MASTERS THESIS PROJECT (ANTEPROYECTO)

TITLE:

Measurement of the Large Hadron Collider luminosity using the CMS silicon pixel detector

TITULO:

Medicíon de la luminosidad del Gran Colisionador de Hadrones usando el detector de pixeles de silicio de CMS

RESEARCH LINE (LGAC):
Fisica Matematica

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Abstract

This research project consists on the precise determination of the luminosity delivered by the Large Hadron Collider to the Compact Muon Solenoid (CMS) experiment at CERN during 2017-2018 period using the Pixel Cluster Counting (PCC) method. Luminosity plays a fundamental role in the measurement of physics processes of elementary particles of the Standard Model, a precise determination of the delivered luminosity allows for precise tests of the Standard Model and searches for new physics. The PCC method consists of the reconstruction and counting of track clusters produced by charged particle tracks using the Inner Tracker of the CMS detector. Due to the fine granularity of the pixel sensors of the Inner Tracker, the hit occupancy in the sensors remains very small ($< 1\%$) during the proton collisions, this leads to a very linear response and small overall systematic uncertainties for the luminosity measurement.

1 BACKGROUND

The standard model (SM) of particle physics is so far the best theoretical model to describe the interaction of elementary particles mediated by three of the four fundamental forces of nature which are electromagnetic force, strong nuclear force and the weak nuclear force. The SM is divided into two categories, the bosonic sector and the fermionic sector. The bosonic sector contains particles which mediate the fundamental forces of nature and the fermionic sector contains particles which make up all known matter in our universe. There are three generations of fermion particles: the first generation consists of up (u) quark, down (d) quark, electron and electron neutrino, the second generation consist of charm (c) quark, strange (s) quark, muon and muon neutrino, and the third generation has the top (t) quark, bottom (b) quark, tau and tau neutrino. The bosonic sector consists of the gauge bosons: gluon, photon, $W^{\pm}$, Z^0 which mediate strong nuclear force, electromagnetic force and weak nuclear force respectively. The Higgs boson (H), is the last of the gauge bosons, it gives mass to the other SM particles via electroweak symmetry breaking mechanism [1]. The heavy particles ($W^{\pm}$, Z^0, H, and top) can only be produced at high energy particle colliders like the Large Hadron Collider (LHC) operating at a center-of-mass energy of 13 TeV in Geneva, Switzerland (Figure 1). Until the 90s, existence of almost all the SM particles were confirmed except the top quark and the Higgs boson. These had eluded previous experiments due to difficulties in the production and reconstruction of its decay products. The top quark was discovered in 1995 at the Tevatron collider of the Fermilab laboratory, this proton collider operated with a center-of-mass energy of 1.8 TeV until 2010. In 2012, the ATLAS and CMS experiments, with detectors placed at two points where the proton beams collide in the LHC, announced the discovery of a new particle with a mass of 125 GeV. This particle has been identified as the Higgs boson by measuring its properties and comparing to those predicted by the SM.

Luminosity, L, is a key parameter at particle colliders along with the energy available in the collision. L is one of the main figures of merit that quantify the potential for observing new particles and measuring their properties. The instantaneous luminosity $L(t)$ is the process-independent ratio between the rate $R(t)$ of events produced per unit time and the cross section for a given process σ: $L(t) = R(t)/\sigma$. During Run 1 (2011-2012) LHC reached a peak instantaneous luminosity of $0.77{\times}10^{34}$ cm^{-2}s^{-1} and delivered an integrated luminosity of about 25 fb^{-1} with a precision of about 2.0% [1]. In the first part of Run 2 (2015-2016), the delivered luminosity has been measured to be 38.4 fb^{-1} with an unprecedented precision

[1] 1 barn is a unit of area corresponding to 10^{-24} cm^2 and 1 femtobarn (fb) = 10^{-39} cm^2. For comparison, the total Higgs production cross section is 48600 fb.

of 1.3% [2]. For the second part of Run 2 (2017-2018), the integrated luminosity is about 78 fb^{-1}, but its precise value and uncertainty remain to be determined and is the main objective of this thesis project [3].

The plan of the LHC till year 2038 is to obtain datasets with up to 10 times higher values of instanteneous luminosities in the final phase, the High Luminosity LHC (HL-LHC), and corresponding integrated luminosities of order 3000 fb^{-1} [4]; the most updated projected luminosity performance along the whole life of LHC/HL-LHC machine is shown Figure 2. These final datasets will provide precise measurements of the properties of the Higgs boson and other SM particles as shown in Fig. 3. This figure shows that one of the dominant uncertainties which remain to be determined is due to the luminosity measurement.

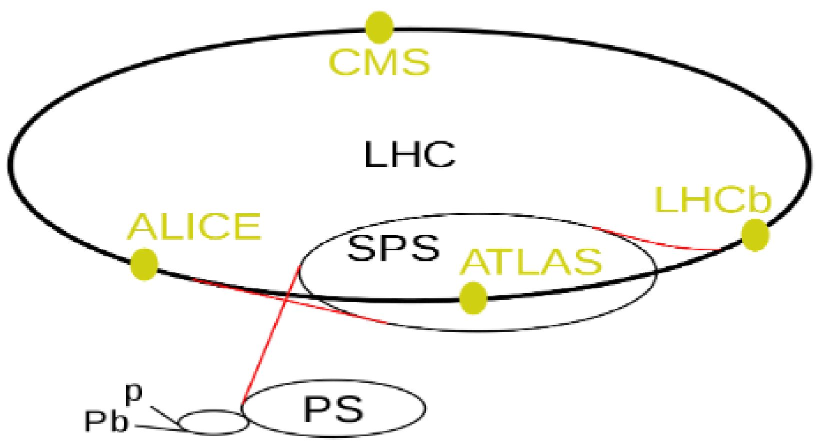

Figure 1: Diagram of the LHC accelerator complex located near Geneva, Switzerland. The complex consists of three accelerator stages: the proton (p) or lead (Pb) source, the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS), and the 27 km LHC ring. Four collision points are shown corresponding to the ALICE, ATLAS, LHCb, and CMS detectors [5].

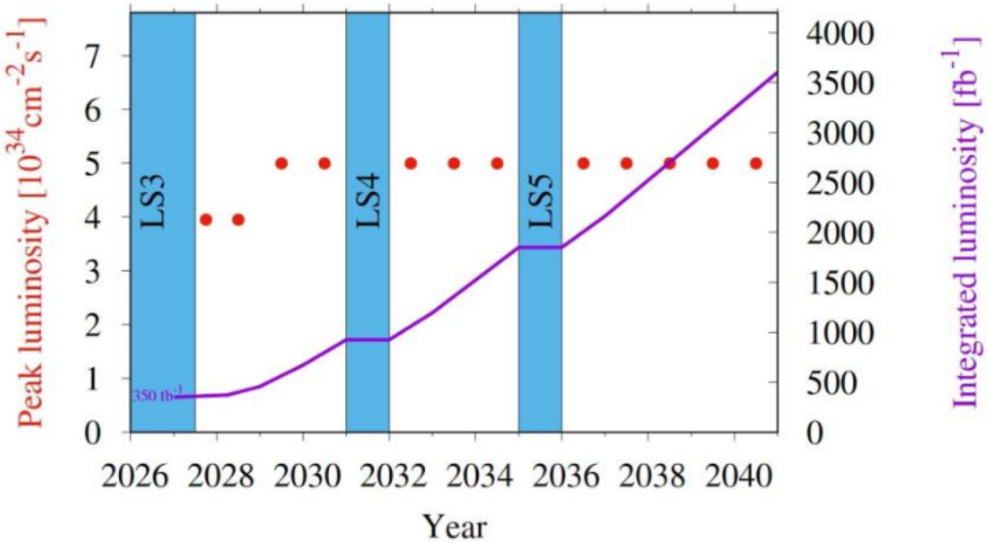

Figure 2: Forecast for peak luminosity (red dots) and integrated luminosity (violetline) in the HL-LHC era with nominal HL-LHC parameters[6].

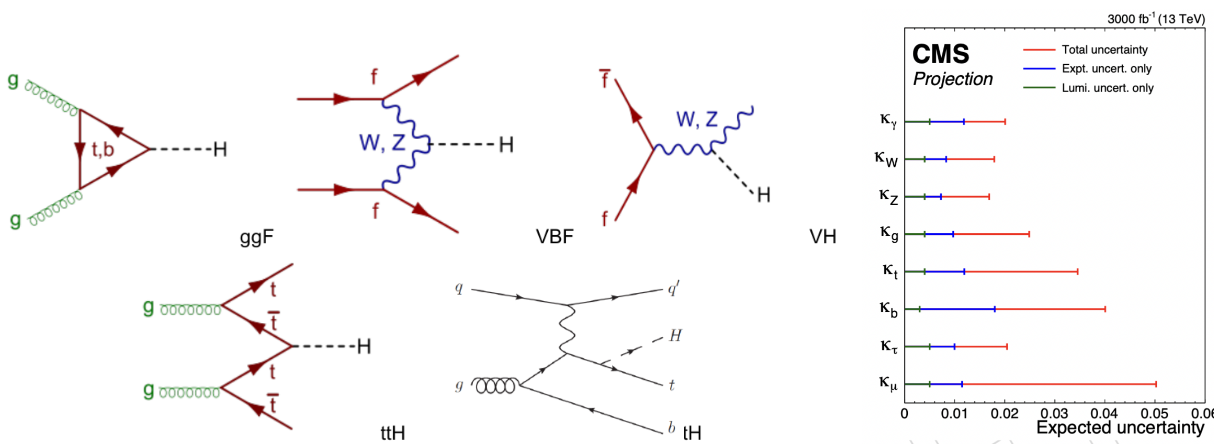

Figure 3: Left: Main production mechanisms for the Higgs boson at the LHC: gluon-gluon fusion (ggF), vector-boson fusion (VBF), associated vector boson (VH), associated top-quark pair (ttH), and associated single-top quark production (tH) [7] [8] . Right: Expected uncertainties on the Higgs coupling parameters for 3000 fb^{-1} of proton-proton collision data at 13 TeV center-of-mass energy [9].

2 PROPOSAL

We propose to perform an analysis of the LHC luminosity data recorded by the CMS experiment during 2017 and 2018 using the Pixel Cluster Counting (PCC) method [10].

3 GENERAL OBJECTIVE

The main objective of this work is to perform a measurement of the 2017-2018 luminosity with a precision at the level of 2% or less using the CMS Pixel detector. This precision is necesary for testing SM of elementary particles and identifying possible new physics which could elucidate the nature of Dark Matter in our universe.

4 HYPOTHESIS

As mentioned in the introduction, the precision achieved in the measurement of the integrated luminosity during Run 1 (2011-2012) was about 2.5% using methods developed for the first time. In 2015 and 2016 runs, the uncertainty achieved was 1.6% and 1.2%, respectively, for datasets corresponding to 2.5 fb^{-1} and 36 fb^{-1} [2]. The methods used for the 2015 and 2016 data are similar to the strategy we propose in this project. We expect that the final uncertainties for the 2017 and 2018 datasets to be similar, but the ultimate goal of the CMS collaboration is to reduce these uncertainties to below 1% [4].

5 SPECIFIC OBJECTIVES

- Understand the CMS pixel detector layout including the barrel layers and endcap disks and their constituent silicon pixel modules.
- Study the stability of the modules in the different layers or disks of the pixel detector and select the stable components.
- Determine the calibration constant corresponding to the PCC luminometer for proton-proton colisions at 13 TeV using the selected pixel detector components.
- Determine the delivered luminosity per lumisection (23 second intervals) and the total integrated luminosity for 2017 or 2018 data.
- Study some of the systematic uncertainties related to the measurement of the luminosity using the PCC. For example, calibration uncertainties, stability, and linearity.

6 METHODOLOGY

The CMS experiment is located at one of the four interaction points of LHC. The CMS detector has the form of a cylindrical onion, with several concentric layers of components.

A powerful magnet is used to bend charged particles as they move away from the point of collision to identify the charge and measure their momentum. A silicon tracker, made of about 75 million electronic sensors arranged in concentric layers, measures the curvature of charged particles with very high precision [11]. The electromagnetic calorimeter detects photons and electrons while the hadron calorimeter detects mainly pions and kaons. The muons are detected by special chambers placed outside the solenoid as shown in Figure 4.

The PCC method for measuring luminosity uses the Pixel detector of the CMS tracker, the layout of the detector used for recording the data during 2016-2018 is shown in Figure 5. The Pixel detector consists of 4 concentric cylindrical layers in the barrel and 2 disks in each endcap. Each detector part is composed of pixel sensors, a schematic of one sensor is shown in Figure 5. The entire Pixel detector contains 1856 sensor modules and a total of 65 million pixels.

The PCC method consists of the reconstruction of track clusters produced by charged particle tracks as shown in Figure 6. Due to the fine granularity of the pixel sensors and the large number of total pixels, the hit occupancy in the sensors remains very small (order of 1%) during physics runs. This low occupancy makes the PCC very linear as a function of pileup, an essential property of a good luminometer.

The calibration of the luminometer consists of a van der Meer (vdM) scan performed in a special LHC run usually at the beginning of the run period (year). In this calibration setup, proton beams are moved across each other in separation steps of about 100 micrometers, by measuring the rates of clusters with the PCC algorithm and knowledge of the beam parameters during the vdM conditions, the calibration constant (σ_{vis}) is determined. This calibration constant is then used to normalize the measured PCC rates during normal running throughout the data-taking year [12].

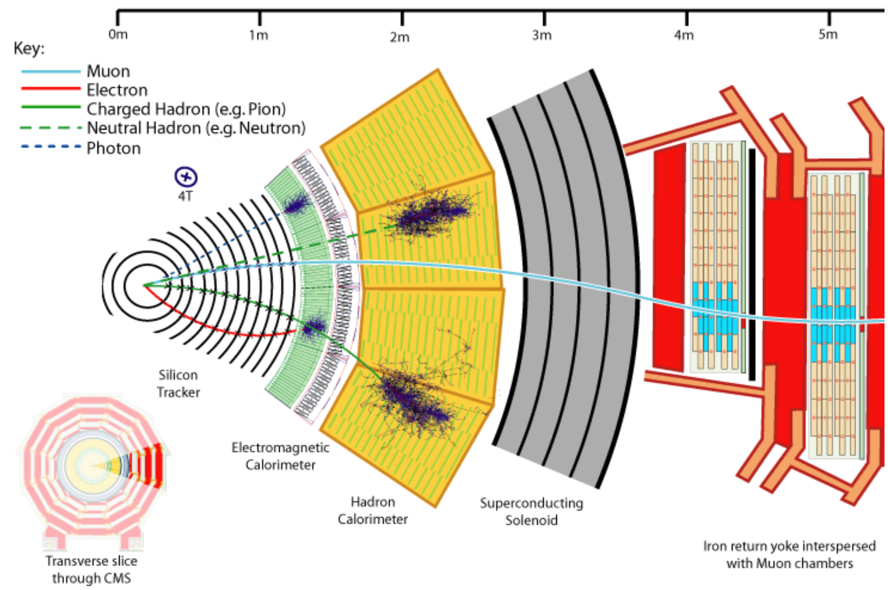

Figure 4: Transverse view of the CMS detector showing the silicon tracker, electromagnetic calorimeter, hadron calorimeter, superconducting solenoid and muon chambers [11].

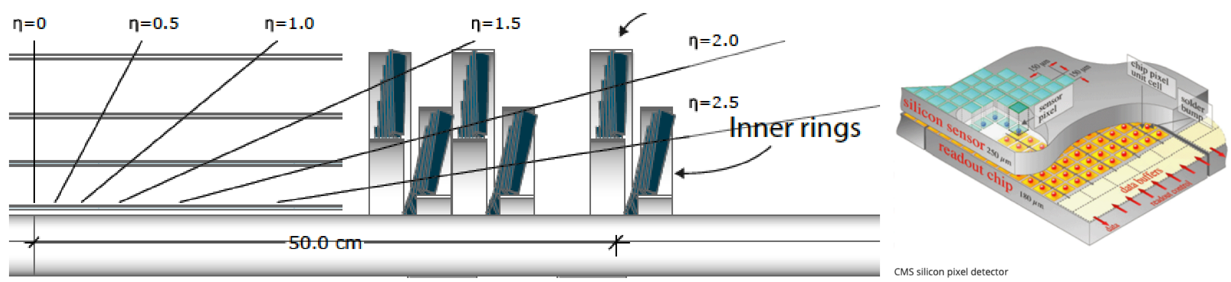

Figure 5: Left: diagram showing the layout of the CMS Pixel detector used during 2016-2018. The layout consists of 4 barrel layers and 2 endcap disks with two rings each. Right: a diagram showing the structure of one pixel sensor. The entire detector consists of 1856 sensors and 65 million pixels [13].

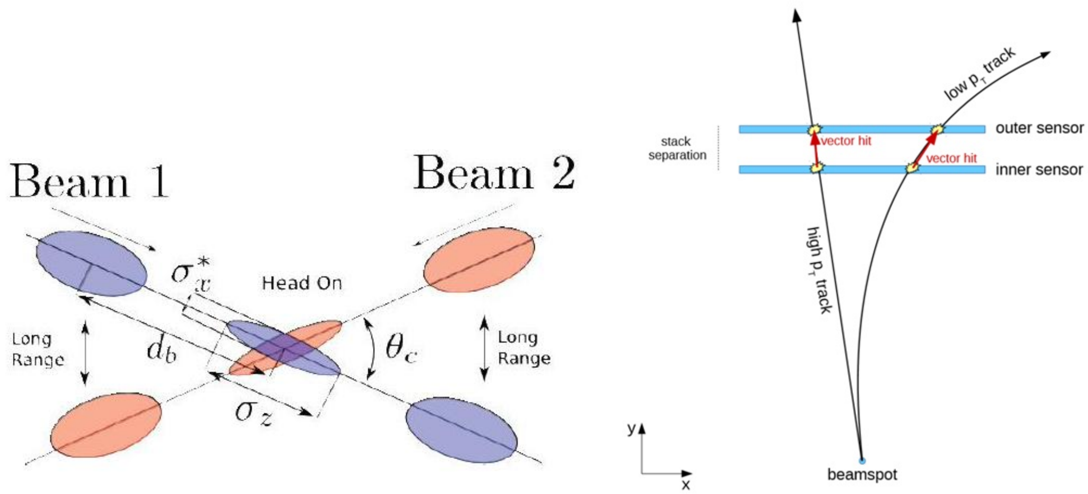

Figure 6: Left: Diagram showing the collision of two proton bunches at LHC, bunches contain about 10^{11} protons [14]. Right: diagram showing example tracks originating from the collision at the beamspot and producing clusters at the pixel sensors in two detector layers.

7 EXPECTED RESULTS

- Final selection of good modules for calculating luminosity using the PCC method.
- Determination of the PCC calibration constant by analyzing the vdM scan data.
- Determination of the luminosity per lumi section and integrated for the 2017 or 2018 data.
- Estimation of the systematic uncertainties associated with the calibration constant or the integrated luminosity values.
- A presentation of the results in a national or international conference.
- Publication of the results in a peer-reviewed scientific journal.

8 CALENDAR OF ACTIVITIES

- **Summer 2021**:
  - Readings on Standard Model of particle physics, the LHC and CMS experiments
  - Linux/Computing skills (Bash, Emacs, c/c++, python, ROOT)

- Computing accounts at CERN and Fermilab
- Initial planning of the analysis strategy

- **Semester 2021-2**:
  - Course I: on particle physics, particle detection, or data analysis
  - Analysis/Computing skills (Bash, Emacs, c/c++, python, ROOT)
  - Analysis of the LHC Run 2 luminosity data using the PCC method
- **Semester 2022-1**:
  - Course II on particle physics, particle detection, or data analysis
  - Completion of the analysis of the LHC Run 2 luminosity data using the PCC method
  - Presentation of results at national or international conference
  - Thesis writing

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