Measuring The Luminosity Of Heavy Ion Collisions With A New Algorithm Using Charged Particle Tracks At The ATLAS Detector

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1. Introduction

A precise measurement of the **luminosity** of collisions at the LHC is crucial for physics measurements at ATLAS. **Luminometers** are used to measure instantaneous luminosity using:

$$\mathcal{L}_{\text{inst.}} = \frac{\langle \mu_{\text{vis}} \rangle \cdot f_{\text{rev}} \cdot n_{\text{B}}}{\sigma_{\text{vis}}}$$

- $\langle \mu_{\text{vis}} \rangle$: Average number of visible interactions per bunch crossing
- f_{rev}: LHC revolution frequency (11.2 kHz)
- n_{B}: Number of colliding bunches in LHC fill
- σ_{vis}: Visible cross section, calibrated using van der Meer method

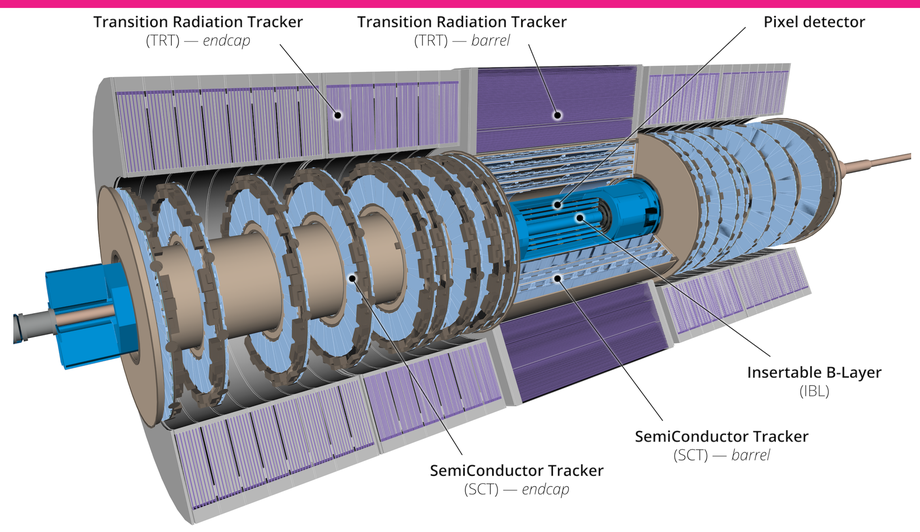
Integrated luminosity is obtained by summing over 60 sec. time blocks:

$$\mathcal{L}_{\text{int.}} = \sum_{\substack{\text{Time} \\ \text{Blocks}}} \frac{\langle \mu_{\text{vis}} \rangle \left(\frac{\text{Time}}{\text{Block}}\right) \cdot f_{\text{rev}} \cdot n_{\text{B}}}{\sigma_{\text{vis}}} \cdot \Delta t_{\substack{\text{Time} \\ \text{Block}}}$$

Quantities proportional to the interaction rate, ex. particle multiplicity, particle flux etc., are important in luminosity determination.

2. Charged Particle Tracks

Charged particles produced in collisions cross the ATLAS Inner Detector. A combinatorial Kalman filter and a neural network based ambiguity solver use **hits** in the IBL, Pixel and SCT sub-detectors (TRT hits are not used) to determine **particle trajectories** i.e. **tracks**. Requirements on the kinematics, number of (expected) hits etc. are applied on the tracks, for data quality assessment and background rejection.



3. Luminosity Determination Using Tracks

Track Counting (TC): Count number of tracks in events passing given selection. Then*:

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

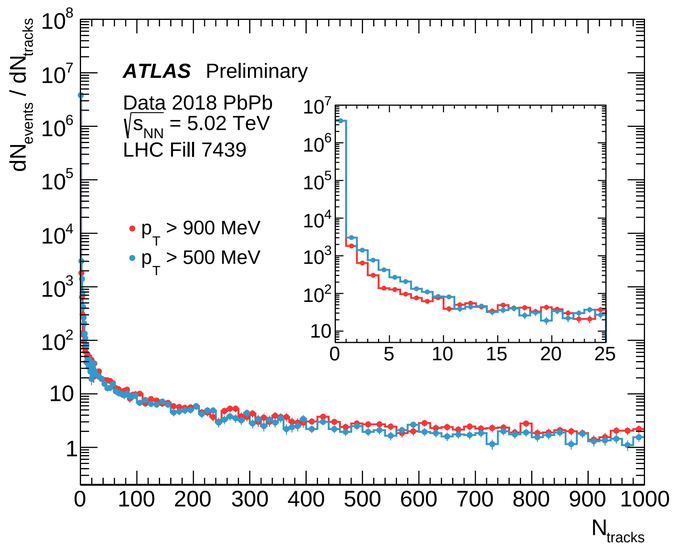
*Assuming $\langle N_{\text{tracks}} \rangle$ is proportional to interaction rate. See: ATLAS Run 2 luminosity (arXiv:2212.09379)

Event Counting (EC): N_{pass} out of N_{total} events have ≥ 1 track passing given selection. Then†:

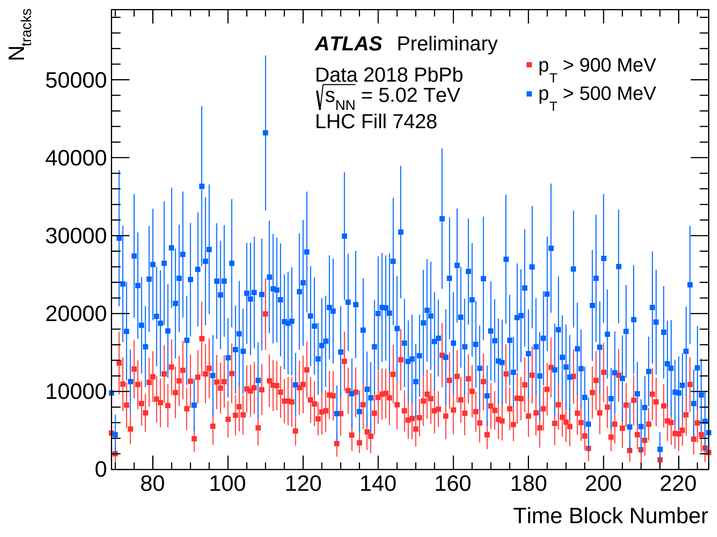
$$\mu_{\text{vis}}^{\text{EC}} = -\ln\left(1 - \frac{N_{\text{pass}}}{N_{\text{total}}}\right) = -\ln\left(1 - f\right)$$
$$\Delta\mu_{\text{vis}}^{\text{EC}} = \left(\frac{f}{N_{\text{total}}(1-f)} \right)^{1/2}$$

†Assuming $dN_{\text{events}}/dN_{\text{tracks}}$ is Poisson-distributed. See: **zero-counting** at LHCb (JINST 9 (2014) 12, P12005)

4. Track Distributions In PbPb Collisions

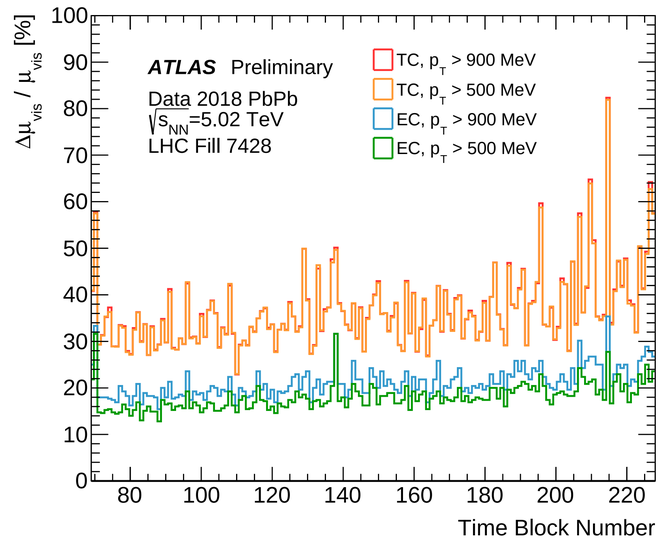


Number of tracks per event. Large tail is due to rare, high multiplicity head-on collisions.



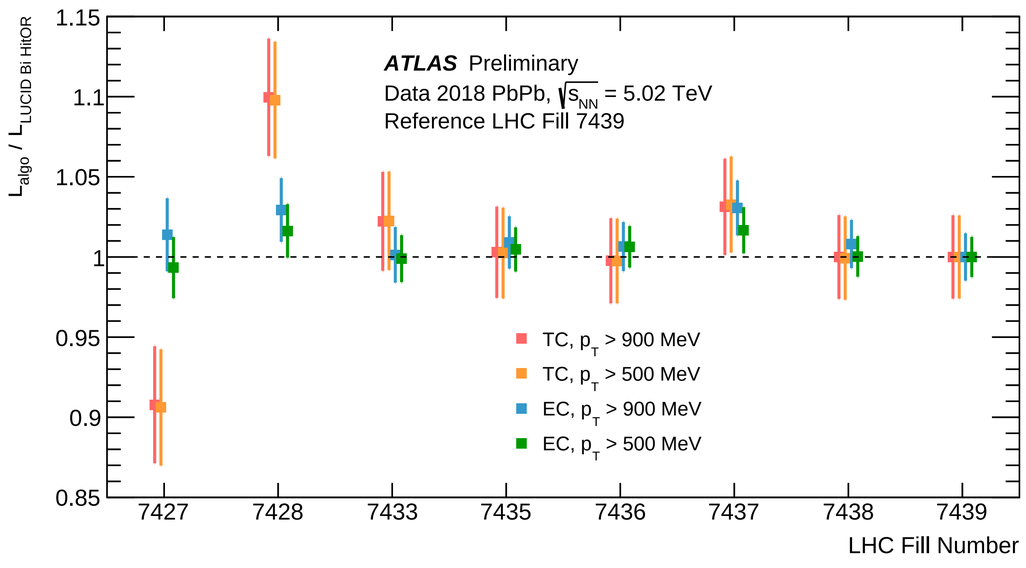
Number of tracks per time block. Large statistical uncertainties are due to rare, high multiplicity head-on collisions.

5. Luminometer Performance



Event counting (EC) offers **2x improvement** in μ_{vis} relative uncertainty over Track Counting (TC), benefits from low track p_T threshold.

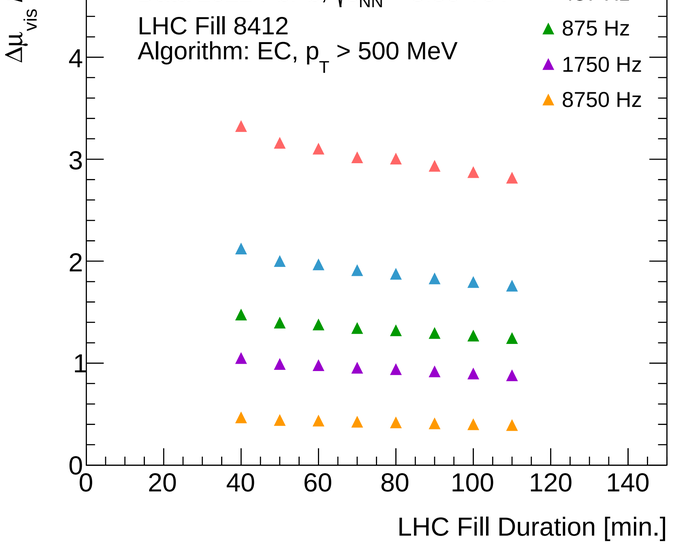
6. Long Term Performance



Integrated luminosity determined using Track Counting (TC) and Event Counting (EC) algorithms, compared to the dedicated **LUCID** sub-detector. Event Counting is observed to be **more stable** over time. Improvements observed per time block (2x improvement in μ_{vis} relative uncertainty, improvement due to reduced track p_T threshold) also seen in integrated luminosity.

7. Effect Of Event Rate

ATLAS uses a **trigger system** to reduce event rate from 40 MHz, to rates compatible with the readout limitations. Event rate affects the μ_{vis} statistical uncertainty.



Data from Nov. 2022 pilot PbPb beams is used to study the effect of event rate on the μ_{vis} statistical uncertainty. The event rate in 2018 was 180 Hz. A **1% fill-integrated precision** can be reached with event rates of **1-2 kHz**.

8. Conclusion And Outlook

- Track Counting and track-based Event Counting algorithms are studied for PbPb luminosity determination at ATLAS
- Event Counting offers **2x reduced uncertainty** of the luminosity compared to Track Counting, also benefits from **looser track selection criteria**
- Effect of event rate on luminosity statistical uncertainty is studied
- Track-based Event Counting is a promising **new luminometer for the LHC Run 3 and beyond**
- Stay tuned for publications!