ATLAS Run-II Luminosity Measurements

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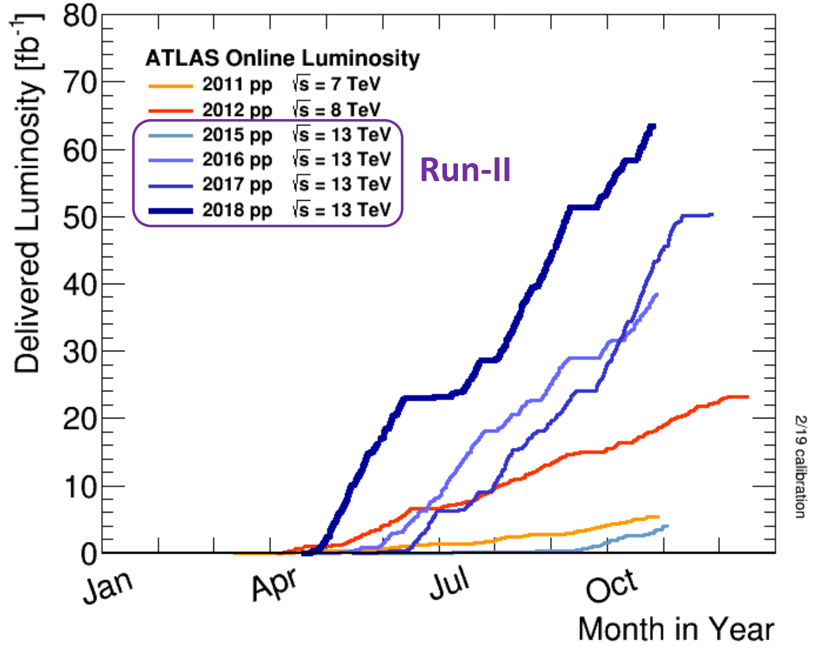
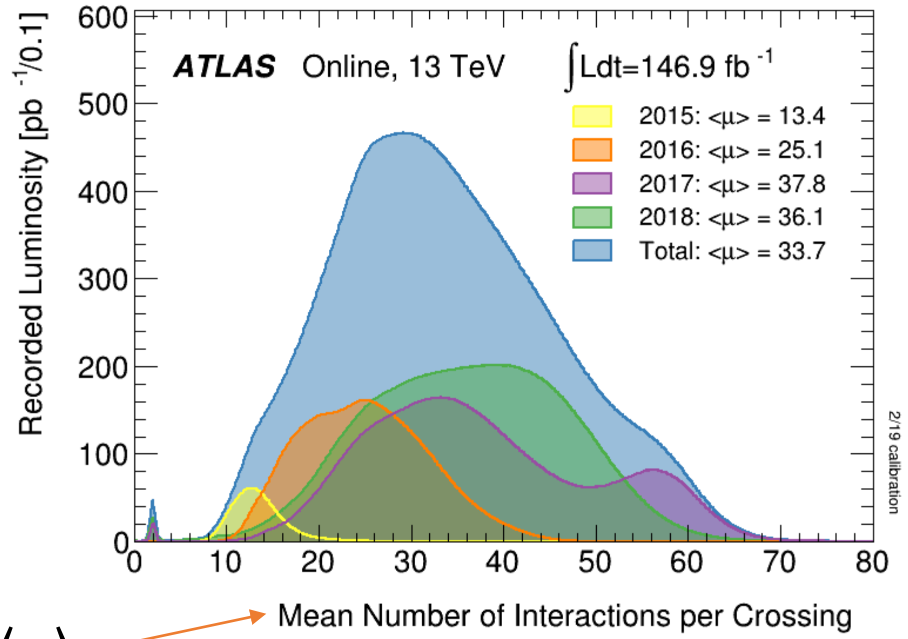
ATLAS Run-II Luminosity

- Total Run-II pp luminosity at $\sqrt{s} = 13$ TeV: 139 fb^{-1} with a 1.7% uncertainty
- Dominant uncertainty in many cross-section analyses
- Primary luminosity detector must be stable over wide ranges of luminosity and pileup, slow to age, and sensitive at 25ns bunch-crossings

$$\mathcal{L}_{\text{LUCID}} \rightarrow \mathcal{L}_{\text{ATLAS}} = f_{\text{LHC}} \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

$$R_{\text{in}} = \sigma_{\text{in}} \mathcal{L}$$

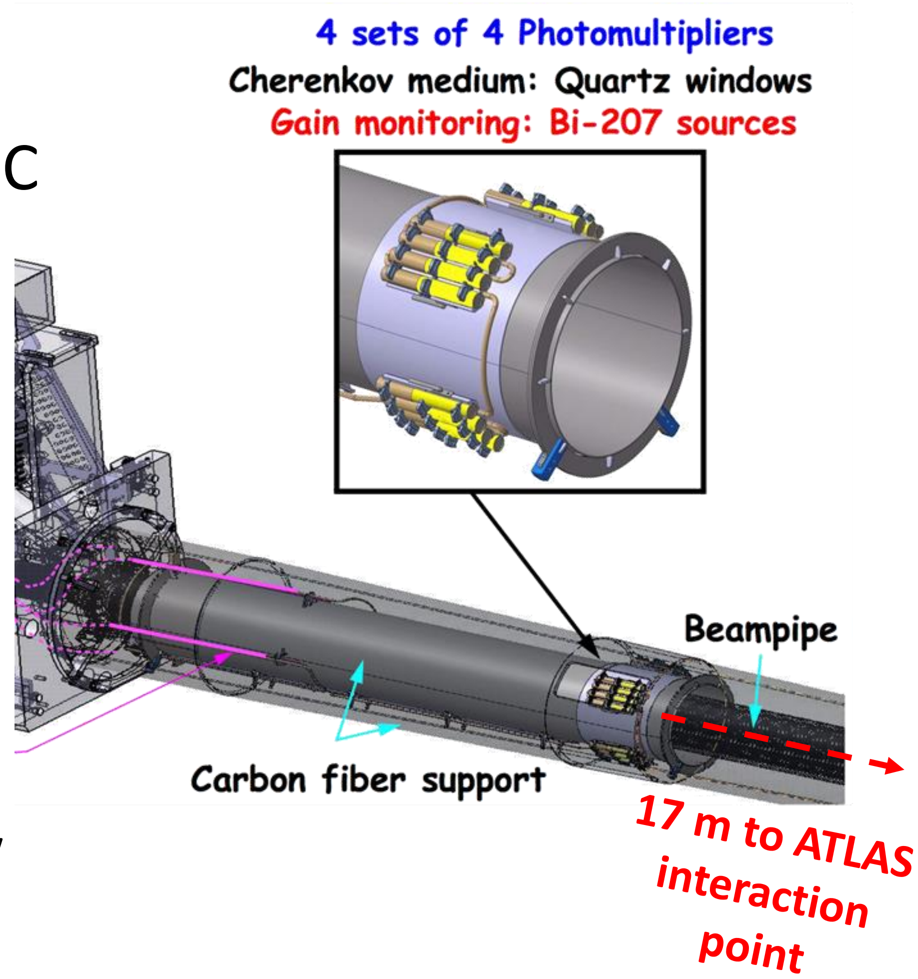




$\langle \mu \rangle$

LUCID-2

- LUCID (LUminosity Cherenkov Integrating Detector): Provides real-time measurement of luminosity at any number of interactions per LHC bunch crossing (μ)
  - Primary luminosity detector in ATLAS from 2015+
- 2*4*4 IP-pointing PMTs with small acceptance (Cherenkov radiation from quartz window sufficient) to cope with high occupancy
- Fast read-out electronics to cope with 25 ns bunch spacing
- Radioactive Bi-207 deposited on quartz window allows for continuous monitoring of PMT gains



Other Systems

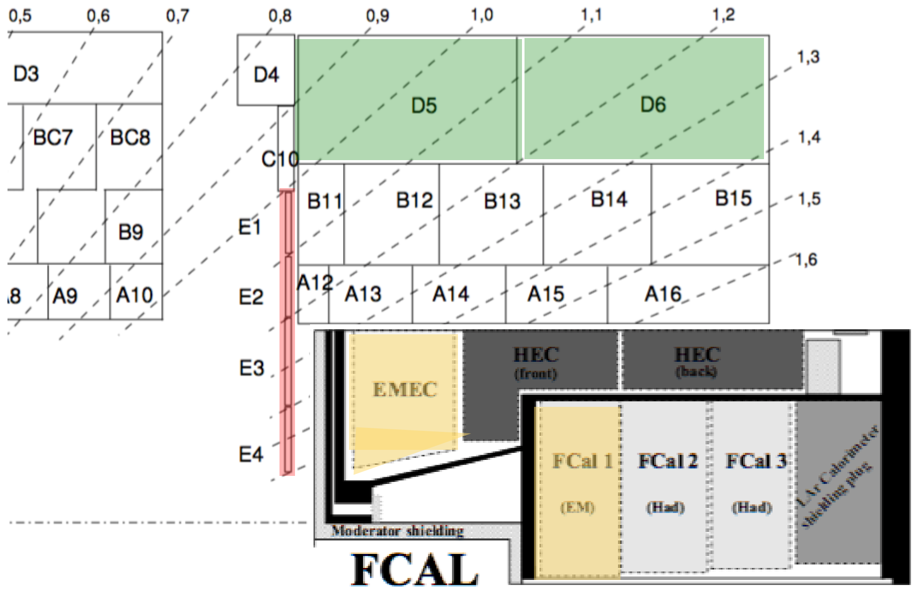
Tracking

Uses track reconstruction in the ID (Si only) in randomly triggered events
TDAQ limited (200 Hz in physics, up to 45 kHz in VdM)
$\langle\mu\rangle \propto N_{Tracks}$

Tile

Diverts ~1% of PMT current and integrates over O(10) ms
Sensitive over a range of luminosities
$L \propto i_{PMT}$

Long-term stability
Calibration transfer



EMEC & FCal

Read out LAr gap HV currents with an integration time O(1) s
Use of HV current bypasses trigger limitations
$L \propto i_{HV}$

Long-term stability

- Bunch-by-bunch algorithms:
  Capable of measuring the luminosity in a single bunch via hit or object counting

- Flux algorithms:
  Average signal over a multi-BC time range to determine average luminosity

Luminosity Calibration Procedure: Overview

Use low luminosity van-der-Meer (VdM) scans to determine absolute luminosity of each colliding bunch as related to bunch intensity ($n_1 n_2$) by measuring beam overlap integral ($\Sigma_x \Sigma_y$)

$$\mathcal{L}_{bunch} = f_{\text{LHC}} \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

LUCID-2 measurements relate visible interactions per bunch crossing (μ_{vis}) and cross section (σ_{vis}) PMT gain stability monitored by Bi-207 calibration

$$\mu_{\text{vis}} = -(1 - P_{\text{HIT}})$$

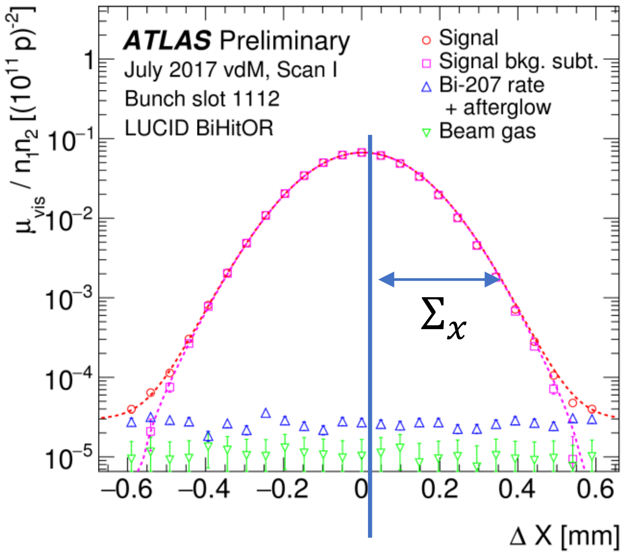
$$\mathcal{L} = f_{\text{LHC}} \frac{\mu_{vis}}{\sigma_{vis}}$$

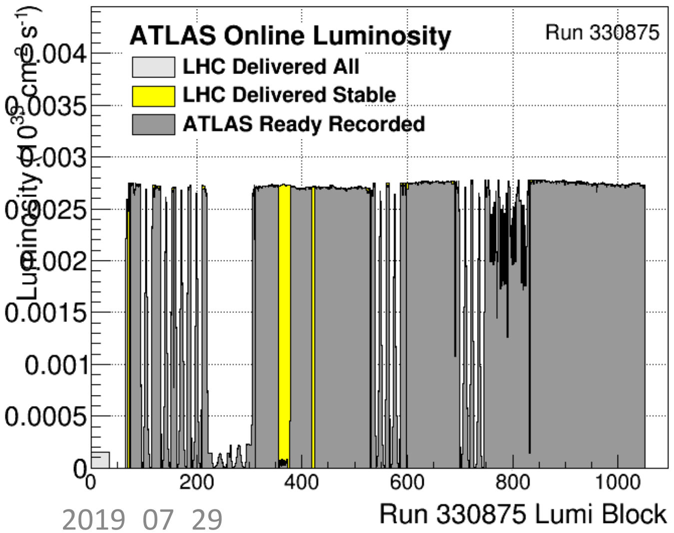
Use linearity of track counting luminosity measurement to extrapolate VdM calibration to “normal” LHC running conditions, i.e. the calibration transfer

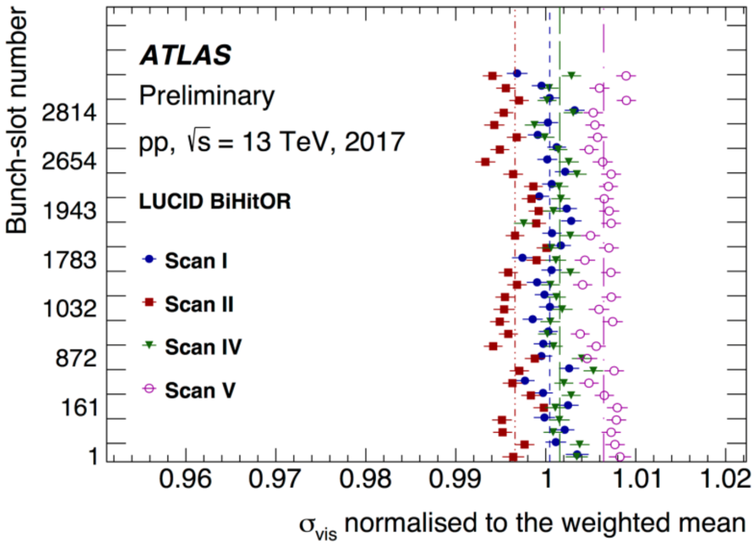
$\mu \sim 0.5 \rightarrow \mu \sim 50$

Absolute Calibration – van der Meer (vdM) Scans

- vdM scans carried out with very low luminosity and isolated bunches
  - Multiple scans allow for evaluation of scan-to-scan reproducibility
  - Off-axis scans allow for evaluation of non-factorization
- Reference luminosity for calibrating LUCID comes from beam parameters
- $O(10^{-4})$ corrections account for Bi-207 and beam-gas interactions





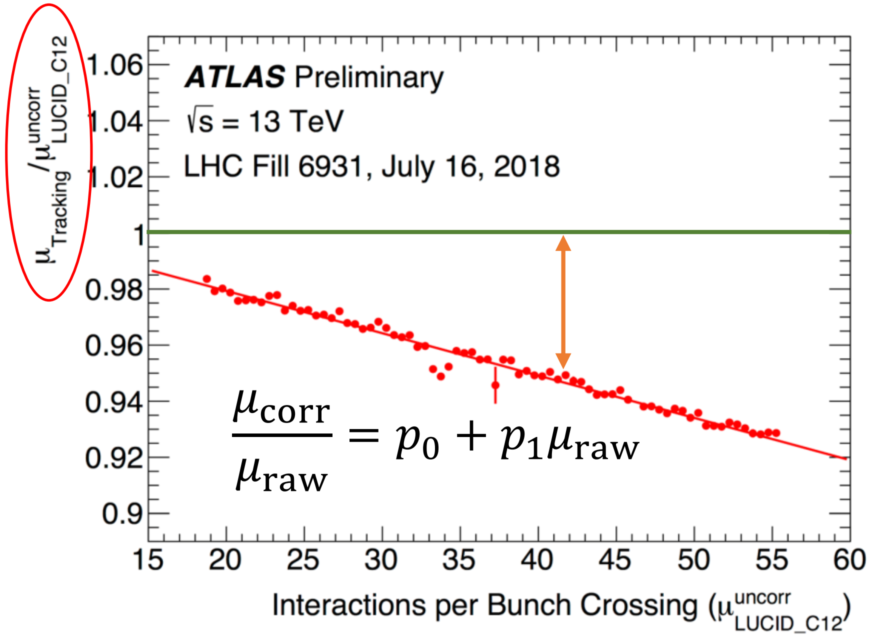


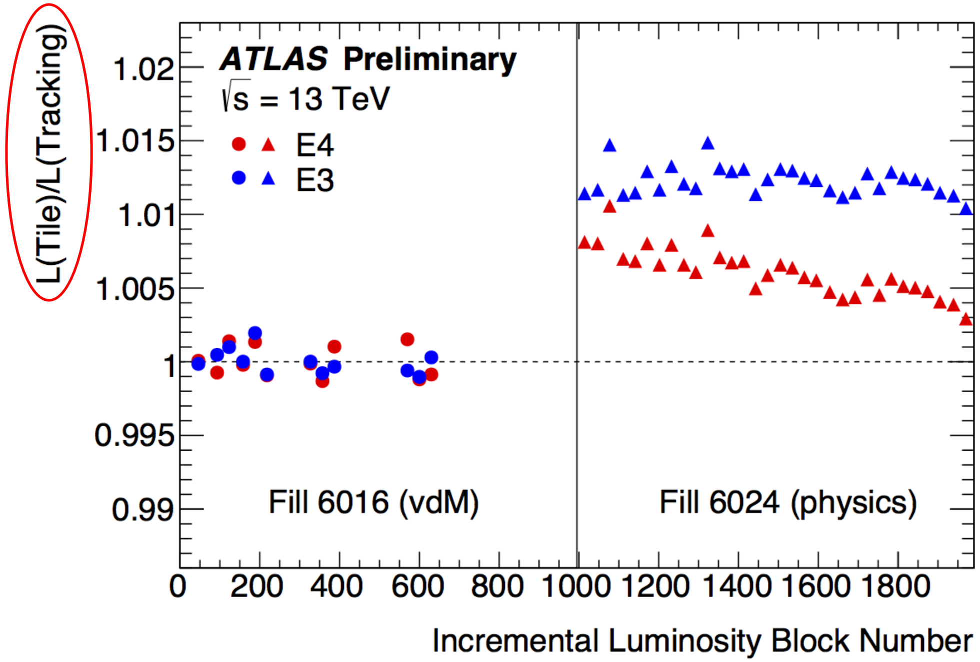
$$\mathcal{L} = f_{\text{LHC}} \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y}$$

$$\sigma_{vis} = f_{\text{LHC}} \frac{\mu_{vis}}{\mathcal{L}}$$

Calibration Transfer

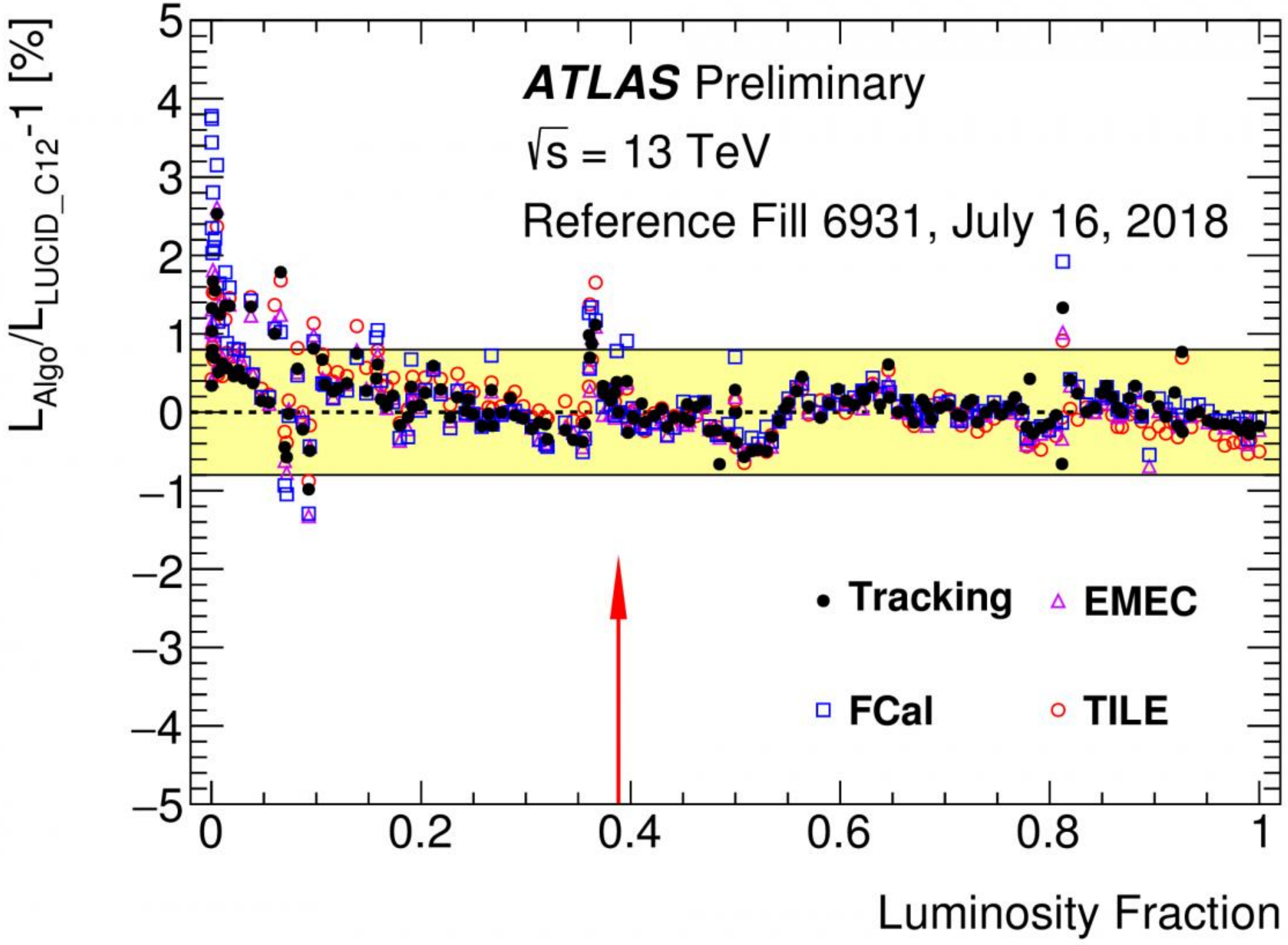
- LUCID measurements sensitive pileup and bunch train running→ calibration from VdM run results in an *overestimate* of luminosity in physics running conditions
- *Correction* needed for μ_{vis} at high luminosities from track counting (recall robustness against pileup and sensitivity over large luminosity range)
- *Uncertainty* on calibration transfer from comparison of track counting and Tile luminosity measurements in same pairs of runs





Long-Term Stability

- Long-term stability uncertainty comes from a comparison of the luminosity measured by other luminometers to LUCID-2
- Reference run chosen for which all systems' luminosities are normalized to LUCID (red arrow)



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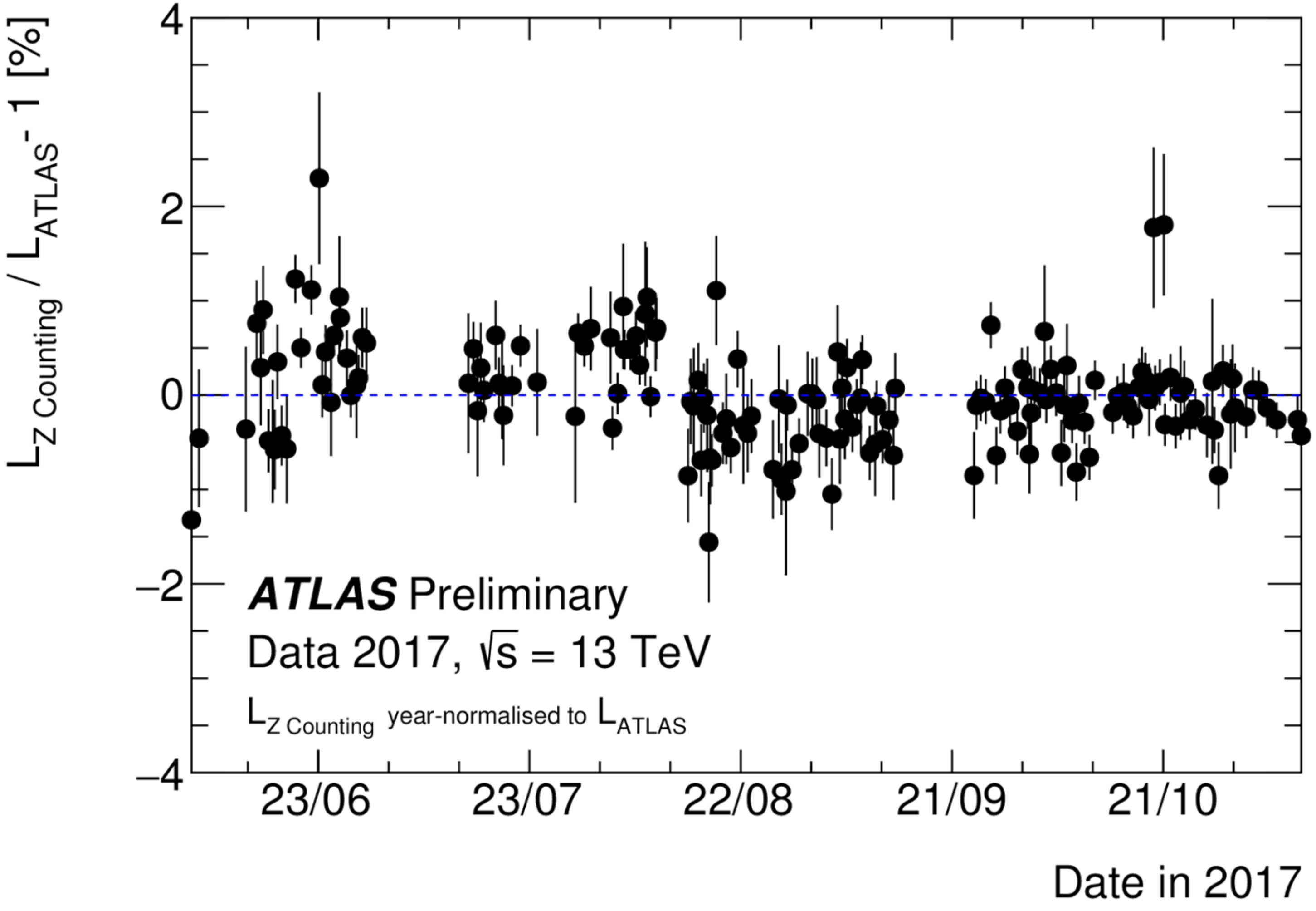


Uncertainty Contributions

Systematic is *partially* correlated between years

Systematic is *fully* correlated between years

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 (%):				
DCCT calibration†	0.2	0.2	0.2	0.1
FBCT bunch-by-bunch fractions	0.1	0.1	0.1	0.1
Ghost-charge correction*	0.0	0.0	0.0	0.0
Satellite correction†	0.0	0.0	0.0	0.0
Scan curve fit model†	0.5	0.4	0.5	0.4
Background subtraction	0.2	0.2	0.2	0.1
Orbit-drift correction	0.1	0.2	0.1	0.1
Beam position jitter†	0.3	0.3	0.2	0.2
Beam-beam effects*	0.3	0.3	0.2	0.3
Emittance growth correction*	0.2	0.2	0.2	0.2
Non-factorization effects*	0.4	0.2	0.5	0.4
Length-scale calibration	0.3	0.3	0.4	0.2
ID length scale*	0.1	0.1	0.1	0.1
Bunch-by-bunch σ_{vis} consistency	0.2	0.2	0.4	0.2
Scan-to-scan reproducibility	0.5	1.2	0.6	0.5
Reference specific luminosity	0.2	0.2	0.4	0.2
Subtotal for 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

Correlations in uncertainty between years results in a reduced combined uncertainty

Conclusions & Outlook

- Luminosity uncertainty measurement a dominate uncertainty in numerous analyses
- ATLAS uses multiple luminometers to monitor the luminosity of proton-proton collisions, with LUCID-2 providing the primary luminosity measurement
- Calibration and calibration transfer of LUCID-2 critical to accurate measurement of luminosity and reducing systematics

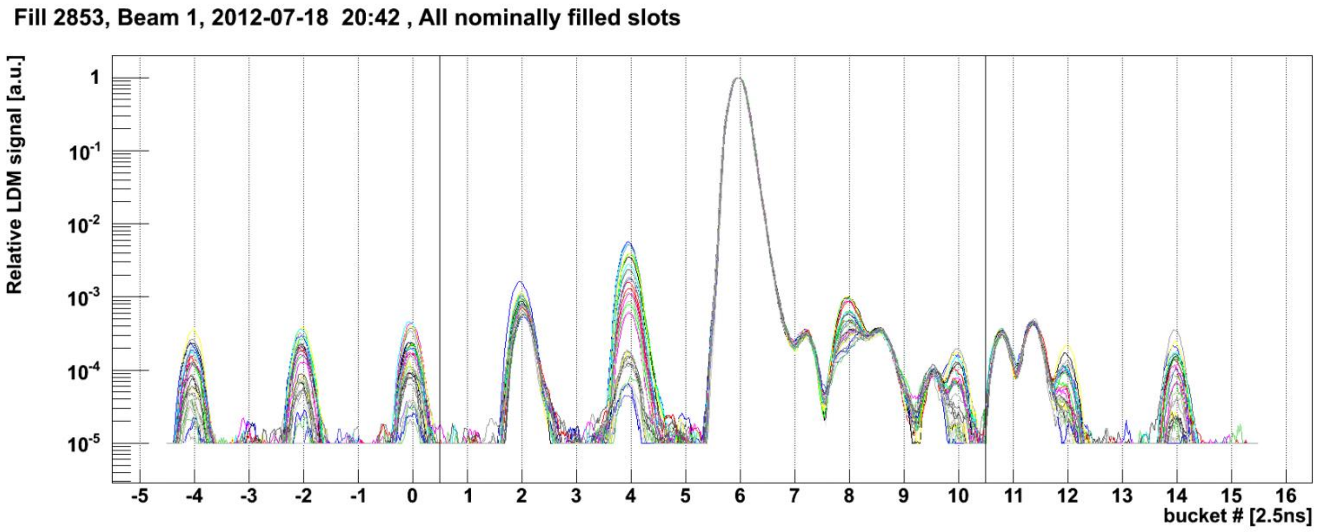
- Above results are preliminary with room for improvement

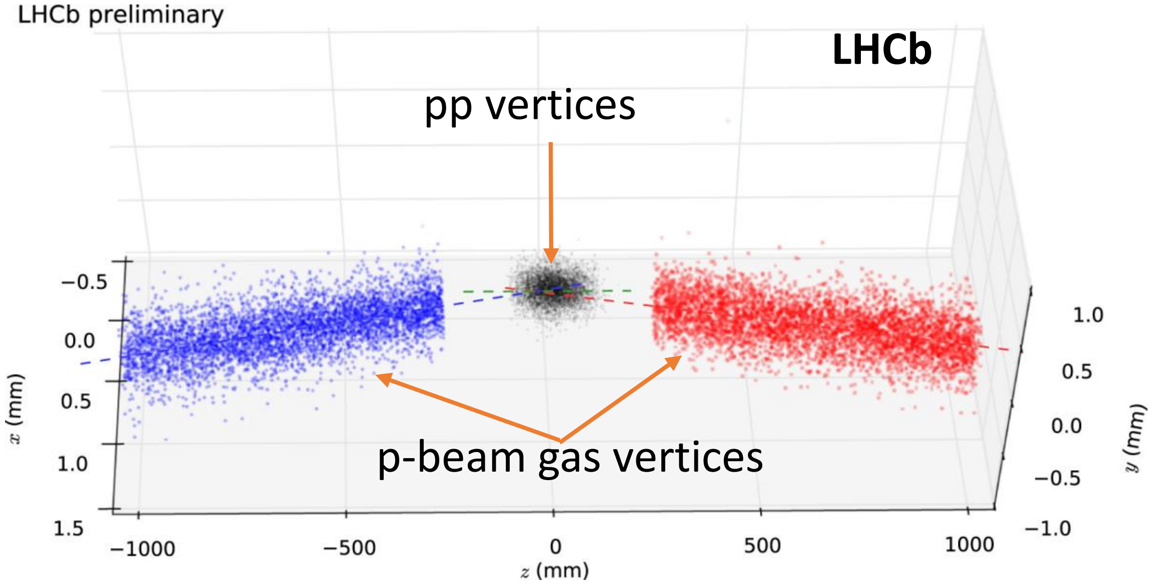
Backup & References

- Longitudinal density monitor: https://cds.cern.ch/record/1427726/files/ATS-Note-2012-028-PERF.pdf
- $\sqrt{s} = 8\ \mathrm{TeV}$ luminosity and detailed discussion on luminosity calculations and uncertainties: https://arxiv.org/abs/1608.03953
- LUCID-2: https://cds.cern.ch/record/2633501/files/document.pdf
- Run-II Luminosity: https://cds.cern.ch/record/2677054/files/ATLAS-CONF-2019-021.pdf
- Run-II public lumi plots: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

Determining $n_1 n_2$

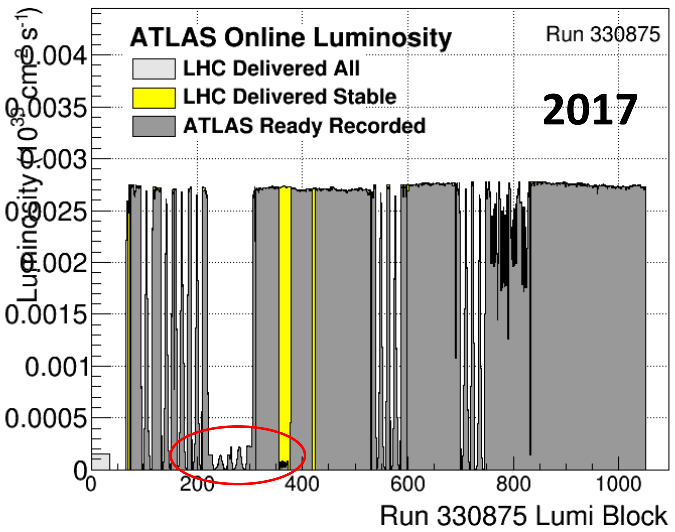
- *Total* beam intensity measured with high precision ($\sigma_{\text{syst}} < 0.3\%$) by DC current transformers
- *Fraction* of intensity in each bunch measured by fast beam current transformers (FBCT) ($\sigma_{\text{syst}} < 0.05\%$)
- Contribution to total beam intensity from protons leaked into non-colliding bunches (*ghost charges*) from by LHCb beam gas measurements ($\sigma_{\text{syst}} < 0.05\%$)
- Contribution to the intensities from *satellite bunches* (protons in "wrong" RF bucket, $\Delta t \sim x * 2.5\text{ns}$) measured by the longitudinal density monitor ($\sigma_{\text{syst}} < 0.08\%$)

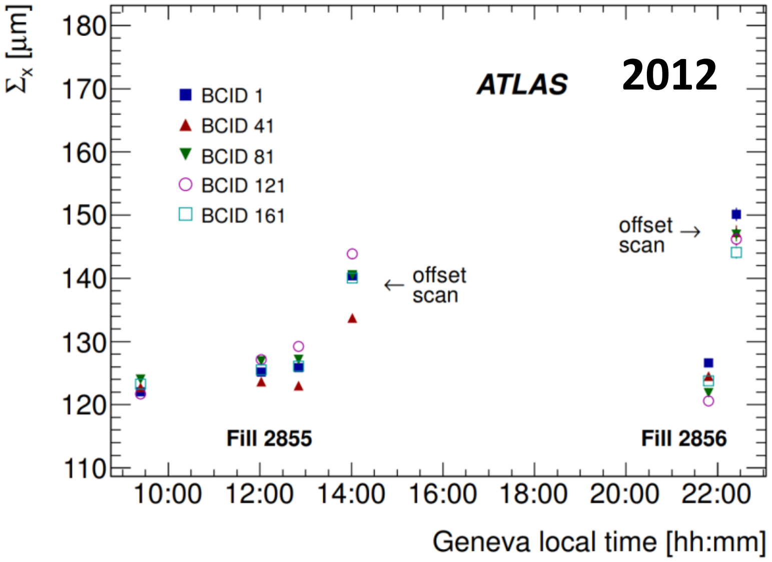


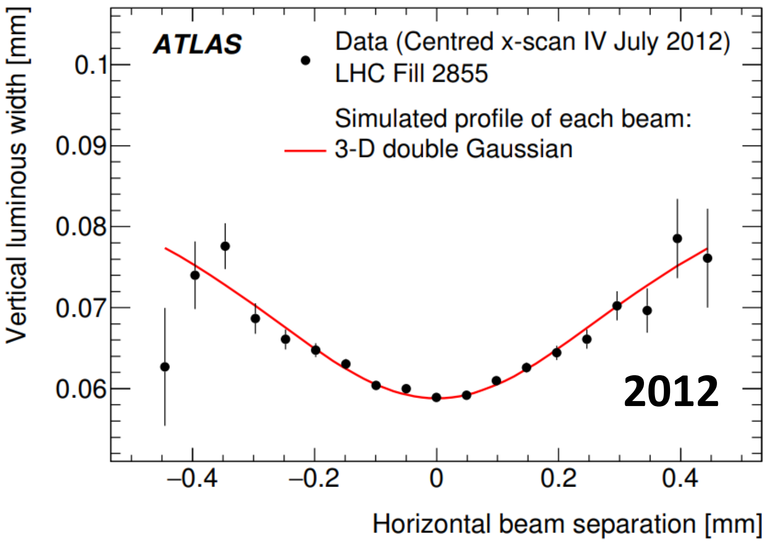


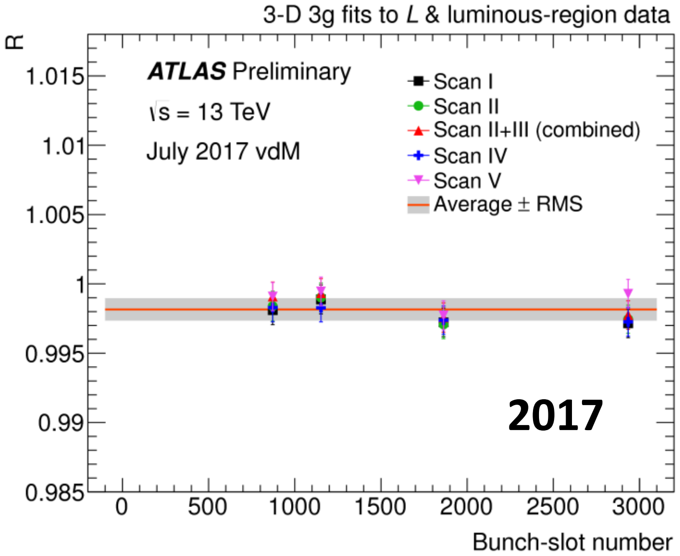
Non-factorization Effects

- Assumption: The dependence of the luminosity on the beam separation can be factorized into uncorrelated x and y components: $\Sigma_x\Sigma_y$
- Validity tested (and corresponding uncertainty measured) in off-axis scans, i.e. $x \neq 0$ for a y-scan and vice-versa









LHC Parameters

Parameter	2015	2016	2017	2018
Maximum number of colliding bunch pairs (n_b)	2232	2208	2544/1909	2544
Bunch spacing (ns)	25	25	25/8b4e	25
Typical bunch population (10^{11} protons)	1.1	1.1	1.1/1.2	1.1
β^* (m)	0.8	0.4	0.3	0.3–0.25
Peak luminosity $\mathcal{L}_{\text{peak}}$ ($10^{33}\,\text{cm}^{-2}\text{s}^{-1}$)	5	13	16	19
Peak number of inelastic interactions/crossing ($\langle\mu\rangle$)	~ 16	~ 41	$\sim 45/60$	~ 55
Luminosity-weighted mean inelastic interactions/crossing	13	25	38	36
Total delivered integrated luminosity (fb^{-1})	4.0	38.5	50.2	63.4