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

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What is luminosity and why is it important?

How often does a process happen?

What is the cross section of the process?

cross section

$$N = \sigma \cdot L_{int}$$

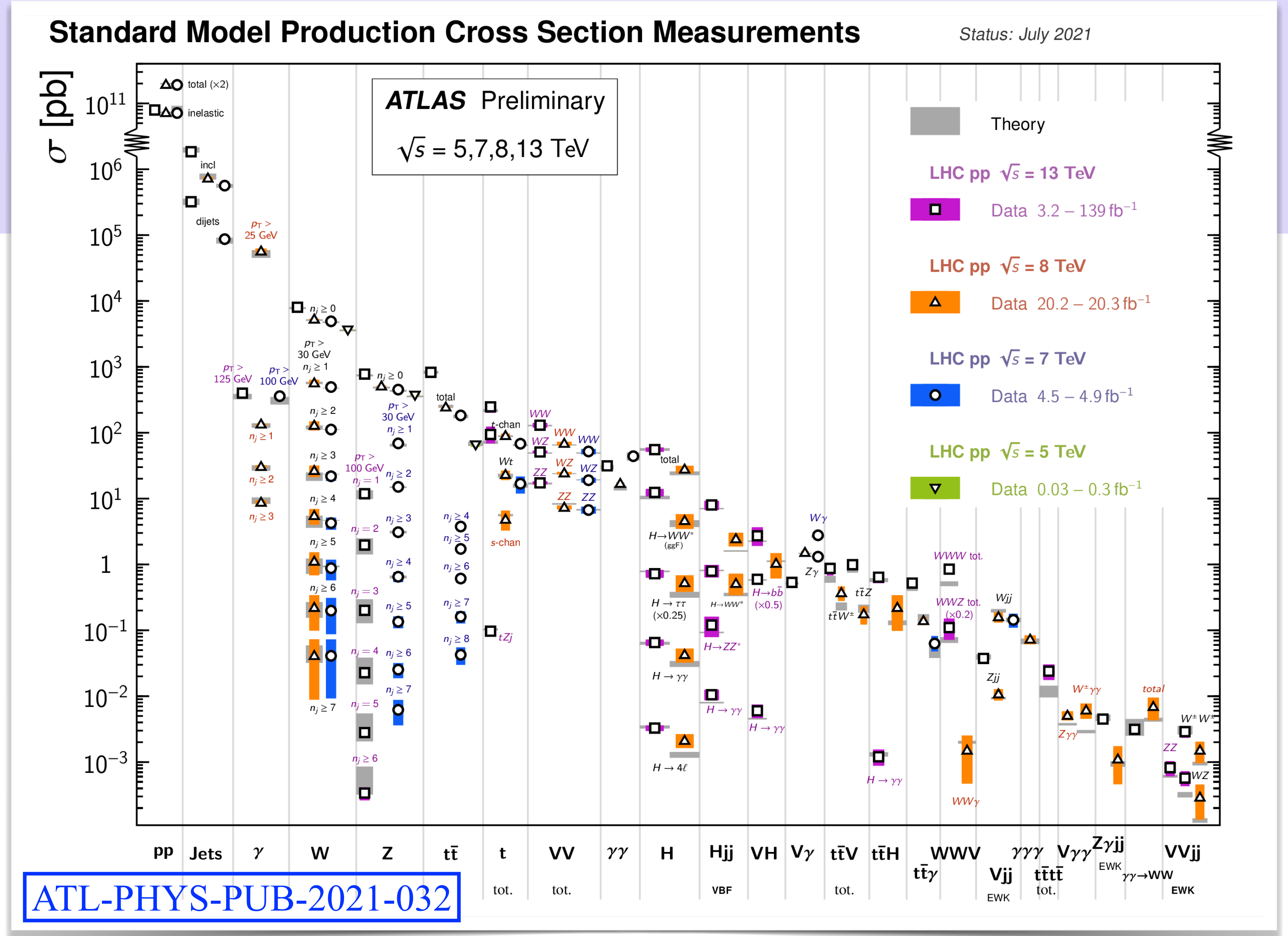
number of events *integrated luminosity*

$$\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.})\ \text{pb}$$

more precise and accurate luminosity

⇓

more precise physics measurement



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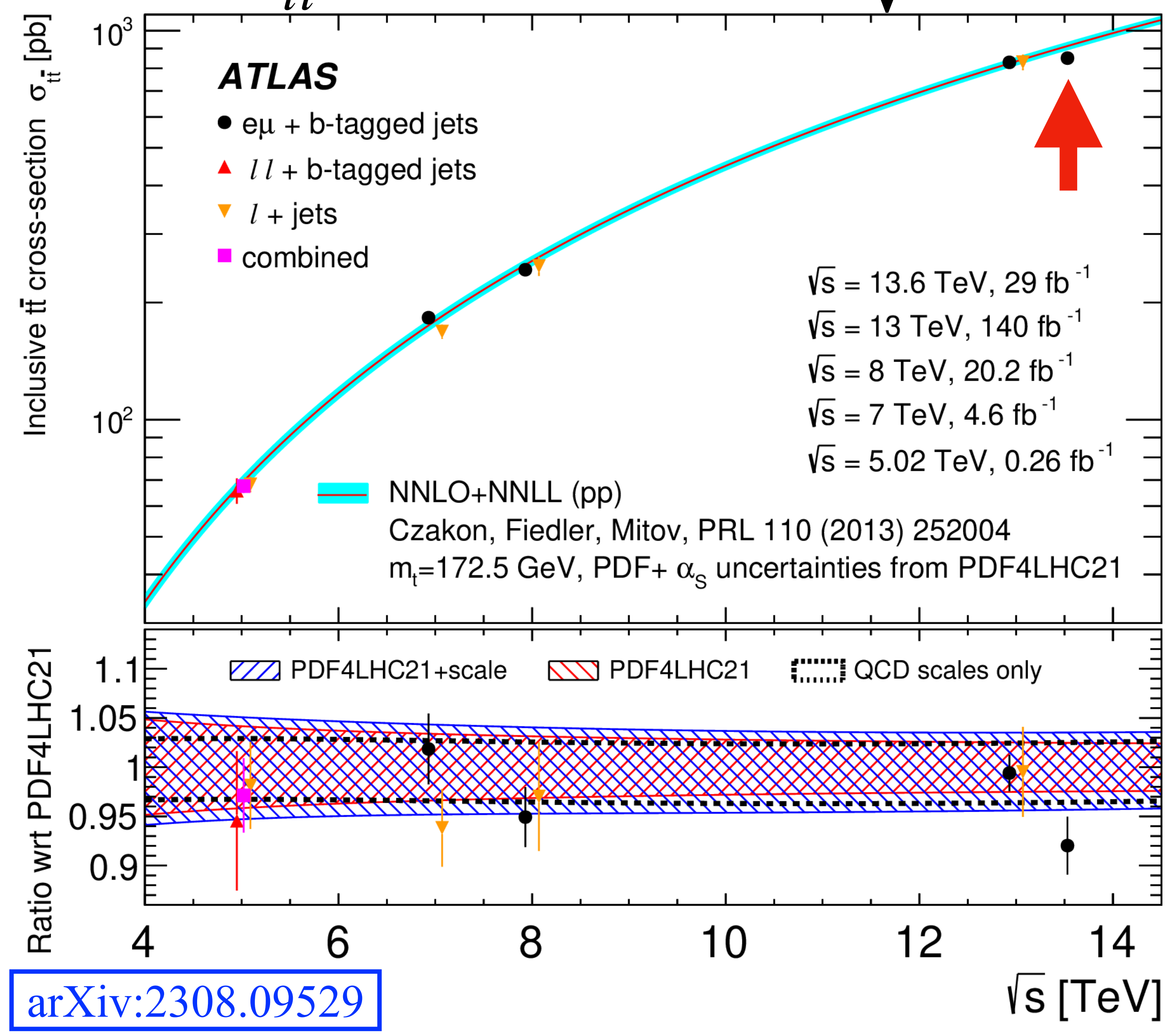
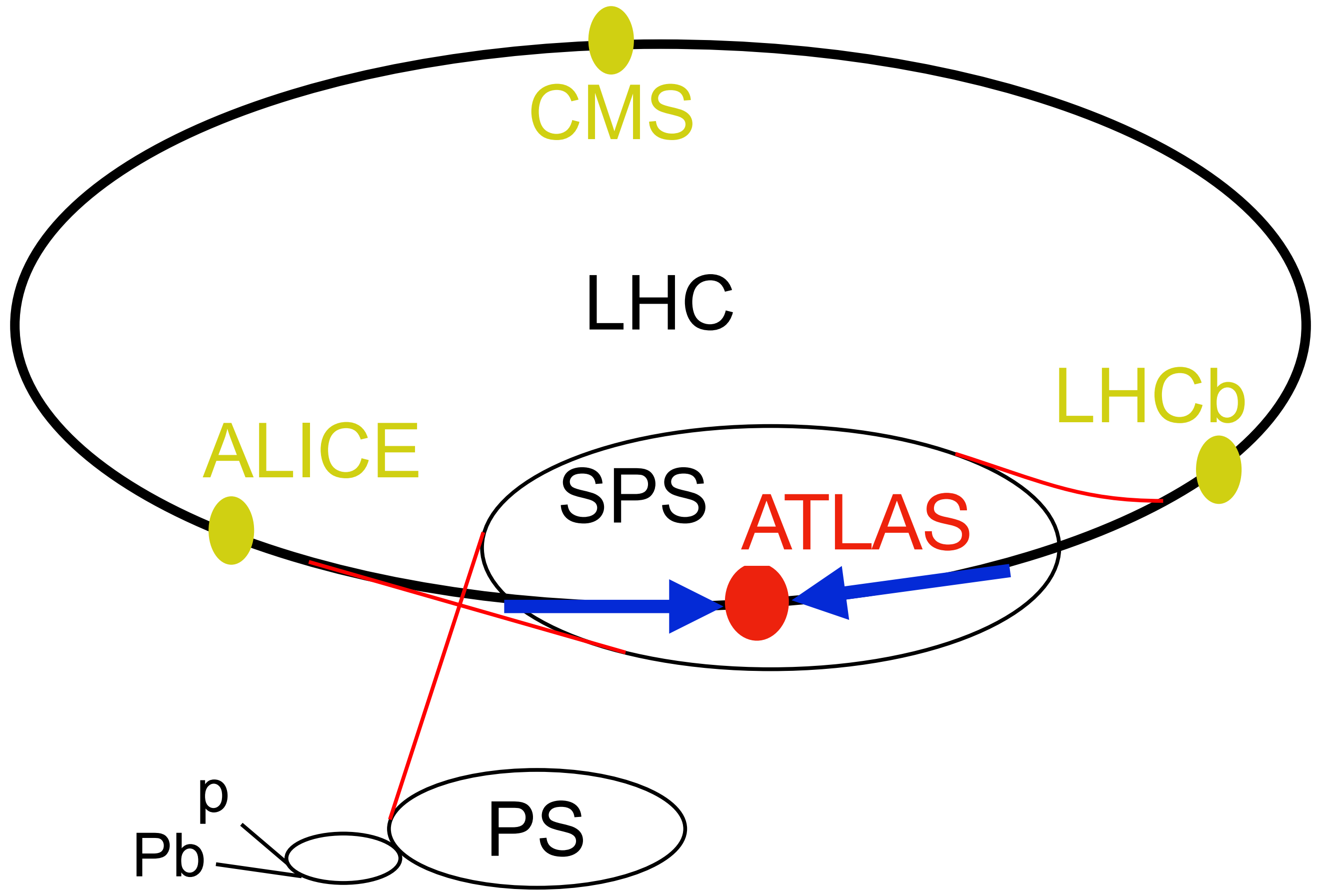
$\sigma_{t\bar{t}}$ as a function of $\sqrt{s}$



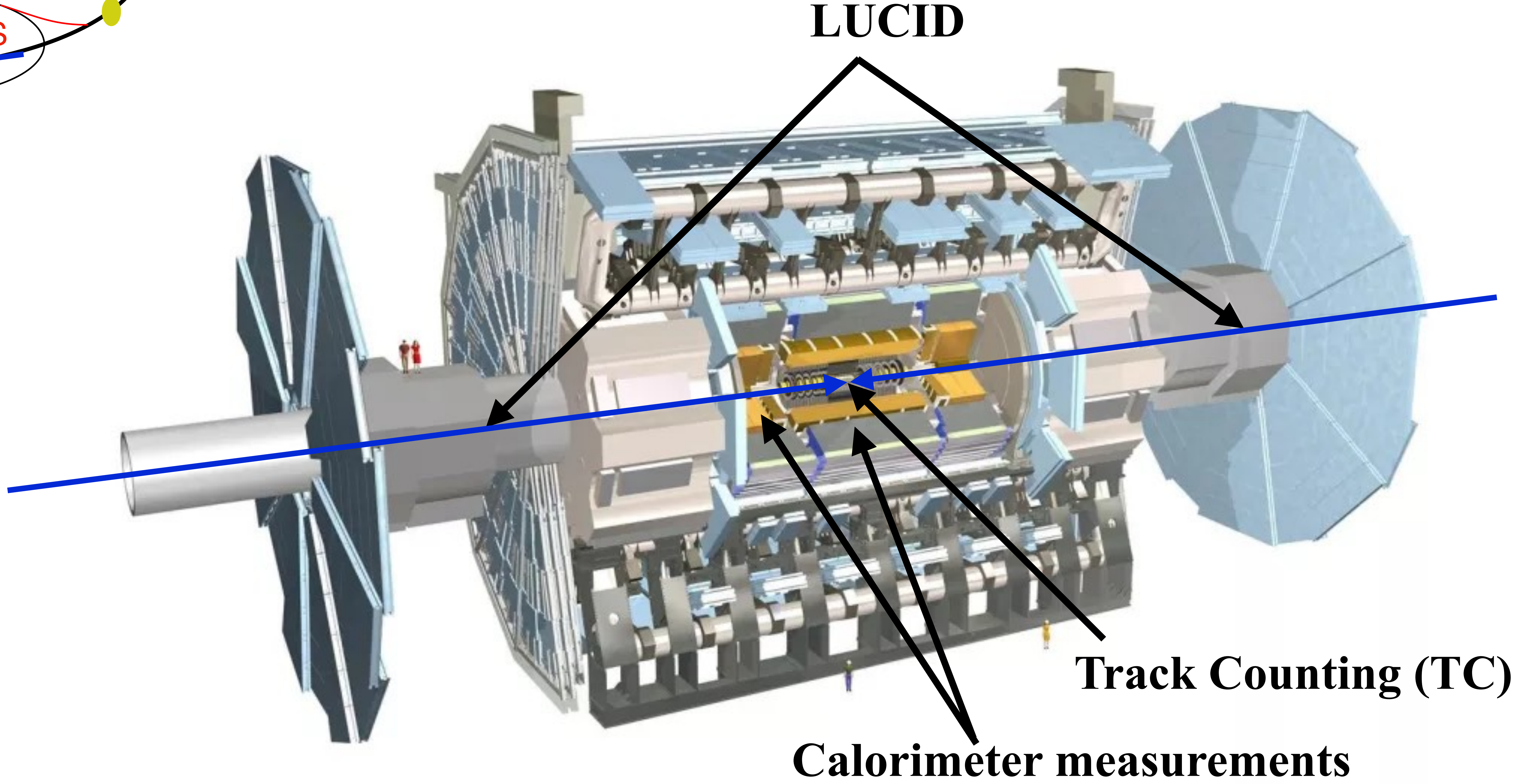
arXiv:2308.09529

Luminosity in ATLAS



How is luminosity measured in ATLAS?

Detectors measure a quantity proportional to luminosity



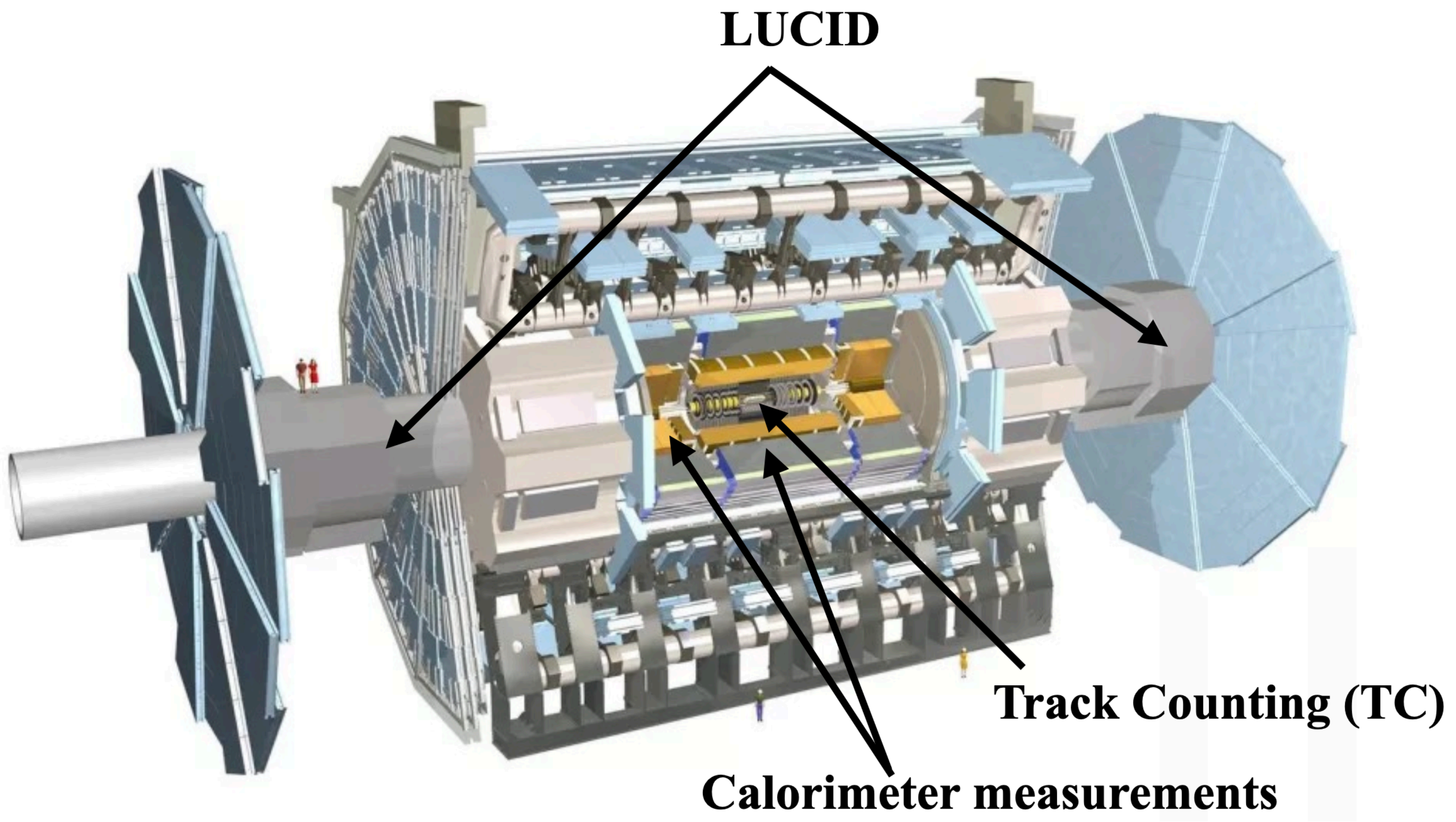
Luminosity in ATLAS

LUCID

- luminosity proportional to number of hits per bunch-crossing
- particle detection based on Cherenkov radiation
- per-bunch luminosity: yes

Track counting (TC)

- Inner Detector: luminosity proportional to the number of tracks per bunch-crossing
- per-bunch luminosity: yes but statistically limited



Calorimeter measurements

- LAr (ECAL and FCAL): luminosity proportional to total ionisation current
- Tile calorimeter: luminosity proportional to current drawn by PMT
- per-bunch luminosity: no, only bunch-integrated

Luminosity determination in 3 steps

Run 2 luminosity paper:
arXiv:2212.09379

Step 1 - Absolute luminosity calibration

van der Meer scans in special conditions

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Step 2 - Calibration transfer

calibration transfer from vdM conditions to physics conditions

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Step 3 - Long term stability

stability of the calibration over time

Step 1 - Absolute luminosity calibration

Absolute luminosity calibration

LUCID measures

we know

$$L = \frac{\mu_{vis} f_r}{\sigma_{vis}}$$

constant we need to find

L = instantaneous luminosity

f_r *= revolution frequency at LHC = 11.245 kHz*

μ_{vis} *= visible interaction rate of a given algorithms/luminometer*

σ_{vis} *= visible pp cross section of that algorithm/luminometer*

+

measure with LHC instrumentation

we know

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

from van der Meer analysis !!!

n_i *= number of protons in the bunch of beam i*

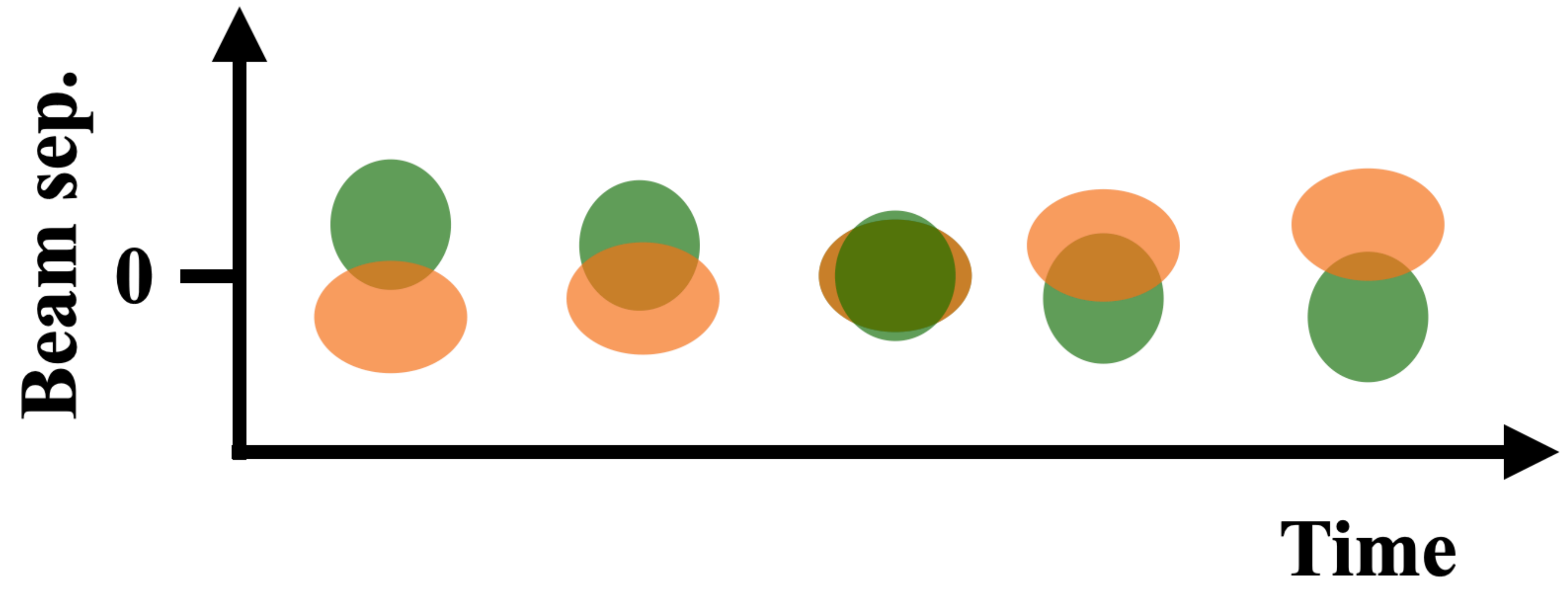
Σ_k *= convolved beam width in plane k*

=

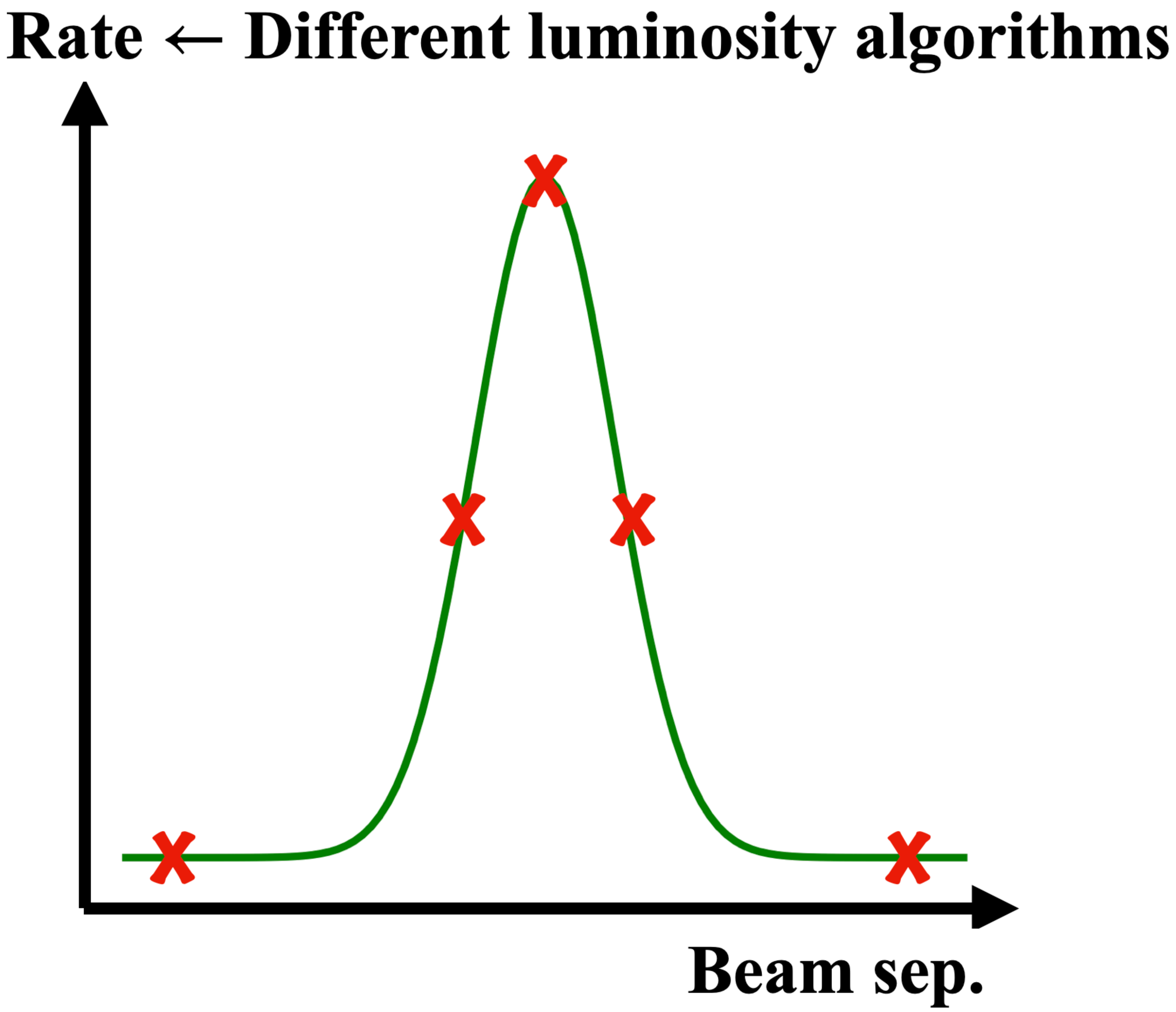
$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y \mu_{vis}}{n_1 n_2 f_r}$$

What are van der Meer scans?

A van der Meer scan is a transverse scan of beams through each other performed in special runs



Special conditions: isolated low intensity bunches, low pileup, small number of bunches, no crossing angle



Interaction rates are measured at different separation of the beams

What are van der Meer scans?

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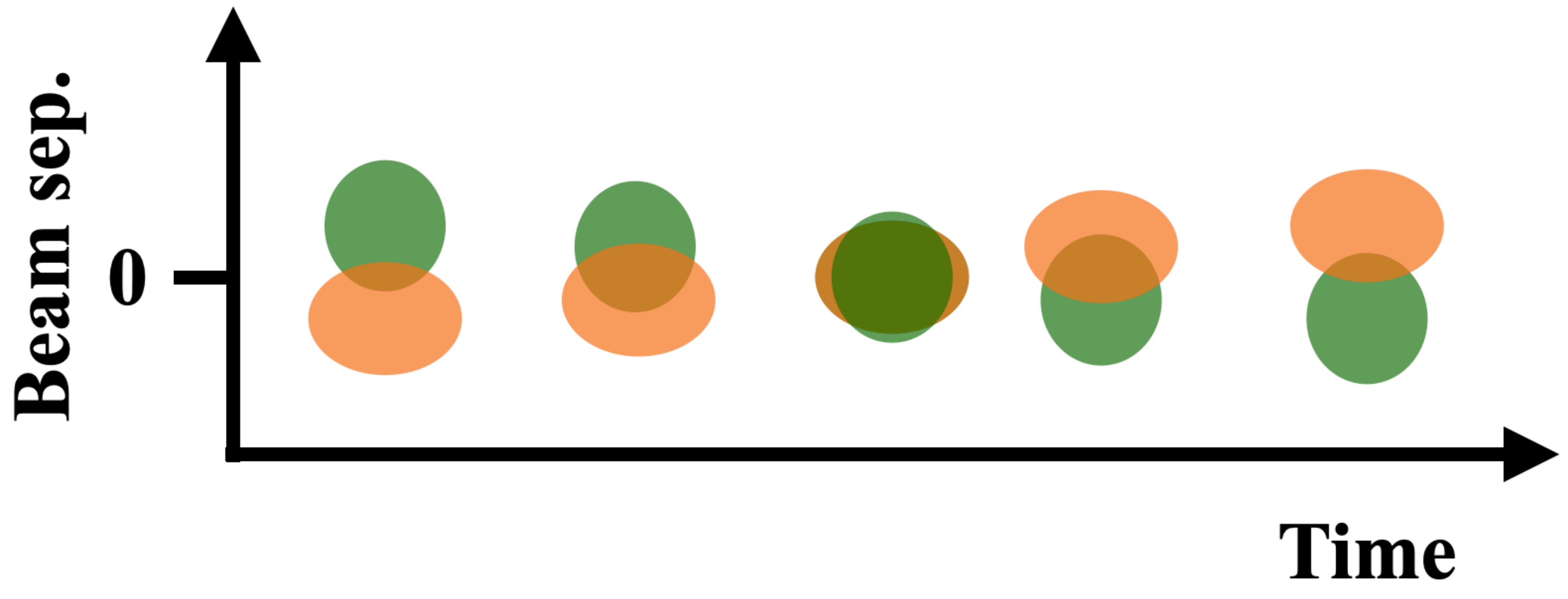

Special conditions: isolated low intensity bunches, low pileup, small number of bunches, no crossing angle

Real scan curve

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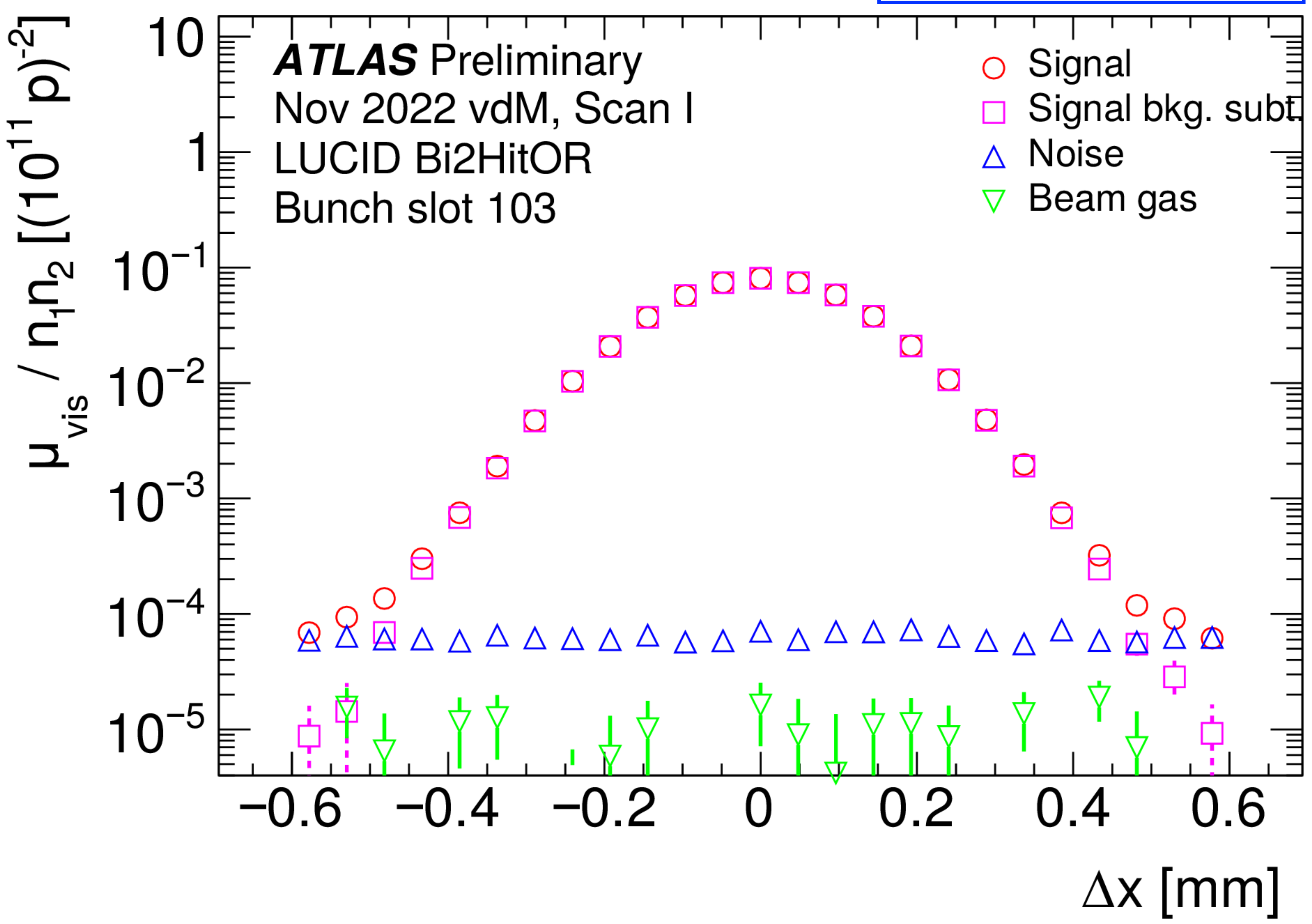


How to calibrate the absolute luminosity?

Rates and beam-beam separations need to be corrected for several effects before extracting a precise σ_{vis}

vdM methodology assumes that the beams are factorisable in x and y plane:

$$\mu_{vis}(x, y) = \mu_{vis}(x)\mu_{vis}(y)$$

plot rate vs separation

⇓

make a fit

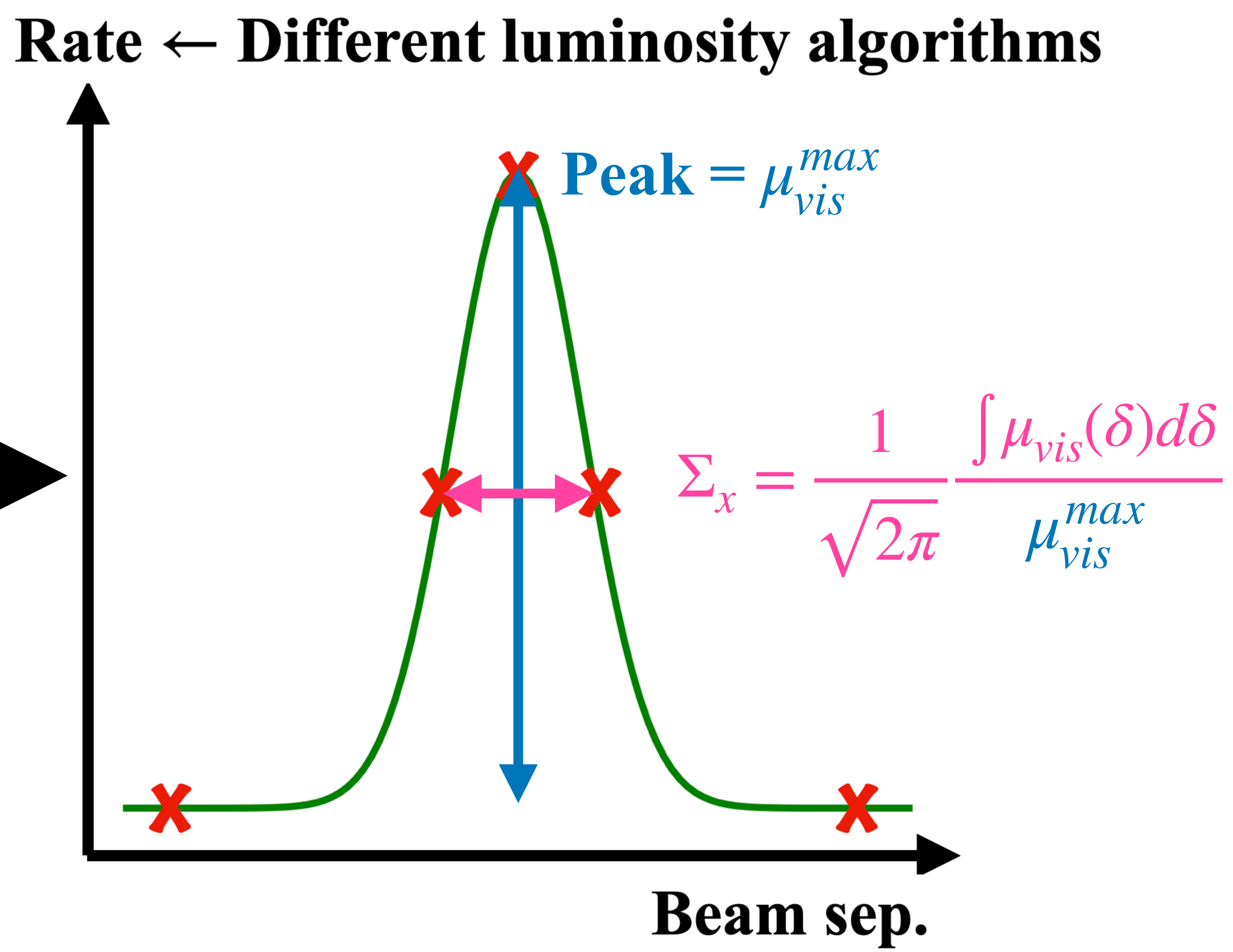
⇓

extract Σ_x, Σ_y and μ_{vis}^{max}

⇓

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

⟷

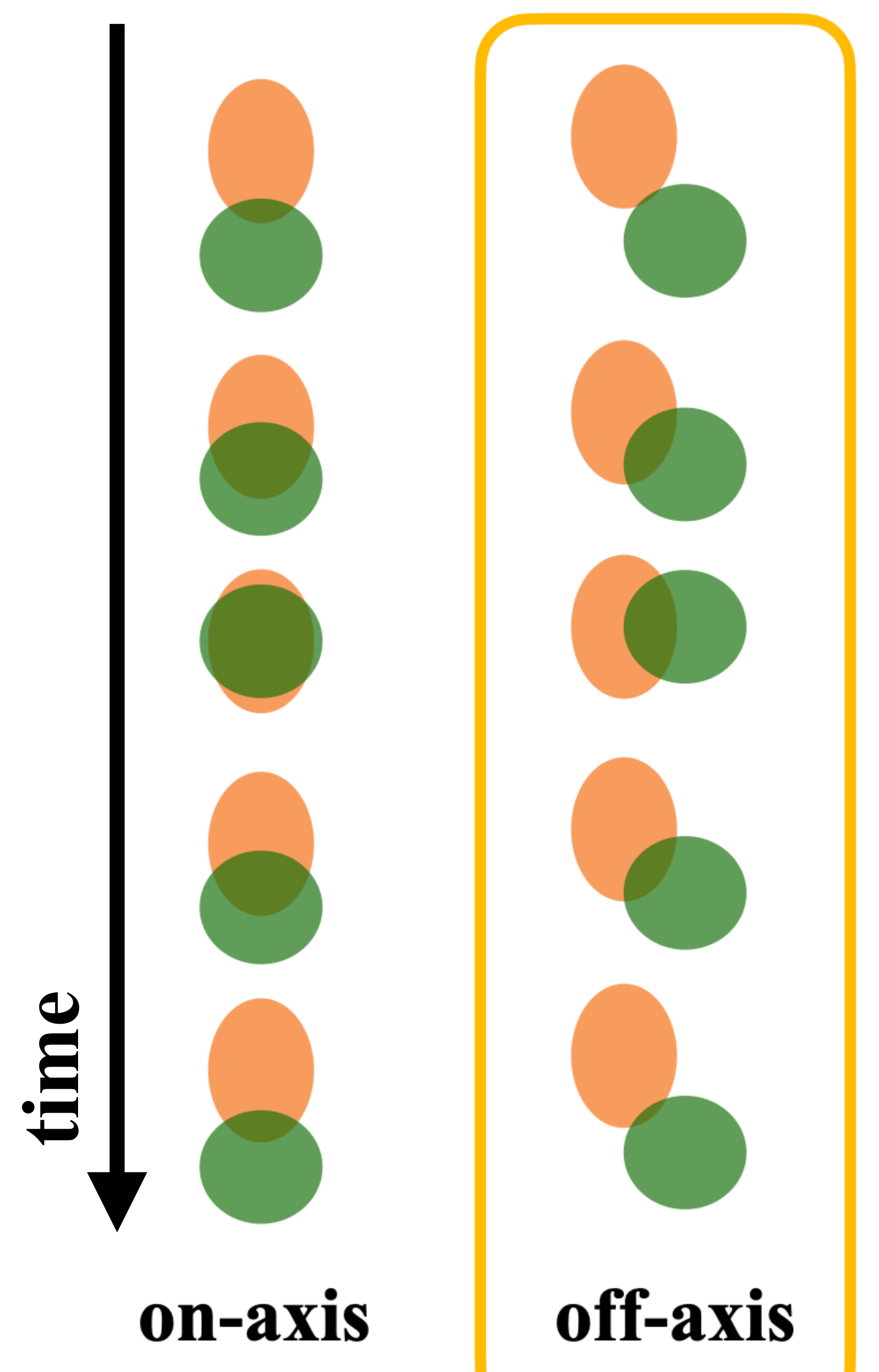


van der Meer scans - corrections

- Non-factorisation correction
- Length Scale Calibration correction
- Beam-Beam corrections
- Ghost and satellite charge corrections
- Background subtraction
- Orbit Drift Correction
- Emittance growth correction
- Bunch current offset

↑ **Size of the correction in 2022**

van der Meer scans - non-factorisation effects



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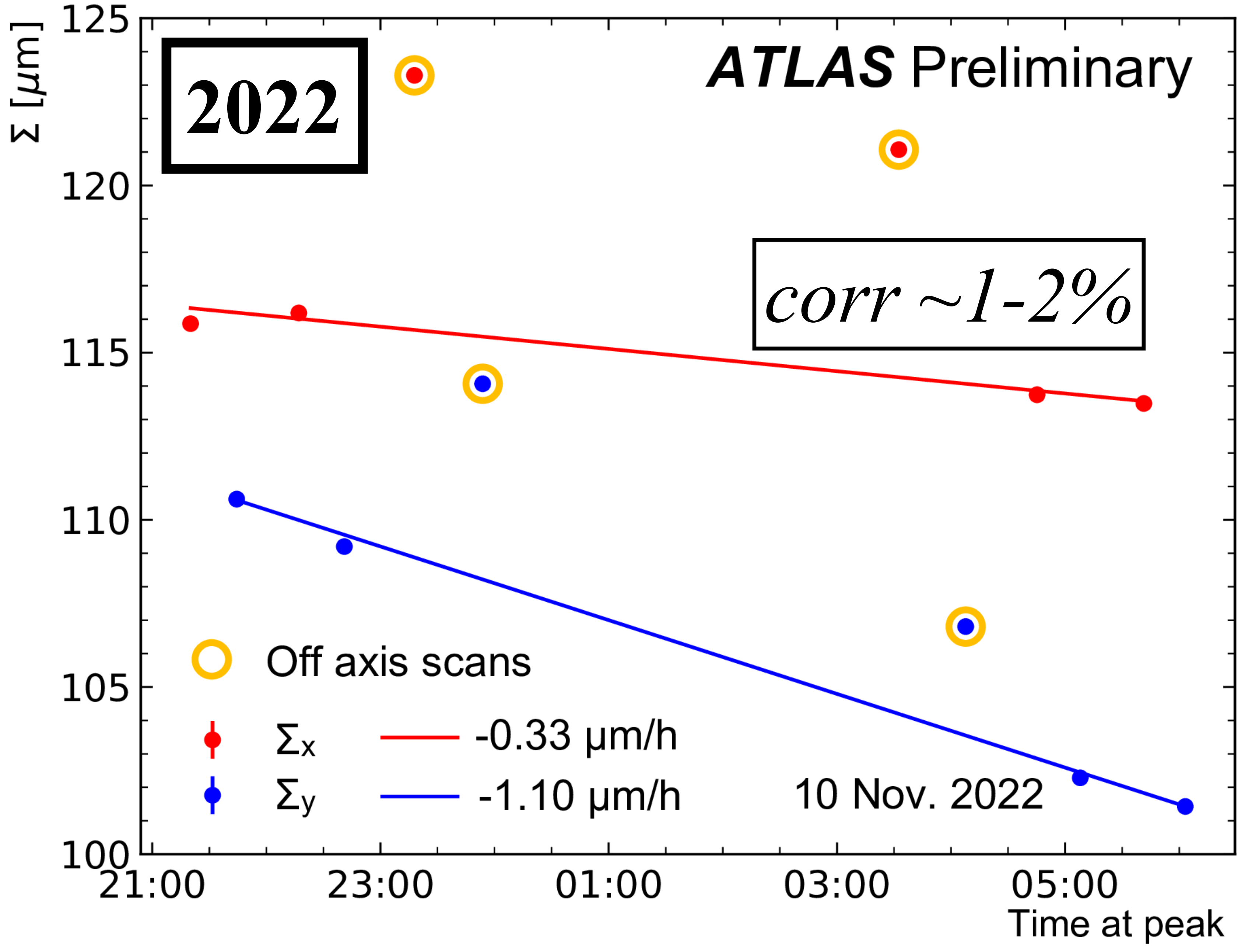
2022: Significant non-factorisation



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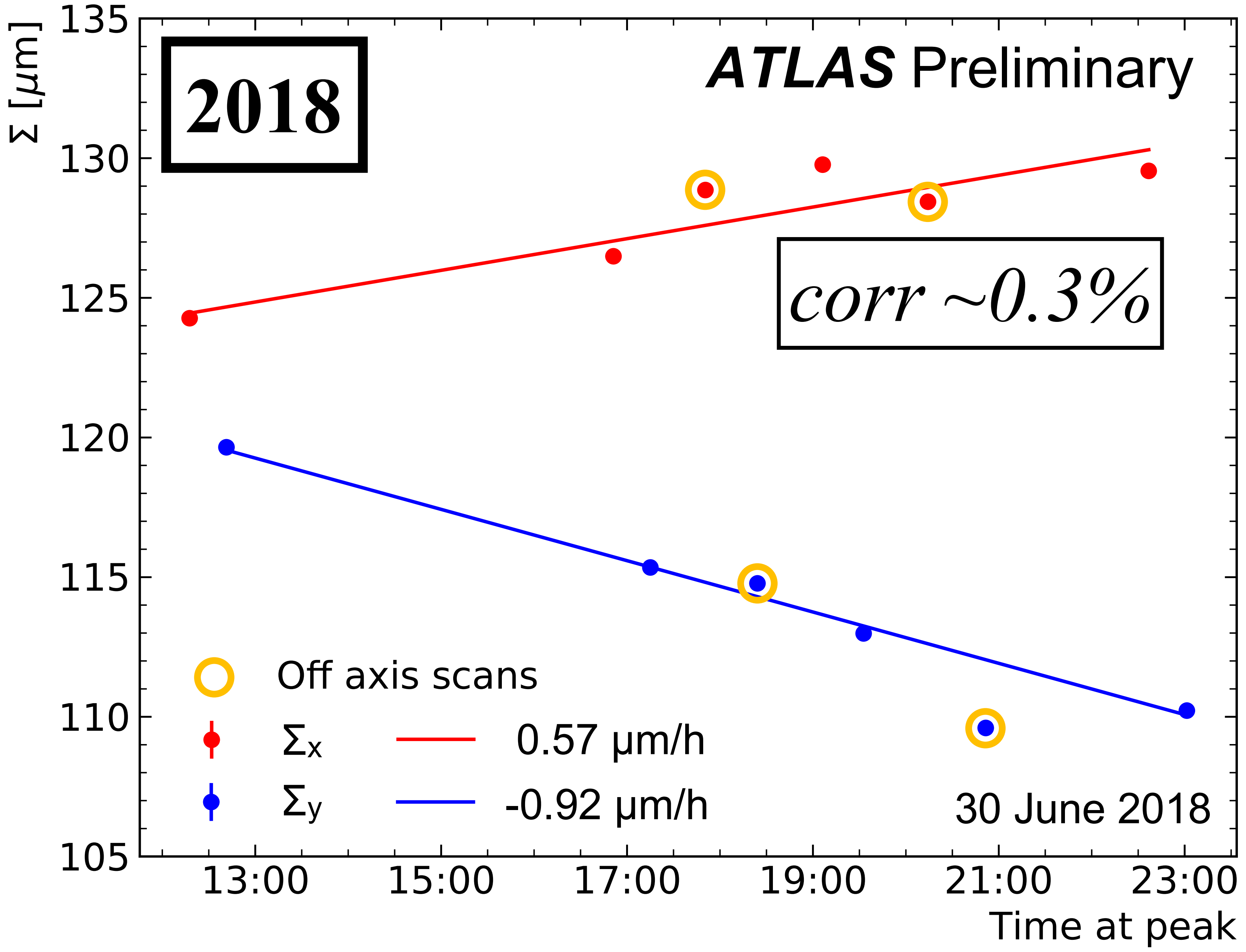
2018: Little non-factorisation



A hint of how big the non-factorisation effects are can be obtained by comparing the off-axis scans with the on-axis scans

Preliminary van der Meer scan uncertainty 2022

Dominant systematic uncertainties to the van der Meer analysis for 2022

Preliminary

Non-factorisation effects	1.1%
Bunch-by-bunch consistency	0.5%
Differences between algorithms	0.4%
Other contributions < 0.4%	0.7%
Subtotal vdM calibration	**1.5%**

Non-factorisation is also the dominant systematic uncertainty!

Step 2 - Calibration transfer

Calibration transfer

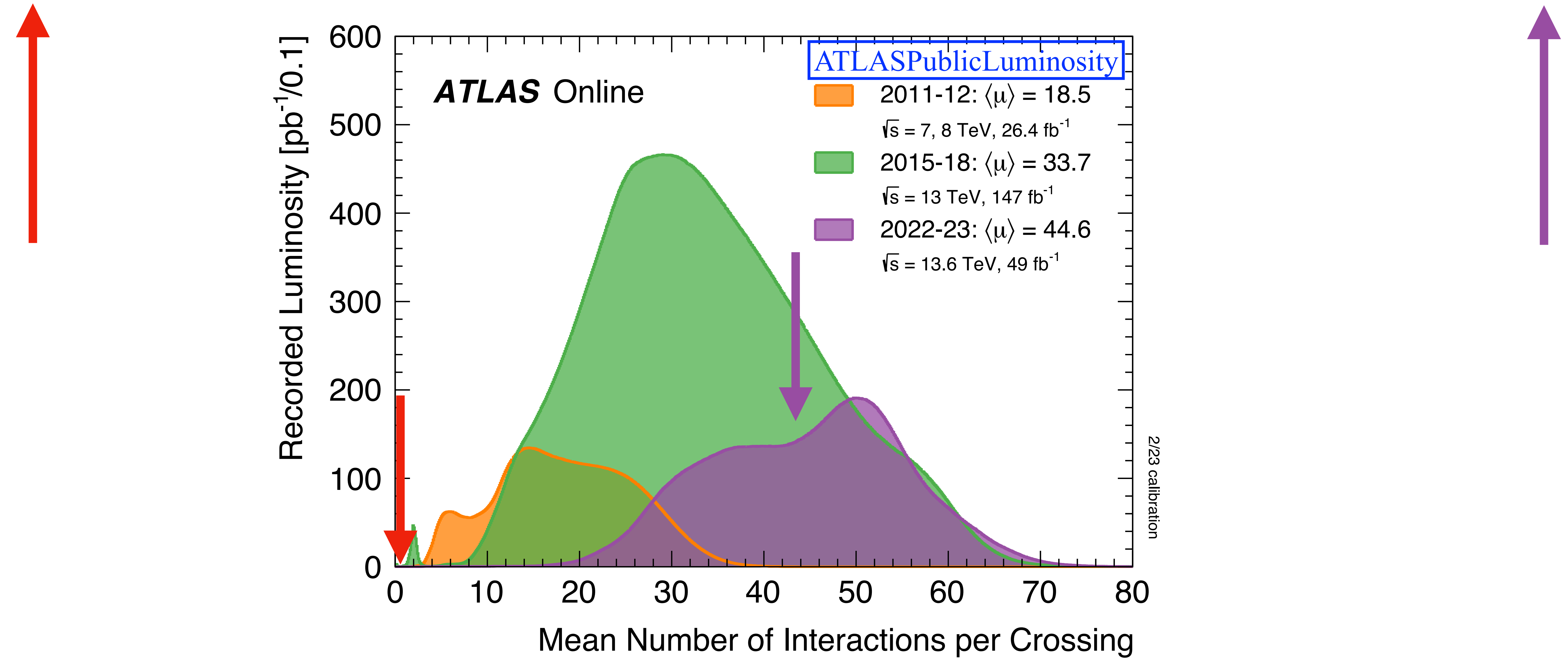
van der Meer scan conditions

- isolated low intensity bunches
  - low pileup
  - small number of bunches
- no crossing angle

calibration transfer →

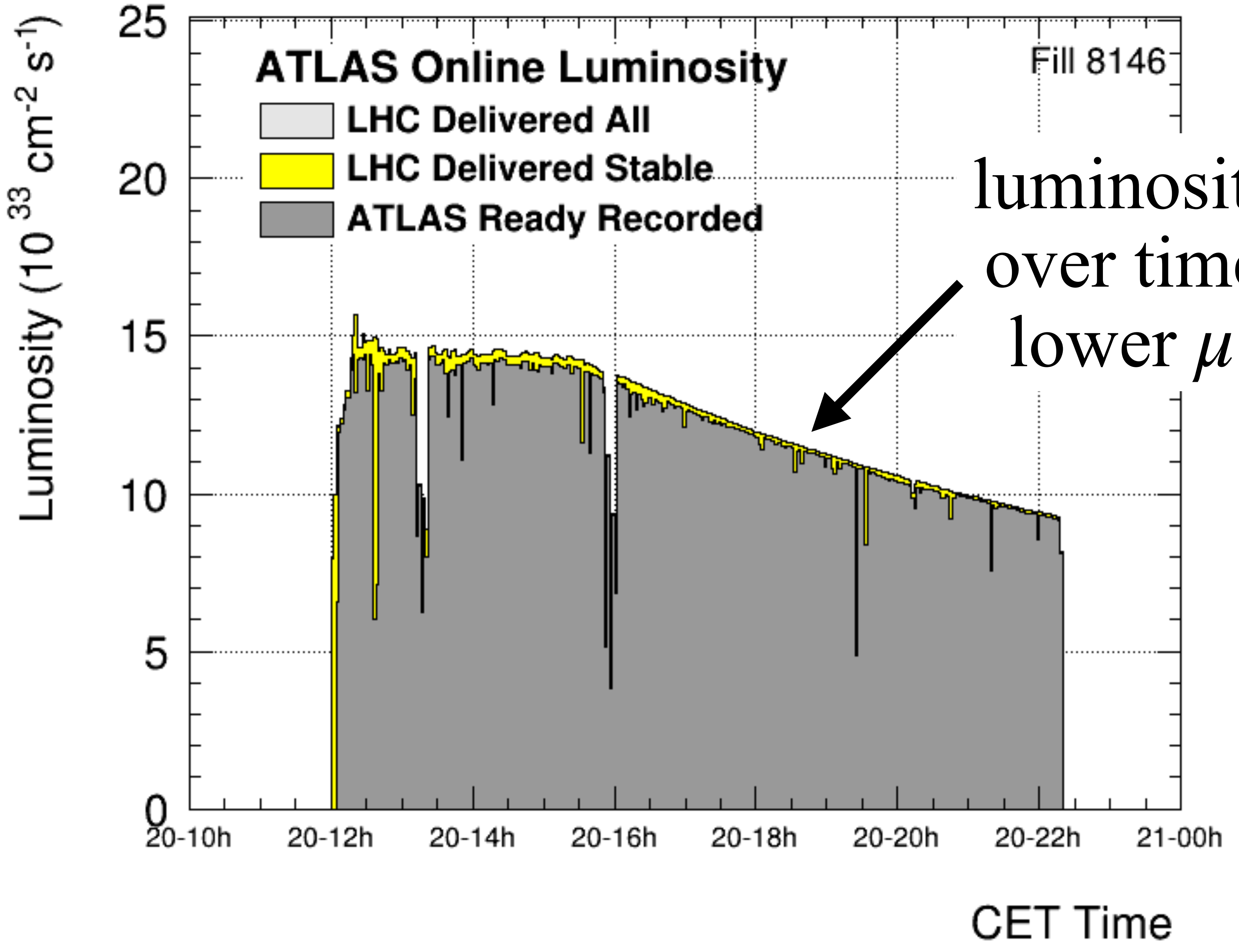
physics conditions

- trains of high intensity bunches
  - high pileup
  - high number of bunches
- with crossing angle

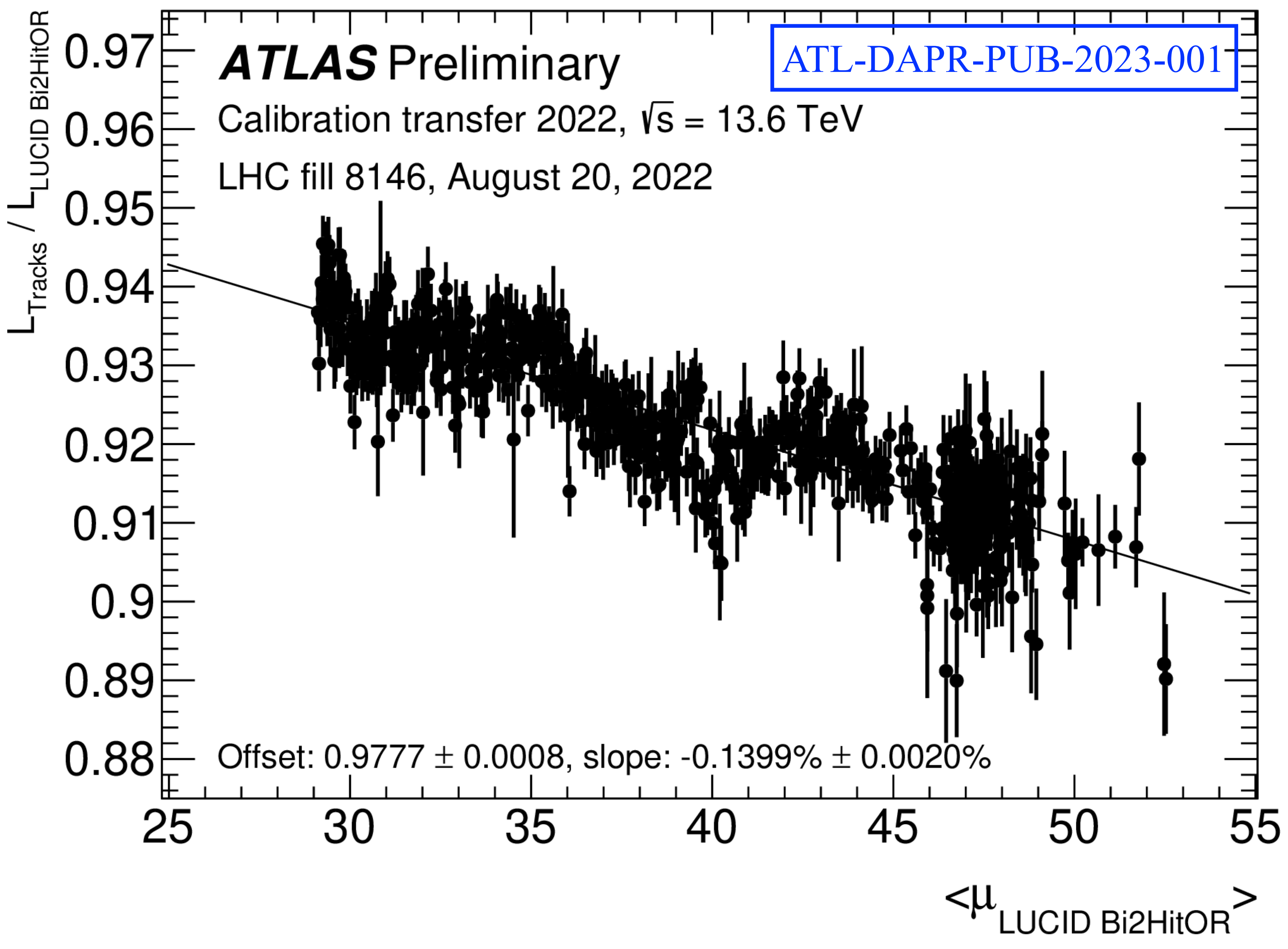


Calibration transfer

- Track-counting is calibrated to LUCID luminosity during vdM quiet periods
- Assumption: track-counting is perfectly linear from vdM conditions to high μ physics regime
- Long physics runs with large μ range (~30-60) are used
- LUCID is corrected for each run and each luminosity block (LB) in the run



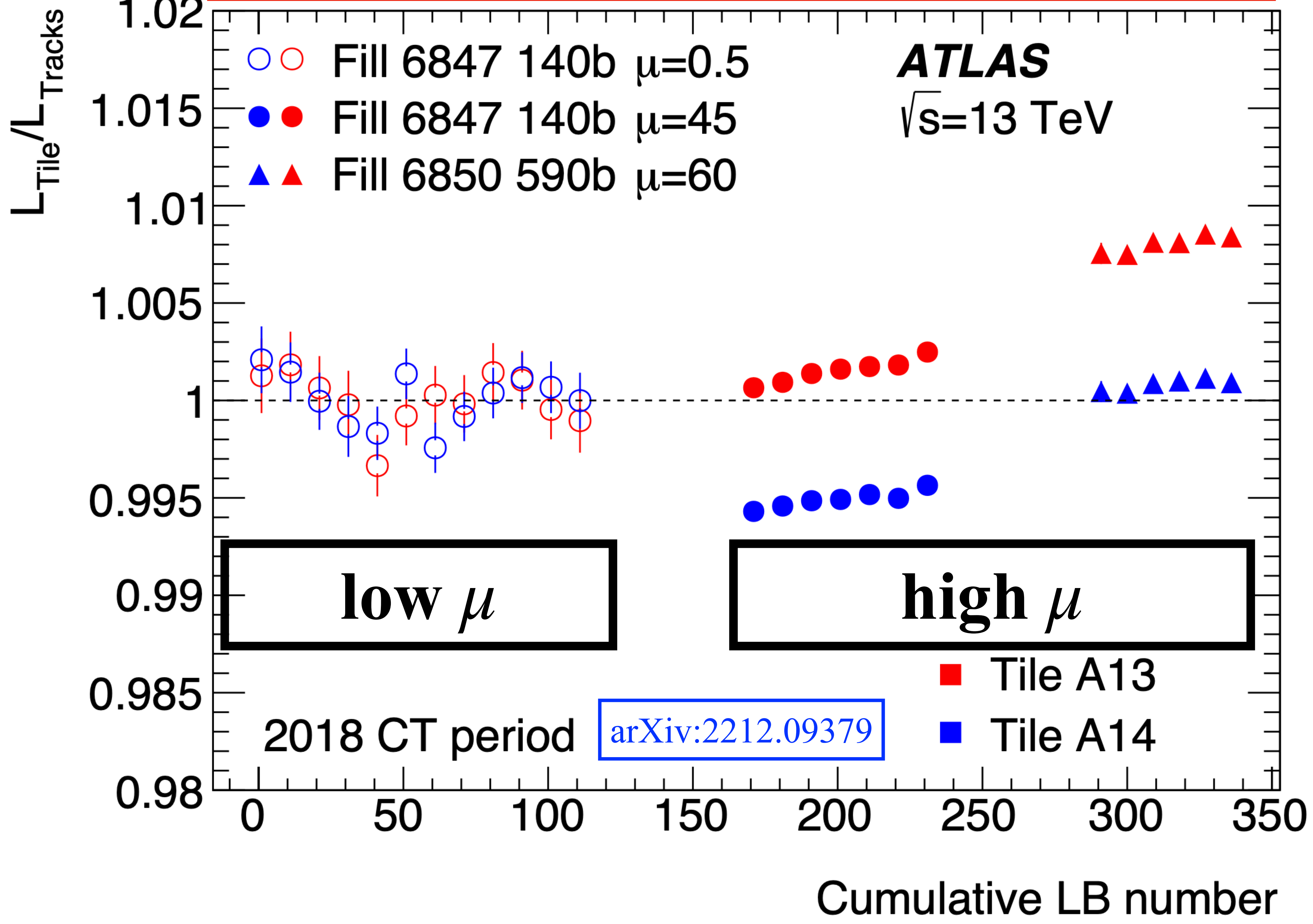
luminosity decay over time due to lower μ values



Calibration transfer uncertainty

- Assumption: track-counting is perfectly linear from vdM conditions to high μ physics regime
- Assumption cross-checked with calorimeter measurements
- Calibration transfer uncertainty: deviation from this assumption
- Very preliminary calibration transfer uncertainty for 2022: 1.50%

Example from Run 2



*Example of track-counting calorimeter check for **Run 2***

Step 3 - Long term stability

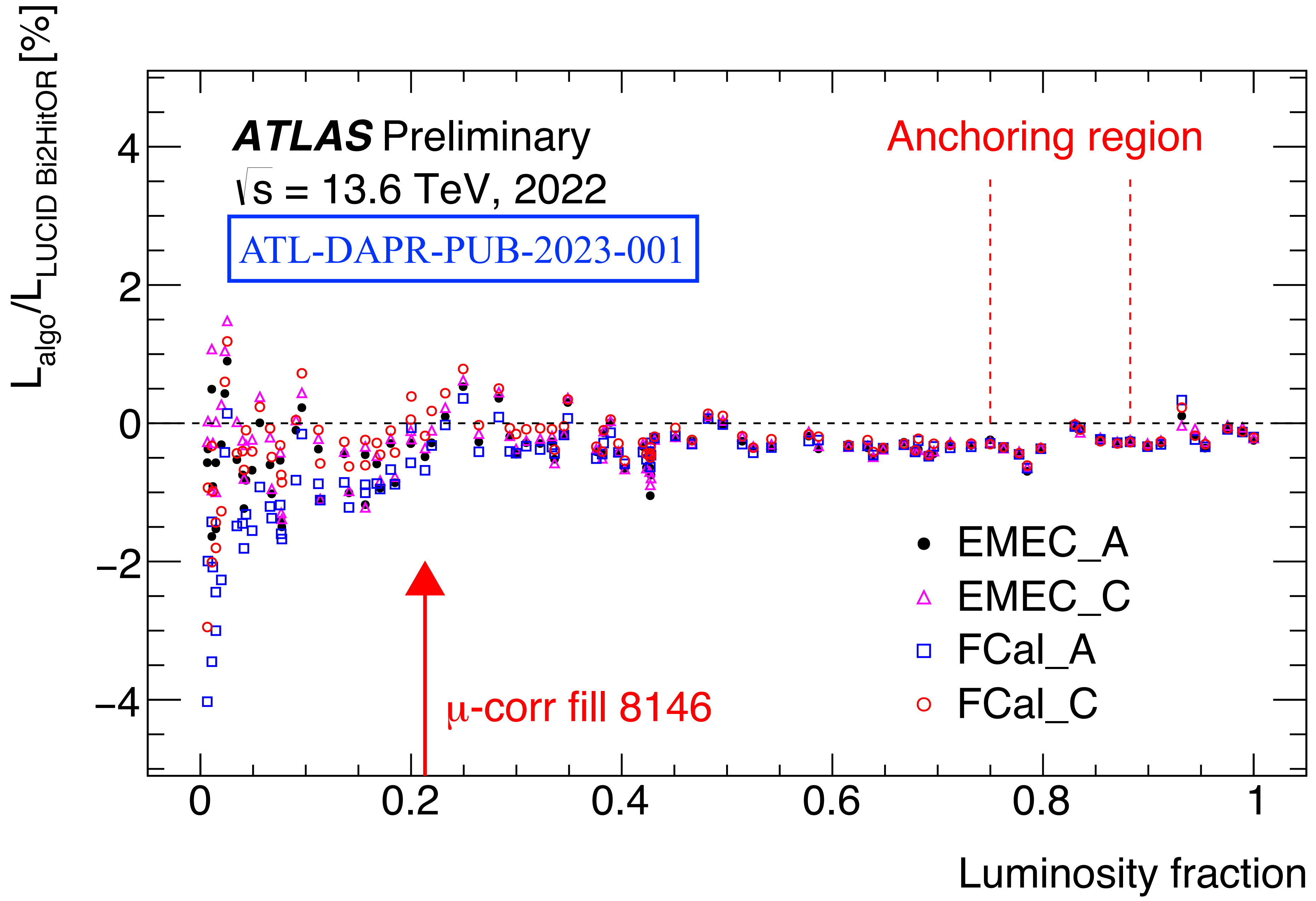
Long term stability uncertainty

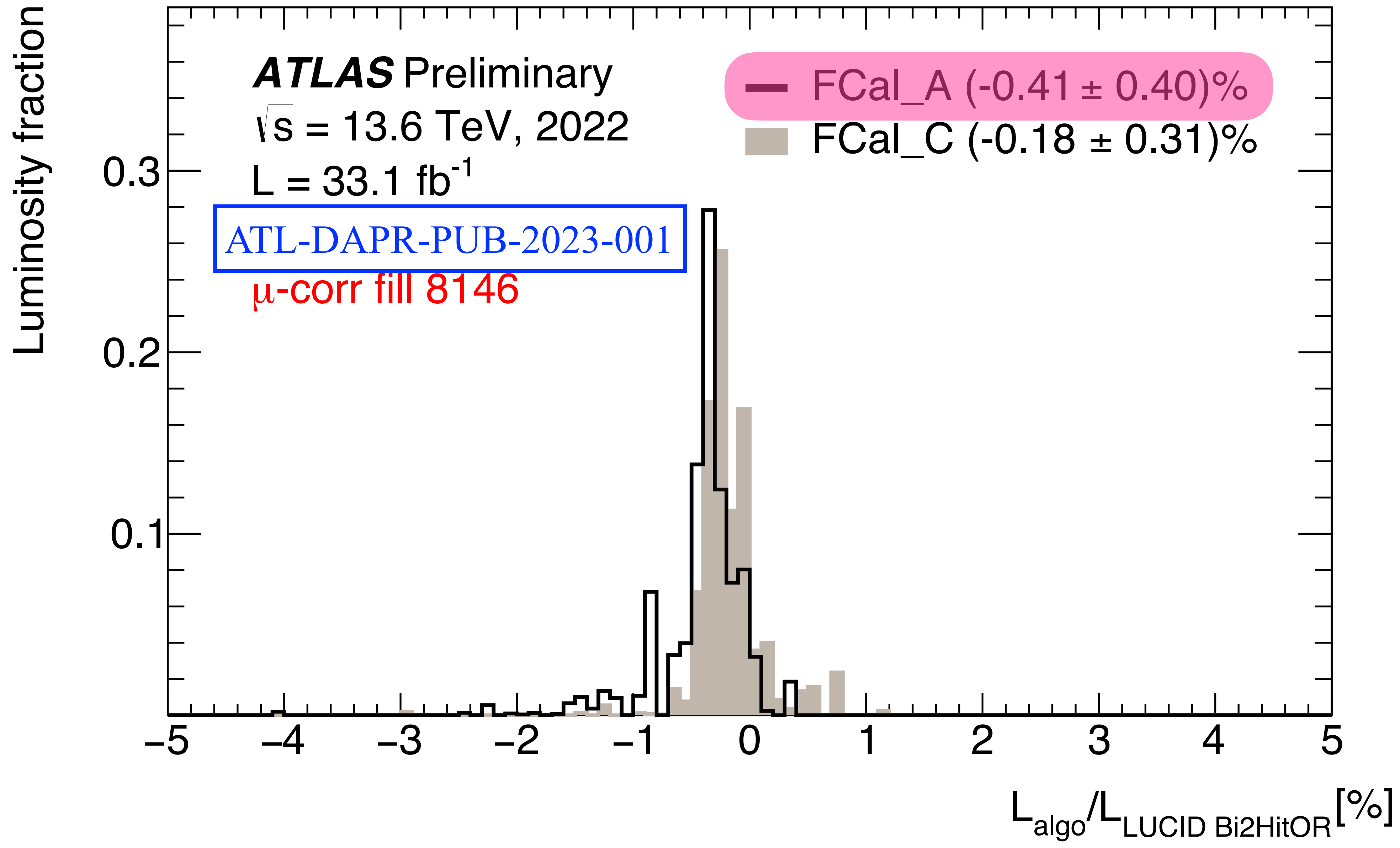
Motivation

- How stable is the luminosity calibration over different runs in a year?
- Are the ratios between different algorithms/luminometers stable over time?

How it is done

- Check how well the different calorimeter measurements agree with LUCID over the different runs in the year
- Long term stability uncertainty: largest mean deviation over all independent luminometers





Summary of the preliminary luminosity determination in 2022

Preliminary

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

Step 1 - Absolute luminosity calibration

1.5%

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Step 2 - Calibration transfer

1.5%

⇓

Step 3 - Long term stability (and calibration anchoring)

0.7%

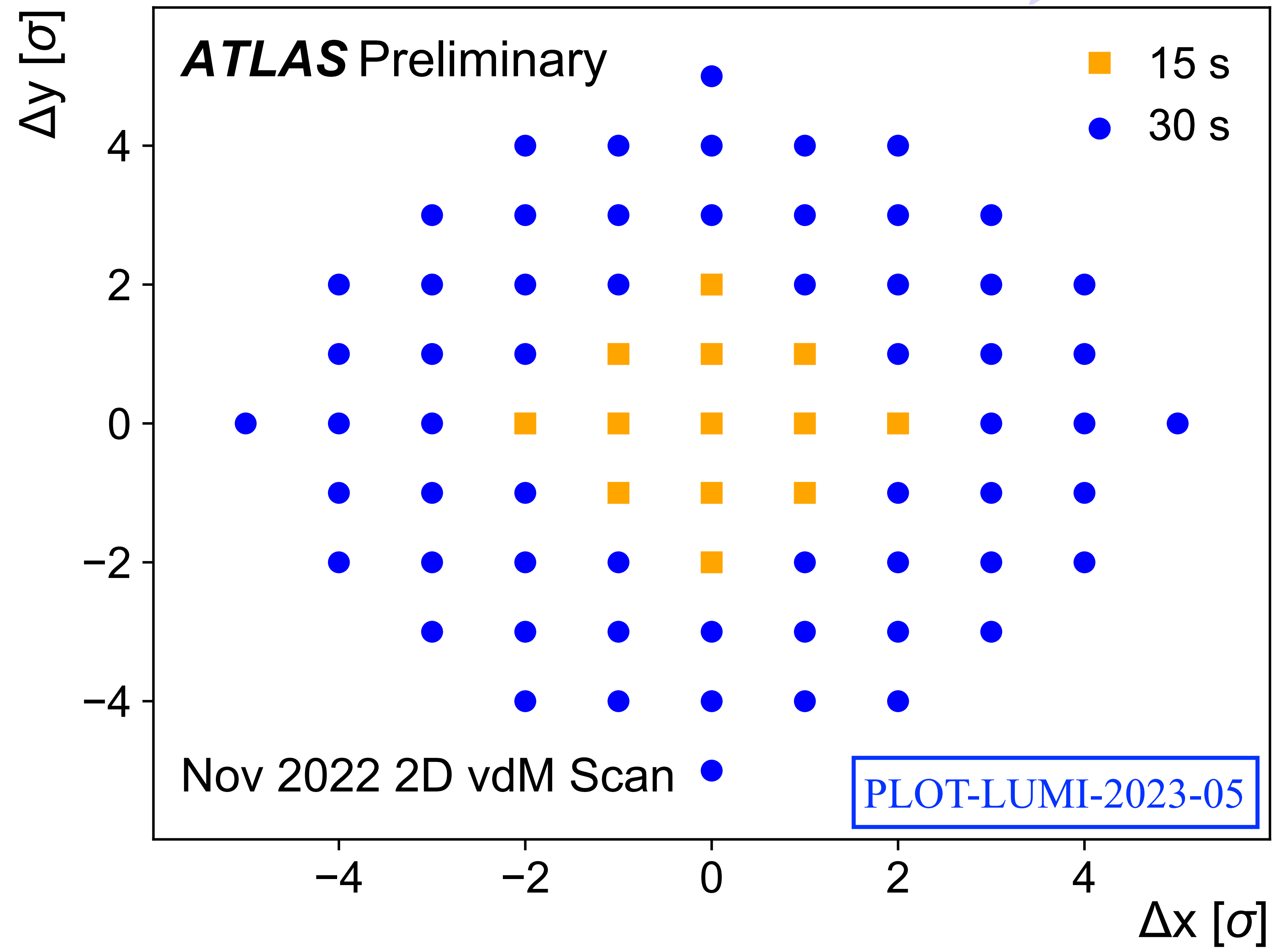
⇓

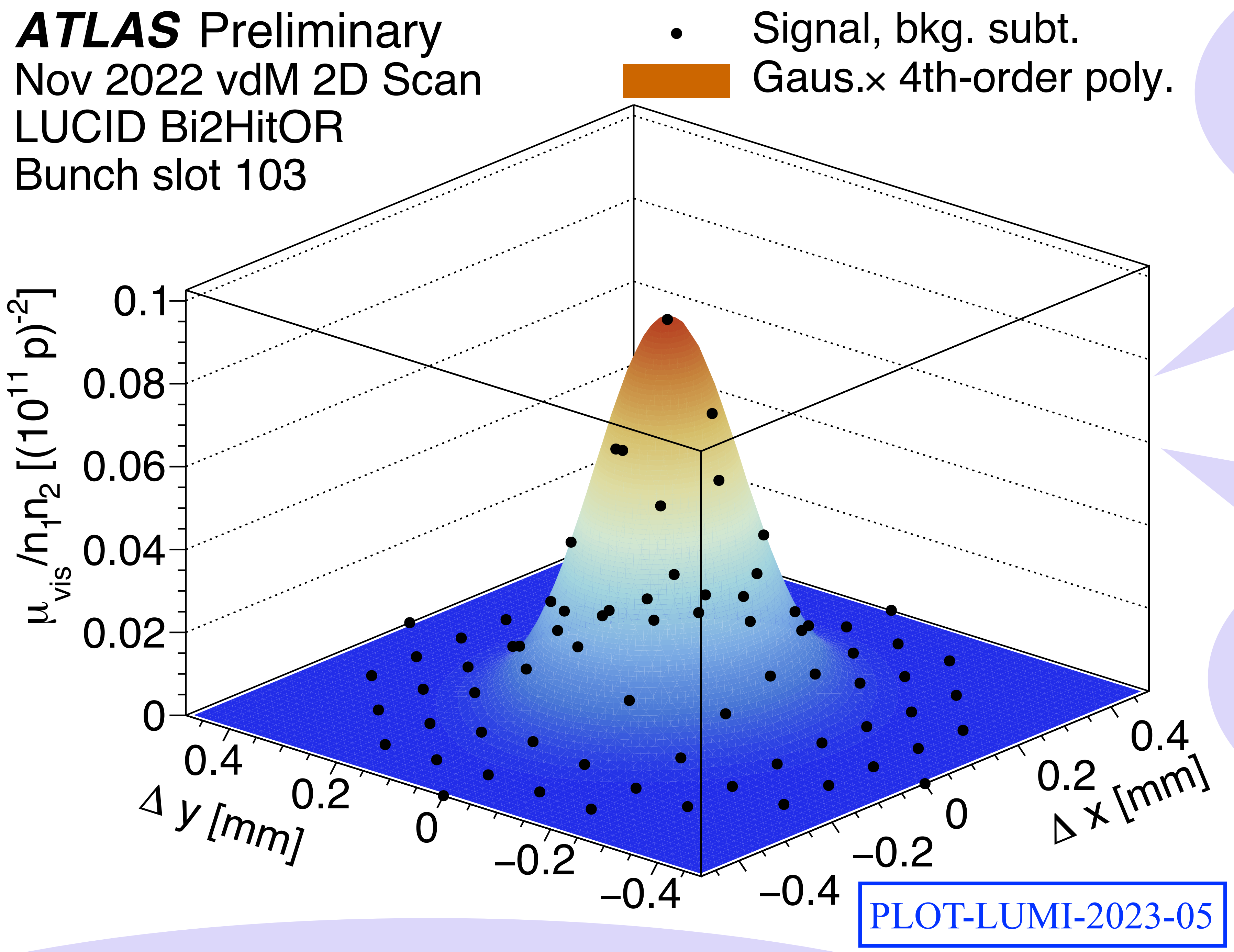
Total

2.2%

Outlook

ATLAS got 2D van der Meer scan!





improve non-factorisation correction and uncertainty

Future:

switch from 1D vdM analysis to 2D analysis?

2023 luminosity calibration ongoing!

References

- Run 2 luminosity paper: arXiv:2212.09379
- Beam-Beam Effects and luminosity calibration paper (Run 2): arXiv:2306.10394
- Run 3 2022 luminosity plots: ATL-DAPR-PUB-2023-001
- Run 3 ttbar cross section result: TOPQ-2023-21
- Other EPS talks:
  - EPS talk about how accelerator physics impacts van der Meer calibrations: Witold Kozanecki's talk (Wed 8:50)
  - EPS talk about Run2 luminosity determination: Rachel Rosten's talk (Tue 8:30)
  - EPS talk about Run3 ttbar cross section measurement: Evan Ranken's talk (Tue 9:50)
- Plots:
  - Cross section plot: ATL-PHYS-PUB-2022-009
  - Run 3 ttbar cross section plot: arXiv:2308.09529
  - Pileup plot: ATLASPublicLuminosity
  - Calibration transfer plot, emittance change plot 2022, long term stability plot and systematic uncertainty table: ATL-DAPR-PUB-2023-001
  - Emittance change plot 2018, 2D vdM scan plots: PLOT-LUMI-2023-05

Questions?