ANTEPROYECTO

TITLE:

Luminosity measurement using Pixel Cluster Counting in the CMS experiment

RESEARCH LINE:

Experimental Particle Physics

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Abstract

This research project proposes to measure the luminosity from RUN 3 made in 2024 with the CMS data using mainly the PCC method. Accurate luminosity measurements are crucial for understanding particle physics, including Higgs boson production. The research involves analyzing the CMS pixel detector, calibrating it for 13.6 TeV collisions, and addressing systematic uncertainties.

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.

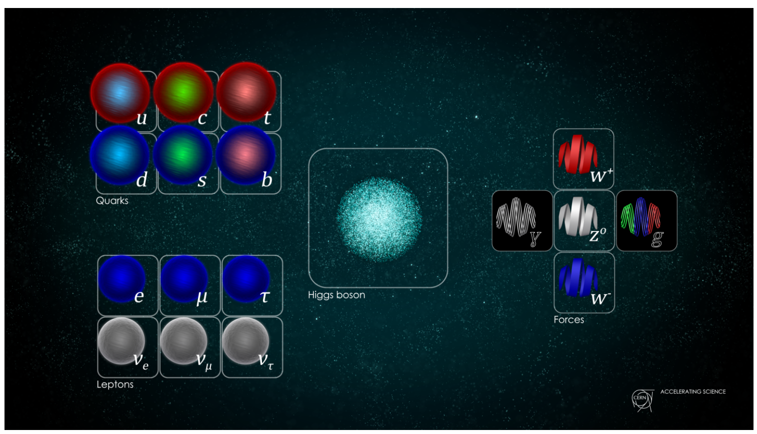


Figure 1: Particles of the Standard Model

The large hadron collider (LHC) is the world largest and more powerful particle accelerator. It first started in 10 september of 2008 and remains the latest addition to CERN's accelerator complex. The LHC consist of a 27 kilometer ring of superconducting magnets with a number of accelerating structures to boost the energy of the particles along the way. All the controls for the accelerator, its services and technical infrastructure are housed under one roof at the CERN Control Centre. From here, the beams inside the LHC are made to collide at four locations around the accelerator ring, corresponding to the positions of four particle detectors; Atlas, CMS, Alice and LHCb.

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: $R(t) = \sigma L(t)$. During Run 1 (2011-2012) LHC reached a peak instantaneous luminosity of 0.77×10^{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 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 [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 LHC Run 3 began in 2022 and will last until 2024, with an expected integrated luminosity of about 450 fb^{-1} [4].

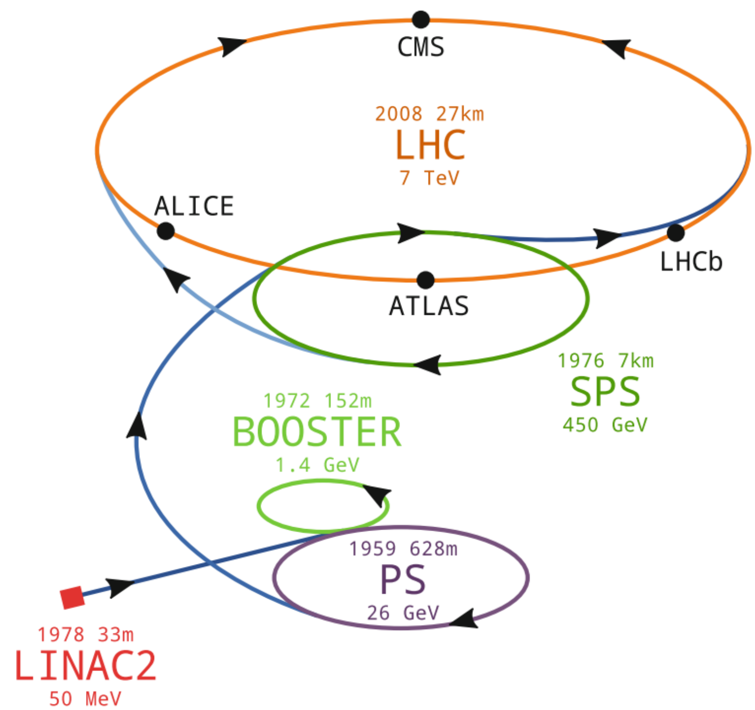


Figure 2: Diagram of the LHC accelerator complex located near Geneva, Switzerland. The complex consists of three accelerator stages: the proton (p) or lead (Pb) source, the Proton Synchrotron (PS), the Super Proton Synchrotron (SPS), and the 27 km LHC ring. Four collision points are shown corresponding to the ALICE, ATLAS, LHCb, and CMS detectors [5].

[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.

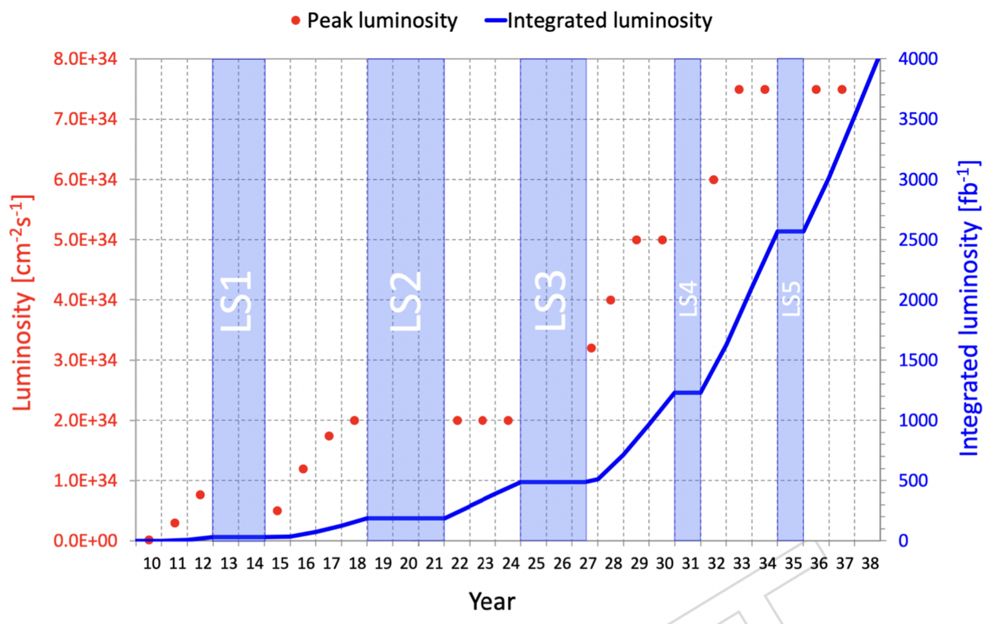


Figure 3: Projected performance of the LHC until 2038, which shows the preliminary dates for prolonged stops (LS) of the LHC and luminosities. Points show instantaneous luminosity while the line shows luminosity accumulated [6].

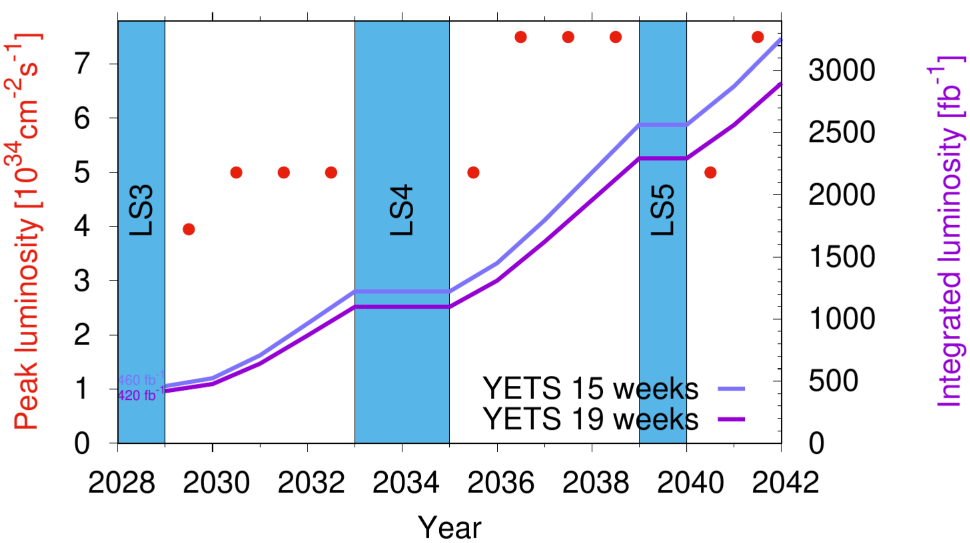


Figure 4: Update performance of the LHC until year 2042, notice that some values are different to those show in figure 4. Points show instantaneous luminosity while the line shows luminosity accumulated [6].

2 PROPOSAL

In this project, we aim to make the measurements of the luminosity for the preliminary data from Run 3 take on 2024 using the Pixel Cluster Counting (PCC) method.

3 GENERAL OBJECTIVE

The main objective of this work is to obtain calibration data for 2024 aiming for a uncertainty less than 2% in this Run. This is results are important for CMS to compare physical process with the Standard Model, these results are likely to be presented on conferences and reviews on 2025. This precision is needed for the measurement of many important physics processes, like the Higgs boson production crossection, which define the Standard Model of particle physics.

4 HYPOTHESIS

Based on the previous work on the Run 2 (2015-2016) datasets which have achieved a precision at the level of 1.3%, we expect that a precision at this level or lower will be possible due to the improved methods we are developing. For reference, the current precision on the Run 2 (2017-2018) and Run 3 (2022) datasets is above 2% [2].

5 METHODOLOGY

The CMS experiment is located at one of the four interaction points of the 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 [7]. 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 5.

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 6, this detector is expected to deliver high-quality data until the end of LHC Run 3 (currently expected for 2024). The Pixel detector consists of 4 concentric cylindrical layers in the barrel and 3 disks in each endcap. Each detector part is composed of pixel sensors, a schematic of one sensor is shown in Figure 6. The entire Pixel detector contains 1856 sensor modules and a total of 124 million pixels [8].

The PCC method consists of the reconstruction of track clusters produced by charged particle tracks as shown in Figure 7. 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 normal collisions. This low occupancy makes the PCC very linear as a function of pileup, an essential property of a good luminometer [2].

In order to evaluate the total number of events we used integrated luminosity, it is a measurement of the collected data size, and it is important value to characterize the performance of an accelerator, defined as:

$$L_{inst} = \int_0^t L_{inst}(t')dt'$$

Because it directly relates to the number of observed events; $\mathrm{L}_{int}\dot{\sigma}_p = number of events of interest.$

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). These scans are performed by varying the separation between the beams in each direction (x and y) at a fixed number of separation steps of about 100 micrometers. Then these rates are fitted by a Gaussian function to obtain the beam overlaps $\Sigma_{x,y}$ and the peak rate of clusters $R(0,0)$ [9]. A schematic view of this method is shown in Fig. 8. Finally the calibration constant (σ_{vis}) is determined as Eq.1.

$$\sigma_{vis} = \frac{R_{det}}{L_b} = \frac{2\pi\Sigma_x\Sigma_y R(0,0)}{N_1 N_2 f} \tag{1}$$

Where f is the LHC frecuency and N_1, N_2 are the buch current used to normalize the rates. This calibration constant is then used to determine the luminosity during a normal running throughout the data-taking year [9].

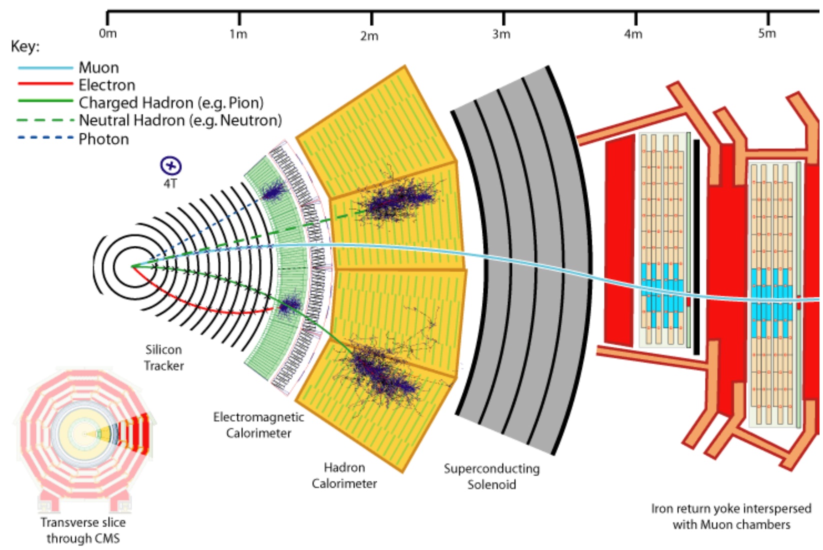


Figure 5: Transverse view of the CMS detector showing the silicon tracker, electromagnetic calorimeter, hadron calorimeter, superconducting solenoid and muon chambers [7].

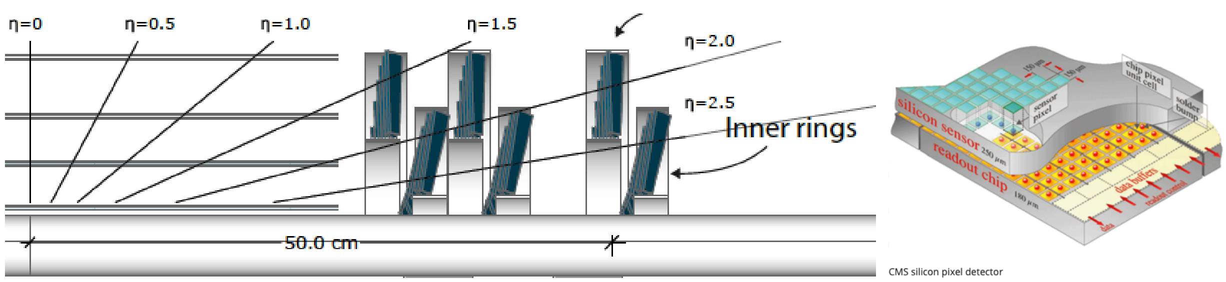
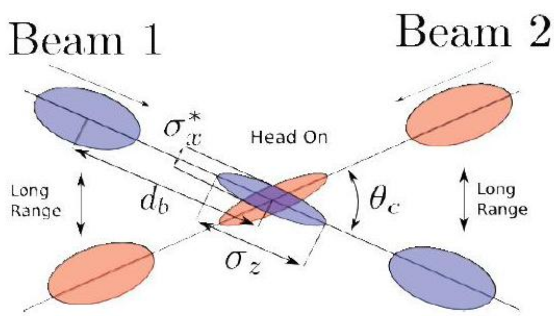


Figure 6: Left: diagram showing the layout of the CMS Pixel detector used during 2016-2018. The layout consists of 4 barrel layers and 2 endcap disks with two rings each. Right: a diagram showing the structure of one pixel sensor. The entire detector consists of 1856 sensors and 65 million pixels [8].



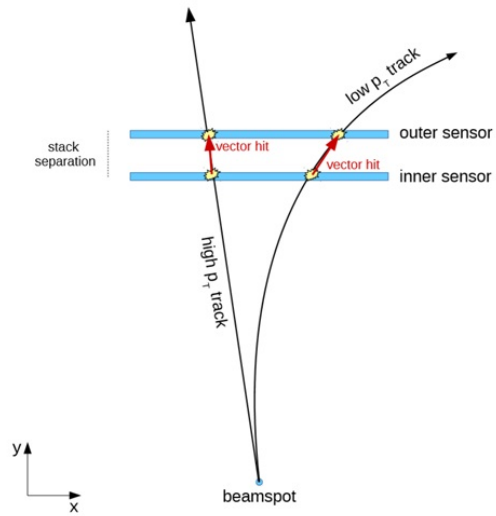


Figure 7: Left: Dagram showing the collision of two proton bunches at LHC, bunches contain about 10^{11} protons [10]. Right: diagram showing example tracks originating from the collision and producing hits in the pixel detector layers [11].

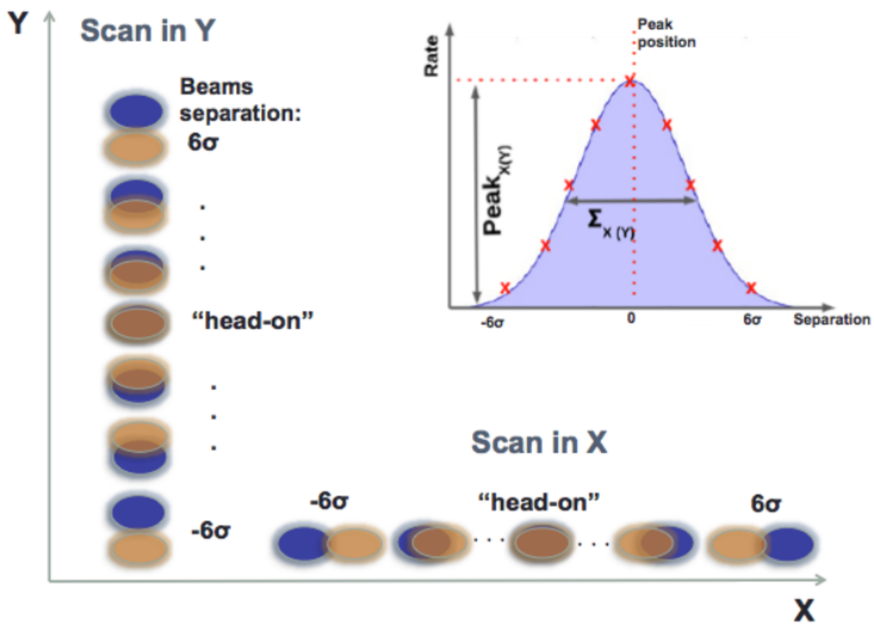


Figure 8: Sketch of a vdM scan in x and y planes. The sketch is an example of the fit of the resulting cluster rates [12].

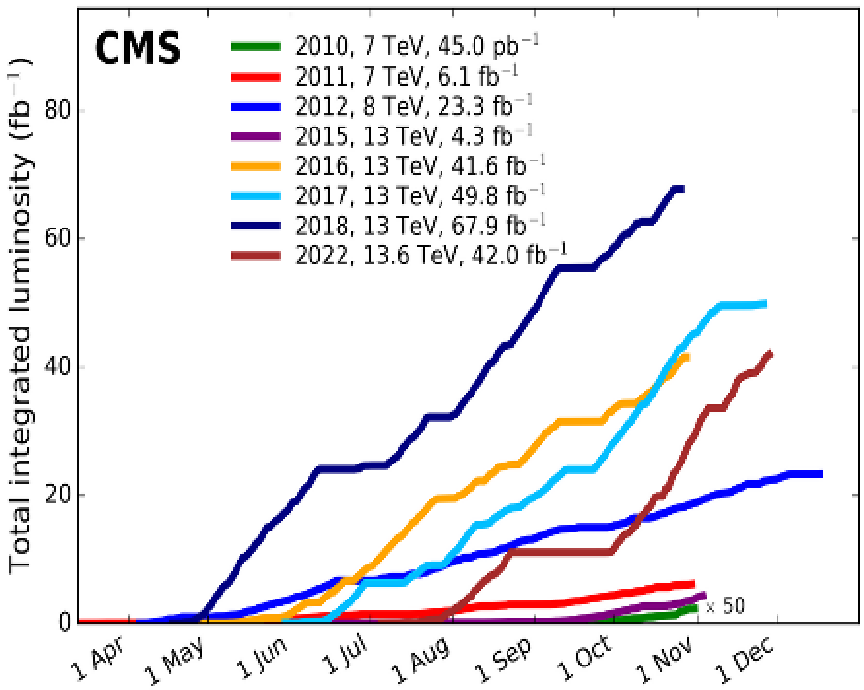


Figure 9: Total integrated luminosity from previous data from CMS

6 SPECIFIC OBJECTIVES

For Run 3 2024 luminosity measurements:

- Understand the CMS pixel detector layout including the barrel layers and endcap disks and their constituent modules.
- Study the evolution of the parameters of photon beams
- Calculate the calibration constant (visible crossection) corresponding to 13.6 TeV proton-proton collision data.
- Study the stability and linearity of the PCC luminosity measurement by comparing to other CMS luminometers.
- Study the variation function in function of the scan with time
- Determine the instantaneous and the total integrated luminosity.
- Determine the systematic uncertainties on the calibration constant and on the integrated luminosity.

7 EXPECTED RESULTS

From this project the following is expected:

- From 2024 data compute the uncertainty from the calibration to contribute with the luminosity measurement in 2024.

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