PoS PROCEEDINGS OF SCIENCE

Beam-beam interaction-induced bias to precision luminosity measurement

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The mutual electromagnetic interaction between counter-rotating bunches crossing at the interaction points (IPs) of a particle collider has been studied since the dawn of the storage-ring era. It can result in a significant bias to absolute-luminosity calibrations determined by the van der Meer (vdM) method. Numerical models developed to study such beam—beam-induced biases at a single IP of the Large Hadron Collider (LHC) have been recently extended to better account for actual operating conditions, such as head-on collisions at non-scanning IPs during vdM scans, or scans performed during physics data-taking using higher-brightness beams than used during vdM-calibration sessions. As part of a long-term effort aimed at quantifying the beam-beam bias to luminosity-related observables in hadron colliders, in this paper we compare results from a dedicated beam-beam experiment performed at the LHC in 2022 to the predictions of the numerical model. We also report some preliminary observations about the impact of the beam-beam interaction on the instantaneous luminosity during physics operation, and investigate beam-beam contributions to the apparent non-linearity and overall stability of experimental luminometers during physics data taking.

**** EPS-HEP ****
**** 20-25 August 2023 ****
**** University of Hamburg, Hamburg, Germany ****

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PoS(EPS-HEP2023)624

1. Introduction

Recent advances have significantly improved our understanding of beam-beam systematic effects, crucial for precise van der Meer (vdM) calibrations. Through extensive multi-particle simulations, these improvements have led to an approximately -1% shift in absolute integrated luminosity compared to pre-2021 results [1]. In this report, we summarize a newly developed strategy for addressing beam–beam-induced systematic effects [2], with a focus on accounting for biases introduced by multiple beam-beam interactions at the four experimental IPs of the LHC; we also discuss some of the factors contributing to the remaining, beam-beam-related systematic uncertainties. The results are based on a so called strong-strong beam-beam model implemented in the COherent Multibunch Beam-beam Interactions (COMBI) code [3]. A benchmark accelerator experiment conducted at the LHC provides an experimental validation of some of the predictions of the simulation model. These simulations can be extended to physics data-taking conditions, for example in the context of quantifying, in a detector-independent way, intrinsic luminometer non-linearities that constitute a critical concern at the HL-LHC [4].

2. Beam–beam-related biases to luminosity calibrations at the LHC

One of the largest biases potentially affecting the vdM-calibration technique [5] arises from the Beam-Beam (BB) interaction. The impact on the absolute luminosity scale can be separated into the beam-beam deflection of the two bunches of the same charge, and the optical distortion of their charge distributions. The former is a well-understood and measured effect [6]. The resulting orbit deflection can be calculated analytically from the Bassetti-Erskine formula [7]. It depends on the separation between the two beams, causing the beams to move further apart. The optical effect is more complex. All particles change their distribution within the bunch as a function of their amplitude and of the relative separation with respect to the opposing bunch. In the linear approximation, where there is no amplitude dependency, this distortion can be seen as the one produced by an extra quadrupole magnet located at the interaction point with a strength that varies as a function of the separation. Such an extra lens will result in a change of the local β-function. This is commonly referred to as the dynamic-β effect, and for an interaction point (IP) it is the change of the β^* value (minimum of the β-function). The beam-beam parameter ξ describes the linearized force for small-amplitude particles (green dotted line in Fig. 1), and is typically used to characterize the strength of the beam-beam interaction:

$$\xi = \frac{N r_0 \beta^*}{4\pi\gamma\sigma^2}, \tag{1}$$

where N is the number of charges in the source bunch, r_0 is the classical particle (proton) radius, γ is the relativistic factor, and σ is the source bunch width at the IP. However, due to the non-linear nature of the beam-beam force (red line in Fig. 1), the changes in the distribution are both separation- and amplitude-dependent. This effect is particularly important for vdM scans when evaluating the total effect over the full scan range. With increasing separation, the overlap integral of the transverse-density distributions of the colliding bunches, and therefore the collision rate (or equivalently the luminosity), are dominated by particles at increasing amplitude from the bunch cores, i.e. by those probing the strongly non-linear part of the force.

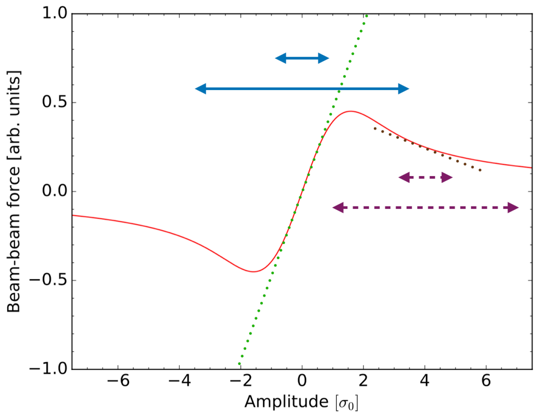

Figure 1: Beam-beam force of the source beam on a particle in another beam as a function of its amplitude. The green dotted line indicates the linear slope for small-amplitude particles. The corresponding linearised slope for higher-amplitude particles is indicated by the brown dotted line.

3. Correction strategy

Currently, the approach adopted by all LHC experiments involves modeling the beam-beam biases on vdM-based luminosity calibrations through a combination of analytical calculations and numerical simulations [2]. Two main effects are corrected for separately: deflection-induced orbit shift and optical distortions. The latter uses a simulation-based parametrization in order that it be easily scalable to the actual scanning conditions. The magnitude of the optical-distortion correction is based on the single-IP case, and depends on the beam separation, the beam-beam parameter ξ, and the nominal transverse tunes. These corrections encompass not only those beam-beam effects that occur at the IP where the scans are conducted, referred to as the "scanning IP", but also those at any additional IPs where the beams remain in a head-on collision. The additional betatron tune shift from these extra collisions [8] can be used to mimic the multi-collision bias on the vdM calibration constant. This simple scaling law was derived from numerical simulations [2, 3]; it is valid for all LHC IPs, within the full range of beam conditions encountered during vdM-calibration sessions.

A comprehensive explanation of this correction methodology as it pertains to vdM-calibration analyses can be found in Ref. [2]. The additional effect of the transverse phase-advance between IPs modulating the beam-beam tune shift and thereby the vdM-calibration constant is discussed in some detail in Ref. [9].

This strategy yields substantial corrections (approximately $1-2\%$) to the vdM-calibration constant, for both the orbit shift and the optical distortions; the combined impact, however, remains relatively minor. This approach has already been applied in the legacy ATLAS Run-2 results [1], and the forthcoming CMS results also adopt this approach.

4. Benchmark experiment

The correction strategy outlined above relies entirely on simulation findings. Although the simulation models used to evaluate the luminosity bias arising from beam-beam interactions had been validated against analytical predictions and experimental, accelerator-related measurements, they had not been tested against vdM measurements, where high precision is required. Consequently, a dedicated beam-beam experiment was designed to confirm the accuracy of the simulation predictions. The tests were conducted in July 2022 at injection energy ($\sqrt{s}$ = 900 GeV), during the Run-3 recommissioning period of the LHC. The beam-beam effects for bunch parameters close to pragmatic operational limits were predicted to be around $\sim 1\%$, while the expected precision in instantaneous luminosity was at the $\sim 0.5\%$ level. To improve the sensitivity of the measurements, the phase advance between IP1 and IP5 was modified so as to maximize the observable beam-beam beta-beating effects. This procedure resulted in a threefold enhancement of the originally expected effect. The tests were performed at different phases chosen to enhance the quality of the observations. All the phase advance adjustments between the IPs were compensated for in other sectors of the ring, in order to keep the nominal LHC collision fractional tunes unchanged. The design of this new lattice configuration was followed by detailed optical measurements and validated up to 1°.

Multiple instruments were used to measure the impact of beam-beam effects on beam properties: ATLAS and CMS luminometers for the luminosity, ADT [10] and BBQ [11] for single-bunch and beam spectra respectively, synchrotron light monitors [12] and wire scanners for transverse beam sizes and DOROS BPMs [13] for orbit displacements at the IPs.

A first measurement of the impact of beam-beam effects at IP5 (CMS) on the luminosity at IP1 (ATLAS) is shown in Fig. 2 (left). The beams are moved from the head-on position at both IPs (blue points) to full separation at the CMS IP (yellow points). The relative difference in luminosity indicates the $2.35 \pm 0.18\%$ effect, which corresponds to the beam-beam-induced bias caused by the presence of one additional collision point. The average effect on the beam width is indicated by the magenta dashed line, and it is significantly different in the single- and two-IP configurations, even when single bunches are considered. The impact of the additional collision

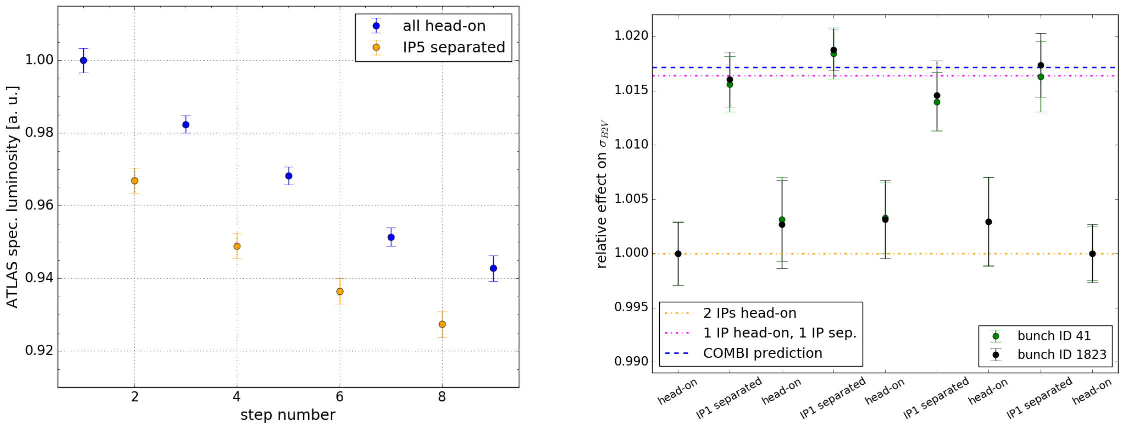

Figure 2: Beam-beam effects on ATLAS luminosity (left) and beam width (right) with comparison to COMBI, shown along the step-function experiment.

was measured to be consistent with COMBI calculations, supporting the predictions of the multi-IP model. Moreover, the linear scaling law with the beam-beam parameter was verified. The observations of beam-beam-induced changes during a separation scan were also made.

5. Extrapolation to physics data-taking conditions

The preceding sections delve into the unique conditions of vdM-calibration sessions. The correction strategy is not applicable to standard physics data-taking conditions. In this scenario, several key differences emerge. Firstly, the single bunch instantaneous luminosity (SBIL) [1] is much higher, approximately $\times 100$, there is also a twofold increase in the beam-beam parameter compared to the vdM regime. The parasitic beam-beam (long-range) interactions have to be taken into account, present in the common vacuum chamber area around the IP due to the compact spacing of bunches. Additionally, the presence of a non-zero crossing-angle introduces coupling between the transverse and longitudinal planes. Moreover, the focusing at the IP is sufficiently strong (β^* reached 30 cm in Run 3) for it to result in variations of the transverse beam size along the collision. To accurately simulate these intricate effects, the COMBI model [14] was extended to include a sliced luminosity integrator to provide a comprehensive description of the transverse overlap throughout the collision.

Understanding the beam-beam-induced biases under these conditions is essential for gaining insights into detector-specific effects. The luminosity measurement can be influenced by instrumental non-linearities in the detector response, especially over a wide SBIL range. Numerous factors can contribute to inefficiencies in experimental systems, potentially affecting the accuracy of the measurement. These include zero-starvation and saturation effects, accidental events, and activation-induced and electronic system inefficiencies. The measurement of the resulting non-linearity mostly relies on cross-detector comparisons, with an assumption of an ideal luminometer. Typically, an uncertainty of 0.5% is assigned for both CMS [15] and ATLAS (with O(10%) correction) [1]. Moreover, non-linearity is expected to be a prominent issue at the HL-LHC, where pile-up is anticipated to be significantly higher.

Emittance scans are transverse beam separation scans performed in physics conditions and their primary goal is to evaluate the convoluted transverse beam sizes. From these scans, an equivalent of the calibration constant σ_{vis} can be extracted [16]. The aforementioned COMBI upgrades enable the generation of dedicated corrections, eliminating the beam-beam-induced biases and thereby minimizing the associated systematic uncertainty. This procedure was applied to a dataset from a special physics fill where no long-range beam-beam interactions were present, encompassing a wide range of per bunch emittances and yielding a wide PU range. Consequently, the measured change of σ_{vis} across SBIL ('uncorrected' in Figs. 3) is assumed to result from two primary contributions. Firstly, the apparent beam-beam-induced slope - which is removed with COMBI-produced corrections, and measured to be approximately -0.2% [1/(Hz/μb)]. It originates from the increasing ξ, and thus BB-related bias with SBIL. Secondly, there are intrinsic detector response inefficiencies. In the case of a perfectly linear luminometer, the COMBI-corrected slope should be flat across SBIL. For the BCM1F-μTCA system [17] (left side of Fig. 3), the final red slope aligns closely with zero, confirming its excellent performance. However, for the second independent system, PLT [18], with distinct behavior and a known issue of excessive accidental hits in the luminosity signal (non-corrected data used), a positive non-linearity is observed with SBIL. It is worth noting that additional systematic errors stemming from non-factorization can bias the results and could not be considered in these studies. Another source of bias arises from the challenging fit quality, a result of the operational limits of the scan range for multiple bunches with varying

[1] Pile-up (PU) = $\sim 7 \times$ SBIL

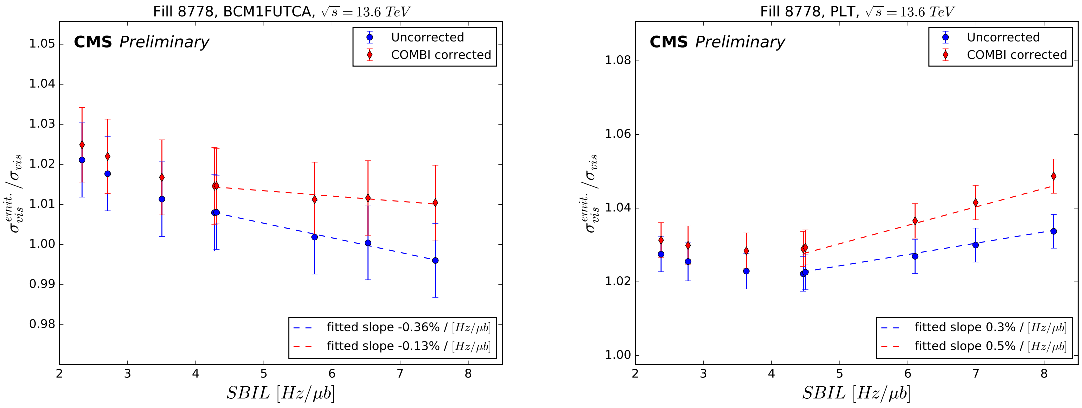

Figure 3: Measured non-linearity slopes from the emittance scan results along a wide range of SBIL for two example CMS luminometers. Two types of data are shown in each of the figures - uncorrected (blue) and beam-beam bias-corrected (red).

transverse emittances. This uncertainty is incorporated into the errors based on the multiple fit models used for the scan data, and it was reduced by removing the widest bunches from the fit. While there is room for data quality improvement in future measurements, this approach shows promise as a means of independently measuring non-linearity.

6. Conclusions

Significant progress has been made in comprehending, through extensive multiparticle simulations, the impact of beam-beam effects on absolute luminosity calibrations at hadron colliders. This resulted, in particular, in a 1%-level readjustment of the magnitude of the associated corrections, and in a more detailed characterization of the sources of systematic uncertainty. One notable advance is the proper accounting for multiple collision points around the LHC rings, that lead, under typical vdM-scan conditions, to an additional correction of about 0.4% on the absolute luminosity scale inferred from vdM calibrations.

To validate some critical aspects of the simulation model, a dedicated beam-beam experiment was conducted at the LHC. The results demonstrate good agreement with the simulation: for instance, the measured impact of additional IPs on the luminosity in head-on collisions agrees with the prediction at the 0.1% level. Furthermore, for the first time, simulation-based beam-beam corrections in demanding physics conditions have been applied to Run-3 CMS luminosity data, to compensate for SBIL-dependent, beam—beam-induced biases, thereby removing a spurious source of apparent luminometer non-linearity. This enables the insight into an intrinsic detector response non-linearity independently of any other system.

It is important to note that the findings summarized above apply to any current and future hadron collider.

A. Acknowledgements

This work is supported by the Swiss Accelerator Research and Technology Institute (CHART).

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