PROCEEDINGS OF SCIENCE

Performance of the track-counting luminosity measurement in pp collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector

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A precise measurement of the luminosity is a crucial input for many ATLAS physics analyses, and represents the leading uncertainty for cross-section measurements of W and Z bosons and of top quarks. The ATLAS luminosity measurement depends on the interplay of a set of complementary luminometers, based on specific subdetectors, such as LUCID-2, or the ATLAS tracking detectors and calorimeter subsystems. The LUCID-2 detector was used as reference luminometer in the second running period of the LHC (Run-2), and remains being used as such during the third running period (Run-3) which started in 2022. The luminosity calibration of LUCID-2, determined from van der Meer (vdM) scans during dedicated running periods in each year, requires a correction for standard physics data-taking conditions, as well as careful monitoring throughout the data-taking year. The track-counting algorithm, based on reconstructing and selecting tracks in the inner detector, is used for this purpose.

The performance of the track-counting algorithm is studied in head-on collisions and beam separation scans in Run-3. Those scans are vdM-like beam separation scans performed under normal physics conditions distributed over the entire data-taking year. Studies calculating the correction of LUCID-2 with the track-counting algorithm from beam separation scans are performed and compared to the nominal correction extracted from head-on collisions. Additionally, the stability from track-counting with respect to the number of proton bunches in the LHC ring and the crossing angle of the proton beams at the interaction point within the ATLAS detector are investigated.

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1. Luminosity Measurements with the ATLAS Detector

For a high precision cross-section (σ) measurement at the Large Hadron Collider (LHC), a precise determination of the integrated luminosity ($\mathcal{L}_{\mathrm{int}}$) is essential. The latter is proportional to the number of events:

$$\mathcal{L}_{\mathrm{int}} = \int \mathrm{d}t \; \mathcal{L} = \frac{N_{\mathrm{events}}}{\sigma} \tag{1}$$

where N_{events} are the number of produced events for the considered process and σ its cross-section.

The integrated luminosity is estimated using Time Blocks (TB), during which the beam conditions are assumed to be constant. If the investigated cross-section is the inelastic cross-section, the formula can be modified to the following

$$\mathcal{L}_{\mathrm{int}} = \sum_{\mathrm{TB}} t\,(\mathrm{TB})\, \frac{N^{\mathrm{TB}}_{\mathrm{events}}/t\,(\mathrm{TB})}{\sigma_{\mathrm{inel}}} = \sum_{\mathrm{TB}} t\,(\mathrm{TB}) \cdot \frac{n_{\mathrm{b}} f_{\mathrm{r}} \left\langle \mu^{\mathrm{TB}}_{\mathrm{alg}} \right\rangle}{\sigma_{\mathrm{inel}}} \tag{2}$$

with $t\,(\mathrm{TB})$ the time of a TB, $N^{\mathrm{TB}}_{\mathrm{events}}$ the number of produced events in this TB, n_{b} the number of bunches colliding inside the ATLAS detector [1], f_r the LHC revolution frequency, σ_{inel} the pp inelastic cross-section and $\left\langle \mu^{\mathrm{TB}}_{\mathrm{alg}} \right\rangle$ the bunch-averaged number of inelastic pp collisions measured by a particular luminosity algorithm (alg).

Several detectors and different algorithms are used to control the systematic uncertainties of the luminosity measurement [2]. The two most important luminometers of the ATLAS detector during Run-2 have been the **LU**minosity **C**herenkov **I**ntegrating **D**etector (LUCID-2, also denoted as LUCID) [3] and the track-counting luminometer. For 2022, the preferred LUCID algorithm is LUCID Bi2HitOR. Track-counting (in figures denoted as *Tracks*) uses the silicon detectors of the Inner Detector and counts the number of tracks, passing a dedicated selection. The track selection is crucial for a stable performance [2, 4]. For 2022 luminosity measurements, the preferred track selection of Run-2 is used.

Both luminometers have advantages and disadvantages. LUCID Bi2HitOR is calibrated following the van der Meer (vdM) method [5], while track-counting is particularly linear over a large range of simultaneous interactions μ. Thus the interplay of both luminometers is crucial. Track-counting is *anchored*, i.e. normalized, to LUCID Bi2HitOR in a dedicated LHC fill. LUCID Bi2HitOr is corrected for non-linearities in the dependence on μ using track-counting via

$$\frac{\langle \mu_{\mathrm{Tracks}} \rangle}{\langle \mu_{\mathrm{LUCID\ Bi2HitOR}} \rangle} = p_0 + p_1 \cdot \langle \mu_{\mathrm{LUCID\ Bi2HitOR}} \rangle \tag{3}$$

which is called calibration transfer. For 2022 data-taking, the calibration transfer is shown in Figure 1.

2. Calibration transfer from Beam Separation Scans

Beam separation scans (BSS) are used to quickly scan a large μ-range through both, vertical and horizontal, beam movements. A scheme is shown in Figure 2. The beams start with a separation

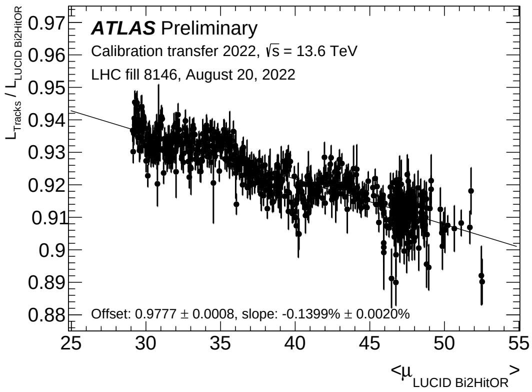

Figure 1: The ratio $\langle\mu_{\mathrm{Tracks}}\rangle / \langle\mu_{\mathrm{LUCID\ Bi2HitOR}}\rangle$ over $\langle\mu_{\mathrm{LUCID\ Bi2HitOR}}\rangle$ in LHC fill 8146 is displayed along with a linear fit to extract the correction to the LUCID Bi2HitOR algorithm [6]. The offset (p_0) and the slope (p_1) with their uncertainties are indicated on the bottom left.

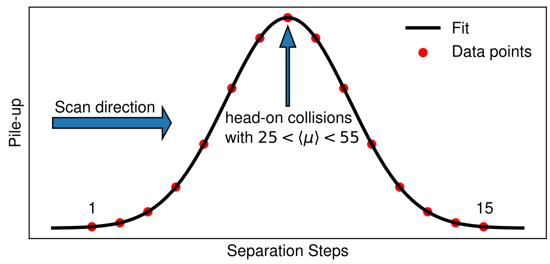

Figure 2: Scheme of beam separation scans (BSS). The beams are separated horizontally at the start. With 15 equidistant separation steps, the beams are first brought into head-on collisions and afterwards separated again.

in the horizontal direction and are brought to head-on collisions with seven separation steps. With further seven separation steps, the same separation but with flipped sign is obtained.

Linear fits applied to the scans displayed as a function of bunch-averaged μ, denoted as $\langle\mu\rangle$, are shown in Figure 3. The distribution can be split into two ranges, with low and high $\langle\mu^{\mathrm{uncorrected}}_{\mathrm{LUCID\ Bi2HitOR}}\rangle$ values with slightly different slopes. Using the same fit range as in Figure 1 (i.e. $\langle\mu^{\mathrm{uncorrected}}_{\mathrm{LUCID\ Bi2HitOR}}\rangle > 28$), the resulting fit parameters are in good agreement with those extracted in Figure 1 which uses a natural luminosity decay over a long LHC fill to cover different μ-values. Some BSS do not reach values of $\langle\mu^{\mathrm{uncorrected}}_{\mathrm{LUCID\ Bi2HitOR}}\rangle > 28$, thus for comparative studies here, the range $2 < \langle\mu^{\mathrm{uncorrected}}_{\mathrm{LUCID\ Bi2HitOR}}\rangle < 20$ is used.

Several systematic uncertainties need to be considered in order to achieve a precision in the overall luminosity calibration better than 1 %. Two possible sources of systematic uncertainties are variations of luminometer response as a function of the number of colliding bunches and the *beam focussing strength* in the ATLAS interaction region, labeled as β^* [2]. Those effects can be studied in the ramp-up phase of Run-3. Here, a large number of fills with different number of colliding bunches have been recorded. In 2022, β^* leveling was introduced across a large part of a fill, where the β^* parameter is stepwise tightened to keep the luminosity approximately constant at the beginning of a fill. Using BSS from different LHC fills, Figure 4 shows the p_1 parameters

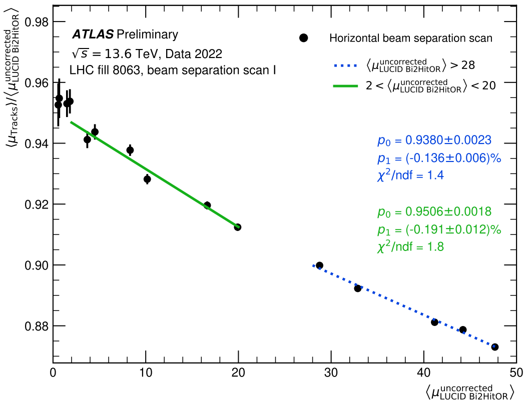

Figure 3: The ratio $\langle\mu_{\mathrm{Tracks}}\rangle / \langle\mu^{\mathrm{uncorrected}}_{\mathrm{LUCID\ Bi2HitOR}}\rangle$ over $\langle\mu^{\mathrm{uncorrected}}_{\mathrm{LUCID\ Bi2HitOR}}\rangle$ of the first BSS of LHC fill 8063 [7]. Additionally, two linear fits in the range $\langle\mu^{\mathrm{uncorrected}}_{\mathrm{LUCID\ Bi2HitOR}}\rangle > 28$ (blue) and $2 < \langle\mu^{\mathrm{uncorrected}}_{\mathrm{LUCID\ Bi2HitOR}}\rangle < 20$ (green) are shown.

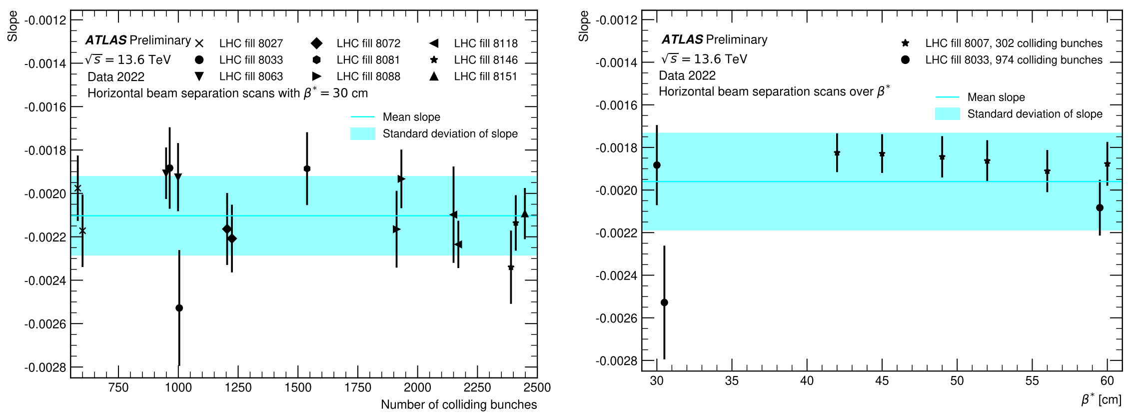

Figure 4: The slope (p_1 parameter) for constant $\beta^* = 30$ cm and varying number of colliding bunches (left) and for different β^* values within the same LHC fills, i.e. at constant number of bunches (right) [7].

from different horizontal BSS for varying number of colliding bunches and from variations of the β^* parameter for BSS in the same LHC fill. No dependence on the number of colliding bunches nor the β^* parameter can be seen in the ramp-up phase of Run-3.

3. Dependence on the crossing angle

The effect of the crossing angle of the LHC beams inside the ATLAS detector on the track-counting luminometer is studied. Figure 5 shows the ratio $\langle\mu_{\mathrm{Tracks}}\rangle / \langle\mu_{\mathrm{Algorithm}}\rangle$ for different algorithms over the TB number. The algorithm LUCID Hit A08 is based on a single photomultiplier tube (PMT), placed almost directly under the beam pipe, and is expected to show a large dependence on the crossing angle. LUCID Bi2HitOR is based on eight PMTs, distributed almost symmetrically around the beam pipe, and is thus expected to show only a residual dependence. The BCM T EventOR algorithm is based on four diamond sensors, placed exactly above and below the beam pipe, as well as left and right, and has been validated to show no crossing angle dependence. In the

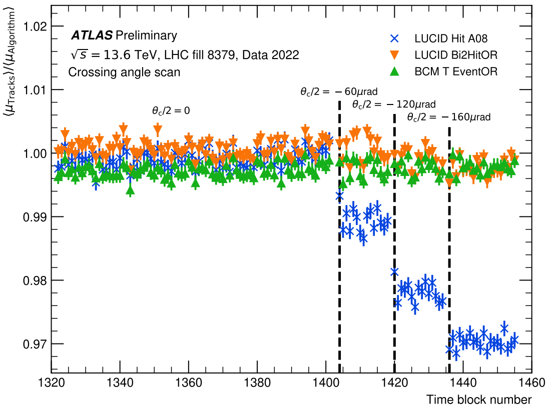

Figure 5: The ratio $\langle\mu_{\text{Tracks}}\rangle / \langle\mu_{\text{Algorithm}}\rangle$ for different algorithms over the TB number [7]. Up to TB number 1404, the half crossing angle $\theta_C/2$ is zero, after which it is increased to $\theta_C/2 = -160\,\mu$rad with three steps, indicated by the black dashed lines. The luminosity algorithms are described in the text.

displayed LHC fill, the crossing angle was modified in several steps, starting from zero crossing angle, to the crossing angle used for standard physics data-taking in ATLAS, which is $-160\,\mu$rad. Since the ratio of track-counting to the last two algorithms is flat, track-counting does not have a dependence on the crossing angle.

4. Summary

Precisely measuring the integrated luminosity is of utmost importance for physics analyses at the ATLAS experiment. Several luminosity detectors are used to control the systematic uncertainties of the luminosity measurement. For 2022, LUCID Bi2HitOR was the preferred luminosity algorithm, while track-counting is used to correct a non-linear response of LUCID as a function of the number of simultaneous interactions, μ. To understand external effects on track-counting, studies of the dependence on the number of colliding bunches, the β^* parameter and the crossing angle have been conducted using beam-separation scans in LHC fills from the start of 2022 data-taking period and dedicated running in 2022. Track counting has shown no dependence on either of the mentioned parameters.

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