Long-term stability uncertainty of luminosity measurements of the ATLAS detector in Run 3 during the 2022 data-taking period

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Introduction

Two Fundamental Parameters of Particle Colliders

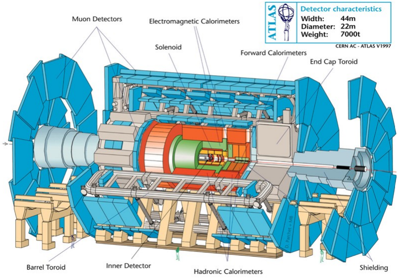
- Center-of-Mass Energy: Energy available to produce new particles or probe smaller scales.
- Luminosity: A measure of the rate at which particles collide.

Why Do We Care About Precise Luminosity?

- Cross-Section Measurements.
- Background levels and sensitivity determination in Beyond-the-Standard-Model Physics searches.

Online Luminosity Measurements

- LHC Machine optimization/levelling.
- Setting trigger thresholds.



Bunch luminosity produced by a single pair of colliding bunches is given by:

$$\mathcal{L}_{\mathrm{b}} = \frac{\mu f_r}{\sigma_{\mathrm{inel}}}, \quad f_r\text{: LHC revolution frequency}$$

μ: average number of inelastic interactions per bunch crossing and $\sigma_{\mathrm{inel}:}$ *pp* inelastic cross-section.

Total Instantaneous luminosity: $\mathcal{L}_{\mathrm{inst}} = \sum_{b=1}^{n_b} \mathcal{L}_{\mathrm{b}} = n_b \frac{<\mu> f_r}{\sigma_{\mathrm{inel}}}$

Using LCH beam parameters to derive the absolute luminosity scale

- Two colliding beams with currents n_1 and n_2 with Σ_x and Σ_y characterising widths of the beam profiles,

$$\mathcal{L}_{\mathrm{inst}} = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} = \frac{f_r \mu_{\mathrm{vis}}}{\sigma_{\mathrm{vis}}},$$

  where σ_{vis} is the visible cross-section for any process, seeing μ_{vis} counts per bunch crossing.
- van der Meer (vdM) also known as beam separation or luminosity scans are used to determine $\mathcal{L}_{\mathrm{inst}}$ (under low pile-up condintions).
- The obtained $\mathcal{L}_{\mathrm{inst}}$ and measured μ_{vis} are used to obtain the calibration constant σ_{vis}.

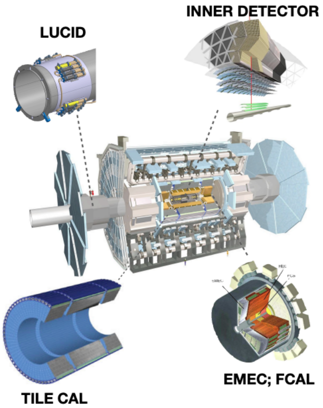
Overview of ATLAS Luminosity Detectors

Bunch-by-bunch luminosity detectors

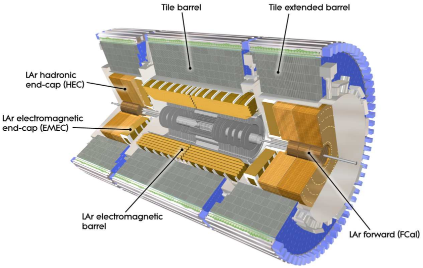
- Luminosity Integrating Detector (LUCID)
  - ★ Primary luminometer in ATLAS.
  - ★ Measures μ_{vis} and relates it to luminosity using $\mathcal{L}_{\text{b}} = \frac{\mu_{\text{vis}} f_r}{\sigma_{\text{vis}}}$.
  - ★ Determines calibration constant, σ_{vis}.
- Inner detector tracks
  - ★ Relates mean number of observed tracks to μ_{vis}.

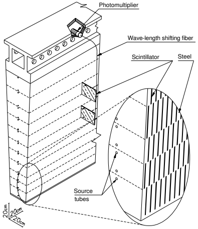
Calorimeter measurements

- Tile Calorimeter (TileCal)
  - ★ Current drawn by each PMT is proportional to luminosity.
- Liquid Argon currents
  - ★ Electromagnetic (EMEC) and Forward (FCAL) Calorimeters.
  - ★ Current drawn by charged particles from the High Voltage power supplies is proportional to luminosity.



TileCal





Sampling calorimeter made of tiles of plastic scintillators sandwiched between steel plates.

Vital in the reconstruction of hadrons, jets τ-lepton hadronic decays and missing transverse energy.

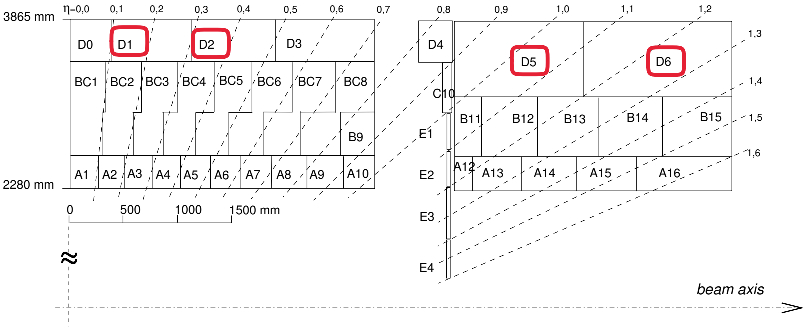
Divided into three segments along the beam axis, η segmentation.

The barrels are segmented into 64 wedge shaped modules, ϕ segmentation.

Scintillation light is transmitted by wavelength shifting fibres to photomultiplier tubes (PMTs).

The TileCal cells' geometry is defined by η segmentation ($\Delta\eta = 0.2$ for the D layer) and ϕ segmentation ($\Delta\phi = 0.1$ rad).

The position of these cells influence their sensitivity and exposure of radiation.



Primary TileCal luminosity measurements are obtained from D6 cells.

D1, D2 and D5 cells will be used for systematic comparisons.

TileCal as a Luminometer

The Anode current (I_{PMT}) in each PMT is proportional to luminosity.

Using the raw response of the PMTs, measured in ADC counts, I_{PMT} is given by:

$$I_{\mathrm{PMT}} = \frac{ADC - \mathrm{pedestal}}{\mathrm{Gain}}$$

- The current is proportional to the number of particles traversing a TileCal cell.
- The pedestal accounts for the electronic noise, beam-induced effects, and non-collision background.
- Gain is the amplification factor for each PMT.

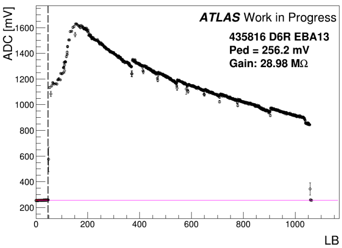
TileCal luminosity is given by:

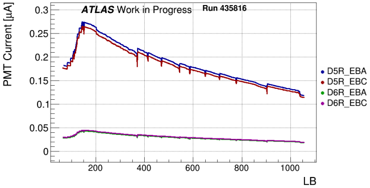
$$\mathcal{L} = \alpha < I_{\mathrm{PMT}} >$$

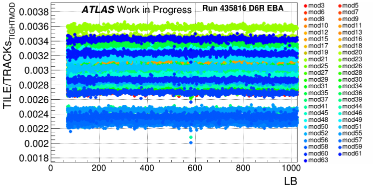
- α is obtained by cross-calibrating (anchoring) Tile to track luminosity.

Analysis Procedure

Pedestal computation | Current computation | Current computation







The pedestal is estimated by the mean number of ADC counts just before the collisions.

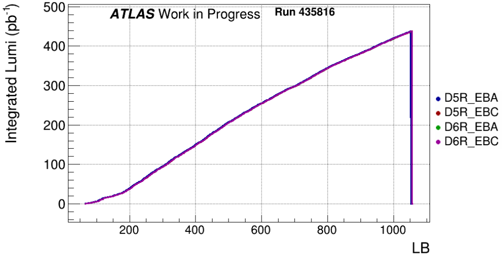
The anchoring constant is obtained from the ratio,

$$\alpha = \frac{\mathcal{L}_{\mathrm{TRACKS}}}{< I_{\mathrm{PMT}} >_{\mathrm{module}}}.$$

Tile Luminosities

The tile luminosity is given by:

$$\mathcal{L}_{Tile} = \alpha < I_{\mathrm{PMT}} >_{\mathrm{module}}$$



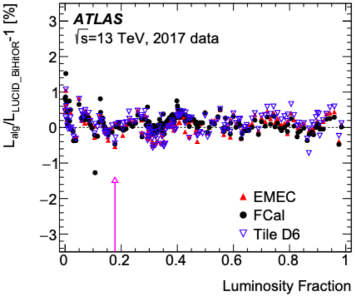
$\mathcal{L}_{\mathrm{inst}}$: gives us information about the number of *pp* collisions per second.

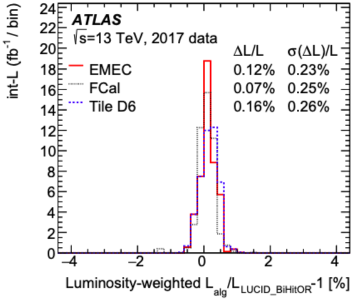
$\mathcal{L}_{\mathrm{int}}$: the number of *pp* collisions in a data set.

Long-Term Stability Study in Run 2

Run-integrated luminosities from LUCID were compared with independent measurements from EMEC, FCAL, and Tile D6 cells.

- The calorimeter algorithm showing the largest difference sets the long-term stability uncertainty.





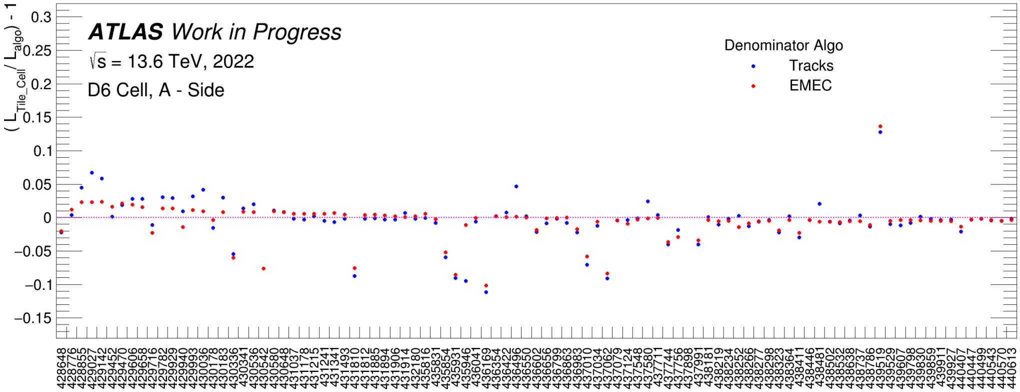
Data sample	2015	2016	2017	2018	Comb.
Integrated luminosity (fb^{-1})	*3.24*	*33.42*	*44.63*	*58.80*	*140.10*
Total uncertainty (fb^{-1})	*0.04*	*0.30*	*0.50*	*0.64*	*1.17*
Uncertainty contributions (%):					
Statistical uncertainty	0.07	0.02	0.02	0.03	0.01
Fit model*	0.14	0.08	0.09	0.17	0.12
Background subtraction*	0.06	0.11	0.19	0.11	0.13
FBCT bunch-by-bunch fractions*	0.07	0.09	0.07	0.07	0.07
Ghost-charge and satellite bunches*	0.04	0.04	0.02	0.09	0.05
DCCT calibration*	0.20	0.20	0.20	0.20	0.20
Orbit-drift correction	0.05	0.02	0.02	0.01	0.01
Beam position jitter	0.20	0.22	0.20	0.23	0.13
Non-factorisation effects*	0.60	0.30	0.10	0.30	0.24
*Beam-beam effects**	*0.27*	*0.25*	*0.26*	*0.26*	*0.26*
Emittance growth correction*	0.04	0.02	0.09	0.02	0.04
Length scale calibration	0.03	0.06	0.04	0.04	0.03
Inner detector length scale*	0.12	0.12	0.12	0.12	0.12
Magnetic non-linearity	0.37	0.07	0.34	0.60	0.27
Bunch-by-bunch σ_{vis} consistency	0.44	0.28	0.19	0.00	0.09
Scan-to-scan reproducibility	0.09	0.18	0.71	0.30	0.26
Reference specific luminosity	0.13	0.29	0.30	0.31	0.18
Subtotal vdM calibration	*0.96*	*0.70*	*0.99*	*0.93*	*0.65*
Calibration transfer*	0.50	0.50	0.50	0.50	0.50
Calibration anchoring	0.22	0.18	0.14	0.26	0.13
Long-term stability	0.23	0.12	0.16	0.12	0.08
Total uncertainty (%)	*1.13*	*0.89*	*1.13*	*1.09*	*0.83*

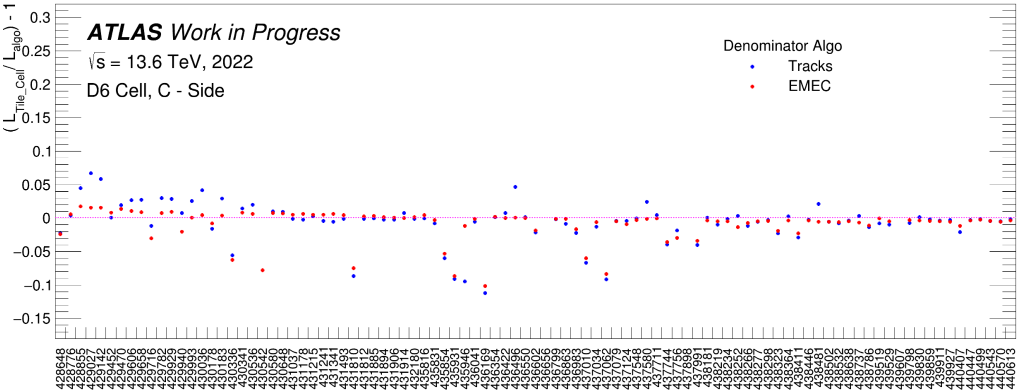
Results from the Run 2 analysis.

First Look into Long-Term Stability using Early Run 3 Data

All runs in 2022 data set are anchored to Run 435816.

Only LB with valid instantaneous luminosity values in both the tracks and tile data are used in computing the run-integrated luminosity.





Tile calorimeter employs a laser calibration system to monitor and correct for variations in PMT responses.

- The raw ADC response used in this analysis will be corrected using the laser calibration constants .

Conclusion and Outlook

Accurate luminosity measurements are crucial for various aspects of particle physics research.

The Tile Calorimeter in the ATLAS detector plays a vital role in providing luminosity information.

Long-term stability studies are essential to ensure the reliability of luminosity measurements over extended periods.

Early Run 3 data shows promising results in terms of stability, with deviations being investigated.

Laser calibration system corrections will enhance the accuracy of luminosity measurements.