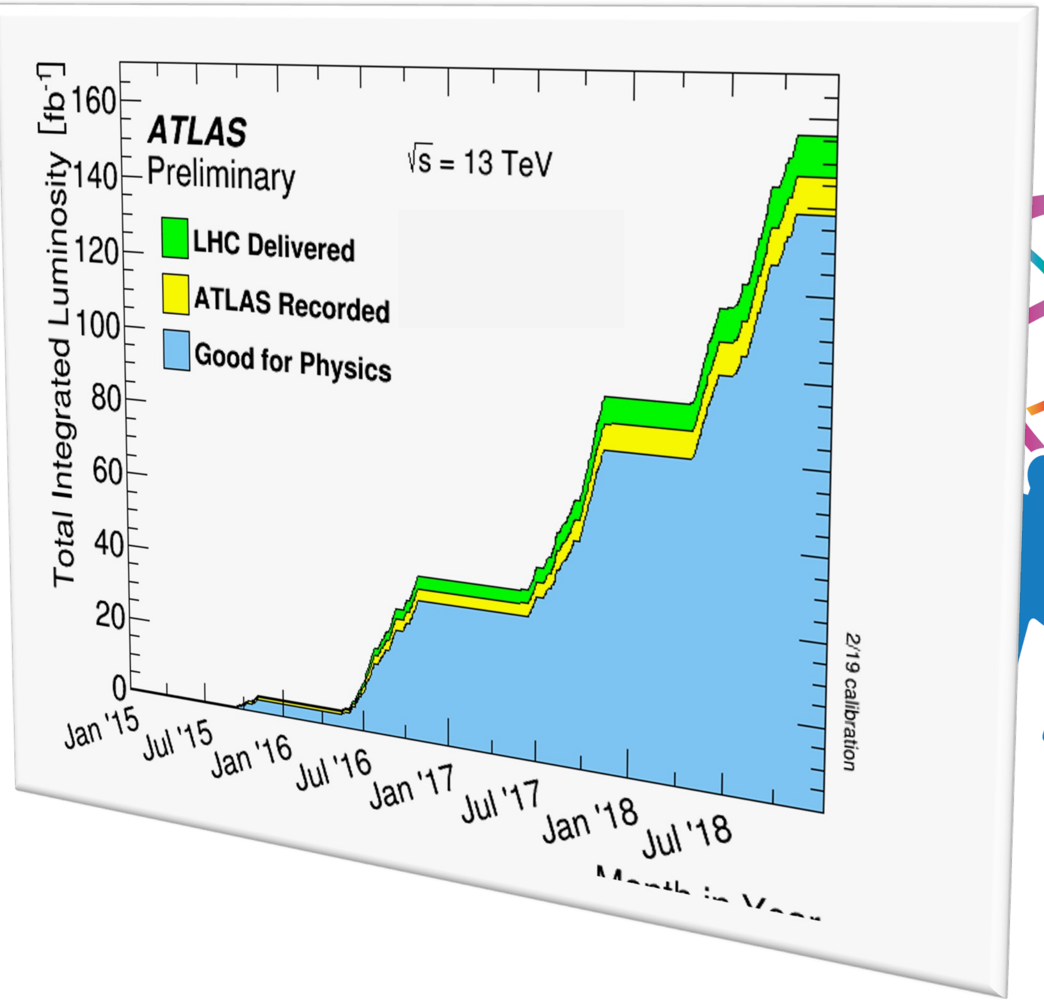

Advancing the precision: Final luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

R Rosten on behalf of the ATLAS Collaboration

EPS 2023

Introduction (and Why You Should Care)

- Accurate measure of the luminosity in ATLAS fundamental for predicting expected number of events

$$\mathbf{N} = \boldsymbol{\sigma}\boldsymbol{\mathcal{L}}_{\boldsymbol{int}}$$

- Luminosity uncertainty **can be the dominating uncertainty** for precision cross-section measurements

- **Complete reanalysis** of Run-II pp luminosity at $\sqrt{s} = 13\ \mathrm{TeV}$ has yielded a final luminosity measurement of:

$$140.1\ \mathrm{fb}^{-1} \text{ with a } 0.83\% \text{ uncertainty}$$

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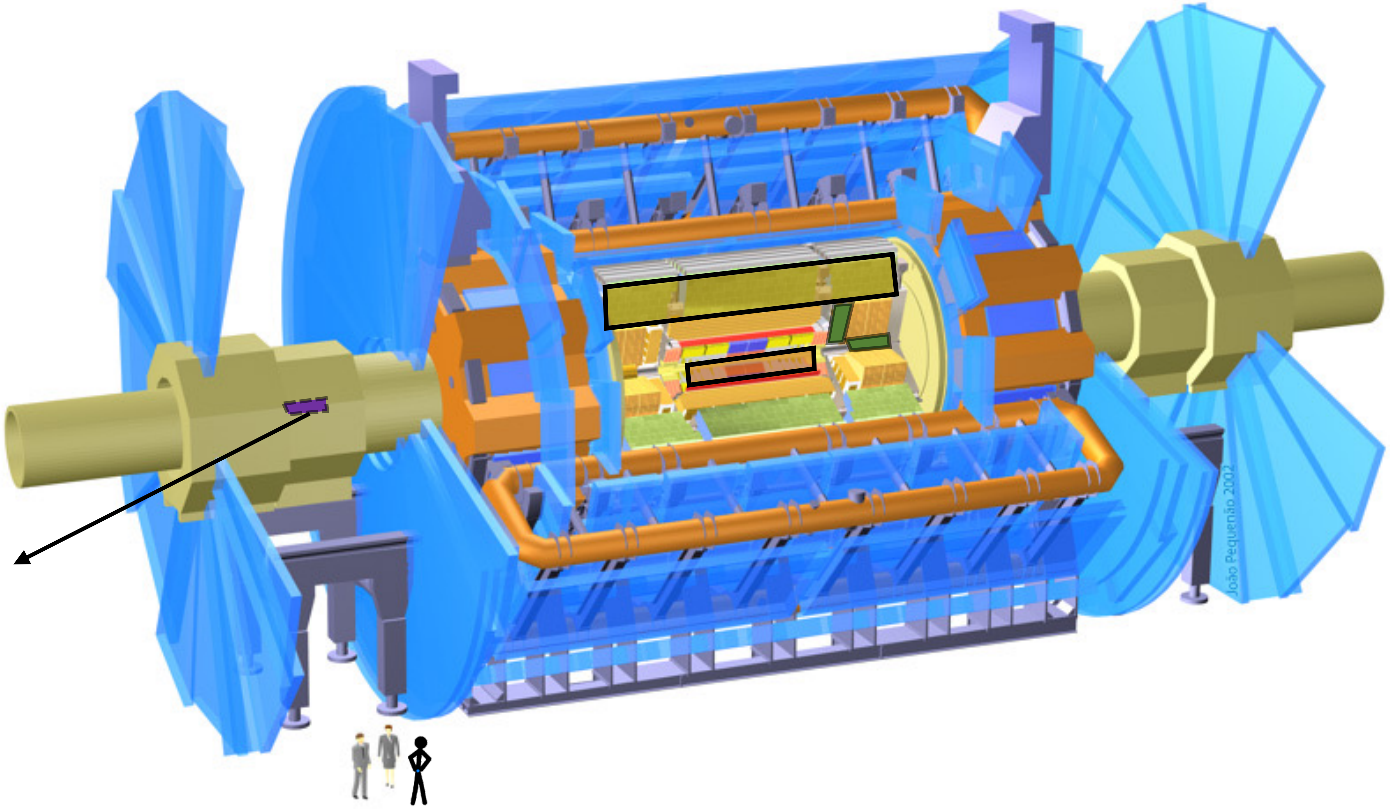
Luminosity Detectors & Algorithms



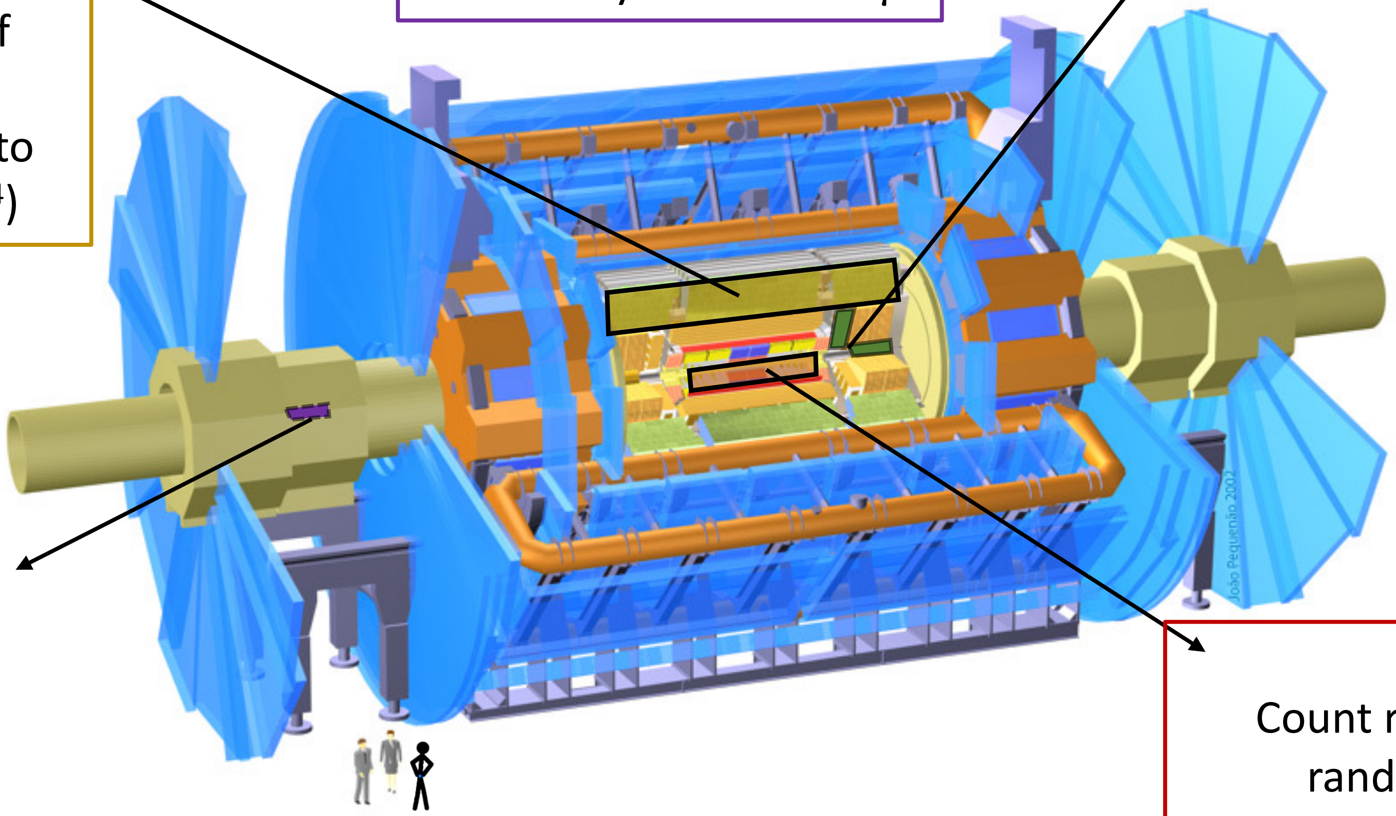
LUCID-2
The ATLAS reference luminometer, uses a hit counting algorithm
Provides real-time measurement of bunch-by-bunch luminosity at any number of interactions per LHC bunch crossing (μ)

Luminosity Detectors & Algorithms

LAr Calorimeters
Read out LAr gap HV currents over O(1) s integration times (bunch-integrated luminosity only)

Tile Hadronic Calorimeter
Samples ~1% of PMT current and integrates over O(10) ms
Sensitive over range of (bunch integrated) luminosities from vdM to physics $O(10^{30})$- $O(10^{34})$

Z-counting
Cross-check of baseline luminosity vs time and μ



LUCID-2
The ATLAS reference luminometer, uses a hit counting algorithm
Provides real-time measurement of bunch-by-bunch luminosity at any number of interactions per LHC bunch crossing (μ)

Tracks
Count reconstructed Si tracks in randomly triggered events
Sensitive over range of luminosities from vdM to physics $O(10^{28})$- $O(10^{34})$

Three Stages of ATLAS Luminosity Analysis

1

Three Stages of ATLAS Luminosity Analysis

1

Absolute Calibration

Calibrate LUCID in van der Meer (vdM) scans

Low pileup and isolated bunches

Three Stages of ATLAS Luminosity Analysis

1

Absolute Calibration

Calibrate LUCID in van der Meer (vdM) scans

Low pileup and isolated bunches

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Three Stages of ATLAS Luminosity Analysis

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Absolute Calibration

Calibrate LUCID in van der Meer (vdM) scans

Low pileup and isolated bunches

2

Calibration Transfer

Transfer of calibration to physics run conditions

High pileup and bunch trains

Three Stages of ATLAS Luminosity Analysis

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Absolute Calibration

Calibrate LUCID in van der Meer (vdM) scans

Low pileup and isolated bunches

2

Calibration Transfer

Transfer of calibration to physics run conditions

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3

Three Stages of ATLAS Luminosity Analysis

Absolute Calibration

Calibrate LUCID in van der Meer (vdM) scans

Low pileup and isolated bunches

Calibration Transfer

Transfer of calibration to physics run conditions

High pileup and bunch trains

Long-Term Stability

Monitor relative consistency and stability of ATLAS luminometers

1

Absolute Calibration

$$\mathrm{R} = \sigma_{\mathrm{vis}}\mathcal{L}$$

- Calibrate LUCID (determine its σ_{vis}) in **van der Meer (vdM) scans**
- Isolated bunches and low μ!

From LHC current measurements

From LHC

$$\mathcal{L}_{\mathrm{LUCID}} = f_{\mathrm{r}} \frac{n_1 n_2}{2\pi\Sigma_x\Sigma_y} = f_{\mathrm{r}} \frac{\mu_{vis}}{\sigma_{vis}}$$

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

- σ_{vis} : Visible cross section
- μ_{vis} : Visible interactions per bunch crossing
- f_r : LHC bunch revolution frequency
- n_1 and n_2 : protons per bunch
- Σ_x & Σ_y : convolved beam size in x & y planes

1

Absolute Calibration

- Calibrate LUCID (determine its σ_{vis}) in **van der Meer (vdM) scans**
- Isolated bunches and low μ!

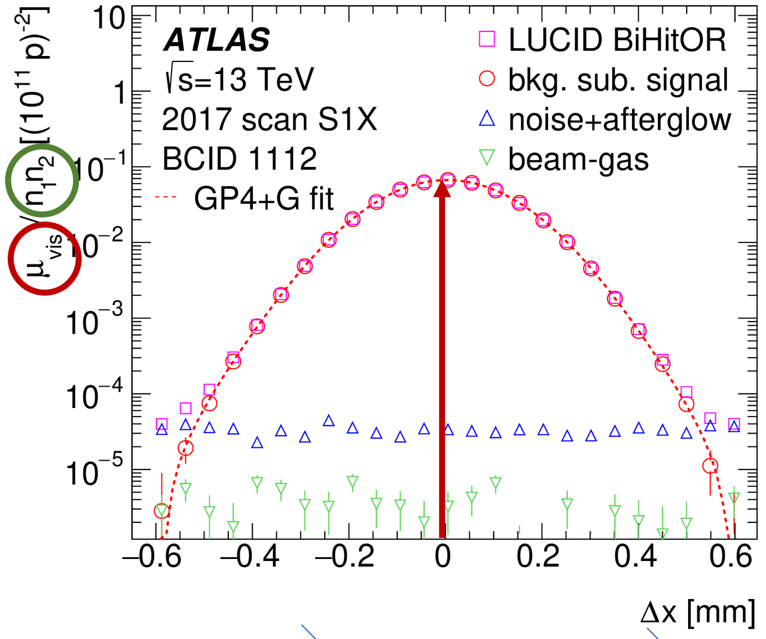
From LHC current measurements

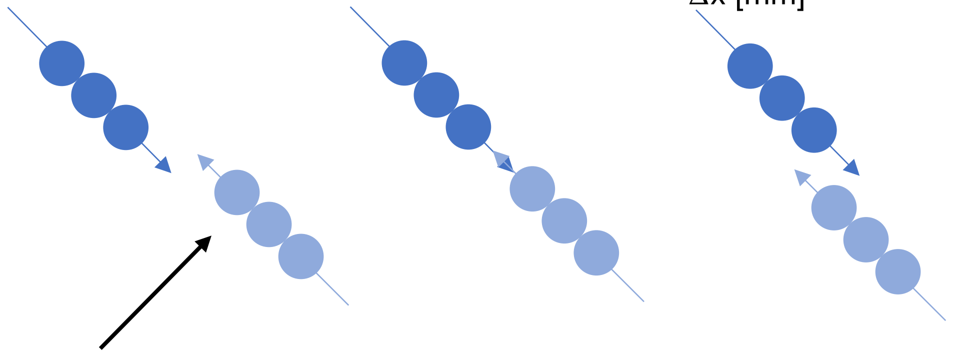
From LHC

$$\mathcal{L}_{\mathrm{LUCID}} = f_{\mathrm{r}} \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y} = f_{\mathrm{r}} \frac{\mu_{vis}}{\sigma_{vis}}$$

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

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int \mu_{\mathrm{vis}}(\Delta x) \mathrm{d}\Delta x}{\mu_{\mathrm{vis}}(\Delta x^{\mathrm{max}})} \cong \textbf{Peak Width}$$



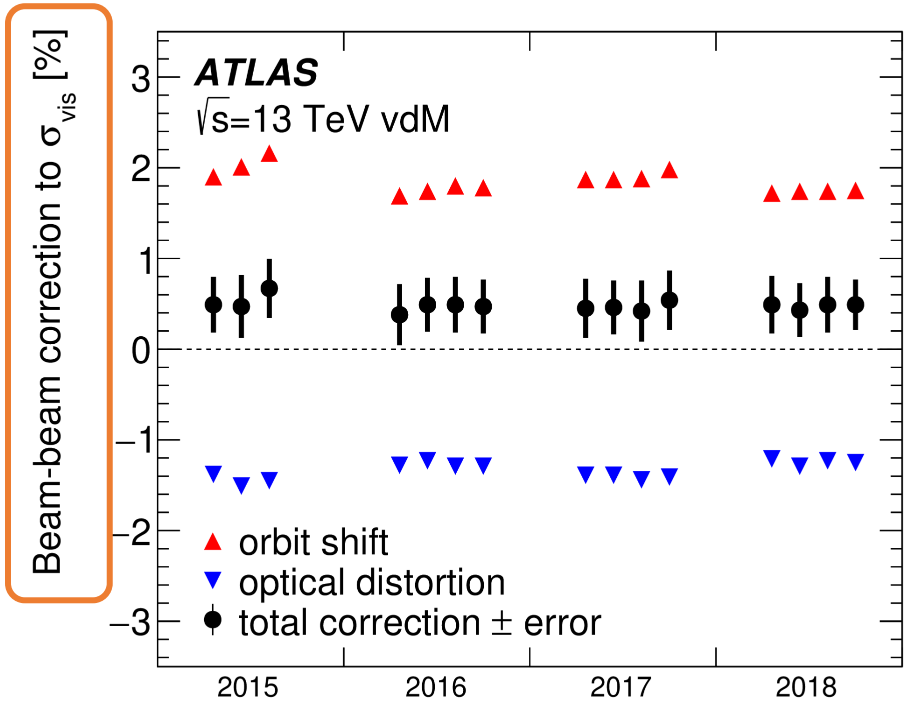


For illustrative purposes only – remember vdM scan uses **isolated** bunches!

1

Absolute Calibration Remarks

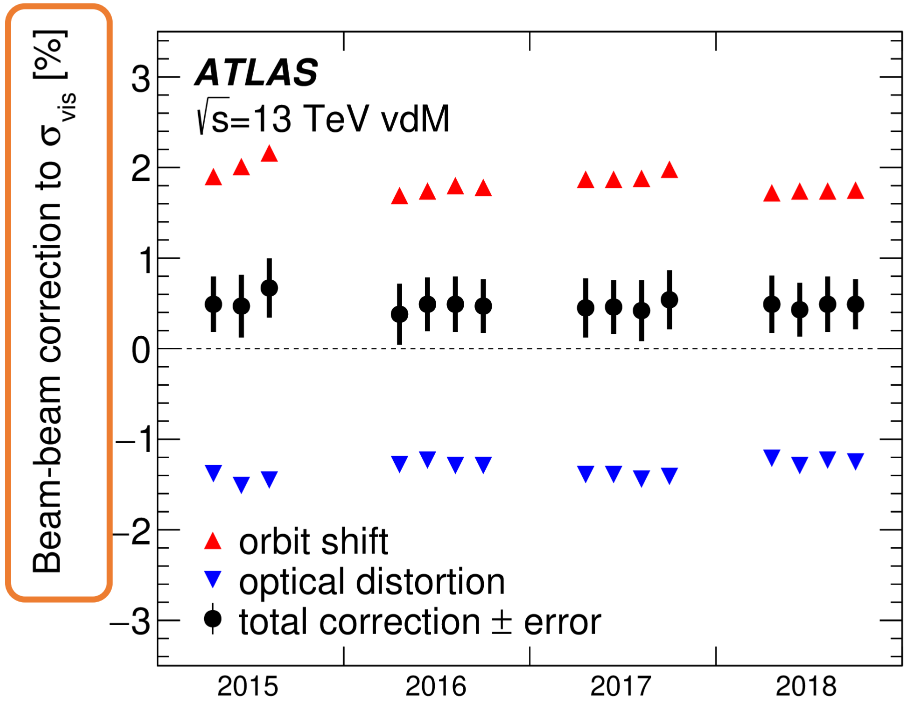
- Impact on the **scale** (σ_{vis}) results in combined upward shift of O(1%):
  - Dominant: Beam-beam effects resulting from from the mutual electromagnetic interactions of the opposing bunches
  - Sub-dominant: Fit improvements in the scan peak
  - + multiple other contributions



1

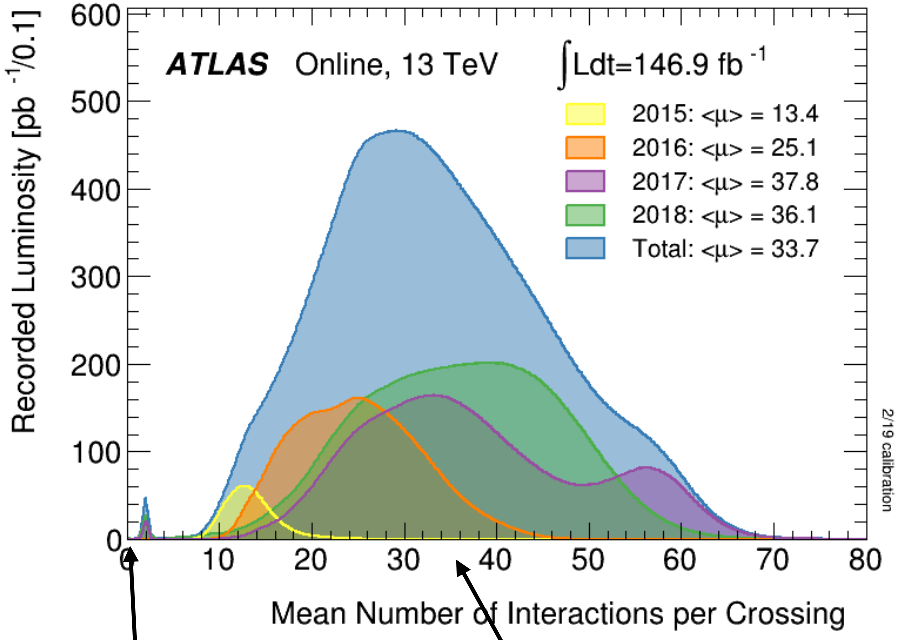
Absolute Calibration Remarks

- Impact on the **scale** (σ_{vis}) results in combined upward shift of O(1%):
  - Dominant: Beam-beam effects resulting from from the mutual electromagnetic interactions of the opposing bunches
  - Sub-dominant: Fit improvements in the scan peak
  - + multiple other contributions
- Dominating **systematics** from:
  - Scan-to-scan and bunch-to-bunch reproducibility: The calibration “constant” should be the same for all
  - Magnetic non-linearity of LHC steering magnets
  - Non-factorization of beam profiles
  - Beam-beam effects



2

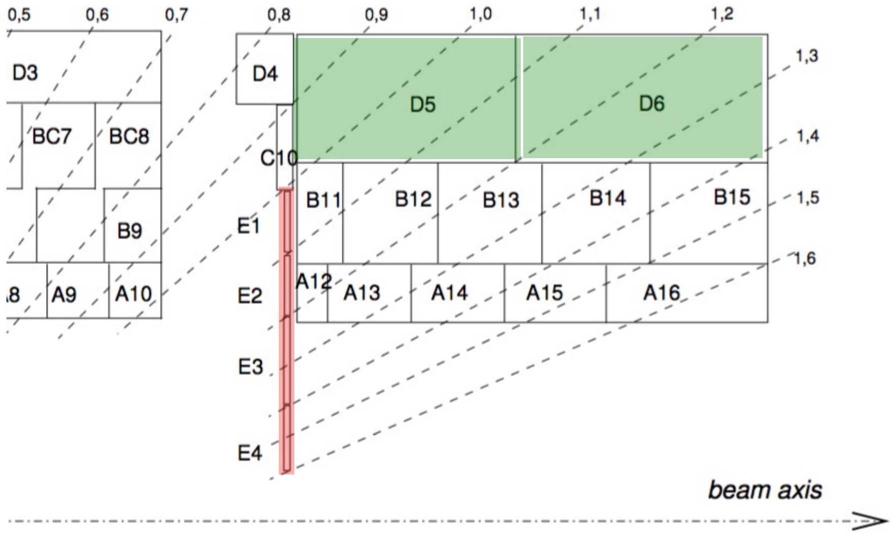
Calibration Transfer Motivation



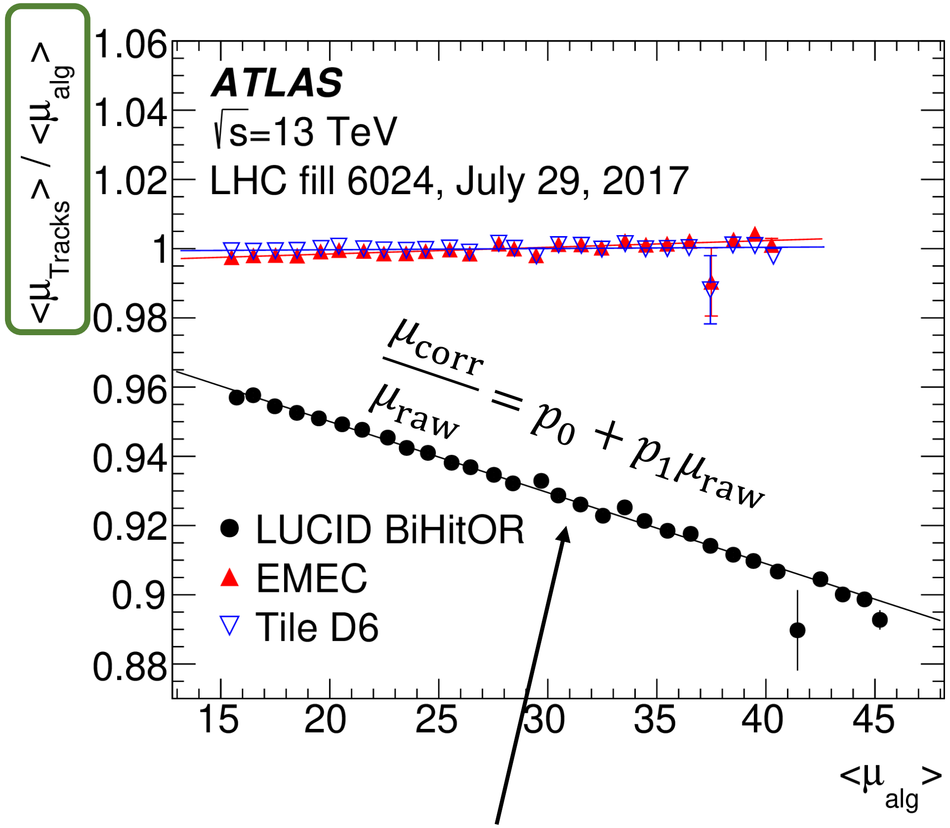
vdM scan at **low pileup** (and with isolated bunches)

Physics runs at **high pileup** (and bunch trains)

- LUCID exhibits **significant nonlinearity** in its response vs **pileup**
- Need to **transfer calibration** from vdM **to physics regime**
- Tracking and calorimeter measurements more robust against pileup-related non-linearities

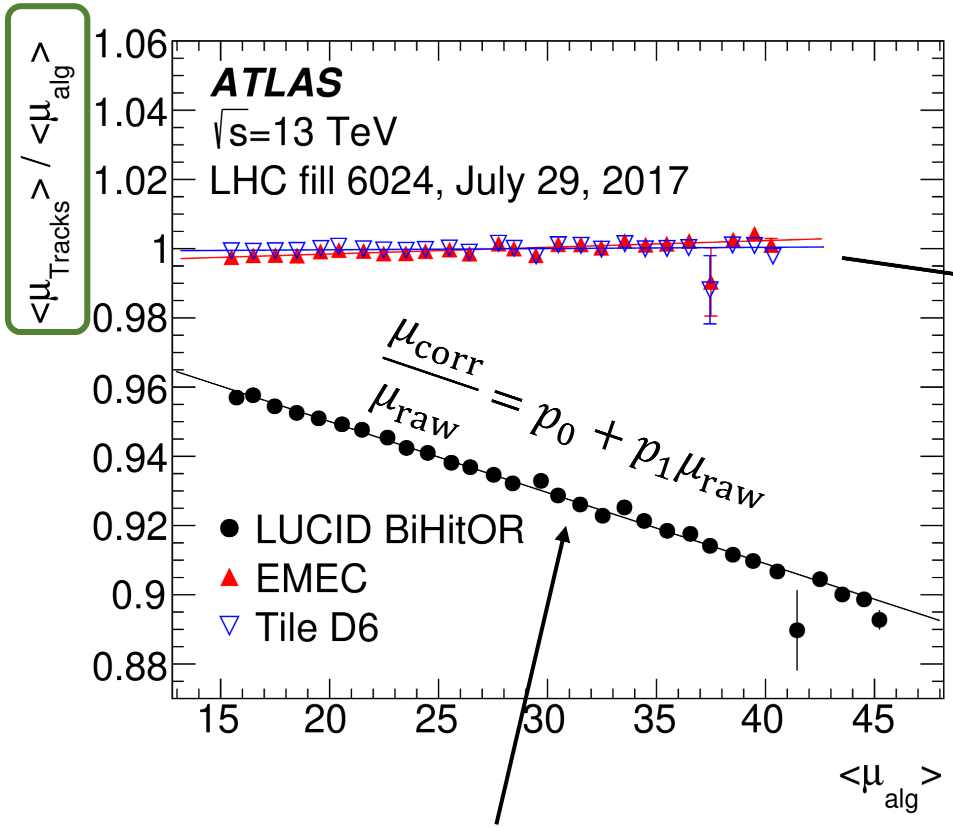


2 Calibration Transfer Procedure



Fit track/LUCID luminosity ratio to allow transfer of σ_{vis} calibration to physics regime

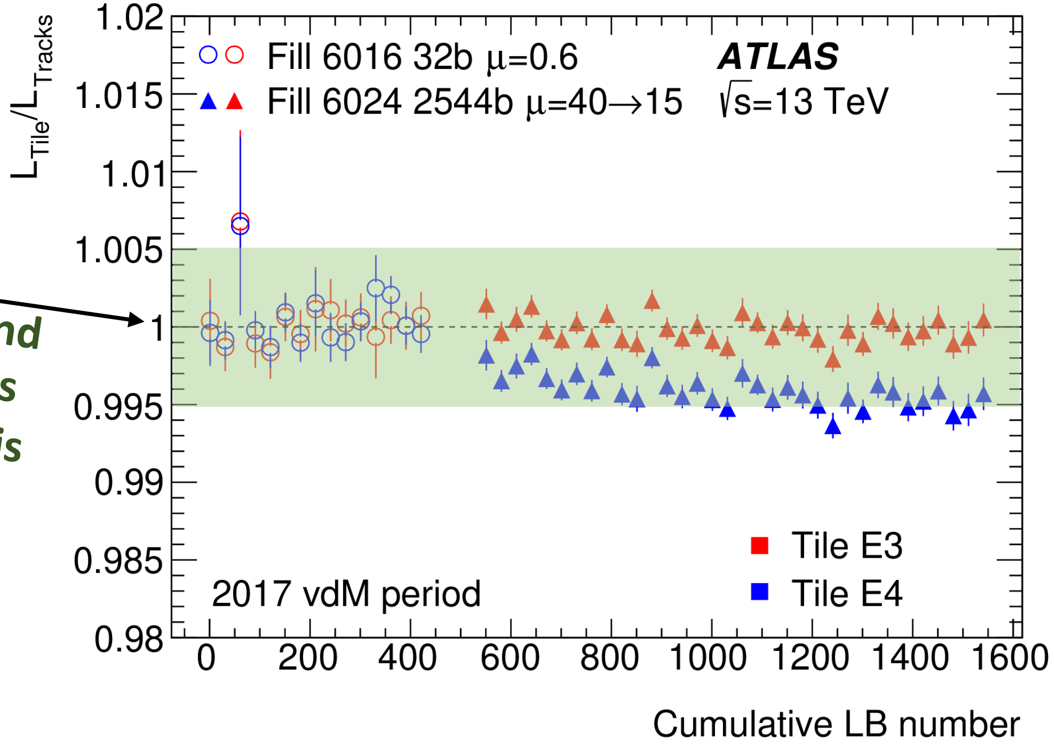
Calibration Transfer Uncertainty



$\frac{\mu_{corr}}{\mu_{raw}} = p_0 + p_1\mu_{raw}$

Fit track/LUCID luminosity ratio to allow transfer of σ_{vis} calibration to physics regime

Compare ratio of Tile and Tracking measurements to set uncertainty on this procedure



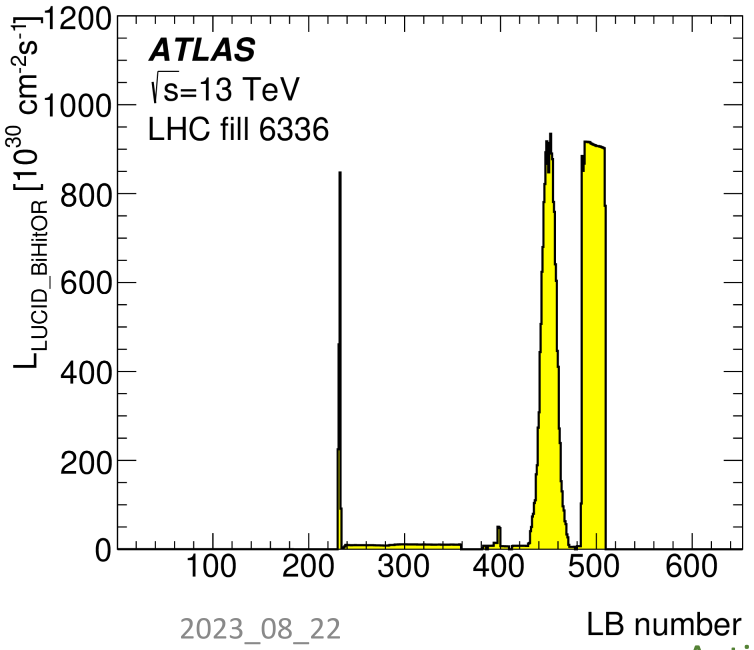
Need to correct raw Tile luminosity to achieve this high level of agreement!

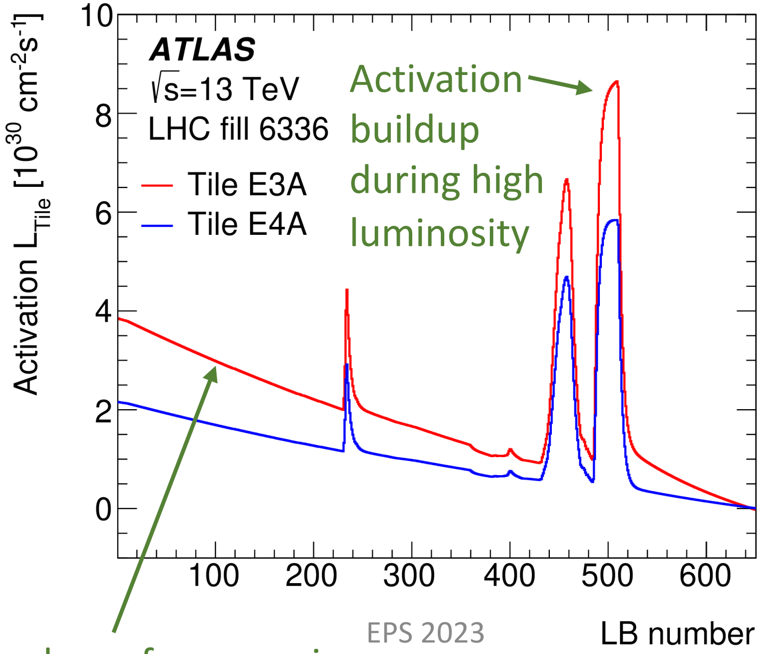
2 Calibration Transfer Developments

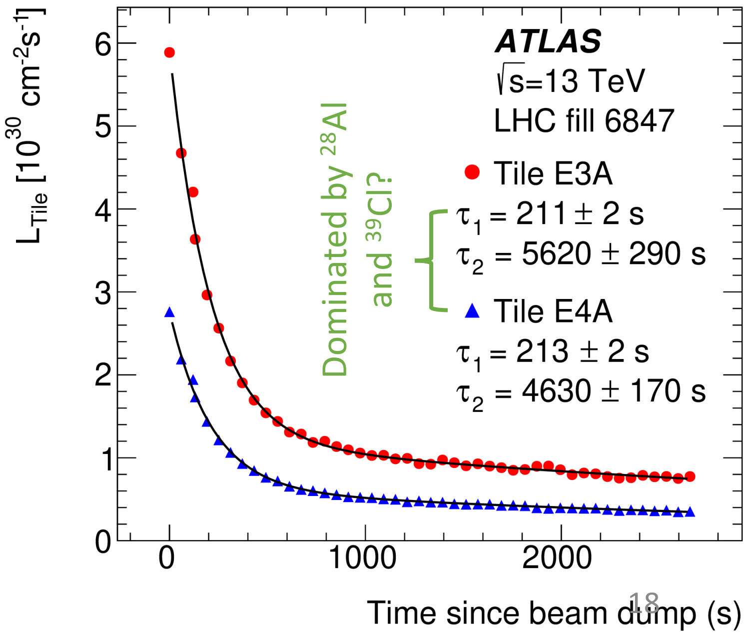
- **Inter-run laser calibration** allows correction of Tile PMT and scintillator **aging**

  - Calorimeter currents ”enhanced” by contributions from surrounding **activated material** (0.5%-1% of typical physics luminosity)
  - **Residual (long-term) activation** from these runs can have a major impact at low (vdM regime) luminosities!
  - Short-term activation modeled with **sum of two decaying exponentials**

- Additional evaluation of **rate-dependent Tile PMT nonlinearity** results in O(0.5%)-O(1%) effect



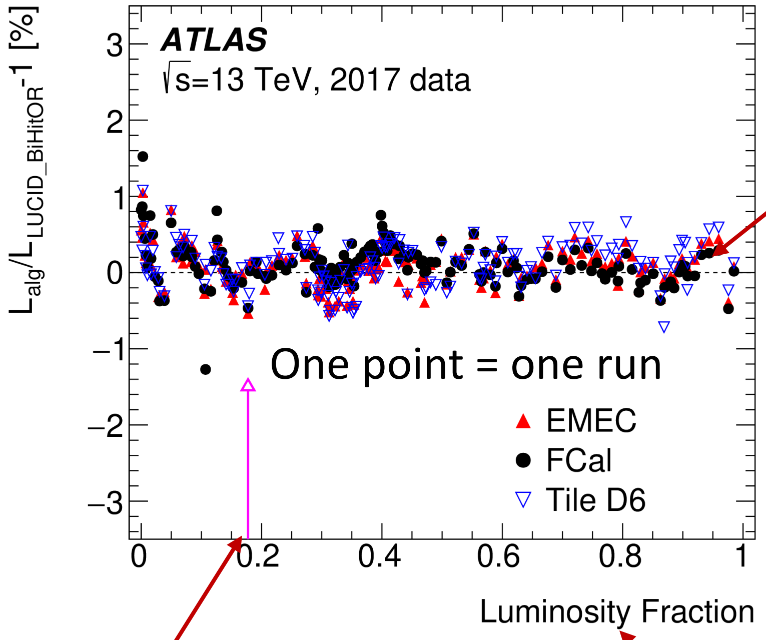




3 Long-Term Stability

Or: How stable and internally consistent is our luminosity measurement after calibration?

Relative consistency between luminometers quantifies long-term stability of ATLAS luminosity measurement

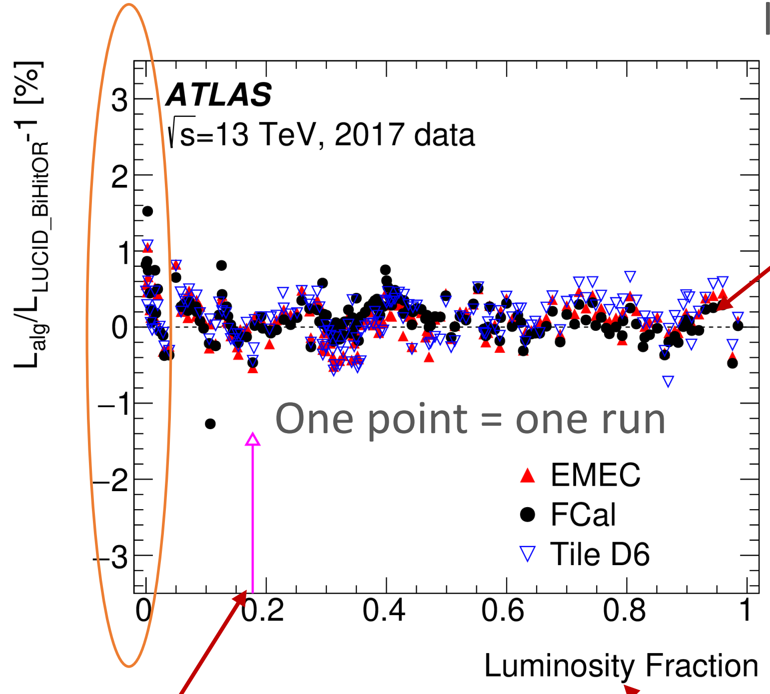


Calorimeter data anchored to LUCID here

Fraction of the year's total integrated luminosity

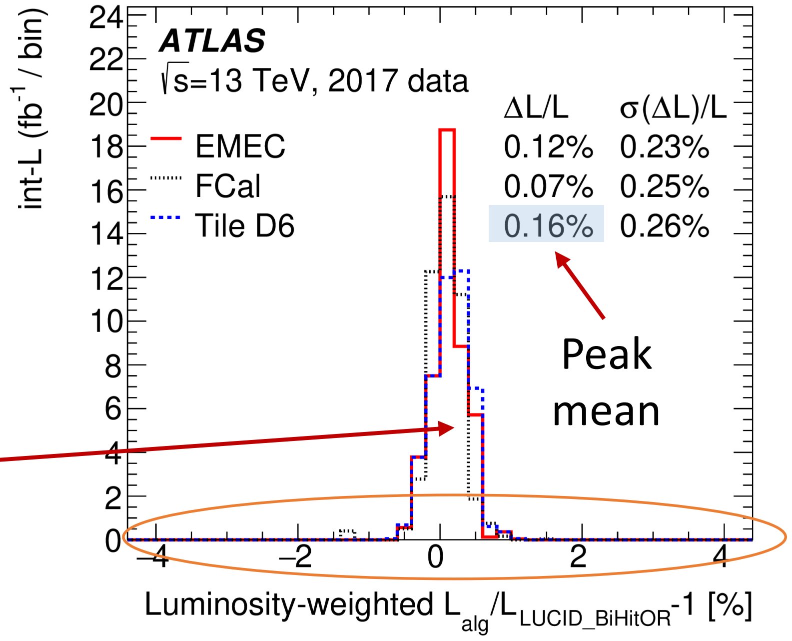
3 Long-Term Stability Uncertainty

Relative consistency between luminometers quantifies long-term stability of ATLAS luminosity measurement



Calorimeter data anchored to LUCID here

Fraction of the year's total integrated luminosity



Area under peak equals total integrated luminosity

- Revised method of calculating the uncertainty associated with the long-term stability
- Compare the total integrated luminosity of LUCID to each other luminometer
- Largest deviation is the uncertainty

Data sample	2015	2016	2017	2018	Comb.
Integrated luminosity [fb^{-1}]	3.24	33.40	44.63	58.79	140.07
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	1.10	0.83

*correlated between years

ATLAS Run-II $\sqrt{s} = 13$ TeV pp collision luminosity finalized!

$140.1\ fb^{-1} \pm 1.2\ fb^{-1}$

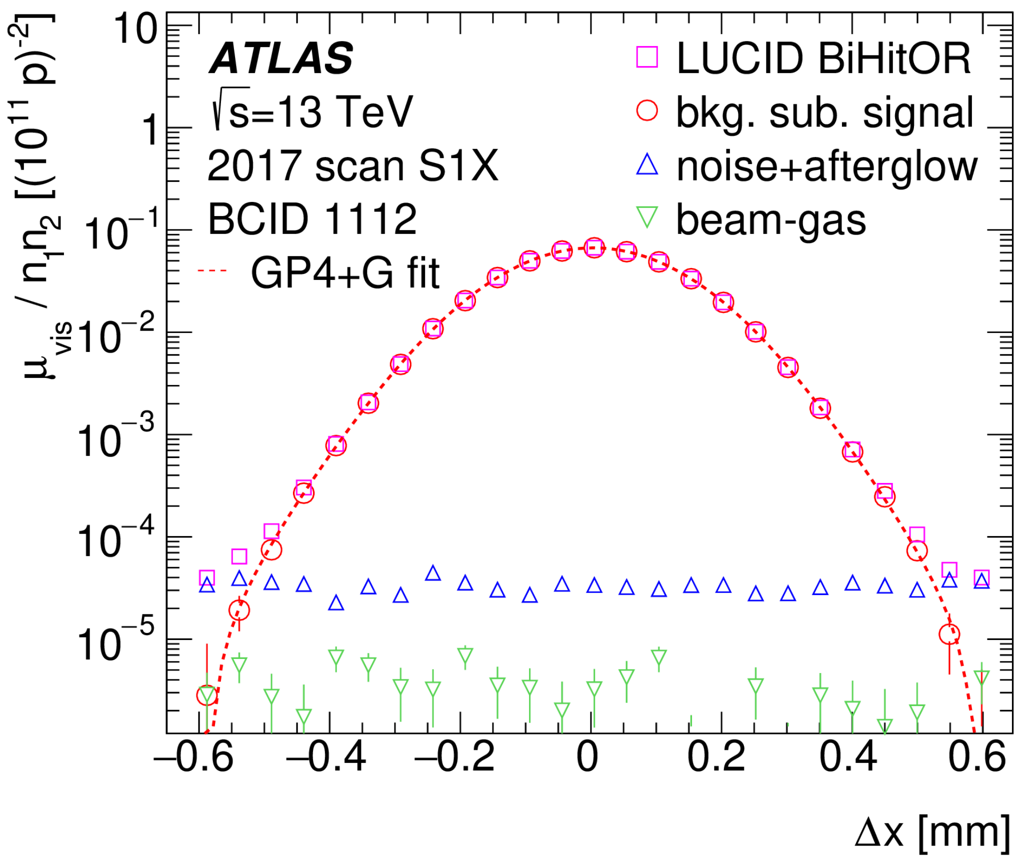
- **See also at EPS**:
  - Impact of accelerator physics on van der Meer luminosity calibrations at the LHC
  - Luminosity determination in pp collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector

Bibliography

- Preliminary luminosity results
- **Final luminosity results**
- Impact of Beam-Beam Effects on Absolute Luminosity Calibrations at the CERN Large Hadron Collider
- Magnetization in superconducting corrector magnets and impact on luminosity-calibration scans in the Large Hadron Collider
- The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS
- Tile laser calibration

Fitting in vdM Scans

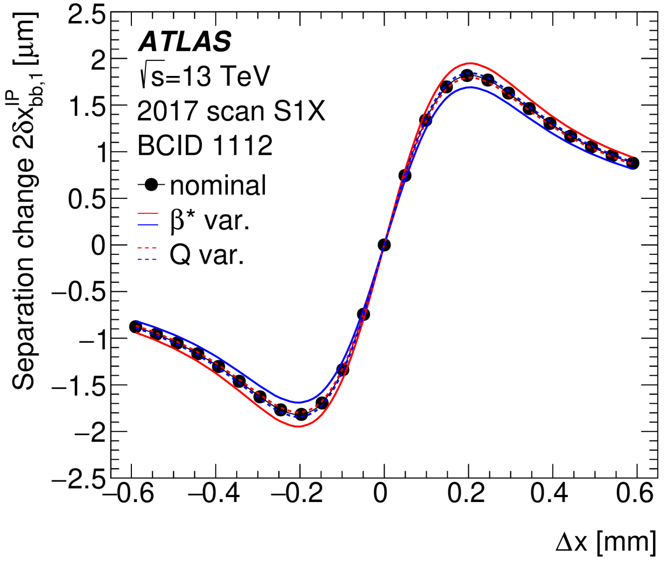
- Background-subtracted peak mostly well modeled by a Gaussian multiplied by a 4th order polynomial (GP4)
- New GP4+G fit adds second gaussian for the five central scan points
  - Corrects for systematic 0.5% overestimation of peak
- Uncertainty comes from using an alternate fit function (GP6) and taking the difference in σ_{vis}

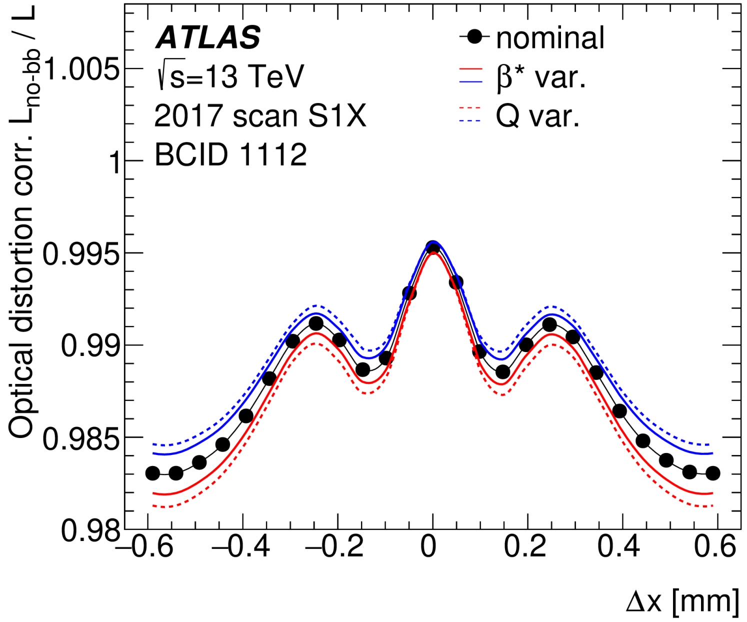


1

Beam-Beam Effects

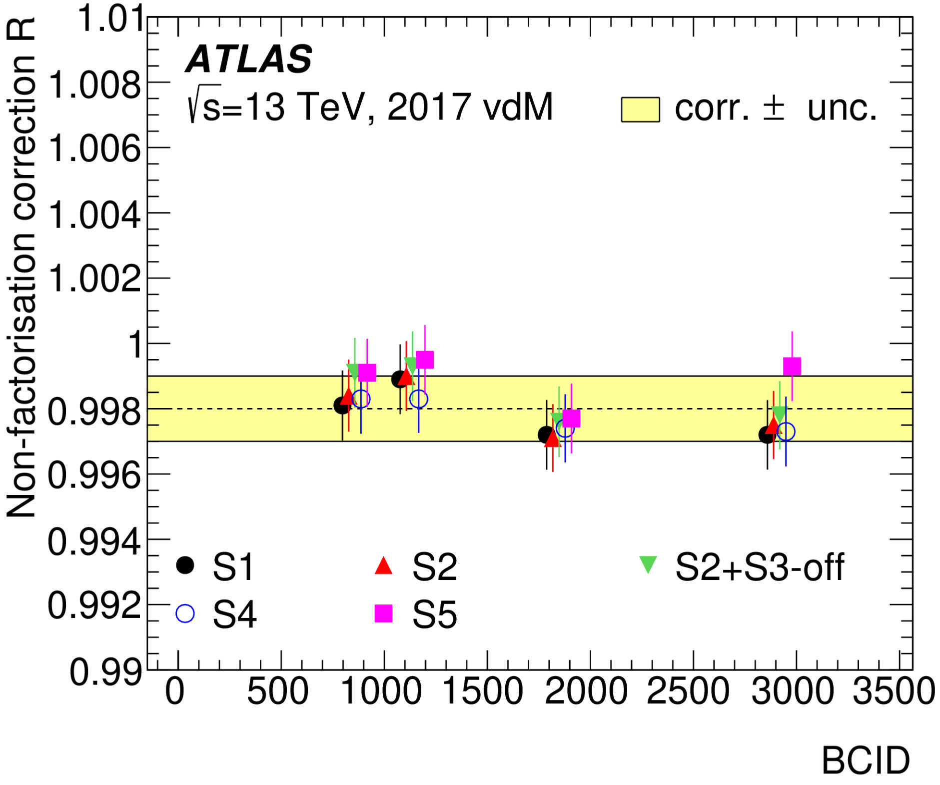
- Refinement of [beam-beam correction]
- Beam-beam deflection
  - Each bunch exerts a repulsive force on other bunch
  - Modifies the bunch separation Δx
- Optical distortion
  - Each bunch defocuses the others
  - Modifies the bunch shape
- Corrections result in a net 0.5% increase to σ_{vis}





Non-Factorization

- Baseline vdM anlaysis assumes factorization independent beam profiles in x and y
- Non-factorization effects analyzed by considering 3D collision vertex profile in both on-axis and off-axis scans
  - Can only be done in a small number of BCs due to need for enhanced track readout
  - Correct bias using the single-bunch parameters of B1 & B2 extracted from a combined fit to the beam-separation dependence of the shape, size, position and orientation of the luminous region (aka "beam spot") and of the luminosity
- Each year's correction R an average from all available bunches and scans

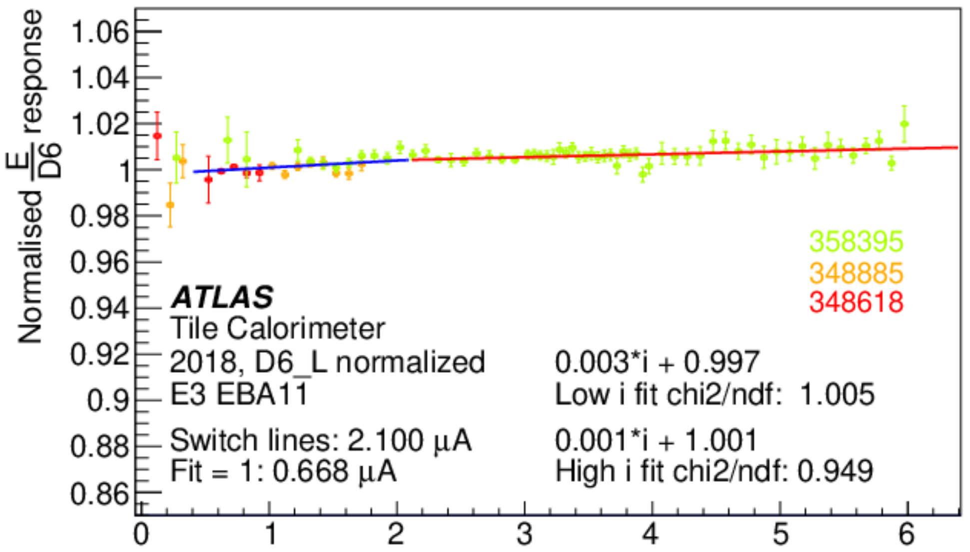


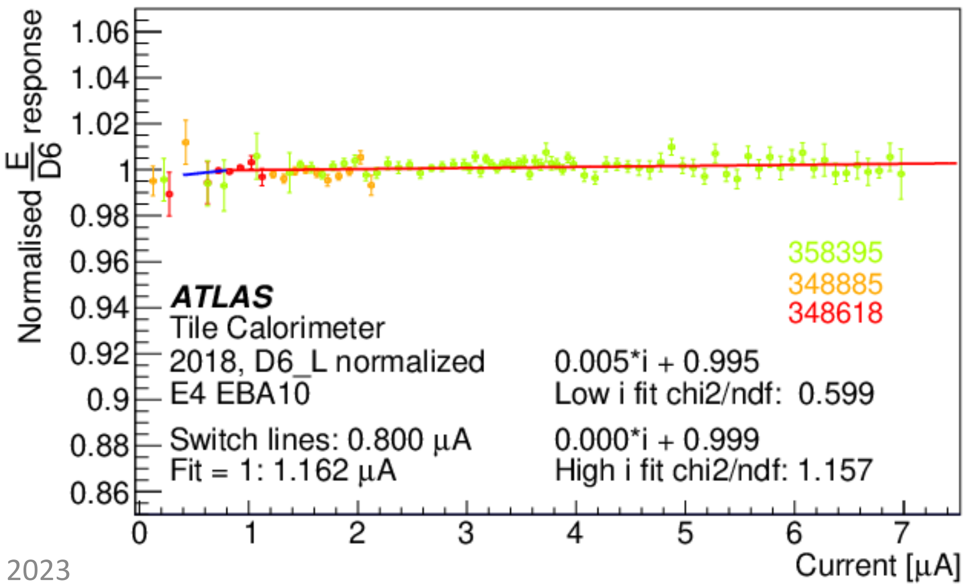
Other Effects

- Orbit Drift
  - Gradual drift in beam positions over the course of scans
  - Applying correction (usually within $\pm 0.5\%$) improves scan-to-scan reproducibility
- Emittance Growth
  - Assumption that beam sizes remain constant during and between scans of the same vdM run
  - Correction to σ_{vis} generally results in an increase of $0.15\text{-}0.3\%$
- Length Scale
  - Actual beam displacements (vs settings from LHC steering magnets)
  - Use dedicated scans to compare intended position to actual center of luminous region from track-reconstruction

Tile PMT Gain Dependence on Anode Current

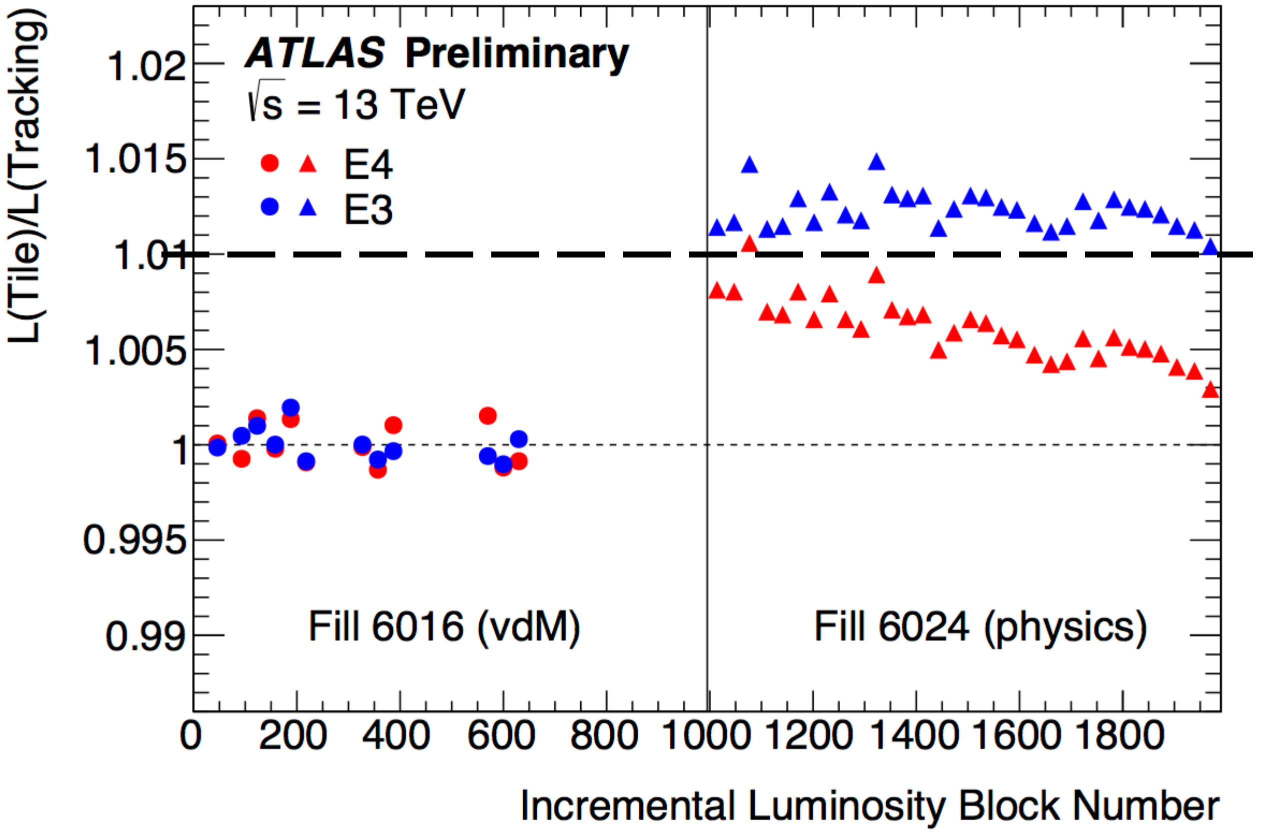
- Tile PMT gains have a dependence on anode current
- Current range from vdM to physics regime large enough in E cells that the impact is non-negligible
- Check PMT reponse to fixed-luminosity laser pulse during LHC abort gap
- Compare to current measurement
- Fit data from multiple runs to cover full current range and extract correction





2 Calibration Transfer (1.3% → 0.5%)

Preliminary luminosity results



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