

UNIVERSITY OF DELHI

SYNOPSIS FOR
DOCTORAL THESIS

Search For Anomalous Gauge
Coupling through Vector Boson
Scattering and Development of
the GEM Detectors at the CMS
Experiment

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Abstract

In the Standard Model (SM) of particle physics, masses of the particles are generated by the Higgs mechanism which require the existence of a spin-0 particle called the Higgs boson. In July 2012, a new Higgs-like particle, with mass ≈ 125 GeV, was discovered at the Large Hadron Collider (LHC). This might be the long-sought SM Higgs boson predicted in the 1960s, or one of the Higgs bosons predicted by the several beyond SM (BSM) scenarios. Several BSM scenarios, such as, super-symmetry, little-Higgs models, and others from the extended Higgs sectors such as the Georgi-Machacek model, contain a multitude of neutral as well as charged Higgs bosons. Till now the existing results contain large uncertainties, thus various extensions of the SM cannot be confirmed or ruled out precisely. This necessitates to scrutinize, the ElectroWeak Symmetry Breaking (EWSB) mechanism rigorously by carrying out the precision measurements of the Higgs boson properties and the couplings of the electroweak vector bosons (W and Z) with the Higgs boson via the Vector Boson Scattering (VBS) processes.

In the absence of the Higgs boson, the VBS processes violate the unitarity at an energy scale ≈ 1 TeV. Thus, this is one of the most important studies that could help us to understand the EWSB mechanism. Due to statistical constraints, VBS could be probed indirectly by measuring the quartic vertices. This thesis is based on the study of the anomalous Quartic Gauge Coupling (aQGC) processes using the proton-proton collision data at a centre-of-mass energy of 13 TeV with an integrated luminosity of 35.9 fb^{-1} , collected using the Compact Muon Solenoid (CMS) detector at the CERN LHC in 2016.

This thesis presents the anomalous quartic gauge coupling (aQGC) measurement in the framework of dimension-eight effective field theory operators. It was performed using two channels: WV and ZV (where, V could be either a W or a Z boson) in association with the two jets produced in the forward pseudo-rapidity regions. For the WV (ZV) channels, only leptonic decay of W (Z) bosons are considered, while the V decays hadronically into a merged jet having large radii, with radius parameter 0.8. The constraints are imposed on the aQGC operators at 95% confidence level (CL).

Furthermore, a theoretical interpretation of the observed results is given using the Georgi-Machacek model. The exclusion limits on the production cross-section for the charged Higgs bosons times the branching fraction at 95% CL as a function of the mass of the charged Higgs boson are reported in this thesis.

On the hardware front, work performed for the upgrade studies of the CMS detector's muon endcaps is reported. For the CMS muon endcap detector system upgrade, the Gas Electron Multiplier (GEM) detectors are proposed to be installed during the Long Shutdown-2 (2019-2020) period. To test the functionality of these GEM detectors, several beam tests were carried out in 2014, to measure their properties and evaluate their performance in terms of spatial and timing resolution, cluster size and efficiency measurements. The outcome from these beam test campaigns and the data analysis for the GEM detectors are presented here. Also, the characterisation studies for the GEM foils developed in India for the first time are also described in terms of its electrical and optical properties.

Synopsis

In the Standard Model (SM) of particle physics, masses of the particles are generated by the Higgs mechanism which require the existence of a spin-0 particle [1, 2, 3, 4, 5, 6] called the Higgs boson. In July 2012, a new Higgs-like particle, with mass ≈ 125 GeV, was discovered at the Large Hadron Collider (LHC) [7, 8]. This might be the long-sought SM Higgs boson predicted in the 1960s, or one of the Higgs bosons predicted by the several beyond the SM scenarios. Several beyond SM scenarios, such as, super-symmetry [9, 10], little-Higgs models [11], and others from the extended Higgs sectors such as the Georgi-Machacek model [12], contain a multitude of neutral as well as charged Higgs bosons. Till now the existing results contain large uncertainties, thus various extensions of the SM cannot be confirmed or ruled out precisely. This necessitates to scrutinize, the ElectroWeak Symmetry Breaking (EWSB) mechanism rigorously, by carrying out the precision measurements of the Higgs boson properties and the couplings of the electroweak vector bosons (W and Z) with the Higgs boson via the Vector Boson Scattering (VBS) processes.

In the absence of the Higgs boson, the VBS processes violate unitarity at an energy scale ≈ 1 TeV. Thus, this is one of the most important studies that could help us to understand the EWSB mechanism. Due to statistical constraints, VBS could be probed indirectly by measuring the quartic vertices. In this thesis anomalous quartic gauge coupling (aQGC) measurement is reported using the model independent way using the Effective Field Theory (EFT) by parametrizing the effects of high energy on the energy scale available to us [13]. The new effective Lagrangian using the EFT is give as:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i=www,w,B,\phi W,\phi B} \frac{c_i}{\Lambda^2} \mathcal{O}_i + \sum_{j=0,1} \frac{f_{S,j}}{\Lambda^4} \mathcal{O}_{S,j} + \sum_{j=0,\dots,9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j} + \sum_{j=0,\dots,7} \frac{f_{M,j}}{\Lambda^4} \mathcal{O}_{M,j} \quad (1)$$

Where, Λ is the scale of new physics, the parameters c_i , $f_{S,j}$, $f_{T,j}$ and $f_{M,j}$ are the

Parameters	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$f_{S,0}, f_{S,1}$	×	×	×						
$f_{M,0}, f_{M,1}, f_{M,6}, f_{M,7}$	×	×	×	×	×	×	×		
$f_{M,2}, f_{M,3}, f_{M,4}, f_{M,5}$		×	×	×	×	×	×		
$f_{T,0}, f_{T,1}, f_{T,2}$	×	×	×	×	×	×	×	×	×
$f_{T,5}, f_{T,6}, f_{T,7}$		×	×	×	×	×	×	×	×
$f_{T,8}, f_{T,9}$			×			×	×	×	×

Table 1: Quartic vertices modified by the different operators are marked with \times . In the first row W, Z and A refers to the W-boson, Z-boson and photon respectively. In the second column the bold parameters are measured and the limits are reported.

dimension less coupling-strength coefficient typically of $\mathcal{O}(1)$. In the above equation the dimension eight operators have only quartic couplings. There are total of 18 independent parameters that are shown in Table 1 out of them we measure 9 parameters, they are: $f_{S,0}, f_{S,1}, f_{M,0}, f_{M,1}, f_{M,6}, f_{M,7}, f_{T,0}, f_{T,1}$ and $f_{T,2}$. This measurement was done using the proton-proton collision data at a centre-of-mass energy of 13 TeV with an integrated luminosity of 35.9 fb^{-1} , collected using the Compact Muon Solenoid (CMS) detector at the CERN LHC in 2016.

The aQGC measurement is performed using two channels: WV and ZV (where, V could be either a W or a Z boson) in association with the two jets produced in forward pseudo-rapidity regions. For the WV (ZV) channels, only leptonic decays of W (Z) bosons are considered, while the V decays hadronically into a merged jet having large radii (having radius parameter 0.8). The events are selected by requiring two jets at large rapidity separation having large di-jet invariant mass, one or two leptons (electrons or muons), a fat jet with large radii and missing transverse momentum. Constraints are imposed on the quartic vector boson interactions in the framework of dimension-eight effective field theory operators at 95% confidence level (CL).

Furthermore, a theoretical interpretation of the observed results is given using the Georgi-Machacek model [12]. This model predicts the existence of doubly and singly charged Higgs bosons using the Higgs triplets. The main feature of this model is that it preserves the custodial symmetry and provides neutrinos with a Majorana mass. The exclusion limits on the production cross-section for the charged Higgs bosons times the branching fraction at 95% CL as a function of the mass of the charged Higgs boson are reported in this thesis.

On the hardware front, work performed for the upgrade studies of the CMS detector's muon endcaps is reported. For the CMS muon endcap detector system upgrade, the Gas Electron Multiplier (GEM) detectors are proposed to be installed during the

Long Shutdown-2 (2019-2020) period due to its excellent performance in the harsh running environment like LHC. To test the functionality of these GEM detectors, several beam tests were carried out in 2014 to measure their properties and evaluate their performance in terms of spatial and timing resolution, cluster size and efficiency measurements. The outcome from these beam test campaigns and the data analysis for the GEM detectors are presented here. Also, the characterisation studies for the GEM foils developed in India for the first time are described.

This thesis is organized in five Chapters. A brief description of each of these chapters is provided below:

Chapter 1 begins with a brief introduction to the Standard Model (SM) of particle physics, followed by a prelude to the main thesis topic, i.e. triple or quartic gauge couplings. A mathematical framework is discussed to explain the generation of triple/quartic gauge couplings in the SM, followed by the brief introduction of the Higgs mechanism and the anomalous triple and quartic gauge interactions based on the approach of Effective Field Theory (EFT). Finally, the chapter concludes with a discussion on the doubly charged Higgs model, i.e., Georgi-Machacek model.

Chapter 2 discusses the experimental apparatus used to collect the data for the physics studies reported in this thesis. This contains a description of the Large Hadron Collider (LHC) [14, 15, 16] and its one of the two general purpose detectors, i.e. the CMS detector [17]. The LHC is the world's most powerful particle accelerator and collider, located inside a tunnel of 27 km circumference, about 100 m underground at Swiss-France border. Currently, the LHC is operating at 13 TeV center of mass energy with peak luminosity $\mathcal{L} \simeq 2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [18, 19]. Also, different sub-detector components of the CMS detector and their working mechanisms are outlined. The trigger system being used in the CMS detector for the data collection is also discussed which consists of the two-tier trigger. The first level (L1) of the CMS trigger consists of custom hardware processes running synchronously with the LHC bunch crossing frequency of $\sim 40 \text{ MHz}$. This uses information from the calorimeters and the muon detectors only to select the most interesting events within the time interval of less than $4 \mu\text{s}$. The second level trigger is known as the High-Level Trigger (HLT). This uses fast offline reconstruction algorithm that uses information from all sub-systems, i.e., calorimeters, muon system as well as tracker to decide to keep or reject the event. This step further decrease the event rate from around 100 kHz to about 100 Hz , before data storage.

Chapter 3 is devoted to the hardware activities carried out for the CMS muon detector system upgrade. Starting from a brief history of the gaseous detectors, the focus is shifted to the Gas Electron Multiplier (GEM) detectors which is one of the excellent gaseous detectors having unprecedented spatial resolution, larger sensitive/detection area, with higher rate capability and good operational stability over the longer operating periods. This detector is approved by the CMS collaboration for the upgrade of the CMS muon endcap system during Long Shut-down 2 (2019-2020). This upgrade project is named as GE1/1 upgrade, where the letter “G” stands for GEM, “E” stands for End-cap, the first “1” corresponds to the first muon station and the second “1” corresponds to the first ring of the station [20]. The proposed design and configuration of these GEM detectors are discussed along with their working principle. For observing the performance of the prototype of GEM in the real environment the GE1/1 detector was tested in several beam tests. This thesis described the details and results from the 2014 beam test in terms of measured efficiency, time resolution and cluster size [21, 22]. In this beam test we tested the GE1/1 detector with gas mixtures of Ar & CO_2 and also Ar, CO_2 & CF_4 . One of the important conclusions drawn from this study was that one can operate the GEM detector without using CF_4 gas, which is a non-eco friendly gas, without compromising the efficiency and the time resolution of the detector.

This chapter also contains the characterization studies of the GEM foil developed in India. An Indian company, Micropack Pvt. Ltd., got the technology for GEM foil production through the Transfer of Technology (TOT) agreement with CERN. It was successfully able to produce $10\text{ cm} \times 10\text{ cm}$ foils using the double mask technique [23]. This GEM foil is characterized using the optical and electrical method. These results are mentioned in terms of the defects and the leakage current in GEM foils that we observed.

Chapter 4 reports the various steps and procedures followed in the analysis for the Anomalous Quartic Gauge Couplings (aQGC) measurement using the model independent way using the Effective Field Theory (EFT) for the dimension-eight operators with the data collected during 2016 (36 fb^{-1}) in proton-proton collision at 13 TeV by the CMS detector. Among all the allowed processes, the process $pp \rightarrow WVjj$ and $pp \rightarrow ZVjj$ is used for the study. Here V denotes W or Z boson and they are always allowed to decay hadronically. The other vector boson decays leptonically. The study starts by measuring the interference between the electroweak process $pp \rightarrow VVjj$

and the QCD initiated process. The study showed that we have less than 1% interference between the two. The major background $W + jets$ was estimated in a data-driven way using the alpha-ratio method. The events are selected by requiring two jets with large rapidity separation having large di-jet invariant mass, one or two leptons (electrons or muons), and a boosted W or Z boson decaying hadronically. The hadronically decaying W/Z boson is reconstructed as one large radius jet having radius parameter 0.8. Finally, the limits on the dimension-eight operators are given using the frequentist approach in asymptotic approximation.

Chapter 5 provides a summary of the work done during this PhD thesis for the physics analysis and the hardware work on the GE1/1 upgrade along with lab development and the characterization of the Indian GEM foil at the University of Delhi. This thesis also discuss the future prospects of the physics and hardware upgrade.

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List of Publications

Journal Publication:

1. “Development, characterization and qualification of first GEM foils produced in India”, Aashaq Shah, Asar Ahmed, Mohit Gola, **Ram Krishna Sharma**, Shivali Malhotra, Ashok Kumar, Md. Naimuddin, Pradeep Menon, K. Srinivasan, “*Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*”, 892 (2018), pp. 10-17 (**Corresponding Author**)
2. “Search for anomalous electroweak production of WW/WZ/ZZ boson pairs in association with two jets in proton-proton collision at 13 TeV”, CMS Collaboration
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CMS Analysis Notes:

1. “Search for anomalous electroweak production of WW/WZ/ZZ boson pairs in association with two jets in proton-proton collision at 13 TeV”, Aram Apyan, Andrew Beretva, Jeffrey Berryhill, Pietro Govoni, Dan Green, Md. Naimuddin, Jakob Salfeld-Nebgen, **Ram Krishna Sharma**, Patricia Rebello Teles, Davide Valsecchi
CMS Analysis Note - 2017/236.

CMS Detector Notes:

1. “Test beam studies of Gas Electron Multiplier (GEM) detectors for the upgrade of CMS endcap muon system”, Vipin Bhatnagar, Brian Dorney, Marek Michal Gruchala, Priyanka Kumari, Ankita Mehta, Md Naimuddin, Jeremie Alexandre Merlin, Archana Sharma, **Ram Krishna Sharma**, J.B. Singh
CMS Detector Note - 16/017.

Conference Proceedings/Poster Presentations:

1. “Test Beam Study of Gas Electron Multiplier (GEM) Detectors for the Upgrade of CMS Endcap Muon System”, **Ram Krishna Sharma.**

Talk presented at the **XXII DAE High Energy Physics Symposium**, University of Delhi, India, December 12-16, 2016.

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2. “Charged particle detection performance of Gas Electron Multiplier (GEM) detectors for the upgrade of CMS endcap muon system at the CERN LHC”, **Ram Krishna Sharma**.

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Registration Details

- **Thesis title:** Search for Anomalous Gauge Coupling through Vector Boson Scattering and Development of the GEM Detectors at the CMS Experiment.
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