EXPERIMENTAL STUDY OF LUMINOSITY CALIBRATION CORRECTIONS USING TUNE SCALING TO MIMIC MULTI-COLLISION CONFIGURATIONS

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Abstract

Accurate luminosity calibration is essential for precise cross-section measurements and reliable machine performance optimization. In colliders with several interaction points, the cumulative beam–beam effects depend on the number of collision partners of individual bunches, which can bias luminosity calibration if not properly accounted for. To investigate this experimentally, a dedicated beam–beam experiment was performed at the LHC using tune scaling to mimic configurations with multiple collision partners within a single interaction region. By adjusting the fractional tunes, while preserving comparable beam–beam parameters, the dependence of luminosity calibration corrections on the effective number of collisions was systematically studied. The results are compared with expectations from numerical simulations, supporting the use of tune scaling as a valid strategy to reproduce multi-collision conditions for luminosity calibration corrections.

INTRODUCTION

The determination of luminosity from van der Meer (vdM) scans relies on the accurate modeling of beam–beam (BB) effects [1]. During a vdM scan, the two beams are separated transversely, and the presence of additional head-on collision partners at other interaction points (IPs) modifies the beam orbits and shapes throughout the scan, biasing the inferred luminosity calibration. The first-order effects of BB interactions include a tune shift, tune spread, and beta function change [2, 3]. A dedicated correction strategy to account for these multi-IP BB effects was derived in [1], and an initial experimental validation was performed in [4]. Building on this, the ATLAS and CMS experiments applied these corrections in their Run 2 luminosity analyses [5, 6], achieving the most precise luminosity measurements to date. The present work extends this validation to the multi-IP case, aiming to demonstrate experimentally that the effect of head-on collisions at multiple additional IPs on a vdM scan is equivalent, in first approximation, to applying a corresponding cumulative tune shift. We assess the consistency of this correction strategy across different IP configurations and evaluate its impact on the luminosity calibration.

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EXPERIMENT DESCRIPTION AND BEAM PARAMETERS

The experiment was performed at the LHC at 6.8 TeV. The tune scaling approach exploits the fact that, in simulations, scaling the fractional tune reproduces the effective BB kick from a collision partner at a distant IP; this empirical rule was subsequently adopted as the basis for the multi-IP correction procedure [1]. The target beam–beam parameter was $\xi = 0.01$, with a sensitivity threshold of $\xi = 0.008$, below which the induced effect on the visible cross section would be too small to be reliably measured.

Since the tune shift had to be kept sufficiently large to remain above the sensitivity threshold, excessive intensity losses were anticipated as a potential risk, particularly for bunches colliding at IP8 with both beams, as these experience the largest total BB tune shift. To mitigate this, ATLAS was brought into collision only for the final scan pair, limiting the total BB tune shift on the most affected bunch families. The tests consisted of six pairs of horizontal and vertical separation scans. The filling pattern comprised four bunch families observed by ATLAS and CMS, with effective numbers of BB interactions ranging from 1 to 3. The BB collisions could occur at CMS, ATLAS and LHCb; due to the asymmetric location of LHCb, pairs of bunches colliding at CMS and ATLAS may have different numbers of collisions at LHCb. Additional interactions were introduced either via genuine changes to the LHC collision configuration or via tune changes applied to mimic the effect on tunes from the BB interaction at additional collisions at IP1, IP8, or both. The experimental scheme is illustrated in Fig. 1. The effective numbers of BB interactions shown in the scheme are estimated for $\xi = 0.01$; during the experiment, this parameter was expected to decrease over time due to bunch intensity losses and emittance growth.

FIRST RESULTS

Beam-Beam Parameter Evolution

The time evolution of the beam–beam parameter ξ for the colliding bunches is shown in Fig. 2. All families were expected to decay from $\xi = 0.01$ toward the sensitivity threshold of $\xi = 0.008$ over the course of the experiment. The IP1+IP5 family and the single-beam IP8 families evolved

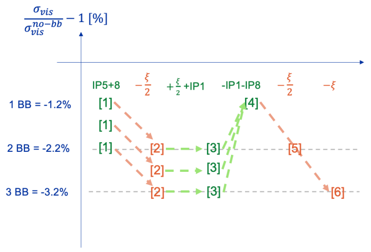

Figure 1: Schematic of the experimental procedure. The y-axis shows the effective number of BB interactions, with non-integer values arising from single-beam IP8 contributions, and the x-axis the scan pair index progressing chronologically. Multiple entries at the same level indicate simultaneous bunch families with different BB configurations. Green: genuine LHC collision configuration changes; orange: single CMS collision with additional tune shift applied.

broadly as expected, remaining above the sensitivity threshold throughout the scan programme. In contrast, the both-beam IP8 family exhibited a significantly stronger decay, attributed to larger intensity losses likely driven by an excessive total BB tune shift of approximately 0.027. This results in a non-constant ξ across scan pairs for this family, which is most visible in the ATLAS witness luminosity measurements discussed below.

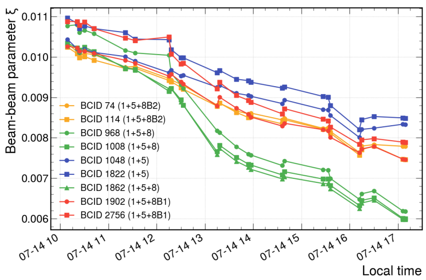

Figure 2: Time evolution of the beam-beam parameter ξ for the selected colliding bunches during fill 10831. Colors indicate the different bunch families corresponding to the studied collision configurations.

Tail Population Evolution

The scan-to-scan evolution of the fitted tail population (q-factor) is shown in Fig. 3 for all colliding bunches at CMS, based on online luminometer measurements [6] without additional corrections. The q-factor is extracted from q-Gaussian fits to the luminosity curves along the separation scans and therefore represents a combined quantity; as it reflects the convolution of both beam profiles, the q-factor of each individual beam may be significantly larger. A clear dependence on the collision configuration is observed in both transverse planes. In contrast, bunches involving IP8 collisions exhibit systematically higher and more scan-dependent q values, reflecting stronger tail growth, consistent with the stronger ξ decay observed in the previous subsection.

A particularly interesting feature is observed for the family in which both beam bunches collide at IP8, in the horizontal plane, where the q-factor increases from approximately 1.05 to 1.3 during the scan pair where a $-\xi/2$ tune shift is applied to both beams (Fig.3 upper plot green lines from scan 1 to 2). Surprisingly, when the tune shift is reverted and IP1 is brought into collision in the following scan pair, the q-factor partially recovers to approximately 1.1 (same lines at scan number 3), suggesting that the tune shift has a stronger impact on the transverse beam profiles than the additional head-on collision. In the vertical plane, the same family shows a different behavior: a small increase from approximately 1.13 to 1.18 is observed later, when IP1 is brought into collision, rather than at the tune shift stage, indicating a plane-dependent response. Throughout these changes, the IP1+IP5 family remains stable, isolating the observed effects to the bunches undergoing a collision at IP8. Notably, at a later stage of the experiment when only CMS is in collision and a stronger tune shift is applied, no further tail growth is observed, suggesting that the effect is not driven by the tune shift magnitude alone but by its interplay with the IP8 collisions.

A possible explanation for the observed plane-dependent behavior is the presence of a crossing angle of 450 μrad at IP8, which is absent at IP1 and IP5. Unlike a head-on collision, a crossing angle introduces a longitudinal position-dependent transverse offset, effectively coupling the horizontal and longitudinal degrees of freedom through synchro-betatron resonances of the form $mQ_x \pm nQ_s = p$, which can drive horizontal emittance growth and tail population. Crucially, tune scaling mimics the coherent BB tune shift but does not reproduce this coupling. Additionally, residual local coupling at IP8 from imperfect solenoid compensation or magnetic field errors may further contribute to the observed plane-dependent behaviour. Both hypotheses require further investigation.

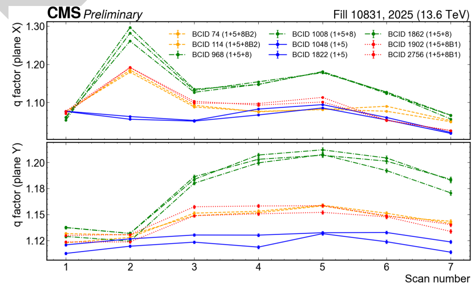

Figure 3: Scan-to-scan evolution of the fitted tail population (q-factor) in the horizontal (top) and vertical (bottom) planes for all colliding bunches at CMS. Different colors indicate distinct bunch families corresponding to different collision configurations [7].

Witness IPs Results

Per-bunch specific online luminosity measurements provided by the ATLAS experiment, are shown in Fig. 4 for the third scan pair, the only scan where ATLAS was in collision. Measurements are normalized to per-bunch FBCT [8] intensity, corrected using DOROS BPM [9] measurements, and normalized to the central head-on point to highlight changes across the transverse scan. The statistical uncertainty is approximately 0.25%. A piecewise emittance correction is applied using the head-on collision points separately for each side of the scan. Despite the beam condition complications identified in the previous subsections, a clear impact of BB interactions at IP5 on the luminosity measurement at IP1 is observed, in good overall agreement with Xsuite [10] simulation predictions, with corrections improving the χ^2. The same analysis was performed for LHCb as a second witness IP, with results shown in Fig. 5 for the first scan pair, where the BB parameter was largest.

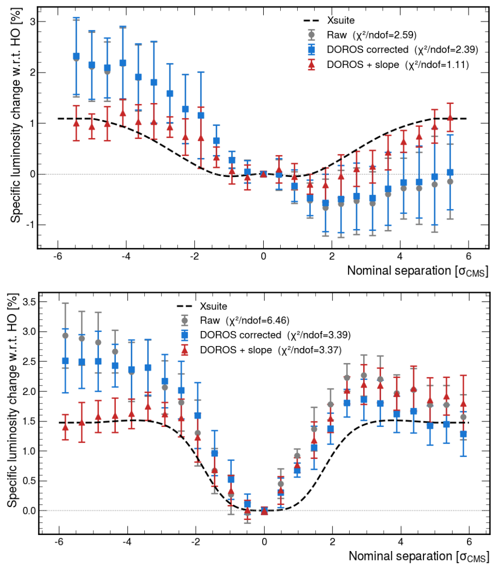

Figure 4: Average per-bunch ATLAS online specific luminosity measurement [11] during (top) horizontal and (bottom) vertical scan at the CMS (third scan pair). The black line shows the Xsuite [10] simulation predictions.

Beam-Beam Effect on the Visible Cross Section

The visible cross section measured during the first scan pair is shown in Fig. 6, using HFET luminosity measurements. The first scan pair is shown as it represents the cleanest conditions, before tune changes affected the beam profiles as discussed earlier. Significant differences are observed among the bunch families, with the visible cross section decreasing systematically with increasing effective number of BB interactions. The measured differences between families are slightly smaller than predicted, consistent with the decay of ξ during the fill, as the simulation assumes a constant value of $\xi = 0.01$. The relative difference between families with 2 and 1 effective collisions is measured at 0.65% against an expectation of 0.9%, between 1.5 and 1 collisions at 0.35% against 0.45%, and between the two types of 1.5 collision configurations at 0.15% against 0.10%. One bunch (968) exhibits outlying behaviour, which is currently under investigation. Residual orbit drift corrections have been applied, however non-factorization corrections are still pending and are expected to be significant given the observed beam profile changes, preventing a full analysis of subsequent scan pairs at this stage.

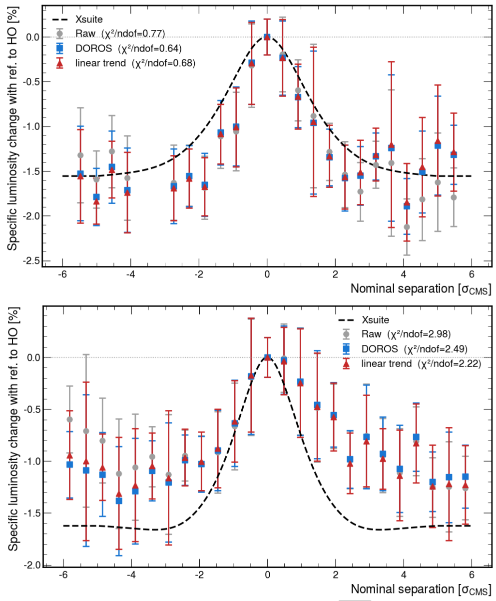

Figure 5: LHCb online average specific luminosity measurement [12] for 5 colliding bunch pairs during (top) horizontal and (bottom) vertical scan at the CMS (first scan pair). The black line shows the Xsuite [10] simulation predictions.

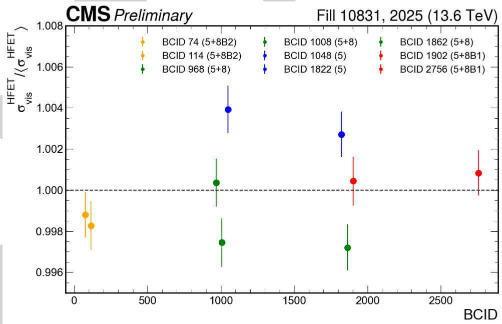

Figure 6: Visible cross section normalized to its mean value measured with HFET during the first scan pair for the colliding bunch families at CMS. Different colors indicate distinct bunch families corresponding to different collision configurations [7].

CONCLUSION

A dedicated beam–beam experiment was performed at the LHC to investigate the dependence of luminosity calibration corrections on the effective number of collision partners using tune scaling. The visible cross section measured during the first scan pair shows differences between bunch families in quantitative agreement with simulation expectations. Per-bunch specific luminosity measurements at both the ATLAS and LHCb witness interaction points show good agreement with simulation, with some residual systematic effects remaining. An interesting plane-dependent evolution of the transverse beam profiles was observed, with the horizontal plane showing a stronger response to the tune shift than to the additional head-on collision, which warrants further investigation. The analysis is ongoing and full results will follow once non-factorization corrections are applied.

ACKNOWLEDGEMENT

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[11] Courtesy of the ATLAS Collaboration

[12] Courtesy of the LHCb Collaboration