Luminosity determination in pp collisions at $\sqrt{s}$ = 13.6 TeV with the ATLAS detector

Olof Lundberg on behalf of the ATLAS Collaboration

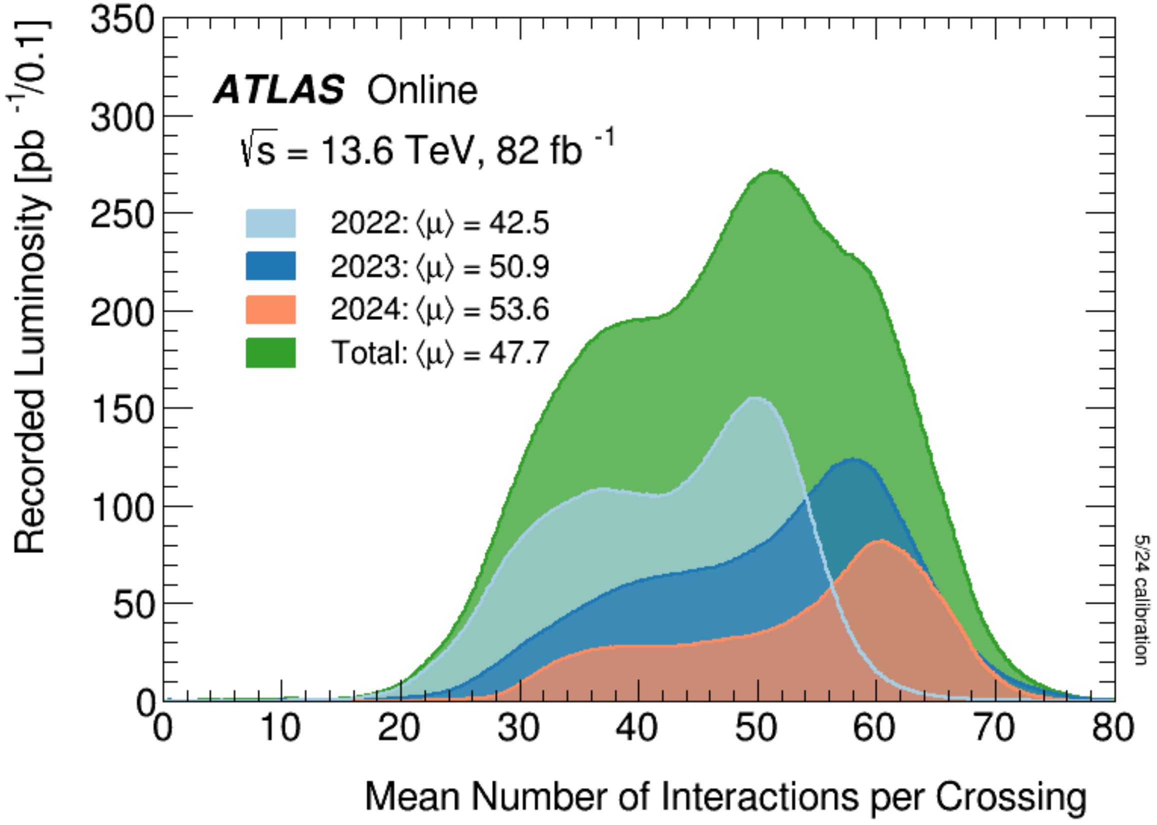
What is Luminosity?

Luminosity: One of the key observables for collider physics

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

$$\mathcal{L}_b = \frac{\mu_b f_r}{\sigma_{inel}} \qquad \mathcal{L} = n_b \frac{\langle\mu\rangle f_r}{\sigma_{inel}}$$

Where μ is the number of collisions per bunch crossing (or pile-up)



The basics

$$\mathcal{L}_b = \frac{\mu f_r}{\sigma_{inel}} = \frac{\epsilon \mu f_r}{\epsilon \sigma_{inel}} = \frac{\mu_{vis} f_r}{\sigma_{vis}}$$

ϵ is acceptance x efficiency of given lumi detector,
μ_{vis}, σ_{vis} are its *visible* interaction rate & cross-section

The basics

Continuously measured during physics data taking

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Measured in dedicated van der Meer sessions

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Expressed in beam parameters:

$$\mathcal{L} = \frac{n_1 n_2 f_r}{2\pi \Sigma_x \Sigma_y}$$

n_1, n_2 number of protons in each bunch

Σ_x, Σ_y convolved beam widths

$\Sigma_i = \sqrt{\sigma_{i,1}^2 + \sigma_{i,2}^2}$ for Gaussian beams

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Measured by LHC using beam instrumentation

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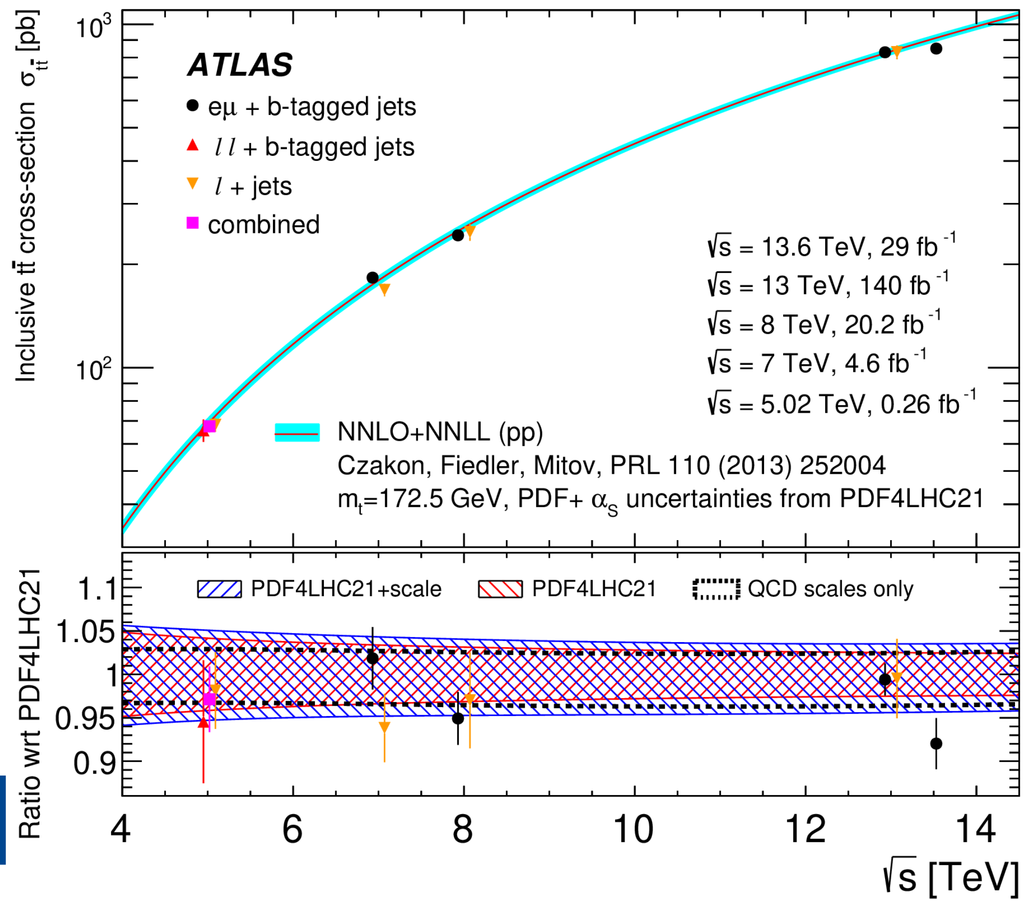
The importance of Luminosity

High integrated luminosity: A key goal of the LHC and experiments.

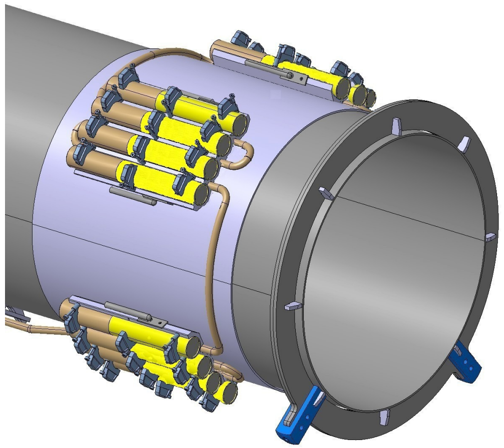
Precision in the determination of luminosity also crucial:
For many precision measurements Luminosity is the leading uncertainty!

Phys. Lett. B 848 (2024) 138376



$$\sigma_{t\bar{t}}(13.6\,TeV) = 850 \pm 3(stat) \pm 18(syst) \pm 20(lumi)$$

The ATLAS luminometers

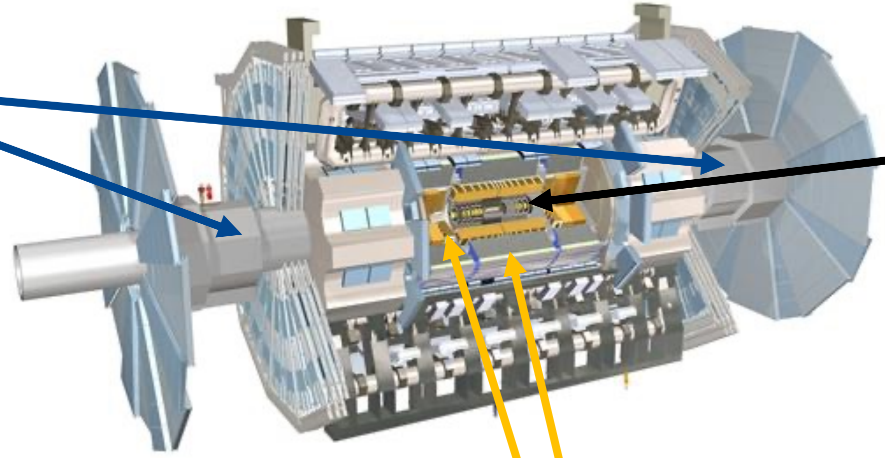


LUCID2

Main luminometer

Count hits in PMTs

Per-bunch readout



Calorimeters (Tile, LAr)

Measure currents (proportional to μ)

Only measure bunch-integrated luminosity

Track Counting (ID)

No of tracks $\propto \mu$

Per-bunch (Low stats at low μ)

Tuned to be very linear with μ

Z counting

Leptonic decays of Z

Used eg. to monitor stability over time or wrt to μ

Determining Luminosity and its uncertainty

Step 1: vdM Scan

Absolute calibration of LUCID luminosity (determination of σ_{vis})

Controlled conditions:
- Few isolated bunches
- No crossing angle
- Larger emittances + β^* = 19 m =>
- Wider luminous region
- Moderate bunch currents
- Peak $\langle\mu\rangle$ ~0.5
- Bunch profile tailoring in injector chain

Step 2: Calibration Transfer

Extrapolation to physics conditions:

- Relative response wrt μ in LUCID, tracks, TILE, EMEC
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Step 3: Long-term stability

Measure stability and consistency of luminometer response over the year

- Run-to-Run stability measurements
- Comparison of integrated lumi between luminometers

See Run 2 paper for all the details! Eur. Phys. J. C (2023) **83**: 982

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Absolute calibration through vdM scans

Scan beams through each other to estimate Σ_x, Σ_y → determine σ_{vis}

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

Fit to scan curve to extract μ_{vis}^{max} and widths Σ_x, Σ_y

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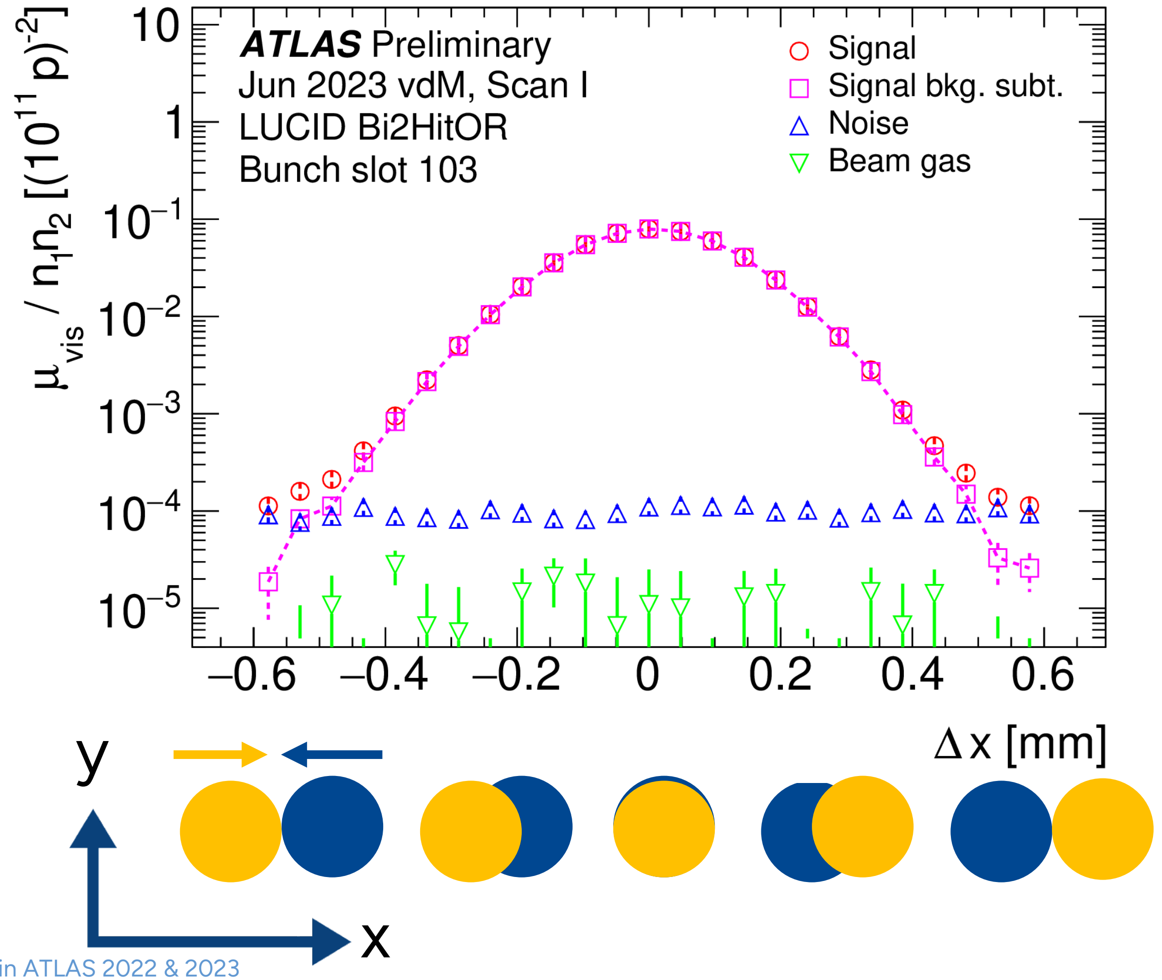

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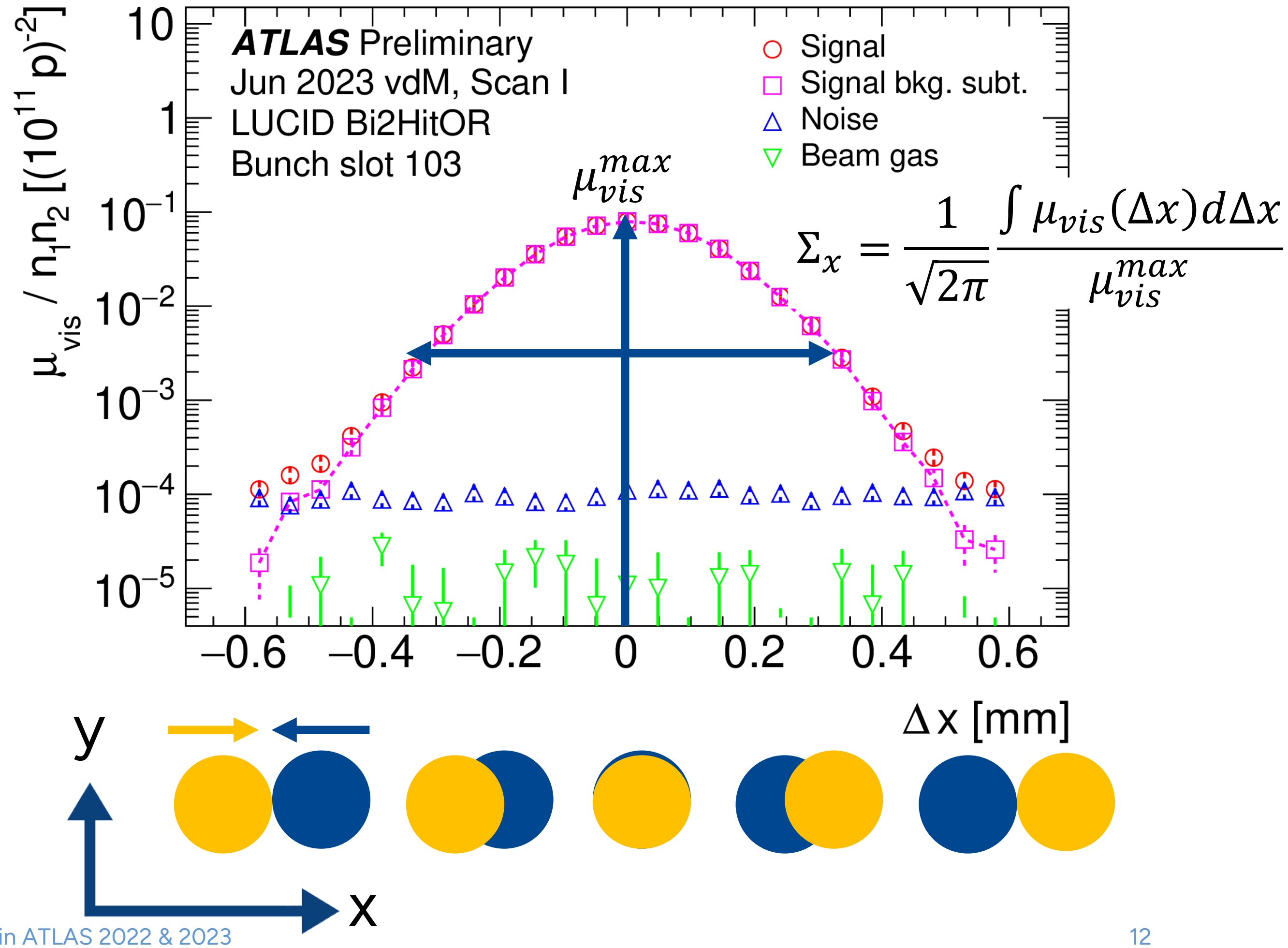

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Corrections; most important (run 3) non-factorization bias

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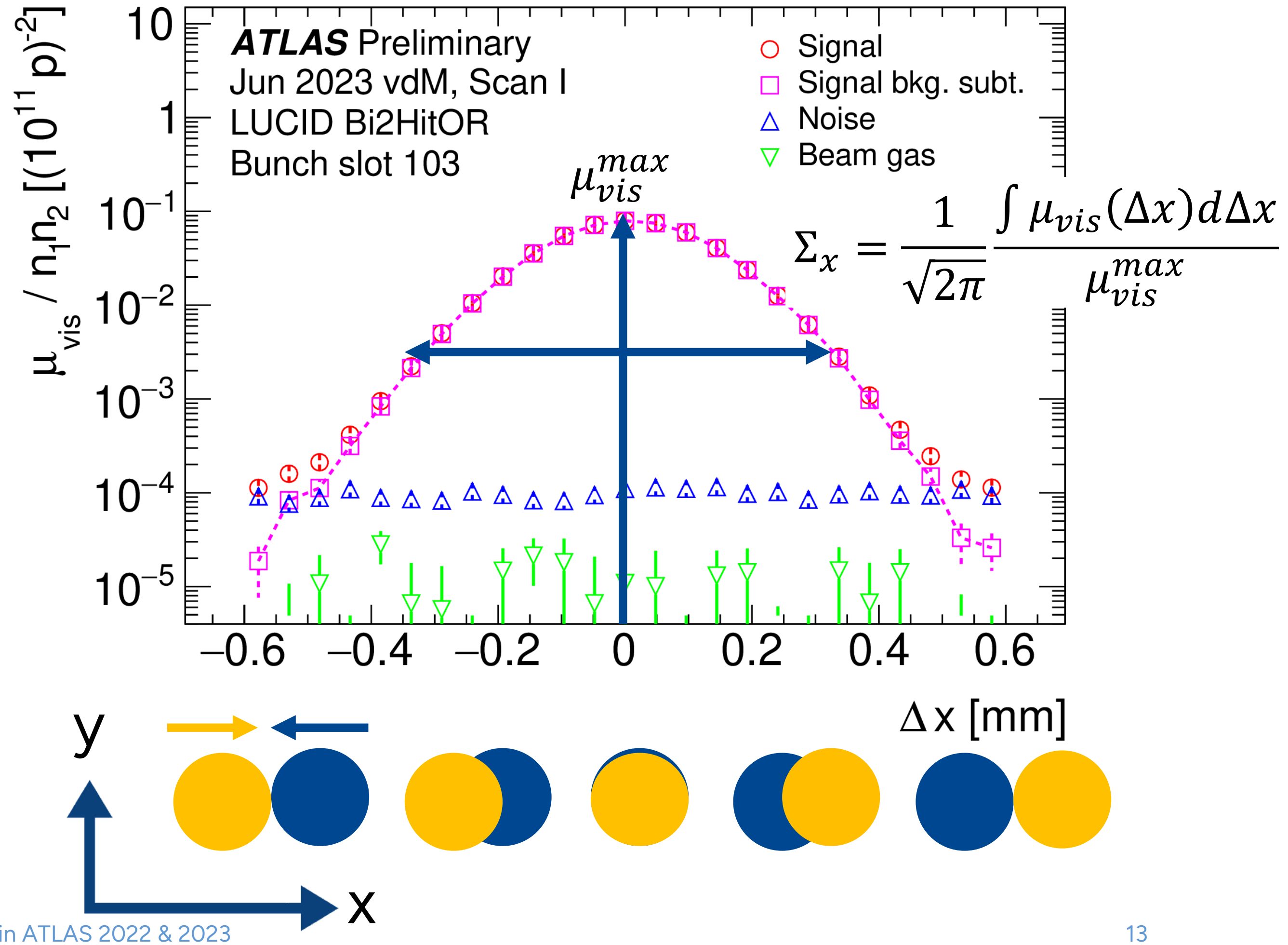


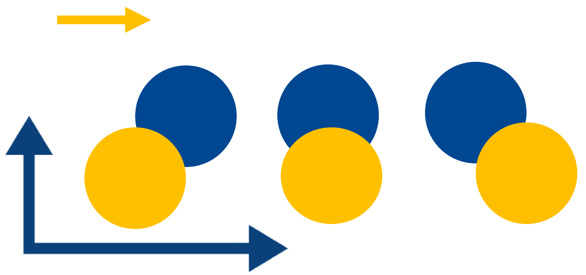
Non-factorization

$$\mathcal{L} = \frac{n_1 n_2 f_r}{2\pi \Sigma_x \Sigma_y}$$

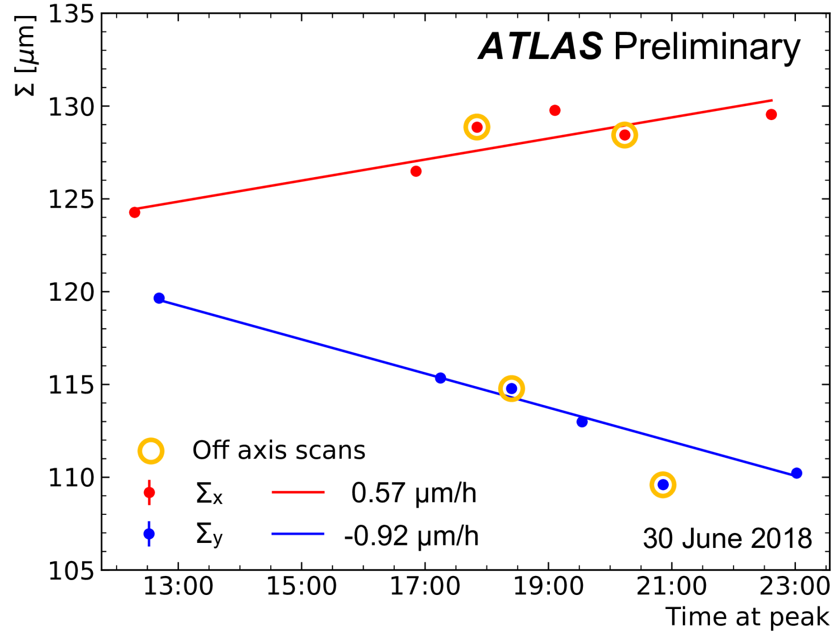
Assumes

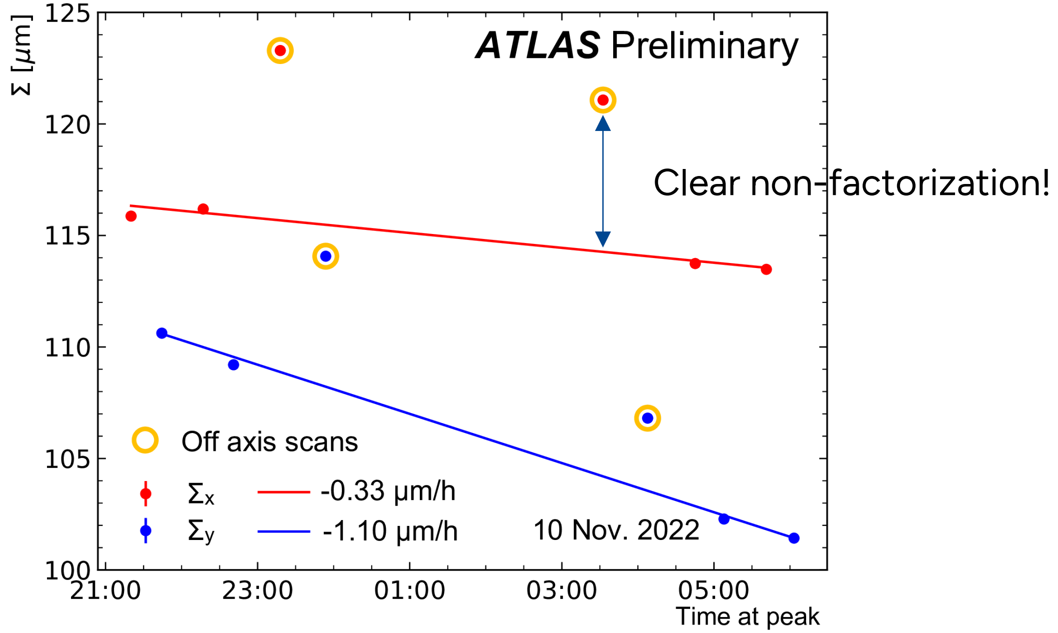
$$\mathcal{L}(\Delta x, \Delta y) = f_x(\Delta x) \cdot f_y(\Delta y)$$

Here characterized by comparing Σ_x, Σ_y in on-axis and *off-axis* scans



Considerably larger effect in Run 3 than Run 2





Non-factorization corrections

Correction derived using two different methods

Luminous Region Evolution (LRE)

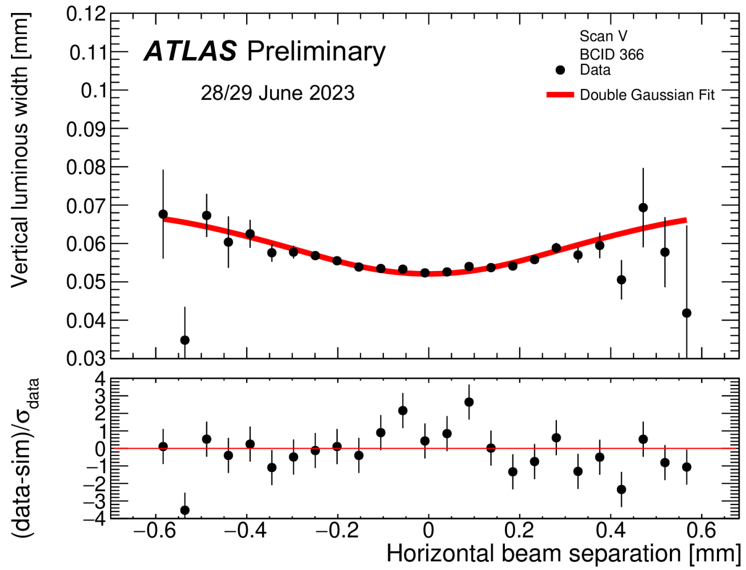
- Extract 3-D proton density of bunches from combined fit to separation dependence of collision rate AND luminous region parameters (displacement, size, shape, orientation) to derive correction to bias

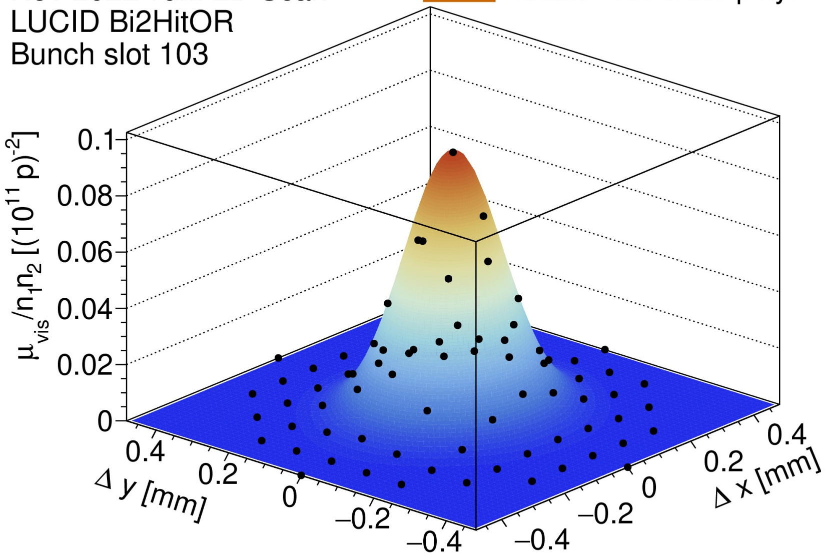
Generalized 2D vdM scans

$$[\Sigma_x \Sigma_y] = \frac{1}{2\pi} \frac{\int \mu_{vis}(\Delta x, \Delta y) d\Delta x d\Delta y}{\mu_{vis}(0,0)}$$

- Scan in x+y and compare derived σ_{vis} to that of 1-d (standard) scan

ATL-DAPR-PUB-2024-001





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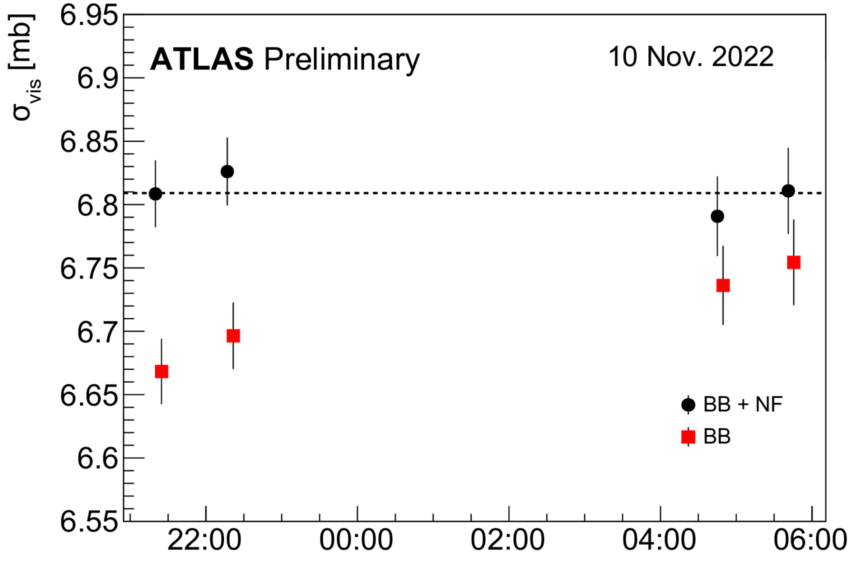

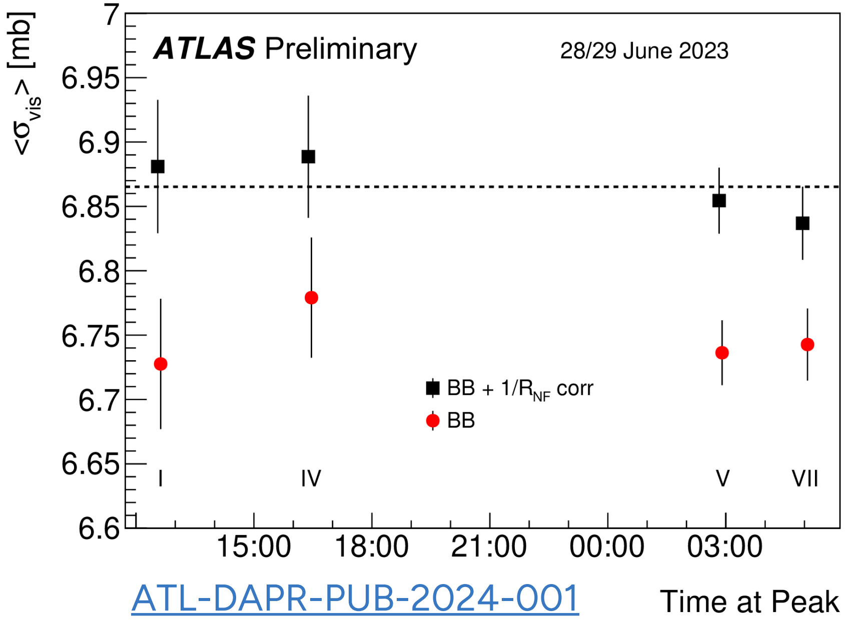

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Uncertainties to absolute calibration

Table to the right not complete – only lists uncertainties that was >0.3% in at least one year

NB. 2022 and 2023 calibrations are ***preliminary***

Clear that non-factorisation correction uncertainties are the major contributions to vdM uncertainties so far in Run 3

Uncertainty Source	2018	2022	2023
Scan-scan reproducibility	0.30	0.27	0.35
Bunch-bunch consistency	0.00	0.50	0.36
Background subtraction	0.11	0.06	0.30
Reference spec. lumi	0.31	0.43	0.44
μ dependence			0.30
Orbit drift	0.01	0.06	0.34
Beam-beam effects	0.26	0.35	0.32
Non-factorisation	0.30	**1.07**	**1.39**
Magnetic non-linearity	0.60	0.32	0.28
vdM total	**0.9**	**1.5**	**1.7**

All uncertainties in percent!

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Step 3: Long-term stability

Measure stability and consistency of luminometer response over the year

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Calibration transfer process

Correct LUCID for non-linearity

Normalise track counting to LUCID in head-on part of vdM period (eg. during CMS scans) ->

Long physics runs with large μ range to derive correction

Assumes track counting is linear from vdM to high μ regime (after tuning)

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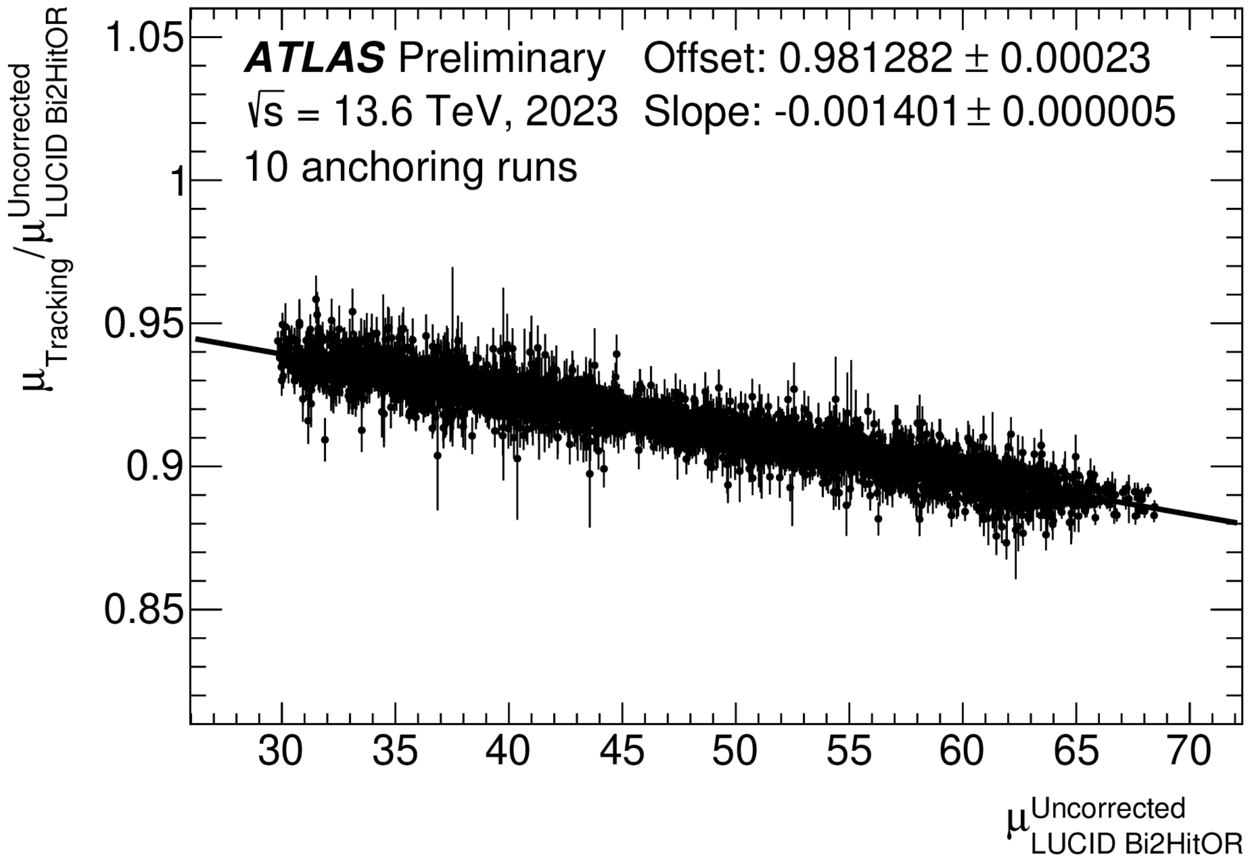

Calibration transfer uncertainties

Check linearity of tracks with calorimeter luminosity:

Example with high-sensitivity Tile cells: going to high μ and trains indicates not complete linearity (but currently with large uncertainty)

Very preliminary 1.5% uncertainty in 2022 and 1.1% in 2023

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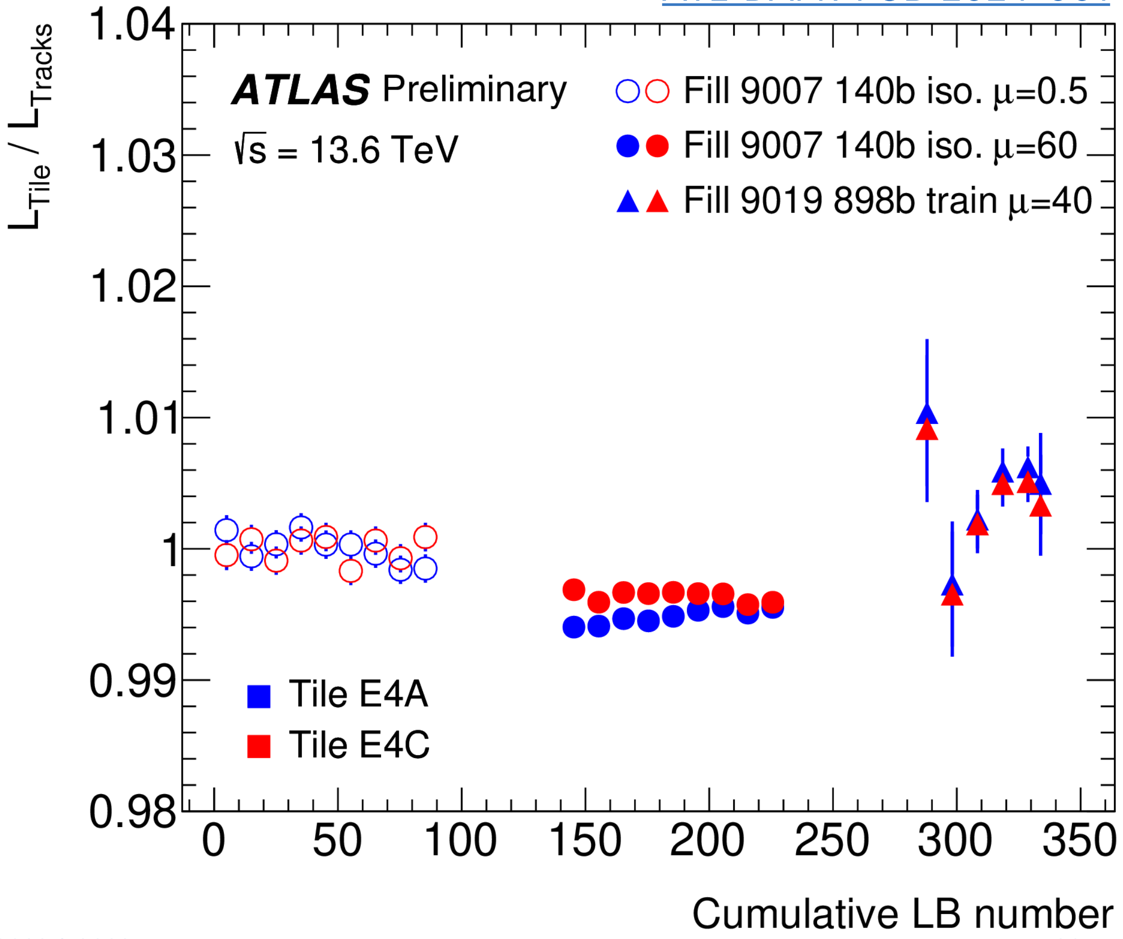

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Long-term stability

vdM scan done once per year:
Are the calibrations valid long-term?

Check how well our normalization, "anchoring" of other luminometers to LUCID work

Check how well different luminometers agree over time -> chose largest deviation over all (independent) luminometers

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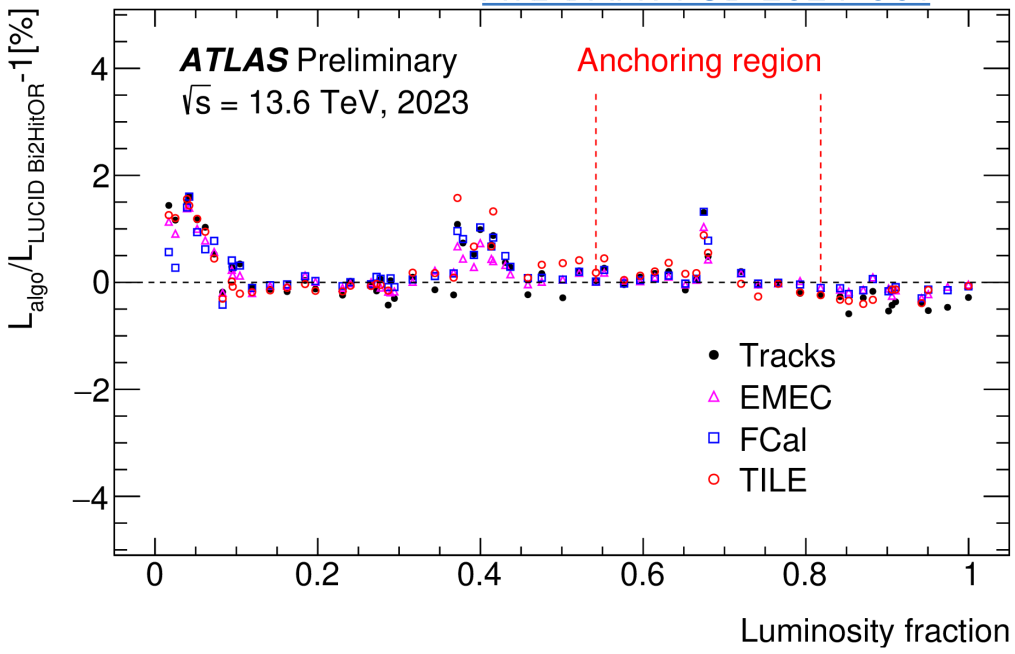

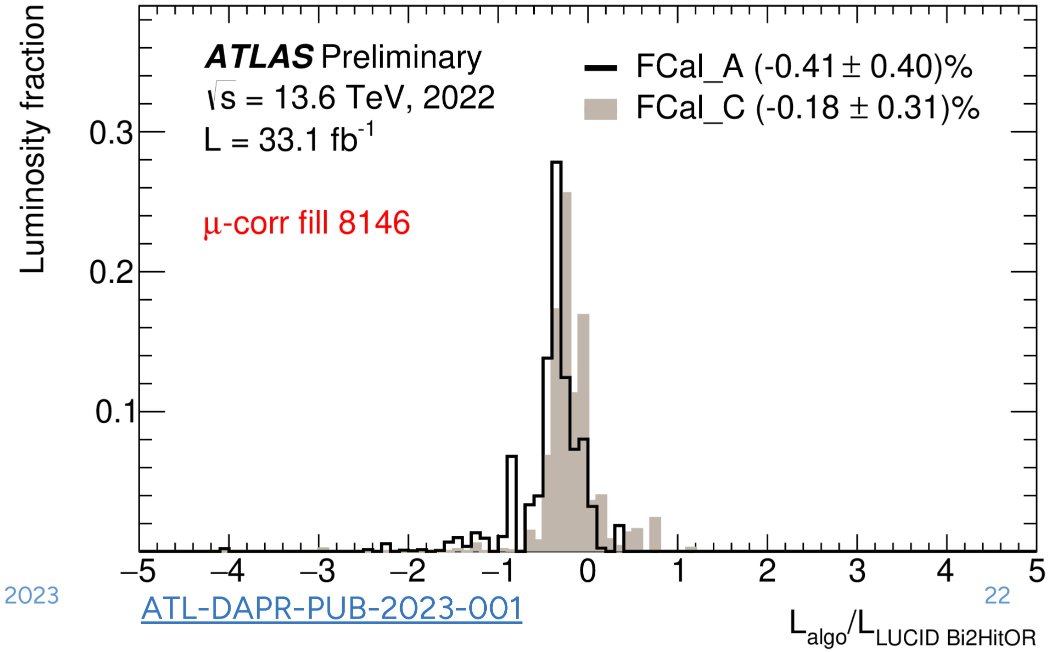

ATL-DAPR-PUB-2023-001

Luminosity determination in 2022 & 2023

Uncertainty Source	2022	2023
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Bunch-bunch consistency	0.50	0.36
Background subtraction	0.06	0.30
Reference spec. lumi	0.43	0.44
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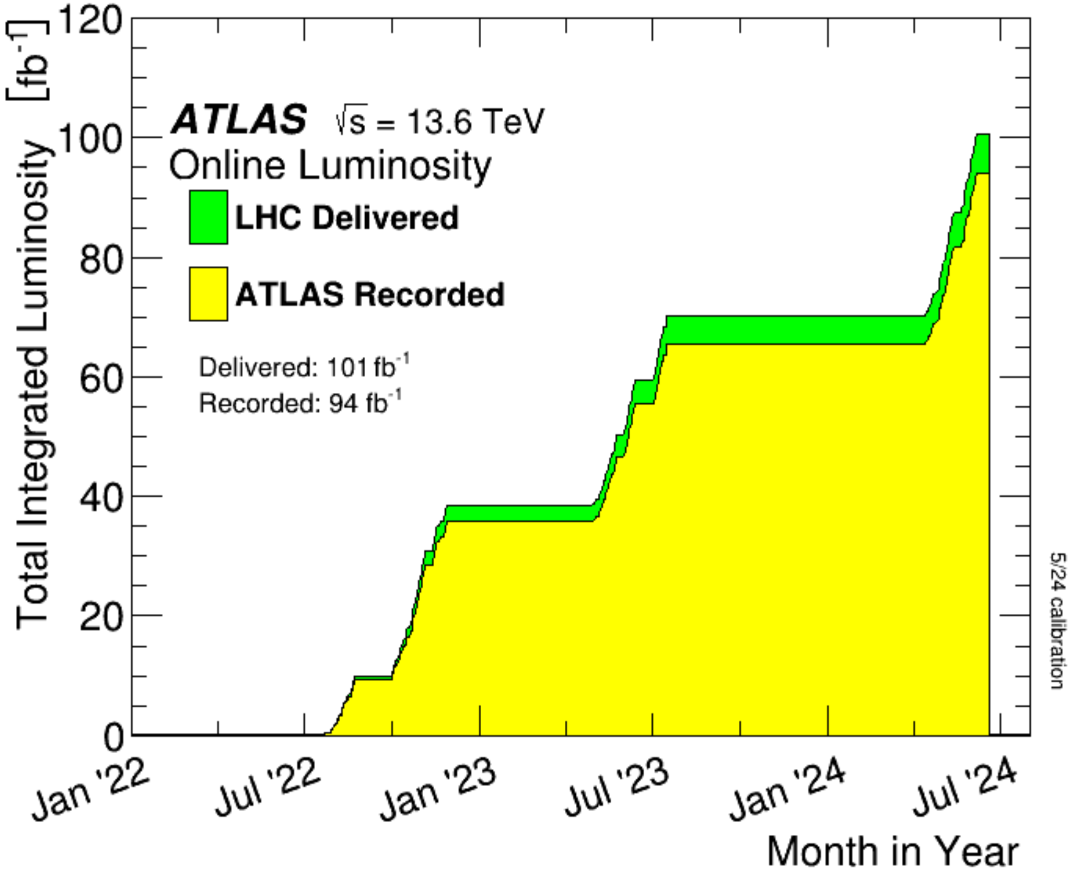
Orbit drift	0.06	0.34
Beam-beam effects	0.35	0.32
Non-factorisation	**1.07**	**1.39**
Magnetic non-linearity	0.32	0.28
vdM total	**1.5**	**1.7**
Calibration transfer	**1.50**	**1.1**
Calibration anchoring	0.53	0.16
Long-term stability	0.41	0.1
Total Uncertainty	**2.2**	**2.0**

Again: Only >0.3%



Summary and Outlook

- We have presented preliminary luminosity estimates and uncertainties from 2022 and 2023 – the uncertainties are 2.2 and 2.0 percent on the total in the two respective years
- The vdM scan-based method is well-tested and provided a sub-percent uncertainty on the full Run 2 luminosity estimate
- For both years, uncertainties are dominated by non-factorisation and calibration transfer
- For non-factorisation many-pronged approach to mitigate issue
  - LHC had dedicated non-factorisation Machine Development session in May
  - Effort in ATLAS to develop new analysis techniques to reduce uncertainty
- For even longer outlook (HL-LHC) see Christian's talk later this session!

More at ICHEP + References

C. Ohm: *Towards an ATLAS Luminosity Measurement at HL-LHC*
Friday 18.12 (THIS SESSION!)

Posters:

R. Wierda: Run-3 improvements in the ATLAS online luminosity measurement

J. Lindon: LUCID-3: the upgrade of the ATLAS Luminosity detector for High Luminosity LHC

D. Bosne: Luminosity measurement using Timepix3 during 2018 pp-collisions at $\sqrt{s}$= 13 TeV in the ATLAS experiment

Read more:

Run 2 paper: Eur. Phys. J. C (2023) **83**: 982

2022 & 2023 results: ATL-DAPR-PUB-2023-001 & ATL-DAPR-PUB-2024-001

BACKUP

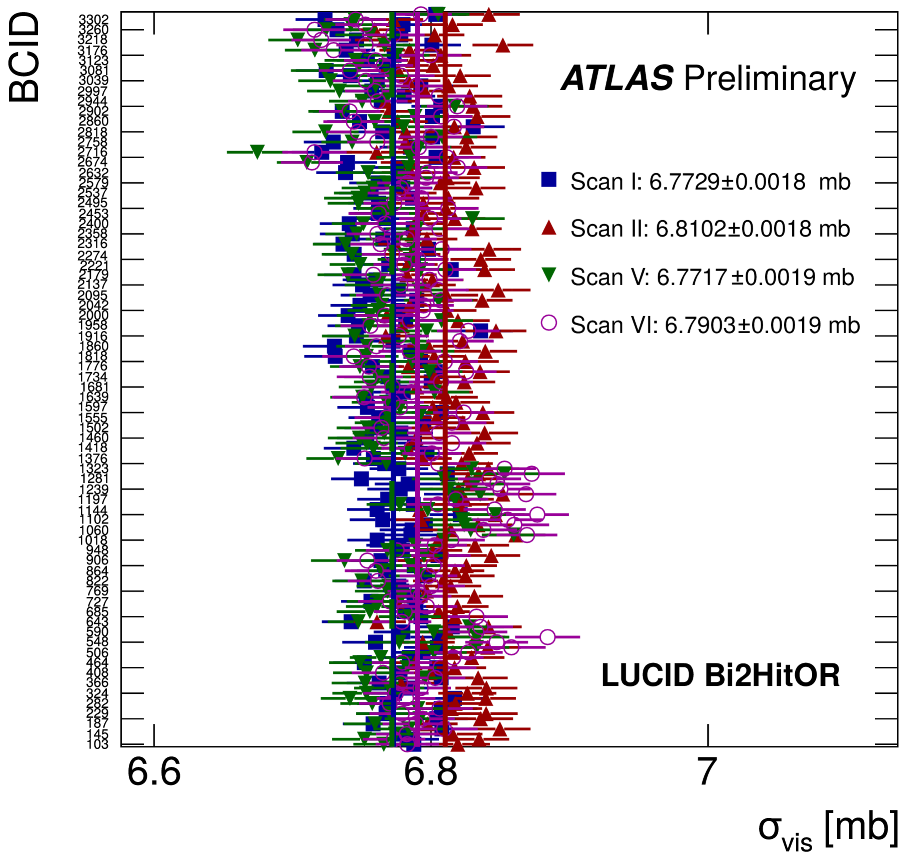
ATL-DAPR-PUB-2023-001

BACKUP

Sigma as measured in each scan, for each separate BCID.

Goes into bunch-bunch consistency , scan-scan reproducibility, similar checks into the reference spec lumi

ATL-DAPR-PUB-2023-001



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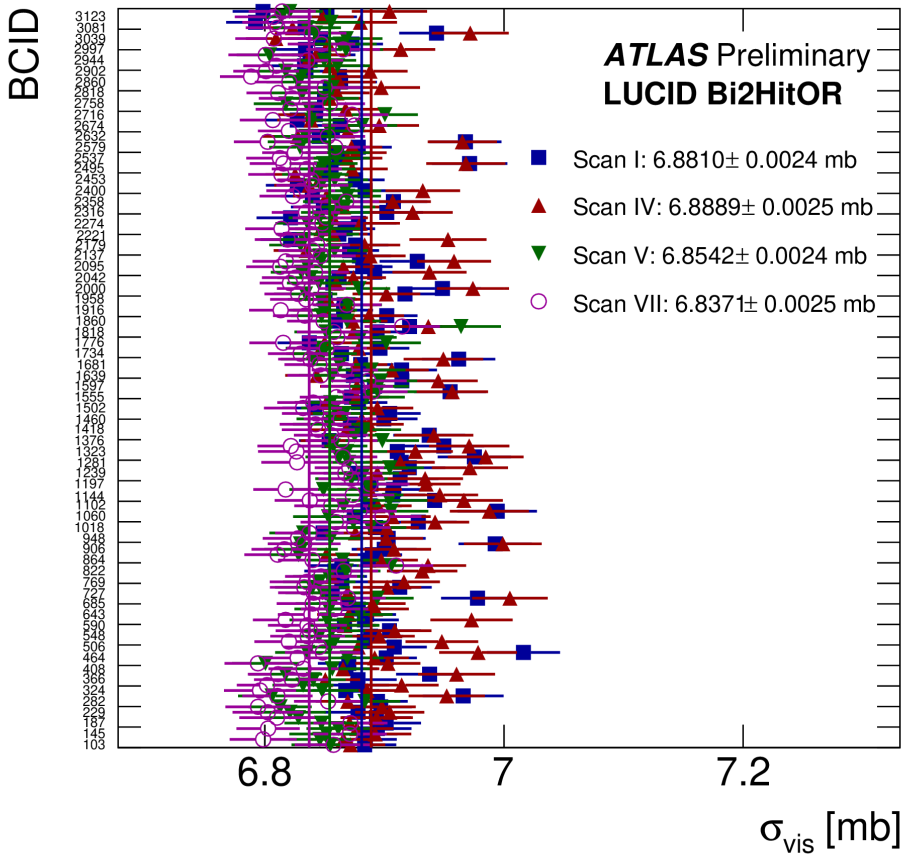

BACKUP

Convolved beam width development in the 2022 scans

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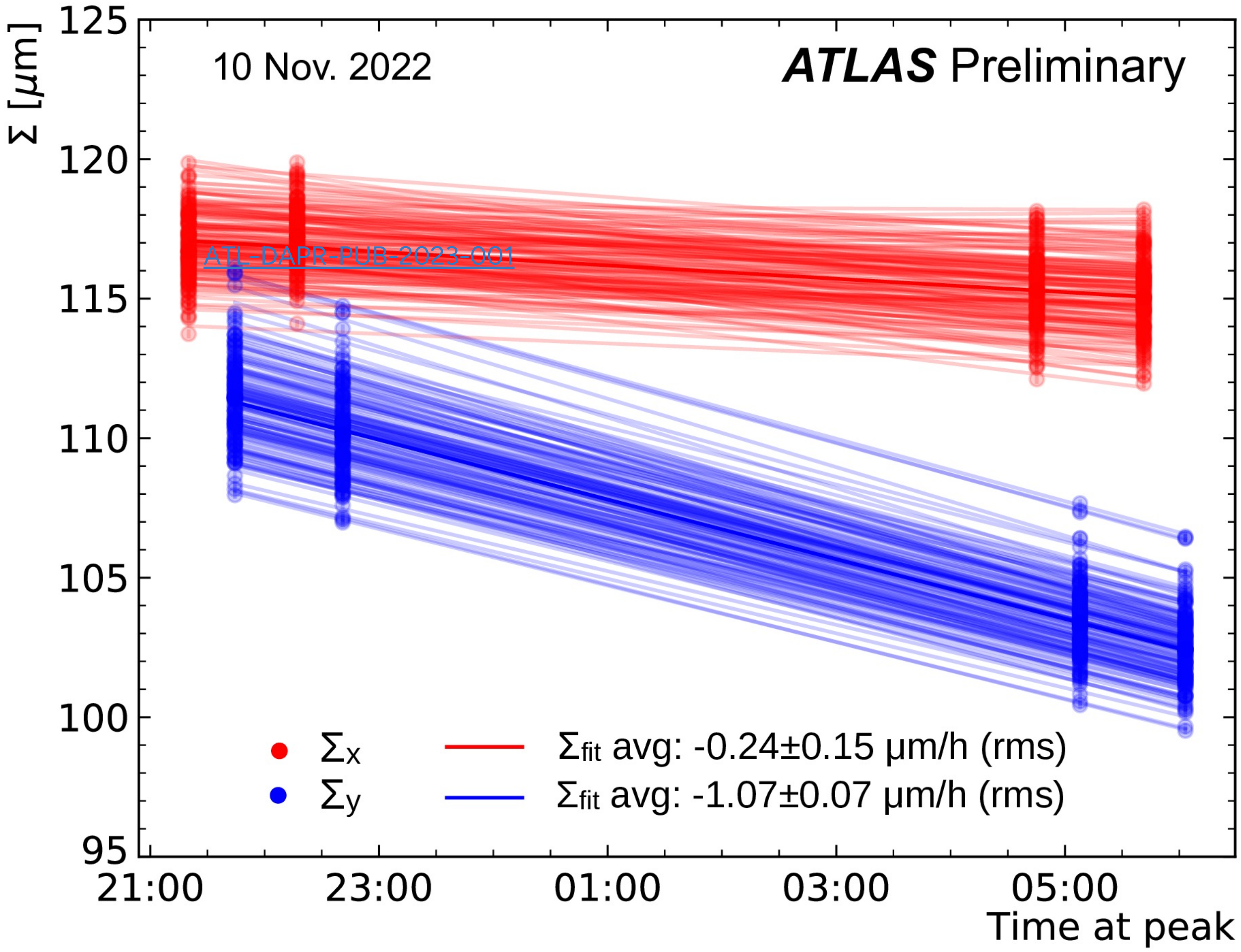
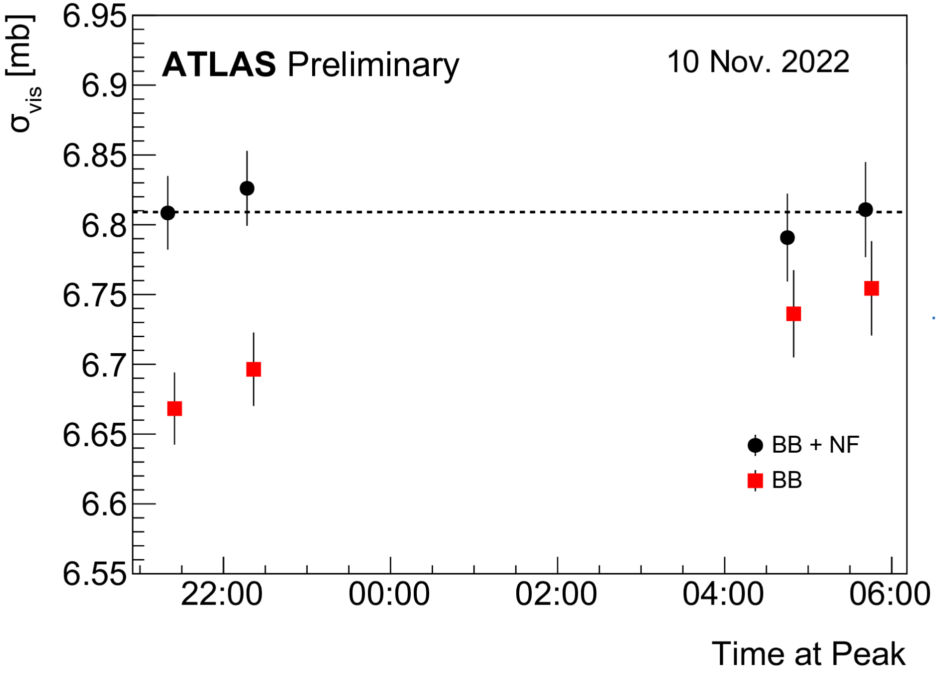
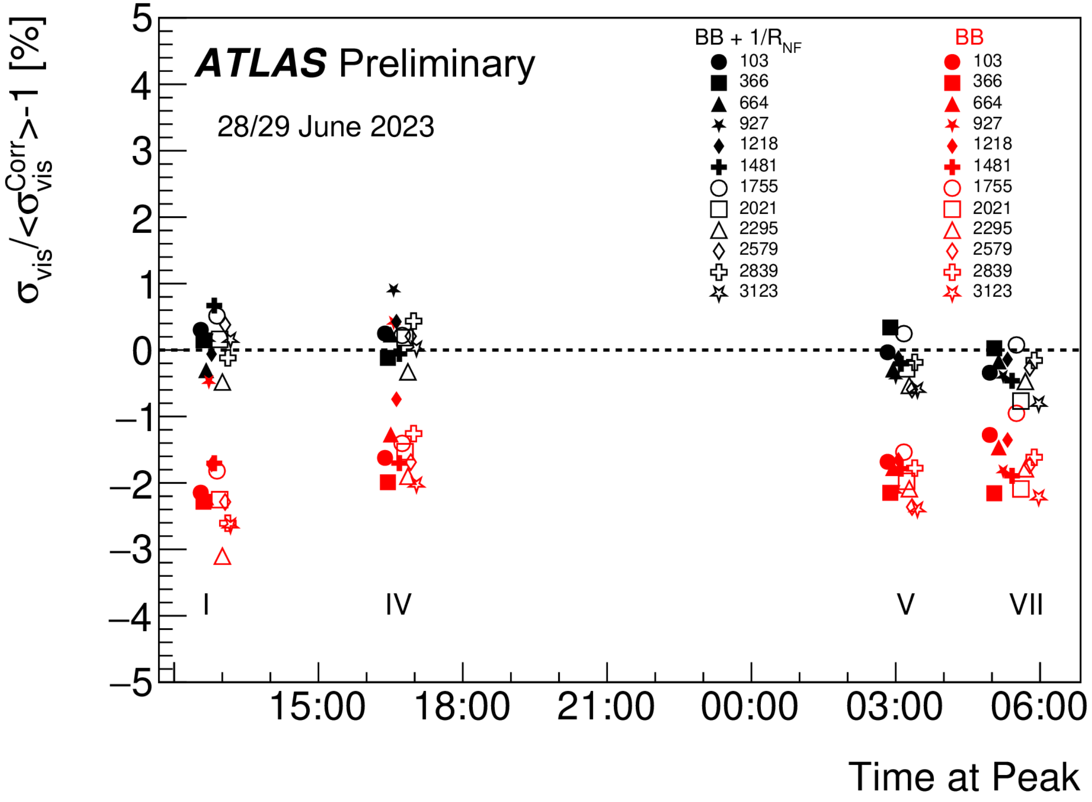


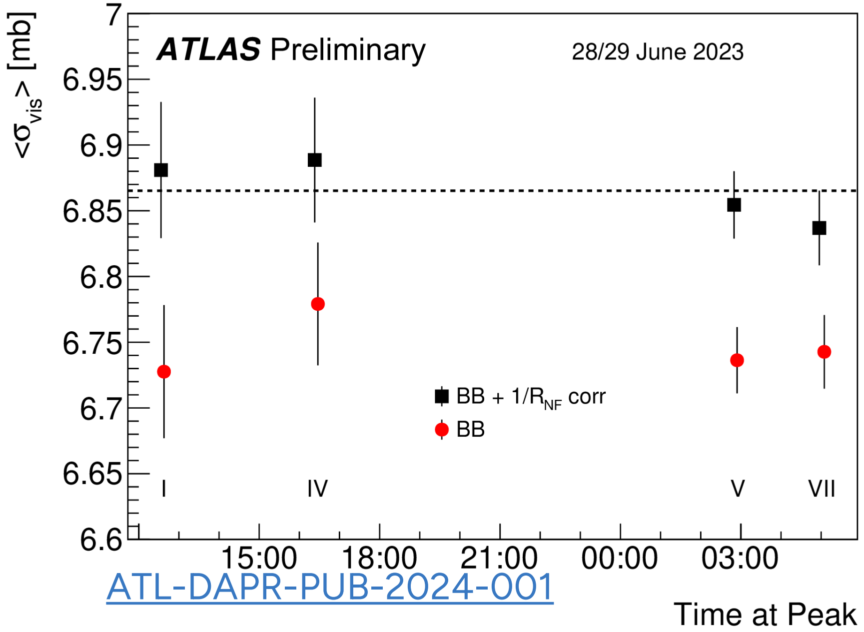
BACKUP

Sigma before and after Non-factorization correction for 2022 and 2023. For 2023 also (below) per-bunch

ATL-DAPR-PUB-2023-001



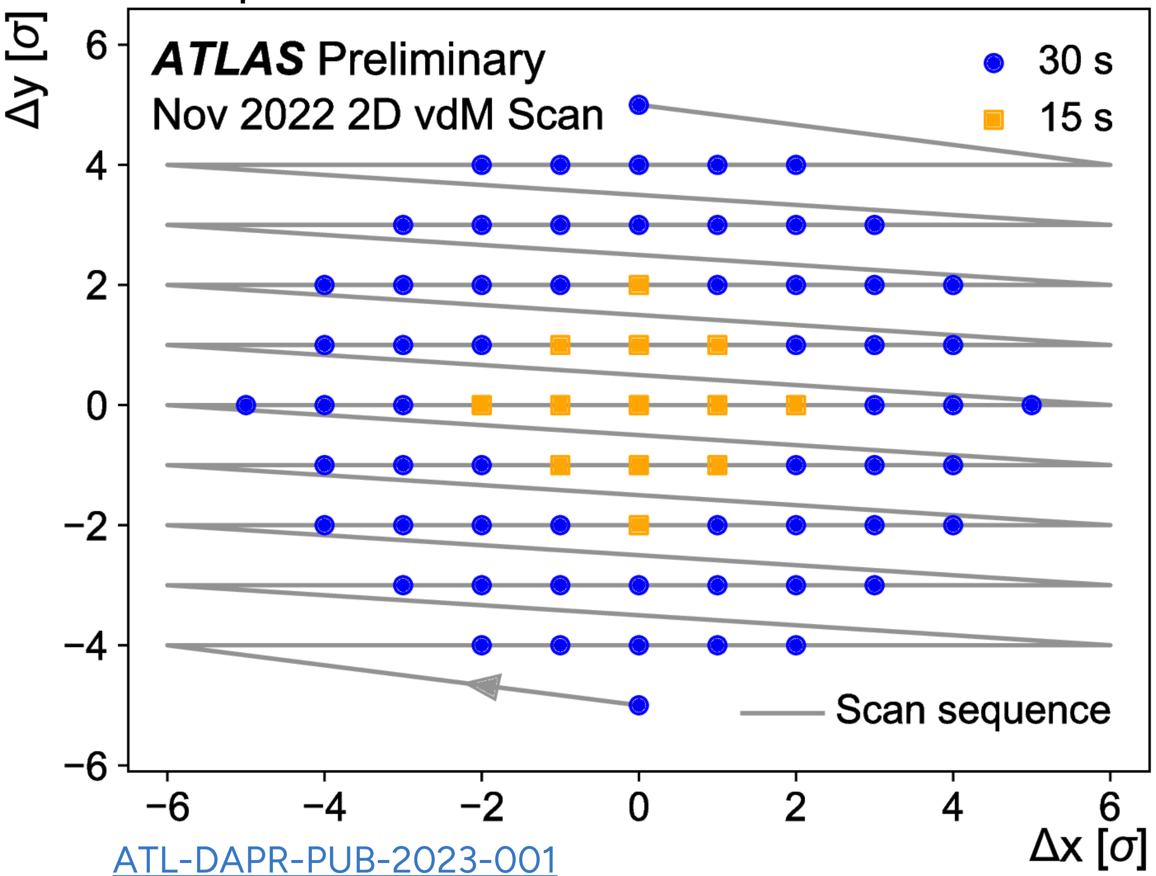




ATL-DAPR-PUB-2024-001

BACKUP

The scan pattern in 2D



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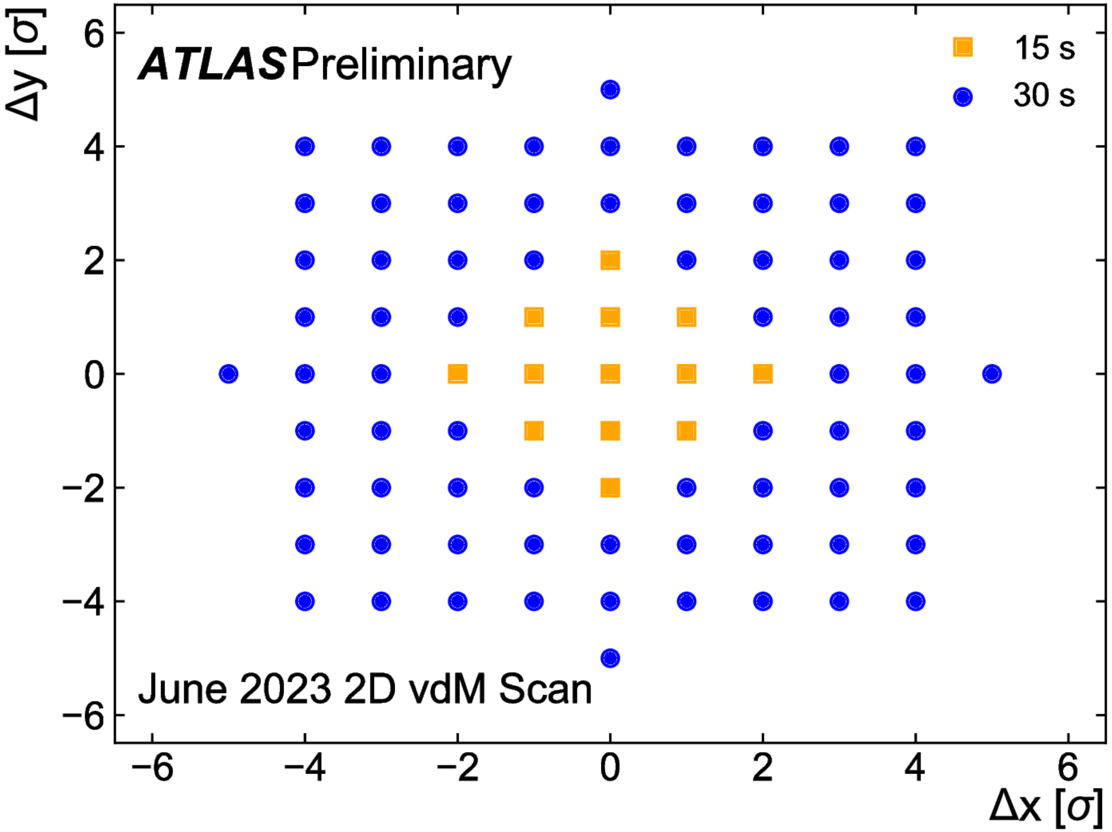
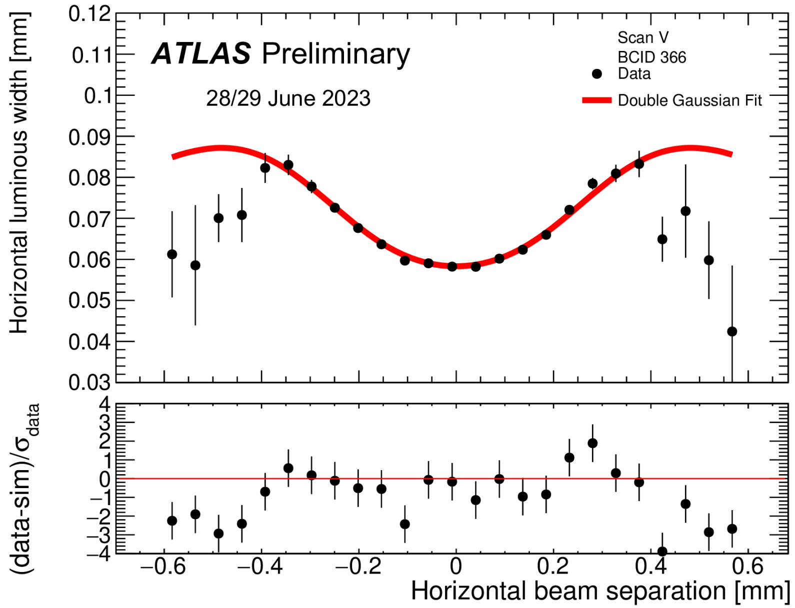
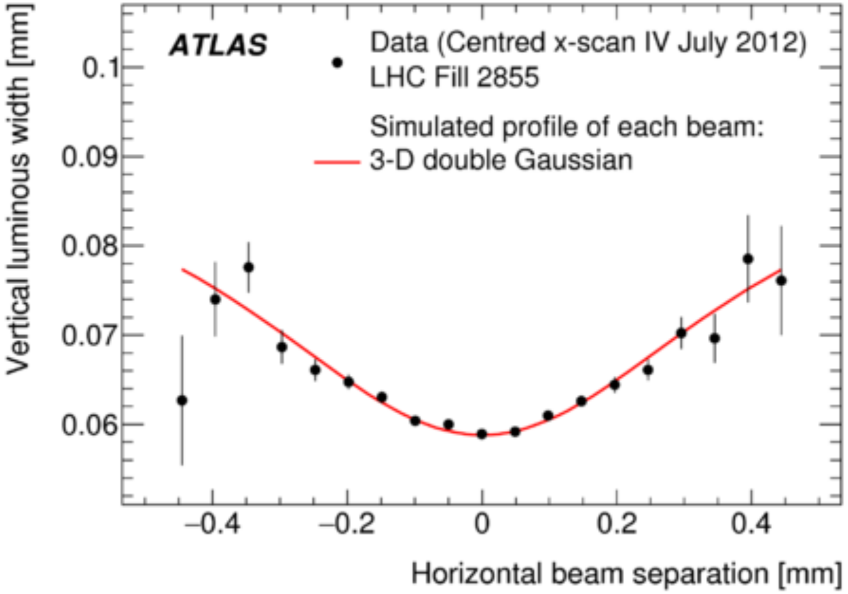


BACKUP

More on the non-factorization



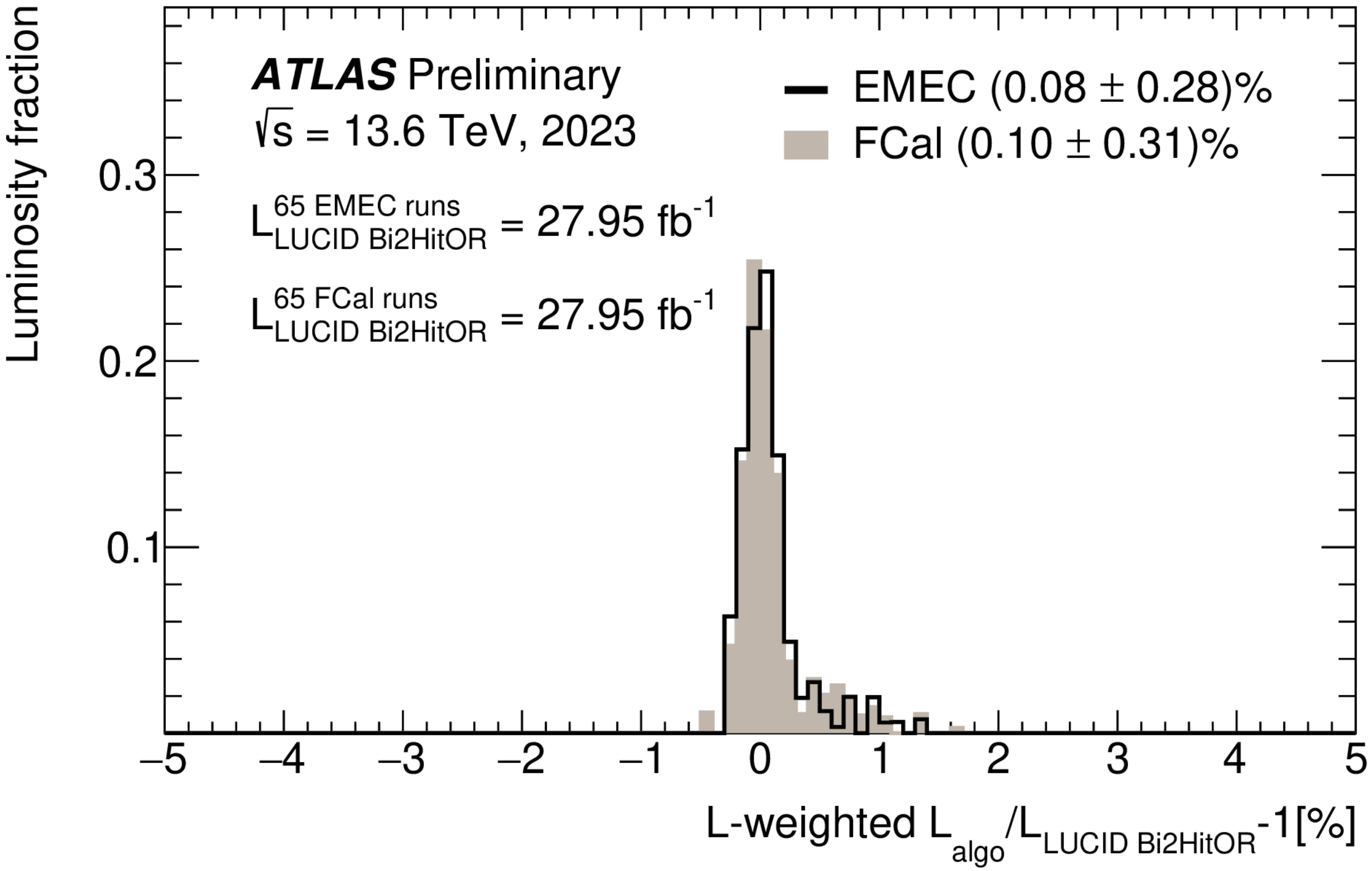
[Eur. Phys. J. C 76 (2016) 653]



[ATL-DAPR-PUB-2023-001]

BACKUP

2023 long-term stability measurement for the LAr luminometers (which again provided the uncertainty on the long-term stability



ATL-DAPR-PUB-2024-001

BACKUP

Calibration transfer uncertainties as estimated in 2022 and 2023

Note the large impact of missing laser corrections in 2022 compared to them being included in 2023

Extrapolation of luminosity calibration	**Used cell families**	**Range of shifts across used cell families**
1-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) $\rightarrow$ ($\mu \approx 40$, 1154b, trains)	A13, A14	[-0.1, 0.8]%
Alternative: 2-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) $\rightarrow$ ($\mu \approx 45$, 144b, trains)	A13, A14, E3, E4	[0.1, 0.7]%
($\mu \approx 45$, 144b, trains) $\rightarrow$ ($\mu \approx 40$, 1154b, trains) (*)	A13, A14	[0.0, 0.4]%
Combined 2-step extrapolation		[0.1, 1.1]%
Upper limit on extrapolation impact (rounded)		< 1%
Effect of missing laser corrections (linearly added)	A14	0.5%
Upper limit on total extrapolation impact		**< 1.5%**

Extrapolation of luminosity calibration	**Used cell families**	**Range of shifts across used cell families**
1-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) $\rightarrow$ ($\mu \approx 40$, 898b, trains)	E3, E4, A13, A14	[0.5, 1.1]%
Alternative: 2-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) $\rightarrow$ ($\mu \approx 60$, 140b, isolated)	E3, E4, A13, A14	[-0.7, -0.3]%
($\mu \approx 60$, 140b, isolated) $\rightarrow$ ($\mu \approx 40$, 898b, trains) (*)	E3, E4, A13, A14	[0.7, 1.3]%
Combined 2-step extrapolation		[0.0, 1.0]%
Upper limit on total extrapolation impact		**< 1.1%**

ATL-DAPR-PUB-2024-001

ATL-DAPR-PUB-2023-001

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

Data sample	2022
Uncertainty contributions [%]:	
Statistical uncertainty	0.01
Fit model	0.24
Background subtraction	0.06
FBCT bunch-by-bunch fractions	0.01
Ghost-charge and satellite bunches	0.17
DCCT calibration	0.20
Orbit-drift correction	0.06
Beam position jitter	<0.01
Non-factorisation effects	1.07
Beam–beam effects	0.35
Emittance damping correction	0.21
Length scale calibration	0.03
Inner detector length scale	0.24
Magnetic non-linearity	0.32
Bunch-by-bunch σ_{vis} consistency	0.50
Scan-to-scan reproducibility	0.27
Reference specific luminosity	0.43
Subtotal vdM calibration	1.45
Calibration transfer	1.50
Calibration anchoring	0.53
Long-term stability	0.41
Total uncertainty [%]	2.19

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%

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