IMPACT OF THE CROSSING ANGLE ON LUMINOSITY ASYMMETRIES AT THE LHC IN 2016 PROTON PHYSICS OPERATION

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Abstract

During 2016 proton physics operation at the CERN Large Hadron Collider (LHC), an asymmetry of up to 10% was observed between the luminosities measured by the ATLAS and CMS experiments. As the same bunch pairs collide in both experiments, a difference in luminosities must be of either geometric or instrumental origin. This paper quantifies the impact of the crossing angle on this asymmetry. As the beams cross in different planes in the two experiments, non-round beams are expected to yield an asymmetry due to the crossing angle. Results from crossing angle measurements at both experiments are also shown and the impact on the luminosities is evaluated.

INTRODUCTION

The luminosity in a collider [1] assuming Gaussian bunches is given by

$$\mathcal{L} = \frac{n_b f_{rev} N_1 N_2}{4\pi\sigma_x\sigma_y}\mathcal{F} \tag{1}$$

where f_{rev} is the revolution frequency, n_b is the number of colliding bunch pairs, $N_{1,2}$ are the bunch intensities, $\sigma_{x,y}$ are the transverse beam sizes at the Interaction Point (IP) and $\mathcal{F}$ is the geometric factor

$$\mathcal{F} = \frac{1}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_{xing}}\frac{\alpha}{2}\right)^2}} \tag{2}$$

where σ_s is the r.m.s. bunch length, σ_{xing} is the transverse beam size in the crossing plane, and α is the full crossing angle.

The transverse beam size in either plane can be expressed as $\sigma_{x,y} = \sqrt{\beta^*\gamma^{-1}\varepsilon_{x,y}}$ where $\varepsilon_{x,y}$ are the normalized transverse emittances, β^* is the β-function at the IP, and γ is the relativistic factor.

At the LHC, the beams cross in the vertical plane in the ATLAS experiment (IP1) and in the horizontal plane in the CMS experiment (IP5). If the beams are not round ($\sigma_x \neq \sigma_y$), or the crossing angles are not equal in the two IPs, this causes a luminosity ratio equal to the ratio of the geometric factors[1] [2]

$$\mathcal{R} = \frac{\mathcal{L}_{ATLAS}}{\mathcal{L}_{CMS}} = \frac{\mathcal{F}_{IP1}}{\mathcal{F}_{IP5}} = \frac{\sqrt{1+\left(\frac{\sigma_s}{\sigma_y}\frac{\alpha_{IP5}}{2}\right)^2}}{\sqrt{1+\left(\frac{\sigma_s}{\sigma_x}\frac{\alpha_{IP1}}{2}\right)^2}} \tag{3}$$

[1] under the assumption of equal β^* and hence equal beam sizes in IP1 and IP5

OBSERVED LUMINOSITY RATIO

The measured[2] peak luminosities during 2016 proton physics are shown in Fig. 1, the ratios are displayed in Fig. 2. The ratio of the total integrated luminosities over the year was $\mathcal{R} = 0.94$.

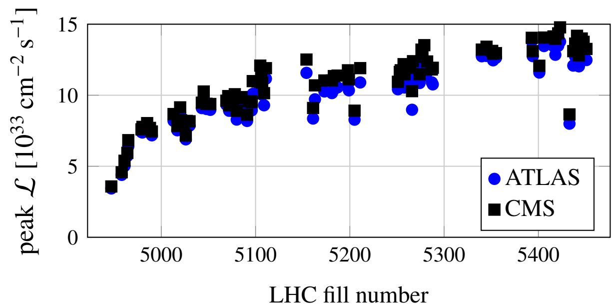

Figure 1: Peak luminosities of ATLAS and CMS in 2016.

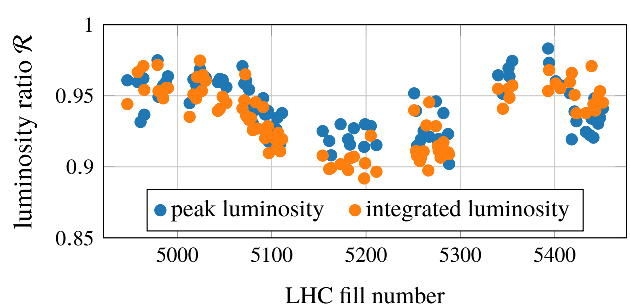

Figure 2: ATLAS/CMS luminosity ratio in 2016.

The trends over the year are introduced by machine setting changes. Starting from fill 5079, the LHC injectors used the "BCMS" beam production scheme [3] for reducing the transverse emittance. As of fill 5300, the nominal crossing angle was changed from ±185 μrad to ±140 μrad.

A change in luminosity ratio was also observed after fill 5416, but could not be traced to a change in the settings, and is thus still under investigation.

PREDICTED LUMINOSITY RATIO

Non-Round Beams

Following Eq. (3), the luminosity ratio $\mathcal{R}$ can be predicted if the transverse emittances $\varepsilon_{x,y}$, the bunch length σ_s and

[2] All luminosity and luminous region data used in this paper is courtesy of the ATLAS and CMS experiments and is based on quasi-online measurements. It is not based on a published luminosity analysis of the experiment collaborations, which is still ongoing.

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the crossing angles α are known. An example for typical 2016 LHC beam parameters is given in Fig. 3.

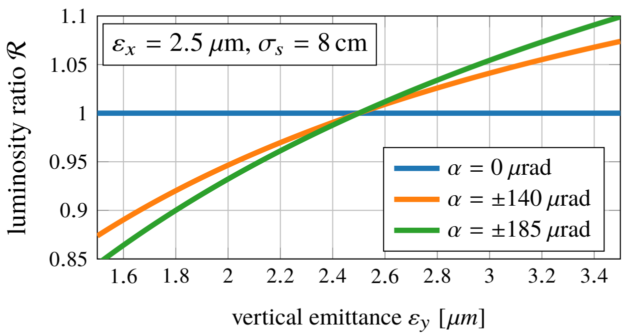

Figure 3: Expected geometrical luminosity ratio for typical 2016 beam parameters. A typical vertical emittance at the start of collisions was $\varepsilon_y \approx 2\,\mu$m, resulting in $\mathcal{R} \approx 0.95$.

The transverse emittances are measured at the LHC by Synchrotron Light Telescopes (BSRT) [4], emittance scans [5] and by the LHC experiments measuring the vertex distribution in collisions ("luminous region") [6, 7]. The bunch length is measured by the LHC Beam Quality Monitor [8]. The crossing angles are assumed to be at their nominal values.

Luminous Length Ratio

Following [9], assuming equal Gaussian beams, the ratio of the longitudinal vertex distributions (luminous lengths, $\sigma_{z,Lum}$) in the two experiments is equal to the ratio of the geometric factors, and hence, to the expected luminosity ratio.

$$\frac{\sigma_{z,Lum,ATLAS}}{\sigma_{z,Lum,CMS}} = \frac{\mathcal{F}_{IP1}}{\mathcal{F}_{IP5}} = \mathcal{R} \qquad (4)$$

It should be noted that this method is independent of any other measurement. In particular, no assumptions on the crossing angles or the bunch length are made.

Error Considerations

The systematic error on the observed ATLAS/CMS luminosity ratio is 4.2 % from uncorrelated errors of 3.4 % [10] on the ATLAS luminosity and 2.5 % [11] on the CMS luminosity.

The transverse luminous region sizes are very sensitive to systematic uncertainties due to the vertex resolution correction, which is a factor of ~3 higher than the measured width. The BSRT predictions have systematics on the calibration at a ~10 % level [12].

A preliminary estimate of the systematic uncertainty affecting the luminous-length ratio during routine physics running suggests that it does not to exceed 5 % [13].

Further general sources of systematic errors, applicable to all predictions, include the non-Gaussianity of the bunch profiles [14] (5 %), bunch-to-bunch differences (1.5 %), and differences between the two beams (1 %).

Comparison to Data

The predicted and observed luminosity ratios over the course of an LHC fill are compared in Fig. 4. All methods exhibit the same time evolution; at any given time, the differences between the absolute magnitude of the ratios remain within the corresponding systematic uncertainties.

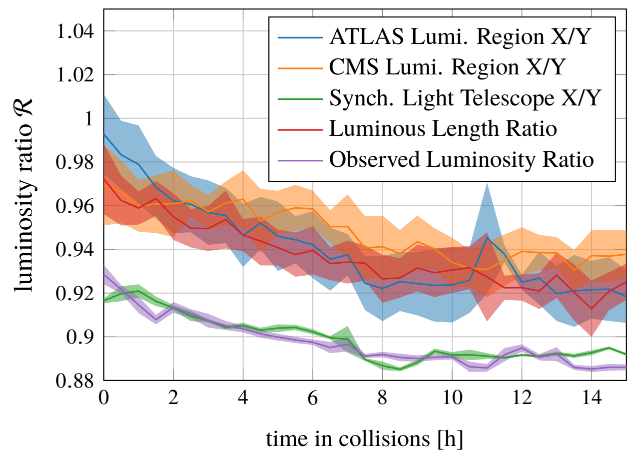

Figure 4: Predicted and observed luminosity ratios in LHC fill 5173. Note that the error bands only include statistical but not systematic errors.

In Fig. 5, the observed ratio of peak luminosities throughout 2016 is compared to the predictions of various methods. Up to fill 5416, the trends following machine settings changes are well represented by all predictions. The absolute estimates are within systematic errors.

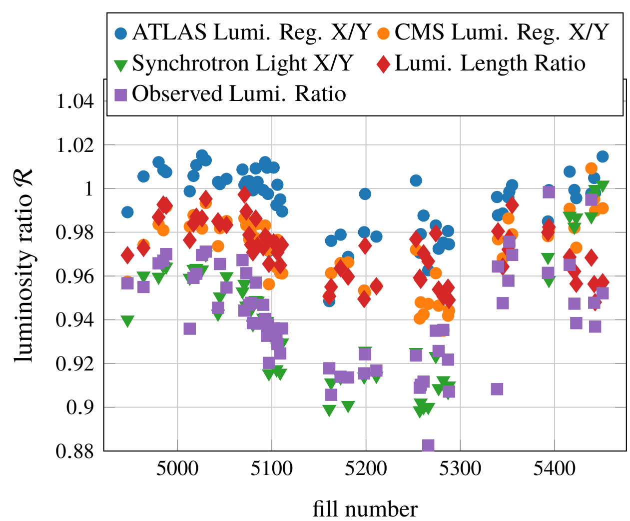

Figure 5: Predicted and observed luminosity ratios at the start of collisions in 2016.

ZERO CROSSING ANGLE TEST

To directly probe the effect of the crossing angle on the luminosity ratio, a special zero crossing angle test fill was carried out in LHC fill 5422. For this test, LHC was filled with 4 colliding bunch pairs of different transverse emittances. Once in collision, the crossing angle was reduced from ±140 μrad to 0 μrad, and the change in luminosity was recorded.

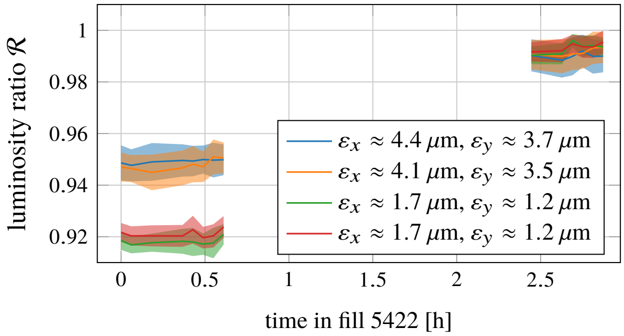

Figure 6: Observed luminosity ratios during the zero crossing angle test fill 5422 with statistical error bands. The period with no data is during the crossing angle adjustment.

In Fig. 6 the bunch-by-bunch luminosity ratio before and after the crossing angle reduction is shown. At the nominal crossing angle, the four bunches exhibited different luminosity ratios due to their different transverse emittances. After the crossing angle was reduced to 0, this difference vanished as the luminosity ratio was decreased by ~7 % for the low-emittance bunches and ~4 % for the high-emittance bunches. The residual luminosity ratio of ~1 % is within the expected systematic uncertainties.

CROSSING ANGLE MEASUREMENT

In LHC fill 5422, the crossing angle was measured using the k-modulation technique [15]. Modulating the current and hence the kick of a quadrupole which the beam passes off-center leads to a dipolar kick which is proportional to the beam offset. The resulting orbit oscillation at a point s in the ring[3] is given in by

$$\Delta u(s) = \frac{\sqrt{\beta(s)\beta_{Q1}}\ \cos(\left|\mu(s) - \mu_{Q1}\right| - \pi Q_u)\,\Delta k L_{Q1}\, u_{Q1}}{2\sin(\pi Q_u)} \tag{5}$$

To measure the crossing angle, the kick of the inner LHC quadrupoles next to the interaction point (Q1) was modulated and the orbit oscillation was measured by the LHC Beam Position Monitor (BPM) system (Fig. 7).

As there is no machine magnetic element between the Q1 and the IP, the distance can be treated as drift space, and the crossing angle results follows directly from the beam separation in the Q1 and the distance $d_{Q1,IP}$ to the IP:

$$\alpha = \frac{\left|u_{Q1,B1} - u_{Q1,B2}\right|}{d_{Q1,IP}} \tag{6}$$

This calculation can be made for both the left and the right sides independently, which should yield the same result.

[3] under a thin-lens approximation

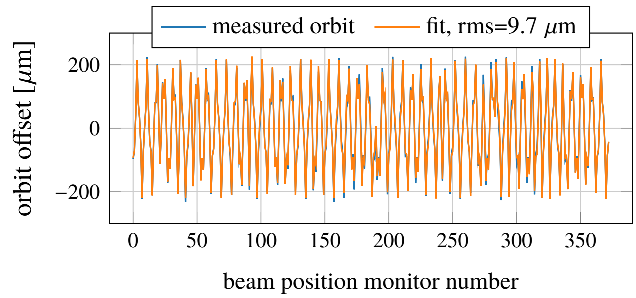

Figure 7: Horizontal orbit oscillation of Beam 1 and fit of Eq. (5) during Q1 k-modulation in IP5. The fit quality is similar for all measurements.

The half crossing angles measured using this method were 155 ± 10 μrad for IP1 (ATLAS) and 153 ± 12 μrad for IP5 (CMS) for a nominal half crossing angle of 140 μrad. The errors are mostly correlated between IP1 and IP5. While this indicates that the crossing angles were up to ~10 % larger than their nominal values, no significant difference between IP1 and IP5 was observed.

CONCLUSIONS

An imbalance between the luminosities delivered to the ATLAS and CMS experiments was observed in 2016. The ATLAS-to-CMS luminosity ratio was ~0.95 early in the year, and dropped to ~0.91 after the reduction of the transverse emittance ("BCMS" beam production scheme). After decreasing the crossing angle from ±185 μrad to ±140 μrad, the ratio increased to ~0.95.

A large part of the imbalance can be explained by geometrical considerations. As the beams are crossing in different planes in the two experiments, non-round beams lead to different geometric reduction factors and hence different luminosities. Using the transverse emittances measured by the Synchrotron Radiation Telescopes (BSRT), the luminosity ratio is well predicted for a large part of the year. The predictions based on the luminous region measurements are subject to significant systematic uncertainties, but agree on trends, both over the course of a fill and over the year.

During a special zero crossing angle test fill, the luminosity imbalance was reproduced at the initial crossing angle of ±140 μrad, and vanished once the crossing angle was removed.

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