Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC

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Abstract

A precise measurement of the integrated luminosity is a key component of the ATLAS physics programme at the LHC, in particular for cross-section measurements where it is often one of the leading sources of uncertainty. The luminosity measurement is based on an absolute calibration of the primary luminosity-sensitive detectors in low-luminosity runs with specially-tailored LHC conditions using the van der Meer (vdM) method. A calibration transfer procedure is then used to transport this calibration to the physics data-taking regime at high luminosity. The vdM calibration was performed once per year during Run 2 data-taking, and relative comparisons of the luminosities measured by different detectors were used to set limits on any possible change of the calibration through the year. Finally, the integrated luminosity and uncertainty for the whole Run 2 data-taking period was derived, taking into account correlations between the uncertainties in each of the component years. After typical data-quality selections, the full Run 2 pp data sample corresponds to an integrated luminosity of 139 fb^{-1}, with an uncertainty of 1.7 %.

The Run 2 13 TeV pp dataset

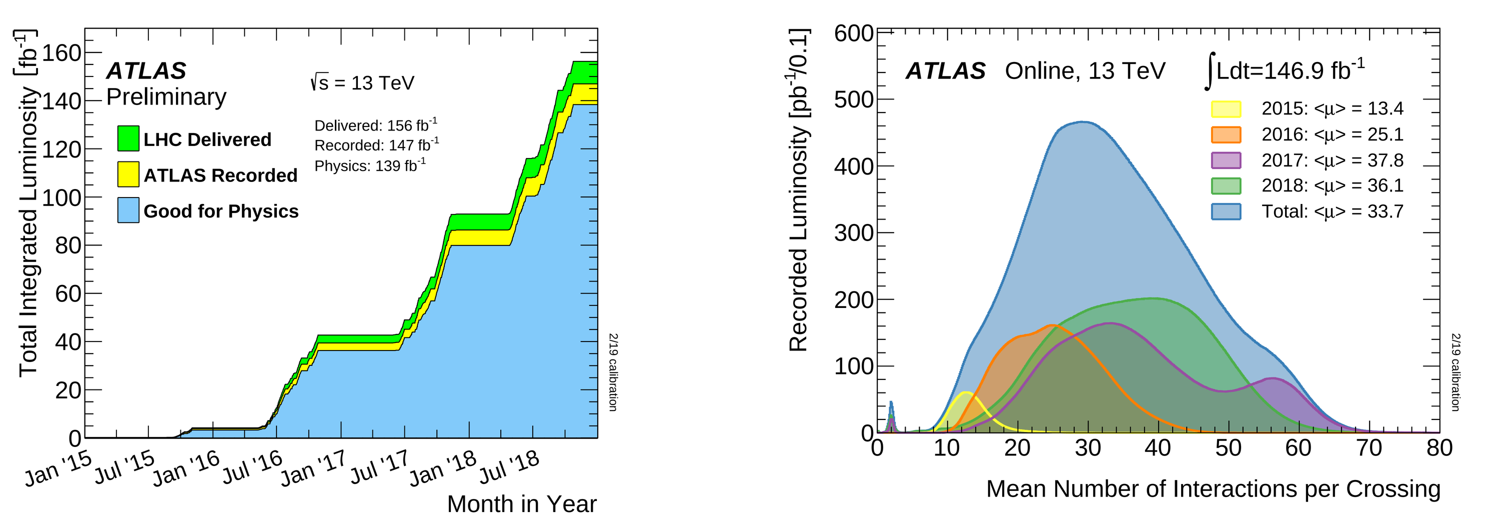

Figure 1. (*Left*) Cumulative luminosity vs. time delivered to and recorded by ATLAS. (*Right*) Luminosity-weighted distribution of the mean number of interactions per bunch-crossing $\langle\mu\rangle$.

Luminosity Detectors and Algorithms

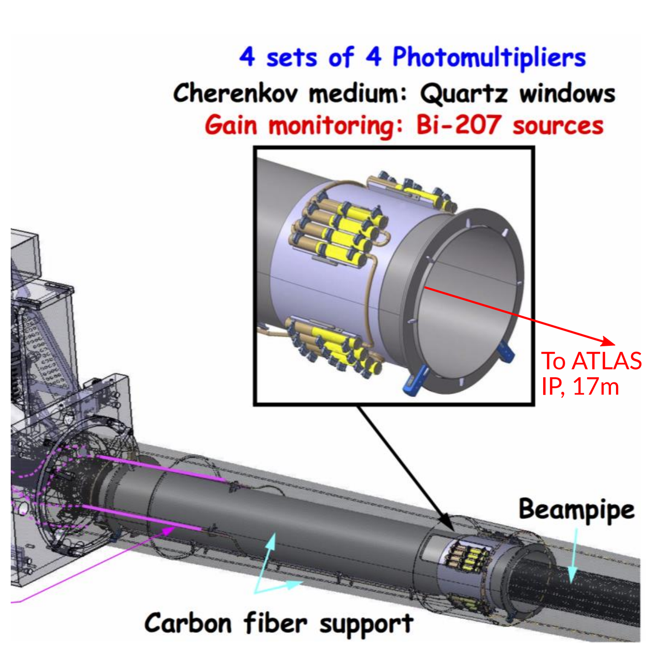

Figure 2. The LUCID-2 detector.

LUCID: The primary luminometer throughout Run 2. Uses Cherenkov light from quartz windows of 2×16 PMTs at ±17 m from the interaction point. Generally used a *HitOR* algorithm for the baseline offline luminosity, except in 2018 when a single PMT tube ("C12") was used.

Track counting: Measures luminosity from the multiplicity of reconstructed charged particles in the silicon layers of the ATLAS Inner Detector in randomly-triggered bunch-crossings.

Calorimeters: Provide bunch-integrated measurements based on quantities proportional to instantaneous luminosity: liquid-argon (LAr) gap currents in the case of the electromagnetic end-cap (**EMEC**) and forward (**FCal**) calorimeters, and photomultiplier currents from the scintillating-tile hadronic calorimeter (**TILE**).

Other detectors and methods used to monitor the luminosity include the ATLAS beam conditions monitor (**BCM**), cluster counting in a network of TimePix readout sensors (**TPX**), and the rate of reconstructed $Z \to \mu\mu$ events in a well-defined fiducial region (**Z-counting**).

LUCID measures the visible interaction rate μ_{vis} bunch-by-bunch from raw hit counts, which is related to the per-bunch instantaneous luminosity by:

$$\mathcal{L}_b = \frac{\mu_{\text{vis}} f_r}{\sigma_{\text{vis}}}$$

where f_r is the LHC revolution frequency (11 246 Hz) and σ_{vis} is the visible cross-section, determined experimentally using the vdM method.

Absolute Luminosity Calibration: the vdM Method

The instantaneous per-bunch luminosity in terms of LHC beam parameters is,

$$\mathcal{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

where n_1 and n_2 are the numbers of protons in the beam-1 and beam-2 colliding bunches, and Σ_x and Σ_y are the convolved beam sizes in the horizontal and vertical planes. Σ_x is determined using the instantaneous luminosity $R(\Delta x)$ measured as a function of the separation Δx between the two beams in the horizontal plane:

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R(\Delta x)\, d\Delta x}{R(0)}$$

The calibration of a given algorithm (i.e. its σ_{vis} value) can then be determined by combining the equations above to give,

$$\sigma_{\text{vis}} = \mu_{\text{vis}}^{\text{max}} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

where $\mu_{\text{vis}}^{\text{max}}$ is the visible interaction rate per bunch crossing at the peak of the scan curve. A single pair of x–y vdM scans thus suffices to measure σ_{vis} for each algorithm active during the scan. Multiple scans are performed per session to estimate the scan-to-scan reproducibility, which is taken as a systematic uncertainty.

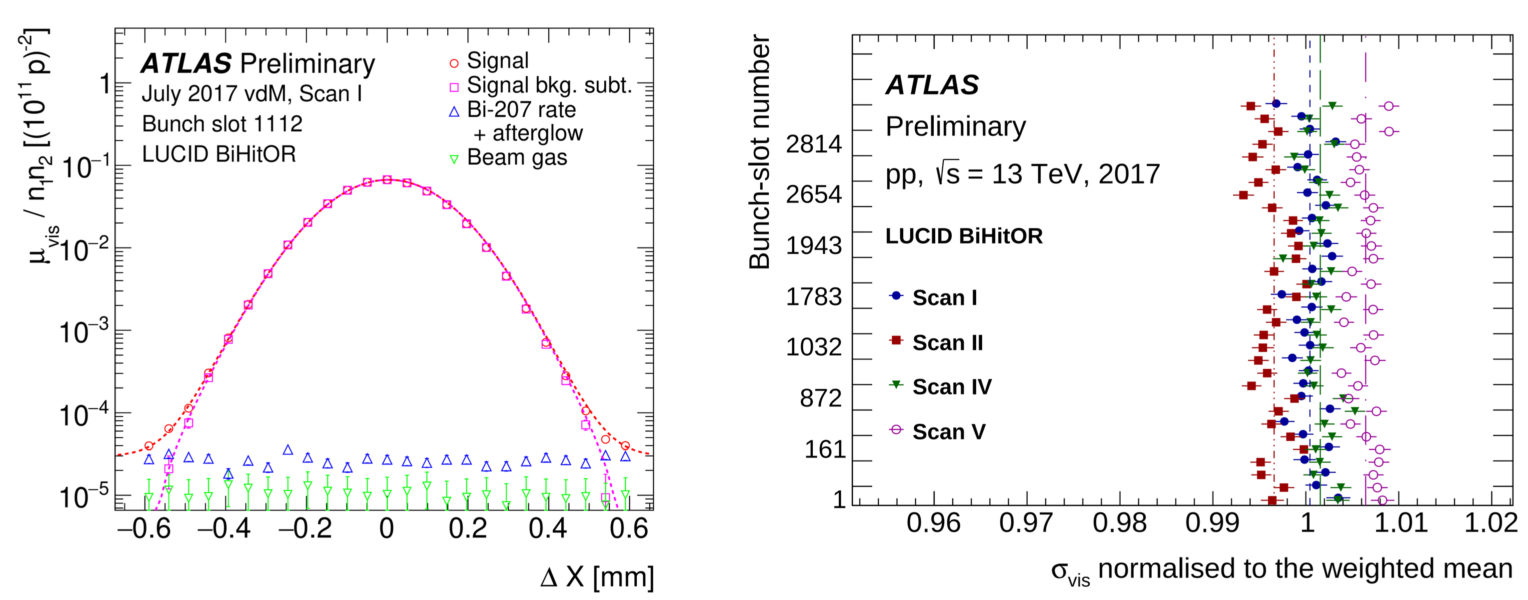

Figure 3. (*Left*) Visible interaction rate vs. beam separation Δx in the horizontal plane measured by LUCID in the July 2017 vdM session. (*Right*) Ratios of bunch-by-bunch visible cross-sections to the weighted mean of σ_{vis} for all colliding bunch pairs and on-axis scans in the 2017 vdM scan session.

Calibration Transfer

Due to a non-linear response of the LUCID detector, a correction is required to "transfer" the calibration from the low-μ conditions during the vdM scans with isolated bunches to the high-μ physics data-taking regime. The effects of this non-linearity were corrected by comparing LUCID to track-counting luminosity measurements and parameterized in terms of μ. This procedure implicitly assumes that track-counting is linear with μ, which is verified by comparing track-counting to TILE in the vdM run and a close-in-time high-luminosity physics fill. The relative difference between track-counting and TILE is assigned as a systematic uncertainty on the correction applied to LUCID at high luminosity (1.3 % in 2018).

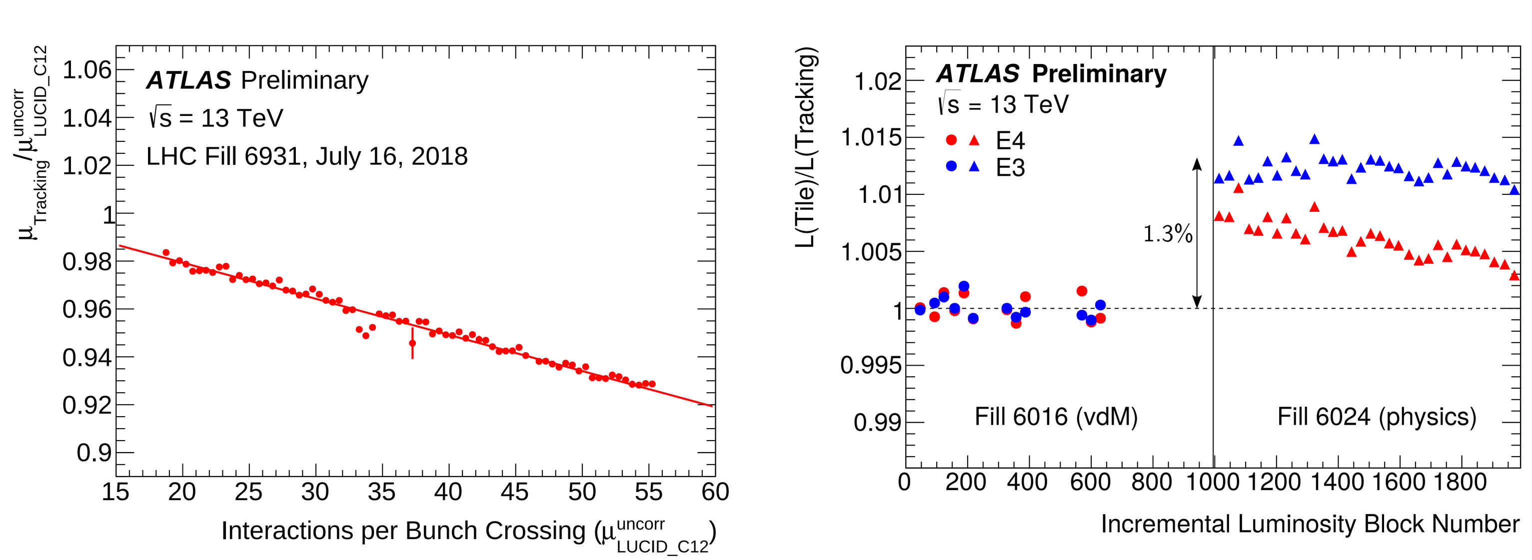

Figure 4. (*Left*) Ratios of instantaneous luminosities measured by track-counting and LUCID as a function of μ. (*Right*) Ratios of the instantaneous luminosity measured by TILE E-cell scintillators to that from track-counting in a vdM fill and a closely-following physics fill.

Long-Term Stability

The long-term stability of the absolute LUCID luminosity calibration is monitored over the course of the data-taking year by comparing LUCID's integrated luminosity estimates in each physics run with those from other subdetectors, after renormalising the other luminosity estimates to agree with LUCID in a long "reference" run close to the vdM scan.

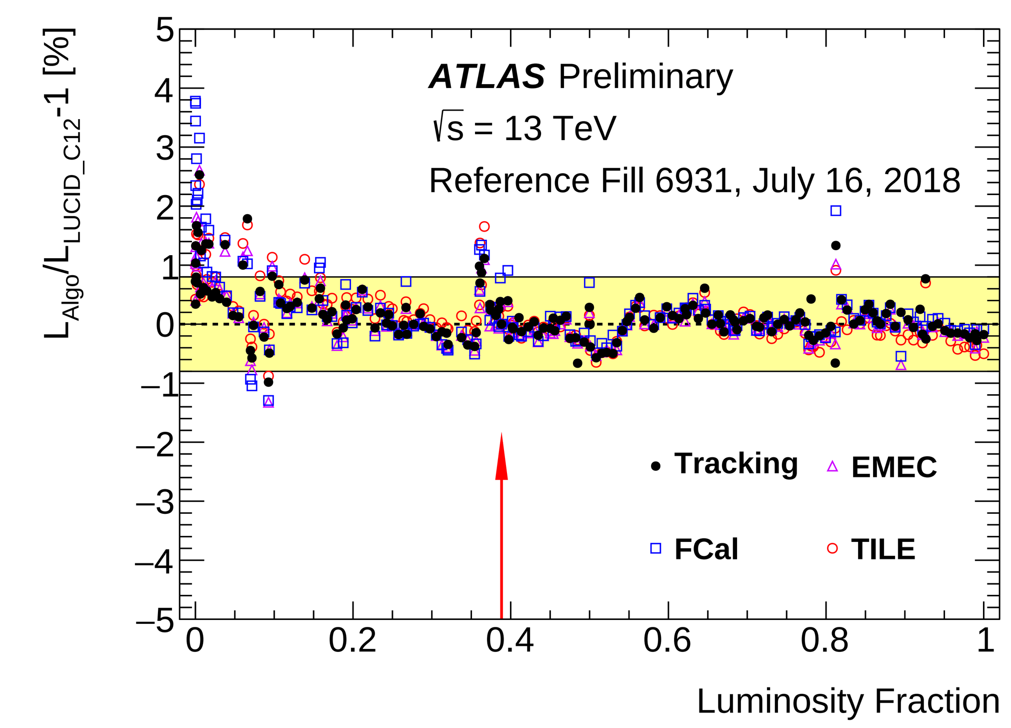

Figure 5. Stability of the primary luminosity algorithm measured by LUCID in 2018.

Fig. 5 shows the fractional differences in run-integrated luminosity between the LUCID C12 single-PMT algorithm and the track-counting, TILE, EMEC and FCal measurements, plotted as a function of the cumulative delivered luminosity normalised to the 2018 total. The reference run is indicated by the red arrow. The yellow "stability band" is chosen to enclose the bulk of the drift between LUCID and any of the other luminosity measurements. The width of this band is assigned as the long-term stability uncertainty (±0.8 % in 2018).

Combined Luminosities and Uncertainties

Table 1. Summary of the integrated luminosities and uncertainties for the preliminary calibration of each individual year of the Run 2 pp data sample and the full combined sample. Contributions marked * are considered fully correlated between years, those marked † are considered partially correlated, and the other uncertainties are considered uncorrelated.

Data Sample	2015+16	2017	2018	Comb.
Integrated luminosity (fb^{-1})	36.2	44.3	58.5	139.0
Total uncertainty (fb^{-1})	0.8	1.0	1.2	2.4
Uncertainty contributions (%):				
Absolute vdM calibration†	1.1	1.5	1.2	–
Calibration transfer†	1.6	1.3	1.3	1.3
Afterglow and beam-halo subtraction*	0.1	0.1	0.1	0.1
Long-term stability	0.7	1.3	0.8	0.6
Tracking efficiency time-dependence	0.6	0.0	0.0	0.2
Total uncertainty (%)	2.1	2.4	2.0	1.7

Total luminosity and uncertainty for the ATLAS Run 2 13 TeV pp dataset:

$$\mathcal{L}_{\text{tot}} = 139\ \text{fb}^{-1}, \qquad \delta\mathcal{L}/\mathcal{L} = \pm 1.7\,\%$$

References

[1] ATLAS Collaboration. Improved luminosity determination in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector at the LHC. *Eur. Phys. J. C*, 73:2518, 2013.

[2] ATLAS Collaboration. Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC. *Eur. Phys. J. C*, 76:653, 2016.

[3] ATLAS Collaboration. Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC. ATLAS-CONF-2019-021, 2019.