 A Brief History of Particle Physics	3
1.3 The Standard Model of Particle Physics	7
1.3.1 Fundamental Particles	7
1.3.2 Fundamental Interactions and their Mediators . . .	9
1.3.2.1 Electromagnetic Interaction	10
1.3.2.2 Weak Interaction	11
1.3.2.3 Strong Interaction	11
1.3.3 Electroweak Unification	12
1.4 Current Shortcomings of the Standard Model	14
1.5 Compositeness Model	16

1.5.1	Introduction	16
1.5.2	A Simple Analogy	17
1.5.3	Theoretical Setup	17
1.5.3.1	Production of μ^* via contact interactions	19
1.5.3.2	Decay of μ^* via gauge mediated interactions	21
1.5.3.3	Previous searches for μ^*	23
2	The LHC and the CMS Experiment	31
2.1	The Large Hadron Collider (LHC)	31
2.2	Luminosity	35
2.3	The LHC experiments	36
2.4	Compact Muon Solenoid (CMS) Detector	37
2.4.1	The Coordinate System of CMS	39
2.4.2	The Tracker	40
2.4.3	Electromagnetic Calorimeter	42
2.4.3.1	Photon Reconstruction	44
2.4.4	Hadronic Calorimeter.	45
2.4.5	Solenoid Magnet	47
2.4.6	Muon System	47
2.4.7	Muon Reconstruction	51
2.4.7.1	Tracking Algorithm	51
2.4.7.2	Reconstruction Algorithms	53
2.4.7.3	Muon Reconstruction at High- p_T	55
2.4.7.4	Muon Identification	56
2.4.7.5	Muon Isolation	57

2.4.8	L1, HLT Triggers and DAQ System	58
3	Gas Detectors Performance	61
3.1	Cosmic Rays	61
3.2	Experimental set up	62
3.2.1	RPC	64
3.2.1.1	Basic principle of operation	66
3.2.2	Scintillation Detectors	69
3.3	RPC Gap performance	70
3.3.1	Leakage Test	70
3.3.2	Spacer Test	72
3.3.3	High Voltage Test	73
4	Event Generation and Simulation	75
4.1	Simulation framework	75
4.2	Mont Carlo (MC) Simulation Samples	78
4.2.1	MC Signal Samples	78
4.2.2	SM background samples	79
5	Analysis and Results	83
5.1	Full simulation Signal analysis	83
5.1.1	Signal Properties	83
5.1.2	Reconstruction and Event Selection	85
5.1.2.1	Trigger and Acceptance	85
5.1.2.2	Muon Identification	86
5.1.2.3	Photon Identification	88

5.1.3	Selection Strategy for Full Simulation ” Control Re- gion”	89
5.2	Fast Simulation Analysis and Results	91
5.2.1	Selection Strategy for Fast Simulation ” Control Region”	91
5.2.2	Results	96
	Conclusion	99
	Bibliography	101

List of Figures

1.1	Fundamental Interactions in Standard Model [26]	9
1.2	Schematic presentation of the ground and excited state of the hydrogen atom. A photon is absorbed by the ground state of the hydrogen atom to reach the excited state. An excited hydrogen atom radiates photons to reach its ground state.	18
1.3	Analogy with excited atom: Excited state resonance of composite quark.	19
1.4	(a) Feynman Diagram of the Contact interactions of excited muons (μ^*) with quarks (q), (b) decay of excited muon (μ^*) into a SM muon (μ) via an electroweak process. [40] . . .	20
1.5	Branching ratios of the decay of excited muons (μ^*) via contact interaction (in blue) and the possible gauge mediated decay modes, $\mu^* \rightarrow \mu\gamma$ (in black), $\mu^* \rightarrow \mu Z$ (in red), $\mu^* \rightarrow \nu_\mu W$ (in violet) as a function of m_{μ^*} and at $\Lambda = 10$ TeV . [40]	23

1.6	OPAL collaboration 95% CL upper limits on the cross-section at $\sqrt{s}=208.3$ GeV times the branching fraction for (a) single and (b) pair production of excited leptons as a function of mass (m^*). The theoretical cross-section times the branching ratio squared is also shown in (b). The 95% CL upper limits on the ratio of the excited lepton coupling constant to the compositeness scale, f/Λ , as a function of the excited lepton mass and assuming $f = f'$ are shown in (c) [43]	24
1.7	L3 collaboration 95% CL upper limits on $ f /\Lambda$, as a function of the excited lepton mass with $f = f'$ for (a) e^*, μ^* and τ^* (b) ν_e^*, ν_μ^* and ν_τ^* with $f = -f'$ for (c) e^*, μ^* and τ^* (d) ν_e^*, ν_μ^* and ν_τ^* [44]	25
1.8	CDF collaboration cross section $\times$ branching ratio limits for the CI and GM models, compared to the CI model prediction for $\Lambda = M_{\mu^*}$ and the GM model prediction for $\Lambda/f = M_{\mu^*}$, The mass limits are indicated.[45]	27
1.9	The region in the (M_{μ^*}, Λ) plane excluded by the D0 experiment.[46]	28
1.10	Exclusion limits for excited muon production in the CMS experiment in the with $5fb^{-1}$ data at $\sqrt{s}=7$ TeV. [47]	28
1.11	Exclusion limits for excited muon production in the $\mu\mu\gamma$ channel from the ATLAS experiment with $13fb^{-1}$ data at $\sqrt{s}=8$ TeV. Left: Cross section limit; right: Limit on the compositeness scale Λ . [48]	29
2.1	Layout of the LHC ring within the CERN accelerator complex[49].	33

2.2	A schematic view of the CMS detector along with its all major subdetector systems[56].	38
2.3	A schematic longitudinal view of the CMS tracker in terms of different layers and their arrangements in η and z direction in one quarter of the CMS detector[49].	40
2.4	Layout of pixel detectors and the turbine shaped end-cap disks in CMS.[25]	41
2.5	Illustration of the Lorentz drift of the charges induced by the charged particle passing through the sensor. Only the drift of the negative charges is shown. Note that the magnetic field direction with respect to the sensor is different in barrel and in the end-cap.[58]	42
2.6	Longitudinal cross section of the quarter of the CMS detector showing the positions of the hadronic calorimeter barrel (HB), hadronic calorimeter endcap (HE), forward hadronic calorimeter (HF), and outer hadronic calorimeter (HO).[61]	46
2.7	Schematic overview of the CMS muon system	48
2.8	Schematic overview of a drift cell [50]	49
2.9	Left: Schematic view of a cathode strip chamber (CSC) as it is used in the endcaps. Right: Working principle of CSCs [50].	50
2.10	reconstruction of global muon inside muon system and silicon tracker.[76]	54
2.11	Detector based Isolation shown left ,and Particle Flow Isolation shown right.	57
2.12	Composition of the Level-1 trigger system, showing the combination of the local trigger to the global trigger [50].	59
3.1	Primary cosmic particle collides with a molecule of atmosphere[66]	61

3.2	Cosmic Stand in Nuclear physics laboratory at Helwan University	63
3.3	RPC Double Gap [69]	65
3.4	Layout of double gap RPC [69]	66
3.5	Read out strip	68
3.6	Scintillation Detectors [66]	69
3.7	leak test system	70
3.8	leak test result under 5 mbar for Top Narrow gap	71
3.9	leak test result under 5 mbar for Top Wide gap	72
3.10	top wide spacer map	73
3.11	current vs HV Top Wide gap	74
3.12	current vs HV Top Narrow gap	74
5.1	Invariant mass plots for different μ^* masses, left, Minimum invariant mass M_{min} ; right, Maximum invariant mass M_{max} ;	84
5.2	Transverse momentum the final state objects, up-left: the p_T for the leading muon; up-right: the p_T for the next to leading muon; down E_T of the highest p_T photon.	85
5.3	Two dimensional $M_{min} - M_{max}$ plane with several signal mass points	91
5.4	show distribution of $(\Delta R(\mu_1, \gamma)$ and $\Delta R(\mu_2, \gamma)$),on left and right respectively after selection 2.	92
5.5	the two leading p_T muons invariant mass distributions before selection 1 (left plot) and after selection 3 (right plot).	93
5.6	the two leading p_T muons $\Delta R(\mu_1, \mu_2)$ distributions before selection 1 (left plot) and after selection 3 (right plot).	94

5.7	On the left, the p_T distribution of the leading muon after the preselection (selection 3). On the right, the E_T distribution of the leading photon.	95
5.8	The minimum (left) and the maximum (right) muon-photon invariant mass distributions after the preselection (selection 3).	95
5.9	On the left, the p_T distribution of the leading muon, On the right, the E_T distribution of the leading photon, after the full selection (selection 4).	96
5.10	The minimum (left) and the maximum (right) muon-photon invariant mass distributions after the full selection (selection 4).	96
5.11	Two dimensional $M_{min} - M_{max}$ plane with several signal simulations and background.	97
5.12	Signal efficiency of different steps in the analysis depending on the generated excited muon mass. Acceptance here refers to the p_T and $ \eta $ cuts.	98

List of Tables

1.1	Three generations of quarks and leptons, the basic constituents of the SM [25]	9
1.2	Fundamental forces with their mediator and some of their properties [25]	10
2.1	Some important LHC parameters.[25]	34
4.1	Summary of signal MC samples generated by pythia 8 , number of generated events and cross sections (LO), used with $\Lambda = 10$ TeV.	79
4.2	Summary of the used MC background samples, generated by MadGraph5 with the corresponding LO cross sections, number of generated events and the corresponding weight.	81
5.1	Summary of the number of weighted events for full simulation signal mass points before any selection, and after each selection.	90
5.2	Summary of the number of weighted events for fast simulation SM background before any selection, after pre selection and after full selection	94
5.3	Summary of the number of weighted events for fast simulation signal mass points before any selection, and after each selection.	97

Chapter 1

General Review

1.1 Introduction

In particle physics, the Standard Model (SM) describes the interaction between particles using the weak, strong and electromagnetic interactions with a great acceptance with the experimental results. But there are still open questions that cannot be answered by the Standard Model, for example; Why quarks and leptons masses span over a large range? Why is there several generations? This may suggest that the leptons and quarks may not be fundamental particles and there might exist a more fundamental basis.

In nature, there are many examples for the existence of excited states. Atoms which are built out of electrons, protons and neutrons, have excited states as well as baryons and mesons which are constructed by quarks. In all cases, the excited states are the result of compositeness. For this reason, a discovery of excited leptons could show evidence for an unknown substructure of these particles.

This thesis is organized in six chapters, a brief description of each chapter is given below.

- Chapter 1 gives a brief introduction to the particle physics, then it

gives introduction to the Standard Model of Particle Physics and its current shortcomings. The last section of this chapter discuss the effective Lagrangian for the theory and the contribution from new physics and for this I'm interested in the final state with two muons and a photon. Possible signatures and their characteristics have also been discussed. A brief review of earlier phenomenological and experimental studies have been outlined and also the latest results from the CMS and ATLAS collaborations.

- Chapter 2 gives a brief introduction to the LHC machine design and different experiments situated on it. A detailed description of one of the detectors at the LHC, the Compact Muon Solenoid (CMS), has been presented. Various sub-detectors of the CMS, their design and performance have been discussed in detail.
- Chapter 3 is an introduction to cosmic rays and how it can be used to test the performance of Resistive Plate Chambers (RPCs). Then the experimental setup used in this work are given including the RPC and the scintillation detectors. finally the results for the different tests which done for the RPC gaps are discussed.
- Chapter 4 summarizes the Monte Carlo simulation in CMS. The full simulation chain starting from event generation and detector response simulation up to the data format used in this analysis is explained briefly. The Monte Carlo signals and background samples generated throughout this analysis are also introduced in this chapter.
- Chapter 5 shows the different steps of the analysis starting with studying the signal properties and then the selection of the signal and to compare it with the background. Afterwards, the final selection will be applied and the results will be presented .

1.2 A Brief History of Particle Physics

We can say that modern particle physics began in 1897, when J.J. Thompson discovered electron, that confirmed the idea of atomic substructure. Throughout the next several decades chemists and physicists worked to understand the structure of the atom. The classical physics of Newton and Maxwell did not describe the emerging world inside the atom. The work of M. Planck, N. Bohr, W. Heisenberg, E. Schrodinger and others heralded the birth of quantum mechanics, a new set of physical laws to describe the behavior of particles at the microscopic scale [1].

In 1909, E. Rutherford's student reported some unexpected results from an experiment assigned by Rutherford. Later in 1911 Rutherford gave the concept of nucleus by analyzing the data of Geiger and Marsden on the scattering of α - particles against a very thin foil of gold. The data was explained by the assumption that the atom contains a nucleus of positively charge dense core and negatively charge cloud of electrons around it. Later with the discovery of Proton (1920) and Neutron (1932) [2], it was confirmed that ordinary matter is made of up of three particles, namely protons, neutrons and electrons.

During the same period, two of the most important theories in science come to light: Relativity theory and Quantum theory. These two new theories together laid to the foundation of Modern particle physics and Quantum field theory. In 1905 A. Einstein's photoelectric theory proposed the existence of a particle, the "photon", as the quanta of electromagnetic field. In 1923 A.H. Compton proved the existence of photon and its particle characteristics by his famous Compton scattering experiment. Subsequently L. de Broglie extended particle-wave duality of matter. E. Schrodinger and W. Heisenberg used wave functions and operators to developing new way to describing the particles and physical observable.

In 1927, P. Dirac combined the theory of Relativity and Quantum Me-

chanics into a theory called Quantum Field Theory (QFT) [3] and described the behavior of free electron. From the solution of the Dirac equation, arose the concept of anti-matter. In his attempt to explain the solution, Dirac predicted that for each particle there must exist an oppositely charged particle with the same mass "antiparticle". Later in 1933 C. Anderson discovered the anti-electron (positron) and confirmed the prediction of P. Dirac. This discovery was the seed for the "radiative effects" (annihilation of particle and anti-particle).

In 1933-34 E. Fermi put forth a theory of beta decay that introduced weak interaction. Fermi's theory of four fermion gave a mathematical proof of the existence of Pauli's 'neutron' dubbed neutrino (or the little neutral one as called by Fermi) and explained the continuous spectrum of electrons in the beta decay [4]. This is the first theory to make explicit use of neutrino.

With the discovery of proton and neutron the next question was how does the nucleus remain in a bound state in a small region ¹ against the repulsive force between positively charged protons. The concept of "strong force" was postulated to overcome the electric repulsion among the protons in the nucleus. In 1933-34 H. Yukawa combined relativity and quantum theory to describe nuclear interaction between nucleons [5] by exchange of a new particle called meson and later known as "pions". Yukawa concluded that the mass of these mesons should be ~ 300 times the electron mass. In 1937 a particle with mass ~ 200 times of electron mass was discovered in cosmic ray experiment and thought to be Yukawa's pion but later it was confirmed to be a muon (μ). The term "lepton" was introduced to describe the object that does not interact strongly and is light weight. The long awaited search for pion completed in 1947 with its discovery by C. Powell of Bristol in cosmic ray experiment. By this time the particles were broadly categorized in three groups, baryons, leptons, and mesons. Further to this M. Gall Men organized hadrons (mesons and baryons) into his famous "Eightfold

¹ $1fm = 10^{-15}m$

way” which predicted the existence of Ω^- with a strangeness quantum number of -3.

With the pioneering work of Feynman [6], Schwinger[7], and Tomonaga [8], who developed quantum electrodynamics (QED), the era of modern particle physics started. The QED explained the electromagnetic phenomena at a basic level in terms of exchange of photons. The predictions given by the QED theory were found to be true with remarkable precision.

The decades of 1940’s and 50’s were full of many interesting discoveries in particle physics which solved many known problems of that time but also tempted physicists to look at particle physics in new perspective. In 1947 a ”strange” particle, K^+ took much attention due to its slow decay pattern. With progress in particle accelerator techniques, in subsequent years more and more new particles (so called hadrons and mesons) were found. While the experimenters were searching for Ω^- meson and other particles, Gell-Mann was confidently exploring the meaning of SU(3) hadrons symmetry. A more skillful possibility was that threefold symmetry was built into the structure of hadrons. Gell-Mann began to entertain the idea that neutrons and protons, and all other baryons are made up of three elementary particles which come in three types, or flavors namely up(u), down(d), and strange(s). He first called these elementary particles ”quarks” [9]. Gell-Mann’s theory builds a proton with two u quarks and one d quark or ”uud” in short. In Gell-Mann’s theory the mesons have fundamentally different structures compared to baryons. They always contain a quark and an anti-quark. Similarly the predicted Ω^- was made up of three s quarks, each contributing a strangeness of -1. In fact the discovery of Ω^- was confirmed in 1964 at Brookhaven National Laboratory (BNL) and from its subsequent decays its mass was measured to be 1683 ± 12 MeV, very close to 1684 MeV predicted by Gell-Mann. This was a major success for the static quark model.

By this time the list of elementary particles known to the physicists

comprised of u, d, and s quarks along with e^- , ν_e , μ^- and ν_μ and the photon; three quarks, four leptons and a boson. This apparent asymmetry between the number of leptons and quarks led Glashow and Bjorken to suggest, in 1964, that there might be a fourth quark to event up the numbers and they named it "charm quark". Later Glashow, Iliopoulos and Maiani provided an explanation for the non-occurrence of the decay $K_0 \rightarrow \mu^+ + \mu^-$. In 1974 two teams of experimentalists announced independent discovery of a new and unexpected type of meson [10, 11]. One group named it J and the other Ψ and now this particle is known as J/Ψ . An explanation already existed for this new particle and it was the lowest mass state of c.

During 1975-1976 more such particles were discovered and existence of charm quark was firmly established. A new lepton tau (τ) was discovered in 1975 that once again created the variation between number of quarks and leptons. Just after two years, L. Lederman announced the discovery of Upsilon(Υ) which established the existence of another but more heavier bottom(b) quark [12]. The Υ meson was the bound state of . Besides discovery of different quarks, by this time a new theoretical framework called Quantum Chromodynamics(QCD) was being developed to explain the interaction between the quarks.

After establishing the existence of new particle called τ lepton, M. Perl et al. performed a deeper study of the properties of the anomalous events they observed [13]. They concluded that if the events are to be explained by a single hypothesis, they must arise from the decay of a pair of new particles each of which decays to a charged lepton and two neutrinos. Due to the indirect and convincing evidence of tau-neutrino, scientists started searching for another quark to maintain the equal number of quarks and leptons. In 1995 Fermi lab announced the discovery of Top quark [14, 15].

Throughout the 1970s and later, physicist tried to put various interactions into a single theory to explain the observed particles and their behavior. Glashow, Salam and Weinberg got success in unifying the electro-

magnetism and weak interaction together into Electroweak theory [16, 17] and predicted the existence of $W^\pm$ and Z^0 bosons which were later discovered by the UA1 and UA2 experiments at CERN[18, 19]. From the precise determination of the mass and width of the Z boson, the number of light neutrinos with standard coupling to the Z can be derived. Assuming that the width is purely due to escaping neutrinos, the experiments at LEP (Large Electron Positron Collider) obtained $N_\nu = 2.984 \pm 0.008$ [20].

All these discoveries and our present understanding of fundamental constituents of matter and their interactions has led to the well established theory of the Standard Model. Whenever a prediction for an experimental observable has been made by the Standard Model, excellent agreement with experiments have been found.

1.3 The Standard Model of Particle Physics

The Standard Model (SM) combines Quantum Chromodynamics (QCD) and electroweak theory to describe the properties of elementary particles and interactions between them [21, 22]. For last several decades the SM has been thoroughly tested in different experiments. Almost all the results obtained so far agree with very high precision with the predictions of the SM.

1.3.1 Fundamental Particles

Fundamental particles can be separated into fermions, which are spin $1/2$ and obey Fermi-Dirac statistics, and bosons, which are integral spin particles and obey Bose-Einstein statistics. The fundamental fermions are further divided into leptons and quarks. In the SM, the matter particles are the six quarks and the six leptons with their corresponding antiparticles. There are three generations of quarks and leptons. Each generation is a

more massive copy of the former.

- **Leptons:** The leptons (l) are: electron (e), muon (μ), tau (τ) and their corresponding neutrinos ν_e, ν_μ, ν_τ . Three of the leptons e, μ and τ carry a unit charge while neutrinos are chargeless. The e, μ and τ interacts via electromagnetic and weak interaction while neutrinos interact only through weak interaction. Earlier it was thought that neutrinos do not have any mass but recent experimental results have confirmed that they carry a very small mass which accounts for the phenomena of neutrino oscillation [23, 24]. Because each lepton has its anti-particle there are a total of 12 leptons in the SM.

- **Quarks:** six quarks are: up (u), down (d), charm (c), strange (s), top (t) and bottom (b). Each quark carries either a fractional charge of $-1/3 e$ (d, s and b) or $+2/3 e$ (u, c and t). The quarks interact via strong interaction as well as electromagnetic and weak interactions. Since quarks are fermions (spin $1/2$) and should obey Pauli's exclusion principle hence another quantum number "color charge" was assigned to each quark. It was formulated that each quark comes in three colors, red, blue and green. The strong interaction binds quarks to form what is known as mesons and baryons for e.g. proton (uud) and neutron (udd). The meson family has one quark and one anti-quark as its constituent e.g. $\pi^0(u\bar{u}), \pi^+(u\bar{d}), K^0(d\bar{s})$ and $\bar{K}^0(s\bar{d})$. Similarly the baryons are made up of three quarks and anti-baryons of three anti-quarks. Properties of mesons and baryons can be derived from quarks quantum numbers. Table 1.1 shows three generations of the family of quarks and leptons.

Generation	Leptons (spin = 1/2)			Quarks (spin = 1/2)		
	Flavor	Charge	Mass GeV/c^2	Flavor	Charge	Mass GeV/c^2
1	e	-1	0.511	u	+2/3	$1.5 - 4.5$
	ν_e	0	$< 3 \times 10^{-6}$	d	-1/3	$5 - 8.5$
2	μ	-1	105.7	c	+2/3	$(1.0 - 1.4) \times 10^3$
	ν_μ	0	< 0.19	s	-1/3	$80 - 155$
3	τ	-1	1777	t	+2/3	$(172.6 \pm 1.4) \times 10^3$
	ν_τ	0	< 18.2	b	-1/3	$(4.0 - 4.5) \times 10^3$

Table 1.1: There generations of quarks and lebtons, the basic constituents of the SM [25]

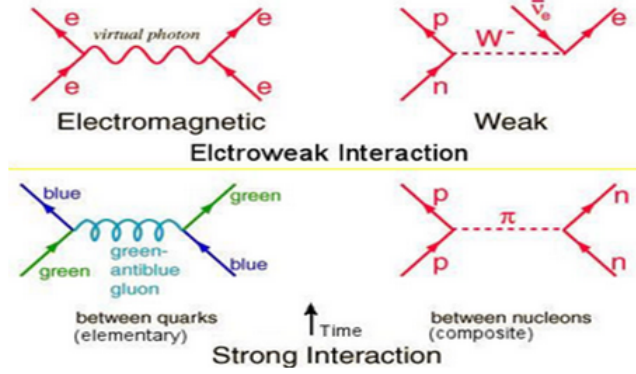


Figure 1.1: Fundamental Interactions in Standard Model [26]

1.3.2 Fundamental Interactions and their Mediators

All the particles and anti-particles in the SM interact via three known fundamental forces: electromagnetic, weak and strong interactions, Figure 1.1 shows Feynman diagrams for these forces. The "gravity" is the fourth and the weakest force among them. all these forces are described via the exchange of 12 gauge bosons, eight colored massless gluons (g) for the strong force, one massless photon (γ) for the electromagnetic force, and three massive gauge bosons for the weak force ($W^\pm, Z$). In Table 1.2 we summarize the fundamental forces and their mediator with their important properties. All these fundamental interactions can be described by gauge

field theories, which can be regarded as the common nature of all these forces.

Force	Gauge Boson	Charge	Spin	Mass GeV/c^2	Range	Rel. Strength
Strong	Gluons (g)	0	1	0	$10^{-15}m$	1
EM	Photon (γ)	0	1	0	∞	1/137
Weak	$W^\pm$	± 1	1	80.42	$10^{-18}m$	10^{-15}
	Z^0	0	1	91.19		
Gravity	Graviton	0	2	0	∞	10^{-38}

Table 1.2: Fundamental forces with their mediator and some of their properties [25]

1.3.2.1 Electromagnetic Interaction

The first unification of fundamental forces in human history was the unification of electric and magnetic forces achieved by Maxwell in 1864 and is known as electromagnetism. The electromagnetic interaction occurs between two particles having electric charge. the electromagnetic force manifests itself through the forces between charges (Coulomb's Law) and the magnetic force, both of which are summarized in the Lorentz force law. Fundamentally, both magnetic and electric forces are manifestations of an exchange force involving the exchange of photons, Thus photons are the mediator of electromagnetic interaction . The quantum approach to the electromagnetic force is called quantum electrodynamics or QED [6, 7, 27]. Now we know that QED is a U(1) Abelian gauge invariant theory [28, 29]. Electromagnetic interaction is responsible for the binding force that causes negatively charged electrons to combine with positively charged nuclei to form atoms. In quantum field theory, any changing electromagnetic fields or electromagnetic waves can be described in terms of photons, the quanta of energy.

1.3.2.2 Weak Interaction

The weak force is the reason for the generation structure of the quarks and leptons. This is because it changes particles from one type to another. the weak interaction involves the exchange of the intermediate vector bosons, the W and the Z. Since the mass of these particles is on the order of 80 GeV, the uncertainty principle dictates a range of about 10^{-18} meters which is about 0.1% of the diameter of a proton.

The discovery of the W and Z particles in 1983 was hailed as a confirmation of the theories which connect the weak force to the electromagnetic force in electroweak unification. The weak interaction acts between both quarks and leptons, whereas the strong force does not act between leptons. Leptons have no color, so they do not participate in the strong interactions; neutrinos have no charge, so they experience no electromagnetic forces; but all of them join in the weak interactions. The strong and electromagnetic interactions respect spatial inversion symmetry (they conserve parity) and are also particle-antiparticle (charge conjugation) symmetric, whereas the weak interaction violates these two symmetries.

1.3.2.3 Strong Interaction

Quantum Chromodynamics is the gauge theory associated with strong interaction and describes the interaction amongst color charged particles. The strong force is responsible for binding quarks together to form hadrons as well as binding protons and neutrons to form nuclei. However, it is not an inverse square force like the electromagnetic force and it has a very short range. Also referred to as the color interaction, the strong force binds colored quarks through the exchange of colored gluons. Both quarks and gluons carry color charge. Gluons are the gauge bosons that mediate the strong force between the quarks. Gluons have eight color states consisting of color and anti-color. They can modify a quark's color state to anti-color

state. The properties of the color charge is explained by a gauge symmetry known as $SU(3)_C$. This gauge symmetry is at the core of QCD. Each quark is in the basic triplet of the $SU(3)_C$ group. The gluons are described by the adjoint representation of this group, which explains why gluons carry both color and anti-color charge at the same time. QCD enjoys two peculiar properties which describe the behavior of quarks inside hadrons and hadrons formation.

Confinement:

it means that the force between quarks does not diminish as they are separated. Because of this, it would take an infinite amount of energy to separate two quarks; they are forever bound into hadrons such as the proton and the neutron. Although analytically unproven, confinement is widely believed to be true because it explains the failure of free quark searches.

Asymptotic freedom:

which means that at very high-energy, quarks and gluons interact very weakly. Asymptotic freedom [30] was rediscovered and described in 1973 by Frank Wilczek and David Gross, and independently by David Politzer the same year. All three shared the Nobel Prize in physics in 2004.

1.3.3 Electroweak Unification

In particle physics, the electroweak interaction is the unified description of two of the four known fundamental interactions of nature: electromagnetism and the weak interaction. Although these two forces appear very different at everyday low energies, the theory models them as two different aspects of the same force. Above the unification energy, on the order of 100 GeV, they would merge into a single electroweak force.

This unification was achieved by S. Glashow, S. Weinberg and A. Salam [16, 17]. The $SU(2)_L \otimes U(1)_Y$ is the symmetry group associated with this theory. The $SU(2)_L$ group describes weak isospin(T) and acts only on the left-handed fermion field. The $U(1)_Y$ group describes weak hypercharge(Y). The electric charge(Q) is related to the weak isospin and weak hypercharge by $Q = T_3 + Y/2$ where T_3 is the third component of weak isospin. This implies that the charge is conserved in the electroweak theory. In $SU(2)_L \otimes U(1)_Y$ model, quarks and leptons are assigned as left handed doublets and right handed singlets. The weak interaction has a very short range and exists between any of the leptons and quarks. It is responsible for the radioactive -decay of nuclei. The mediators of the weak force are $W^\pm$ and Z^0 bosons as summarized in Table 1.2. The question of how the W and Z got so much mass in the spontaneous symmetry breaking is still a perplexing one. The symmetry-breaking mechanism is called a Higgs field, and requires a new boson, the Higgs boson to mediate it.

In the SM, the Higgs mechanism is used to give masses to fermions as well as bosons, including the photon. But we know this is not the case for photon. To overcome this, the combination of spontaneous symmetry breaking for $SU(2)_L \otimes U(1)_Y$ in conjunction with the Higgs mechanism is used to give masses (proportional to the vacuum expectation value of the Higgs field) to fermions (through Yukawa coupling between the Higgs field and massless fermions) and to Z^0 and $W^\pm$ bosons while keeping the $U(1)_Y$ symmetry exact and therefore leaving the photon massless.

On 4 July 2012, the two main experiments at the LHC (ATLAS and CMS) both reported independently that they found a new particle with a mass of about $125 \text{ GeV}/c^2$ [31, 32], which is consistent with the Higgs boson. On 14 March 2013, it has been confirmed that it is actually Higgs boson.

1.4 Current Shortcomings of the Standard Model

Despite the success of the Standard Model, it is rightly believed that it is not the complete or the final theory. Many unsolved mysteries seem to require concepts and mechanisms that go beyond our present knowledge. In this section, a list of some examples of the SM shortcomings is given:

- **Unification of Fundamental Forces:** An important goal of theoretical physics is to achieve a further simplification in understanding of nature and to describe the presently known three basic interactions in a unified way, usually referred to as the Grand Unified Theory (GUT). The SM leaves, unexplained the reason for very different strengths of the gauge group of the strong and electroweak interaction is $SU(3) \otimes SU(2) \otimes U(1)$ [21], and particular values of the quantum numbers. The idea of Grand Unified Theory(GUT) is that $SU(3)$, $SU(2)$ and $U(1)$ are subgroups of a larger gauge symmetry groups G and that quarks and leptons belong to the same multiplet of G . This higher symmetry is supposed to be unbroken above some very large mass scale.
- **Gravity:** SM describes both the strong and electroweak forces but it does not tell us anything about the fourth fundamental force, gravity. This led theories to attempt to unify the strong and electroweak with gravity, Theories of Everything.
- **Dark matter and Dark energy:** Cosmological observations tell us the standard model explains about 5% of the energy present in the universe. About 26% should be dark matter, which would behave just like other matter, but which only interacts weakly (if at all) with the Standard Model fields. The SM does not have candidate for dark matter. The rest (69%) should be dark energy, a constant energy density for the vacuum. Attempts to explain dark energy in terms of vac-

uum energy of the standard model lead to a mismatch of 120 orders of magnitude[33] .

- **Neutrino masses:** experiments show that a neutrino created with a specific lepton flavor (ν_e, ν_μ or ν_τ) can later be measured to have a different flavor. Moreover the probability of measuring a particular flavor for a neutrino varies periodically as it propagates. This neutrino oscillation phenomena between different favors is not possible if neutrinos have zero masses as assumed in the SM.
- **CP Violation:** The baryon asymmetry problem in physics refers to the fact that there is an imbalance in baryonic matter and antibaryonic matter in the observable universe. The standard model of particle physics doesn't provide an obvious explanation for why this should be so, and it is a natural assumption that the universe be neutral with all conserved charges. The Big Bang should have produced equal amounts of matter and antimatter. Since this does not seem to be the case, it is likely some physical laws must have acted differently or did not exist for matter and antimatter. There are several competing hypotheses to explain the imbalance of matter and antimatter that resulted in baryogenesis, but there is as of yet no one consensus theory to explain the phenomenon.
- **Hierarchy problem:** the standard model introduces particle masses through a process known as spontaneous symmetry breaking[34] caused by the Higgs field. Within the standard model, the mass of the Higgs gets some very large quantum corrections due to the presence of virtual particles (mostly virtual top quarks). These corrections are much larger than the actual mass of the Higgs. This means that the bare mass parameter of the Higgs in the standard model must be fine tuned in such a way that almost completely cancels the quantum corrections[35] . This level of fine-tuning is considered unnatural

by many theorists. There are also issues of Quantum triviality, which suggests that it may not be possible to create a consistent quantum field theory involving elementary scalar particles.

- **Fermion generations and their masses:** the SM does not explain why there are three generations of leptons and quarks. Why does Nature need the two other generations? Why the fermions masses span over many orders of magnitude?

- **Free parameters:**

there are 19 free parameters in the SM that must be determined by experiments:

- lepton masses: M_e, M_μ and M_τ .
- quark masses: M_u, M_c, M_t, M_d, M_s and M_b .
- CKM matrix parameters: $\theta_{12}, \theta_{13}, \theta_{23}$ and δ .
- U(1), SU(2), and SU(3) gauge couplings: g_1, g_2 , and g_3 .
- QCD vacuum angle: θ_{QCD} .
- Higgs quadratic coupling: μ .
- Higgs self-coupling strength: λ .

1.5 Compositeness Model

1.5.1 Introduction

The Standard Model (SM) of elementary particles is a great theory that has successfully explained the interaction between elementary particles and agrees with the experimental results. However, there are still several fundamental questions that SM cannot answer them. One of this unanswered question is Why quarks and leptons masses span over a large range? Why

is there several generations? This may suggest that the leptons and quarks may not be fundamental particles [36] and there might exist a more fundamental basis [37, 38]. The Compositeness Model supposes that above a characteristic energy scale Λ , leptons and quarks may not be fundamental particles but made of smaller constituents called preons. The constituents could be three fermions or a fermion and a boson. Below the compositeness scale Λ , the interaction become strong and binds the preons together to form quarks and leptons. At the scale of the constituent binding energies Λ , a new strong interaction among quarks and leptons constituents, preons, should appear. The signature for this compositeness could be a significant deviation in the measured cross section (in certain final states) at large center of mass energy compared to the predictions of the Standard Model. There is, as yet, no experimental evidence of such a deviation. Null results from such experimental searches are used to set lower bounds on the energy scale Λ above which composite particles of mass μ^* can be found.

1.5.2 A Simple Analogy

We know that the excited states of particles, atoms and molecules have the same nature, e.g., the excited state of hydrogen atom as shown schematically in Fig.1.2. In similar manner if quarks have substructure, we expect them to exhibit excited states. For example the interaction between quarks with gluons can excite such quarks and they will radiate either a photon or gluon and come to ground state (as shown in Fig.1.3).

1.5.3 Theoretical Setup

In phenomenological models, it is assumed that any theory of compositeness at large mass scale must have a low energy limit that preserves the symmetries of the SM. Contact interactions between quarks and leptons may appear as the low energy limit of the exchange of heavy particles. At

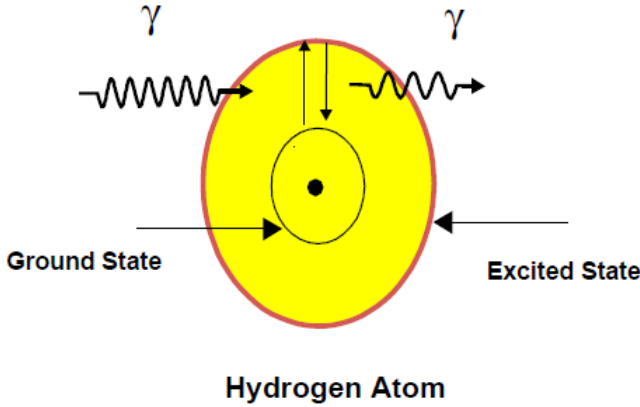


Figure 1.2: Schematic presentation of the ground and excited state of the hydrogen atom. A photon is absorbed by the ground state of the hydrogen atom to reach the excited state. An excited hydrogen atom radiates photons to reach its ground state.

sufficiently high energies excited fermions could be produced directly. According to the model we consider [39], they should form weak iso-doublets and carry electromagnetic charges similar to those of the ordinary fermions. Excited leptons are assumed to have spin and isospin $1/2$ to limit the number of parameters. The only theoretical difference between excited electrons and muons is the mass of the particles. It is assumed that excited leptons and neutrinos form a weak isospin doublet [39].

$$\left(\frac{\nu_l}{l^-}\right)_L, l_R^-, \left(\frac{\nu_l^*}{l^{*-}}\right)_L, \left(\frac{\nu_l^*}{l^{*-}}\right)_R \quad (1.1)$$

This scenario allows excited leptons to acquire masses prior to $SU(2) \otimes U(1)$ symmetry breaking and to limit the number of parameters [41, 42]. The quantum numbers of excited and ordinary leptons are expected to be the same and to be conserved in the production and decay processes.

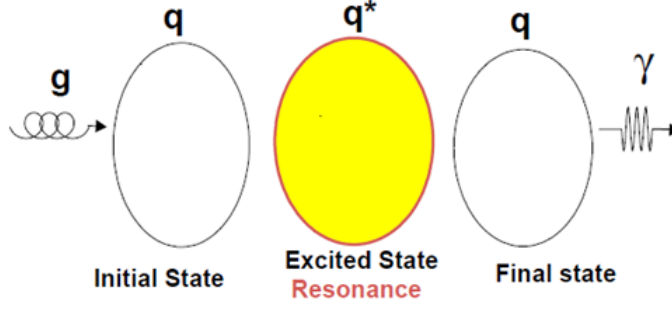


Figure 1.3: Analogy with excited atom: Excited state resonance of composite quark.

1.5.3.1 Production of μ^* via contact interactions

Excited muons can couple to other fermions via contact interaction which results from the interaction between the subcomponents "preons". It strongly depends on the energy scale of the substructure Λ (compositeness scale) and can be described by the effective four-fermion Lagrangian [39]

$$\mathcal{L}_{CI} = \frac{g^{*2}}{2\Lambda^2} j^\mu j_\mu \quad (1.2)$$

where Λ is the compositeness scale, g^{*2} represents a coupling constant chosen to be 4π , and j_μ is the fermion current:

$$j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta'_L \bar{f}_L^* \gamma_\mu f_L^* + \eta''_L \bar{f}_L^* \gamma_\mu f_L + h.c. + (L \rightarrow R) \quad (1.3)$$

The SM and excited fermions are denoted by f and f^* , respectively. γ_μ is the gamma matrices and the subscripts L (R) refer to left (right) handed fermions. The η factors for left-handed currents are set to be one, and those for right-handed currents are set to zero for simplicity. The excited muons can be produced either singly $q\bar{q} \rightarrow \mu\bar{\mu}^*(\mu^*\bar{\mu})$, or in pairs $q\bar{q} \rightarrow \mu^*\bar{\mu}^*$, through contact interactions. Since $\mu^*\bar{\mu}^*$ pair production requires larger centre of mass energy than single $\mu\bar{\mu}^*$ production, it is less favored. Thus, we

will consider only the case of single production which shown in Fig. 1.4. In case of single μ^* production $q\bar{q} \rightarrow \mu^* \mu$, the effective Lagrangian, equation(1.3), is reduced to:

$$\mathcal{L}_{CI} = \frac{g^{*2}}{2\Lambda^2} (\bar{q}_L \gamma^\mu q_L) (\bar{\mu}_L^* \gamma_\mu \mu_L) + h.c. \quad (1.4)$$

The parton level cross sections for single excited muons production through

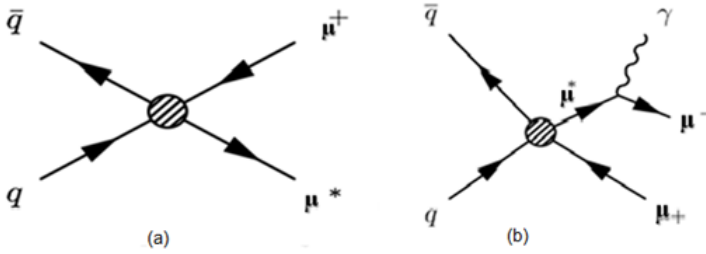


Figure 1.4: (a) Feynman Diagram of the Contact interactions of excited muons (μ^*) with quarks (q), (b) decay of excited muon (μ^*) into a SM muon (μ) via an electroweak process. [40]

contact interactions are given by[39]:

$$\hat{\sigma}(q\bar{q} \rightarrow l\bar{l}^*, l^*\bar{l}) = \frac{\pi}{6\hat{s}} \left(\frac{\hat{s}}{\Lambda^2} \right)^2 \left(1 + \frac{\nu}{3} \right) \left(1 - \frac{M_{l^*}^2}{\hat{s}} \right)^2 \left(1 + \frac{M_{l^*}^2}{\hat{s}} \right) \quad (1.5)$$

$$\hat{\sigma}(q\bar{q} \rightarrow l^*\bar{l}^*) = \frac{\pi\tilde{\nu}}{12\hat{s}} \left(\frac{\hat{s}}{\Lambda^2} \right)^2 \left(1 + \frac{\tilde{\nu}^2}{3} \right) \quad (1.6)$$

where

$$\nu = \frac{\hat{s} - M_{l^*}^2}{\hat{s} + M_{l^*}^2} \quad , \quad \tilde{\nu} = \left(1 - 4 \frac{M_{l^*}^2}{\hat{s}} \right)^{1/2} \quad (1.7)$$

$\hat{s}$ denotes the Mandelstam variable for the subprocess centre of mass energy and M_{l^*} is the excited lepton mass.

1.5.3.2 Decay of μ^* via gauge mediated interactions

The effective Lagrangian which describes the coupling of excited fermion states and ground states via gauge interactions is given by[39]:

$$\mathcal{L}_{GM} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} [g_s f_s \frac{\lambda^a}{2} G_{\mu\nu}^a + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}] f_L + h.c. \quad (1.8)$$

where $\sigma^{\mu\nu}$ is the covariant bilinear tensor; $G_{\mu\nu}^a$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are field strength tensors of the gluon, SU(2), and U(1) gauge fields, with the group generators λ^a (Gell-Mann matrices), τ (Pauli matrices) and Y (weak hypercharge), respectively; and g_s , g and g' are the corresponding gauge couplings. The scaling parameters f_s , f and f' are assumed to be equal to one. The first term describes the coupling of excited fermions to the QCD gluon field, thus it is not applicable to excited muons and the effective Lagrangian becomes:

$$\mathcal{L}_{GM} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} [g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}] f_L + h.c. \quad (1.9)$$

An excited muon can then decay via gauge interactions to a gauge boson and a SM muon, where it is assumed that the excited muon has a mass larger than the W and Z boson masses and the main decay mode via gauge interaction will be two-body decays.

The partial decay width for the gauge mediated interactions is given by [29]:

$$\Gamma(f^* \rightarrow fV) = \frac{1}{8} \frac{g_V^2}{4\pi} f_V^2 \frac{m^{*3}}{\Lambda^2} \left(1 - \frac{m_V^2}{m^{*2}}\right)^2 \left(2 + \frac{m_V^2}{m^{*2}}\right) \quad (1.10)$$

where V is the gauge boson (γ , W or Z), and f_V is a parameter that depends on the boson type:

$$f_\gamma = f T_3 + f' \frac{Y}{2} \quad (1.11)$$

$$f_Z = f T_3 \cos^2 \theta_W - f' \frac{Y}{2} \sin^2 \theta_W \quad (1.12)$$

$$f_W = \frac{f}{\sqrt{2}} \quad (1.13)$$

where T_3 and Y denotes the third component of the weak isospin and hypercharge of μ^* respectively, and $g_W = e/\sin \theta_W$ ($e = \sqrt{4\pi\alpha}$), (θ_W is the Weinberg angle) and $g_Z = g_W/\cos \theta_W$ are the standard-model W and Z coupling constants.

Hence the partial width for the gauge mediated decay of excited muons into ordinary muons and photon is given by:

$$\Gamma_{GM}(e^* \rightarrow \gamma_\mu, W_\nu, Z_\mu) = \frac{\alpha_\gamma}{4} \frac{m^{*3}}{\Lambda^2} f_\gamma^2 \quad (1.14)$$

For $m_{\mu^*} \gg m_W, m_Z$ we can neglect $m_W^2/m_{\mu^*}^2$ and $m_Z^2/m_{\mu^*}^2$ terms, and the total width for gauge interaction decay can be obtained as follows:

$$\Gamma_{GM}(e^* \rightarrow \gamma_\mu, W_\nu, Z_\mu) \simeq \frac{1}{4} \frac{m^{*3}}{\Lambda^2} (\alpha_\gamma f_\gamma^2 + \alpha_W f_W^2 + \alpha_Z f_Z^2) \quad (1.15)$$

Figure 1.5 shows the branching ratios (BR) of the three gauge mediated decay modes of excited muons, $\mu^* \rightarrow \mu\gamma$ (in black), $\mu^* \rightarrow \mu Z$ (in red), $\mu^* \rightarrow \nu_\mu W$ (in violet) as a function of m_{μ^*} and at compositeness scale $\Lambda = 10 \text{ TeV}$. The excited muon decay into the $\nu_\mu W$ has the highest branching ratio, but W will decay further to lepton + ν_l or mostly to hadrons. Therefore, the decay via photon radiation is the preferred decay mode if a leptonic final state is demanded. This analysis concentrates on the decay mode $\mu + \gamma$, such that the final state is $\mu\mu\gamma$. The BR can be renormalized for all possible decays with muon final state as:

$$BR(\mu^* \rightarrow \mu\gamma) = \frac{\Gamma(\mu^* \rightarrow \mu\gamma)}{\sum_{V=\gamma, W, Z} \Gamma_{GM}(l^* \rightarrow lV)} \quad (1.16)$$

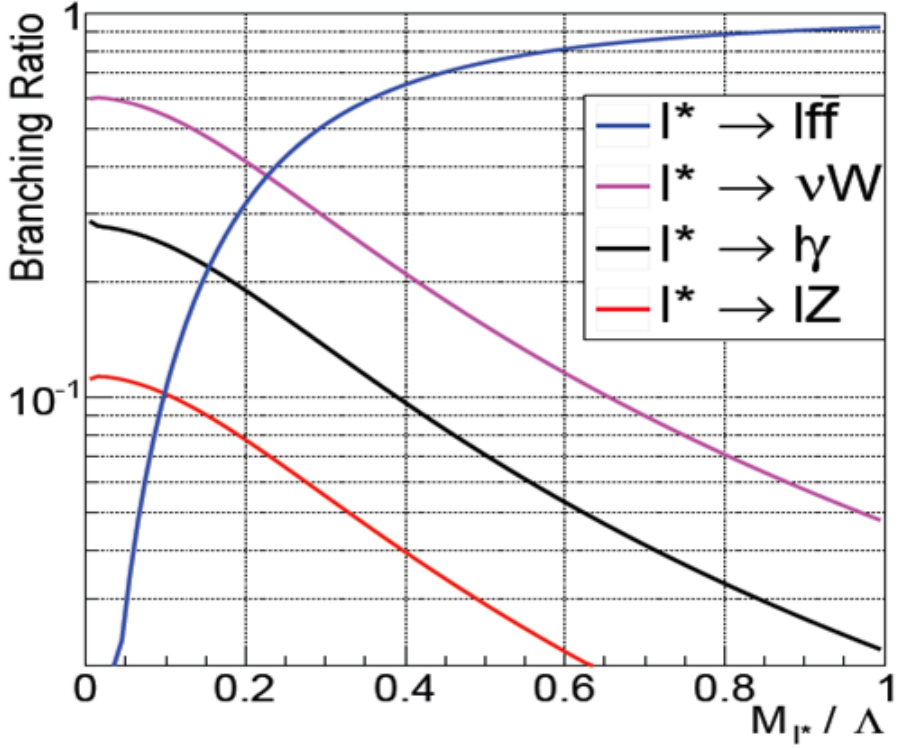


Figure 1.5: Branching ratios of the decay of excited muons (μ^*) via contact interaction (in blue) and the possible gauge mediated decay modes, $\mu^* \rightarrow \mu\gamma$ (in black), $\mu^* \rightarrow \mu Z$ (in red), $\mu^* \rightarrow \nu_\mu W$ (in violet) as a function of m_{μ^*} and at $\Lambda = 10 \text{ TeV}$. [40]

1.5.3.3 Previous searches for μ^*

Since there is no discovery of μ^* (or any other f^*) so far, many experiments that previously searched for excited fermions set limits on the μ^* . In most cases the limit is expressed in the form of an excluded region in the (Λ, m_{μ^*}) plane. The latest experimental previous results are listed below:

- OPAL (2002) [43]: the OPAL collaboration searched for pair and single production of excited leptons ($l = e, \mu, \tau$) by the processes $(e^+e^- \rightarrow l^*l^* \rightarrow l\gamma l\gamma), (e^+e^- \rightarrow l^*l \rightarrow ll\gamma)$ at $\sqrt{s}=183 - 209 \text{ GeV}$. The amount of data used in this analysis was 680 pb^{-1} .

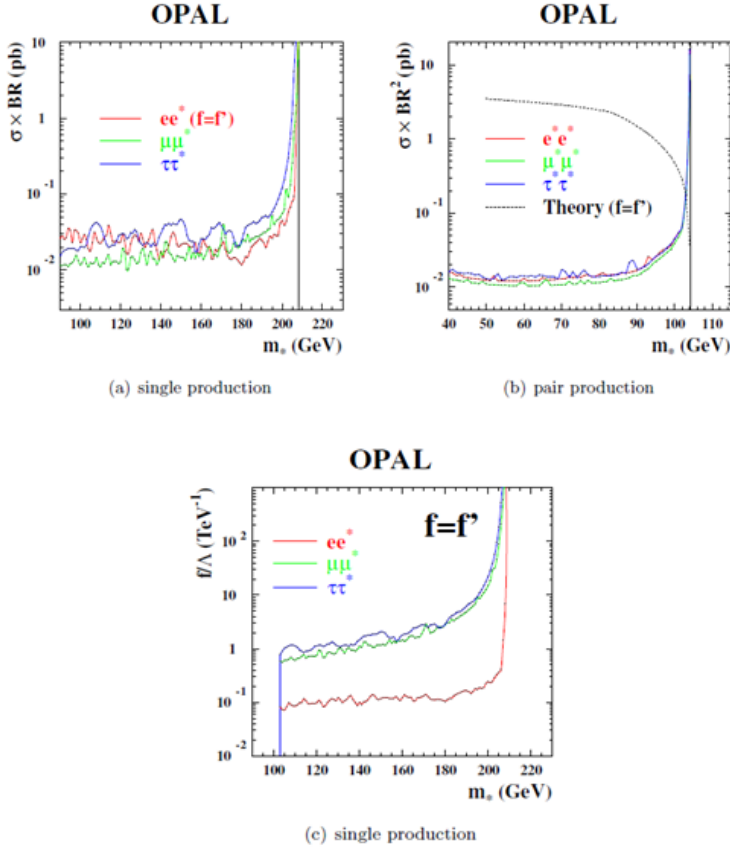


Figure 1.6: OPAL collaboration 95% CL upper limits on the cross-section at $\sqrt{s}=208.3$ GeV times the branching fraction for (a) single and (b) pair production of excited leptons as a function of mass (m^*). The theoretical cross-section times the branching ratio squared is also shown in (b). The 95% CL upper limits on the ratio of the excited lepton coupling constant to the compositeness scale, f/Λ , as a function of the excited lepton mass and assuming $f = f'$ are shown in (c) [43]

Figures 1.6 show 95% CL upper limits on the cross-section times branching ratio at $\sqrt{s}=208.3$ GeV for (a) single and (b) pair production of excited leptons as a function of mass (m^*). The limit obtained for the single production of excited muons is calculated assuming

$f = f'$ (see equation 1.9). The regions above the curves are excluded. The 95% CL upper limits on the ratio of the excited lepton coupling constant to the compositeness scale, f/Λ , as a function of the excited lepton mass and assuming $f = f'$ are shown in (c). The regions above the curves are excluded by single production searches while pair production searches exclude masses below 103.2 GeV for excited electrons, muons and taus with $\Lambda = 1 \text{ TeV}$.

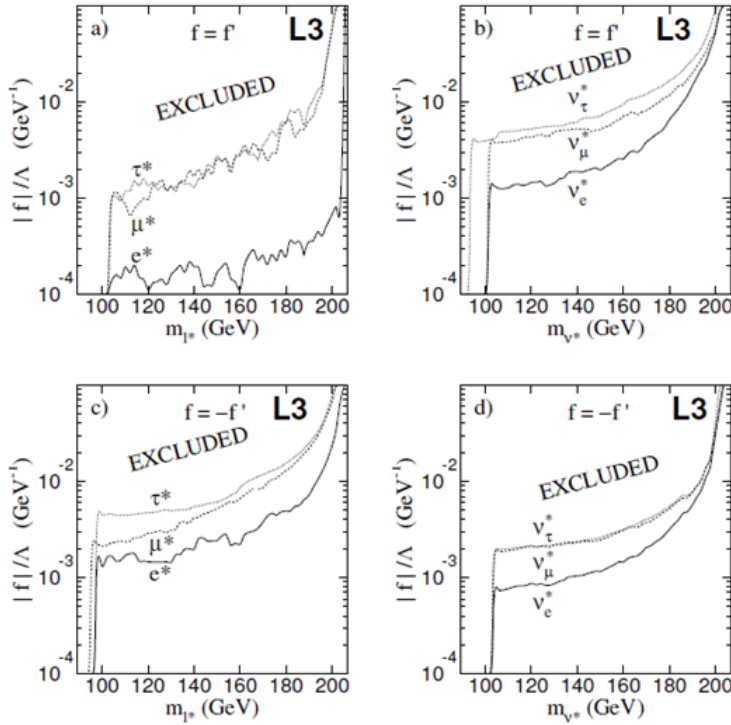


Figure 1.7: L3 collaboration 95% CL upper limits on $|f|/\Lambda$, as a function of the excited lepton mass with $f = f'$ for (a) e^* , μ^* and τ^* (b) ν_e^* , ν_μ^* and ν_τ^* with $f = -f'$ for (c) e^* , μ^* and τ^* (d) ν_e^* , ν_μ^* and ν_τ^* [44]

- L3 (2003)[44]: the L3 collaboration also searched for pair and single production of excited leptons ($l = e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$) at $\sqrt{s} = 202 - 209$ GeV. The amount of data used in this analysis was 217 pb^{-1} . They

set lower limit at 95% CL of 102.8 GeV (96.6 GeV) for the excited muon mass assuming $f = f'$ ($f = -f'$) for excited muon from the results obtained from pair production searches. In the case of single-production searches, an upper limit on the cross section was set as a function of the excited lepton mass.

Figures 1.7 a-d the L3 collaboration 95% CL upper limits on $|f|/\Lambda$, as a function of the excited lepton mass with $f = f'$ for (a) e^*, μ^* and τ^* , (b) ν_e^*, ν_μ^* and ν_τ^* , and with $f = -f'$ for (c) e^*, μ^* and τ^* , (d) ν_e^*, ν_μ^* and ν_τ^* .

- CDF (2005) [45]: the CDF collaboration searched for single production of excited muons by the process $(p\bar{p} \rightarrow \mu^*\mu \rightarrow \mu\mu\gamma)$ at $\sqrt{s} = 1.96 \text{ TeV}$. The amount of data used in this analysis was 371 pb^{-1} . In case of contact interaction production, excited muons can be excluded for $107 \text{ GeV} < M_{\mu^*} < 853 \text{ GeV}$ ($\Lambda = M_{\mu^*}$) by CDF. The exclusion limit for gauge production from CDF is $100 \text{ GeV} < M_{\mu^*} < 410 \text{ GeV}$ $f/\Lambda = 0.01 \text{ GeV}^{-1}$.

Figure 1.8. shows CDF cross section $\times$ branching ratio limits for the CI and GM models, compared to the CI model prediction for $\Lambda = M_{\mu^*}$ and the GM model prediction for $\Lambda/f = M_{\mu^*}$.

- D0 (2008)[46]: the D0 collaboration searched for single production of excited muons by the process $(p\bar{p} \rightarrow \mu^*\mu \rightarrow \mu\mu\gamma)$ at $\sqrt{s} = 1.96 \text{ TeV}$. The D0 data was interpreted in the context of CI production model and decay via GM model. The amount of data used in this analysis was 380 pb^{-1} . D0 sets a 95% CL upper limit on the production cross section ranging from 0.057 to 0.112 pb, depending on the mass of the excited muon. A lower mass limit of the excited muon of 618 GeV for $\Lambda = 1 \text{ TeV}$ was set, see figure 1.9.
- CMS and ATLAS: The newest and best limits on excited muons are

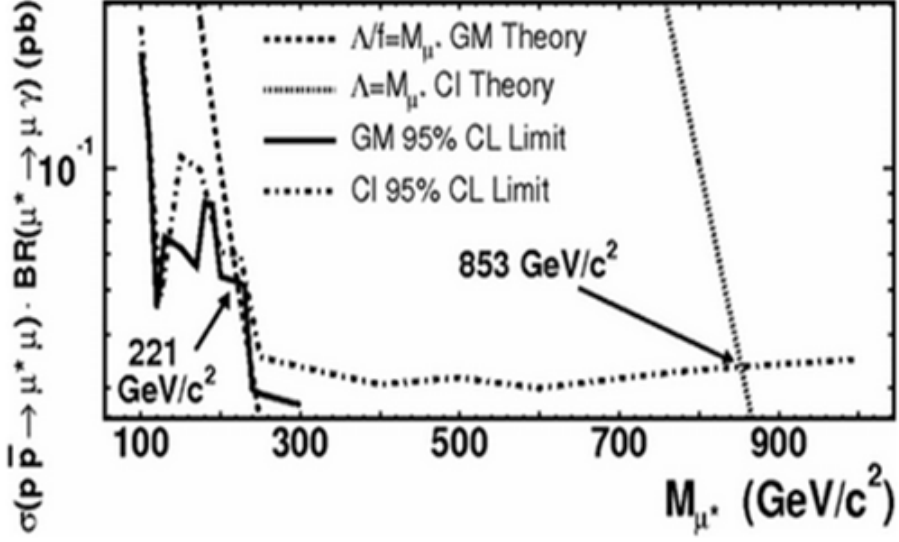


Figure 1.8: CDF collaboration cross section $\times$ branching ratio limits for the CI and GM models, compared to the CI model prediction for $\Lambda = M_{\mu^*}$ and the GM model prediction for $\Lambda/f = M_{\mu^*}$. The mass limits are indicated.[45]

from the CMS and ATLAS collaborations. CMS excluded excited muons with $5fb^{-1}$ data at $\sqrt{s} = 7 \text{ TeV}$ [47] for the range $M_{\mu^*} > 1.9 \text{ TeV}$ for $\Lambda = M_{\mu^*}$ as shown in figure 1.10. The exclusion limit from ATLAS is $M_{\mu^*} > 2.2 \text{ TeV}$ for $\Lambda = M_{\mu^*}$ with $13fb^{-1}$ data at $\sqrt{s} = 8 \text{ TeV}$ [48]. Figure 1.11 shows the exclusion limit from the ATLAS experiment. As far as known, there are no limits for the four lepton final state of excited leptons only a search in a two lepton final state has been performed.

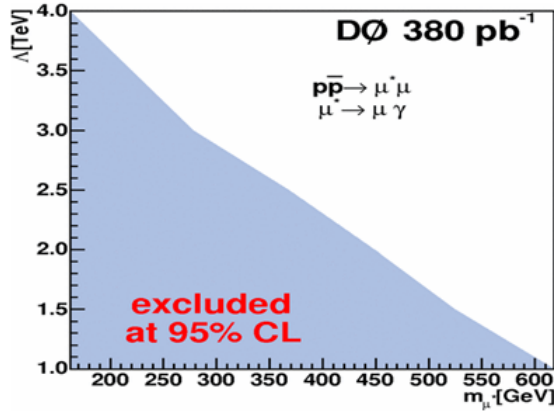


Figure 1.9: The region in the (M_{μ^*}, Λ) plane excluded by the D0 experiment.[46]

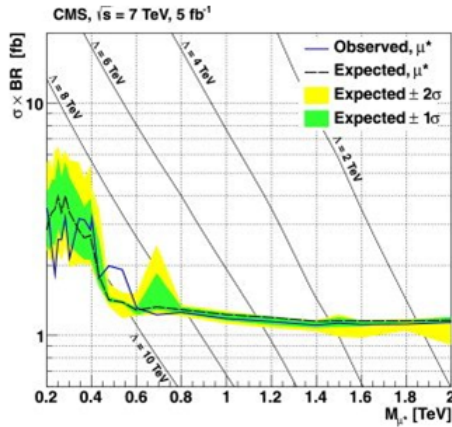


Figure 1.10: Exclusion limits for excited muon production in the CMS experiment in the with 5 fb^{-1} data at $\sqrt{s} = 7 \text{ TeV}$. [47]

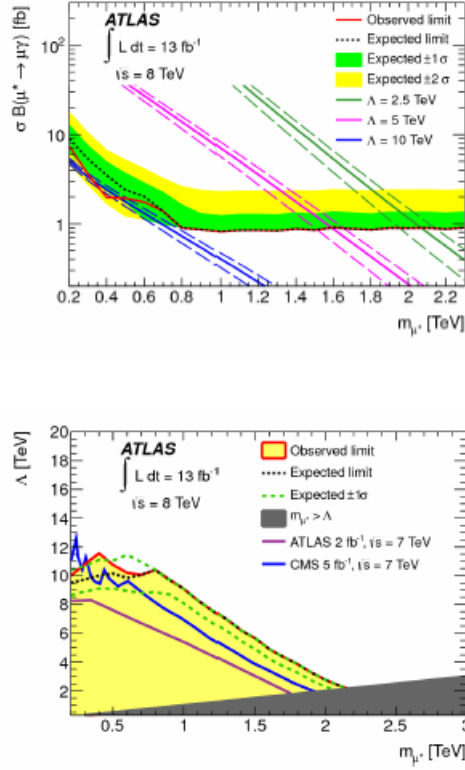


Figure 1.11: Exclusion limits for excited muon production in the $\mu\mu\gamma$ channel from the ATLAS experiment with 13 fb^{-1} data at $\sqrt{s} = 8 \text{ TeV}$. Left: Cross section limit; right: Limit on the compositeness scale Λ . [48]

Chapter 2

The LHC and the CMS Experiment

The CMS (Compact Muon Solenoid) detector is one of the two Large Hadron Collider (LHC) general purpose detectors. It is located at one of the four interaction points on the LHC. It is designed to detect the particles that comes out of proton collisions at $\sqrt{s} = 14$ TeV (currently, LHC is running at 13 TeV). The first part of this chapter is dedicated to the LHC, the second is devoted to the CMS detector and in the third part CMS trigger and data acquisition (DAQ) systems are mentioned.

2.1 The Large Hadron Collider (LHC)

The Large Hadron Collider (LHC) [49], colloquially known as "the machine", is the world's largest and most powerful accelerator. It has a 26.7 km circumference and located on the Swiss-French border near Geneva. It was built as a discovery machine, with its main focus on discovering the Higgs boson, the last undiscovered building block of the Standard Model, but also with the possibility of discovering physics beyond the Standard

Model, miniature black holes and many other new phenomena which are possible at high momentum transfer.

The previous accelerator in the current LHC tunnel was the Large Electron Positron (LEP) accelerator. It accelerated and collided electrons and positrons at a center of mass energy of 209 GeV . However, very high energy loss due to synchrotron radiation made it technically impossible to accelerate electrons to higher energies. Since the losses due to synchrotron radiation are inversely proportional to the fourth power of the particle mass, the proton was chosen for the LHC in order to achieve higher collision energies.

At its full operational capacity of the collider (expected soon), it will have two counter-rotating proton beams each with an energy of 7 TeV thus giving a total collision energy of 14 TeV in the center of mass frame. now, the LHC collides protons at a center of mass energy of 13 TeV, or a beam energy of 6.5 TeV/beam.

The LHC is a natural choice as the next step in particle physics. Historically discoveries of new particles have been dominated by hadron colliders extending the accessible energy range upwards. In this way the LHC can be seen as a discovery machine with a dynamic range of discovery from energy scales of few hundred MeV in case of B-physics to a few TeV for the discovery of new vector bosons or composite leptons.

The full accelerator complex is shown in figure 2.1. The path of the proton from production to a collision point begins from a hydrogen gas bottle that supplies protons to the first stage linear accelerator, Linac2. The Linac2 uses Radio Frequency Quadrupoles to accelerate the protons to 50 MeV, then, after passing through an 80 m long transfer line, the protons enter a 157 m circumference Proton Synchrotron Booster (PSB) ring, which further accelerates them to 1.4 GeV before injecting them into the Proton Synchrotron (PS). The PS acts as a pre-injector for the LHC. It accelerates the protons to 26 GeV and splits the 6 bunches injected from the PSB into

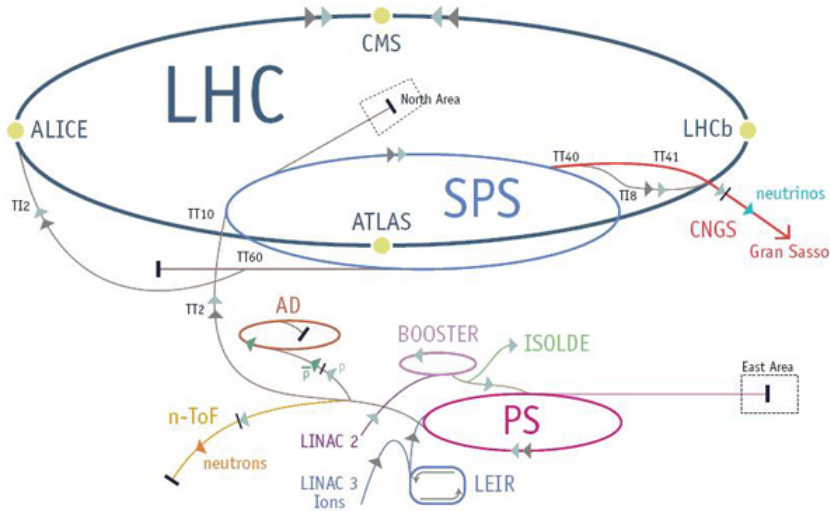


Figure 2.1: Layout of the LHC ring within the CERN accelerator complex[49].

bunch trains of equally spaced series of bunches, up to 72 bunches long with 25 ns time separation between bunches. Then, the bunch trains are injected into the Super Proton Synchrotron (SPS), which is the final stage of acceleration before injection into the LHC. The SPS accelerate the 26 GeV proton bunches to 450 GeV and injects them via two separate transfer lines into the clockwise (beam 1) and anti-clockwise (beam 2) LHC rings.

The two main parameters of an accelerator of interest to particle physicists are the center of mass energy of the collision, $\sqrt{s}$, and the integrated luminosity. The LHC is designed to accelerate the 450 GeV proton bunches injected from the SPS up to 7 TeV in two counter rotating beams, thus ultimately achieving a 14 TeV center of mass collision energy. The limiting factor to the achievable energy of the beam is the magnetic field strength of the bending dipole magnets. In order to bend 7 TeV protons in the LHC ring, the average magnetic field needed is 5.5 T. However, because it is impossible to cover the whole LHC circumference only with the bending dipoles, the actual magnetic field needed is 8.36 T approaching the limit

of the maximum reachable magnetic field of 10 T for the superconducting niobium-titanium filaments that the LHC magnets use. During the 2010 operation, due safety precaution related to the operation of the LHC bending dipole magnets, the protons were accelerated only up to 3.5 TeV per beam, half of the design energy, making the center of mass energy of the collision $\sqrt{s} = 7$ TeV. Now protons is accelerated up to 6.5 TeV per beam, to reach center of mass energy to $\sqrt{s} = 13$ TeV, and it is expected that we reach to the designed energy ” $\sqrt{s} = 14$ TeV” soon. To attain the design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, each proton beam will circulate 2808 bunches with $\sim 1.15 \times 10^{11} \text{ protons/bunch}$ in the beam pipe. The proton bunches will cross each other every 25 ns which will be the collision frequency(40 MHz). Some of the machine and beam parameters are shown in Table2.1 .

Beam Parameters		
Beam Energy	(TeV)	7
Luminosity	($\text{cm}^{-2} \text{s}^{-1}$)	10^{34}
Time between collisions	(ns)	25
Bunch length	(cm)	7.7
Beam radius at interaction point	(μm)	15.9
Machine parameters		
Ring circumference	(m)	26658.9
RF frequency	(MHz)	400.8
Number of bunches		2808
Number of bunches dipoles		1232
Magnetic length of bending dipoles	(m)	14.2
Field of the bending dipoles	(T)	8.3
Bending radius	(m)	2784
Tempereature of the main magnets	(K)	1.9

Table 2.1: Some important LHC parameters.[25]

The LHC will also be used to collide heavy ions with heavy ions (as well with protons) with collision energy of 1.15 PeV. The Pb ions will be first accelerated by the linear accelerator LINAC3, and the Low-Energy Ion Ring (LEIR) will be used as an ion storage and cooler unit. The ions will

be further accelerated by the PS and SPS before being injected into LHC ring, where they will reach energy of 2.76 TeV per nucleon.

2.2 Luminosity

One of the most important parameters of the LHC or any such other accelerator is its capability at which it can produce the expected or any new phenomena. This parameter is called the *luminosity* (L) and characterizes the number of collisions in a collider. Mathematically luminosity can be expressed as:

$$L = \frac{f N_1 N_2 n_b \gamma_r F(\theta)}{4\pi \epsilon_n \beta^*} \quad (2.1)$$

where,

- f is the frequency of interaction of the proton beams with each other. For LHC the collision frequency is $f = 40 \text{ MHz}$.
- $N_{1,2}$ are the number of particles per bunch in two colliding beams.
- n_b is the number of bunches per beam.
- γ_r is the relativistic gamma factor.
- ϵ_n is the normalized transverse beam emittance.
- β^* is the beta function at the collision point.
- $F(\theta)$ is the factor accounting for reduction in luminosity due to the crossing angle $\theta = 285 \mu\text{rad}$ of the two beam in the circular ring. The factor $F(\theta)$ depends on the length of the bunch and it is about 85% for the LHC machine.

The collision frequency of 40 MHz corresponds to a bunch separation of 7.5 m in the LHC ring. The transverse dimension (known as emittance) of

the beam is another parameter which can affect the luminosity. The RMS beam size at the interaction point is about $16.7\mu m$ (with a β function of 0.55) while for collision the normalized transverse emittance is $3.75\mu m$. To achieve higher luminosity, a simple way is to increase the number of protons in each bunch. But this is limited by electromagnetic forces between the colliding bunches. Although the maximum luminosity achievable will be close to $2 \times 10^{34} cm^{-2}s^{-1}$, at this point to be in a stable region the nominal luminosity is fixed at $10^{34} cm^{-2}s^{-1}$. For the early phase of LHC operation it is foreseen to operate at lower luminosity $L_{low} \sim 10^{32} - 10^{33} cm^{-2}s^{-1}$ and gradually increases to the design luminosity of $L_{high} \sim 10^{34} cm^{-2}s^{-1}$.

The number of observed events (n_{obs}) for any physics process and L are related as,

$$n_{obs} = \sigma.BR.\varepsilon. \int L.dt \quad (2.2)$$

where, σ is the cross-section for a particular physics channel, BR is the branching ratio for the selected decay mode, ε is the detection efficiency, and $\int L.dt$ is the integrated luminosity.

2.3 The LHC experiments

The LHC hosts six experiments four of them placed at the four collision points:

- CMS and ATLAS (A Toroidal LHC ApparatuS) [50, 51] are located at points 5 and 1 respectively. Both are aiming at peak luminosity of $L = 10^{34} cm^{-2}s^{-1}$ for proton operation CMS and ATLAS are two general purpose detectors. They have a very rich physics program: starting from high precision measurements, searching for Higgs boson, looking for new physics, extra dimensions, and even looking for clues to the nature of dark matter.

- ALICE (An LHC Ion Collision Experiment)[52] is located at point 2 and is optimized to study quark-gluon plasma, a state of matter wherein quarks and gluons are de-confined. It is aiming at a peak luminosity of $L = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$ for nominal Pb-Pb operation.
- LHCb (LHC beauty)[53] is located at point 8 and is aiming at peak luminosity of $L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ with 156 bunches for proton operation. It is dedicated to b-physics, particularly aimed for measuring the parameters of CP violation in the interactions of b-hadrons.
- LHCf (LHC forward)[54] is a small experiment that is located near from point 1 and is dedicated to measure the energy and numbers of neutral pions (π^0) generated in the forward region of collisions. It consists of two detectors, 140 m on either side of point 1.
- TOTEM (TOTAl Elastic and diffractive cross section Measurement)[55] is sharing point 5 with CMS and is dedicated to measure total cross section, elastic scattering and diffractive processes. It is aiming at peak luminosity of $L = 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ with 156 bunches for proton operation.

2.4 Compact Muon Solenoid (CMS) Detector

The Compact Muon Solenoid (CMS) [50] is one of two multipurpose particle detectors at the LHC designed to perform searches for a broad spectrum of physics. It is cylindrical in a diameter of 14.6 m and is 21.6 m long. The detector weighs about 12,500 tons and is one of the heaviest particle physics detectors ever built. Inside the solenoid, immersed in a 3.8 T field, are the central tracker and the electromagnetic and hadronic calorimeters. Outside the solenoid, are the outer and forward calorimeters and, interspersed with the solenoid's return yoke steel, are the muon detectors. A

schematic layout of the CMS detector along with main sub-detector systems is shown in figure 2.2.

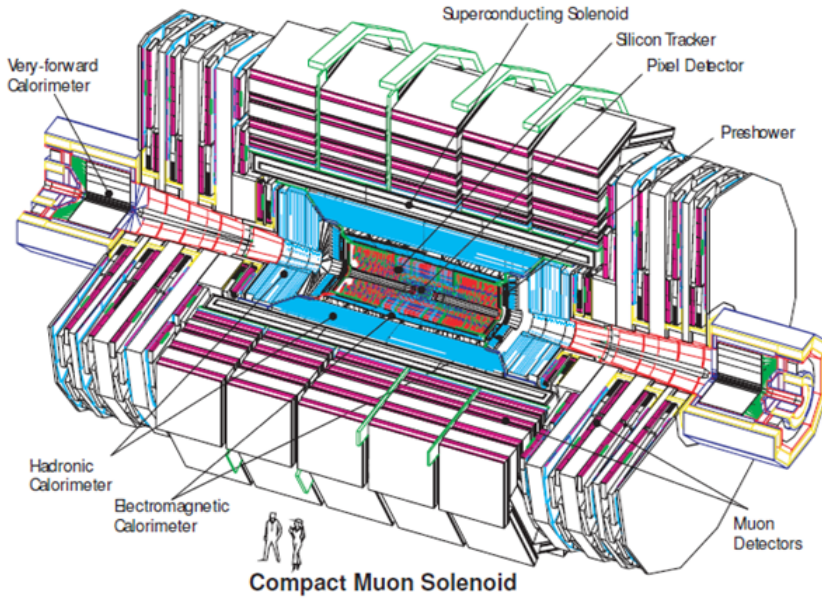


Figure 2.2: A schematic view of the CMS detector along with its all major subdetector systems[56].

The main characteristics of CMS detector are[50]:

- A high quality tracking system with excellent charged particle momentum resolution and reconstruction efficiency.
- An excellent electromagnetic calorimeter having a wide coverage of $|\eta| < 3.0$, with $\sim 1\%$ (at 100 GeV) mass resolution for diphoton and dielectron system. It has excellent photon and electron isolation with efficient π^0 rejection.
- Good measurement of missing-transverse energy due to hermitic coverage of the detector.
- A high performance muon system for muon identification and momentum resolution ($\sim 1\%$ at 100 GeV) over a wide range of energy

scale and angles.

- Efficient triggering and offline tagging of τ 's and b jets due to presence of pixel detector close to the interaction vertex.

2.4.1 The Coordinate System of CMS

The origin of the coordinate system used by CMS is the nominal collision point in the beam pipe. The x-axis radially points to the center of the LHC while the y-axis points vertically to the surface of the earth and the z-axis points horizontally in the counter-clockwise direction of the LHC ring, i.e. in the same direction as beam 2 of the LHC. Due to the cylindrical symmetry of the detector and the nature of the physics of the hadronic collisions, three more coordinates are useful when talking about the position of the detector components and physics objects. First, is the azimuthal angle ϕ in the xy plane with $\phi = 0$ in the $+x$ direction and $\phi = \pi/2$ in $+y$ direction. Second, is the polar angle θ measured from the $-x$ axis with $\theta = 0$ at $+z$ and $\theta = \pi$ at $-z$. Instead of θ one can also use the pseudorapidity.

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

As a possibility to describe distances in the detector, one uses

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

This variable defines a distance between two particles and can be used for different measurements

Geometrically the CMS detector can thought of as consisting of three parts. The "barrel" - consisting of coaxial cylinders parallel to z direction and two "end-caps" - consisting of disks, on $+z$ and $-z$ ends of the detector. The magnetic field, inside the solenoid, points in the $+z$ direction.

2.4.2 The Tracker

Here, the inner tracker of the CMS experiment will be described, based on [57]. Two parts form the inner tracker: A pixel detector and a strip detector. Figure 2.3 shows a schematic overview of the tracking system of CMS. It was developed for a high number of particles per bunch crossing and for the measurement of a momentum of charged particles up to $|\eta| < 2.5$ based on their bending by the magnetic field. Another purpose is the reconstruction of decay vertices with a very high precision. Both goals are archived by detecting the hits produced by charged particles in the pixel and strip detectors. Due to the short time between two bunch crossings (25 ns), the tracker has to have a fast response time. For these reasons, the tracker is based on silicon and placed close to the beamspot, 4.4 cm apart from the interaction point.

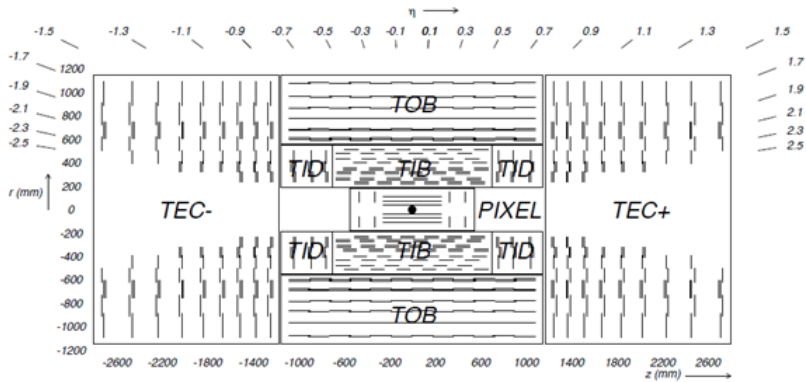


Figure 2.3: A schematic longitudinal view of the CMS tracker in terms of different layers and their arrangements in η and z direction in one quarter of the CMS detector[49].

Pixel detector

The central part of the tracker is the pixel detector, shown separately in figure 2.4. It consists of three barrel layers, with radii ranging from 4.4

cm to 10.2 cm , and four end-cap disks, two on each side at $z = \pm 34.5\text{ cm}$ and $z = \pm 46.5\text{ cm}$. Together they cover the pseudo-rapidity range up to $|\eta| = 2.5$.

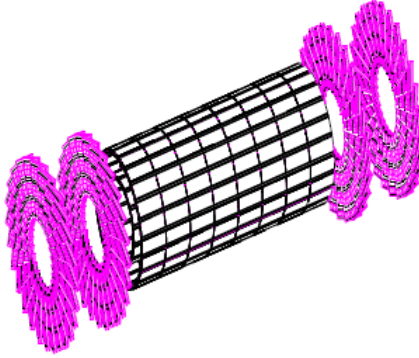


Figure 2.4: Layout of pixel detectors and the turbine shaped end-cap disks in CMS.[25]

Strip detector

The outer part of the tracking system is the silicon-strip-tracker. Its total length is 5.8 m and its outermost diameter is 2.5 m , it has a lower density of tracker layers. The strip detector consists of different sub-components: The tracker inner barrel (TIB), tracker inner disks (TID) and tracker outer barrel (TOB) that form the barrel region ($|\eta| < 0.9$) and the tracker endcaps (TEC) in the endcap region ($0.9 < |\eta| < 2.5$) as shown in figure 2.5.

The measurement of the particle's trajectory is done by silicon sensors. When a charge particle penetrates the sensor, it creates electrons and holes, which then drift in the direction of the electric field applied between the front and the back electrodes. In addition, due to the Lorentz force induced by the magnetic field, they also drift perpendicular to the electric field, along the plane of the sensor, until collected by the front and the back electrodes, see figure 2.5. The front side of each sensor is divided into many

small electrodes and due to the Lorentz drift, the charge deposited by the particles is collected by several neighboring electrodes. Thus the position resolution of the hits depends on the size of the electrodes and on the degree of the charge sharing between the electrodes.

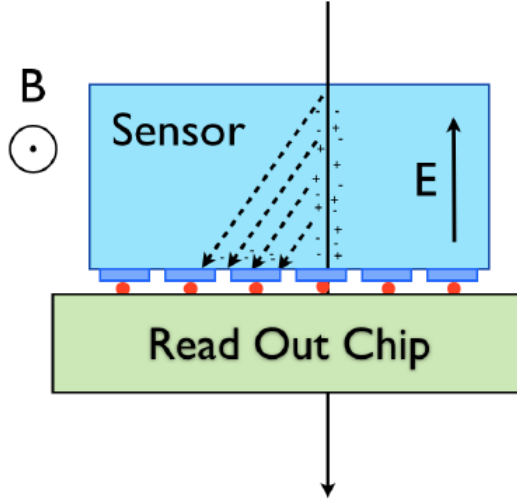


Figure 2.5: Illustration of the Lorentz drift of the charges induced by the charged particle passing through the sensor. Only the drift of the negative charges is shown. Note that the magnetic field direction with respect to the sensor is different in barrel and in the end-cap.[58]

2.4.3 Electromagnetic Calorimeter

The main task of the electromagnetic calorimeter (ECAL) [59] is the measurement of the energy deposit of electrons and photons in a range of $\eta < 3.0$. It is built out of 75848 tungstate (PbWO_4) crystals with a length of 230 mm, a density of 8.28 g/cm^3 and a radiation length of $X_0 = 0.89 \text{ cm}$ which results in nearly 26 radiation lengths for each crystal. The high number and density of the crystals lead to a fast calorimeter response with a precise measurement of the energy deposit of electrons and photons. With a light radiation of 80% in 25 ns. Avalanche photodiodes in the barrel

region and vacuum phototriodes in the endcaps are used to detect light. An incoming particle produces an electromagnetic shower that excites the material of the ECAL which afterwards emits light. This light can then be detected by the photodetectors to measure the energy of the particle. At the endcaps in front of the ECAL, preshower detectors are applied. They are used to distinguish between photons from π^0 -decays and photons from the hard interaction. The granularity of those preshower detectors is even higher than in the ECAL to distinguish two nearby photons from boosted π^0 -decays.

The resolution of the ECAL gets better for higher energies because of the rising number of particles from the electromagnetic shower. This leads to higher statistics for the energy measurement. The resolution is given by

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{\sigma_n}{E}\right)^2 + C^2 \quad (2.5)$$

The first term contains the stochastic effects of the energy deposit, the second one represents the noise of the ECAL from electronics and pileup, and the third one is a constant for calibration errors. The design values of these constants lead to [50]:

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E/GeV}}\right)^2 + \left(\frac{12\%}{\sqrt{E/GeV}}\right)^2 + (0.3\%)^2 \quad (2.6)$$

During the first collisions, anomalous energy deposits were discovered in the barrel of the electromagnetic calorimeter. These deposits are believed to be due to the direct ionization of the scintillation light sensors, Avalanche Photo Diodes (APD), positioned at the rear faces of the scintillating crystals, by highly ionizing charged particles, such as secondary low energy protons, produced during collisions. Because these energy deposits were observed in single crystals, they were called "spikes". These anomalous energy deposits were separated from normal scintillating shower deposits by their topological and timing characteristics. The topological variable

compares the energy of the single crystal, E_1 , to the sum of the energy in the four adjacent crystals, E_4 , the so-called "swiss-cross" variable. A cut on $(1 - E_4/E_1) < 0.95$ was implemented, which has rejection power that depends on the transverse energy of the signal:

- 92% for $ET > 3 \text{ GeV}$
- 97% for $ET > 5 \text{ GeV}$
- 99% for $ET > 10 \text{ GeV}$

The timing variable takes advantage of the fact that the charged particles excite the shower sensor directly, thus causing it to peak about 10 ns earlier. The timing variable has helped to clean up the anomalous energy deposits for the non-isolated spikes.

2.4.3.1 Photon Reconstruction

Because of the large Tracker material budget, photons easily convert into e^+e^- pairs before reaching ECAL. Tracks from e^+e^- can be reconstructed in the Tracker adding extra information to that already available from ECAL. Tracks are reconstructed with a specific seed /track finding method which combines an Out In seed finding starting from the SuperClusters in ECAL. Tracks found in this way are subsequently used as starting point for In Out seed/track finding. For each SuperCluster the all positive - negative track combinations are considered and a Conversion object is created for each valid pair. This implies that for a single SuperCluster there can be more than just one Converted Photon. A maximum number of 3 candidates is stored in the event (the number is configurable).

However, an MVA exploiting the likelihood is built from E/P (E from Super Cluster and p from the track pair), the tracks delta cot theta, the tracks delta phi at vertex and the track normalized chi2 is used to chose the best

candidate. The training is done with a sample of photons for which the two reconstructed tracks are correctly associated to e^{+-} -MC truth and one sample in which the two reconstructed tracks fail the association. The former is considered signal, the latter background. The MVA data can be accessed whenever at analysis time if one uses directly the Conversion collection. What is actually done for reconstruction is that we store in the Photon object only the reference to the best candidate, i.e. the conversion with the largest likelihood value.

2.4.4 Hadronic Calorimeter.

The CMS hadron calorimeter (HCAL)[60] will play a crucial role in search for new physics at the LHC. It will not only measure the jets from quarks and gluons but is also important for the measurement of missing transverse energy (E_T), where Neutrinos cannot be detected directly by the detector, but they can be reconstructed as Missing Transverse Energy (MET). The HCAL also complements electron, photon and muon identification in ECAL and muon detector respectively. The HCAL in CMS detector can be categorized in the following pseudorapidity ranges:

Hadron Barrel (HB) in $|\eta| \leq 1.305$, Hadron Endcaps (HE) in $1.305 < |\eta| < 3.0$, Hadron Forwards (HF) in $3.0 \leq |\eta| \leq 5.0$, and the barrel central barrel calorimeter is complimented by the hadronic outer (HO) "tail catcher", positioned just outside of the solenoid and covering the pseudorapidity range, for $|\eta| \leq 1.26$. Amongst these only HO is located outside the solenoid magnet. Fig. 3.6 shows the above categorization schematically in $r - z$ plane and the respective η coverage.

The barrel, end-cap, and outer hadronic calorimeters are all sampling calorimeters. They consists of plastic scintillators sandwiched between brass absorbers for energy measurement and material with a high density (mostly brass and steel) for absorption. The absorber depth of the HCAL

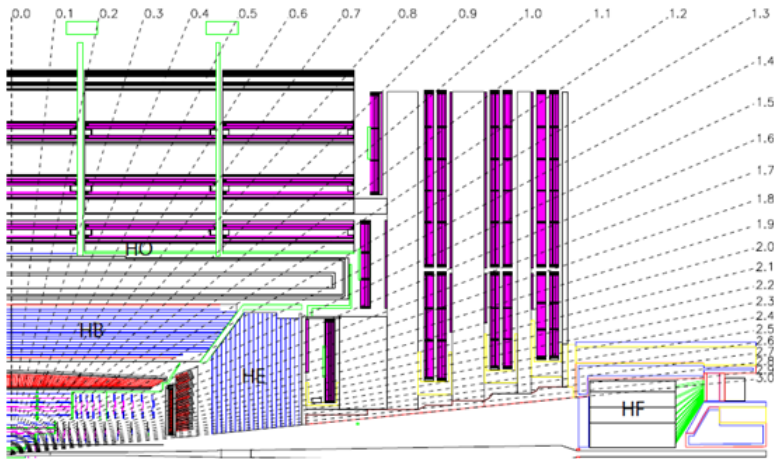


Figure 2.6: Longitudinal cross section of the quarter of the CMS detector showing the positions of the hadronic calorimeter barrel (HB), hadronic calorimeter endcap (HE), forward hadronic calorimeter (HF), and outer hadronic calorimeter (HO).[61]

corresponds to a minimum of 5.8 radiation lengths. For showers that are not completely stopped in the inner part of the HCAL, the hadronic outer calorimeter is used. The resolution of the hadronic calorimeter is much worse than the resolution of the ECAL, it is given by [60]

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{100\%}{\sqrt{E/GeV}}\right)^2 + (4.5\%)^2 \quad (2.7)$$

Besides measuring the energy deposits of the hadrons, electrons, and photons, the forward calorimeter has another important function, the luminosity measurement. It is designed to provide luminosity information on a bunch-by-bunch basis with statistical precision 1% every second. The systematic error is approximately 5%.

2.4.5 Solenoid Magnet

The momentum of particles and their charge is measured by their curvature in the tracker. To guarantee a good resolution also for particles with a high momentum, one needs a magnetic field of a high strength. The magnet of the CMS experiment is realized as a superconducting solenoid [50], resulting in a field strength of 3.8 T. It covers the tracker, the ECAL and parts of the HCAL and is returned outside by an iron yoke. The cooling system uses liquid helium with a temperature of 4.65 K. Since the magnetic field is parallel to the beam axis, the transverse momentum can be measured due to the bending of a particle with

$$\left(\frac{p_T}{\text{GeV}}\right) \sim 0.3 \cdot \frac{B}{T} \frac{r}{m} \quad (2.8)$$

where B is the magnetic field strength and r the radius of the bending.

2.4.6 Muon System

One of the essential parts and the outermost component of the CMS detector is the muon system [62, 63]. Many interesting signatures in particle physics result in final states with muons, this work depend on an accurate measurement of the muon momentum and charge up to high energies. Since muons are relatively long living and minimum ionizing particles, they can leave the detector and can be detected in the muon system. Due to the small interaction with the ECAL and HCAL material, their energy cannot be measured. The way how the muon system works is similar to the tracker: A charged particle, here a muon, travels through the muon system and produces hits in the different layers. To guarantee an optimal momentum resolution, the hits from the muon system and the silicon tracker can be combined. This gives the possibility to reach a resolution in the order of 5 % for high energetic muons of 1 TeV. Figure 2.7 presents a schematic overview of the CMS muon system. It can be seen that it is built out of three

different kinds of gaseous detectors - namely the Drift Tubes (DT), Cathode Strip Chambers (CSC), and Resistive Plate Chambers (RPC) - that will be described below. The three detectors together cover a range of $|\eta| < 2.4$.

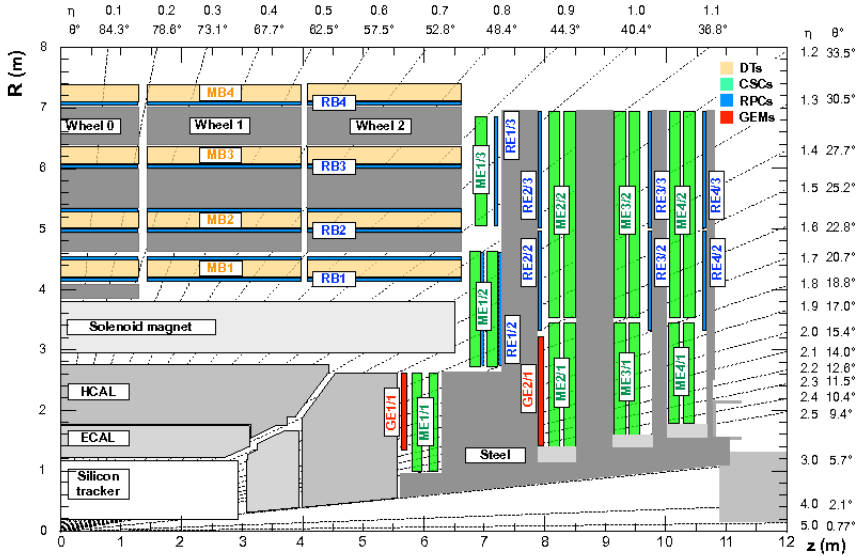


Figure 2.7: Schematic overview of the CMS muon system

Drift Tubes

In the barrel region of the detector ($|\eta| < 1.2$), a system built out of drift tubes (DT) is used since the magnetic field is nearly homogeneous and the muon rate is expected to be small here. The DTs are arranged in four concentric cylinders (muon stations) around the beam pipe - one between the hadronic calorimeter and the iron yoke (MB1), two inside the iron yoke (MB2 + MB3) and one outside the yoke which is the outermost part of the detector (MB4). Except for MB4 which has 70 drift tube chambers, all muon stations consist of 60 chambers, summing up to a number of 250 drift chambers in total. Each of them is built out of superlayers which themselves are formed from four layers of drift cells. The drift cells contain $50 \mu m$ anode wires with a voltage of +3600 V, two cathodes with -1200 V,

and two electrodes with a voltage of +1800 V (figure 2.8). They are filled with 85 % Argon and 15% CO_2 . If a charged particle passes the DT, it ionizes the gas in the cells. The produced ions and electrons travel to the cathode and anode and cause an electric pulse that can be measured. While the fourth muon station contains only two superlayers, the other stations have three. In case of the three first stations, the two outer ones are used for the measurement of the $r - \phi$ component and the inner one is used for the measurement in z-direction. In comparison to this, both layers of MB4 do only measure the $r - \phi$ component, meaning that no z-measurement is performed here.

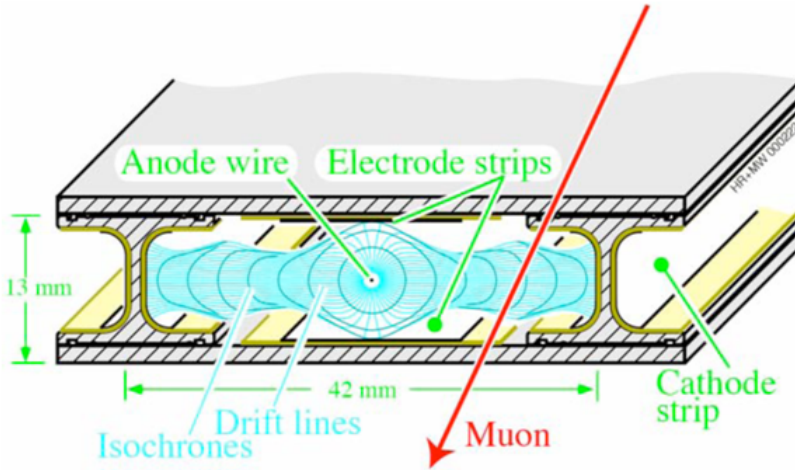


Figure 2.8: Schematic overview of a drift cell [50]

Cathode Strip Chambers

In the endcap region of the detector, cathode strip chambers (CSC) are used, covering a range from $0.9 < |\eta| < 2.4$ which means that there is an overlap region with the DTs for $0.9 < |\eta| < 1.2$. In the endcaps, the magnetic field is inhomogeneous and the expected muon rate higher than in the barrel region. Therefore, CSCs are used since they have a shorter response time and perform better in an inhomogeneous magnetic field. The CSCs are

shaped trapezoidal and consist of seven panels with cathode strips installed radially for a precise measurement in ϕ - direction as shown in figure 2.9. In the gas filled gaps between the panels, six planes of anode wires are orientated perpendicular, allowing the CSCs to measure the radial component of the muon momentum. Each endcap contains four CSC stations that are installed perpendicularly to the beam pipe and separated by the iron yoke. The working principle is similar to the one of DTs: A passing charged particle causes an ionization of gas that leads to an electric pulse. The CSCs guarantee a spatial resolution between $75 \mu m$ next to the beam spot and $150 \mu m$ for CSCs which are further away due to more separated wires.

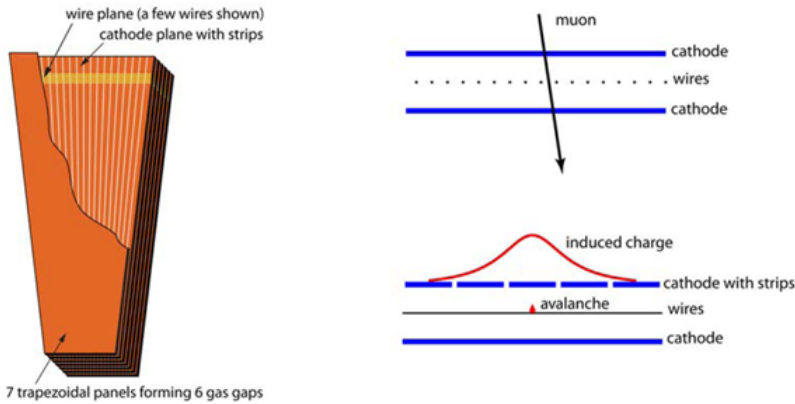


Figure 2.9: Left: Schematic view of a cathode strip chamber (CSC) as it is used in the endcaps. Right: Working principle of CSCs [50].

Resistive Plate Chamber

The third type of muon detectors are the resistive plate chambers (RPC). In comparison to DTs and CSCs, RPCs have a worse spatial resolution, but a much better response time of a few ns. Due to this short time resolution, RPCs can separate between different bunch crossings, meaning that a detected particle can be matched to its origin bunch crossing. Therefore, RPCs are mainly used as a trigger system. In the barrel region, six lay-

ers of RPCs are installed: Two at MB1 and MB2 and one at MB3 and MB4. This is done because of the fact that also low-pT muons which do not travel through the whole muon system shall have a high number of hits in the RPCs. The endcaps consist of four layers of RPCs, covering a range of $|\eta| < 1.6$. They are built out of two gas filled chambers with a small gap of 2 *mm* where the read-out strips are located. RPCs are operating in avalanche mode: If a particle passes the RPC, ionizes the gas. The detached electrons themselves ionize additional gas atoms producing an avalanche. This avalanche leads in the end to a strong signal that can be read out.

2.4.7 Muon Reconstruction

Because of the nature of the CMS detector, identification of muons has high efficiency and also has few misidentification contamination. Muons are relatively heavy particles therefore their energy loss in materials is much less. Thus they leave only a track in the central tracker system, a small energy deposit in the calorimeters, and penetrate the calorimeters, the solenoid, and the return yoke steel leaving a track in the muon system

2.4.7.1 Tracking Algorithm

A muon passing the CMS detector causes hits in different subdetectors. These hits are used to reconstruct its trajectory within the detector. An accurate track reconstruction is essential for the measurement of the muon momentum and its charge, both can be computed from the bending of the track in the magnetic field. there are three main effects have to be taken into account in the muon reconstruction procedures:

- The magnetic field is not homogeneous across the detector.
- Muons with high momentum suffer from an energy loss due to photon radiation in the whole detector (especially in the iron yoke between

the muon chambers).

- the flight direction of muons is affected by multiple scattering.

An algorithm based on four steps - trajectory seeding, building, cleaning and smoothing - converts the muon hits to track segments in the silicon tracker and the muon system [75]:

1. **Trajectory Seeding:** The starting point for the track reconstruction defined in this step. It has to be compatible with the beam-spot as well as with the assumed physics process from the hard interaction. The two most common trajectory seeds in CMS are either "hit-based" seeds which require a pair or triplet of hits compatible with the beam spot or "state-based" seeds which are specified by an initial momentum and direction without requiring any hits.
2. **Trajectory Building:** The building of the trajectory starts from the trajectory seed which was defined in the first step. From this point, the algorithm proceeds in the direction specified by the seed to find compatible hits in the following detector layers. This is done by using a combinatorial Kalman filter [77] which depends on an iterative approach to update the trajectory estimation and its covariance matrix by incorporating material effects, for example energy loss due to radiation or multiple scattering. The final estimation of the trajectory is then weighted with the information from the measurement of the new layer combined with the measurements of the other layers. The propagation of a trajectory state to another position has to take into account the effects due to the inhomogeneous magnetic field and the detector materials.
3. **Trajectory Cleaning:** Within the trajectory building, a large number of trajectories is produced. Most trajectories share a large fraction of

their hits which means that they are ambiguous. Therefore, a cleaning step is applied which resolves these ambiguities and keeps a maximum number of track candidates.

4. Trajectory Smoothing: In the last step of the track building, a backward is applied which allows to use all covariance matrices to all the intermediate points that have been measured, meaning that the full gathered information is used to build the track.

2.4.7.2 Reconstruction Algorithms

There are different ways to reconstruct muons in CMS. All of them start with an independent reconstruction of the muon in the silicon tracker (tracker track) and in the muon system (standalone-muon track). In the next step, these two tracks are used to optimize the muon reconstruction [75].

Standalone Muon

The reconstruction of standalone muon tracks uses measurements and trajectory building in the muon system. Most of the standalone muons can later be associated with a tracker track, only a fraction of 1 % of all muons are standalone without and associated tracker. If the combination with a tracker track is successful, the muon can be classified as a global muon, as described below.

Tracker-only track

The tracker-only track reconstruction is similar to the standalone muon reconstruction, but based on silicon tracker hits. In contrast to standalone muons, tracker-only tracks cannot be identified as muons but rather have to be matched to segments in the muon system.

Global Muon

Global muons combine the information of the silicon tracker and the muon system to describe the muon with a higher accuracy. At low transverse momentum ($p_T < 200 \text{ GeV}$), the inner tracker measurement provides the best momentum resolution since the reconstruction in the muon system suffers from multiple scattering while at high- p_T the momentum measurement can be improved by combining both sub-detectors. The global muon reconstruction follows an outside-in approach, starting with the standalone muon track and matching it to a subset of appropriate tracker tracks as shown in figure 2.10. For this purpose, a rectangular $\eta - \phi$ tracking region is defined which includes a number of possible tracker-only tracks. Only tracks that have a transverse momentum of at least 60 % of the standalone muon track are considered here. Afterwards, additional spatial and momentum criteria are applied to reduce the number of possibly matching tracker track for the combination with the standalone muon track. In a last step, a global fit is applied to all remaining pairs and the one with the lowest χ^2 is finally used as the reconstructed global muon. In comparison to the inside-out reconstruction (see tracker muon), this approach can improve the momentum resolution at high transverse momentum ($p_T > 200 \text{ GeV}$).

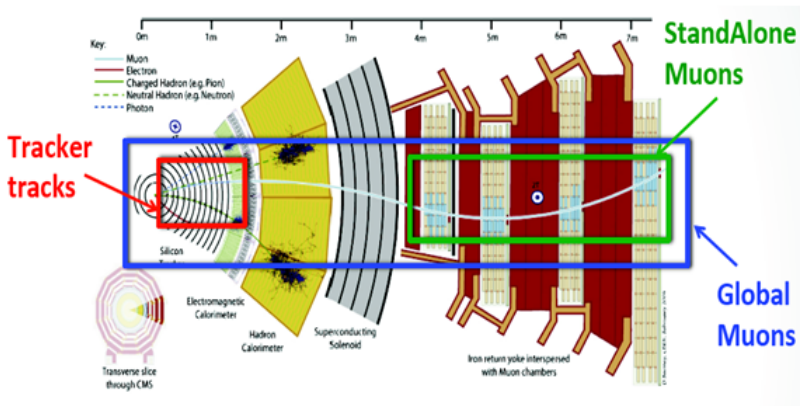


Figure 2.10: reconstruction of global muon inside muon system and silicon tracker.[76]

Tracker Muon

While the global muon reconstruction follows an outside-in approach, the tracker muon reconstruction depends on an inside-out propagation which means that it starts with the tracker-only track and matches it to hits in the calorimeters and the muon system to obtain the tracker muon track. This approach is very useful for muons that cannot be reconstructed as standalone muons for some reasons which is the case for a large fraction of low p_T muons ($p_T < 6 - 7 \text{ GeV}$) since they do not add enough hits in the muon system. Nevertheless, the tracker muon approach can still use the hits in the muon system for the reconstruction.

2.4.7.3 Muon Reconstruction at High- p_T

This analysis depends on an accurate reconstruction of high- p_T muons. The reconstruction of muons with high momentum suffers highly from energy loss by Bremsstrahlung in the iron of the magnet return yoke and from additional hits produced by the resulting electromagnetic showers. Therefore, CMS has developed specialized algorithms for the measurement of TeV muons [78]:

- **Tracker-Plus-First-Muon-Station (TPFMS) fit:** Since the first muon station is located before the magnetic return yoke, the measurements in this station suffer less from Bremsstrahlung than the other stations. This is exploited in the TPFMS fit which starts with the list of hits used in the global track, but then only uses the hits from the first muon station.
- **The Picky Fit:** Just like the TPFMS fit, the Picky fit starts with the hits from the global track, but then requires the hits used from muon chambers with possible contributions from showers (high occupancy) to have a x^2 below a certain threshold.

To improve the resolution of high- p_T muons (and to reduce the tails of the momentum resolution distribution), the so called "Cocktail" or "Tune-P" algorithm has been developed. Based on a muon-by-muon approach, the algorithm chooses between the tracker, global, TPFMS, and picky fits. At the beginning of the algorithm, it is checked if there is at least one muon with $\Delta p_T/p_T < 0.25$. Here, Δp_T is the uncertainty of the transverse momentum that is extracted from the muon fit. If no muon with $\Delta p_T/p_T < 0.25$ can be found, the threshold is raised by 0.15 until at least one muon can be selected. After a valid muon has been selected, it is tested if the p_T of the inner track is smaller than 200 GeV. If yes, it is used, if not, the algorithm proceeds with the picky fit if it is valid. In this case, it is compared to the inner track fit to decide which one is used. If there is no Picky fit, the TPFMS fit and afterwards the global track is chosen. In the end, the chosen muon track is compared to the TPFMS fit and the better one is selected [79, 80].

2.4.7.4 Muon Identification

The combination of different algorithms provides efficient muon reconstruction. We study the performance of three basic muon identification algorithms: Soft Muon selection, which requires the candidate to be a Tracker Muon, with a tighter requirement on the matched muon segment; Tight Muon selection, for which the candidate must be a Global Muon with the $\chi^2/d.o.f.$ of the global-muon track fit less than 10, additional quality requirements for the track and transverse impact parameter $|d_{xy}| < 2mm$ with respect to the primary vertex, the Particle Flow Muon selection, based on the CMS particle-flow event reconstruction, which combines the information from all subdetectors to identify and reconstruct individually particles produced in the collision. Finally we have High p_T muon selection which used in this analysis and it will be described in detail later.

2.4.7.5 Muon Isolation

There are two types of isolation of muon , Detector based Isolation and Particle Flow Isolation, shown in figure 2.11. For Detector based Isolation , the isolation of the muon is measured in the tracker, in the electromagnetic calorimeter, in the hadronic calorimeter, and in the outer hadronic calorimeter. In all cases a hollow cone around the muon with the outer radius $\Delta R = 0.3$ is used. The inner, hollow part of the cone is called the veto cone. It is designed to remove

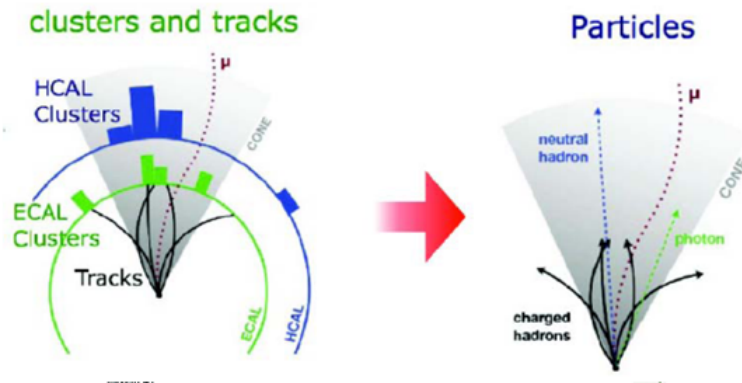


Figure 2.11: Detector based Isolation shown left ,and Particle Flow Isolation shown right.

the muon's own deposits from the calculation of the isolation. In the tracker the isolation cone is centered around the direction of the muon track at the interaction point, in the calorimeters the isolation cone is centered around the point where the muon hits the calorimeters. Particle Flow Isolation attempts to reconstruct all stable, strongly or electromagnetically interacting, particles in the event, that is, electrons, photon, muons, and all charged and neutral hadrons, using information from all of the CMS sub-detectors. Particle Flow Isolation avoids double counting of energy deposited in the calorimeters by charged tracks. The two isolation types calculated as Isolation sum the energy deposits per track momentum in cone with radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ equal 0.3 to 0.5 . Equation 2.9

and 2.10 describe the Detector based Isolation and Particle Flow Isolation, respectively.

$$I_{CombRelIso} = \frac{\sum P_T^{tracks} + \sum E_T^{ecal} + \sum E_T^{hcal}}{P_T^{muon}} \quad (2.9)$$

$$I_{PFRelIso} = \frac{\sum_{had}^{char} P_T + \sum_{neutr}^{had} E_T + \sum_{\gamma} E_T}{P_T^{muon}} \quad (2.10)$$

2.4.8 L1, HLT Triggers and DAQ System

The LHC was designed for a bunch crossing time of 25 ns which corresponds to a collision rate of 40 MHz. Although the LHC did only operate with a bunch crossing time of 50 ns in 2012, a huge number of events was produced. These processes do also contain events that are not interesting for further studies. Since it is not possible to store every single event, a preselection has to be performed. Therefore, a trigger system has been developed for CMS which is based on two levels: The Level-1 trigger (L1) and the high level trigger (HLT).

Level-1 Trigger

The first part of the CMS trigger system is the Level-1 trigger. It is located in the electronics of the different components of the calorimeters and the muon system, but not the silicon tracker. The L1 trigger uses only coarse information about the objects (for example muons and electrons). For this purpose, it selects characteristic information about them like the energy deposit in the calorimeter and hits in the muon system to form the trigger object. The information of all measured muon and calorimeter objects of the local triggers are then combined in the global muon and calorimeter trigger and afterwards in the global trigger which takes the final decision if an event passes the L1 trigger (Fig. 2.12). With help of the L1 trigger system, the output rate can be decreased to a few 100 kHz [42]. The Data

Acquisition (DAQ) system collects the events that pass the L1 trigger and sends them to a computer farm where the HLT are processed.

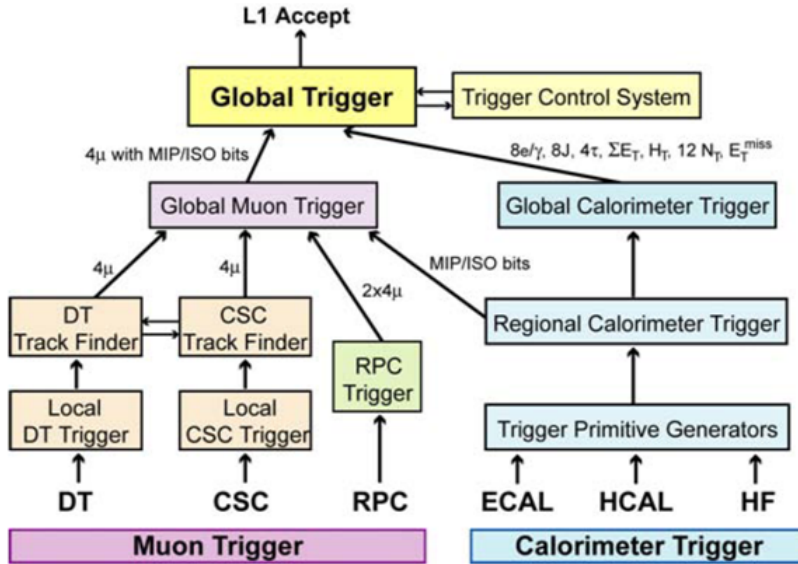


Figure 2.12: Composition of the Level-1 trigger system, showing the combination of the local trigger to the global trigger [50].

High Level Trigger

After an event passes the Level-1 trigger, it is sent to a computer farm to be further processed in the high level trigger. In contrast to the L1 trigger, the HLT is software based and depends on the full data information. Therefore, its selection is more advanced. Depending on the analysis target, different HLT can be selected, for example muon, electron (photon) or jet triggers. The HLT starts with L1 trigger objects and improves their performance by adding additional information. In the case of muons, the L1 track is optimized by including for example tracker information to decide if the muon is a HLT object. The typical p_T threshold for single muon triggers is about 40 GeV and for double muon triggers between 8-22 GeV. for example The HLT_Mu17_Mu8 which is used in this analysis has trigger

thresholds of 17 GeV on the highest pt muon(leading muon) and 8 GeV for the next leading muon. The combination of the L1 trigger and the HLT reduces the event rate to about 100 Hz. The recorded data that pass the HLT are reconstructed and send to computing centers (Tiers) all over the world by the world wide LHC computing grid [64]. One copy of the recorded data is stored at the Tier-0 at CERN where it can be used for several reprocesses and reconstructions. The Tier-1 computing centers can also be used to reconstruct data events, but also the computation of Monte-Carlo simulation can be performed here. Tier-2 are used for the storage of a small amount of reconstructed data and Monte-Carlo simulation that is needed for analyses.

Chapter 3

Gas Detectors Performance

3.1 Cosmic Rays

In August 1912, Austrian physicist Victor Hess discovered the cosmic rays. These high-energy particles arriving from outer space are mainly (89%) protons but they also include nuclei helium (10%) as well as heavier nuclei (1%). When cosmic rays penetrate the Earth's atmosphere, chain of successive reactions with other atomic nuclei are produced until reaching to smallest elementary particles producing the so-called hadronic showers[65].

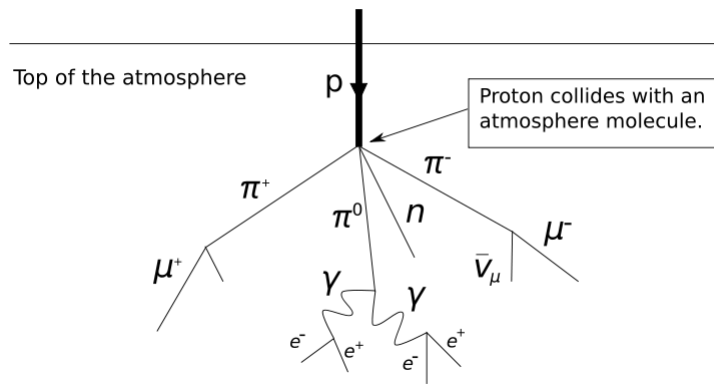


Figure 3.1: Primary cosmic particle collides with a molecule of atmosphere[66]

The hadronic shower usually ends with pions that mainly decay to photons, muons and electrons. These secondary particles produced by the effect of cascading that eventually get down to the ground [67]. The showers for secondary particles are spread over a large area and one is constantly being bombarded by these particles[68]. The rate of the charged particles produced in the cascade is mostly pions. Some of these will interact via the strong force with air nuclei while others will spontaneously decay via the weak force into a muon plus a neutrino or antineutrino:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (3.1)$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (3.2)$$

The muon does not interact with matter via the strong force but only through the weak and electromagnetic forces. It travels a relatively long distance while losing its kinetic energy and decays into an electron plus, neutrino and antineutrino.

So we can consider cosmic rays are a muon source to calibrate the RPC detector.

3.2 Experimental set up

The detection of energetic muons (which come from cosmic rays eq 3.1,3.2 helps us to study the performance of the Resistive plate chambers (RPCs). The detection process is presented using the scintillation detectors as a reference.



Figure 3.2: Cosmic Stand in Nuclear physics laboratory at Helwan University

The testing area for RPC (cosmic stand fig 3.2) is located in Nuclear physics laboratory at Helwan University. It is equipped with crane, low and high voltage power supplies, gas-distribution lines, weather stations and data acquisition systems (DAQ). It consists of metallic towers where chambers can be placed horizontally and read out in coincidence with the passage of triggering muons. Temperature in the halls is kept constant by

air-conditioning systems. The experimental set-up for cosmic ray muon test stand consists of a muon trigger system that is provided by a set of 2 scintillators one of them located, on the top and another one in bottom of the test tower. The gas used is $C_2H_2F_4$ (*Freon*) , it is distributed via a parallel system to the chambers. Water vapors are also added to humidify the operating gas within 40 – 45%. The gas composition is monitored and known with a relative precision better than 1%. The values of humidity, temperature and pressure are monitored by Weather Station.

3.2.1 RPC

In (CMS) experiment the RPCs are present in both barrel and end-cap regions. Wich it plays an important role in achieving the various physics objectives including measurement of properties of the lately discovered Higgs boson in the CMS experiment.

The RPC system is complementary to the DT and CSC systems, and adds robustness and redundancy to the muon system. RPC provide limited spatial resolution, but excellent time resolution, few nanoseconds.

RPC chambers follow the segmentation of DT chambers (in the barrel). All of six layers of RPCs are present; the first four are attached to each side of the MB1 and MB2 DT chambers. The last two are attached to MB3 and MB4. The chambers are trapezoidal in the end-caps (as shown previously in fig 2.7).The present CMS end-cap RPCs system consists of three stations: RE1, RE2 and RE3. One unit of the standard CMS end-cap RPCs consists of there gas gaps forming a double gap chamber. In CMS the 4th disc which missed it was installed in LS1.

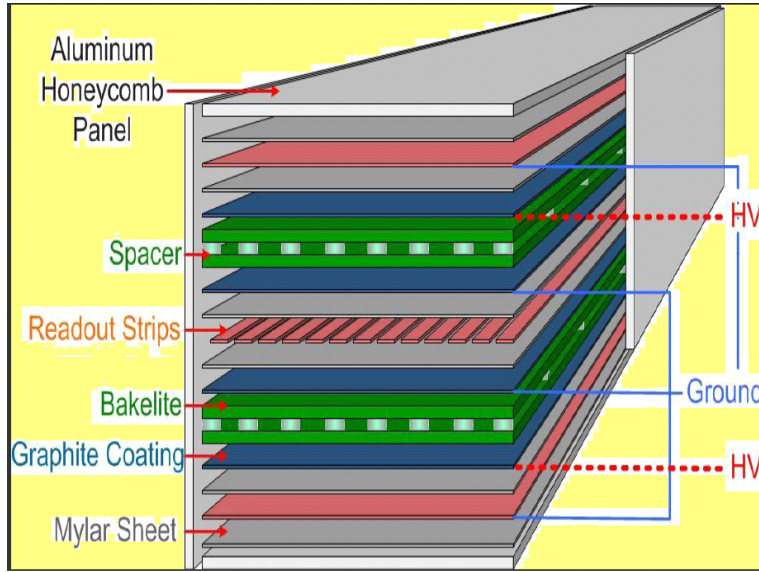


Figure 3.3: RPC Double Gap [69]

CMS RPC is made of two parallel high-resistivity Bakelite plates ($10^{10} \Omega cm$) with a 2 mm gas gap in between. The gap between the electrodes is kept constant by small plastic separators. The gaps are filled with $C_2H_2F_4$ (*Freon*). The Bakelite planes are externally coated by graphite electrodes, the two innermost ones set to +9.5 kV, collect the signal induced by crossing particles using insulated copper strips placed in the middle. This two-gap design is adopted to add redundancy and increase the charge induced on the strips (fig 3.3)[70].

CMS requirements for RPCs:

- Efficiency more than 95%
- Time resolution less than 3 ns (98% within 20 ns)
- Average cluster size less than 3 strips
- Rate capability more than $1 kHz/cm^2$
- Power consumption less than $2-3 W/m^2$

- Operation plateau more than 300 V
- No. of streamers less than 10%

The main gap parameters are:

- Bakelite thickness: 2 mm
- Bakelite bulk resistivity: $1 - 2 \cdot 10^{10} \Omega cm$
- Gap width: 2 mm
- Operating High Voltage: 9 – 9.5 kV
- No. of gaps: 3

3.2.1.1 Basic principle of operation

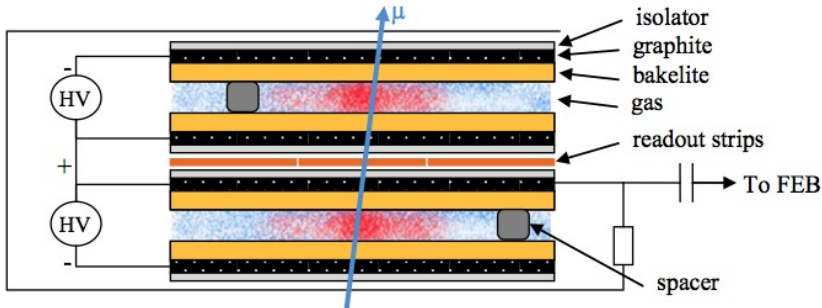


Figure 3.4: Layout of double gap RPC [69]

The physical process upon which any gas detector is based on the ionization: when the charged particle passes through a gas volume, it gives rise to the production of electron-ion pairs. The electrons drift velocity is much higher compared to that of ions. If an intense enough electric field is applied throughout the gas volume then the primary electrons produce more ionizations. The results of this multiplication mechanism in a distribution of free charged particles in the gas which has the characteristic shape of

an avalanche. The recombination processes usually take place during the avalanche development. Photons are produced in such recombination and they can start the development of secondary avalanches. These are mainly produced along the axis of the primary avalanche. The regime in which several secondary avalanches are produced causing large amounts of free charge in the gas is called streamer regime. Moreover, if the ion-electron plasma is so large as to connect the two electrodes, then the so called spark is created. The propagation of the growing number of charges induces a signal on a read out electrode.

The simplest configuration of RPC detector is shown in fig3.4. Two planar electrodes made out of a resistive material Bakelite having bulk resistivity of $1 - 2 \times 10^{10} \Omega cm$ are spaced by 2 mm using spacers. The electrodes are connected to a high voltage power supply 10 KV in order to create a uniform and intense electric field in the gap between them. The importance of the thin layer of graphite which coats the external surface of the electrodes is to permit uniform application of the high voltage.

The surface resistivity of the graphite coating is high enough to render it transparent to the electric pulses which are generated by the charge displacement in the gas gap. Because of that the electric charge can be induced on metallic strips capacitively coupled to the gap. The strips are mounted on the external surface of the gap from which separated by a layer of mylar insulator. The strips are like transmission lines with typical characteristic impedance of about 50Ω .



Figure 3.5: Read out strip

The read out strip consists of 96 strips divided into 3 different regions (A&B&C 32 strips in each one) fig 3.5. There are a 96 coaxial cables to connect the electric charge between the strips and the front board(which transfer the electric charge to signal) by soldering there at the end of the strip. Each coaxial cable is an indicator to the quality of strips. There is a flat cable to connect the signal from the front board to the DAQ system.

In principle, RPCs are suitable for detecting all kinds of charged particles, but in CMS, due to their performance and operation conditions, they have mostly been placed behind many other detectors to detect muons.

RPCs were operated in streamer mode, i.e., the electric field inside the gap is kept intense enough to generate limited discharges localized near the crossing of the ionizing particle. Due to the relatively long relaxation time of the resistive electrode, this mode is suitable for low-rate experiments, especially for cosmic-ray experiments. In the last few years a significant improvement has been achieved by operating the detector in the so-called avalanche mode [71]. In this mode the electric field across the gap ¹ is reduced and a robust signal amplification is introduced at the front-end elec-

¹and consequently the gas amplification

tronics level. The substantial reduction of the charge produced in the gap improves the rate capability by more than an order of magnitude, allowing application of RPCs to high-rate experiment ¹ [72].

3.2.2 Scintillation Detectors

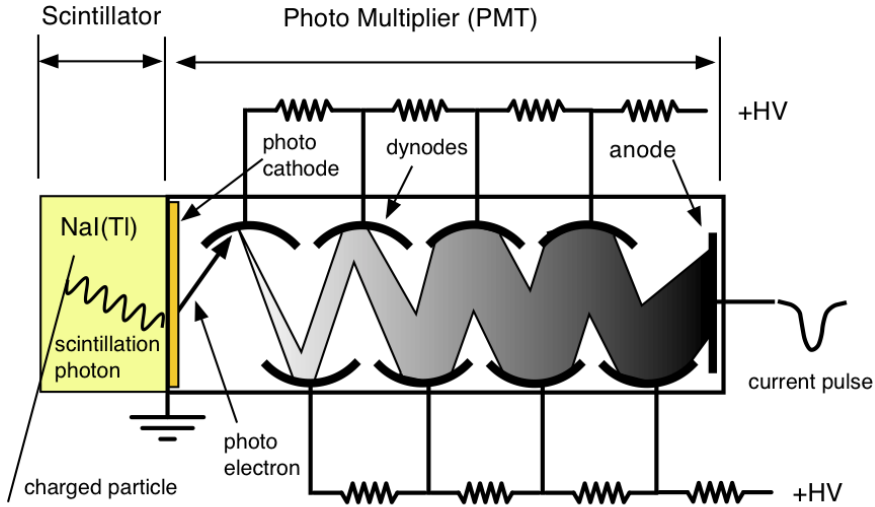


Figure 3.6: Scintillation Detectors [66]

A scintillator depends on the property of luminescence when excited by ionizing radiation. When striking the luminescent material by an incoming particle, it absorbs its energy and scintillates, (i.e., re-emit the absorbed energy in the form of light). Sometimes, the excited state is metastable, so the relaxation back down from the excited state to lower states is delayed (necessitating anywhere from a few nanoseconds to hours depending on the material), the process then corresponds to either one of two phenomena, depending on the type of transition and hence the emitted optical photon wavelength, delayed fluorescence or phosphorescence, also called after-glow.

¹such as CMS at LHC

A scintillation detector is obtained when a scintillator is coupled to an electronic light sensor such as a photomultiplier tube (PMT), photodiode, or silicon photomultiplier. PMTs absorb the light emitted by the scintillator and reemit it in the form of electrons ¹. The subsequent multiplication of those electrons ² results in an electrical pulse which can then be analyzed and yield meaningful information about the ionizing particle that originally struck the scintillator.

3.3 RPC Gap performance

There are 3 types of tests for RPC gap performance:

3.3.1 Leakage Test



Figure 3.7: leak test system

¹via the photoelectric effect

²sometimes called photo-electrons

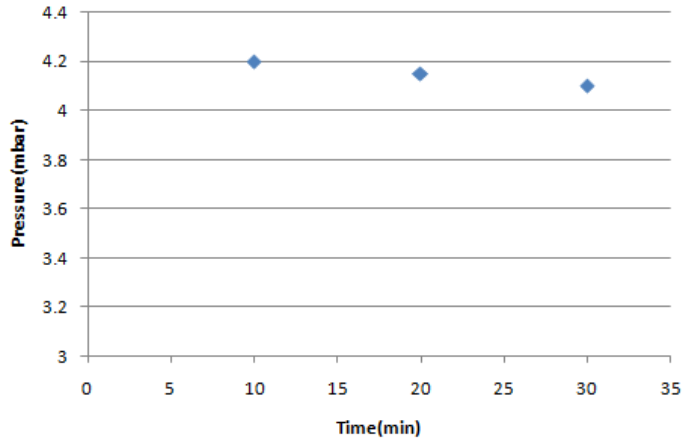


Figure 3.8: leak test result under 5 mbar for Top Narrow gap

The leak rate test is performed measuring the pressure drop with time for each gap (fig 3.7). We apply a pressure of 5 mbar using gas system flow and using U type manometer to detect the change in pressure after keeping gap 10 minutes under 5 mbar pressure.

The maximum allowed leakage rate is 1% from gap volume (0.3, 0.4 mbar for TW, TN respectively). **Notice**

- The chamber tripped off at 10000 Volt.
- The flow rate of the gas was 16.5 Liter/Hour for (about 6 hours).

For top Narrow gap (fig3.8) , after checking that there is no leak from the connectors using leak detector, we noticed that after 10 minutes that the pressure difference was less than 1% from gap volume. For top wide gap (fig3.9) , after checking that there is no leak from the connectors using leak detector, we noticed that after 10 minutes that the pressure difference was more than 2% from gap volume.

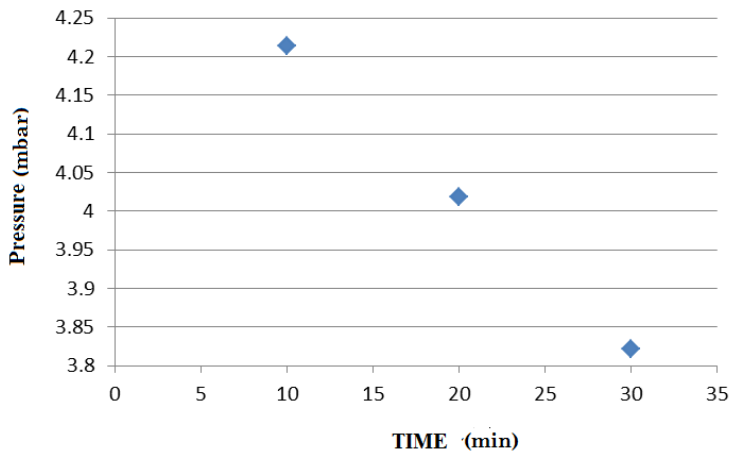


Figure 3.9: leak test result under 5 mbar for Top Wide gap

3.3.2 Spacer Test

At the end of the leak test all gap spacers are checked in order to spot any detached one. Using the spacer map which is a transparent sheet having the layout of the spacer positions is kept aligned on the gap to be tested fig3.10.

Pressure (equal to 5 mbar) is applied at each spacer position and the change in the manometer reading is noted ¹. Practically almost all the spacers incurred a slight change in pressure when the test was conducted . If the change is less than 0.2 mbar, the spacer is qualified.

For the top narrow gap the pressure difference was high which indicates that the spacers could be broken and for the top wide gap the pressure difference was low which indicates that the spacers are ok.

¹Ideally there should be no change in the reading

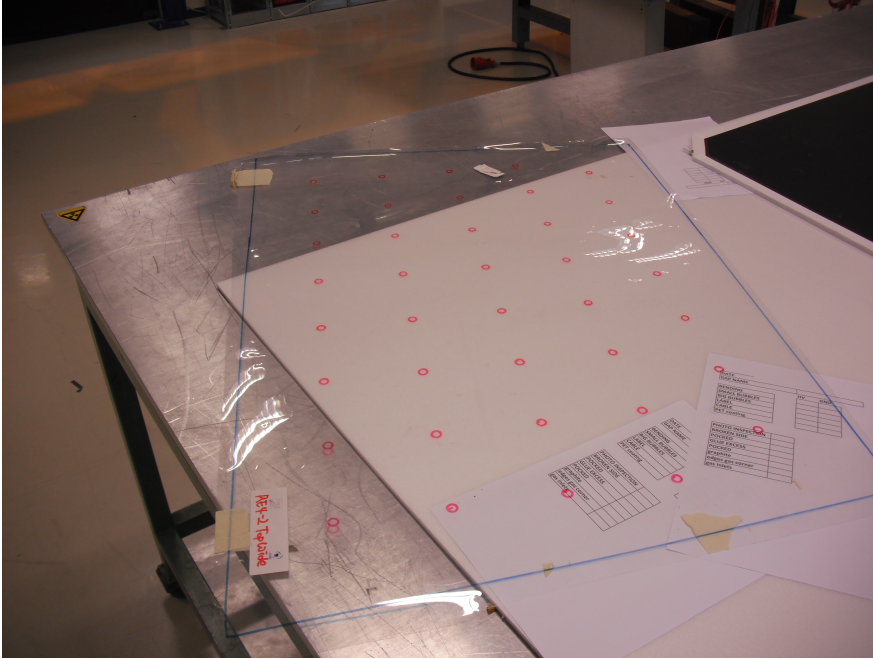


Figure 3.10: top wide spacer map

3.3.3 High Voltage Test

Once the leak and spacer test successfully ended, the gaps are subjected to a high voltage scan to measure the dark current response. During this test the high voltage is ramped from 1 kV to 10 kV with steps of 1 kV up to 8 kV and step of 100 V between 8 kV and 10 kV.

The gap is accepted if the current does not exceed $5\mu A$ ¹. The current not exceed 1.8 A for both Top Wide and Top Narrow gaps, so the two gaps are accepted for high voltage test.

Fig 3.11 shows current value with HV for Top Wide gap .

¹The increasing current is indicator to the decrease of the surface resistivity

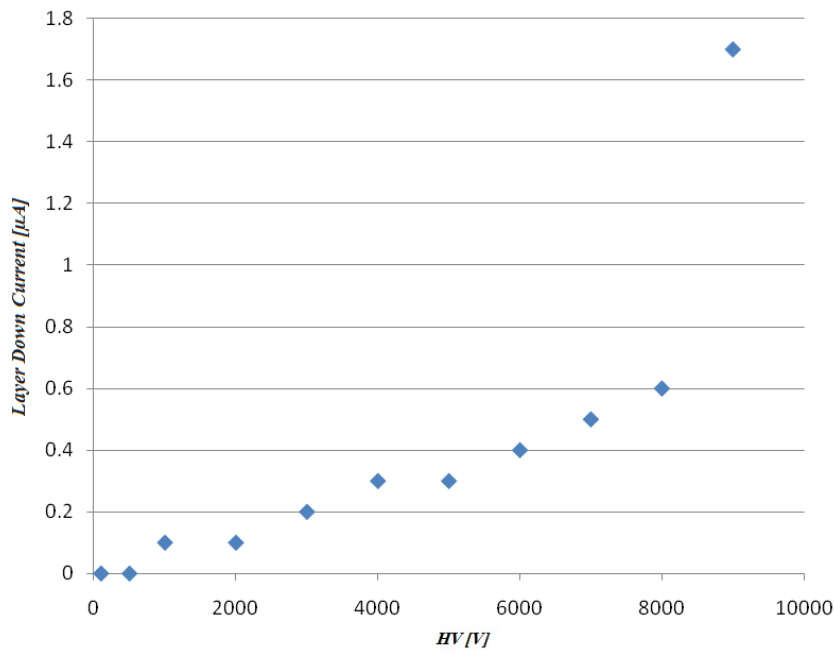


Figure 3.11: current vs HV Top Wide gap

Fig 3.12 shows current value for Top Narrow gap.

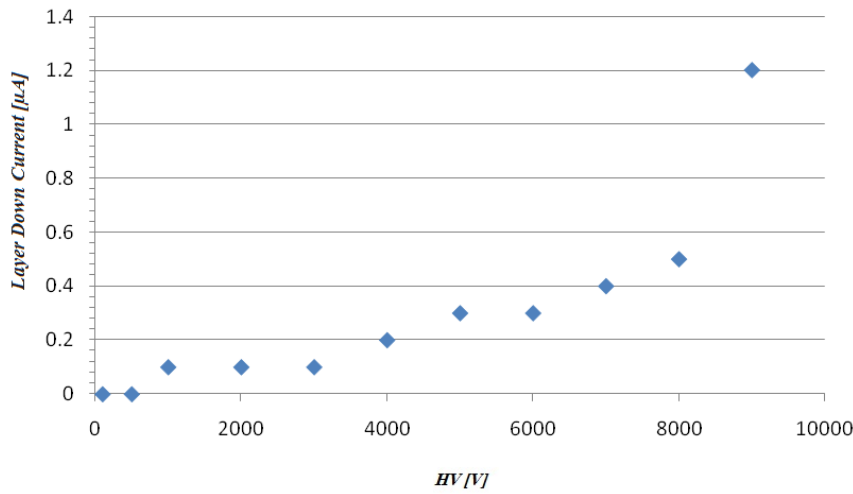


Figure 3.12: current vs HV Top Narrow gap

Chapter 4

Event Generation and Simulation

4.1 Simulation framework

Physics event generation and detector simulation are the earliest steps in the event processing chain that leads to producing a Monte Carlo samples suitable for physics analysis. Generation of high-energy-physics events, i.e. sets of outgoing particles produced in the interactions between two incoming particles, must be the first step in the Monte Carlo event processing chain, then we have later steps depending on the type of simulation what you want to do.

Standard Steps for full simulation:

- the generation of the particles plus the creation of GenParticles and GenJets " GEN".
- Geant4 simulation of the detector (energy deposits in the detector volumes) " SIM".
- simulation of detector signal response to the energy deposits " DIGI".
- simulation of the L1 trigger " L1".

- data format conversion of the digi signals into the RAW format that will be provided in the online system "DIGI2RAW".
- high level trigger "HLT".
- data format conversion of the RAW format into digi signals "RAW2DIGI".
- full event reconstruction "RECO".
- production of alignment and calibration streams "ALCA".
- code run for Data Quality Monitoring "DQM".
- code run for validation "VALIDATION".

Standard steps for fast simulation

- generation of the particles "GEN".
- fast simulation "FASTSIM".

Brief description for the three basic processes for full simulation: generation, simulation, and digitalization are given below

- generation of the event: Monte Carlo Event Generators are used to generate high-energy-physics events, that in the end will be a set of outgoing particles produced in the interactions between two incoming particles (mostly proton-proton). a generator is used to produce data in standard Hep MC format [81]. These events can be filtered at generation time so that only events with a certain property, for example leptonic decay, are kept. The generator is responsible for any prompt decays (e.g. Z or W bosons) but stores any "stable" particle expected to propagate through a part of the detector. Because it only considers immediate decays, there is no need to consider detector geometry during the generation step, except in controlling what

particles are considered stable. During this step, the run number for the simulated data set and event numbers for each event are established. Event numbers are generally ordered in a single job, though events may be omitted because of filtering at each step. Run numbers for simulated data sets derive from the job options used to generate the sample and mimic real run numbers used during data taking. A record of all particles produced by the generator is retained in the generation output file, MC Truth (Gen), in which the truth is a history of the interactions from the generator, including incoming and outgoing particles.

- simulation of the detector and physics interactions [82]: the generated events are then read into the simulation. Cuts can be applied to select only certain particles to process in the simulation. Each particle is propagated through the full CMS detector. The configuration of the detector, including misalignments and distortions, can be set at run time by the user. The energies deposited in the sensitive portions of the detector are recorded as "hits", containing the total energy deposition, position, and time, and are written to a simulation output file, called a hit file. Like event generation, the detector simulation information called "truth" is recorded for each event, MC Truth (Sim). A record is kept for every particle, whether the particle is to be passed through the detector simulation or not. In the simulation jobs, truth tracks and decays for certain particles are stored. This truth contains, for example, the locations of the conversions of photons within the inner detector and the subsequent electron and positron tracks.
- digitization [82]: in the digitization jobs, Simulated Data Objects (SDOs) are created from the truth. These SDOs are maps from the hits in the sensitive regions of the detector to the particles in the simulation truth record that deposited the hits' energy. The truth information is further processed in the reconstruction jobs and can be used

during the analysis of simulated data to quantify the success of the reconstruction software. Also, during the digitization stage, Read Out Driver (ROD) electronics are simulated. At this stage, detector noise is added to the event. The first level trigger, implemented with hardware on the real detector, is also simulated in a "pass" mode. Here no events are discarded but each trigger hypothesis is evaluated. The digitization first constructs "digits," inputs to the read out drivers (RODs) in the detector electronics. The ROD functionality is then emulated, and the output is a Raw Data Object (RDO) file.

4.2 Mont Carlo (MC) Simulation Samples

4.2.1 MC Signal Samples

For this analysis, MC signal samples for μ^* are carried out with proton-proton collisions with the CMS detector at LHC, using $300fb^{-1}$ of integrated luminosity at a center-of-mass energy $\sqrt{s}=14\text{TeV}$. The samples are produced using PYTHIA 8 event generator [83] based on the leading order (LO) compositeness model [39], with mass points ranging from 0.5 to 3 TeV with 0.5 TeV steps with $\Lambda = 10\text{ TeV}$ and ran through GEANT4 for CMS detector simulation through CMS software release "CMSSW_7_2_0_patch1" with the following conditions:

- conditions PHYS14_25_V3: Define the conditions, such as calibration, alignment and noise levels.
- pileup AVE_20_BX_25ns: define pileup scenario.
- beam-spot NominalCollision2015: define beamspot position.
- magField 38T_PostLS1: Use magnetic field description.

The different generated mass points and its corresponding cross sections are shown in table. 4.1

M_{μ^*} (in GeV)	Cross section [pb] [LO]	N Events
500	0.0141791	10000
1000	0.00626384	10000
1500	0.0028749	10000
2000	0.0013137	10000
2500	0.000608637	10000
3000	0.000276288	10000

Table 4.1: Summary of signal MC samples generated by pythia 8 , number of generated events and cross sections (LO), used with $\Lambda = 10$ TeV.

MC signal samples for fast simulation for are produced using PYTHIA 8 event generator like the full simulation signal based on the leading order (LO) cross section , with mass points ranging from 0.5 to 3 TeV with 0.5 TeV steps with $\Lambda = 10$ TeV and ran through Delphes Fast Simulator for CMS detector simulation. The different generated mass points and its corresponding cross sections are shown in table. 4.1.

4.2.2 SM background samples

The main sources of background for our search are the processes which produce two leptons and one photon signatures in the detector. The backgrounds can be categorized into irreducible and reducible types. We consider irreducible backgrounds to be due to Standard Model processes which produce real, isolated leptons and photons. Reducible backgrounds are backgrounds due to jet to photon misidentification.

The dominant, irreducible SM background in this search is DrellYan production of $\mu^+\mu^-\gamma$ where the final state photon is either radiated by an initial-state parton (initial-state radiation, ISR), or originates from one of the final-state muons (final-state radiation, FSR). The second most impor-

tant background is due to DrellYan production associated with jets (Z+jets), where a jet is misidentified as a photon [84]. Other less significant backgrounds originate from diboson events (WW, WZ, ZZ), and also from $t\bar{t}\gamma$ production. These backgrounds are mainly suppressed by requiring high transverse momentum thresholds on the leptons and photon. All backgrounds are estimated from the MC simulation.

The SM background samples: $Z\gamma, t\bar{t}, \gamma, WW, WZ$ and ZZ are generated with MadGraph5 [85]. PYTHIA 8 was also used to perform the fragmentation and hadronization of samples that were generated with MadGraph. All MC events used in this analysis have been passed through Delphes Fast Simulator for CMS detector simulation.

To get the number of expected background events, the different processes are scaled to the correct luminosity, using the event weight

$$W_t = \frac{L_{data}}{L_{mc}} \quad (4.1)$$

$$L_{mc} = \frac{N_{events}}{\sigma_{mc}} \quad (4.2)$$

In this case, N stands for the number of generated events, for the cross section of the process, L_{data} the integrated luminosity of the data ($300fb^{-1}$), and L_{mc} the luminosity of the background process.

Table 4.2 presents the number of events generated for SM background samples, the corresponding Leading Order (LO) cross sections and the calculated weights.

Process	Cross section [pb] [LO]	N Events	weight
$Z\gamma \rightarrow 2\mu\gamma$	1.3940 ± 0.0011	500000	0.8364
$t\bar{t}\gamma$	$0.02274 \pm 1.1\text{e-}05$	500000	0.013638
WW	0.45500 ± 0.00028	500000	0.273
WZ	0.33860 ± 0.00017	500000	0.20316
ZZ	$0.004737 \pm 2\text{e-}06$	500000	0.0028422

Table 4.2: Summary of the used MC background samples, generated by Mad-Graph5 with the corresponding LO cross sections, number of generated events and the corresponding weight.

Chapter 5

Analysis and Results

5.1 Full simulation Signal analysis

5.1.1 Signal Properties

Before starting with the optimization of the event selection (Sec. 5.1.2), the behavior of the signal has to be understood. Therefore, characteristic distributions of the basic kinematics variables of the signal are studied, and their dependence on the μ^* mass. Later, this will help to distinguish signal from background events to discriminate the background without losing much signal efficiency.

As said before, a search for excited muons in the two muons plus one photon final state will be performed in this analysis. The excited muon decays to a Standard Model muon and photon. But there is a small problem, each event contains two muons, only one of them are from the μ^* decay and the other from production process. There are two combinations of muons and photon which could be form the μ^* , Those two combinations can be divided into the minimum invariant mass M_{min} and the maximum invariant mass M_{max} , shown in figure 5.1 for different μ^* masses. It can be seen that the mass peak from the excited muon is well reconstructed for low in-

variant masses if M_{min} is used and for high invariant masses if M_{max} is used. This leads to the problem that it is not really sure which of the two distributions is the better one for the optimization of the search window. A possible solution can be found by using the two-dimensional $M_{min} - M_{max}$ invariant mass plane. This application leads to an "inverse letter L" which can be used for a combined cut on M_{min} and M_{max} . If the excited muon is reconstructed by using M_{min} , it leads to the vertical leg around the signal mass while a reconstruction via M_{max} gives the entries for the horizontal leg. A more about L-Shape cut will be discussed in section (5.1.3).

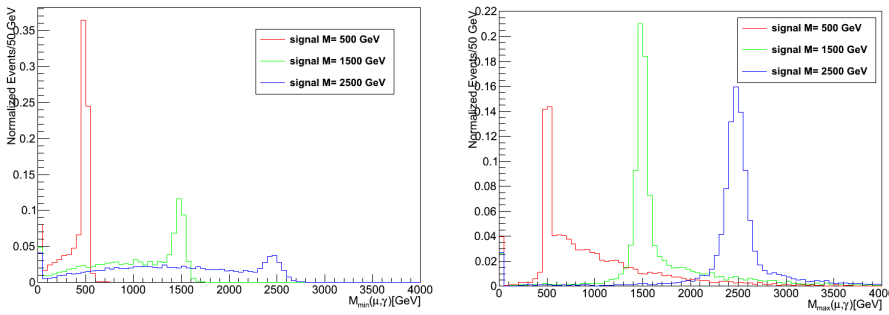


Figure 5.1: Invariant mass plots for different μ^* masses, left, Minimum invariant mass M_{min} ; right, Maximum invariant mass M_{max} ;

The next important step is to understand the properties of the final state objects. the final state is represented by two muons plus one photon. Since the selection of the identification criteria as well as the acceptance cuts depend on the transverse momentum of final state objects it is important to have a look at the p_T of these objects (see figure 5.2) . The two leading muons nearly have a p_T of at least 35 GeV for every mass point, and for leading photon a large fraction of them have a $E_T > 35$ GeV. In addition to this, it can be seen that even for low masses a large fraction of the two muons have a $p_T > 200$ GeV which will be used for an optimal signal selection see section(5.1.3).

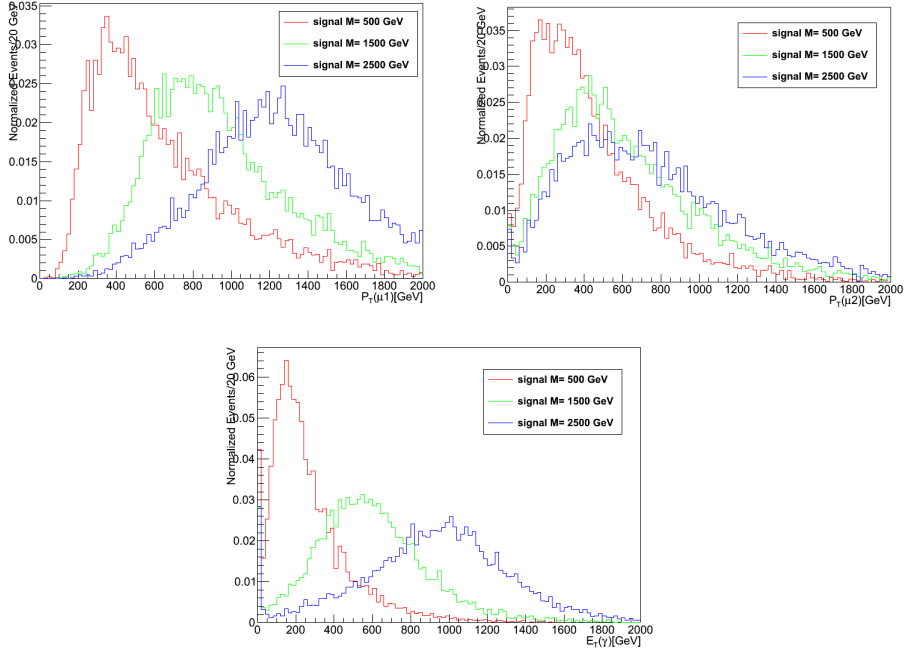


Figure 5.2: Transverse momentum the final state objects, up-left: the p_T for the leading muon; up-right: the p_T for the next to leading muon; down E_T of the highest p_T photon.

5.1.2 Reconstruction and Event Selection

After understanding the signal kinematics, its selection can be discussed. The main goal is to distinguish it from the background.

5.1.2.1 Trigger and Acceptance

The trigger used in this analysis is the HLT_Mu17_Mu8 trigger, which put cut on leading muon to be has transverse momentum greater than 17 TeV and the next to leading muon to has 8 TeV . Therefore, the acceptance cuts are applied to both two leading muons and leading photon. For muons the acceptance cuts are set to $|\eta| < 2.1$ and $p_T > 35 GeV$, while for photon set to $|\eta| < 1.4442$ and $E_T > 35 GeV$.

5.1.2.2 Muon Identification

After setting the trigger and the geometrical acceptance, the quality criteria for the muon identification (muon ID) have to be applied. Only well reconstructed muons should pass the quality criteria. There are different kinds of muon requirements based on the target of an analysis. Since the signal leads to muons with medium or high transverse momentum (Sec. 6.1), the high- p_T muon ID [86] recommended by the CMS Muon Physics Object Group (POG) [87] for muons with high transverse momentum (> 200 GeV) is used. The quality criteria for the high- p_T muon ID are:

- The muon has to be reconstructed as a global muon: A global-muon track (outside-in) has been fitted by combining the hits from the standalone-muon track and the tracker muon track. More details about muon reconstruction are given in Chap. 2.
- There has to be at least one muon chamber with hits included in the global-muon track fit. If this is not the case, the muon is most likely also not reconstructed as a global muon.
- At least two muon stations must have muon segments. This cut also implies that the muon has to be a tracker muon. It is applied to suppress the hadronic "punch-through" as well as muons from decays-in-flight. Hadronic "punch-throughs" are high energy hadrons that are not fully absorbed in the HCAL and generate hits in the muon system. Normally, these events do not reach the second muon station being absorbed by the iron yoke of the magnet before. Muons from decays-in-flight originate from the decay of, for example, kaons and pions.
- The transverse impact parameter with respect to the primary vertex d_{xy} has to be less than 0.2 cm. This selection is used to suppress cosmic muons and again muons from decays-in-flight.

- The longitudinal distance with respect to the primary vertex d_z has to be less than 0.5 cm. This selection suppresses cosmic muons and again muons from decays-in-flight. In addition, it can also suppress tracks from pileup.
- For a good p_T Requiring more than five tracker layers leads to a better p_T measurement and to a smaller uncertainty. Until 2012, the number of tracker layers with hits had to be more than 8, but it has been reduced and an additional cut on $\Delta p_T/p_T$ has been applied to increase the selection efficiency.
- The ratio of the uncertainty on the p_T measurement with respect to the measured p_T has to be less than 30% ($\Delta p_T/p_T < 0.3$). This cut was added to compensate the reduction of the number of tracker hits, leading to an increase of absolute the overall efficiency per muon by 5% without additional, badly reconstructed muons passing the selection.
- There has to be at least one hit in the pixel detector to suppress muons from decays in- flight and to guarantee a good vertex reconstruction.

In addition to the muon identification criteria, it is required that the muons have to be isolated. There are different ways of applying isolation to muons, but the two most common ones are the tracker relative isolation (TRK-isolation) and the particle-flow isolation (PF-isolation). The TRK-isolation adds up any track in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ with respect to the muon, except the track of the muon itself. Afterwards, the ratio between the sum- p_T of those tracks and the muon track p_T is used as the discriminator variable for the isolation. In contrast to TRK-isolation, particle-flow isolation uses the sum- p_T of all charged hadrons and the transverse energy of all photons and neutral hadrons within a cone of $\Delta R < 0.4$. The discriminator variable is then the ratio of this number and the muon

track p_T . In comparison to TRK-isolation, PF isolation mostly has a better performance and can also include pileup corrections [78]. Therefore, PF-isolation with $\Delta\beta$ -correction (pileup correction) is applied to the muons in this analysis with a loose cut of

$$l_{PFRelIso} = \frac{\sum_{had}^{char} p_T + \max\{0., \sum_{had}^{neutr} E_T + \sum_{\gamma} E_T - c \sum_{pileup} p_T\}}{p_T^{muon}} < 0.12 \quad (5.1)$$

where the factor $c = 0.5$ corresponds to a naive average of neutral to charged particles. Here, "char. had." are the charged hadrons, "neutr. had." are the neutral hadrons, " γ " are the photons and "pileup" are the additional pileup tracks in $\Delta R < 0.4$.

5.1.2.3 Photon Identification

Photons (γ) can only be reconstructed in the electromagnetic calorimeter in form of showers that are called superclusters. As they are neutral, they do not leave any signature in the tracker. The selection criteria we use on the photons rely on the recommended "CutBasedPhotonIdentification-Run2" with the "tight" selection [88]:

- $E_T > 35 \text{ GeV}$ and $|\eta| < 1.444$ (barrel only).
- ratio between energy deposited in hadronic calorimeter and energy deposited in electromagnetic calorimeter $H/E < 0.01$ to reduce hadronic contamination.
- $\sigma_{i\eta i\eta} < 0.01$ ¹
- Charged Hadron $Iso^* < 1.66$.
- Neutral Hadron $Iso^* < (0.14 + \exp(0.0028 * p_T^\gamma + 0.5408))$.

¹ $\sigma_{i\eta i\eta}$ variable measure shower shape defining it in units of the crystal spacing.

- Photon $I_{so}^* < (1.40 + (0.0014 * p_T^\gamma))$.

The isolation variables (*) are the so called rho-corrected particle flow isolation. It is defined by:

$$I_{so} = \max(PFI_{so} - \rho \cdot EA_i, 0.) \quad (5.2)$$

where EA is the $|\eta|$ -dependent effective area.

5.1.3 Selection Strategy for Full Simulation ”Control Region”

- Preselection region
 - Selection 1: applying Double muon trigger ($P_T > 17$ GeV and 8 GeV).
 - Selection 2: Acceptance for two muons and photon:
 - * for muons: each muon needs to have $p_T > 35$ GeV and $|\eta| < 2.1$.
 - * for photon: $E_T > 35$ GeV and $|\eta| < 1.444$ (barrel only).
 - Selection 3: select the high- p_T muon ID [86] recommended by the CMS Muon Physics Object Group (POG) [87].
 - Selection 4: select photons rely on the recommended ”Cut-BasedPhotonIdentificationRun2” with the ”tight” selection [88]. Each event needs to have at least two muons, as well as at least one photon, where photon should be separated from each of the selected muons in the $\eta - \phi$ plane by $\Delta R > 0.7$, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$) and $\Delta\phi$ and $\Delta\eta$ are the azimuthal angle and pseudorapidity differences between the photon and the muon.

- Selection 5: As many background simulations have a lower cut on invariant masses and we want to avoid to include simulations for low mass resonances, we apply a cut on the invariant dimuon mass:

$$M(\mu, \mu) > 60 GeV \quad (5.3)$$

- Full Selection region

To further reduce the dominant background ($Z\gamma$) and maximize signal significance, in particular for low m^* we apply a tighter cut on the invariant dimuon mass:

$$M(\mu, \mu) > M(Z) + 25 GeV \quad (5.4)$$

these cuts are referred to as the full selection. Table 5.1 summarized number of weighted events after each selection.

signal mass points (GeV)	# of Weighted events	Trigger	Acceptance	Mu selection	Pho selection	$M(\mu, \mu) > 60$	Z-veto
500	4253.73	3707.551068	2593.073808	154.410399	58.701474	58.701474	58.701474
1000	1879.152	1706.270016	1282.7091552	79.86396	35.1401424	35.1401424	35.1401424
1500	862.47	799.682184	632.018016	38.293668	19.83681	19.83681	19.664316
2000	394.11	366.443478	297.355995	18.12906	8.433954	8.433954	8.433954
2500	182.5911	171.65389311	140.9603292	9.00174123	4.7473686	4.7473686	4.7473686
3000	82.8864	77.9961024	65.14042176	4.15260864	1.92296448	1.92296448	1.92296448

Table 5.1: Summary of the number of weighted events for full simulation signal mass points before any selection, and after each selection.

- Final Selection

From the selected objects, as shown in figure 5.1, it is not clear how to reconstruct the mass of a potential excited muon. There are two possibilities. Instead of choosing one, we calculate both invariant masses and distinguish them by mass, calling the higher one as M_{max} , while the smaller one is referred as M_{min} . Plotting both in a 2 dimensional plane. The signals accumulate in regions around the generated μ^* mass that have the shape of an inverted L see figure 5.3. this figure

describe M_{min} and M_{max} in 2 dimensional plane after applying the all selections described above.

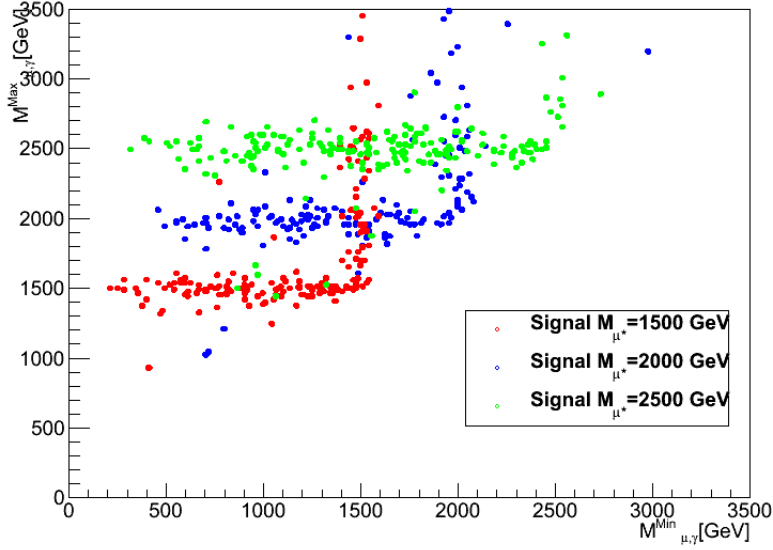


Figure 5.3: Two dimensional $M_{min} - M_{max}$ plane with several signal mass points

5.2 Fast Simulation Analysis and Results

5.2.1 Selection Strategy for Fast Simulation ” Control Region”

- Preselection region A preselection lower p_T cut of 17 GeV and 8 GeV were set on the leading and the next to leading muons respectively. This cut acts like a trigger cut in data, therefore whenever we refer to trigger we mean this p_T offline cut. Further selections on the event content are applied on several steps as shown:

- Selection 1: Acceptance for two muons and photon:

- * for muons: each muon needs to have $p_T > 35 \text{ GeV}$ and $|\eta| < 2.1$.
- * for photon: $E_T > 35 \text{ GeV}$ and $|\eta| < 1.444$ (barrel only).
- Selection 2: Each event needs to have at least two muons, as well as at least one photon, where photon should be separated from each of the selected muons in the $\eta-\phi$ plane by $\Delta R > 0.7$, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ and $\Delta\phi$ and $\Delta\eta$ are the azimuthal angle and pseudorapidity differences between the photon and the muon. Figure 5.4 show distribution of $\Delta R(\mu_1, \gamma)$ and $\Delta R(\mu_2, \gamma)$ after applying this selection.

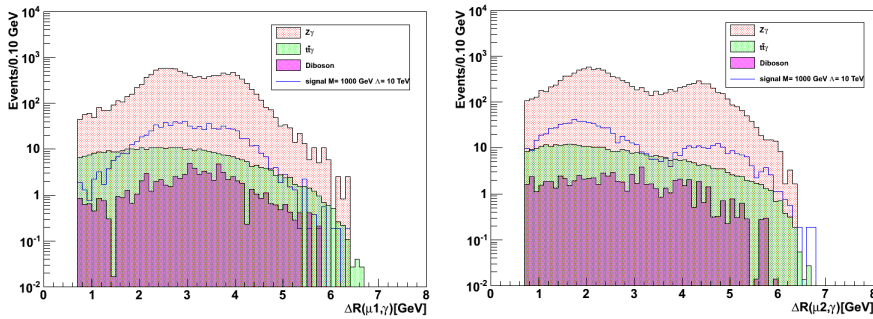


Figure 5.4: show distribution of $(\Delta R(\mu_1, \gamma)$ and $\Delta R(\mu_2, \gamma)$), on left and right respectively after selection 2.

- Selection 3: As many background simulations have a lower cut on invariant masses and we want to avoid to include simulations for low mass resonances, we apply a cut on the invariant di-muon mass: $M(\mu, \mu) > 60 \text{ GeV}$.

Figures 5.5 and 5.6 show the distribution of the invariant mass of the two highest p_T muons. $M_{inv}(\mu_1\mu_2)$ and their $\Delta R(\mu_1\mu_2)$ before selection 1 and after the selection 3. From these two sets of plots, the effect of our preselection cuts is clear and lead to enhance the ratio of the signal over the background.

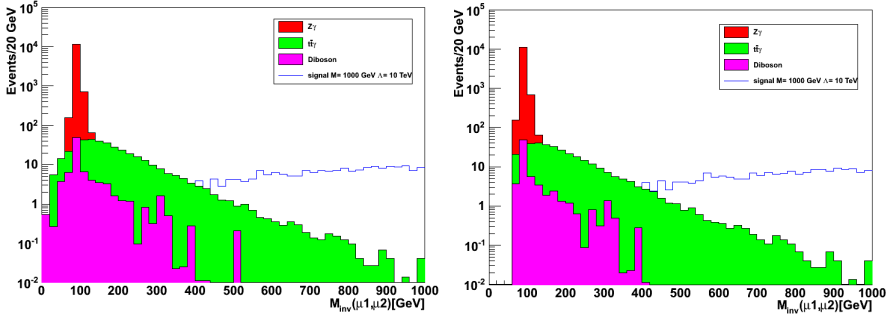


Figure 5.5: the two leading p_T muons invariant mass distributions before selection 1 (left plot) and after selection 3 (right plot).

With all the above selections, we have achieved what we refer to as the preselection. Figure 5.7 show the leading muon transverse momentum (p_T) and the leading photon transverse energy (E_T) respectively. Figure 5.8 show the minimum and the maximum invariant mass distributions of the muon-photon system after the preselection.

- Full Selection region

To further reduce the dominant background ($Z\gamma$) we apply a tighter cut on the invariant dimuon mass:

$$M(\mu, \mu) > M(Z) + 25\text{GeV}$$

These cuts are referred to as the full selection. Figures 5.9 show corresponding distributions for the leading muon transverse momentum (p_T) and the leading photon transverse energy (E_T) respectively and figure 5.10 represent the minimum and the maximum invariant mass distributions of the muon-photon system after the full selection. According these distributions, our selection cut are very effective and especially the last one that affect the SM $Z\gamma$ background while minimally affect the signal.

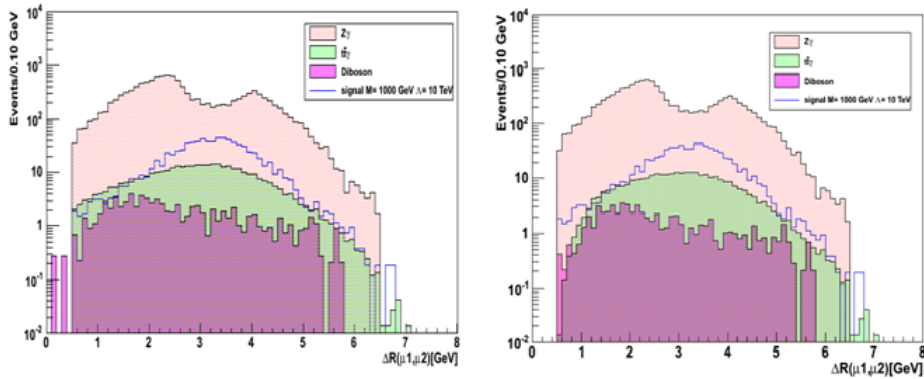


Figure 5.6: the two leading p_T muons $\Delta R(\mu_1, \mu_2)$ distributions before selection 1 (left plot) and after selection 3 (right plot).

Figure 5.12 shows the selection efficiency of the different steps for different mass points of signals that lead to the full selection.

Background	# of weighted events before any selection	# of weighted events after pre selection	# of weighted events after full selection
$Z\gamma$	418200	12016.5588	122.9508
$t\bar{t}\gamma$	6819	344.441328	258.78105
WW	136500	3.822	2.184
WZ	101580	47.13312	1.42212
ZZ	28.422	3.0468384	1.3159386

Table 5.2: Summary of the number of weighted events for fast simulation SM background before any selection, after pre selection and after full selection

- Final Selection

From the selected objects, it is not clear how to reconstruct the mass of a potential excited muon. There are two equal possibilities; the excited muon decays to the leading muon plus the photon or it decays to the next-to-leading muon plus the photon. Instead of choosing one, we calculate both invariant masses and distinguish them by mass, calling the higher one as M_{max} , while the smaller one is referred as M_{min} . Plotting both in a 2 dimensional plane leads to the distributions that can be seen in Fig. 5.11. The background is here spread in the low mass region, while the signals accumulate in regions around

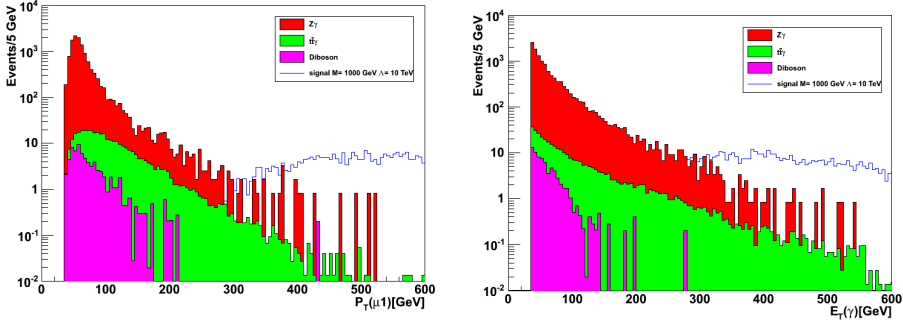


Figure 5.7: On the left, the p_T distribution of the leading muon after the preselection (selection 3). On the right, the E_T distribution of the leading photon.

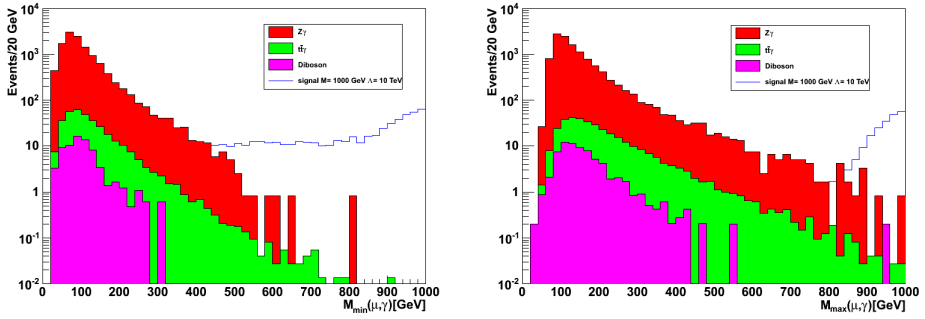


Figure 5.8: The minimum (left) and the maximum (right) muon-photon invariant mass distributions after the preselection (selection 3).

the generated μ^* mass that have the shape of an inverted L.

To apply the final selection and further increase ratio of signal to background, we form search regions of the shape of those Ls for the further statistical interpretation (L-shape cut). These search regions are placed symmetrically around the generated mass of each signal point. Their width is chosen by optimizing with respect to the best expected limit.

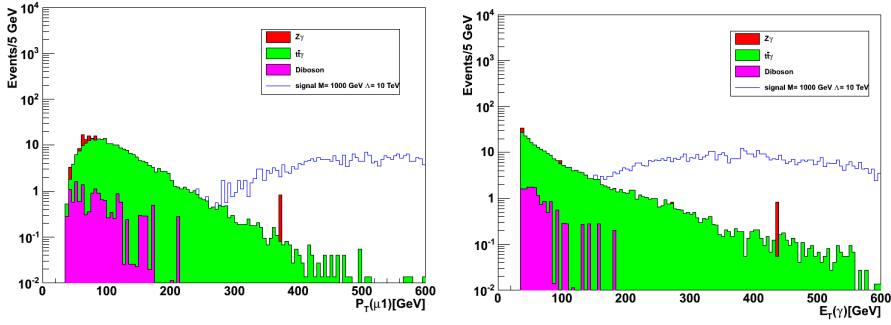


Figure 5.9: On the left, the p_T distribution of the leading muon, On the right, the E_T distribution of the leading photon, after the full selection (selection 4).

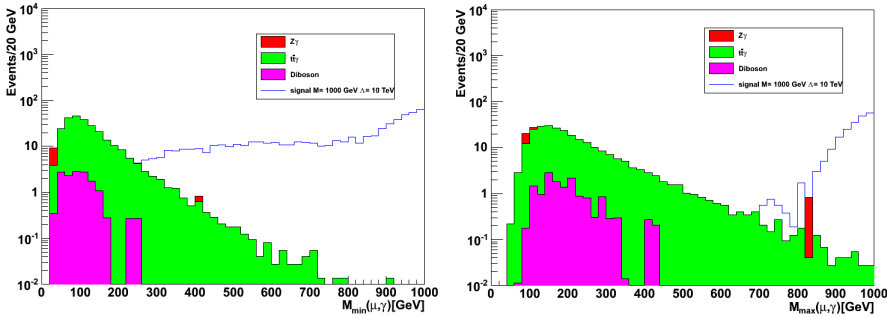


Figure 5.10: The minimum (left) and the maximum (right) muon-photon invariant mass distributions after the full selection (selection 4).

5.2.2 Results

Fig. 5.12 shows the selection efficiency of our cut flow for different mass points of signals that lead to the full selection. It is clear from this plot that our event selection does not depend on the excited muon mass. This is so important to avoid base in our analysis. The number of weighted events left after each cut are listed in table 5.2 for background and table 5.3 for signal at different simulated excited muon mass.

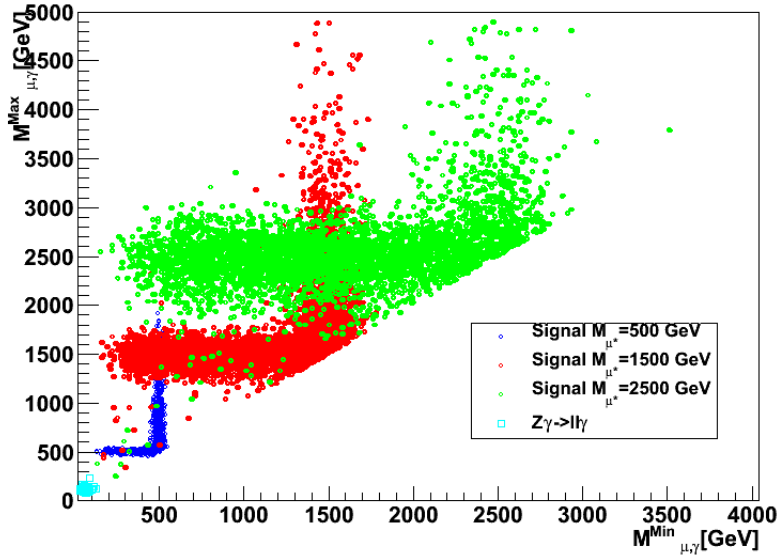


Figure 5.11: Two dimensional $M_{min} - M_{max}$ plane with several signal simulations and background.

Signal	# of weighted events before any selection	# of weighted events after pre selection	# of weighted events after full selection
500	4253.73	1595.14875	1590.89502
1000	1879.152	803.33748	802.7737344
1500	862.47	375.346944	375.260697
2000	394.11	170.452575	170.452575
2500	182.5911	74.07720927	74.07720927
3000	82.8864	32.26767552	32.26767552

Table 5.3: Summary of the number of weighted events for fast simulation signal mass points before any selection, and after each selection.

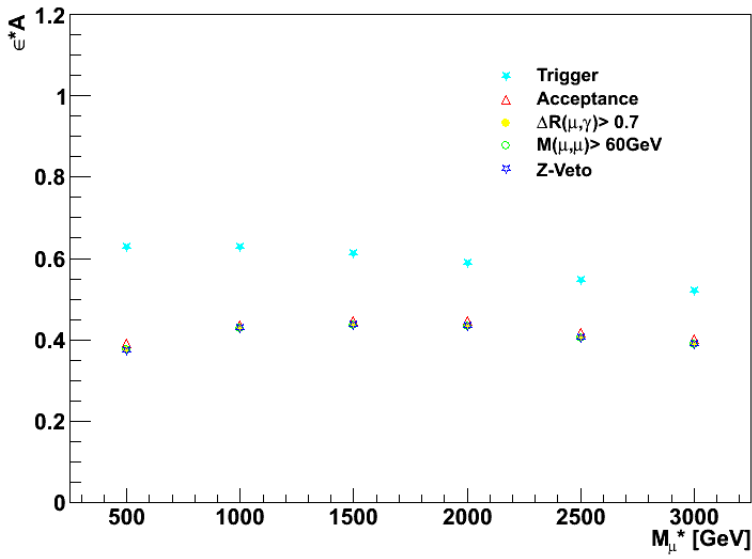


Figure 5.12: Signal efficiency of different steps in the analysis depending on the generated excited muon mass. Acceptance here refers to the p_T and $|\eta|$ cuts.

Conclusion

What is so special about the number "three", in which the quark and lepton families exist? Could possibly be answered if we find that quarks do have substructure. This may also shed some light on some other fundamental questions like the difference mass amongst the three families and could possibly reveal any new hidden underlying interaction among these constituent of quarks. We have investigated the potential of using the $2\mu + \gamma$ final states at the LHC for probing possible substructure of leptons (we focused our search on excited muon). We optimized the objects and event selection in order to get the maximum signal to SM background ratio, as follow:

- Select two highest p_T muons and the highest p_T photon within acceptance (p_T & $|\eta|$)
 - for muons: each muon needs to have $p_T > 35 \text{ GeV}$ and $|\eta| < 2.1$.
 - for photon: $E_T > 35 \text{ GeV}$ and $|\eta| < 1.444$ (barrel only).
- put cut on $\Delta R(\mu, \gamma)$ to be greater than 0.7.
- we apply a cut on the invariant di-muon mass: $M(\mu, \mu) > 60 \text{ GeV}$ to avoid including simulations for low mass resonances.
- To further reduce the dominant background ($Z\gamma$) we apply a tighter cut on the invariant dimuon mass: $M(\mu, \mu) > M(Z) + 25 \text{ GeV}$.

Finally to overcome the problem of existing two muons in the final state one from the production of μ^* and the other from its decay, we use the inverted L-Shape cut, to distinguish our signal from SM background.

According to our study, the excited lepton is accessible in LHC run II, using a data size of about 300 fb^{-1} , excited lepton should be discovered if it exist and its mass is lower than 5000 GeV at compositeness scale of 10000 GeV.

The Resistive Plate Chambers (RPCs) are present in both barrel and in end-cap regions of the CMS. They play a crucial role in triggering interesting events and identification of muons in the CMS experiment. The basic RPC gap performance tests are done in RPC lab at Helwan University including: Leakage Test, Spacer Test, and High Voltage Test.

Bibliography

- [1] N. Bohr, Philosophical Magazine, 26, 1 (1913); Philosophical Magazine, 27, 488 (1913); W. Heisenberg, Z. Phys. 77, 1 (1932).
- [2] J. Chadwick, Nature, 129, 312 (1932).
- [3] P. A. M. Dirac, Proc. R. Soc., London A114, 243 (1927).
- [4] E. Fermi, Z. Phys. 88, 161 (1934).
- [5] Y. Yukawa, Proc. Phys. Math. Soc., Japan, 17, 48 (1935).
- [6] R.P. Feynman, Phys. Rev. 76, p.749,769 (1949); "QED: The Strange Theory of Light and Matter", Princeton University Press, Princeton, New Jersey, 1985. R. P. Feynman, "Space-time Approach to Non-Relativistic Quantum Mechanics", Rev. Mod. Phys. 20, 367-387 (1948). R.P. Feynman, "A Relativistic Cut-Off for Classical Electrodynamics", Phys. Rev. 74, 939-946 (1948).
- [7] J. Schwinger, "On Quantum Electrodynamics and the Magnetic Moment of the Electron", Phys. Rev. 73, 416-417 (1948). J. Schwinger, "Quantum Electrodynamics I. A Covariant Formulation", Phys. Rev. 74 1439-1461 (1948).
- [8] S. Tomonaga, J. R. Oppenheimer, "On Infinite Field Reactions in Quantum Field Theory", Phys. Rev. 74, 224-225 (1948).

- [9] Murray Gell-Mann, Phys Lett 8, 214 (1964); G. Zweig, CERN Report No.8182/TH401 (1964).
- [10] J. J. Aubert et al., Phys. Rev. Lett. 33, 1404 (1974).
- [11] J. E. Augustin et al., Phys. Rev. Lett. 33, 1406 (1974).
- [12] S. W. Herb et al., Phys. Rev. Lett. 39, 252 (1977).
- [13] M. L. Perl et al., Phys. Rev. Lett. 35, 1489 (1975);
- [14] S. Abachi et al., DCollaboration, "Observation of Top Quark", Phys. Rev. Lett. 74 2632 (1995).
- [15] F. Abe et al., CDF Collaboration, "Observation of Top Quark Production in pp Collisions with the Collider Detector at Fermilab", Phys. Rev. Lett. 74, 2626 (1995).
- [16] S.L. Glashow, Nucl. Phys. 22, 579 (1961); A. Salam and J. C. Ward, Phys. Lett. 13, 168 (1964); S. Weinberg, Phys. Lett. 19, 1264 (1967).
- [17] A. Salam, "Elementary Particle Theory", Nobel Symposium, edited by N.Svartholm (Almqvist and Wiksells, Stockholm, 1969) p.367.
- [18] G. Arnison et al., UA1 Collaboration, "Experimental observation of isolated large transverse energy electrons with associated missing energy at $\sqrt{s}=540$ GeV ", Phys. Lett. B 122, 103-116(1983). M. Banner et al., UA2 Collaboration, "Observation of single isolated electron of high transverse momentum in events with missing transverse energy at the CERN $p - \bar{p}$ collider ", Phys. Lett. B 122, 476-485(1983).
- [19] G. Arnison et al., UA1 Collaboration, "Experimental observation of lepton pairs of invariant mass around 95 GeV at the CERN SPS collider ", Phys. Rev. Lett. B 126, 398-410 (1983). G. Arnison et al., UA1 Collaboration, "Further evidence for charged intermediate vector bosons at the SPS collider ", Phys. Lett. B 129, 273 (1983). P.Bagnaia et al., UA2

- Collaboration, "Evidence for $Z^0 e^+ + e^-$ at the CERN $p - \bar{p}$ collider", Phys. Lett. B 129, 130-140 (1983).
- [20] The LEP Collaboration and LEP Electroweak Working Group, as reported by J.Mnich at the International Europhysics Conference, Tampere, Finland (July 1999).
- [21] Chris Quigg, "Gauge Theories of the Strong, Weak, and Electromagnetic Interaction", Addison-Wesley (1983).
- [22] Gordon L.Kane, Modern Elementary Particles physics, Addison-Wesley(1993).
- [23] T. Araki et al., KamLAND Collaboration, "Measurement of Neutrino Oscillation with KamLAND: Evidence of Spectral Distortion", Phys. Rev. Lett. 94 081801 (2005).
- [24] D. G. Michael et al., MINOS Collaboration, "Observation of Muon Neutrino Disappearance with the MINOS Detectors and the NuMI Neutrino Beam", Phys. Rev. Lett. 97, 191801 (2006).
- [25] SUSHIL SINGH CHAUHAN, "SEARCH FOR QUARK COMPOSITENESS AT $\sqrt{s} = 14 \text{ TeV}$ AT THE LARGE HADRON COLLIDER", 2009, PhD thesis 110007, UNIVERSITY OF DELHI.
- [26] <https://nige.wordpress.com>
- [27] M. Peskin, D. Schroeder, "An Introduction to Quantum Field Theory", Westview Pres (1995).
- [28] V. Fock, Zeit. f. Physik, 39 (1927) 226.
- [29] H. Weyl, Zeit. f. Physik, 56 (1929) 330.
- [30] D.J. Gross, F. Wilczek, "Ultraviolet Behavior of Non-Abelian Gauge Theories", Phys. Rev. Lett. 30, 1343-1346 (1973). H. D. Politzer, "Reliable Perturbative Results for Strong Interactions", Phys. Rev. Lett.

- 30, 1346-1349 (1973). D.J. Gross, F. Wilczek, "Asymptotically Free Gauge Theories. 1 ", Phys. Rev. D 8, 3633-3652 (1973). D.J. Gross, F. Wilczek, "Asymptotically Free Gauge Theories. 2 ", Phys. Rev. D 9, 980-993 (1974). H. D. Politzer, "Asymptotically Freedom: An Approach to Strong Interactions", Phys. Rep. 14, 123456 (1974) 129-180.
- [31] CMS collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. Physics Letters B, 716(1):3061, 2012.
- [32] ATLAS collaboration. Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC. Physics Letters B, 716(1):129, 2012.
- [33] Krauss, L. (2009). A Universe from Nothing. AAI Conference
- [34] M. K. Gaillard, P. D. Grannis, and F. J. Sciulli, The standard model of particle physics, Rev. Mod. Phys. 71(2) (Centenary 1999) 96-111.
- [35] J. Ellis, J.R. Espinosa, G.F. Giudice, A. Hoecker, and A. Riotto, The Probable Fate of the Standard Model , Phys.Lett. B(679) (Jun. 4, 2009) 369375.
- [36] J. C. Pati, A. Salam, and J. A. Strathdee, Are quarks composite?, Phys. Lett. B 59 (1975).
- [37] H. Harari, Composite models for quarks and leptons, Physics Reports 104 (1984) 159.
- [38] E. Eichten, K. Lane, and M. Peskin, New Tests for Quark and Lepton Substructure, Phys. Rev. Lett. 50 (1983) 811.
- [39] U. Baur, M. Spira, and P. M. Zerwas, Excited Quark and Lepton Production at Hadron Colliders, Phys. Rev. D42 (1990) 815-824.

- [40] S. Banerjee, S. Bhattacharya, S. Jain, M. Endres, T. Esch, T. Hebbeker, K. Hoepfner, C.-M. Kuo, and S.-H. Mai, Search for Excited Electrons and Muons in pp Collisions at $\sqrt{s} = 8$ TeV with the CMS Experiment and 20 fb^{-1} of data, CMS Analysis Note: AN-12-418 (2014).
- [41] O.J.P. Boli, S.M. Lietti, and P. Mathews, Excited Leptons at the CERN Large Hadron Collider, arXiv:0111001v2. doi:10.1103/PhysRevD.65.075003.
- [42] T. N. Trinh and E. Sauvan, Single Production of Excited Leptons at the LHC. <http://cds.cern.ch/record/1354237/files/ExcitedFermions.pdf>, 2011.
- [43] The OPAL Collaboration, Search for Charged Excited Leptons in e^+e^- Collisions at $\sqrt{s} = 183 - 209$ GeV, Phys. Lett. B544 (2002) 57-72.
- [44] The L3 Collaboration, Search for Excited Leptons at LEP, Phys. Lett. B568 (2003) 23-34.
- [45] The CDF Collaboration, Search for Excited and Exotic Muons in the $\mu + \gamma$ Decay Channel in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. Lett. 97 (2006) 191802, arXiv:0606043. doi:10.1103/PhysRevLett.97.191802.
- [46] The D0 Collaboration, Search for Excited Muons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 73 (2006) 111102, arXiv:0604040. doi:10.1103/PhysRevD.73.111102.
- [47] The CMS Collaboration, Search for excited leptons in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Letter B 720 (2013) 309329, arXiv:1210.2422. doi:10.1016/j.physletb.2013.02.031.

- [48] The ATLAS Collaboration, Search for excited electron and muons in $\sqrt{s} = 8$ TeV proton-proton collisions with the ATLAS detector, New Journal of Phys. 15 (2013) arXiv:1308.1364.
- [49] CERN, The CERN accelerator complex. <http://cds.cern.ch/record/1260465>, 2008.
- [50] CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3 (2008) S08004.
- [51] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider , JINST 3 (2008) S08003.
- [52] ALICE Collaboration, The ALICE experiment at the CERN LHC, JINST 3 (2008) S08002.
- [53] LHCb Collaboration, The LHCb Detector at the LHC, JINST 3 (2008) S08005.
- [54] LHCf Collaboration, The LHCf detector at the CERN Large Hadron Collider , JINST 3 (2008) S08006.
- [55] TOTEM Collaboration, The TOTEM Experiment at the CERN Large Hadron Collider , JINST 3 (2008) S08007.
- [56] The CMS Collaboration, CMS-PHO-GEN-2012-002-5. <http://cds.cern.ch/record/1433717>, 2012.
- [57] The CMS Collaboration, The CMS Tracker System Project: Technical Design Report, 1998.
- [58] DMITRY HITS, A MULTI-LEPTON SEARCH FOR NEW PHYSICS IN 35 Pb^{-1} PROTON-PROTON COLLISIONS AT THE LHC WITH A CENTER MASS ENERGY OF $\sqrt{S} = 7 \text{ TEV}$ USING THE CMS DETECTOR, Doctor of Philosophy, Rutgers, The State University of New Jersey.

- [59] The CMS Collaboration, The CMS Electromagnetic Calorimeter Project: Technical Design Report, 1997.
- [60] The CMS Collaboration, The CMS Hadron Calorimeter Project: Technical Design Report, 1997.
- [61] Thomas Esch, Search for excited muons in the process $pp \rightarrow \mu\mu^* \rightarrow \mu\mu Z \rightarrow 4\mu$ with CMS data, Masterarbeit in Physik, 2014, Physikalisches Institut.
- [62] The CMS Collaboration, The CMS Muon Project: Technical Design Report, 1997.
- [63] The CMS Collaboration, Performance of CMS muon detector in proton-proton collisions $\sqrt{s} = 7$ TeV at the LHC, 2013.
- [64] I. Bird et al, LHC Computing Grid: Technical Design Report. <http://cds.cern.ch/record/840543>, 2005.
- [65] R. Abbasi et al. (High Resolution Fly's Eye Collaboration), Phys.Rev.Lett. 92, 151101 (2004), astro-ph/0208243.
- [66] <http://en.wikipedia.org/>
- [67] M. Takeda, N. Hayashida, K. Honda, N. Inoue, K. Kadota, et al., Phys.Rev.Lett. 81, 1163 (1998), astro-ph/9807193.
- [68] J. Abraham et al. (Pierre Auger Collaboration), Phys.Rev.Lett. 101, 061101 (2008), 0806.4302.
- [69] <http://cms.web.cern.ch/>
- [70] Anna Cimmino, 2006, Development and Study of Different Muon Track Reconstruction Algorithms for the Level-1 Trigger for the CMS Muon Upgrade with GEM Detectors, Master thesis, Napoli University
- [71] Crotty I et al 1994 Nucl. Instrum. Methods A 337 370

- [72] CMS Muon Project 1997 Technical Design Report
- [73] S. Colafranceschi, Resistive Plate Chambers for 2013-2014 muon upgrade in CMS at LHC, CMS CR -2014/128
- [74] M. Abbrescia et al., Cosmic ray tests of double-gap resistive plate chambers for the CMS experiment", Nucl. Instrum. Meth. A 550 (2005) 116.
- [75] G. Abbiendi et al., Muon Reconstruction in the CMS Detector, CMS Analysis Note AN-08-097 (2009).
- [76] <http://www.lhc-closer.es/>
- [77] R. Frhwirth, Application of Kalman filtering to track and vertex fitting, 1987. doi:10.1016/0168-9002(87)90887-4.
- [78] The CMS Collaboration, Performance of CMS muon reconstruction and identification in pp collision events at $\sqrt{s} = 7$ TeV, 2012. doi:10.1088/1748-0221/7/10/P10002.
- [79] Piotr Traczyk, Muon Object Review. <https://indico.cern.ch/getFile.py/access?contribId=6&resId=0&materialId=slides&confId=172473>, 2012.
- [80] Julien Caudron, Retuning of muon cocktail for high p_T muons with fully segment based fit. <https://indico.cern.ch/getFile.py/access?contribId=7&resId=0&materialId=slides&confId=184964>, 2012.
- [81] M. Dobbs and J.B. Hansen, The HepMC C++ Monte Carlo event record for High Energy Physics, Comput. Phys. Commun. 134 (2001) 41-46.

- [82] Ahmed Aly Abdelalim Aly, "Search for Excited Electron Production Using Di-Electron + Photon Signature and Search for New Heavy Neutral Gauge Boson Using Di-Electron Signature with ATLAS at $s = 7$ TeV", 2011, PhD 4373 ,UNIVERSITY OF GENEVE.
- [83] T. Sj ostrand, S. Mrenna, and P. Z. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. 178 (2008) 852.
- [84] CMS Collaboration, Search for Contact Interactions in $\mu^+\mu^-$ Events in pp Collisions at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-EXO-11-009, (2011).
- [85] J. Alwall et al., MadGraph/MadEvent v4: The NewWeb Generation, JHEP 0709 (2007) 028.
- [86] The CMS Muon Object Group, Base-line muon selections, TWiki Website. <https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideMuonIdRun2>, 2015.
- [87] The CMS Collaboration, Muon Particle Object Group, TWiki Website. <https://twiki.cern.ch/twiki/bin/viewauth/CMS/MuonPOG>, 2015.
- [88] EgammaIDRecipesRun2," CutBasedPhotonIdentificationRun2, TWiki Website". <https://twiki.cern.ch/twiki/bin/view/CMS/CutBasedPhotonIdentificationRun2>.