ATLAS-CONF-2019-021
ATLAS-CONF-2020-023

Luminosity measurement with the ATLAS experiment at the LHC

ICHEP 2020

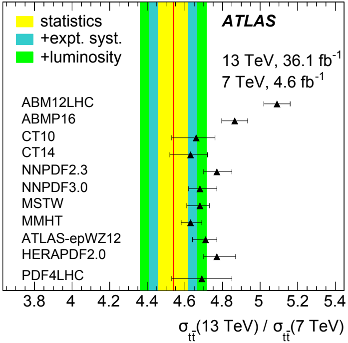
Joey Carter, on behalf of the ATLAS Collaboration

University of Toronto

July 29, 2020

Introduction

- Precision measurements of both the online and offline luminosity are a critical component of the LHC physics programme.
- **Online** luminosity with accuracy of $\sim 5\,\%$ was achieved in Run 2: required for operating the accelerator and the experiments (e.g. for performance optimization, levelling, trigger optimization).
- Precise **offline** luminosity measurement is important for all analyses, particularly for precision cross section measurements:
  - → For Z, W and top cross sections, a $\sim 1\,\%$ luminosity uncertainty would be required to make it subleading among other well-controlled systematics.



Eur. Phys. J. C **80** (2020) 528

New for ICHEP 2020: Preliminary luminosity measurements for low-pileup *pp* collision datasets

The Run 2 physics programme also included dedicated periods of low-pileup running at $\sqrt{s} = 5.02$ and 13 TeV:

- → 13 TeV: for precision W boson measurements, where high pileup degrades the detector resolution of $W \to \ell\nu$ decays.
- → 5.02 TeV: served as *pp* reference data with the same nucleon-nucleon collision energy as the Run 2 PbPb dataset for the LHC heavy-ion programme (also useful for precision W/Z physics measurements).

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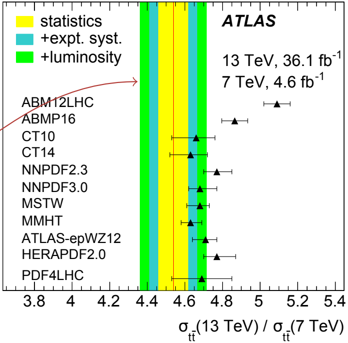

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The Run 2 pp Datasets

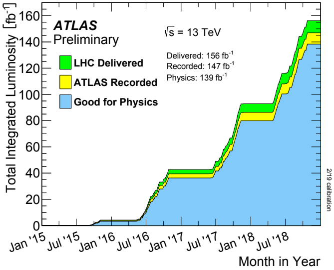
Typical running conditions for physics:

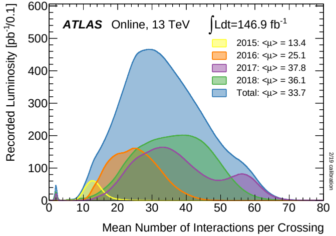
13 TeV high-μ

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 ($\langle\mu\rangle_{\text{peak}}$)	~ 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

5.02 TeV and 13 TeV low-μ

	5.02 TeV	13 TeV	
Parameter	2017	2017	2018
Bunch config (N_b, bunch spacing)	512–1828, 8b4e	644–1866, 8b4e	2448–2544, 25 ns trains
β^* (m)	3.1	0.4	0.3
Peak luminosity $\mathcal{L}_{\text{peak}}$ ($10^{33}\,\text{cm}^{-2}\,\text{s}^{-1}$)	0.5–1.3	0.5	0.7
Typical $\langle\mu\rangle$	0.5–4	2, 1 (level)	2 (level)





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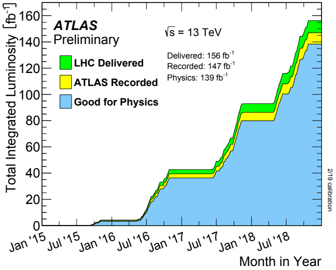

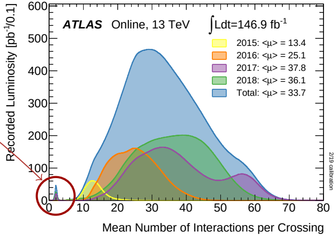

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Observed Event Rate

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Visible cross section

The detector's calibration constant

Measuring Event Rates: ATLAS Luminometers

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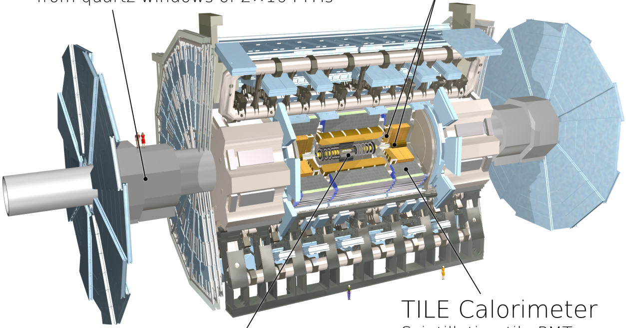
LUCID
Hit counting using Cherenkov light from quartz windows of 2×16 PMTs

EMEC & FCal
LAr calorimeter gap currents

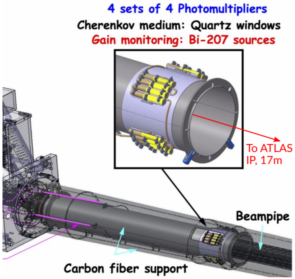


TILE Calorimeter
Scintillating-tile PMT currents

Track counting
Multiplicity of reconstructed charged particles in the silicon layers of the Inner Detector

LUCID

- Primary ATLAS luminometer throughout Run 2
- Bunch-by-bunch measurements, integrated over "luminosity blocks" of typically 60 seconds
- Generally used a hit-counting algorithm of 2×4 PMTs for the baseline offline luminosity



Absolute Luminosity Calibration: The vdM Scan Method

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$$\mathcal{L}_b = f_r n_1 n_2 \int \hat{\rho}_1(x,y) \hat{\rho}_2(x,y)\, dx dy$$

→ Per-bunch luminosity $\mathcal{L}_b$ from bunch revolution frequency f_r, bunch populations n_1 and n_2, and proton transverse-density distributions $\hat{\rho}_{1,2}(x,y)$.

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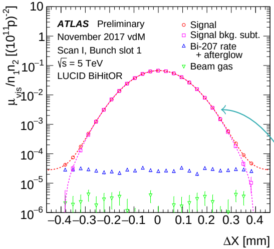
- Scan beam separation $\Delta x, \Delta y$ in x and y planes, compute overlap integral to extract convolved beam sizes $\Sigma_{x,y}$:

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R(\Delta x)\,d\Delta x}{R(0)}, \qquad \mathcal{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} = \frac{\mu_{\text{vis}} f_r}{\sigma_{\text{vis}}}$$



Scan curve fitted with Gaussian × polynomial to compute overlap integral.

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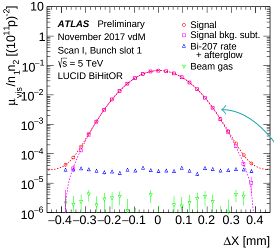
- Calibration constant σ_{vis} from visible interaction rate at peak of scan:

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



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vdM Details and Uncertainties

- Scan-to-scan variations: expect same σ_{vis} for different bunch pairs and scan sets: take max difference between extreme scans as uncertainty.
  - → 1.2 % in 2017 at 13 TeV, typically half that in other years.
- Length scale calibration: relation between *nominal* (i.e. requested) and *actual* beam displacement at IP.
  - → Uncertainties of 0.3–0.4 %, dominated by orbit-drift corrections and magnetic-hysteresis effects.

Beam-beam effects (EM interactions between bunches)

Two main effects to correct for:

- → Optical distortions (defocusing of one beam by the other), also called "dynamic β".
- → Non-linear distortion of the intended beam separation.

Treatment of these corrections is under review: correction on σ_{vis} had been **overestimated** by $\sim 1\,\%$ (until 2019):

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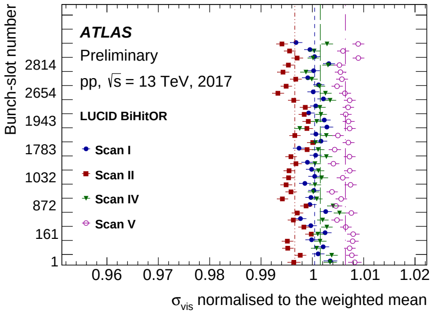

- Non-factorization: $\hat{\rho}(x, y) \neq \rho_x(x)\rho_y(y)$
  - → Correction applied from combined fits to the beam-separation dependence of the luminosity and of the parameters of the 3D luminous region, in both on- and off-axis vdM scans.
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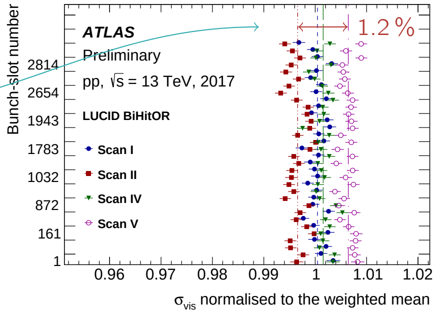

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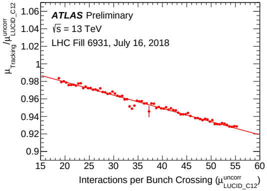

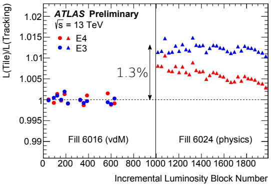

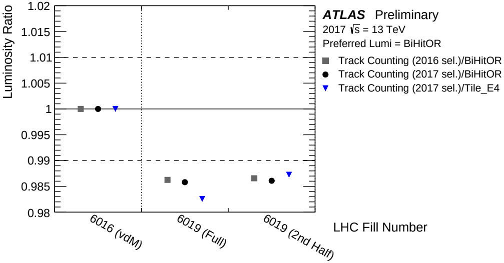

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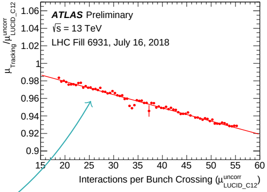

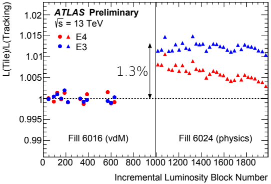

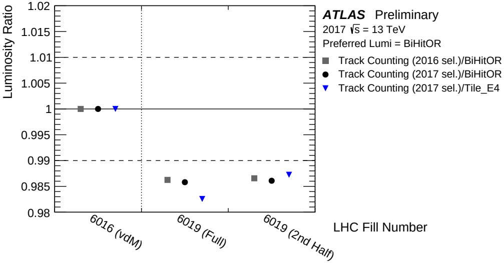

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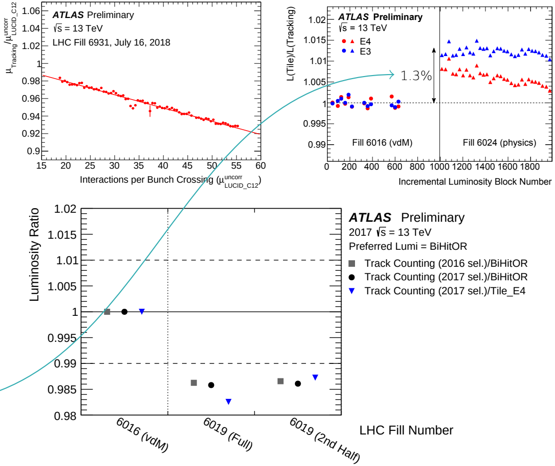

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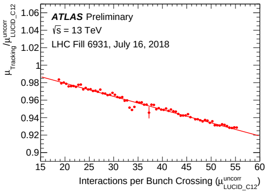
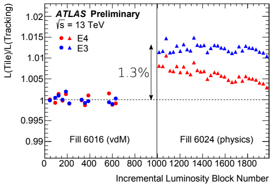
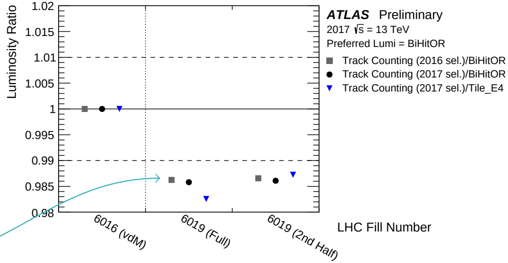
- At low-μ, a calibration transfer is still required, although the size of the correction is smaller (only $\sim 1\,\%$).







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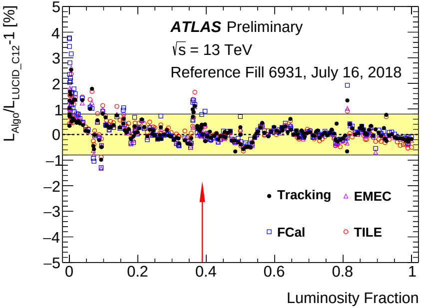
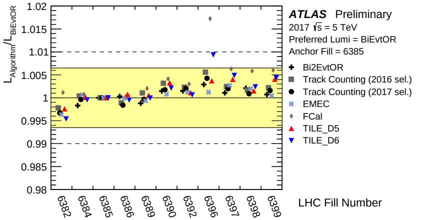
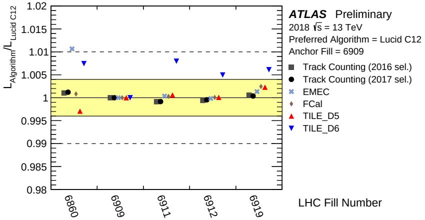
- Assign "stability band" uncertainty to enclose bulk of points:







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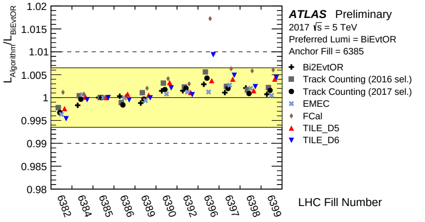

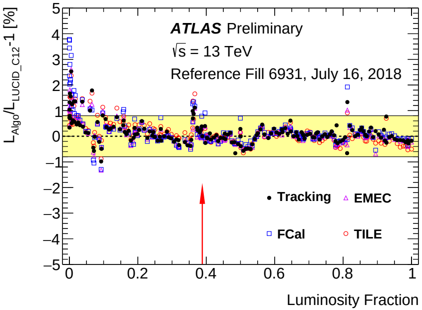

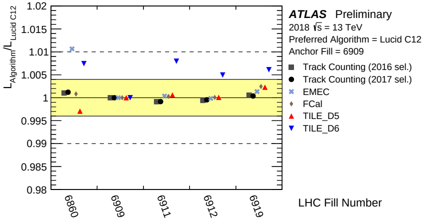

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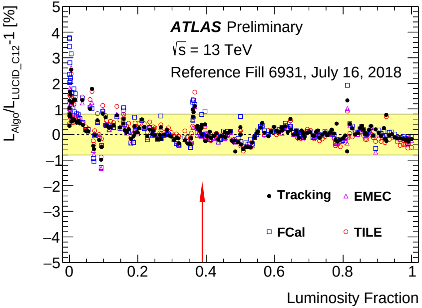

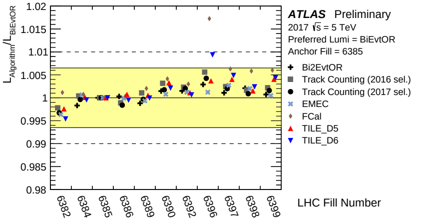

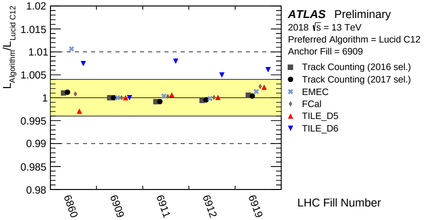

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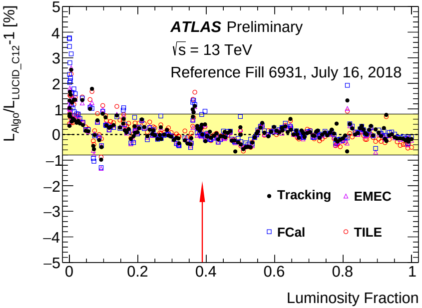

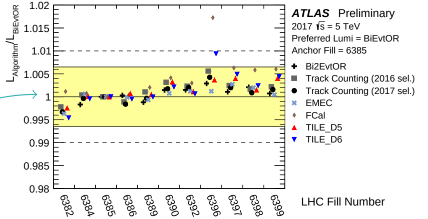

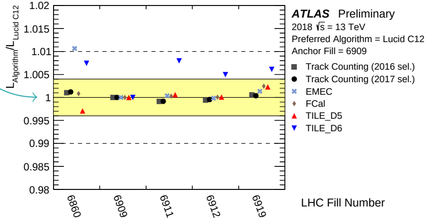

Final Uncertainties and Combination

Treat datasets with common CoM energy and running conditions from different years as a single combined dataset.

→ Need to combine luminosity and uncertainties, accounting for inter-year correlations

	13 TeV High-μ				13 TeV Low-μ			5.02 TeV Low-μ		
Data Sample	**2015+16**	**2017**	**2018**	**Comb.**	**2017**	**2018**	**Comb.**	**2015**	**2017**	**Comb.**
Integrated luminosity (fb^{-1})	36.2	44.3	58.5	139.0	0.1449	0.1902	0.3352	0.0251	0.2569	0.2820
Total uncertainty (fb^{-1})	0.8	1.0	1.2	2.4	0.0030	0.0029	0.0050	0.0005	0.0041	0.0043
Absolute vdM calibration	1.1	1.5	1.2	–	1.5	1.2	–	1.2	0.8	–
Calibration transfer	1.6	1.3	1.3	1.3	1.2	0.8	1.0	1.0	1.2	1.2
Afterglow and beam-halo subtraction	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Long-term stability	0.7	1.3	0.8	0.6	0.8	0.4	0.4	1.0	0.7	0.6
Tracking efficiency time-dependence	0.6	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Total uncertainty (%)	2.1	2.4	2.0	1.7	2.1	1.5	1.5	1.9	1.6	1.5

Total luminosity and uncertainty for the ATLAS Run 2 *pp* datasets:

13 TeV high-μ

$\mathcal{L}_{tot} = 139\,fb^{-1}, \ \ \delta\mathcal{L}/\mathcal{L} = \pm 1.7\,\%$

13 TeV low-μ

$\mathcal{L}_{tot} = 335\,pb^{-1}, \ \ \delta\mathcal{L}/\mathcal{L} = \pm 1.5\,\%$

5 TeV low-μ

$\mathcal{L}_{tot} = 282\,pb^{-1}, \ \ \delta\mathcal{L}/\mathcal{L} = \pm 1.5\,\%$

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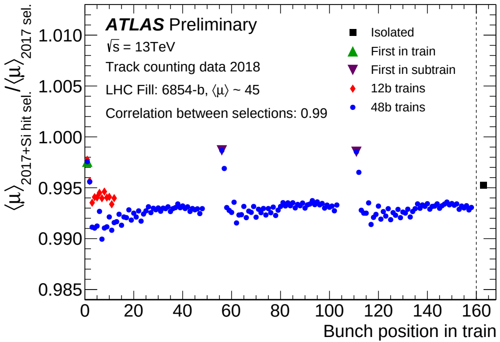
$$\mathcal{L}_{\text{tot}} = 282\,\text{pb}^{-1},\quad \delta\mathcal{L}/\mathcal{L} = \pm 1.5\,\%$$

Outlook: How can we reduce $\delta\mathcal{L}/\mathcal{L}$?

The single largest uncertainty arises from the calibration transfer procedure. Possible avenue for improvement:



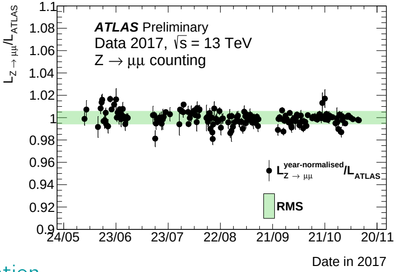
Track counting

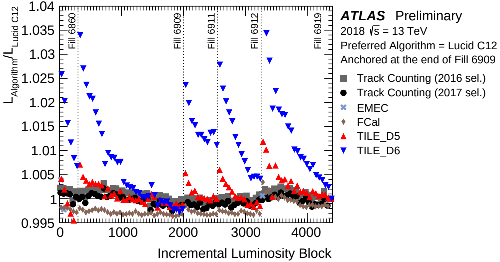
- The calibration transfer relies on the track-counting luminosity being linear with μ in a broad range of LHC running conditions.
- Performance of a track-counting algorithm depends on the choice of track-selection working points.
- Currently investigating other working points (e.g. changing requirements on number of silicon hits).
  - → Provides a means to monitor the stability and internal consistency of the track-counting measurements.

Outlook: How can we reduce $\delta\mathcal{L}/\mathcal{L}$?

Z boson counting

- Z boson production rate at the LHC is sufficiently high that counting $Z \to \ell\ell$ ($\ell = e, \mu$) events can act as a "luminometer."
- Serves as an additional check on the stability of the primary ATLAS luminosity measurement from LUCID.





Calorimeter Activation

- Running with head-on collisions activates the calorimeter materials, leading to an artificially high luminosity measurement that gradually decays away (order of a few hours).
- Important to understand these activation effects for both the calibration transfer and the long-term stability.
- Exploring both data-driven and simulation-based approaches to model and correct for these effects.

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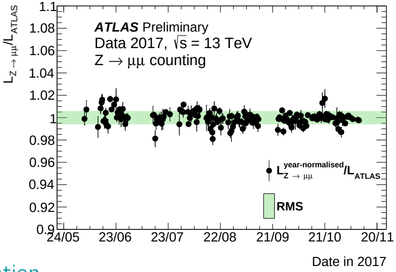

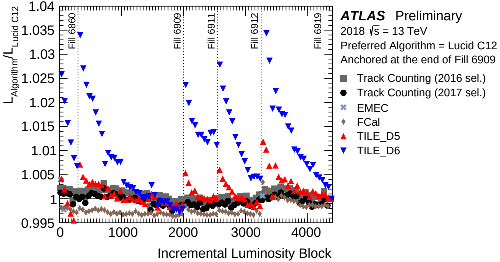

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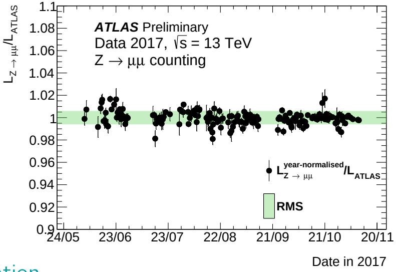

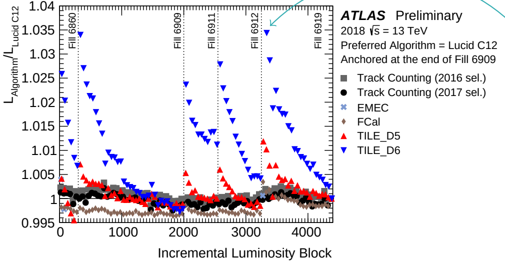

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- Exploring both data-driven and simulation-based approaches to model and correct for these effects.

Summary

ATLAS Run 2 luminosity results to date:[1]

Year	Dataset	Uncert.	Status
2015-18	pp $\sqrt{s} = 13$ TeV high-μ	1.7 %	Prelim. ATLAS-CONF-2019-021
2015+17	pp $\sqrt{s} = 5$ TeV low-μ	1.5 %	Prelim. ATLAS-CONF-2020-023
2015+18	pp $\sqrt{s} = 13$ TeV low-μ	1.5 %	
2015	Pb+Pb	1.5 %	Final
2016	p+Pb	2.4 %	Final
2018	Pb+Pb	4.1 %	Prelim., update in progress

ATLAS Luminosity Posters at ICHEP

- P. Moder: Measuring luminosity with track counting in the ATLAS experiment
- S. G. Fernandez: Measurements of Luminosity in ATLAS with Tile Calorimeter
- M. O'Keefe: Luminosity Determination using $Z \to \ell\ell$ Counting for Run-2 ATLAS Data

[1] Analysis of high-β^* datasets is ongoing.

Backup

ATLAS Luminosity Public Results

Public Results TWiki: twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

- Luminosity determination for low-pileup datasets at $\sqrt{s} = 5$ and 13 TeV using the ATLAS detector at the LHC
  - → Preliminary (Summer 2020) Run 2 luminosity results for low-pileup datasets [ATLAS-CONF-2020-023]
- Luminosity determination in *pp* collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC
  - → Preliminary (Spring 2019) Run 2 luminosity results [ATLAS-CONF-2019-021]
- Luminosity determination in *pp* collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC
  - → Final 2012 luminosity results [*Eur. Phys. J. C* **76** (2016) 653]
- Improved luminosity determination in *pp* collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector at the LHC
  - → Final 2010 and 2011 luminosity results [*Eur. Phys. J. C* **73** (2013) 2518]

LHC Lumi Days Workshop, June 4–5 2019: indico.cern.ch/event/813285/ · ATLAS Presentations:

- R. Hawkings: Overview of ATLAS luminosity determination methodology in Run 2
- W. Kozanecki: Impact of orbit drifts & magnetic-hysteresis effects on vdM & length-scale calibrations
- M. Dyndal: Non factorization in ATLAS & ALICE vdM scans
- V. Lang: Long-term monitoring of delivered luminosity & calibration stability in ATLAS
- R. Hawkings: Combination of luminosity uncertainties for the full Run-2 dataset: the ATLAS example

5 TeV and 13 TeV low-μ Datasets

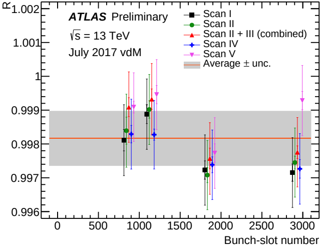
Dataset	Date	LHC fill(s)	Bunch config.	β^* (m)	Peak $\mathcal{L}$ (cm^{-2} s^{-1})	Typical $\langle\mu\rangle$
$\sqrt{s} = 5.02$ TeV	2017					
- vdM scan	11 Nov	6380	22, isolated	3.1	4×10^{30}	0.75–1.0
- calibration transfer	13 Nov	6385	1828, 8b4e	3.1	1.2×10^{33}	1–4
- physics	12–20 Nov	6381–6399	512–1828, 8b4e	3.1	$0.5–1.3 \times 10^{33}$	0.5–4
$\sqrt{s} = 13$ TeV	2017					
- vdM scan	28 Jul	6016	32, isolated	19	2.7×10^{30}	0.6
- calibration transfer	29 Jul	6019	591 25 ns trains	0.4	8×10^{31}	1 (level)
- physics	21–26 Nov	6404–6417	644–1866, 8b4e	0.4	5×10^{32}	2, 1 (level)
$\sqrt{s} = 13$ TeV	2018					
- vdM scan	30 Jun	6868	124, isolated	19	8×10^{30}	0.5
- calibration transfer	28 Jun	6860	2448, 25 ns trains	0.3	7×10^{32}	2 (level)
- physics	28 Jun + 9–13 Jul	6860 + 6909–6919	2448–2544, 25 ns trains	0.3	7×10^{32}	2 (level)

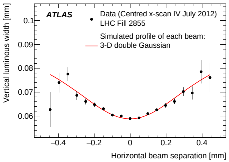
vdM Details I

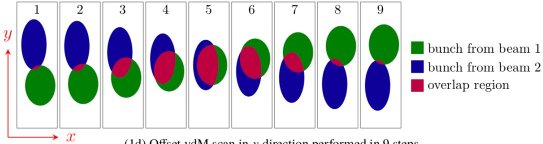
- Determining bunch populations n_1 and n_2
  - → **DC C**urrent **T**ransformers to obtain the total current in each beam.
  - → **F**ast **B**eam-**C**urrent **T**ransformers to resolve the total current into the fractions in individual bunches.
- Orbit drifts during scans
  - → Measured using LHC arc and triplet (DOROS) **B**eam **P**osition **M**onitors.
  - → Have observed drifts up to $\mathcal{O}(10\,\mu\text{m})$ in the position of one or both beams during the course of a single vdM scan.
- Beam position jitter
  - → Beam movement within one scan step.
  - → BPMs constrain possible movement within a scan step, input to simulated vdM scans.
- Emittance growth
  - → Accounts for possible variations of the horizontal and vertical beam emittances, and therefore the convolved beam sizes Σ_x and Σ_y, during the course of an x-y scan pair.
  - → Creates bias only if horizontal and vertical emittances grow at different rates (which they do).
  - → Uncertainty carried over from Run 1 analysis.

vdM Details II

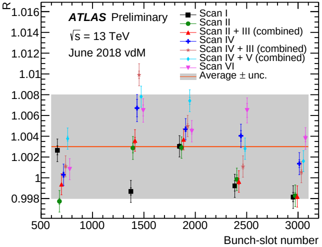
- Non-factorization
  - → Clear signature of non-factorization: strong horizontal-separation dependence of the vertical luminous size (from reconstructed vertices).







(1d) Offset vdM scan in y direction performed in 9 steps



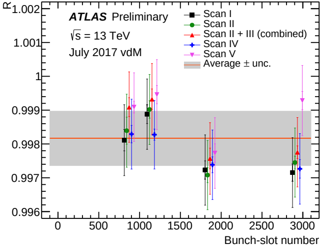
Eur. Phys. J. C **76** (2016) 653

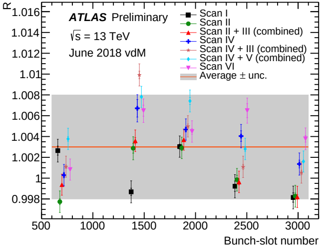
vdM Details II

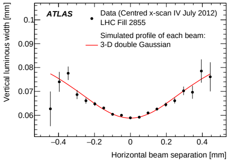
Non-factorization

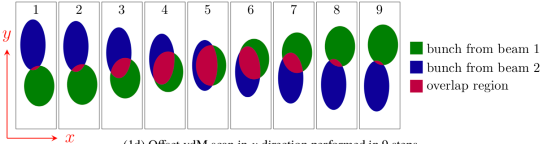
- Clear signature of non-factorization: strong horizontal-separation dependence of the vertical luminous size (from reconstructed vertices).
- To estimate the correction to σ_{vis} due to non-factorization effects, compute the quantity R, such that $\sigma_{\text{vis}}^{\text{corr}} = \sigma_{\text{vis}}/R$:

$$R = \frac{\text{True Luminosity}}{\text{Factorized Luminosity}} = \frac{\int \hat{\rho}_1(x,y)\hat{\rho}_2(x,y)\,dx dy}{\int \rho_1(x)\rho_2(x)\,dx \int \rho_1(y)\rho_2(y)\,dy},$$









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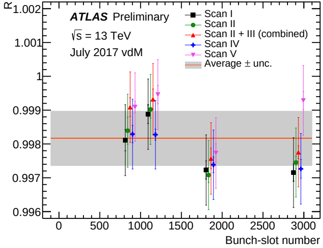
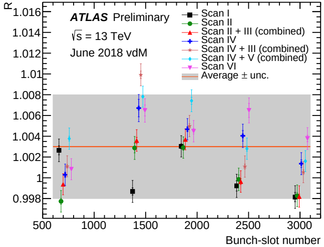
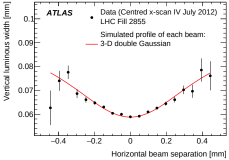
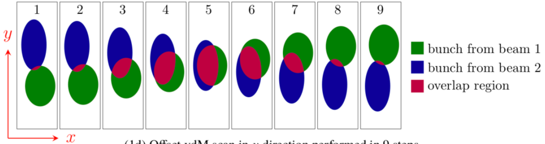
- Do combined fits to the beam-separation dependence of the luminosity and of the parameters of the 3D luminous region, in both on- and off-axis vdM scans, to extract non-factorisable single-beam luminosity profiles, which are fed into simulated vdM scans to compute the true beam overlap integral.









(1d) Offset vdM scan in y direction performed in 9 steps

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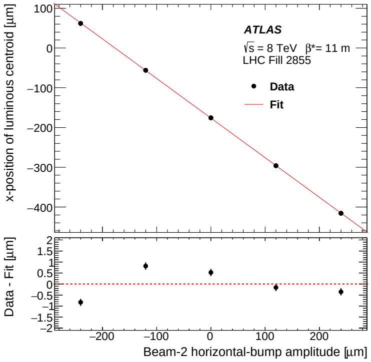
vdM Details III

- Length scale calibration
  - Relation between *nominal* (i.e. requested) and *actual* beam displacement at IP.
  - Displace both beams in same direction.
  - Reconstruct luminous centroid position using vertices reconstructed in ATLAS inner detector.
    - Perform a mini-scan in beam-2 x-pos around fixed beam-1 x-pos to find peak position.
  - Fit linear relation between bump amplitude and luminous centroid to find calibration.
  - Repeat for each of beam-1 x, y and beam-2 x, y.
    - Since Nov 2017, use same directions of movement as in vdM scan, to get same hysteresis effect.



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- Additional systematics from ID alignment
  - Assessed by considering "realistic" misalignment scenarios, giving a $\sim 0.1\,\%$ uncertainty.

Combination Methodology and Inter-Year Correlations

- Final uncertainty calculated using simple error propagation:
  - → Total integrated luminosity is sum of all years: $\mathcal{L}_{\text{tot}} = \Sigma_i \mathcal{L}_i$
  - → Variance of the total depends on covariance matrix V_L encoding the errors on individual years:

$$(\sigma_{\mathcal{L}_{\text{tot}}})^2 = \mathbf{G}\mathbf{V}_L\widetilde{\mathbf{G}}, \quad \text{where } \mathbf{G} = \left(\frac{\partial\mathcal{L}_{\text{tot}}}{\partial\mathcal{L}_1}, \frac{\partial\mathcal{L}_{\text{tot}}}{\partial\mathcal{L}_2}, \frac{\partial\mathcal{L}_{\text{tot}}}{\partial\mathcal{L}_3}, \cdots\right) = (1, 1, 1, \ldots)$$

- Evaluation of the covariance matrix V_L:
  - → Sum of individual sources with uncertainties σ_i in each year (many separate uncorrelated and correlated sources):

$$V_L = \underbrace{\begin{pmatrix} \sigma_1^2 & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{pmatrix}}_{\text{uncorrelated}} + \underbrace{\begin{pmatrix} \sigma_1^2 & \sigma_1\sigma_2 & \sigma_1\sigma_3 \\ \sigma_2\sigma_1 & \sigma_2^2 & \sigma_2\sigma_3 \\ \sigma_3\sigma_1 & \sigma_3\sigma_2 & \sigma_3^2 \end{pmatrix}}_{\text{correlated}} + \cdots$$

  - → Sources with both correlated and uncorrelated parts are broken into two separate contributions to V_L.
  - → “Random” uncertainties taken as uncorrelated, e.g. scan-to-scan σ_{vis} consistency, long-term stability.
  - → “Systematic” uncertainties (and those obtained using the same methodology) taken as correlated—always have the same bias, e.g. non-factorization, beam-beam effects, calibration transfer.

Individual and Combined Dataset Uncertainties

Data Sample	13 TeV High-μ 2015+16	13 TeV High-μ 2017	13 TeV High-μ 2018	13 TeV High-μ Comb.	13 TeV Low-μ 2017	13 TeV Low-μ 2018	13 TeV Low-μ Comb.	5.02 TeV Low-μ 2015	5.02 TeV Low-μ 2017	5.02 TeV Low-μ Comb.
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Total uncertainty (fb^{-1})	0.8	1.0	1.2	2.4	0.0030	0.0029	0.0050	0.0005	0.0041	0.0043
Uncertainty contributions (%):										
DCCT calibration†	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.4	0.2	0.2
FBCT bunch-by-bunch fractions	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
Ghost-charge correction*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.1
Satellite correction$^{\dagger **}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Scan curve fit model$^{\dagger **}$	0.5	0.4	0.5	0.4	0.4	0.5	0.5	0.6	0.2	0.2
Background subtraction	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.1	0.1	0.0
Orbit-drift correction	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.2	0.2
Beam position jitter$^{\dagger()*}$	0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.3	0.1	0.1
Beam-beam effects*	0.3	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2
Emittance growth correction*	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.2	0.2
Non-factorization effects*	0.4	0.2	0.5	0.4	0.2	0.5	0.4	0.2	0.3	0.3
Length-scale calibration	0.3	0.3	0.4	0.2	0.3	0.4	0.3	0.5	0.4	0.4
ID length scale*	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bunch-by-bunch σ_{vis} consistency	0.2	0.2	0.4	0.2	0.2	0.4	0.2	0.4	0.2	0.2
Scan-to-scan reproducibility	0.5	1.2	0.6	0.5	1.2	0.6	0.6	0.3	0.3	0.2
Reference specific luminosity	0.2	0.2	0.4	0.2	0.2	0.4	0.3	0.1	0.4	0.3
Subtotal for absolute vdM calibration	1.1	1.5	1.2	–	1.5	1.2	–	1.2	0.8	–
Calibration transfer$^{\dagger **}$	1.6	1.3	1.3	1.3	1.2	0.8	1.0	1.0	1.2	1.2
Afterglow and beam-halo subtraction*	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Long-term stability	0.7	1.3	0.8	0.6	0.8	0.4	0.4	1.0	0.7	0.6
Tracking efficiency time-dependence	0.6	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Total uncertainty (%)	2.1	2.4	2.0	1.7	2.1	1.5	1.5	1.9	1.6	1.5

Low-μ 13 TeV and 5 TeV Combined Uncertainties