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

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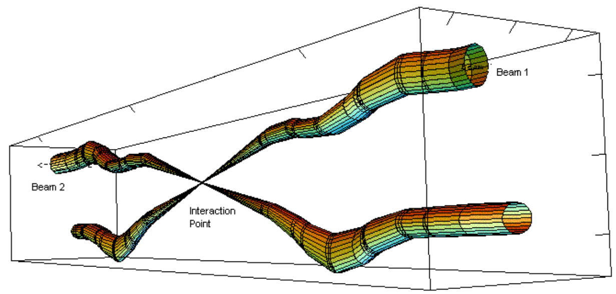
On behalf of the ATLAS collaboration

Introduction

$$\sigma = \frac{N_{events}}{\mathcal{L}_{int}}$$



Relative beam sizes around IP1 (Atlas) in collision

- A precise measurement of the integrated luminosity ($\mathcal{L}_{int}$) is a key component of the ATLAS physics programme at the LHC
  - Often one of the leading sources of uncertainty for cross-section measurements (σ).
  - It allows the determination of background levels and sensitivity of searches for new physics.

ATLAS-CONF-2019-021

Preliminary Run-2 uncertainty on $\mathcal{L}_{int}$ is 1.7% for $\sqrt{s} = 13$ TeV.

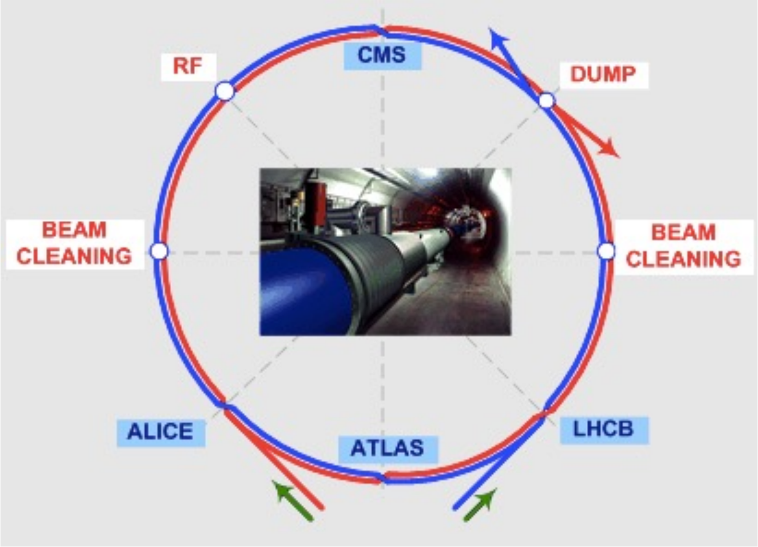
The Run-2 luminosity analysis in ATLAS is being extensively refined.
Some of these refinements will be illustrated in this talk.

Instantaneous luminosity ($\mathcal{L}_{inst}$) at LHC

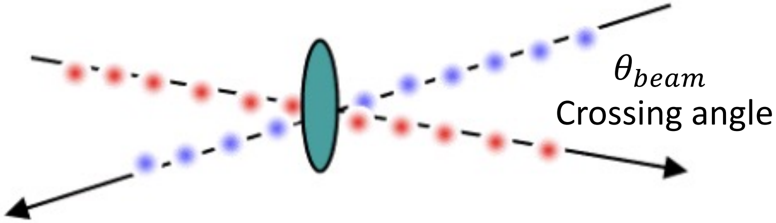
$$\mathcal{L}_{inst}(t) = \frac{n_b f_r}{\sigma_{inel}} \mu(t)$$

μ is the average number of inelastic pp collisions per bunch crossing

- Protons collide in bunches (n_b) with a revolution frequency f_r = 11245.5 Hz and an inelastic cross-section $\sigma_{inel} \sim 80$ mb @ $\sqrt{s} = 13$ TeV.



ATLAS interaction Point (IP)



Up to 2544 colliding bunches
Bunch spacing = 25 ns
$\theta_{beam}/2$ = 140-160 μrad

Luminosity monitoring

$$\mathcal{L}_{int} = \frac{n_b f_r}{\sigma_{vis}} \int \mu_{vis}(t)\, dt$$

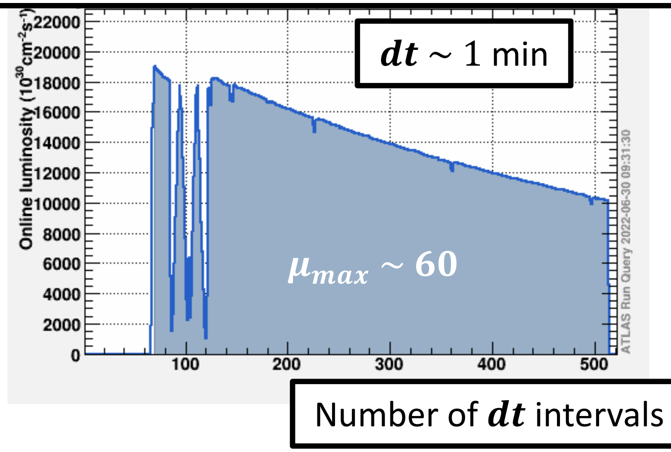
$$\mu_{vis} = \varepsilon\mu$$
$$\sigma_{vis} = \varepsilon\sigma_{inel}$$

- **Several luminosity monitors with different acceptance (ε)** are used in ATLAS to provide complementary measurements of μ_{vis}.
- **The luminosity scale (σ_{vis}) is measured in low-luminosity calibration scans ($\mu_{scan} \sim 10^{-4}$ - 0.5).**

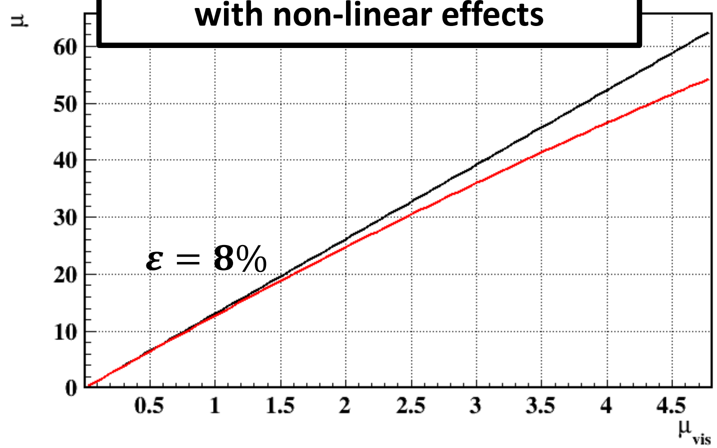
<u>Challenge</u>

Extrapolate luminosity from calibration to physics regime with high accuracy (< 1%).

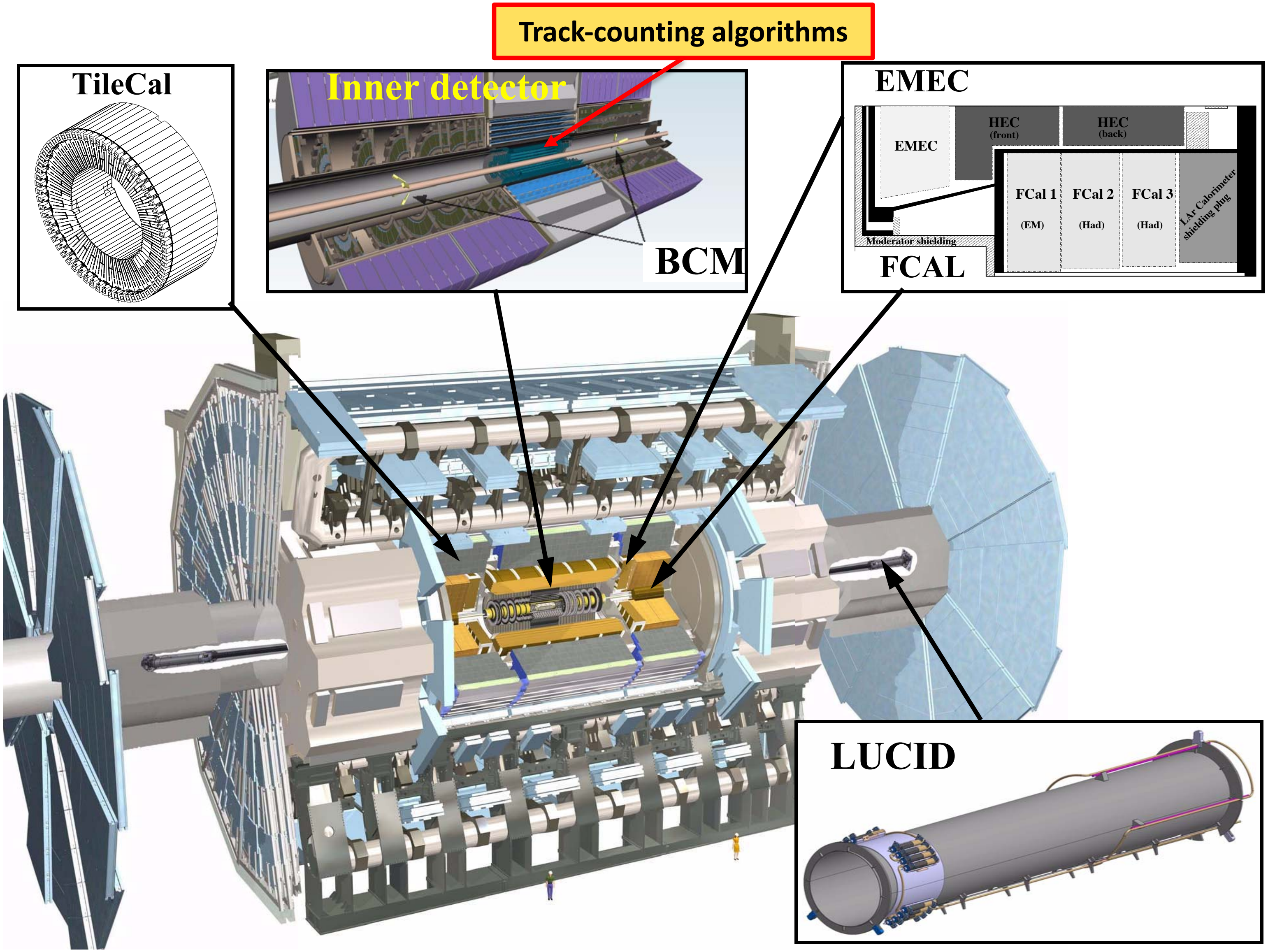
Time-evolution of luminosity in a typical ATLAS physics run



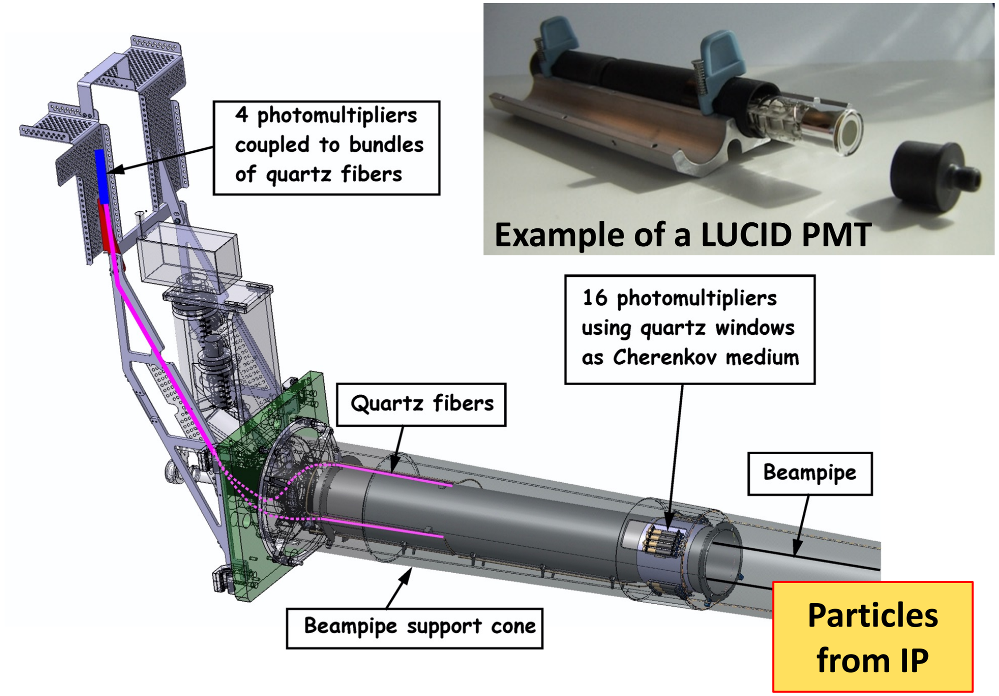
Example of luminosity monitor with non-linear effects



ATLAS luminosity monitors

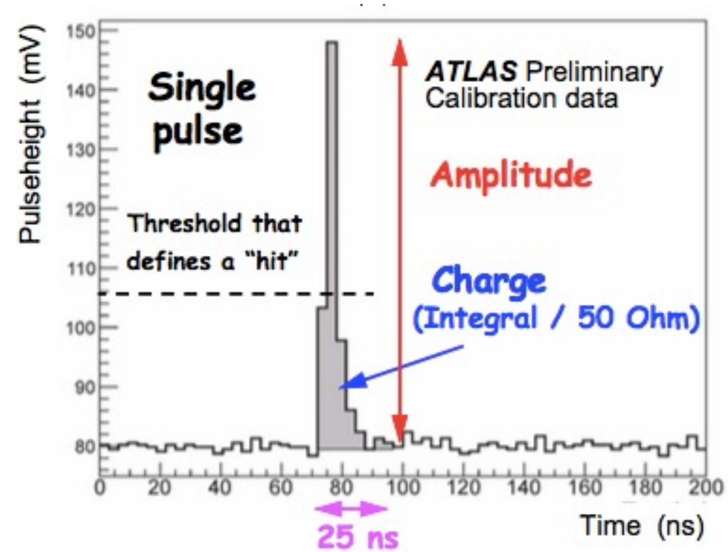


Luminosity measurement with LUCID



Example of a LUCID PMT

Main ATLAS luminosity monitor in Run-2



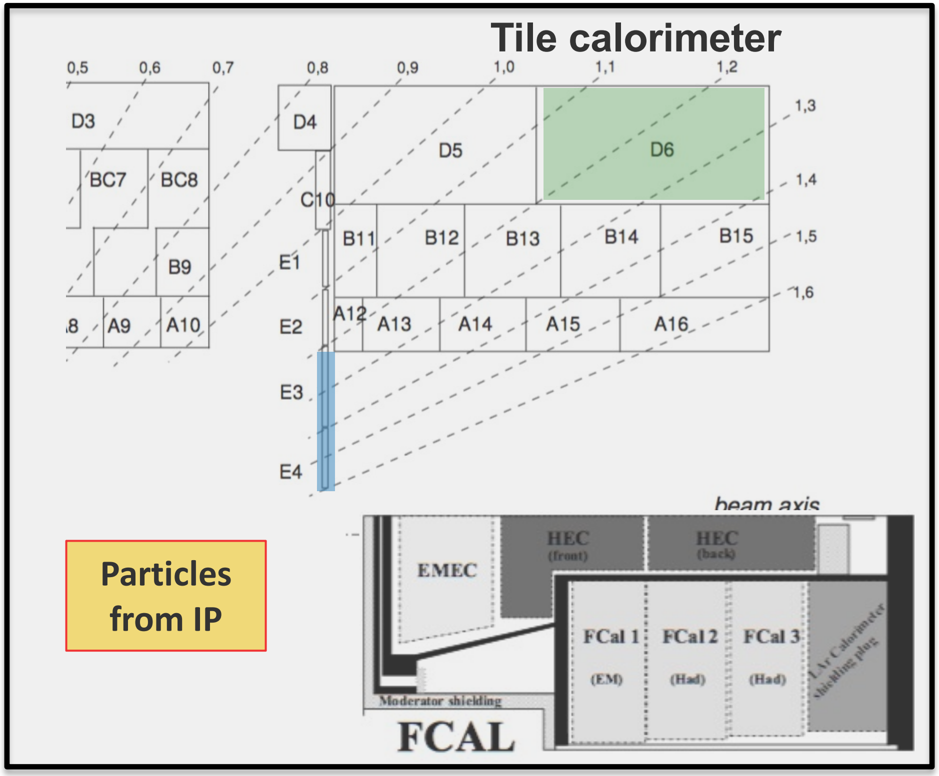
- μ_{vis} is extracted from the number of hits per bunch crossings (N_{hit}/N_{BC}) recorded in a set of photo-multipliers (N_{PMT}).

$$\mu_{vis} = -\log\left(1 - \frac{N_{hit}}{N_{BC}N_{PMT}}\right)$$

PMT gain is kept constant with ^{207}Bi calibration sources deposited on the quartz window.

Other Luminosity detectors

- **Track-counting algorithms** extract μ_{vis} from the **number of tracks in the ATLAS Inner Detectors** (SCT, pixel, IBL) produced in randomly sampled colliding bunch crossings and that satisfy selection criteria optimized for luminosity measurement.
  - Statistically limited.
- **TILE algorithms** extract μ_{vis} from the **currents drawn by the PMTs**
  - **D6 for stability in physics runs.**
  - **E3, E4 gap scintillators for low μ runs.**
  - Only bunch integrated signals.
- **EMEC and FCal algorithms** extract μ_{vis} from the **ionization currents** produced by particles crossing the LAr-filled gaps between absorbers.
  - Only bunch integrated signals (slow signals).



Track-counting and Calorimeter algorithms are intrinsically linear with μ

ATLAS strategy for luminosity

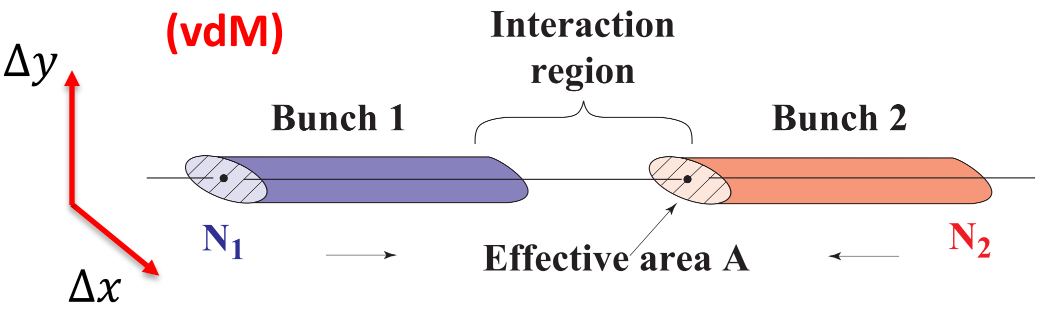
Multiple complementary algorithms to extrapolate luminosity from the CALIBRATION to the PHYSICS regime.

	Bunches	μ	θ_{beam} [μrad]
Calib.	30 – 140 (isolated)	10^{-4} - 0.5	0
Phys.	500 – 2500 (trains)	10 - 60	140 - 160

- **CALIBRATION regime (isolated bunches)**
  - σ_{vis} is measured with LUCID and BCM algorithms bunch by bunch @ μ = 10^{-4} - 0.5
  - Track-counting algorithms are normalized to LUCID algorithm @ $\mu \sim 0.5$.
- **CALIBRATION transfer to PHYSICS regime**
  - Potential non-linear effects in track-counting are constrained using the TILE calorimeter.
- **PHYSICS regime (bunch-trains)**
  - Calorimeter algorithms are normalized to track-counting algorithm in a few physics runs.
  - Non-linear effects in LUCID are corrected using track-counting in all physics runs.

Calibration run

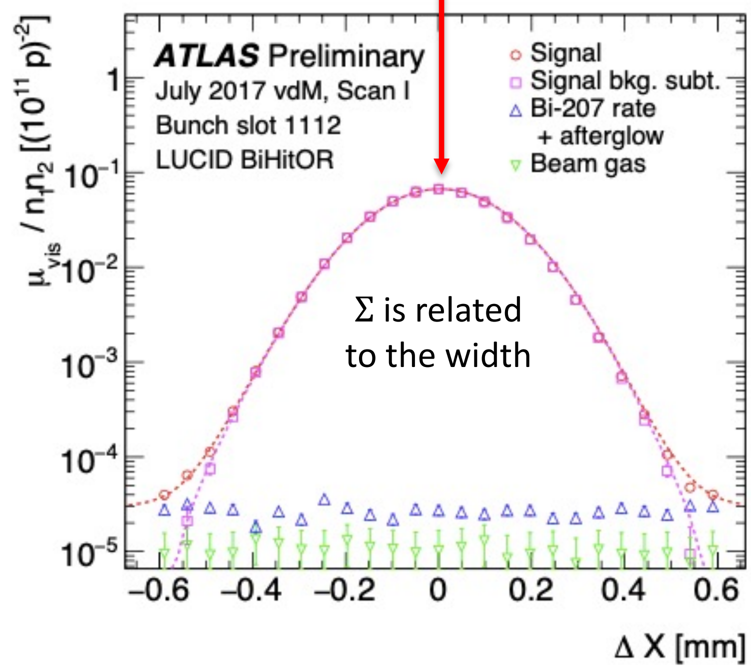
van der Meer scan (vdM)



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

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

- σ_{vis} is extracted from the rate (R) as a function of the distance between the beams (Δx,Δy).
- Bunch intensities ($n_1 n_2$) are measured with LHC beam current transformers.



Ongoing refinements in the analysis

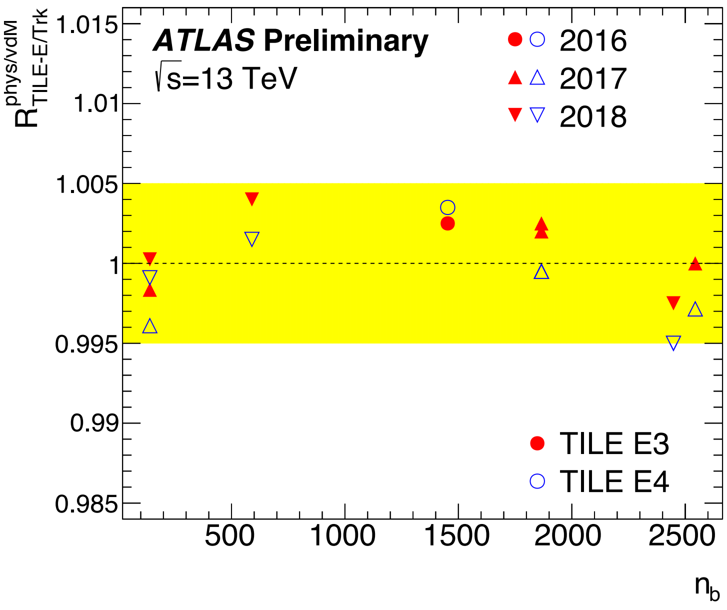
Magnetic non-linearities

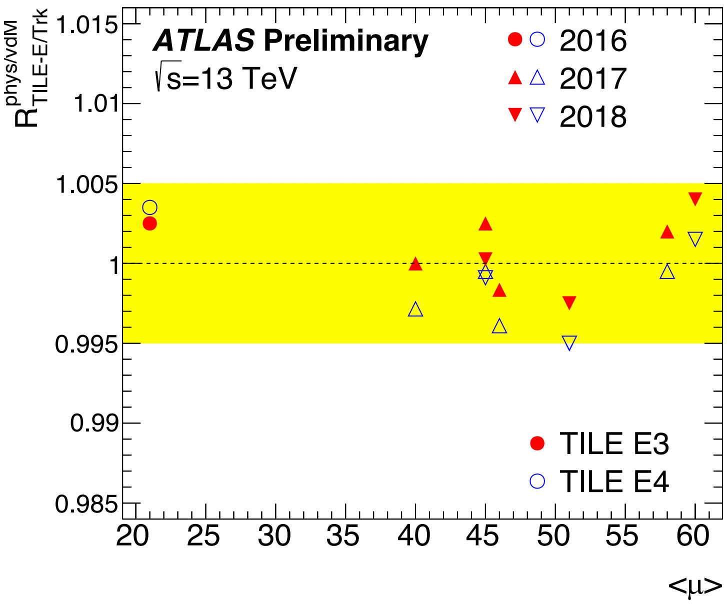
Beam-Beam interaction

Orbit-drifts

Scan-by-Scan reproducibility

Calibration transfer to physics regime



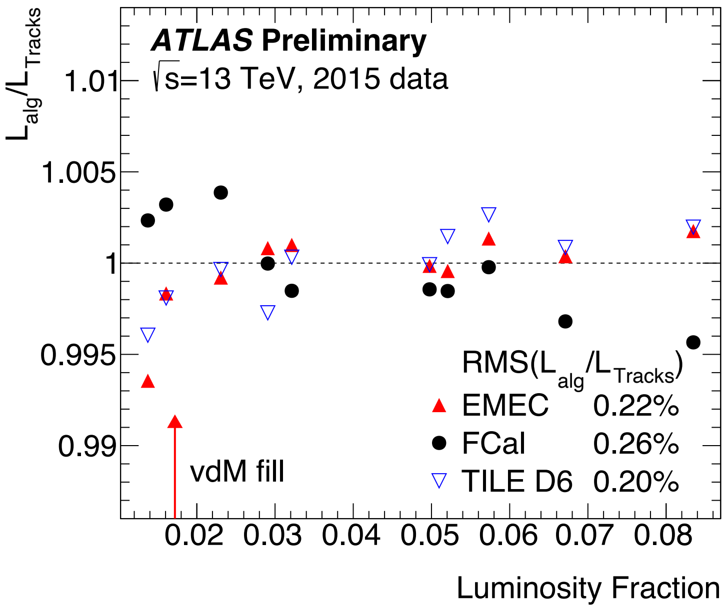


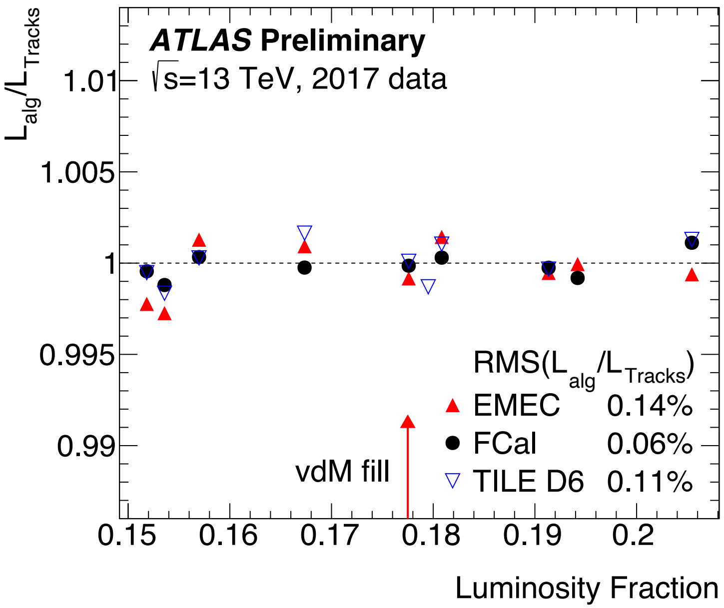
- **TILE gap scintillators** are sensitive both in calibration and in physics data-taking conditions.
  - They are used to constraint possible track-counting non-linearities in the physics regime.

<u>**Refined analysis**</u>
Modelling of TILE activation
Laser-based correction of PMT gains

Preliminary result (1.3%) improved by at least a factor 2.

Normalization of Calorimeters to track-counting



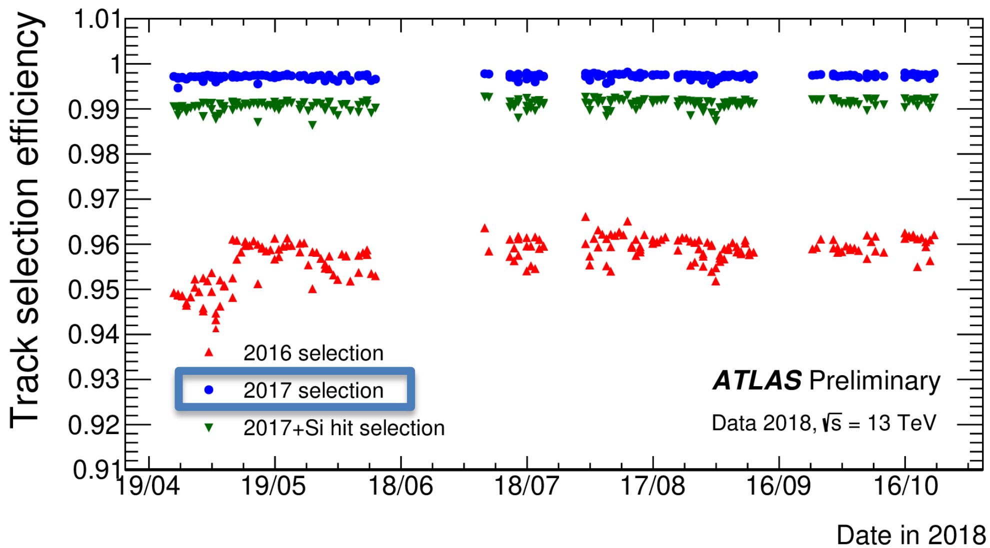


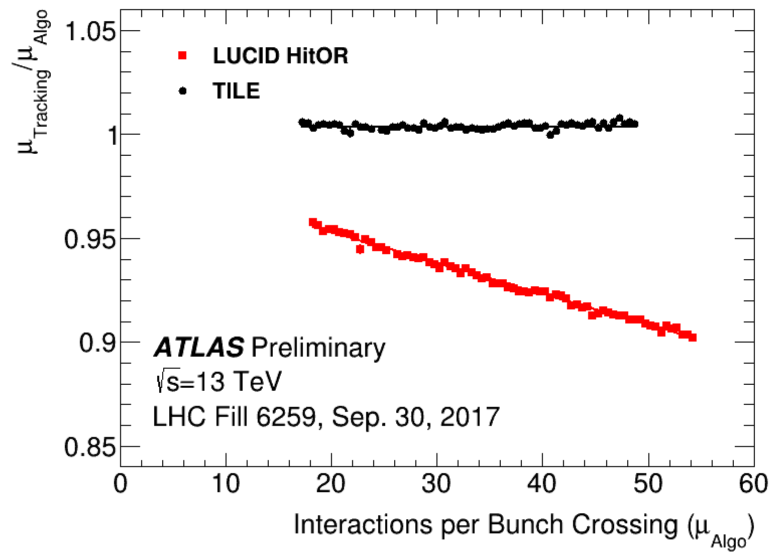
- **Calorimeters are normalized to track-counting around the calibration run.**
  - They are not sensitive in the calibration regime due to the limited number of colliding bunches.

Refined analysis

For a given data-taking year, the calorimeter/track-counting luminosity ratio with the largest RMS determines the systematic uncertainty associated with the normalization.

Correction of LUCID with track-counting



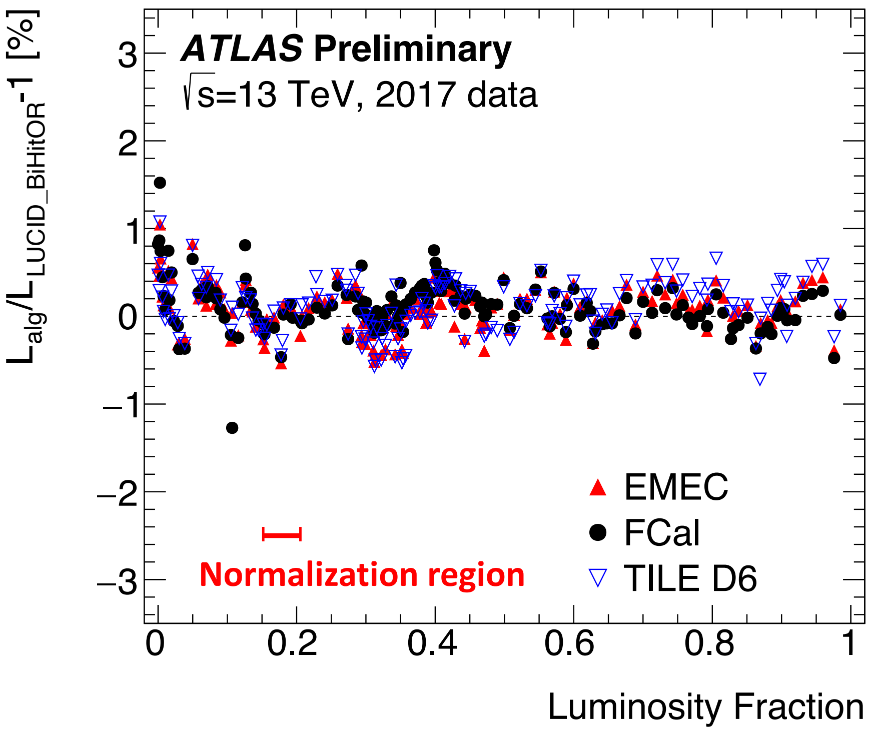


- **The track-counting algorithm is the most stable in time** (checked with $Z \to \mu\mu$ decays).
- **Non-linear effects in LUCID are corrected with track-counting** (up to 10% @ μ~50).

$$\langle \mu_{corr} \rangle = p_0 \langle \mu_{uncorr} \rangle + p_1 \langle \mu_{uncorr} \rangle^2$$

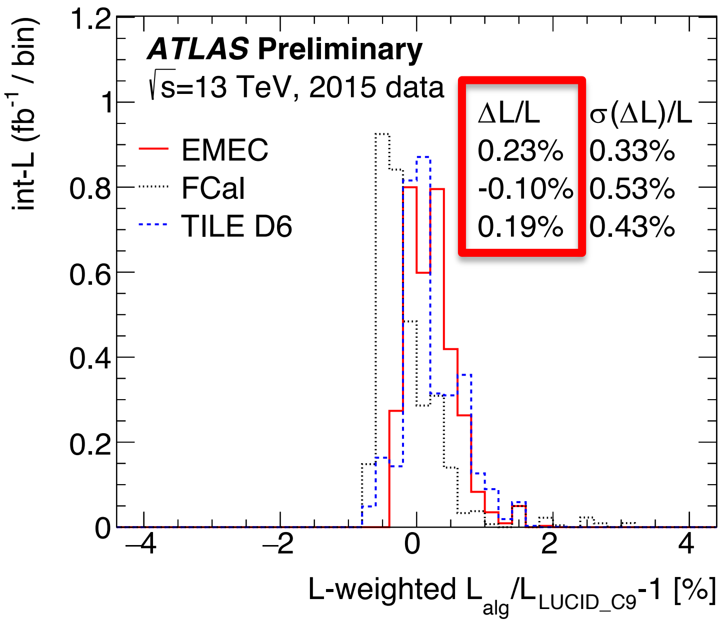
- p_0 and p_1 include the effects of **crossing angle** and **bunch-trains.**
  - They are updated up to 3 times in a year.

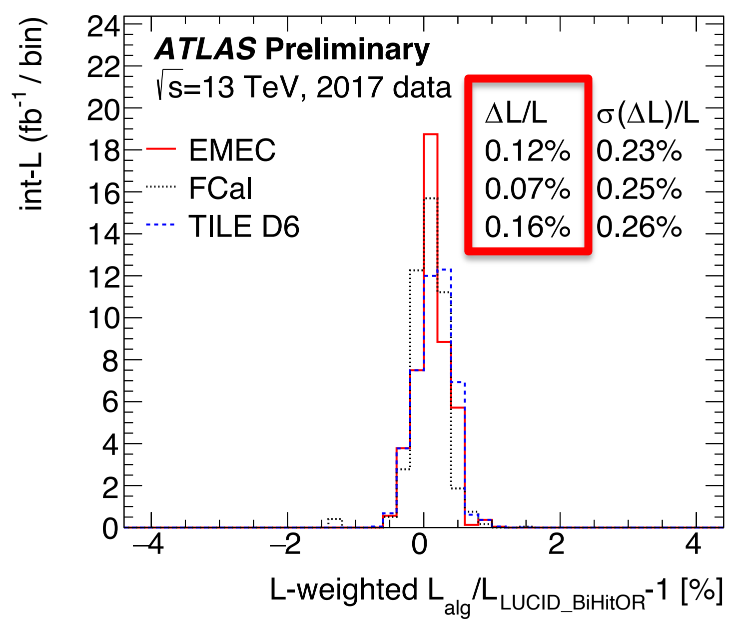
Comparison between LUCID and Calorimeters



- LUCID measurements are compared to Calorimeter measurements in each run to study long-term stability.
- **Track-counting is excluded** because it is used to correct LUCID in each run.
- **Deviations are mostly within $\pm 1\%$.**

Long-term stability uncertainty



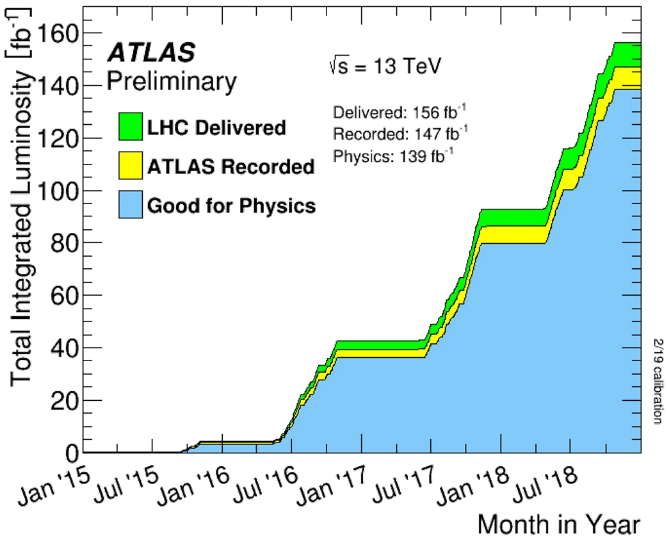


- **Physics analyses are based on total integrated luminosity.**

Refined analysis
The long-term stability uncertainty is taken as the maximum $\Delta L/L$ in a year.

Preliminary result (0.6%) improved by at least a factor 2
(contribution from normalization included)

Summary



Preliminary Run-2 Total Integrated Luminosity (ATLAS-CONF-2019-021)

$$\mathcal{L}_{int} = 139 \pm 2.4\ \mathrm{fb}^{-1}$$

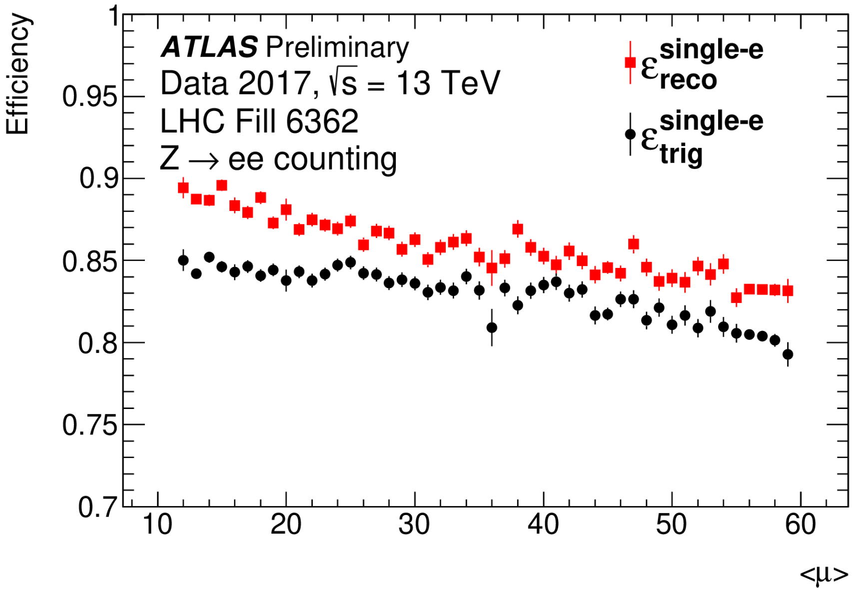
Systematic uncertainty (**1.7%**) is dominated by calibration transfer and then long-term stability.

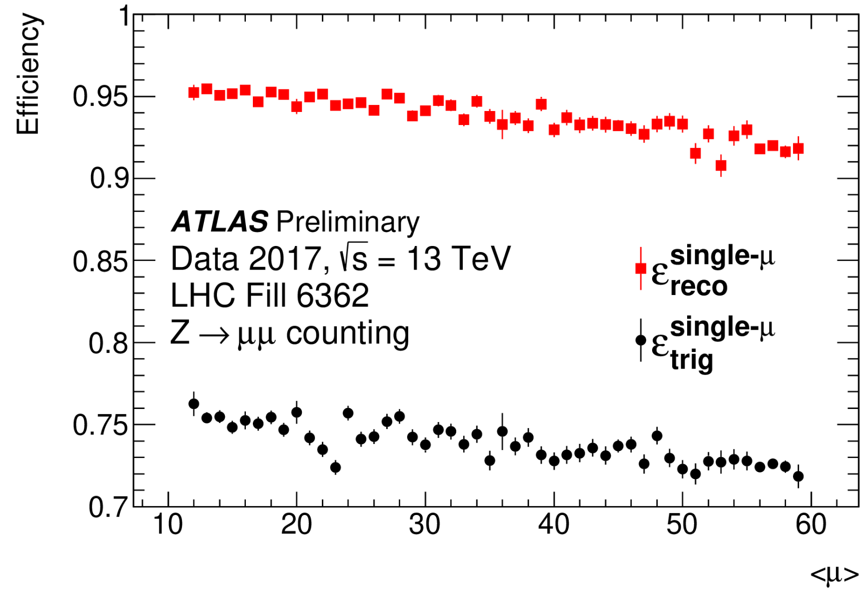
- **Nearly all aspects of the luminosity measurement in ATLAS are being extensively refined since the preliminary Run-2 results.**
- **The refined Run-2 analysis leads to an improvement by at least a factor two of the dominant systematic uncertainties.**

- **Hence, the final ATLAS Run-2 combined systematic uncertainty is expected to be significantly improved.**

Backup slides

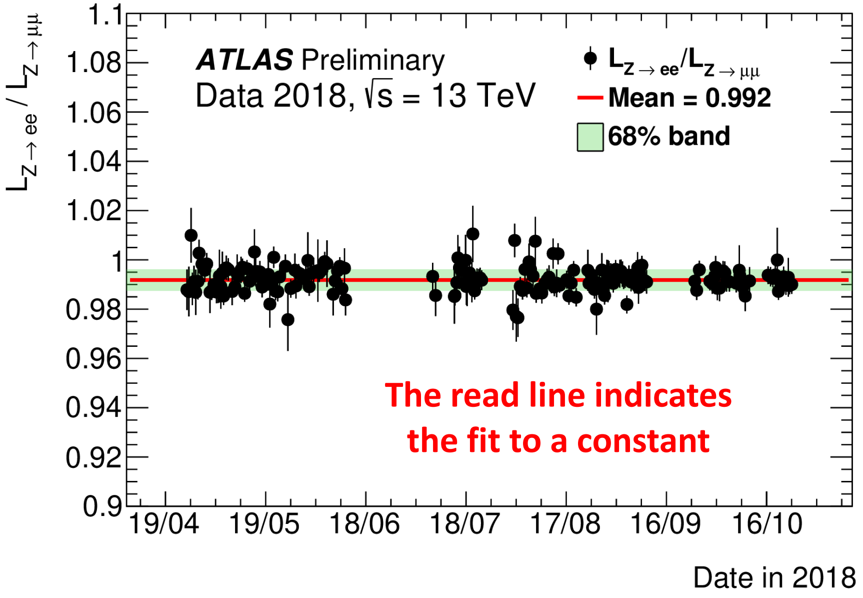
Z-counting efficiencies

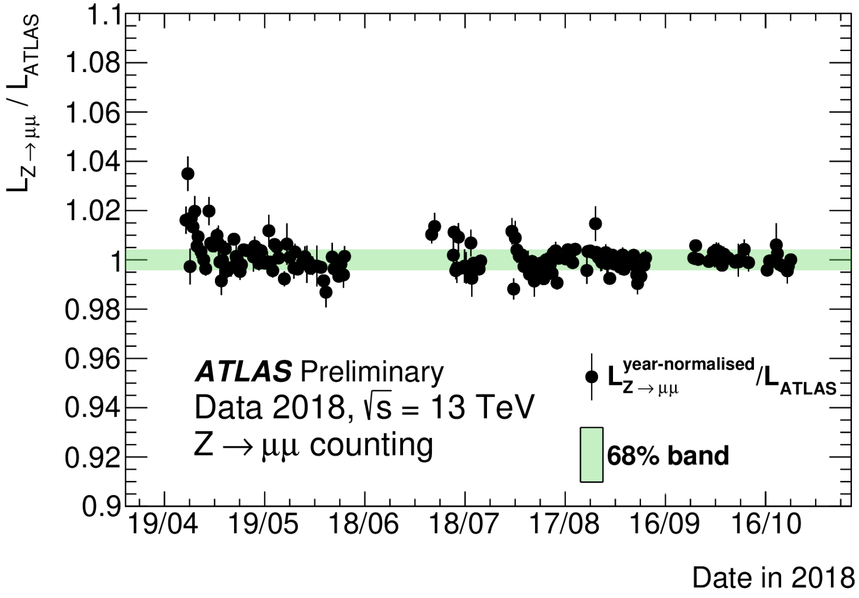




- **Data-driven tag-and-probe method.**
- **Each point represents the average over a 20 minutes data-taking period.**
- **The errors bars show statistical uncertainty only.**
- **Efficiencies decrease as a function of the pile-up parameter (μ).**
- **They account for changes of detector and beam conditions during data-taking.**
- **Residual corrections are estimated from Monte-Carlo simulations.**

Z-counting perfomance





- **Each point represents a data-taking period of at least 40 minutes.**
- **The errors bars show statistical uncertainty only.**
- **The green bands include 68% of the data-points.**
- **Consistent results between electron and muon channels.**
- **The spread of the time-dependent ratio to the main ATLAS luminosity algorithm ranges between 0.4% and 0.8% depending on the data-taking year.**