To the Graduate Council:

I am submitting herewith a thesis written by Krishna Thapa entitled "Correction to Luminosity Measurement for the Pixel Luminosity Telescope at CMS." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in High Energy Physics.

Stefan M. Spanier, Major Professor

We have read this thesis
and recommend its acceptance:

Dr. Stefan Spanier

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(Original signatures are on file with official student records.)

Correction to Luminosity Measurement for the Pixel Luminosity Telescope at CMS

A Thesis Presented for
The Master of Science
Degree
The University of Tennessee, Knoxville

Krishna Thapa

December 2016

dedication...

Acknowledgements

I would like to thank...

Some quotation...

Abstract

The search for and detailed study of new particles and forces with the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) of CERN is fundamentally dependent on the precise measurement of the rate at which proton-proton collisions produce any particles, the so-called luminosity. Pixel Luminosity Telescope (PLT), a dedicated online luminoter for the CMS experiment, became operational in 2015. Methods were developed to calculate the corrections to the luminosity measurement of the PLT.

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Introduction

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Physics Background

2.1 Introduction

The Standard Model of particle physics is described briefly. This theory describes the interactions between subatomic particles. Luminosity, the relevant metric in particle physics experiments as the measure of amount of particle interactions is also described briefly.

2.2 Standard Model of Particle Physics

The Standard Model of particle physics describes the interaction between elementary particles through electromagnetic, weak, and strong forces. This model came about with the unification of theories on electromagnetic and weak interactions in 1961 by Sheldon Glashow, and with the addition of Higgs mechanism in 1967 by Steven Weinberg and Abdus Salam. This theory successfully explained the experimental observations in the past, as shown in Figure 2.1, and continues to provide avenues to probe the theory further.

Interaction	Strength	Theory	Mediator
Strong	10	Quantum Chromodynamics	Gluon
Electromagnetic	10^{-2}	Quantum Electrodynamics	Photon
Weak	10^{-3}	Flavordynamics	W and Z Bosons
Gravitation	10^{-42}	Geometrodynamics	Graviton

Table 2.1: Rough order of the interaction strengths, the mediator and the theory, which describes these interactions

2.2.1 Elementary Particles

According to the Standard Model, matter consists of 12 particles of spin 1/2 known as fermions each of which has its own antiparticle of opposite spin.

2.2.2 Fundamental Forces

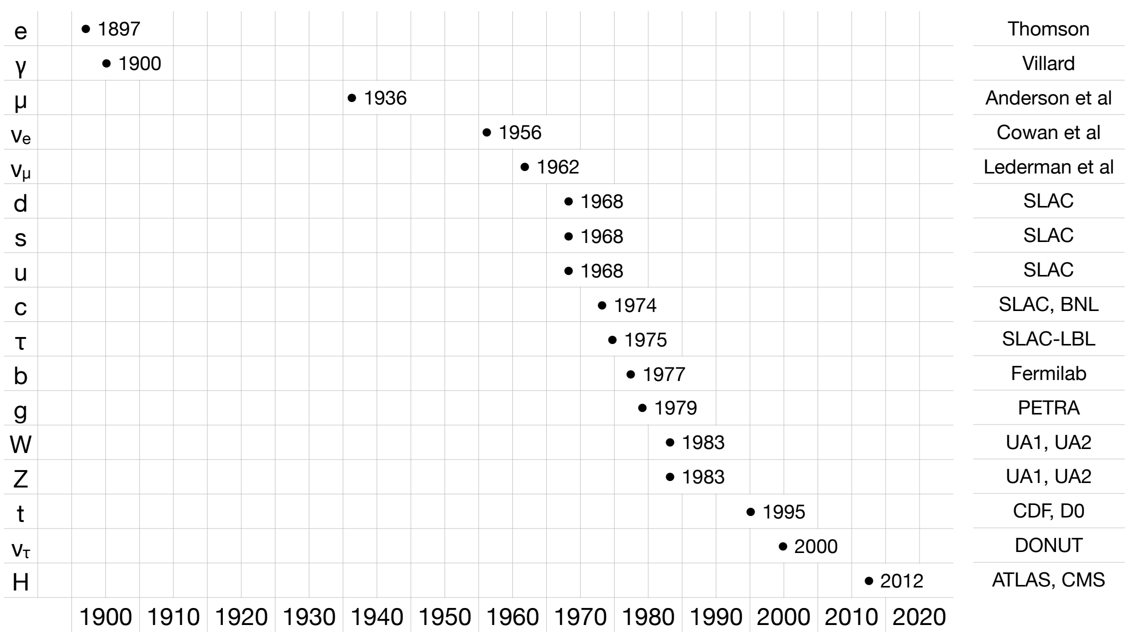

Figure 2.1: The discoveries of fundamental particles of the Standard Model vs time Tuna (2015)

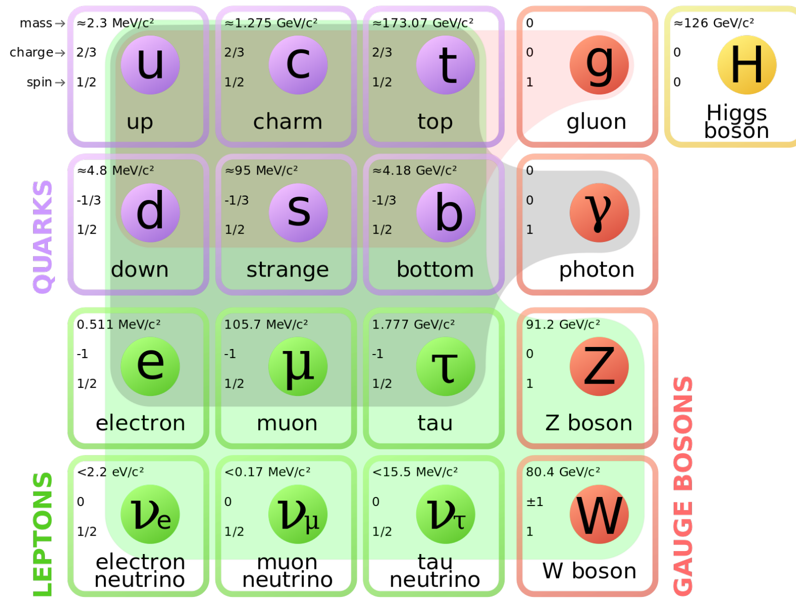

Figure 2.2: The Standard Model of Elementary Particle Physics with three generations of matter fermions, gauge bosons and a Higgs boson. Figure taken from User:MissMJ et al. (2014)

2.3 Luminosity

The quantity that measures the ability of a particle collider to produce the required number of interactions is called the luminosity $\mathcal{L}$. Its precise knowledge is important since for many cross-sections measurements the uncertainty factor on the luminosity dominates the final result. Luminosity is the proportionality factor between the number of events per second $R(t)$ at a given time t and its production cross-section σ_P for a process:

$$R(t) = \mathcal{L}(t) \cdot \sigma_P \tag{2.1}$$

This defines the so-called instantaneous luminosity commenly measured in units of $cm{-}2s^{-1}$. Typically running conditions vary with time t. Therefore, the luminosity of a collider also has a time dependence that needs to be carefully measured to arrive at an (time) integrated luminosity for a given data taking period which is given as:

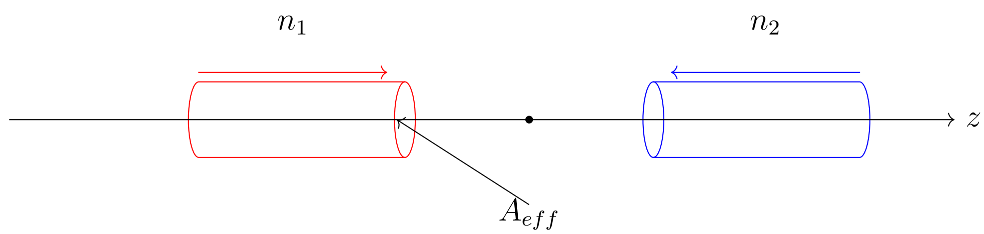

Figure 2.3: Colliding beam bunches

$$\mathcal{L}_{int} = \int \mathcal{L}(t)dt \tag{2.2}$$

and measured in units of b^{-1}. The delivered integrated luminosity, which refers to the integrated luminosity which the machine has delivered to an experiment, and recorded integrated luminosity, which refers to the amount of data that has actually been stored to disk by the experiments typically differ and hence an independent measurement by experiment is necessary.

As $\mathcal{L}$ is process-independent it is possible to measure the luminosity with any process whose cross-section is known. For a precise luminosity determination, however, it is essential that the process has precise theoretical predictions and at the same time that its rate can be accurately measured, i.e. enough are produced in a limited time interval. The production of Z^0 bosons ($pp \to Z^0X$) that decay into leptons, particularly muons ($Z^0 \to \mu^+\mu^-$), is such a "standard candle process", because the leptons can be well identified and theoretical prediction of the cross section has only a few percent relative uncertainty. The cross-section of Z^0 production is large enough and there are almost no fake signals.

The instantaneous luminosity can be extracted from certain beam parameters. A simplified case for a head-on collision of two bunches is shown in Figure 2.3. The luminosity can be expressed from geometry and the number of particles in each of the two colliding beam bunches $n_{1(2)}$:

$$\mathcal{L} = \frac{n_1 n_2 f}{A_{eff}} \tag{2.3}$$

with f the collision frequency. Beam parameters for the LHC are listed in Table 2.2. Of the possible 3564 bunches only $n_b = 2808$ are filled reducing the peak luminosity accordingly. The beam current $I_{1(2)}$ is given in terms of the charge of the beam particle e and the collision frequency f as $I_i = e_i f n_i$. Hence, one obtains

$$\mathcal{L}_{int} = \frac{I_1 I_2}{e^2 f A_{eff}} \tag{2.4}$$

With a nominal instantaneous luminosity of $\mathcal{L} = 10^{34} cm^{-2} s^{-1} (= 10 nb^{-1} s^{-1})$ and a Higgs production cross section of $\sigma \simeq 0.1 nb$ one expects about 1 Higgs per second. Figure 2.4 shows the cross sections for several processes at a 10 times lower nominal luminosity that has been achieved so far with the LHC. At this luminosity also about 100 Z^0 particles are produced per second. Only 3.4 % of Z^0's decay into a muon pair resulting in about 3 Z^0 particles per second that are potentially detected with CMS.

Beam Parameter	**Unit**	**Value**
Proton Energy	[GeV]	6500
Stored energy per beam	[MJ]	363
Number of particles per bunch n_i		1.15×10^{11}
Number of bunches n_b		2808
Bunch collision frequency f	MHz	40
Circulating beam current	[A]	0.584
Transverse beam size $(\sigma_{x,y})$	μm	16.7
RMS bunch length $(\sigma_z$	cm	7.55
Geometric luminosity reduction factor F		0.836
Peak luminosity in IP1 and IP5	$[cm^{-2} sec^{-1}]$	10^{34}

Table 2.2: LHC beam parameters relevant for the peak luminosity Bailey and Collier (2004)

Assuming that the transverse profile of the two bunches distribute identically and that the profiles do not change along the bunch a good approximation is a Gaussian profile for the beam transverse distribution in x and y, each characterized with a standard deviation σ_x and σ_y, respectively. In this case $A_{eff} = 4\pi\sigma_x\sigma_y$. It implies that the profiles in x and y are not correlated.

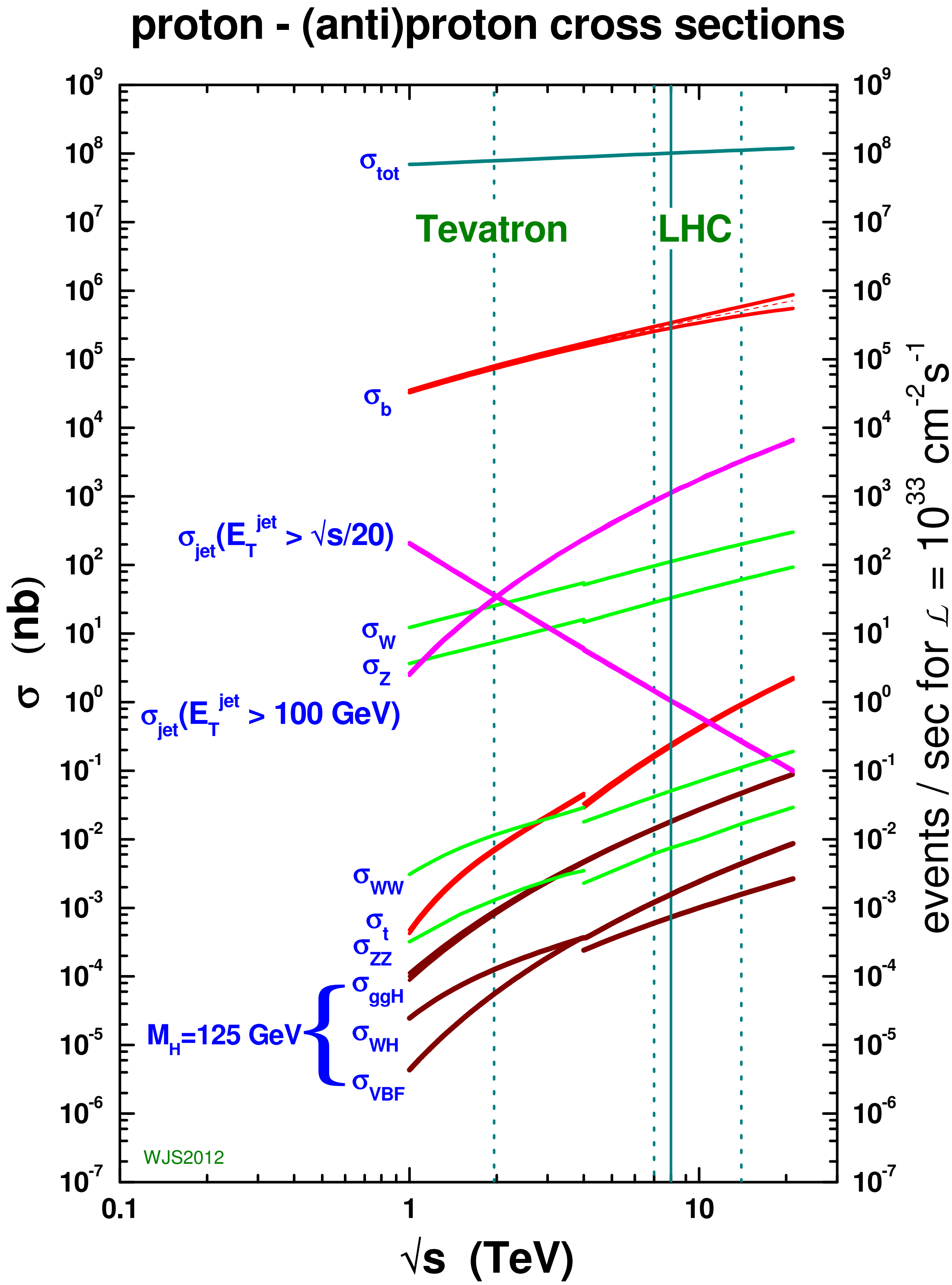

Figure 2.4: The cross sections and expected production rates at the LHC and the Tevatron.

The two beams at the LHC corss each other under an angle of $\theta_C = 285\mu rad$ to direct the beams after collision into their respective vacuum pipe and to avoid multiple unwanted interactions. Figure 2.5 shows a schematic illustration of the beam crossing. It also shows a change in the profile along the beam width. The correct evaluation of the effective beam size is obtained from an overlap integral of beam density distribution functions in all three coordinates Herr and Muratori (2003). For small angles, Gaussian profiles and $\sigma_x \simeq \sigma_y$ in good approximation this results in the so called geometric luminosity reduction factor F, given as

$$F = \left(\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2} \right)^{-1} \tag{2.5}$$

that multiplies eq. 2.3.

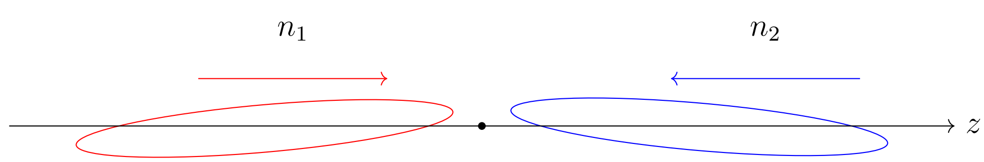

Figure 2.5: Beams colliding at some angle

In practice, however, there are complications: beams do not factorize as the profile changes over the length of the bunch and bunches do not collide exactly head-on but with offsets. Imperfections in the beam steering lead to widening of the beam profile and in turn smaller luminosity. So far also a uniform population of the beam bunches is assumed while in reality the actual fill pattern can vary. The LHC provides measurements of beam currents and beam profiles along the LHC accelerator but not in the vicinity of the interaction points. Furthermore, the beam parameters and conditions change over the time period of a LHC fill. To arrive at the best time-integrated luminosity the time integral has to be taken over time intervals short enough to measure significant variations and exclude dead times. Typically the beam intensity decays exponentially with time resulting in a similar reduction in the instantaneous luminosity. The effective mean lifetime of the luminosity is further reduced by the increase of the transverse and longitudinal beam size over time. To reduce uncertainties due to extrapolation from beam parameter measurements the CMS experiment has to measure the relative luminosity with dedicated detectors and calibrate them with standard candle processes or dedicated calibration runs of the LHC.

2.4 Luminosity Calibration

One can obtain the absolute luminosity directly from beam parameters according to Eq. 2.2, without the a priori knowledge of any physics cross section. The revolution frequency f is well known and the number of particles $n_{1(2)}$ can be measured by dedicated beam charge monitors. In contrast, the transverse area of beam overlap A_{eff} is difficult to determine. Different monitors such as wire scanners or synchrotron light monitors can sample the beam profile but not close to the collision points and extrapolations lack precision. In the year 1968 Simon van der Meer has proposed a method to measure A_{eff} Van Der Meer (1968), now known as van der Meer- (vdM-) or beam separation- scans.

Simon van der Meer proposed that it is possible to measure the profile of colliding beams by observing the counting rate R in a particle counting system, while scanning the two beams vertically through each other. One of the two beams is displaced vertically with respect to the other one, and the counting rate in the monitor is plotted versus displacement. A bell-shaped curve will result with its maximum at zero displacement irrespective of beam shape heff is equal to the area under this curve, divided by the ordinate for zero displacement Van Der Meer (1968). At the LHC bunched beams are colliding and therefore the measured counting rate depends on both horizontal and vertical beam sizes. The main assumption is that the density distributions of particles in bunches can be factorized, and two scans along the transverse planes are sufficient. If one assumes that the beam density functions are uncorrelated one can write for the counting rate R as function of displacement in

x and y, δx and δy, respectively:

$$R(\delta x; \delta y) = R_x(\delta x) R_y(\delta y) \tag{2.6}$$

By scanning the two transverse planes, one gets a direct measurement of the transverse effective beam sizes and therefore of the effective area A_{eff}:

$$A_{eff} = \frac{\int R_x(\delta x) d\delta x}{R_x(0)} \frac{\int R_y(\delta y) d\delta y}{R_y(0)} \tag{2.7}$$

The convoluted transverse width per scan direction of the two beams can be written as:

$$\Sigma_x = \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2} = \frac{1}{\sqrt{2\pi}} \frac{\int R_x(\delta x) d\delta x}{R_x(0)} \tag{2.8}$$

and the same expression for Σ_y in y direction. The luminosity Eq. 2.2 becomes:

$$\mathcal{L}_{\text{int}} = \frac{n_1 n_2 f}{2\pi \Sigma_x \Sigma_y} \tag{2.9}$$

In case of a crossing angle, the vdM scan measures directly the correct effective beam size, including the effect of a crossing-angle for scans performed exactly in the crossing plane White et al. (2010) Figure **??** shows the rate of particle tracks as measured with the PLT versus the separation in the beam in x direction. The data points have been fit to a Gaussian function. A refined fit uses two Gaussian functions to achieve an improved description of the tails in the distribution.

The CMS collaboration uses the PLT detector to measure and monitor the relative luminosity. Once calibrated, one can extrapolate the absolute luminosity measurement of the vdM scan to any other luminosity scenario. With R_{inel} to be the rate of inelastic pp events, σ_{inel} the pp inelastic cross-section, f the revolution frequency of the bunches, and μ the average number of pp-collisions per bunch-crossing:

$$\mathcal{L}_{\text{int}} = \frac{R_{\text{inel}}}{\sigma_{\text{inel}}} = \frac{\mu f}{\sigma_{\text{inel}}} \tag{2.10}$$

The PLT detector with limited acceptance times detection efficiency ω will only see a subset of the events:

$$\mathcal{L}_{\text{int}} = \frac{\omega\mu f}{\omega\sigma_{\text{inel}}} = \frac{\mu_{\text{vis}} f}{\sigma_{\text{vis}}} \tag{2.11}$$

The index *vis* stands for visible value. Hence, the μ_{vis} can be measured and svis = esinel is practically the calibration constant to obtain the absolute luminosity. In general, this equation is valid only in the case of a linear response of the detector with respect to μ. Otherwise corrections for the non-linearity must be taken into account.

2.5 Luminosity Measurement

The PLT detector consists of two symmetric detector arms placed on each side of the CMS interaction point (IP5). Each side is further divided into eight telescopes with each treated as separate readout channel. Particles passing through one of these telescopes are counted as hit if their charge signals in all three detectors of the telescope are simultaneously above threshold (Fast-OR). A bunch crossing is counted as an event when there is at least one hit. The typical rate μ per bunch crossing in 2015 was 1 hit on each side respective a detector occupancy of about 0.15/BCX. Particles not originating from bunch collisions but rather collision in the beam gas and with beam halo particles result in a miscount of the luminosity and are subtracted statistically after a detailed analysis of their relative contribution.The relative contribution from such background was at most 7% in 2015. The analysis is described in Sect. **??**. The luminosity is determined by event-counting. A disadvantage of this method is that one is limited to measure either any hit or no-hit event which at high μ results in the event probability approaching one. Then every bunch crossing will be counted as an event and the method does not work anymore (is saturated).

One can derive the probability for multi-interaction events making the assumption that the number of *pp* interactions during a bunch crossing follows a Poisson statistics the following:

$$P_\mu(n) = \sum_{n=0}^{\infty} \frac{\mu^n e^{-\mu}}{n!} \tag{2.12}$$

where $P_\mu(n)$ is the probability to have n interactions in a bunch crossing when the average number of interactions is μ. Furthermore, the probability to detect a single interaction ω (efficiency $\times$ acceptance of the PLT Fast-OR) is assumed not to change when several events in the same bunch crossing happen. This effect is expected to be negligible for occupancies of significantly less than 1 per bunch crossing per channel. The probability for *not* detecting a bunch crossing that has n interactions is given as:

$$P_0(n) = (1 - \omega)^n \tag{2.13}$$

With n distributed according to a Poissonian the probability to measure μ interactions when the average number is zero is:

$$P_0(\mu) = \sum_{n=0}^{\infty} (1 - \omega)^n \cdot P_\mu(n) \tag{2.14}$$

and using the expansion one obtains:

$$P_0(\mu) = e^{-\omega\mu} = e^{-\mu_{vis}} \tag{2.15}$$

With N_{OR} the number of Fast-OR events in a given time interval, and N_{BCX} the corresponding number of bunch crossings, the probability to observe a Fast-OR P_{OR} in a given bunch crossing is:

$$P_{OR}(\mu) = \frac{N_{OR}}{N_{BCX}} = 1 - P_0(\mu) = 1 - e^{\mu_{vis}} \tag{2.16}$$

From the latter two one obtains an expression for μ_{vis}:

$$\mu_{vis} = -ln(1 - P_{OR}(\mu)) \tag{2.17}$$

The PLT obtains μ_{vis} per telescope for each of the potential 3564 bunch positions for 4096 orbits of the LHC beam, also called nibble corresponding to 0.365 ms. Instead of counting N_{OR} the fraction $f_0 = (1 - N_{OR}/N_{BCX})$ of no triple coincidences in that interval is measured. This has the advantage that the multiplicity of tracks does not have to be resolved and readout only has to register signal or no signal, 0 or 1, respectively. This is the digital mode and the method is called zero-counting. The mean number of tracks per collision is given as $\mu_{vis} = -\ln(f_0)$. The μ_{vis} is then summed over all bunch crossings and averaged over all telescopes and translated into the luminosity with the calibration constant σ_{vis}. Recently, instead of averaging over telescopes, the luminosity is provided on a per-telescope basis.

Chapter 3

Experimental Setup

Chapter 4

Operations of PLT

Chapter 5

Event Reconstruction

Chapter 6

Luminosity Correction

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Appendix

Appendix A

Summary of Equations

A.1 Cartesian

some equations here

A.2 Cylindrical

some equations also here

Vita

Vita goes here...