PROCEEDINGS OF SCIENCE

Measuring the luminosity of Pb+Pb collisions with a new algorithm using tracks at the ATLAS detector

PoS(EPS-HEP2023)587

ATL-DAPR-PROC-2023-002
11 November 2023

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Determining the number of collisions delivered by the LHC inside the ATLAS detector is a key part of the ATLAS luminosity program. Several sub-detectors and algorithms are used, among which is the track counting method. This method assumes that the number of tracks reconstructed in the ATLAS Inner Detector is proportional to the number of simultaneous collisions, thereby providing a measurement of luminosity. Track counting is well understood in proton-proton collisions, but needs to be adjusted for Pb+Pb collisions, where the track multiplicity is dominated by rare head-on collisions. Potential improvements to the track counting method for heavy ions are investigated, in particular, a track-based event counting algorithm, where events are accepted if they have at least one track passing a set of track selection criteria. The performance of the new algorithm based on Pb+Pb collision data recorded by the ATLAS detector in 2018 and 2022 is compared to the reference luminometer LUCID-2. This work demonstrates the potential of the track-based event counting algorithm as a new luminometer for heavy ion collisions recorded by the ATLAS detector in Run 3 and beyond.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

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1. Introduction

Precisely measuring the luminosity of collisions delivered by the Large Hadron Collider (LHC) is an important part of the physics program of the ATLAS experiment [1]. It is especially relevant for high-precision cross section measurements, where the luminosity uncertainty can be one of the leading systematic uncertainties.

Luminosity is measured in ATLAS using algorithms based on data recorded by several sub-detectors, denoted as *luminometers*. The primary luminometer at the ATLAS experiment is the LUCID-2 sub-detector [2], hereafter referred to as LUCID.

The luminosity of a colliding bunch pair is given by:

$$\mathcal{L}_b = \frac{\mu \cdot f_{\text{rev}}}{\sigma_{\text{inel}}} = \frac{\epsilon\mu \cdot f_{\text{rev}}}{\epsilon\sigma_{\text{inel}}} = \frac{\mu_{\text{vis}} \cdot f_{\text{rev}}}{\sigma_{\text{vis}}} \tag{1}$$

where μ is the number of inelastic collisions per bunch crossing, $f_{\text{rev}} = 11245$ Hz is the LHC revolution frequency, and σ_{inel} is the total inelastic cross section [3]. Since luminometers observe only a fraction ϵ of the activity of an event i.e. the collisions per bunch crossing, the luminosity can be expressed using a *visible* interaction rate μ_{vis} and a *visible* cross section σ_{vis}[1]. Summing over n_{B} colliding bunches in a LHC fill gives:

$$\mathcal{L} = \frac{\langle\mu_{\text{vis}}\rangle \cdot f_{\text{rev}} \cdot n_{\text{B}}}{\sigma_{\text{vis}}} \tag{2}$$

where $\langle\mu_{\text{vis}}\rangle$ is the average number of visible interactions per bunch crossing.

Summing the instantaneous luminosity over time gives the integrated luminosity $\mathcal{L}_{\text{int}}$. At the ATLAS experiment this is done over *time blocks* typically lasting 60 seconds, where it is assumed that the data-taking conditions and the luminosity are stable within the time block. Then:

$$\mathcal{L}_{\text{int}} = \sum_{\substack{\text{time}\\ \text{blocks}}} \frac{\langle\mu_{\text{vis}}\left(\substack{\text{time}\\ \text{block}}\right)\rangle \cdot f_{\text{rev}} \cdot n_{\text{B}}}{\sigma_{\text{vis}}} \cdot \Delta t_{\substack{\text{time}\\ \text{block}}} \tag{3}$$

The integrated luminosity over a full data-taking year for a given particle type (p+p or Pb+Pb) is used in physics analyses, so its uncertainty directly impacts physics measurements in ATLAS.

2. Luminosity determination using tracks in the ATLAS Detector

The luminosity of collisions in the ATLAS detector can be measured using charged particle trajectories, i.e. *tracks* in the ATLAS Inner Detector, which are generated by charged particles produced in the collisions. A combinatorial Kalman filter and a neural-network-based ambiguity solver use hits in the Insertable B-layer (IBL), Pixel (PIX) and Semiconductor Tracker (SCT) sub-detectors to determine particle tracks[2]. Requirements on the kinematics, number of (expected) hits etc. are applied on the tracks for data quality assessment and background rejection. In

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[1] The visible cross section, for several luminometers including LUCID, is calibrated in special LHC fills using the *van-der-Meer method* [5].

[2] The Transition Radiation Tracker (TRT) sub-detector, efficient in the reconstruction of secondary tracks, is not used for the track-based luminosity measurement, as only primary tracks are of interest.

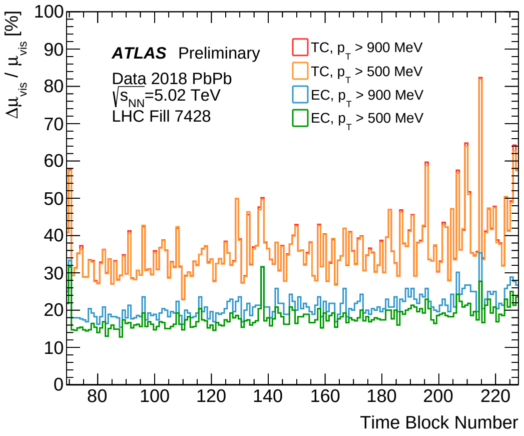

Figure 1: Relative uncertainty of the visible number of simultaneous interactions μ_{vis} (in percent) as a function of time block number, in one Pb+Pb fill at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in 2018 recorded by the ATLAS detector [6]. The track reconstruction and selection is described in Sec. 2. The colors correspond to different luminosity algorithms, with "TC" and "EC" referring to the track counting and event counting algorithms respectively.

this work the "TightPrimary" selection described in Ref. [4] is applied on the tracks, with an additional requirement on the significance of the beam-spot-corrected transverse impact parameter of $\left|d_0/\sigma_{d_0}\right| < 7$. Two different requirements on the minimum transverse momentum (p_T) of the tracks are tested, $p_T > 500$ MeV and $p_T > 900$ MeV.

The track counting (TC) algorithm uses the average number of tracks observed in a given data-taking period as the visible interaction rate $\mu_{\mathrm{vis}}^{\mathrm{TC}}$. The statistical uncertainty on $\mu_{\mathrm{vis}}^{\mathrm{TC}}$ is derived using the central limit theorem, assuming that each collision produces on average the same number of tracks. Thus:

$$\mu_{\mathrm{vis}}^{\mathrm{TC}} = \langle N_{\mathrm{tracks}} \rangle \qquad \text{and} \qquad \Delta\mu_{\mathrm{vis}}^{\mathrm{TC}} = \left(\frac{\left\langle N_{\mathrm{tracks}}^2 \right\rangle - \langle N_{\mathrm{tracks}} \rangle^2}{N_{\mathrm{events}}} \right)^{1/2} \tag{4}$$

where N_{events} is the number of triggered events recorded in the given data-taking period.

The event counting (EC) method assumes that the number of visible collisions $\mu_{\mathrm{vis}}^{\mathrm{EC}}$ is Poisson-distributed with a probability f. In this work, f is defined as $N_{\mathrm{pass}}/N_{\mathrm{total}}$, such that N_{pass} out of N_{total} triggered recorded events have at least one reconstructed track. The statistical uncertainty on $\mu_{\mathrm{vis}}^{\mathrm{EC}}$ is derived from error propagation. Thus:

$$\mu_{\mathrm{vis}}^{\mathrm{EC}} = -\log\left(1 - f\right) \qquad \text{and} \qquad \Delta\mu_{\mathrm{vis}}^{\mathrm{EC}} = \left(\frac{f}{N_{\mathrm{total}}\left(1 - f\right)} \right)^{1/2} \tag{5}$$

3. Luminosity algorithm performance

The relative statistical precision on μ_{vis} that can be achieved using the track counting and event counting algorithms is shown in Figure 1. The event counting algorithm, which is noted to be more

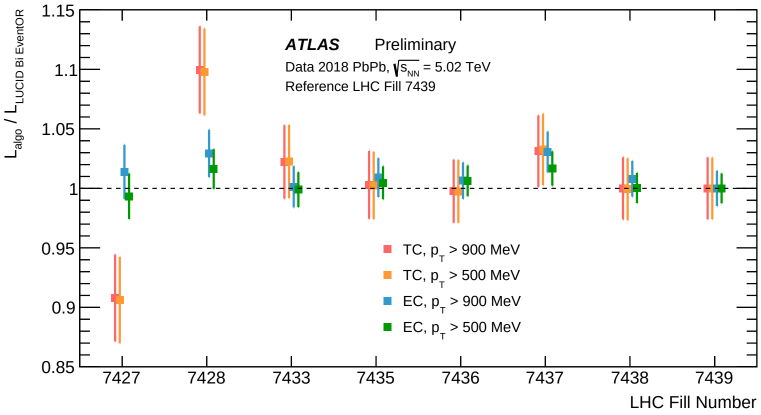

Figure 2: History of the ratio of run-integrated luminosity determined with charged particle tracks using different algorithms, to the BiEventOR algorithm based on the LUCID sub-detector, during Pb+Pb collisions at the LHC in 2018 [6]. The track reconstruction and selection is described in Sec. 2. Here, the "TC" and "EC" refer to the track counting and event counting algorithms respectively.

precise than hit counting algorithms in low pileup collisions [7], is two times more precise than track counting. It also improves when looser track selection criteria are applied; in contrast, the track counting performance does not improve when the minimum track p_T threshold is lowered.

The long term stability of the track counting and event counting algorithms is studied using Pb+Pb collision data recorded by the ATLAS detector in 2018. The fill-integrated luminosities are compared to the BiEventOR algorithm based on the LUCID sub-detector, shown in Figure 2 as a function of LHC fill number. Overall, a good stability over the fills is observed for both track counting and event counting algorithms, with larger variations in the first two fills for the track counting algorithm. The improvements of the event counting algorithm over the track counting algorithm seen in Figure 1 are visible at the integrated luminosity level of Figure 2 as well. The track-based event counting algorithm is therefore the preferred choice for measuring the luminosity of Pb+Pb collisions in the LHC Run 3, and for evaluating the long term stability of LUCID.

The impact of the recorded event rate[3] on the statistical precision of μ_{vis} was studied with data from pilot Pb+Pb beams in Nov. 2022. This data was recorded at an event rate of roughly 8.75 kHz[4], which for this study was artificially lowered at the analysis level by randomly skipping events in the luminosity determination. Since the duration of the LHC fill, i.e. the range of integration in Eq. 3 is not constant, the relative precision is computed as a function of the LHC fill duration. The results of this study are shown in Figure 3. A $1/\sqrt{R}$ trend is observed as a function of the fill duration, where R is the event rate. A 1% precision can be reached with event rates between 1-2 kHz[5].

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[3] The event rate is determined by the ATLAS trigger system, which selects collision events for storage. For the track-based luminosity measurement, a random trigger is applied on events with paired colliding bunches.

[4] For reference, Pb+Pb collisions in 2018 were recorded by the ATLAS detector at a rate of roughly 180 Hz.

[5] This prediction should be appropriately scaled in the presence of atypical instantaneous interaction rates, for example during luminosity levelling via beam separation.

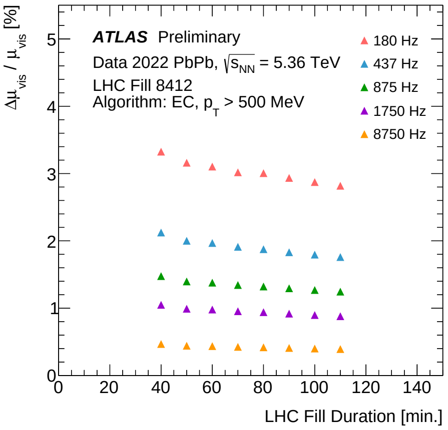

Figure 3: Relative uncertainty of the visible number of simultaneous interactions μ_{vis} (in percent) as a function of the LHC fill duration (in minutes), for different choices of event rates [6]. The filled triangles correspond to data recorded during pilot Pb+Pb beams in 2022. The event counting algorithm is used to determine μ_{vis}. The track reconstruction and selection is described in Sec. 2.

4. Summary

Precise measurements of the luminosity of collisions delivered by the LHC are crucial for the ATLAS physics program. The track counting method, based on counting the number of reconstructed charged particle tracks in the ATLAS Inner Detector, is a vital part of the measurement strategy in p+p collisions, but needs to be adjusted for Pb+Pb collisions. A new track-based event counting algorithm is developed; it is twice as precise as the track counting algorithm, and benefits from looser track selection. Moreover, it shows improved long term stability with respect to LUCID, the reference luminometer at the ATLAS experiment. This work highlights the potential of the event counting algorithm as a new luminometer for heavy ion collisions in the LHC Run 3.

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