Analysis of Long-Term Stability Uncertainty in Luminosity Measurements Using the Tile Calorimeter of the ATLAS Detector for Run 3 Proton-Proton Collisions at $\sqrt{s} = 13.6$ TeV in 2023

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Overview

INTRODUCTION

Two Key Parameters of Particle Colliders

- **Centre-of-Mass Energy**: Energy available to produce new particles or probe smaller scales
- **Luminosity**: determines the rate at which particles collide

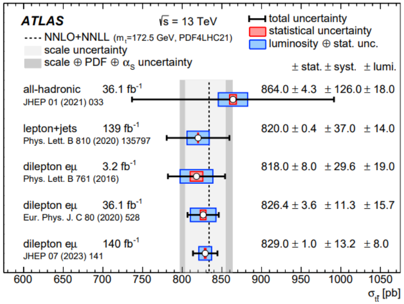
Why Measure Luminosity Precisely?

- Often leading source of uncertainty in cross-section measurements
- Crucial for estimating backgrounds and sensitivity in Beyond Standard Model searches

ATLAS Online Luminosity Measurements

- LHC Machine optimisation/levelling
- Setting trigger thresholds

https://arxiv.org/pdf/2404.10674



Dataset	Stat (%)	Syst (%)	Lumi (%)
2015–2016, 36.1 fb^{-1} (prelim. lumi)	0.4	1.4	1.9
2015–2018, 140 fb^{-1} (final lumi)	0.1	1.6	0.9

★ Reduced luminosity uncertainty due to improved luminosity calibration transfer, long-term stability analyses, and refined van der Meer procedures

Luminosity Basics

Event Rate: A Foundational Formula

Luminosity

$$R_{pp\to X} = \mathcal{L} \cdot \sigma_{pp\to X}$$

Rate of interesting process

Cross section of interesting process

- Luminosity is essentially a measure of the number of proton collisions produced by the LHC at a given interaction point (IP)
- Determined by the LHC beam parameters

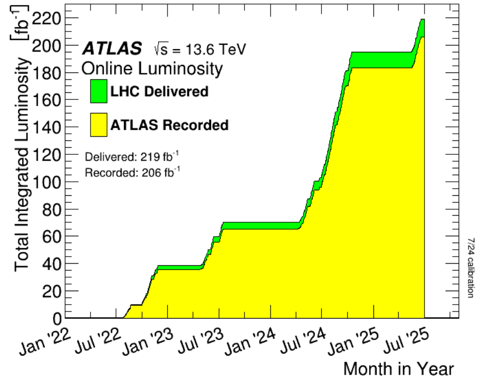
$$\mathcal{L} = f_{LHC}\frac{n_1 n_2}{2\pi\Sigma_x\Sigma_y} \longleftrightarrow \mathcal{L} = f_{LHC}\frac{\mu_{vis}}{\sigma_{vis}}$$

$n_{1,2}$: Bunch Intensity
$\Sigma_{1,2}$: Beam Overlap integral
μ_{vis}: Visible Interactions/bunch
σ_{vis}: Visible cross-section
f_{LHC}: LHC rev. Frequency

$\mu_{\rm vis}$ — measured visible interaction rate from the luminometer

$\sigma_{\rm vis}$ — visible cross section (calibration constant linking $\mu_{\rm vis}$ to absolute luminosity)

Total Integrated Luminosity in Run 3 (*pp* data only)



Instantaneous Luminosity $\mathcal{L}$ [cm^{-2} s^{-1}]

- Number of *pp* collisions per second

Integrated Luminosity $\mathcal{L}_{\rm int} = \int \mathcal{L}dt$ [cm^{-2}] $\equiv$ [fb^{-1}]

- Number of *pp* collisions in a data sample

ATLAS Luminosity Detectors and Algorithms

- Bunch-by-bunch luminosity:

  LUCID — LUminosity Cherenkov Integrating Detector

  - ATLAS's primary luminometer
  - μ_{vis} from the average number of hits per bunch crossing

$$\mu_{\mathrm{vis}} = -\ln\left(1 - P_{\mathrm{hit}}\right)$$

  Inner Detector

  - μ_{vis} is proportional to number of reconstructed tracks

$$\mu_{\mathrm{vis}} =< N_{\mathrm{trk}} >$$

- Bunch-integrated luminosity:

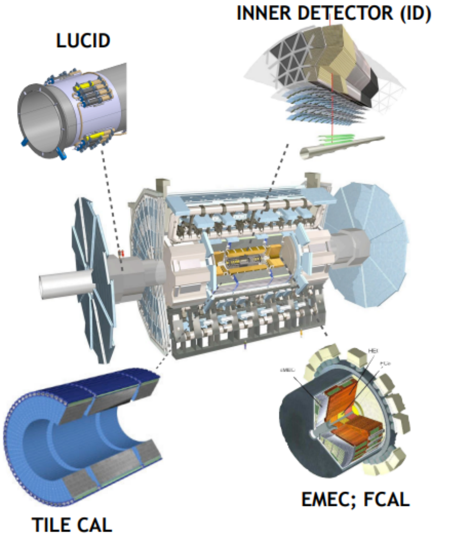
$$\mu_{\mathrm{vis}} =< I_{PMT} >$$

  LAr calorimeters: EMEC and FCAL

  - Luminosity assumed proportional to the currents drawn across LAr gaps by HV power supplies

  Tile Calorimeter

  - Luminosity assumed proportional to PMT currents



ATLAS Luminosity Measurements in a Nutshell

Basic idea:

- Measure visible interaction rate in a luminosity-sensitive detector

$$\mathcal{L}_b = f_{\text{LHC}} \frac{\mu_{\text{vis}}}{\sigma_{\text{vis}}}, \; \mu_{\text{vis}} = \epsilon\mu, \; \sigma_{\text{vis}} = \epsilon\sigma_{\text{inel}}$$

ϵ = Efficiency of algorithm, $\sigma_{\text{inel}} \approx$ 80 mb (13–14 TeV), $f_{\text{LHC}} \approx$ 11.245 kHz

Step 1: vdM Calibration

- $\mathcal{L}$ derived from beam parameters
- Used to determine σ_{vis} from the measured detector counts
- Well-controlled conditions: $\mu \approx 0.5$, few isolated bunches

Step 2: Calibration Transfer (CT)

- Transfer LUCID calibration from vdM to physics regime with Track Counting measurements
- Cross-check with Tile Calorimeter measurements to assess CT uncertainties

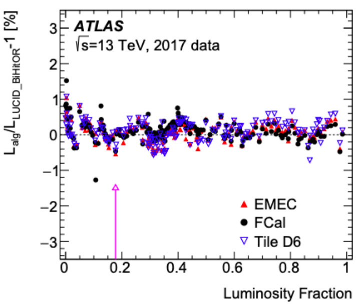
Step 3: Long-Term Stability

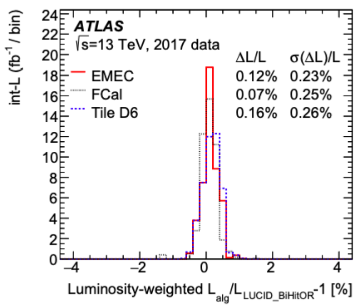
- Verify stability of luminosity calibration from run to run over entire running period
- Compare run-integrated luminosities from LUCID, Tile, EMEC, FCAL

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

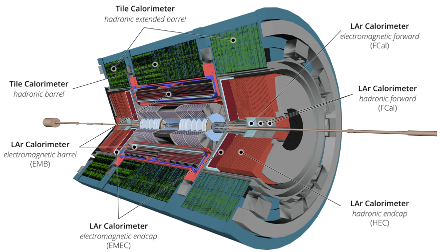


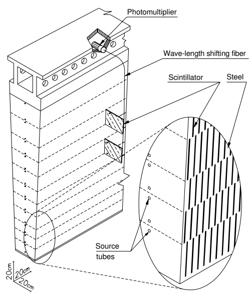


Results from the Run 2 analysis

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*

ATLAS Tile Calorimeter





Central hadronic calorimeter of ATLAS

Reconstructs energy deposits from hadrons, jets and taus, missing transverse energy

Provides input for L1Calo

Mechanical Structure

- 3 tile 'cylinders', a Long Barrel and two Extended Barrels, segmented into 64 wedge shaped modules, ϕ segmentation
- Made of alternating layers of plastic scintillators (**active material**) and low carbon steel (**absorber**)
- Divided into three segments along the beam axis, η segmentation

Readout Architecture

- Scintillation light is transmitted by wavelength shifting fibres to photomultiplier tubes (PMTs)
- Most cells are readout by 2 PMTs; E-cells are readout by a single PMT

Tile Calorimeter as a Luminometer

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)

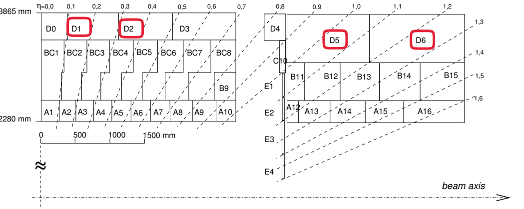
Luminosity proportional to PMT currents

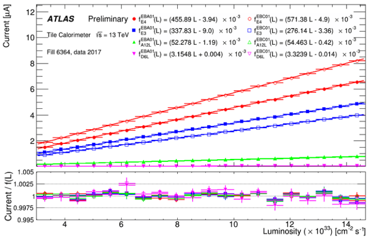
- Integrator-based readout every 10 ms for luminosity
- PMT gain change during the year corrected with laser calibration runs

Cell position affects both sensitivity and radiation dose

Different cells used for luminosity measurement

- D-cells used for long-term stability studies [subject of this talk]
- A13, A14 and E3 and E4 (gap scintillators) used for Calibration-transfer uncertainity studies





From PMT Currents to Luminosity (1)

The collision induced PMT current is given by:

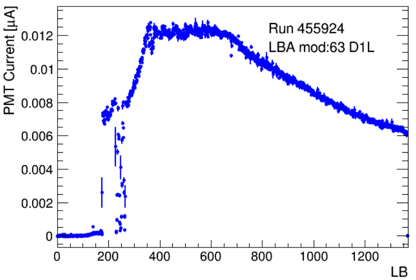
$$I_{\mathrm{PMT}} = \frac{\mathrm{ADCs} - \mathrm{pedestal}}{\mathrm{Gain}}$$

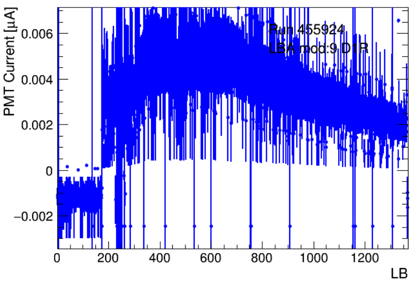
- The pedestal accounts for the electronic noise, beam-induced effects, and non-collision background
- Gain is the amplification factor for each PMT

The current is proportional to the number of particles traversing a cell

Not all PMT currents are used

- Bad PMTs: power-cycled mid-run, saturated, burnt cards, noisy channels



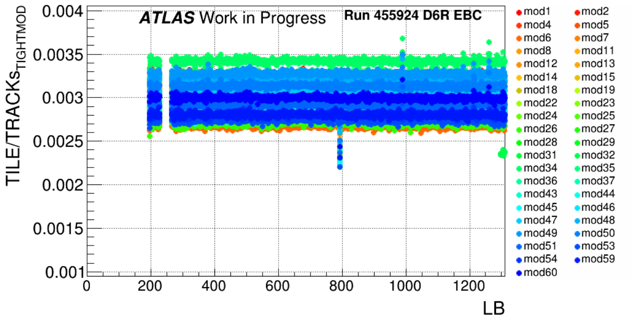


From PMT Currents to Luminosity (2)

Cross-calibrate Tile currents to Track luminosity in an 'anchor run'

Anchoring constants calculated per PMT per module

$$\alpha_{module} = \frac{\mathcal{L}_{TRACKs}}{< I_{\mathrm{PMT}} >_{module}}$$



Anchoring in the range LB 700 - 1200

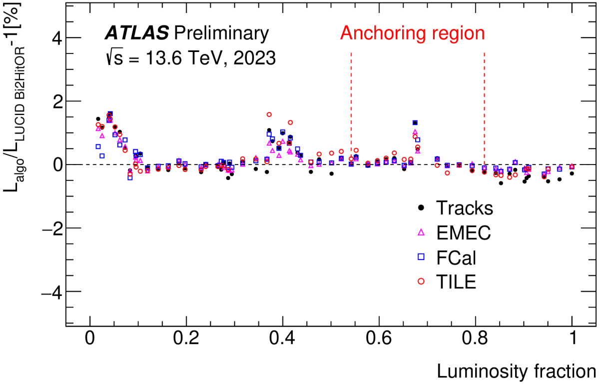
Multiply anchoring constants by Tile currents to compute luminosity per run

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

- **Module luminosity**: average of left and right PMT currents
- **Cell luminosity**: average over all good modules

LONG-TERM STABILITY STUDY USING 2023 DATA (1)

- Runs from the standard GRL are to be used.
- The Runs are required to have at least 100 LBs during Stable Beams.
- All runs to be anchored to Run 455924



- Monitor possible drifts in LUCID or track-counting over the year
- Study stability via comparisons between calorimeters and LUCID
- EMEC, FCal, and Tile D6-cell values are averaged over A-side and C-side
- Anchoring region defined by 10 fills surrounding the vdM fill

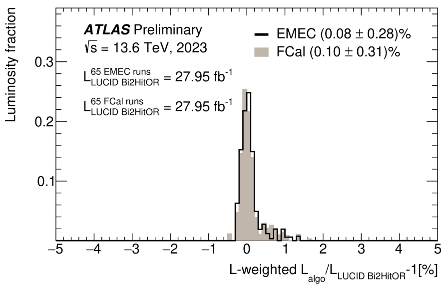
Long-Term Stability Study using 2023 Data (2)

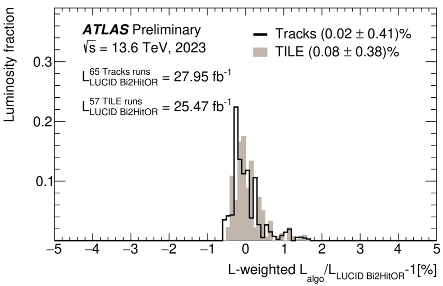
Traditional stability plots (see previous slide) overweight runs with small $\mathcal{L}_{\text{int}}$

- Physics analyses care about integrated deviation, not per-run scatter

Long-term stability is evaluated via luminosity-weighted differences between calorimeters and LUCID

Final stability uncertainty taken as the largest mean offset among EMEC, FCal, and Tile D6 vs. LUCID





Source	Relative Uncertainty	Total
vdM statistical uncertainty	< 0.01	
Scan-to-scan reproducibility	0.35%	
Bunch-to-bunch σ_{vis} consistency	0.36%	
Fit model	0.15%	
Background subtraction	0.30%	
Reference specific luminosity	0.44%	
Orbit drift correction	0.34%	
μ dependence	0.30%	
Beam-beam effects	0.32%	
Beam position jitter	< 0.01%	
Emittance variations	0.06%	
Factorised vdM analysis subtotal		0.93%
Non-factorisation	1.39%	
Length scale calibration (stat)	0.02%	
Absolute inner detector length scale	0.12%	
Magnetic non-linearity	0.28%	
Scan subtotal		1.70%
DCCT calibration	0.20%	
Bunch charge product	< 0.01%	
Ghost and satellite charges	0.04%	
vdM total		1.71%
Calibration transfer	1.1%	
Calibration anchoring	0.16%	
Long-term stability	0.1%	
Luminosity total		2.04%

Long-term stability uncertainty: 0.10% (FCal)

Conclusions

Accurate luminosity measurements are crucial in the ATLAS physics program

- Often one of the leading systematic uncertainties in SM measurements
- Needed for evaluation of background levels and search sensitivity

It is vital for operations

- LHC machine optimisation / levelling
- Setting trigger thresholds / prescales

TileCal plays a key role in ATLAS luminosity calibration

Long-term stability checks ensure reliable luminosity over time

Long-Term Stability in 2023

- Luminosity-weighted comparisons of LUCID with EMEC, FCal, and Tile D6-cell reveal excellent consistency
- Final long-term stability uncertainty: **0.10%** set by FCal