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DIVISIÓN DE CIENCIAS EXACTAS Y NATURALES
DEPARTAMENTO DE INVESTIGACIÓN EN FÍSICA

MEASUREMENTS OF THE LARGE HADRON COLLIDER LUMINOSITY USING THE CMS SILICON PIXEL DETECTOR

THESIS

in partial fulfillment of the requirements for the degree of:

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Acknowledgements

Abstract

Resumen

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Chapter 1

Introduction

1.1 Fundamental Particles

shown in table 1.1.

Table 1.1 Force experienced by the fermions

		Electromagnetic	**Weak**	**Strong**
Leptons	e μ τ	✓	✓	
	ν_e ν_μ ν_τ		✓	
Quarks	u c t	✓	✓	✓
	d s b	✓	✓	✓

1.2 Particle Colliders

1.3 Cross section

1.4 Luminosity

1.5 Importance of Luminosity precision

1.6 The Large Hadron Collider

1.7 LHC Luminosity

Chapter 2

Experiment Description

2.1 The Compact Muon Solenoid

2.2 CMS Tracking System

$$-\frac{dE}{dx} = \frac{Dq^2 n_e}{\beta^2}\left[\ln\left(\frac{2m_e c^2 \gamma^2}{I}\right) - \beta^2 - \frac{\delta(\gamma)}{2}\right] \tag{2.1}$$

2.2.1 Pixel Detector and Clustering

2.2.2 CMS Luminometers

Chapter 3

Luminosity Measurement and Calibration

$$R = \mathscr{L}_{inst}\sigma_{vis} \tag{3.1}$$

3.1 Pixel Cluster Counting method

$$\langle N_{\text{cluster}} \rangle = \left\langle N_{\text{pixel/interaction}} \right\rangle \langle N_{\text{interactions}} \rangle \equiv \left\langle N_{\text{pixel/interaction}} \right\rangle \mu \tag{3.2}$$

where in the last step, the average number of interactions per bunch crossing, pileup, is denoted by the symbol μ.

3.2 Luminosity calibration: van der Meer method

$$\int \rho_{x1}(x)\rho_{x2}(x)dx = \frac{R_x(0)}{\int R_x(\Delta)d\Delta} \tag{3.3}$$

where $R_x(\Delta)$ is the rate measured when the two beams are separated in x by a distance Δ; a asimilar equation can be written in y. Then the beam overlap width Σ_x (and similarly Σ_y) is defined as [1]:

$$\Sigma_x = \frac{1}{\sqrt{2\pi}}\frac{\int R_x(\Delta)d\Delta}{R_x(0)} \tag{3.4}$$

yielding the final expression for luminosity (for one single bunch):

$$\mathscr{L}_{inst} = \frac{N_1 N_2 f}{2\pi \Sigma_x \Sigma_y} \tag{3.5}$$

where $N_{1,2}$ are the particles per bunch (bunch current) and $f = 11246$ Hz is the bunch orbit frequency around the LHC ring.
This expression can be finally used in 3.1 to get σ_{vis}:

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y R(0,0)}{N_1 N_2 f} \tag{3.6}$$

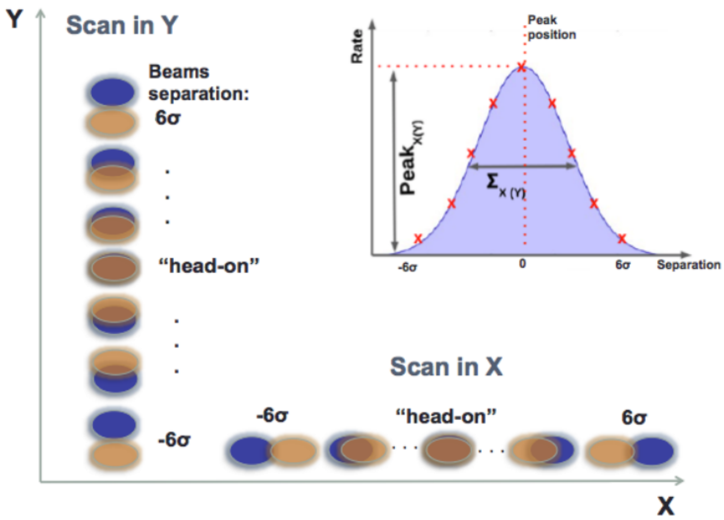

Fig. 3.1 The sketch of a vdM scan in X and Y planes. The indent sketch is an example of the fitting of the resulting rates [2].

Backgrounds

Chapter 4

Analysis and Results

4.1 2018 vdM scan program

4.2 Data analysis

4.3 Module selection

4.4 Background estimation

Table 4.1 Background mean value and SEM of each BCID for both SS periods .

SS period I

BCID	**Mean**	**SEM**
265	0.3111	0.0172
865	0.2732	0.0135
1780	0.3223	0.0187
2192	0.2875	0.0159
3380	0.3157	0.0162

$\mathrm{SSI}_{\mathrm{Avg}} = \quad 0.302 \pm 0.0073$

SS period II

BCID	**Mean**	**SEM**
265	0.3027	0.0148
865	0.297	0.0156
1780	0.304	0.0167
2192	0.2225	0.0114
3380	0.3064	0.0169

$\mathrm{SSII}_{\mathrm{Avg}} = \quad 0.287 \pm 0.0068$

Table 4.1 shows the mean en SEM values for each BCID for both SS periods and the average and error ($AvgErr = \sqrt{SEM_1^2 + SEM_2^2 + \cdots SEM_N/N})$) per SS period. Having both average values of SS, the average and error is taken, being this the value applied as a background correction: 0.29 ± 0.005.

4.5 Corrections

The PCC rates per NB4 are averaged per scan step (30s) and the uncertainty is calculated as the SEM. The following corrections are applied in the vdM FW:

1. Ghost and Satellite. Corrects for the presence of ghost and satellite spurious charges. This correction affects bunch currents. Satellite charges refers to charge in the colliding bunch crossing but not in the colliding RF bucket, while spurious charges refers to charge not in any nominally filled bunch slot.
2. Background. Value estimated above is subtracted to the rates.
3. Orbit drift. The Orbit Drift (OD) correction is composed of two independent corrections: separation correction and a rate correction. OD separation aims at correcting for the orbit drift in the scanning direction and only affects beam separation. OD rate aims at correcting for the orbit drift in the direction orthogonal to the scanning direction and only affects luminometer rate. The derived correction assumes that the beam overlap has a single gaussian shape. The correction reads the Σ in the orthogonal direction from the previous correction.
4. Beam Beam. Corrects Beam Beam deflection (BB) that happens during bunch crossings at the collision point. The deflection is calculated and added to the nominal separation.
5. Dynamic Beta. The so-called dynamic-$\beta*$ effect, which accounts for the fact that each beam has a defocusing effect on the other. This effect is calculated using reference beam transport simulations that are scaled to the beam energies, the β^* settings, and the measured intensities and convoluted beam widths.
6. Length Scale. It applies a linear scaling to the beam separation to convert it from the "CMS scale" to the actual "physics scale". This correction is estimated by analyzing pp collision vertices reconstruced by the CMS tracker.
7. Peak to peak. Corrects for error in peak calculation, when the scan does not cover the actual head-on collision of the beams.

4.6 van der Meer Scans and σ_{vis} Results

The measurements of PCC, beam separation and beam currents were plotted, fitted and corrected with the corrections described above. The fit model impleted is a guassian-like function:

$$Poly\mathbf{2}G = P \cdot \left[1 + r_2 \cdot \left(\frac{x - \bar{x}}{\frac{\sigma}{1+r_2}}\right)^2\right] \cdot \exp\left[-\frac{1}{2}\left(\frac{x - \bar{x}}{\frac{\sigma}{1+r_2}}\right)^2\right]$$

where P is the peak value, $\bar{x}$ the mean, and σ (standard deviation) and r_2 are fit parameters. This model will be referred as "Poly2G". Fig. 4.1 shows the fitted graphs of the first vdM scan pair for BCID 1780. Fig. 4.2 shows the same graphs in logarithmic scale. Note that rates are normalized by the beam currents, which is a factor of eq. 3.6 ($R(0,0)/N_1N_2$).

The rest of the BCIDs, vdM and imaging scans present a very similar behaviour. Fig 4.3 shows a plot of the chi2/ndof for all the seven scan pairs, having a mean value of 2.23. In all cases the fits converged. The $\Sigma_{x,y}$ (referred also as CapSigma) and peak values were extracted from the fits to compute σ_{vis}. Fig 4.4 shows $\Sigma_{x,y}$ and peak values for all scan pairs. As can be seen, both values reflects the fact that beam size increased over time in the x dimension and decreased over time in the y dimension.

Chapter4/plots/xscan.png Chapter4/plots/yscan.png

Fig. 4.1 Normalized rates and the resulting fitted curves with the Poly2G fit model (see text) as a function of the beam separation (Δ) for BCID 1780 for X (left) and Y (right) scan for the first vdM scan. Background subtraction and the corrections described in the previous section have been applied to the raw data before the fit.

Chapter4/plots/xscan_logy.png Chapter4/plots/yscan_logy.png

Fig. 4.2 Fig. 4.1 in logarithmic scale.

Chapter4/plots_thesis/chi2_Poly2G.png

Fig. 4.3 chi2/ndof for all the scan pairs. Vertical blue lines divide the X (left) and Y (right) scans. In each scan, the BCIDs follow the same order: 265, 865, 1780, 2192, 3380.

The σ_{vis} of each BCID is computed from the fit results parameters showed in previous section ($\Sigma_{x,y}$ and peak) using 3.6 with $R(0,0) = (Peak_x + Peak_y)/2$; $Peak_{x,y}$ values are already normalized so 3.6 is rewritten as $\sigma = 2\pi\Sigma_x\Sigma_y(Peak_x + Peak_y)/2$.
Fig 4.5 shows σ_{vis} per BCID for all the scans. The error on σ_{vis} is assigned as $\sigma_{vis\mathrm{Err}} = 2\pi\sqrt{(\Sigma_y \cdot R \cdot \Sigma_{x\mathrm{Err}})^2 + (\Sigma_x \cdot R \cdot \Sigma_{y\mathrm{Err}})^2 + (\Sigma_x\Sigma_y R_{\mathrm{Err}})^2}$.
Fig 4.6 shows σ_{vis} per Scan, which corresponds to the weighted average of the five BCIDs with the weight as $1/\sigma^2_{vis\mathrm{Err}}$. The error is assigned as $1/\sqrt{\sum \frac{1}{\sigma^2_{vis\mathrm{Err}}}}$.

The σ_{vis} per scan are averaged and assigning the error in the same way described above, giving a value of 9229 ± 8(stat.)mb.
As can be seen in Fig 4.6 (and Fig 4.5), there is some systematic variation in σ_{vis} from scan to scan, being the first vdM scan lower than the rest of the scans. The systematic error is assigned as $\sqrt{RMS^2 - stat^2}$.
Therefore the σ_{vis} value is

$$\sigma_{vis} = 9229 \pm 8(\text{stat.}) \pm 28(\text{syst.})\text{ mb.} \tag{4.1}$$

This value is higher than the previously reported in ref. [1]: 5982 mb, which corresponds to a different selection of modules in the pixel detector. In the previous result, Chapter4/plots_thesis/CapSigma_Poly2G.png Chapter4/plots_thesis/peak_Poly2G.png

Fig. 4.4 Σ (left) and Peak values (right) extracted from the fitted graph to compute σ_{vis}. Vertical blue lines divide the X (left) and Y (right) scans. In each scan, the BCIDs follow the same order: 265, 865, 1780, 2192, 3380.

Chapter4/plots_thesis/Poly2G_xsec.png

Fig. 4.5 σ_{vis} per BCID for all the scans. In each scan the BCIDs follow the same order: 265, 865, 1780, 2192, 3380.

1069 modules were removed, whereas the value of 9229 mb corresponds to 802 modules removed; the rate of pixel clusters is proportional to the number of modules.

Chapter4/plots/xsec_perscan_v2.png

Fig. 4.6 σ_{vis} per scan.

Chapter 5

Summary and Outlook

References

[1] CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV. Technical report, CERN, Geneva, 2019. URL https://cds.cern.ch/record/2676164.

[2] Olena Karacheban. Performance of the BRIL luminometers at CMS in Run 2. *PoS*, EPS-HEP2019:194, 2020. doi: 10.22323/1.364.0194.