Status of the ATLAS Luminosity Measurements

ATLAS Collaboration Week

CERN, February 21, 2024

F. Dattola, on behalf of the Luminosity Working Group

Counting collisions: luminosity in ATLAS

Overview

- Luminosity crucial input for any cross section measurement: $\sigma(pp \to X) = N(pp \to X)/L$
- Precise determination of luminosity is therefore essential for ATLAS physics analyses
  - Leading systematic uncertainty for some measurements

    $\sigma(Z \to ll) = 751 \pm (\text{stat.}) \pm 15(\text{syst.}) \pm 17(\text{lumi.})\ \text{pb}$ at 13.6 TeV [ATLAS-CONF-2023-006]
- Record **0.83%** uncertainty **achieved in Run 2** → **Target**: keep final Run-3 uncertainty **within 1%**

▪ **ATLAS Luminosity Highlights in 2024**

- Preliminary calibration for 2023 *pp* data [ATL-DAPR-PUB-2024-001]
- Preliminary calibration for 2023 *PbPb* data [Preliminary HI Result (Talk)]
- Complete Run-3 tag with current best knowledge of luminosity [ATLGBLCONDTAGS-85]
- Final calibration for 2018 *pp* data at 900 GeV in EdBoard [Approval Talk]
- **3 separate vdM-calibration campaigns in 2024**: *pp* at 13.6 TeV (May), *pp* at 5.4 TeV (*pp*-ref, October), *PbPb* at 5.4 TeV NN (heavy ion, November)

Luminosity detectors and algorithms

ATLAS *luminometers* in Run 3

▪ LUCID

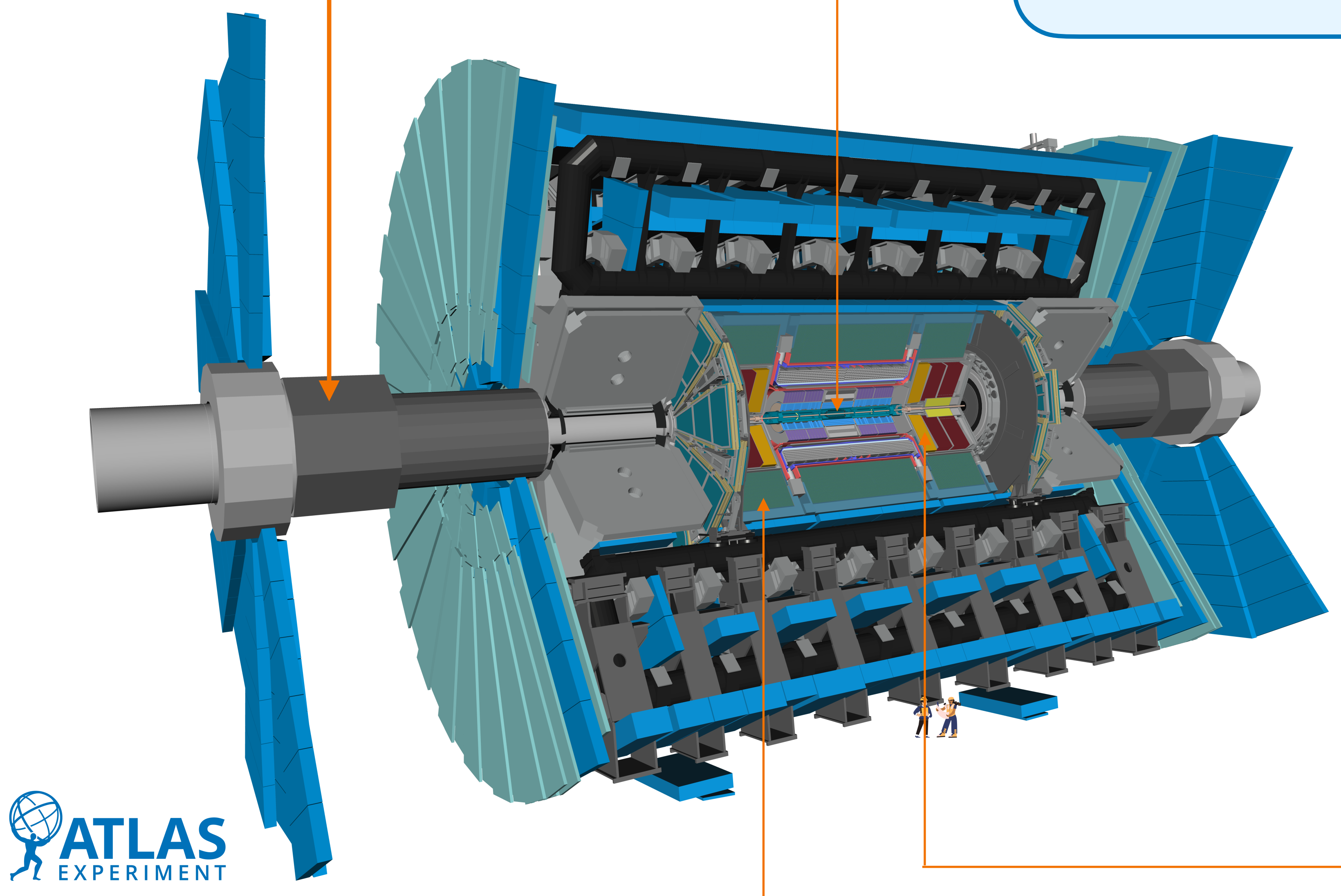
- **Reference luminometer**: usable over full μ range
- Cherenkov light detector: 2×16 PMTs
- Several algorithms: event- and hit-counting
- Sensitive on single bunch resolution

▪ Z-Counting

- Used for independent cross checks of baseline luminosity over time and μ

▪ Tile calorimeter

- Luminosity from PMT currents
- Usable over wide μ range
- Bunch-integrated sensitivity



▪ Inner Detector

- **Track Counting**: count reconstructed tracks with Pixel + SCT in randomly triggered events
- Usable over wide μ range
- Very linear in μ for different track selections
- Sensitive on single bunch resolution
- **Pixel Cluster Counting (in development)**: count reconstructed Pixel clusters in randomly triggered events

▪ LAr calorimeters (EMEC and FCal)

- Luminosity measured with LAr gap HV currents over O(1) s integration times.
- Mostly usable in high-μ physics fills.
- Very stable over time.
- Bunch-integrated sensitivity.

Luminosity measurement strategy

Steps in luminosity determination

- **Basic idea:**
  - Measure luminosity through **visible interaction rate in a luminosity-sensitive detector**

$$\mathscr{L}_b = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y} = \frac{\mu \cdot f_r}{\sigma_{\text{inel}}} = \frac{\mu_{\text{vis}} \cdot f_r}{\sigma_{\text{vis}}}$$

- LHC beam parameters

- μ = number of inelastic collisions per bunch
- σ_{inel} = inelastic cross section
- μ_{vis} = visible interaction rate
- σ_{vis} = visible cross section

- **Step 1: vdM calibration**
  - Scan beams against each other in dedicated fills with specially-tailored LHC conditions
  - Calibration of LUCID σ_{vis}

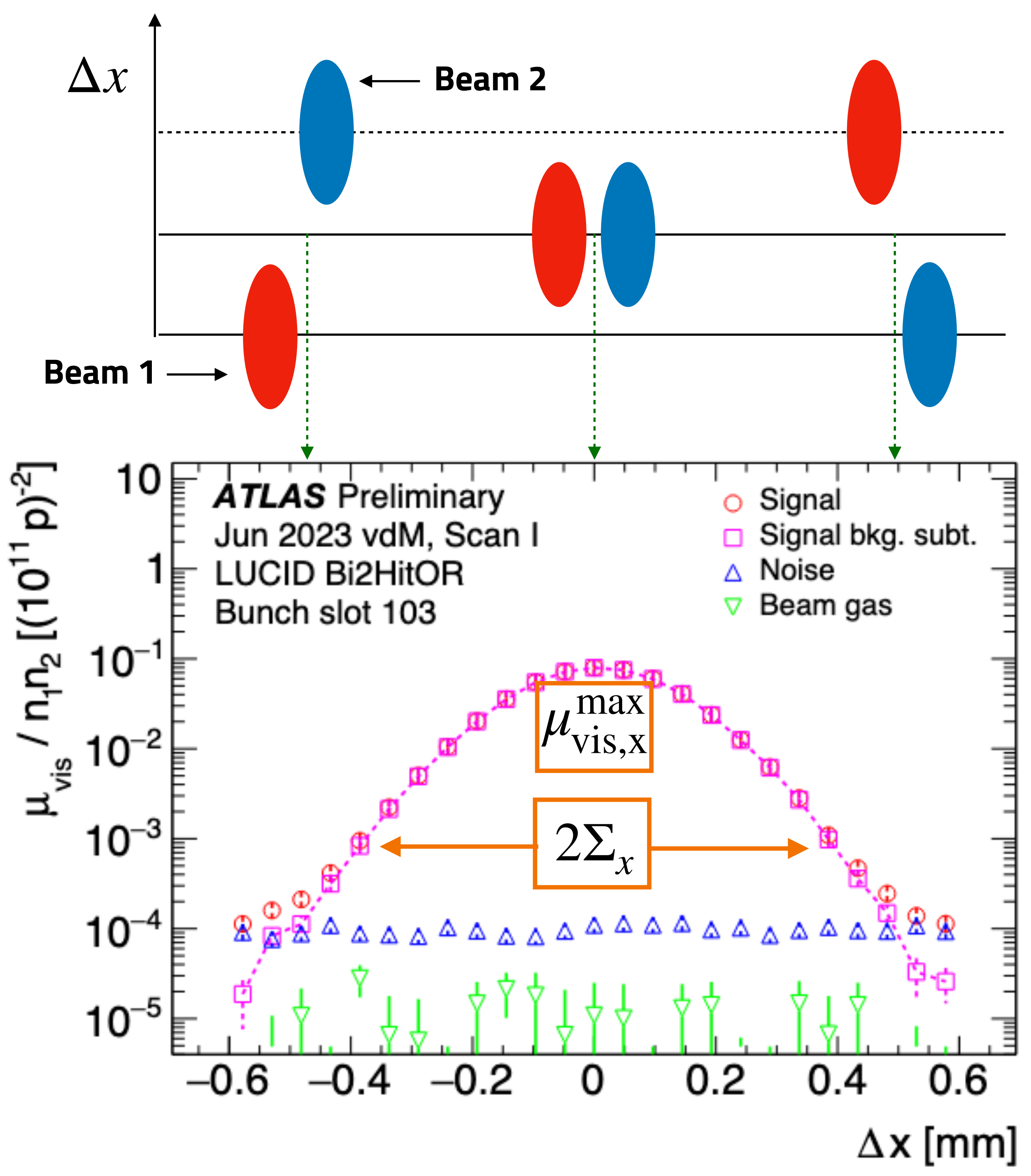
- **Step 2: calibration transfer**
  - Transfer LUCID measurement from vdM regime to physics regime
  - Correct LUCID response with Track Counting measurement
  - Cross-check with Tile measurement to assess uncertainties

- **Step 3: long-term stability**
  - Verify stability of luminosity calibration from run to run over entire running period
  - Compare run-integrated luminosities from LUCID, Tile, EMEC, FCAL

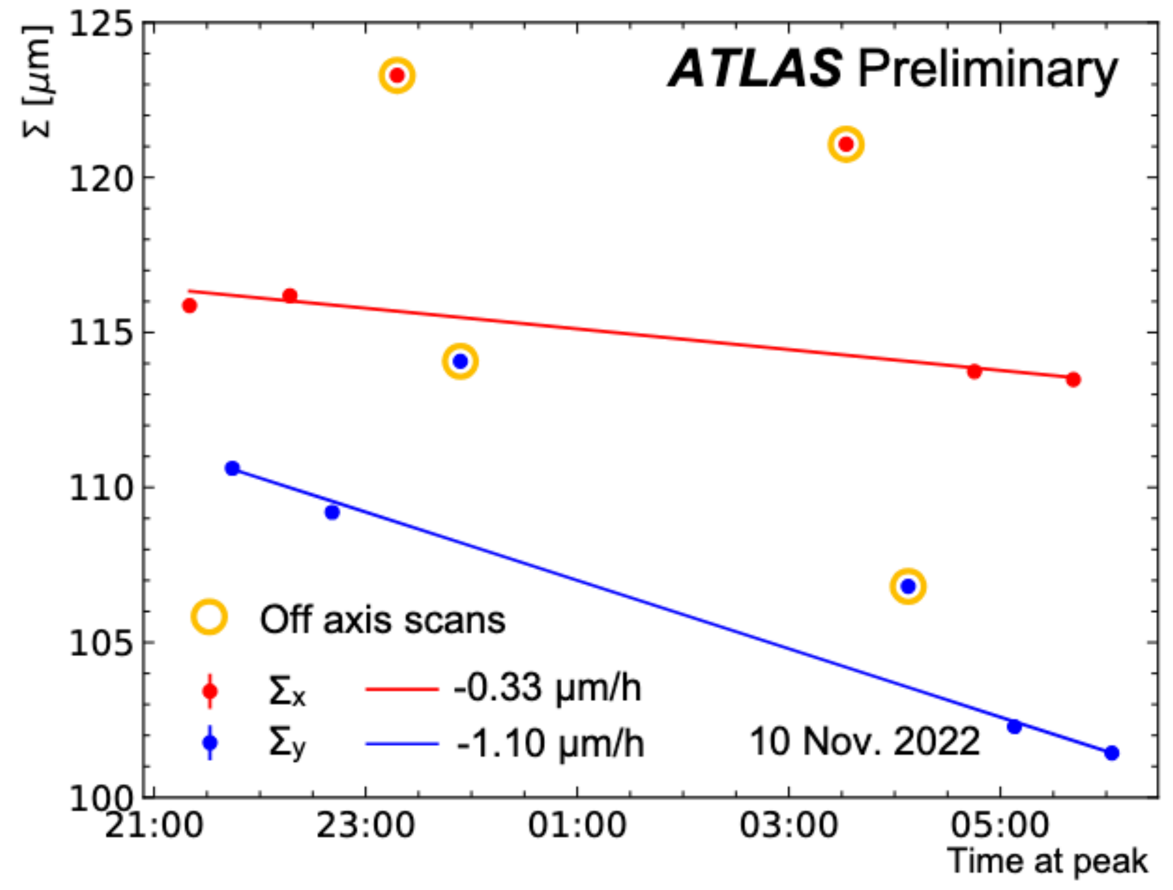
vdM calibration

Analysis of van der Meer scans

- **Determine visible cross-section** $\sigma_{\mathrm{vis}} = \mu_{\mathrm{vis}}^{\mathrm{max}} \cdot (2\pi\Sigma_x\Sigma_y)/n_1 n_2$ through fits of the measured interaction rate μ_{vis} vs beam separation in x- and y-directions
- vdM calibration requires **specially-tailored LHC conditions**: low $\mu \sim 0.5$, isolated bunches, no crossing angle
- **Many corrections needed:** orbit drifts, emittance growth, non-factorisation, beam-beam effects, length scale, magnetic non-linearity



- **Non-factorisation** main systematic in Run 3: **1.07%** in 2022 and **1.39%** in 2023 (*pp*) → **combined 1.22% vs 0.24% in Run-2**
- Breaks factorisation of beam profiles assumed in the basic formalism
  - **Transverse profile:** $\rho(x,y) \neq \rho(x) \cdot \rho(y) \rightarrow [\Sigma_x\Sigma_y] \neq \Sigma_x \cdot \Sigma_y$
- Evidence for strong non-factorisation in Run 3 from off-axis scans

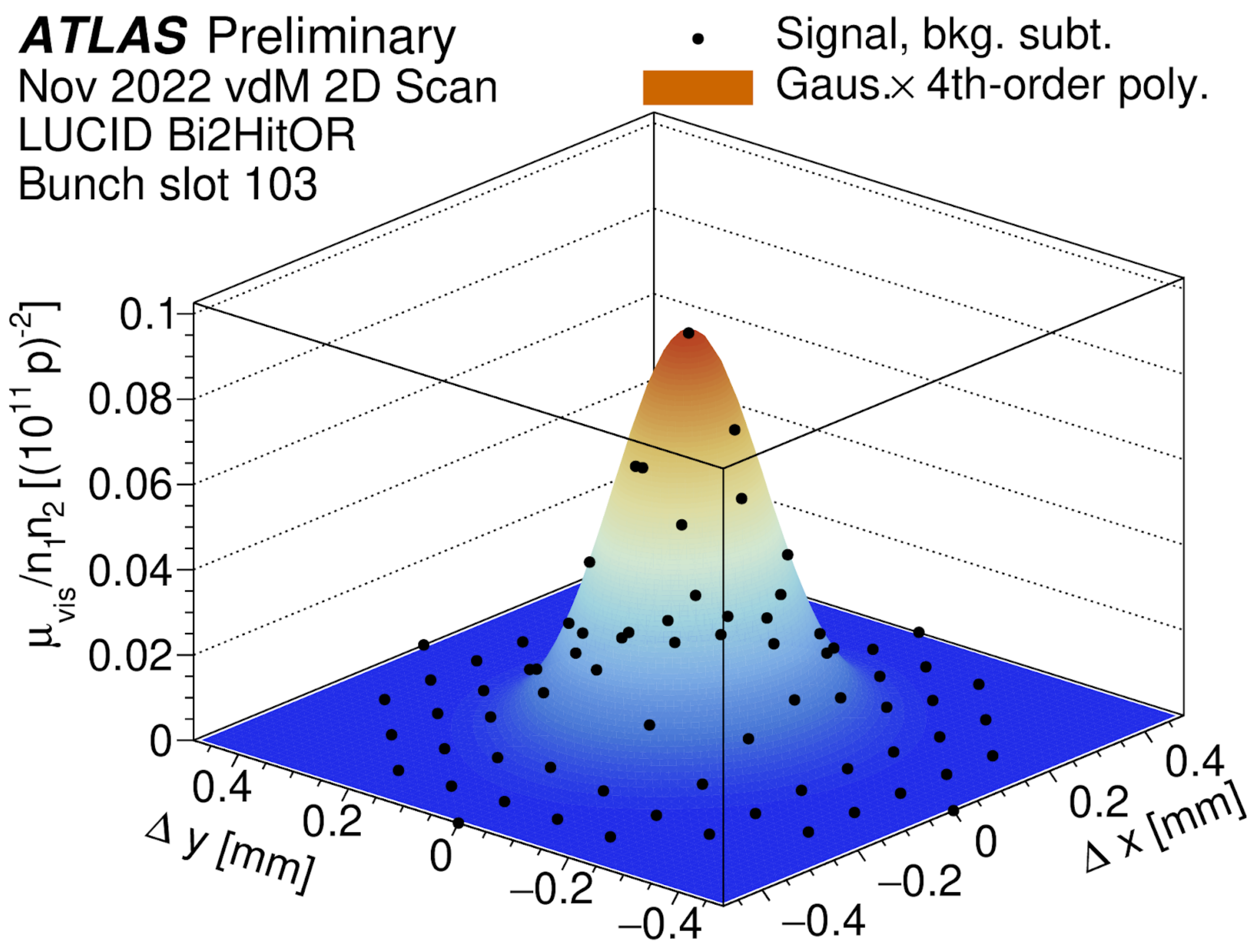


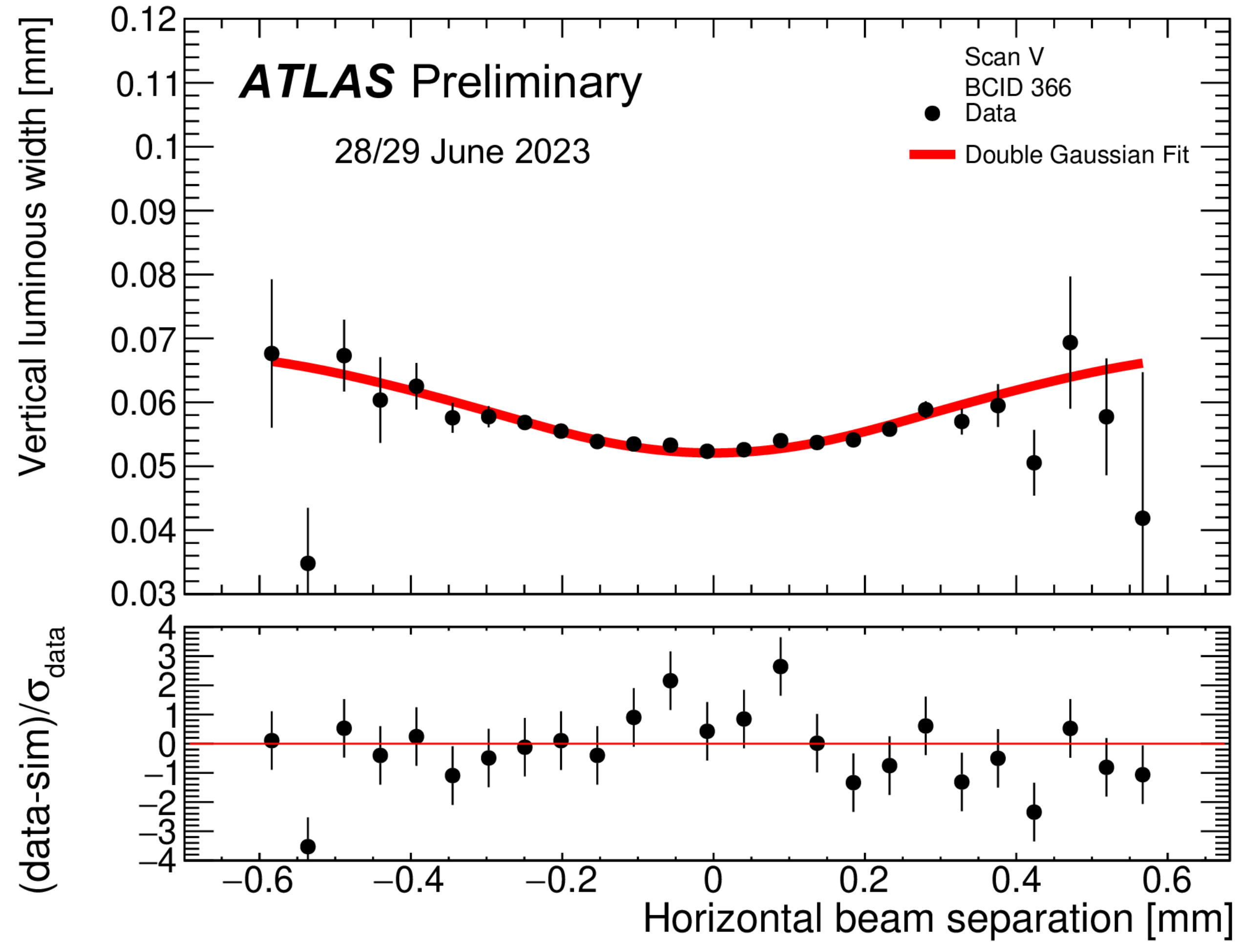
vdM calibration

Analysis of van der Meer scans

- **Two orthogonal approaches to improve control of non-factorisation**

- **LRE analysis**: combined fit of expected luminous region and luminosity to the data recorded at each scan step → model dependent
- **2D grid scans**: perform a scan over a grid in (x, y) → model independent





- Many vdM scans in 2024, including special scans to improve understanding of non factorisation (i.e. diagonal scans)
- Data to be analysed for the first time → not simple routine work, requires **own intellectual input**!

Calibration transfer

Going to high-pileup physics conditions

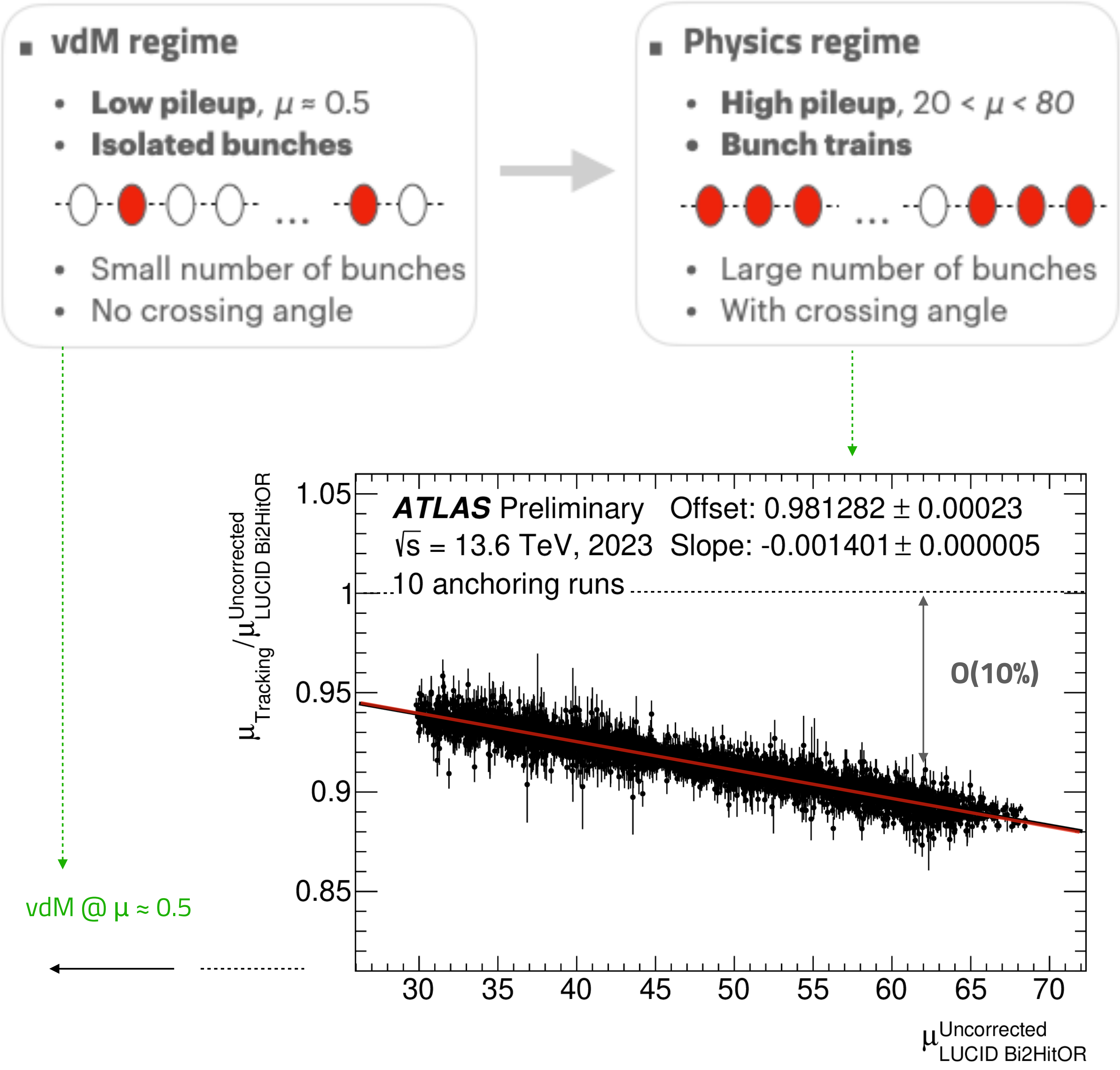
- **Transfer LUCID vdM calibration to physics regime**
  - Normalise Track Counting (TC) to LUCID in head-on parts of vdM fill and compare LUCID vs TC at high-luminosity in physics regime

→ **LUCID response shows strong dependence on** μ:

- **up to ~ 10%** overestimation of luminosity at high-μ

→ **correct using Track Counting (TC)**: $\langle \mu_{\text{corr}} \rangle = p_0 \langle \mu_{\text{uncorr}} \rangle + p_1 (\langle \mu_{\text{uncorr}} \rangle)^2$

- use a few long high-luminosity reference fills per year



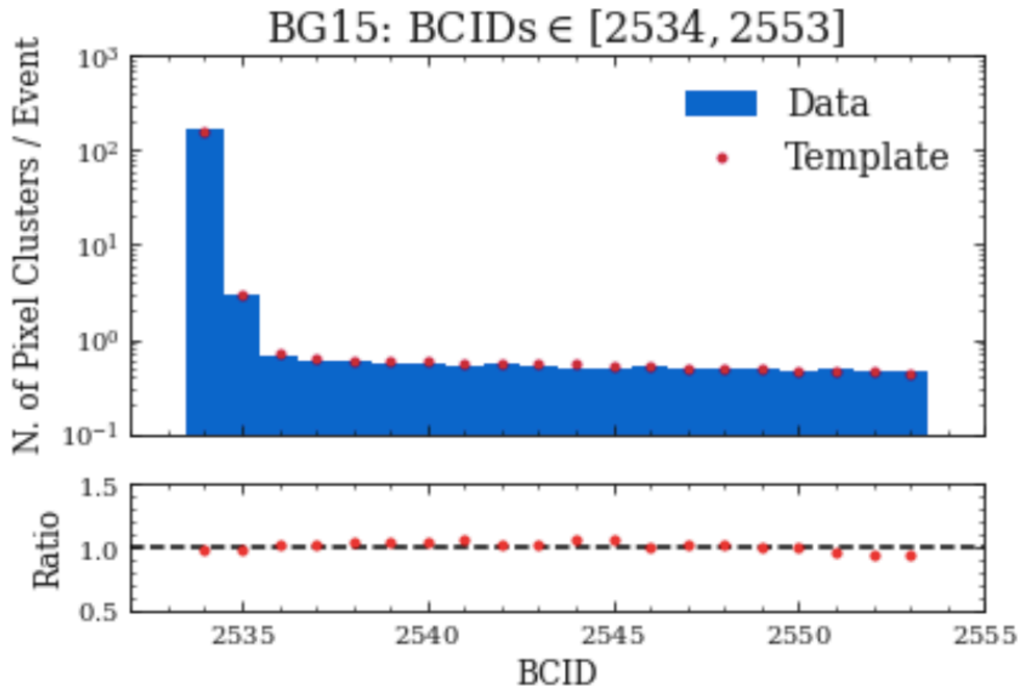
- TC stability constantly monitored with dedicated data stream
- Close collaboration with Tracking/Inner Detector experts

Intermezzo: luminosity with the Inner Detector

Not only corrections to LUCID...

- **Pixel Cluster Counting (PCC)**
  - ATL-COM-DAPR-2023-028

- **Assumption**: number of pixel clusters per bunch crossing proportional to μ
- Already in use at CMS, **could be key for Run 4**
- **Developing in Run 3**: implementation of PCC software and crucial studies for control of *afterglow* background



Intermezzo: luminosity with the Inner Detector

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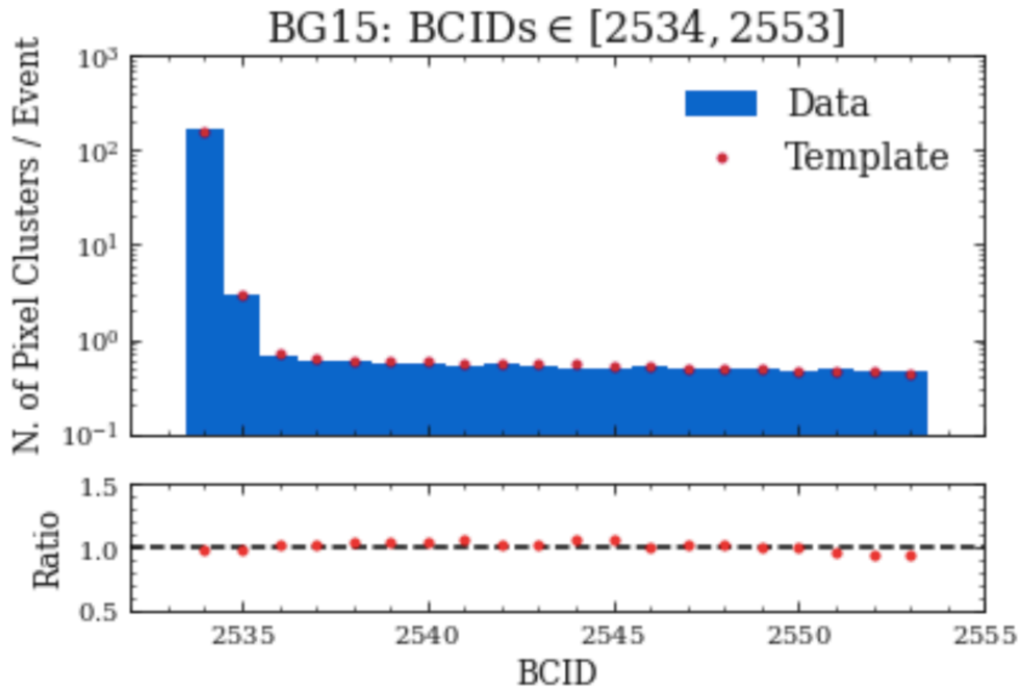


TC calibration in emittance scans

- Extraction TC σ_{vis} from emittance scans: vdM-like analysis
- **Developing in Run 3**: would provide TC calibration orthogonal to LUCID

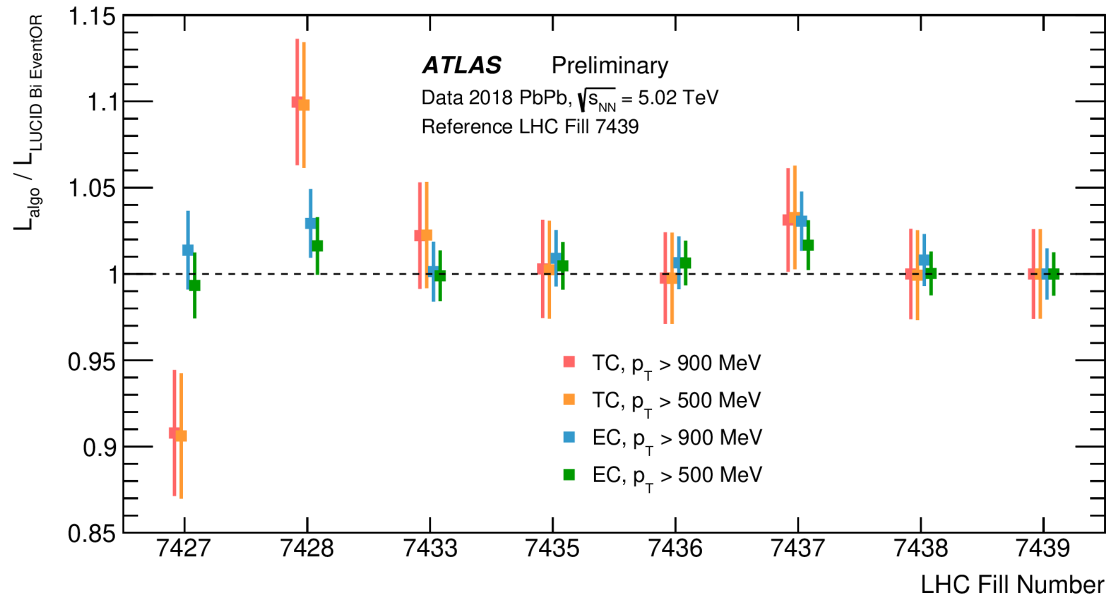
Track-based luminosity in PbPb

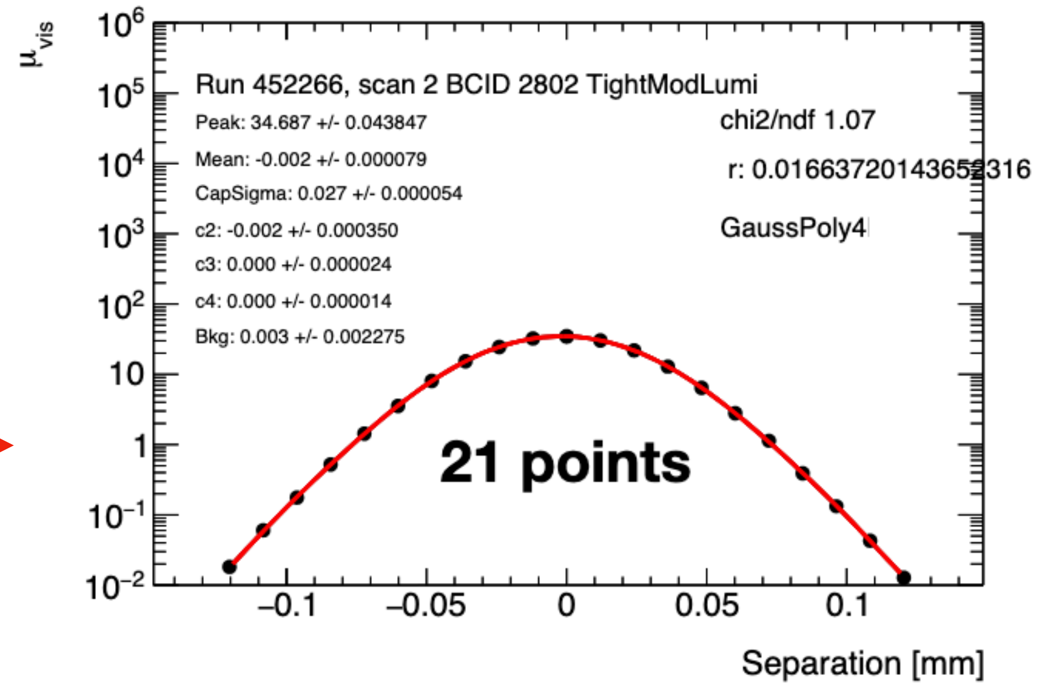
- ATL-COM-DAPR-2023-025

- **Event Counting (EC)**: count number of events in a given time period with at least one track (Pixel + SCT) of a given working point

$$\mu_{\text{vis}}^{\text{EC}} = -\ln(1 - N_{\text{pass}}/N_{\text{tot}})$$

- EC is statistically precise and stable: sets long-term stability uncertainty in PbPb calibration





Calibration transfer

Uncertainty in track-counting luminosity

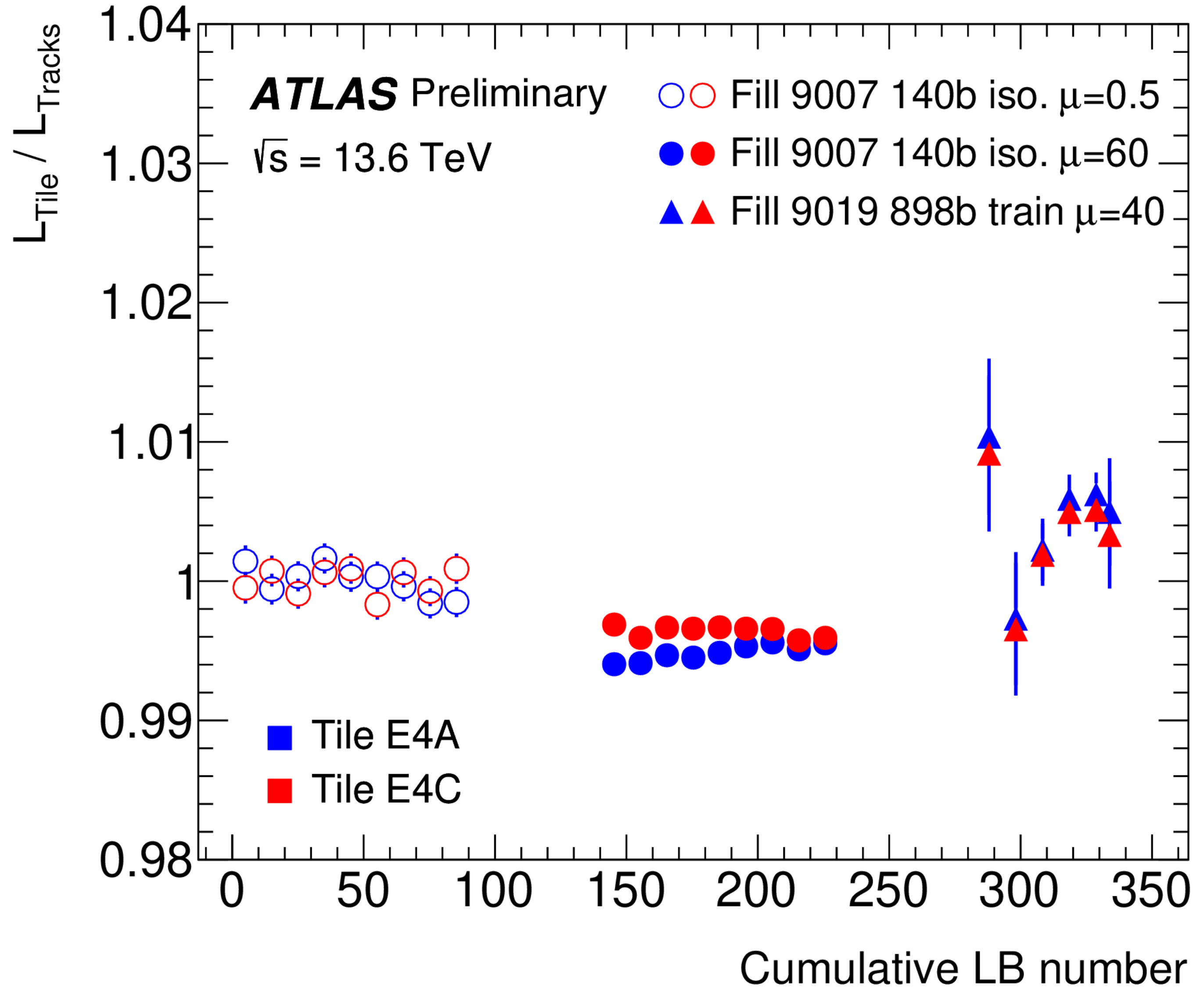
- Track-based LUCID **correction assumes that TC is perfectly linear** from vdM to physics regime

- **Probe TC linearity with Tile data** corrected for material activation, primarily using Tile E3/E4 gap scintillators

- Compare Tile/TC ratio in

  ○○ vdM conditions

  ▲▲ physics fill scheduled shortly after vdM



- Combined 2022-2023 uncertainty = **1.23%**
  → **second largest systematic**

Very limited personpower:
new analysers with Tile experience needed!

2022 → 1.5%

...tion	Used cell families	Range of shifts across used cell families
1-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) → ($\mu \approx 40$, 1154b, trains)	A13, A14	[-0.1, 0.8]%
Alternative: 2-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) → ($\mu \approx 45$, 144b, trains)	A13, A14, E3, E4	[0.1, 0.7]%
($\mu \approx 45$, 144b, trains) → ($\mu \approx 40$, 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%**

2023 → 1.1%

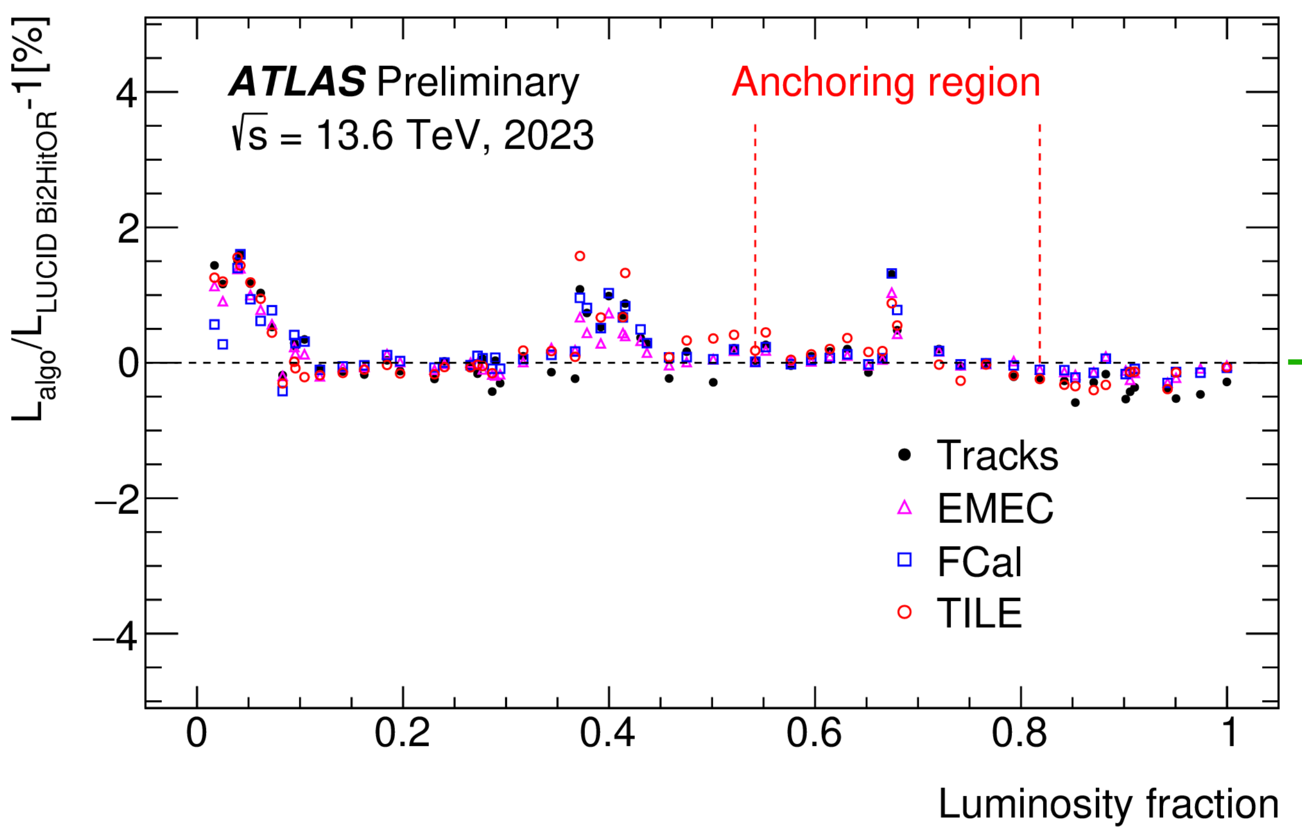
...ion	Used cell families	Range of shifts across used cell families
1-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) → ($\mu \approx 40$, 898b, trains)	E3, E4, A13, A14	[0.5, 1.1]%
Alternative: 2-step extrapolation		
($\mu \approx 0.5$, 140b, isolated) → ($\mu \approx 60$, 140b, isolated)	E3, E4, A13, A14	[-0.7, -0.3]%
($\mu \approx 60$, 140b, isolated) → ($\mu \approx 40$, 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%**

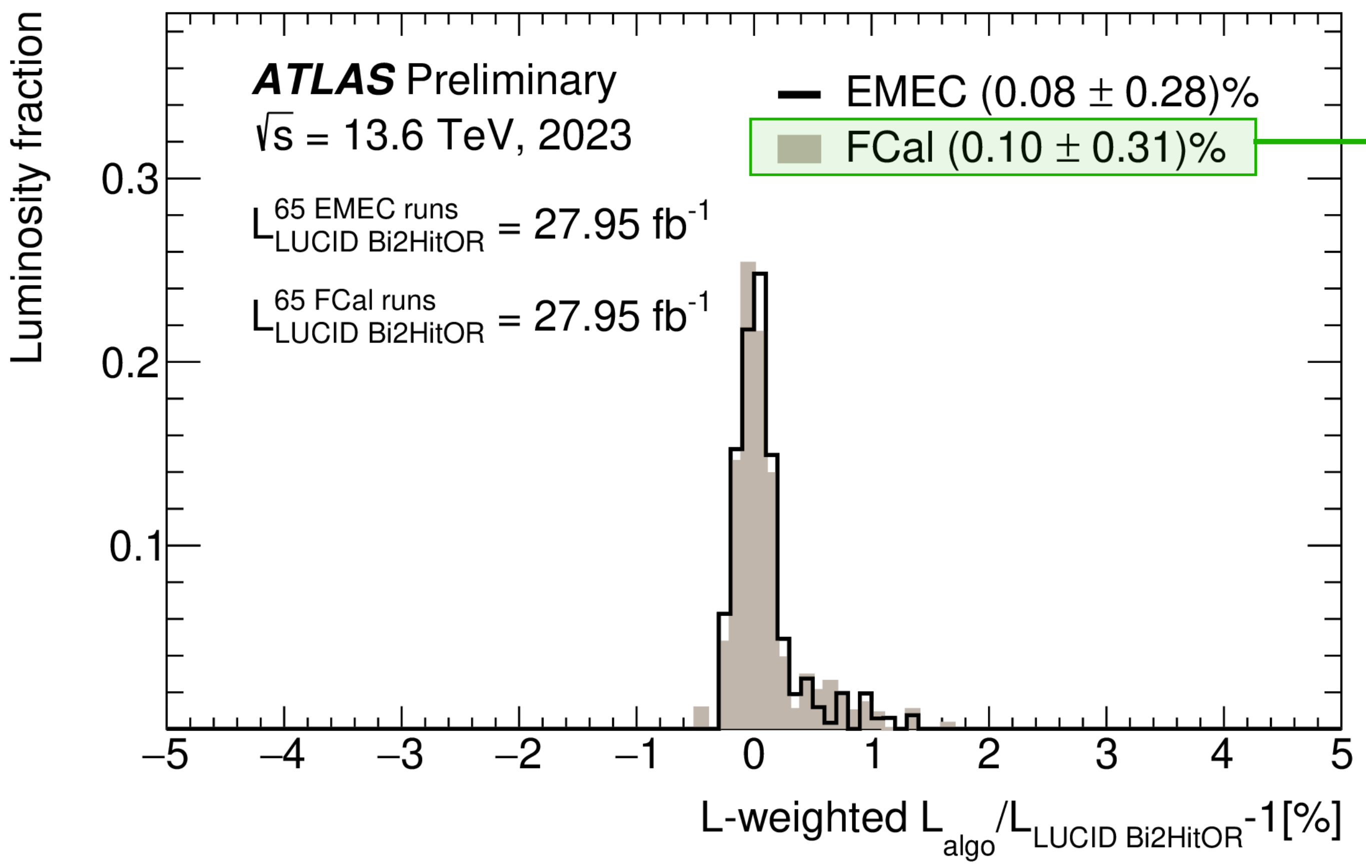
Long-term stability

Check of luminosity stability over time

- **Use independent measurements from calorimeters** normalised (*anchored*) to track-counting around vdM fill
  - **LAr calorimeters**: EMEC and FCal
  - Tile calorimeter: D6 Cells

- Long-term stability derived from luminosity-weighted **difference between calorimeters and LUCID**



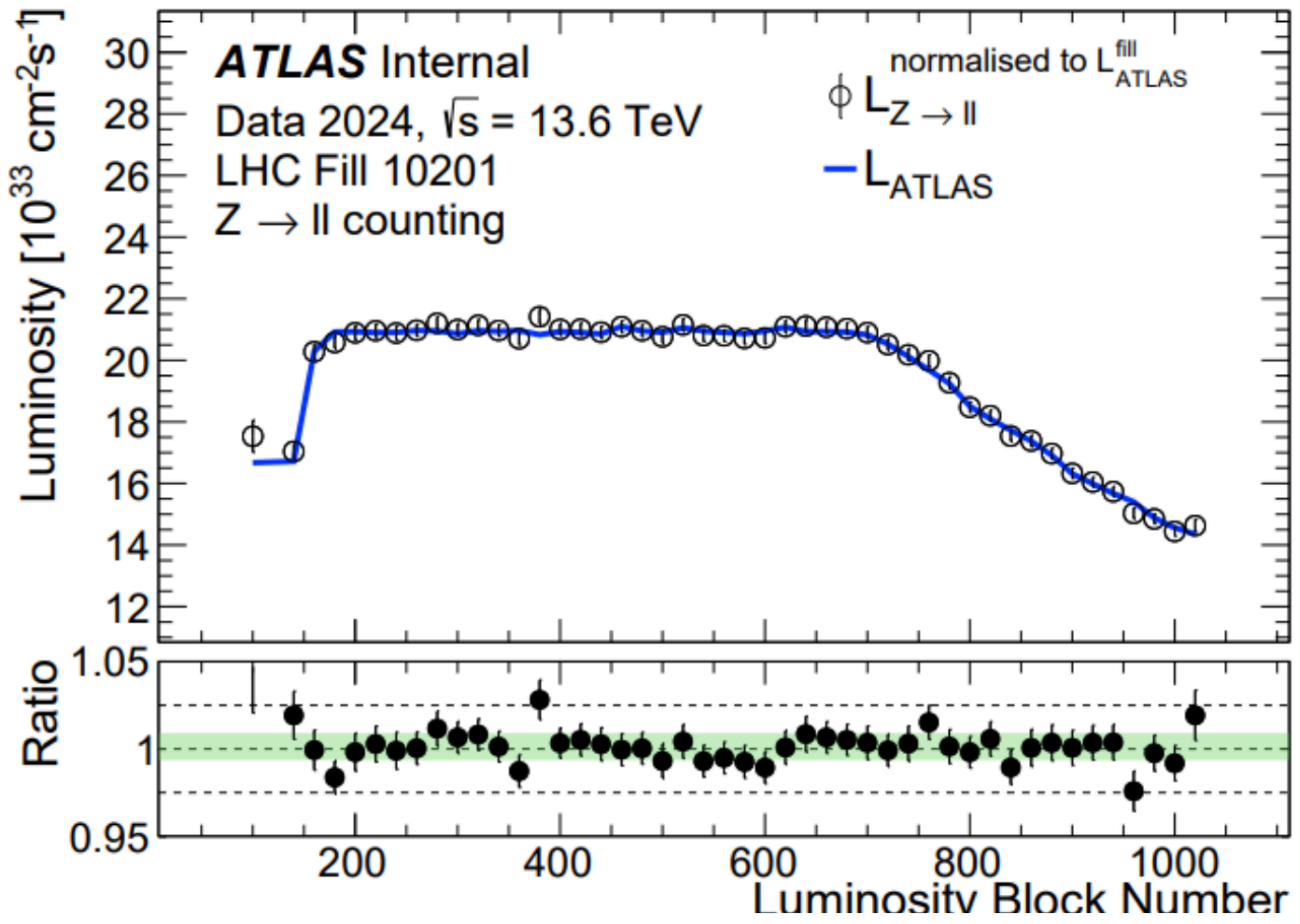


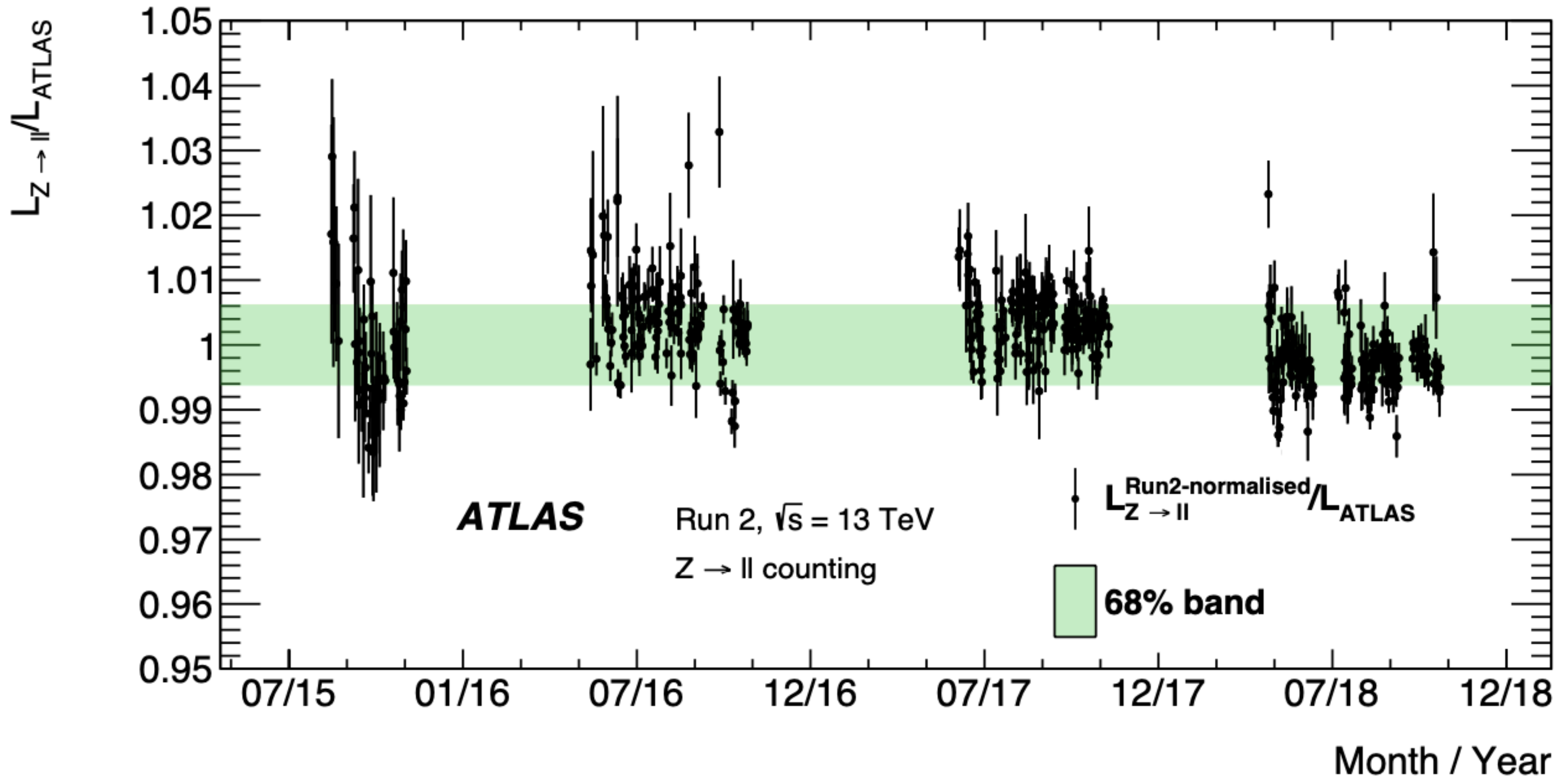
- Uncertainty ≡ largest mean $\Delta L/L$
  → equivalent to taking L_{calo} instead of L_{LUCID}
- **0.41% (2022), 0.10% (2023)**
  → **0.22% combined**

Z-Counting

Independent validation

- Counting $Z \to ee$ and $Z \to \mu\mu$ can be used for **relative luminosity measurement**
  - σ_Z only known to 3-4% (PDFs) – cannot use for absolute luminosity scale :(
  - Comparison with baseline luminosity evaluated per data-taking period, with **L(Z) normalised to L(ATLAS)** in the period
  - **Validates calibration** stability with time and μ
  - Over full Run **probes inter-year consistency of vdM calibration**
  - Could *backport* future improved knowledge of non-factorisation to earlier years





Putting it all together

Status and plans

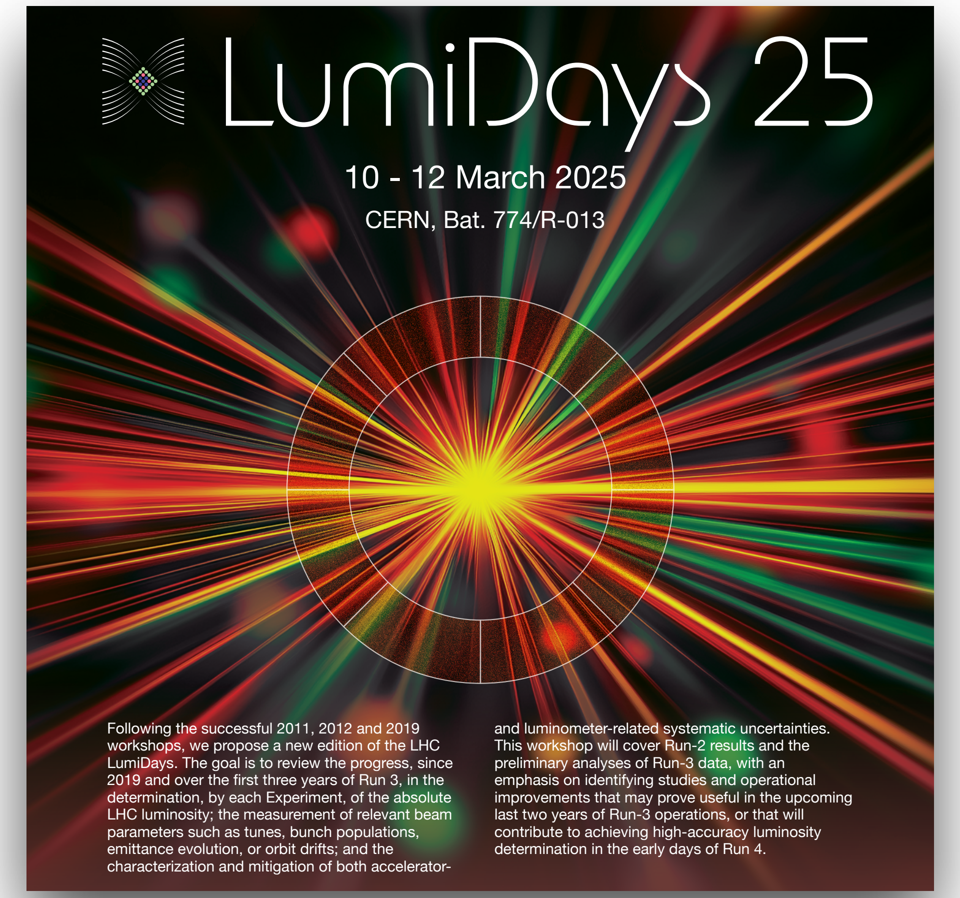
- **Calibration status:**
  - Good **accuracy in preliminary 2022-23 *pp*** analysis **(~2% per year)** but dominated by correlated systematics: non-factorisation (1-1.5%), calibration transfer (1-1.5%)
  - Preliminary uncertainty **in 2023 PbPb analysis is 3.71%**: expected to improve with better evaluation of systematics
  - **Calibration with 2024 *pp* data before the upcoming summer is the highest priority** (less strict timelines for 2024 *pp*-ref and *PbPb*)

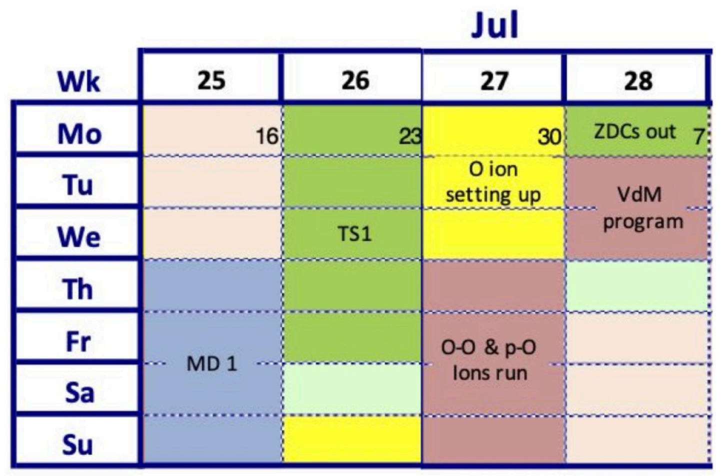
[ATL-DAPR-PUB-2024-001]

Data sample	2022	2023	Comb.
Integrated luminosity [fb^{-1}]	31.40	27.58	58.98
Total uncertainty [fb^{-1}]	0.69	0.56	1.16
Uncertainty contributions [%]:			
Statistical uncertainty	0.01	0.01	0.01
Fit model*	0.24	0.15	0.20
Background subtraction*	0.06	0.30	0.17
FBCT bunch-by-bunch fractions*	0.01	0.01	0.01
Ghost-charge and satellite bunches†	0.17	0.04	0.11
DCCT calibration*	0.20	0.20	0.20
Orbit-drift correction	0.06	0.34	0.16
μ-dependence	0.00	0.30	0.14
Beam position jitter	0.00	0.01	0.01
Non-factorisation effects*	1.07	1.39	1.22
Beam–beam effects*	0.35	0.32	0.34
Emittance damping correction*	0.21	0.06	0.14
Length scale calibration	0.03	0.02	0.02
Inner detector length scale*	0.12	0.12	0.12
Magnetic non-linearity*	0.32	0.28	0.30
Bunch-by-bunch σ_{vis} consistency	0.50	0.36	0.31
Scan-to-scan reproducibility	0.27	0.35	0.22
Reference specific luminosity*	0.43	0.44	0.43
Subtotal vdM calibration	1.44	1.71	1.49
Calibration transfer†	1.50	1.10	1.23
Calibration anchoring	0.53	0.16	0.29
Long-term stability	0.41	0.10	0.22
Total uncertainty [%]	2.19	2.04	1.97

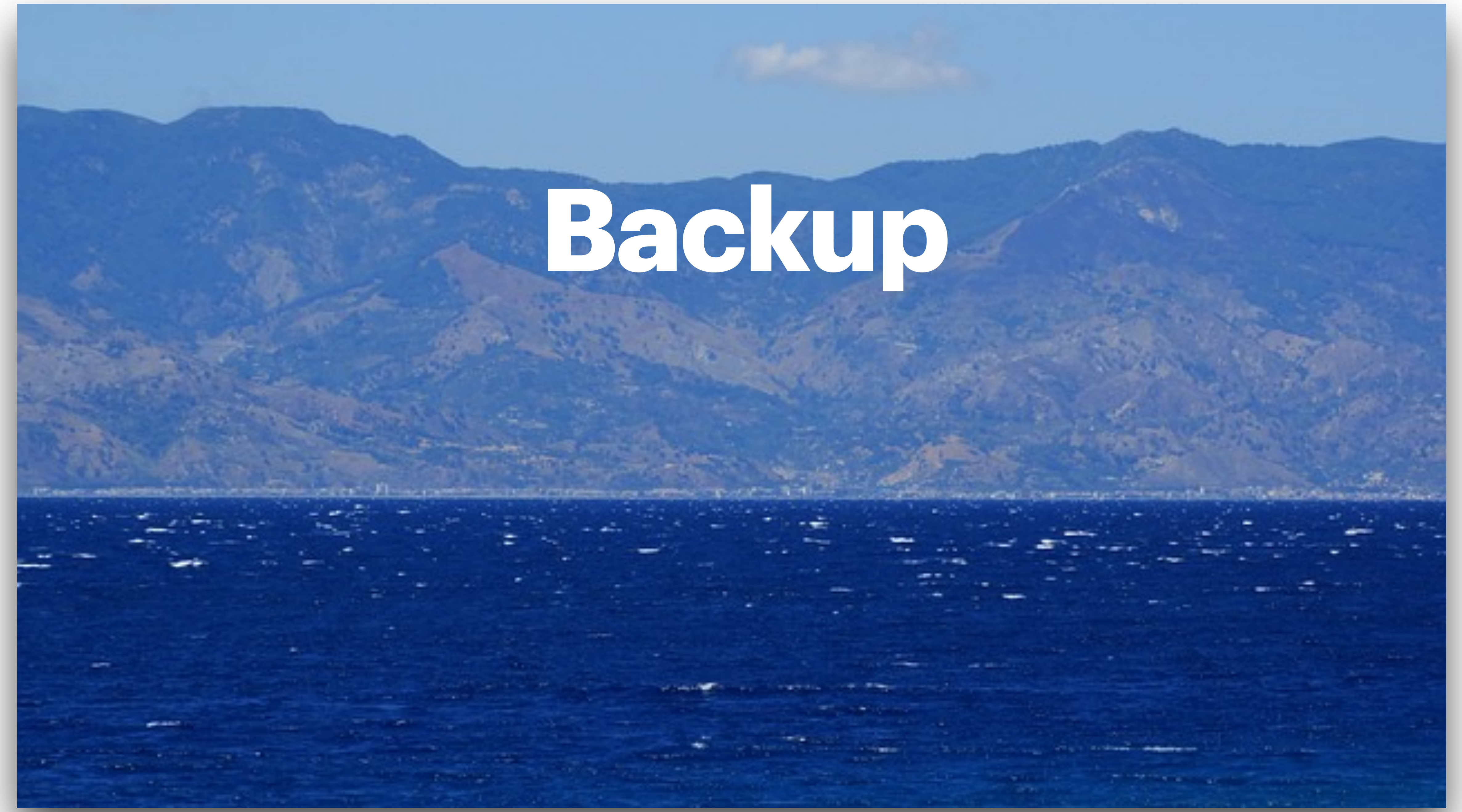
- ***Chronic* lack of personpower and several critical areas understaffed:**
  - **2024 luminosity measurement for EPS-HEP 2025 at risk**
  - **Urgent need for person-power in the Online Luminosity team**

- **Bonus: LHC LumDays 2025 (Mar 10-12)**





- **Preparing for a busy 2025**
  - **Intense scan program:** pp, PbPb and Oxygen Run (pO, OO)
  - Lots of data to analyse!


Backup

Final Run 2 luminosity determination

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

Personpower issues

Current scenario

[E. Torrence]

- Personnel are still (always) an issue. Currently missing people for
  - Online subgroup convener
  - vdM subgroup convener
  - Calibration transfer subgroup convener
  - Soon Lumi Convener
  - Non-factorization analysis - losing main analyzer here
  - …
- Large number of scans in 2024 also means lots to analyze
  - Some new people interested, but still ramping up
  - Currently don’t see that we will have 2024 pp calibrations before Summer (priority), ppref and PbPb timelines unclear
  - Situation will be similar (or worse) in 2025 - pp, p-O, O-O, PbPb

vdM calibration

Factorisation assumption

[T. Barklow]

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

$$[\Sigma_x \Sigma_y] = \frac{1}{2\pi} \frac{\int R_{x,y}(\delta_x,\delta_y)\, d\delta_x\, d\delta_y}{R_{x,y}(0,0)} = \frac{1}{2\pi} \frac{1}{\int \hat{\rho}_1(x,y)\hat{\rho}_2(x,y)\,dx\,dy}$$

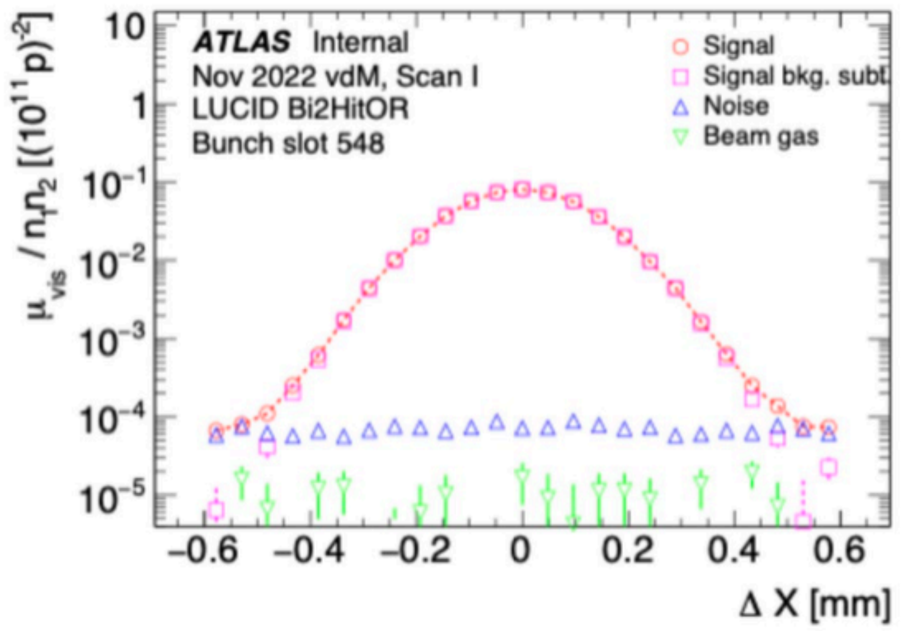
$f_r =$ bunch revolution frequency $\quad n_1 n_2 =$ bunch population product $\quad \sigma_{\text{vis}} =$ visible cross section

$\mu_{\text{vis}} =$ visible interaction rate per bunch crossing as measured e.g. in LUCID

$\delta_x\ ,\ \delta_y =$ horizontal, vertical beam separation

$R_{x,y}(\delta_x,\delta_y) =$ any quantity proportional to the luminosity, such as LUCID μ_{vis}

$\hat{\rho}_1(x,y)\ ,\ \hat{\rho}_2(x,y) =$ normalized transverse particle density of beam 1, 2



In practice, a grid scan covering the δ_x, δ_y 2-d plane is expensive in beam time, so the factorization assumption

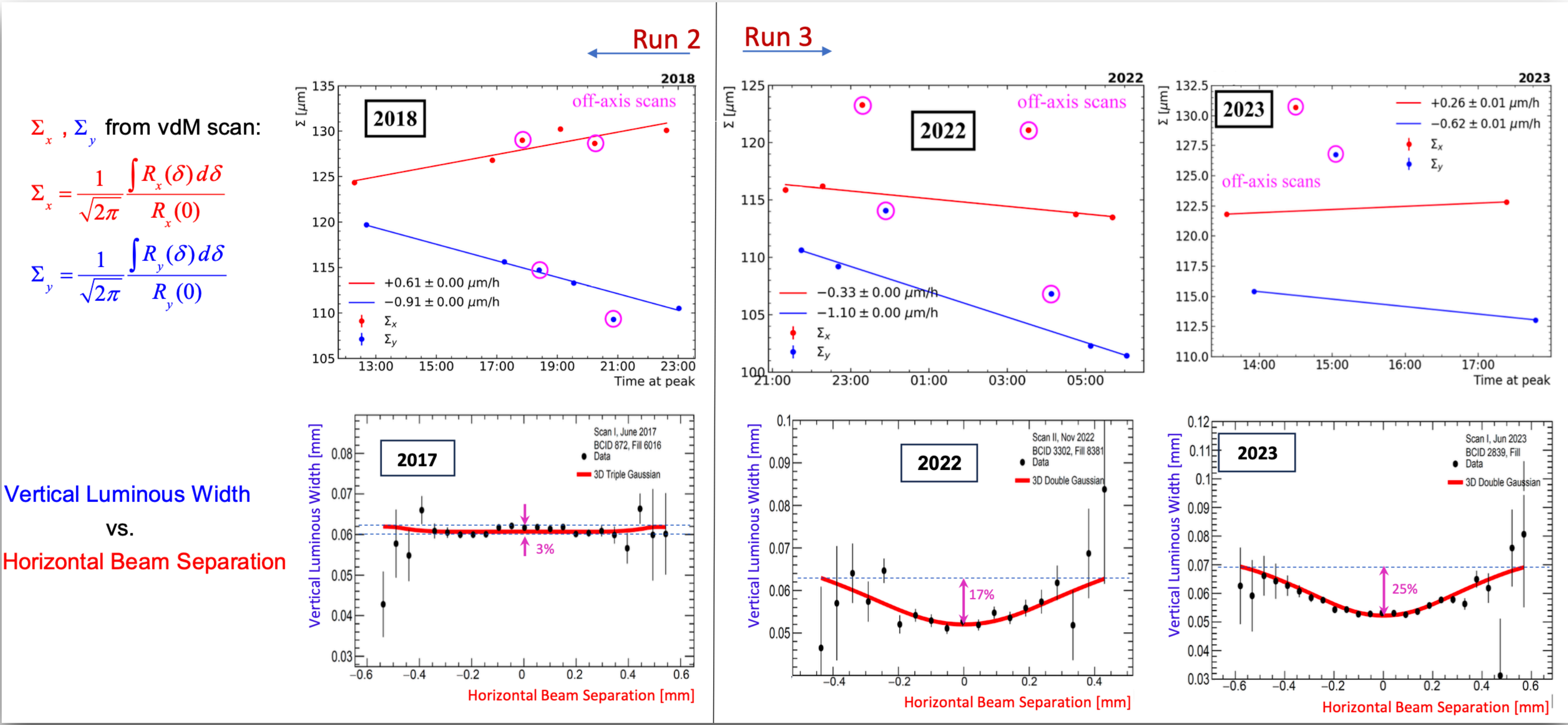
$R_{x,y}(\delta_x,\delta_y) = R_x(\delta_x) R_y(\delta_y)$ is often used $\Rightarrow [\Sigma_x \Sigma_y] = \Sigma_x \Sigma_y$ where 1-d scans provide $\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int R_x(\delta)\, d\delta}{R_x(0)}$ & $\Sigma_y = \frac{1}{\sqrt{2\pi}} \frac{\int R_y(\delta)\, d\delta}{R_y(0)}$

$\Sigma_x (\Sigma_y) =$ horizontal (vertical) convolved beam size: $\Sigma_x = \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}$ for single Gaussian beams, where $\sigma_{jx} =$ horiz beam size

vdM calibration

Evidence for Large Run 3 Non-Factorisation from vdM Scans & LRE

[T. Barklow]



vdM calibration

LRE analysis

[T. Barklow]

Single-beam parameters are obtained from a combined fit to the beam separation dependence of:

- $R(\delta_x,\delta_y)$ ($\mathcal{L}$)
- luminous-region observables: $<x,y,z>_{\mathcal{L}}$, $\sigma_{x,y,z\,\mathcal{L}}$, …

- Single beam parameters provide normalized transverse beam particle densities $\hat{\rho}_1(x,y)$, $\hat{\rho}_2(x,y)$
- Directly calculate $[\Sigma_x \Sigma_y] = \frac{1}{2\pi \int \hat{\rho}_1(x,y)\hat{\rho}_2(x,y)dx\,dy}$.
- Combine $[\Sigma_x \Sigma_y]$ with bunch population product $n_1 n_2$ to get luminosity $L_b = \frac{f_r n_1 n_2}{2\pi\,[\Sigma_x \Sigma_y]}$ free of factorization assumptions.

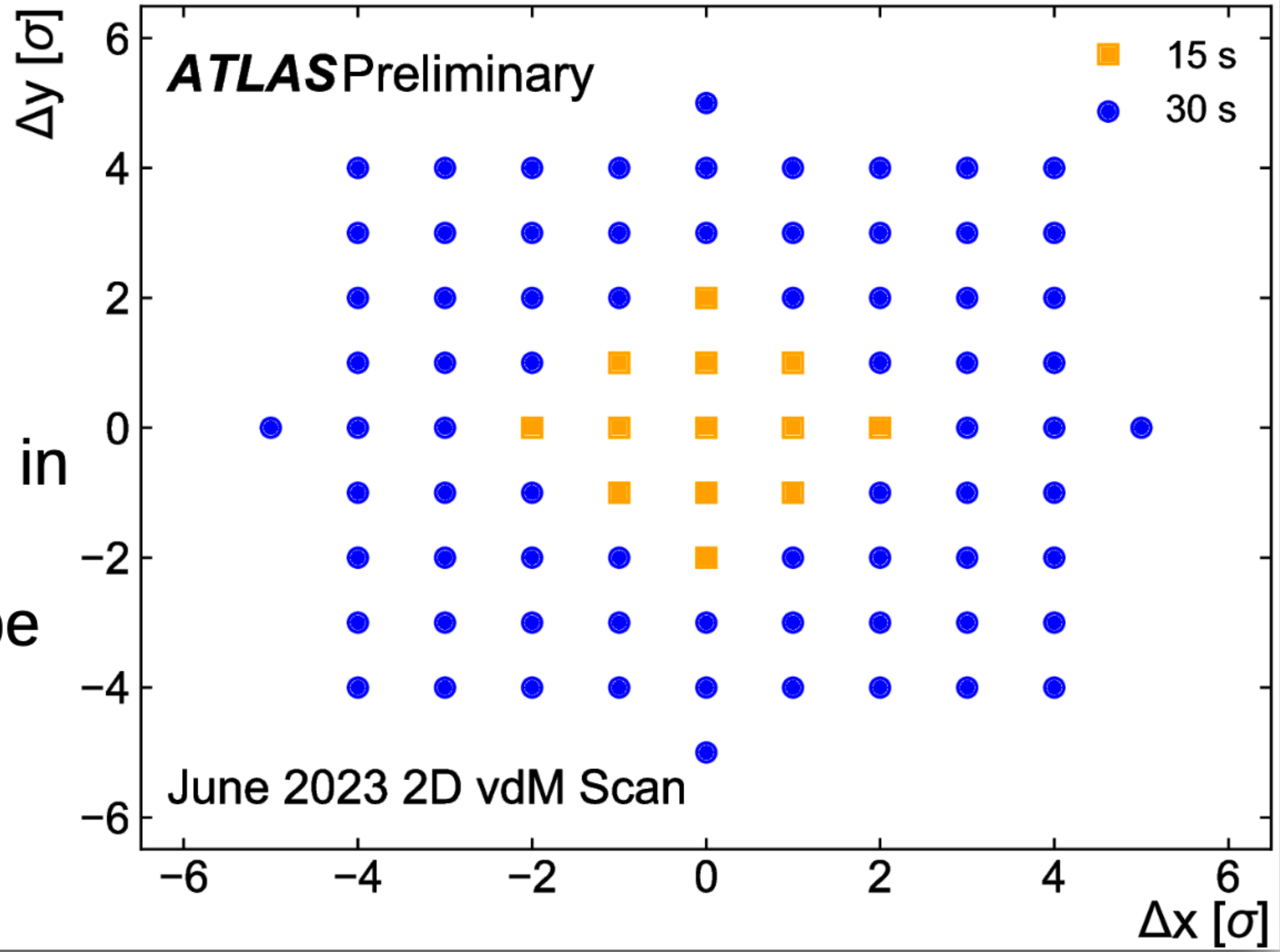
- $\hat{\rho}_1(x,y)$, $\hat{\rho}_2(x,y)$ also used to generate simulated 1D vdM scans
- These scans are analyzed in the same fashion as real vdM scan data (i.e., with the factorization assumption)
- Non-factorization bias $R_{NF} \equiv \frac{L_b}{L_b^0}$ where $L_b^0 = \frac{f_r n_1 n_2}{2\pi \Sigma_x \Sigma_y}$ is from the simulated 1D vdM scan analysis. Historically $1/R_{NF}$ has been applied directly to $\sigma_{\text{vis,1DvdM}}$ to correct for non-factorization: $\sigma_{\text{vis,corrected}} = \sigma_{\text{vis,1DvdM}} / R_{NF}$
- Only 12 of the 136 lumi data beam crossings have beamspot data, so the average $\langle R_{NF} \rangle$ over the 12 BCID's is taken as the correction for each scan.

Non-factorisation analysis

Two roads to understand non factorisation

[K. Mönig]

- LRE analysis: parametrise single beam profile using scan data plus beamspot
  - can measure non-factorisation during scans
  - only possible for few bunches due to trigger limitations
  - needs some assumptions on shape
- Grid scan:
  - perform a scan over a 2d grid
  - can run on all bunches
  - in principle can measure non-factorisation in a model independent way
  - however due to time limitations can only be done once
  - Since non-factorisation changes with time cannot use it to correct 1d scans

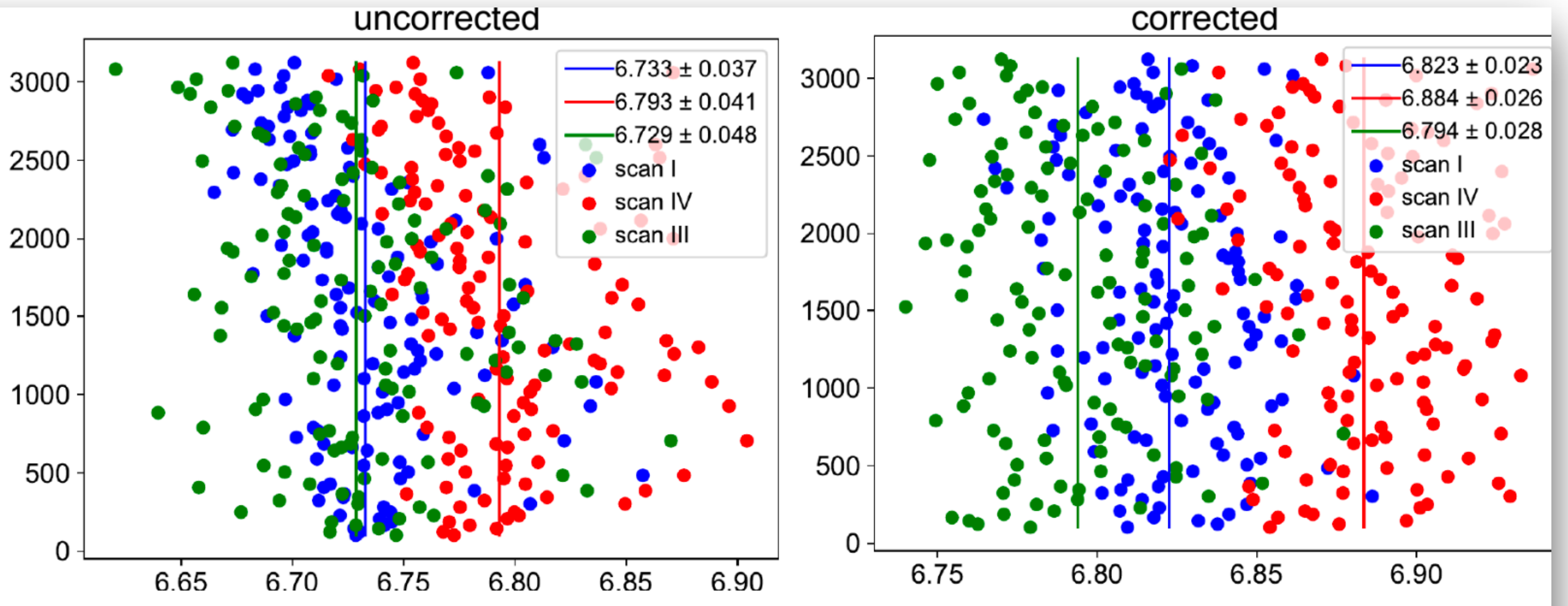


Non-factorisation analysis

Current issues

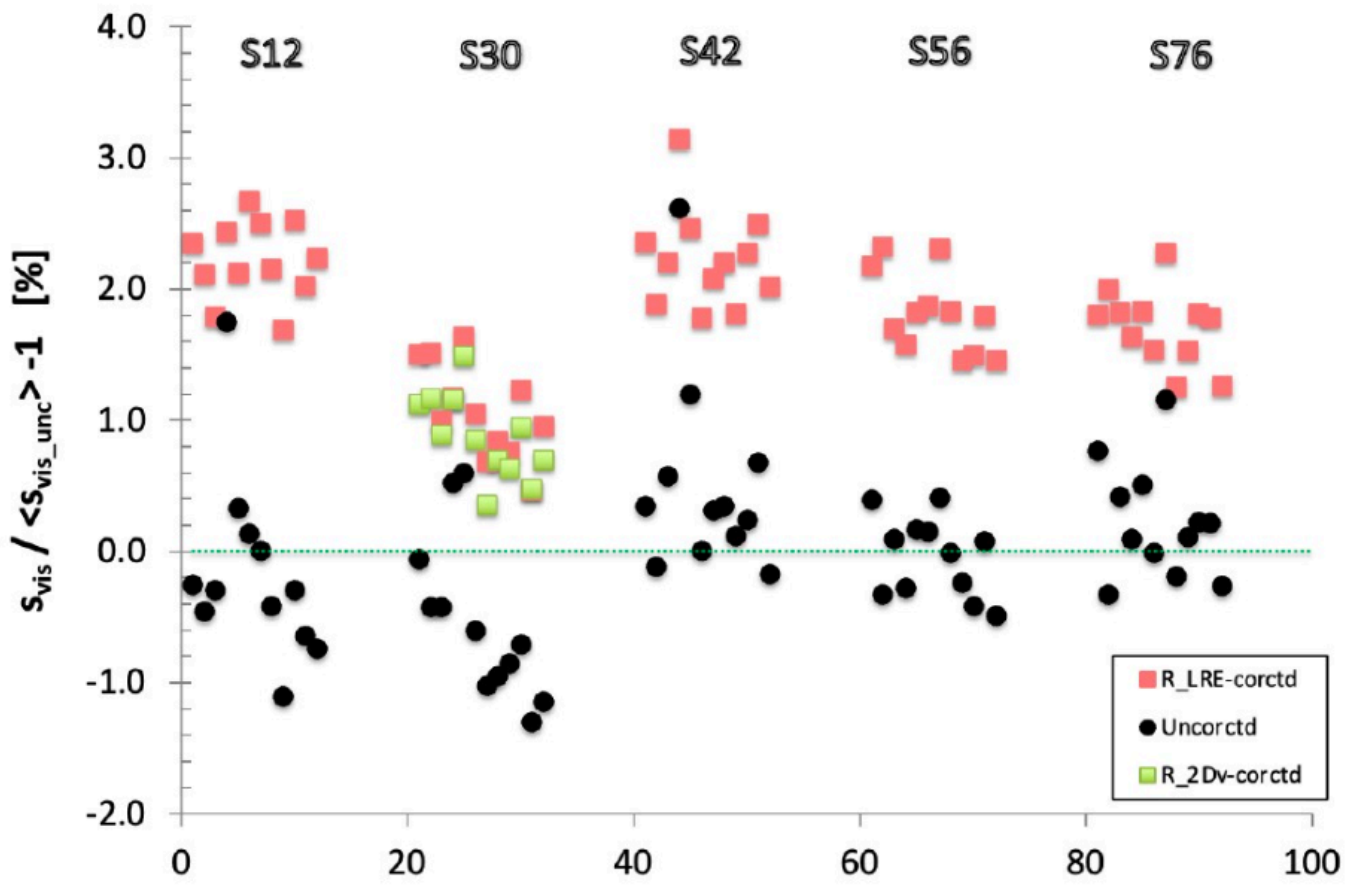
[K. Mönig]

- The 2d scan seems to catch the bunch-by-bunch pattern but cannot be used to correct the 1d scans due to time dependence



2D grid scan (Scan III)

- The LRE fit agrees well with the 2d fit but there seems a bias between the 1d scans and the 2d scan

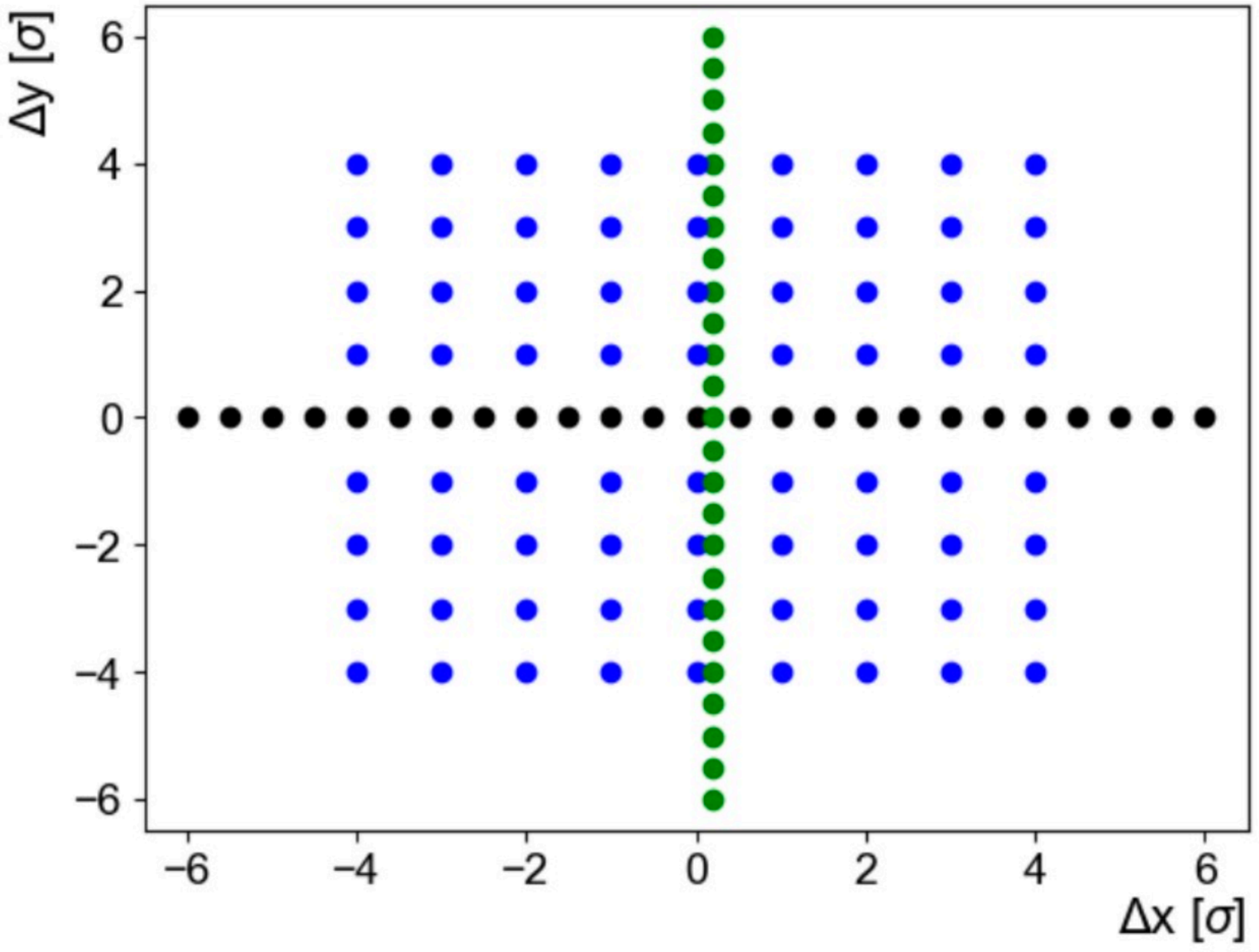


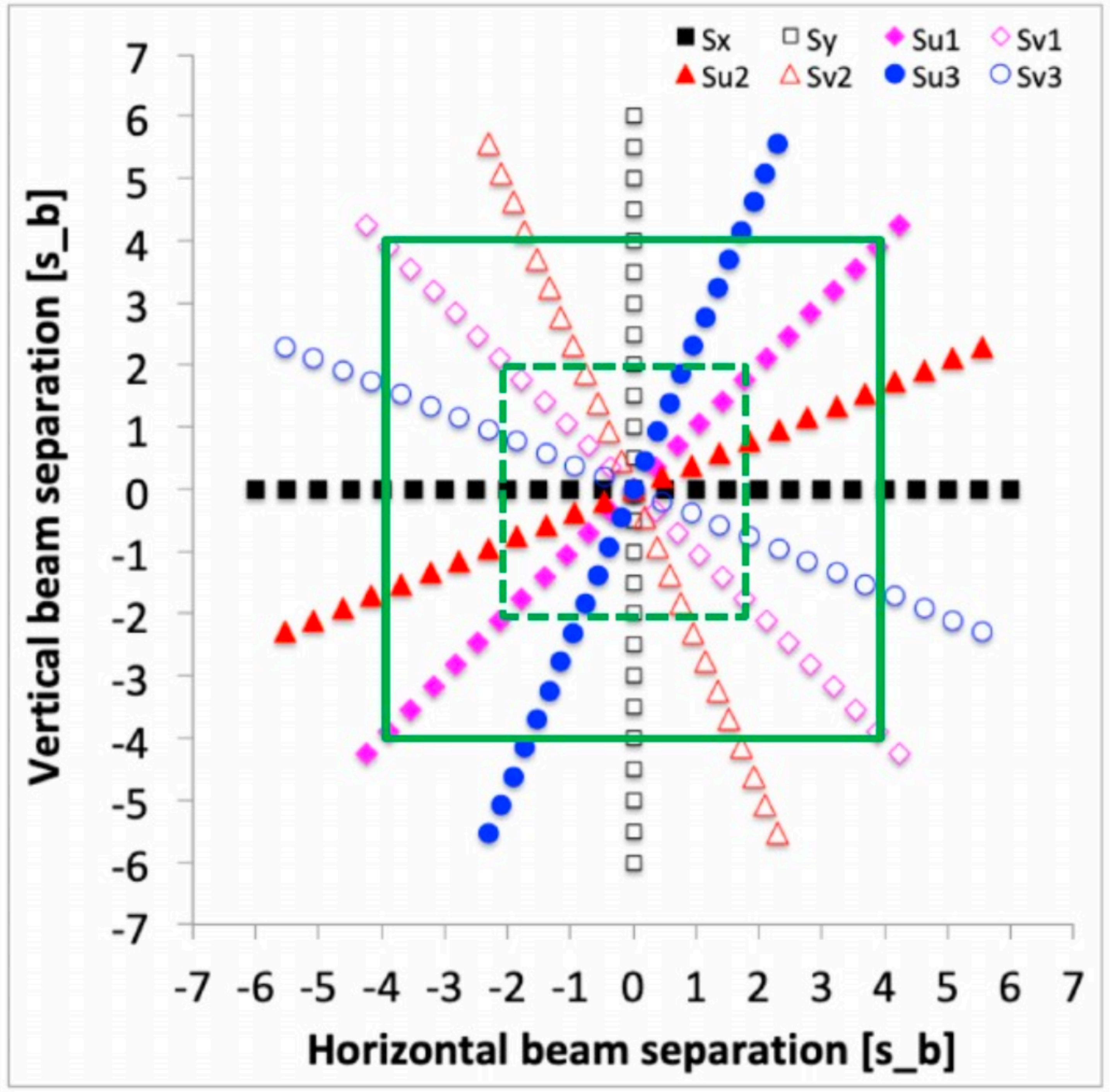
Non-factorisation analysis

Mitigation strategies

[K. Mönig]

- For 2024 embedded a 1d scan into the grid scan to understand possible biases
- Also added diagonal scans to check off-axis points without large time-delays between points





- **Dedicated 'beam tailoring' in injectors to produce Gaussian-like beams reduces non-factorisation**

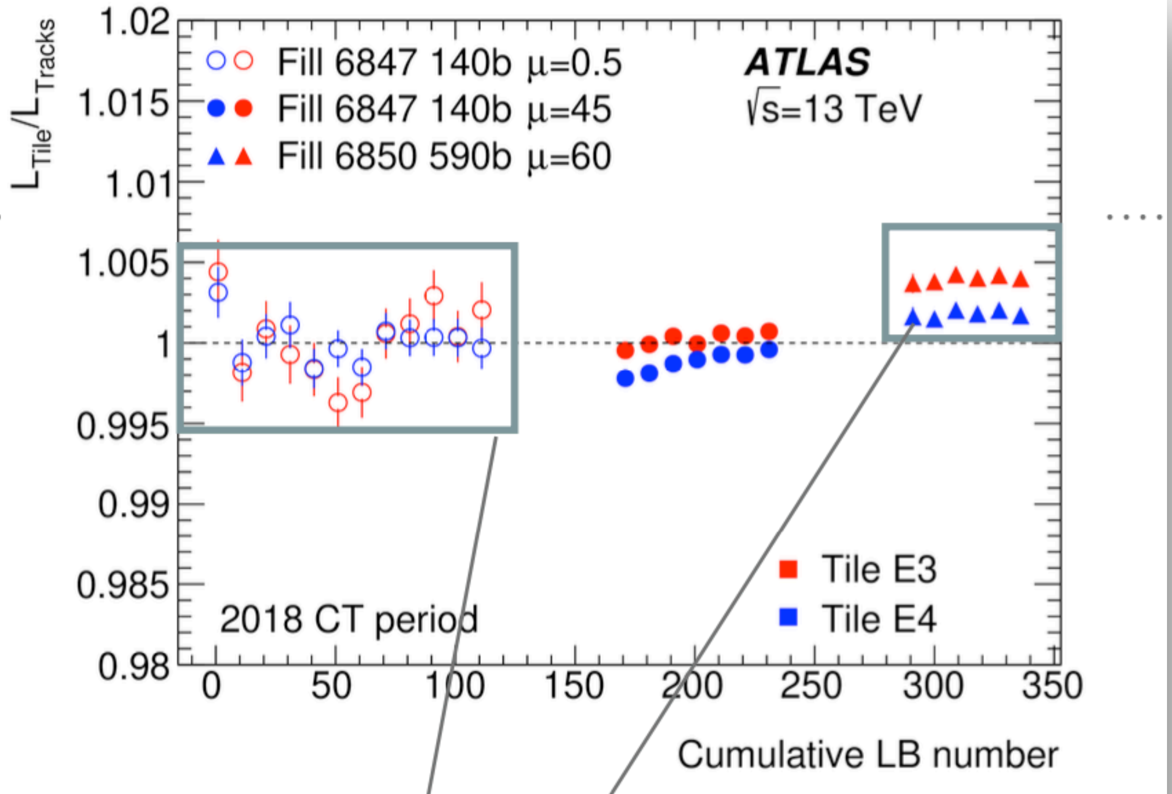
Calibration Transfer

Uncertainty in track-counting luminosity

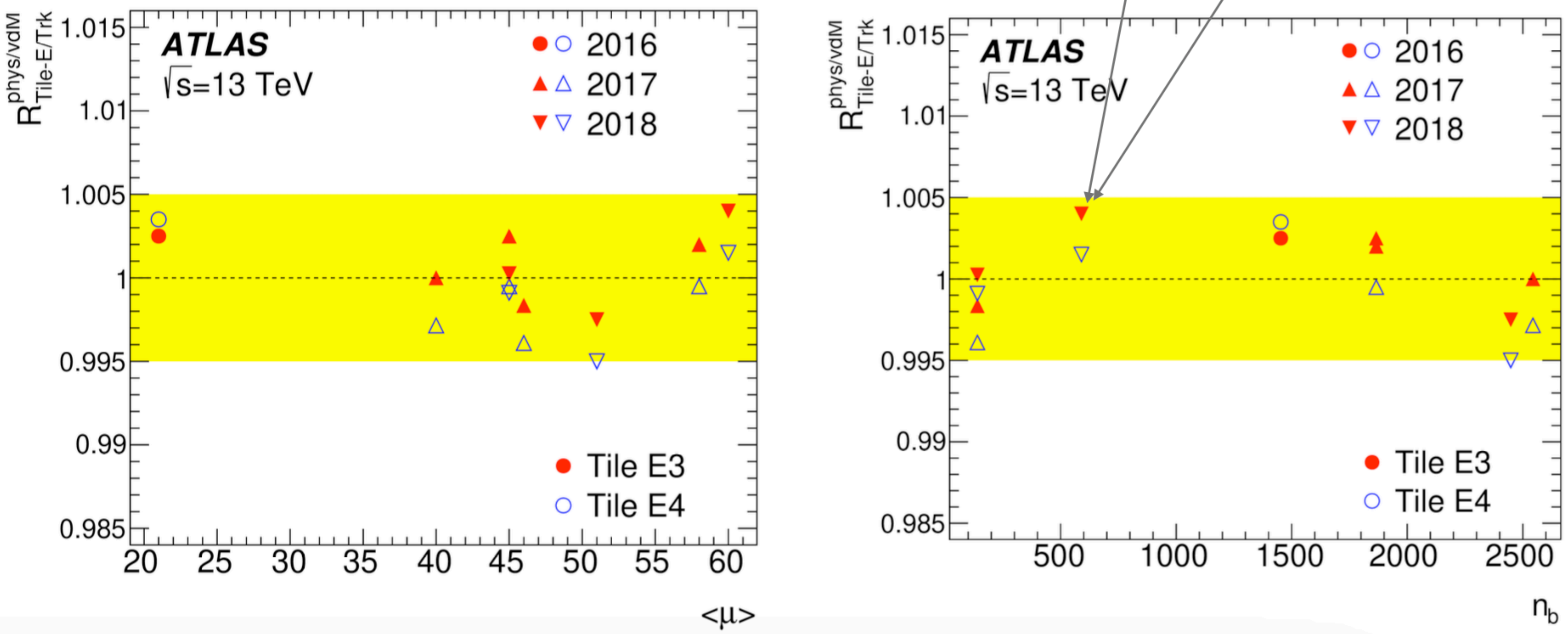
[C. Seitz]

2. Calibration transfer uncertainty

- Check double ratio of $R_{Tile-e/TC}$ in physics vs vdM conditions as a function of $\langle\mu\rangle$ and the number of bunches



Yellow band covers scatter **calibration transfer uncertainty i.e. 0.5 %**



Claudia Seitz, DESY

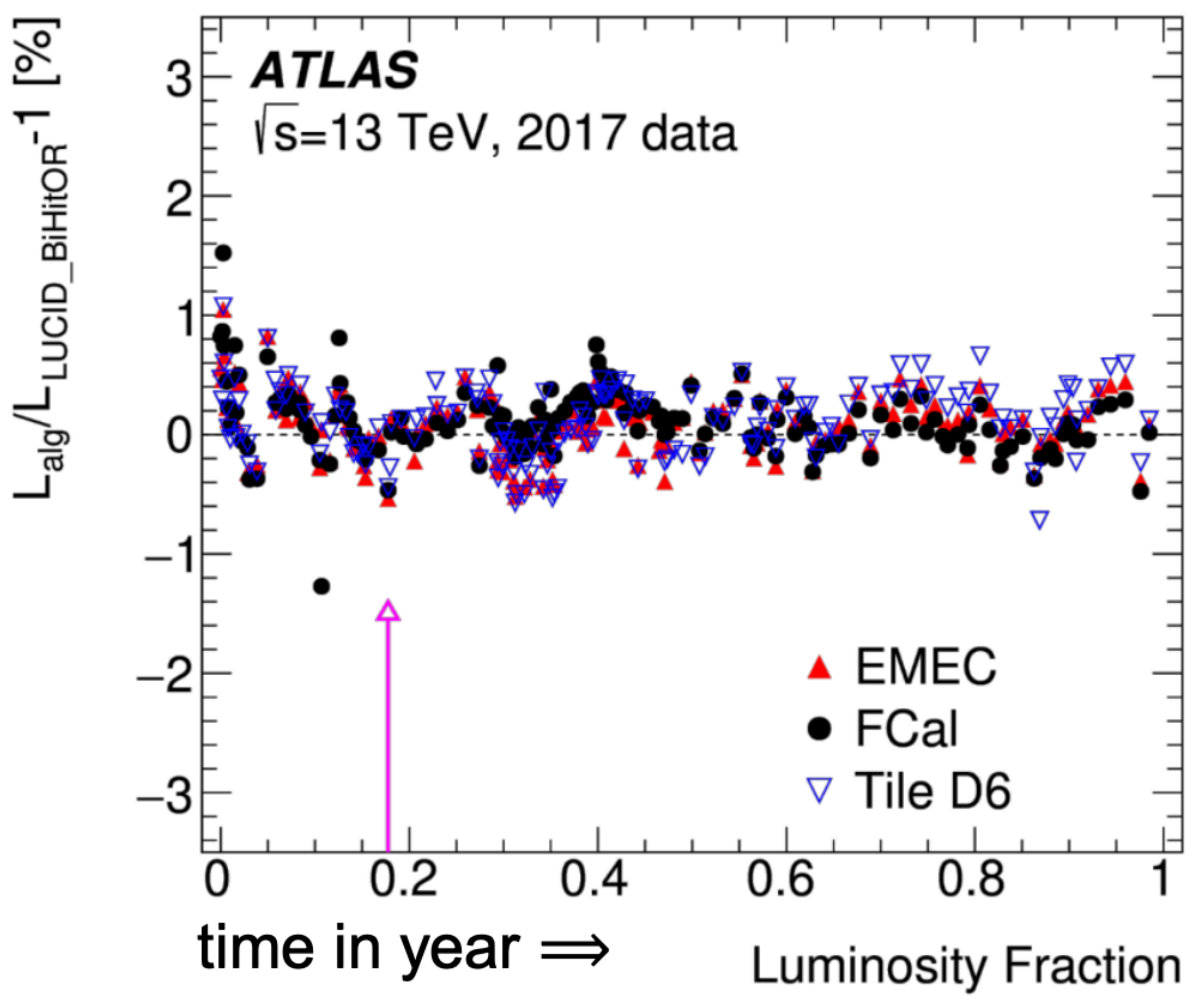
Long-term stability

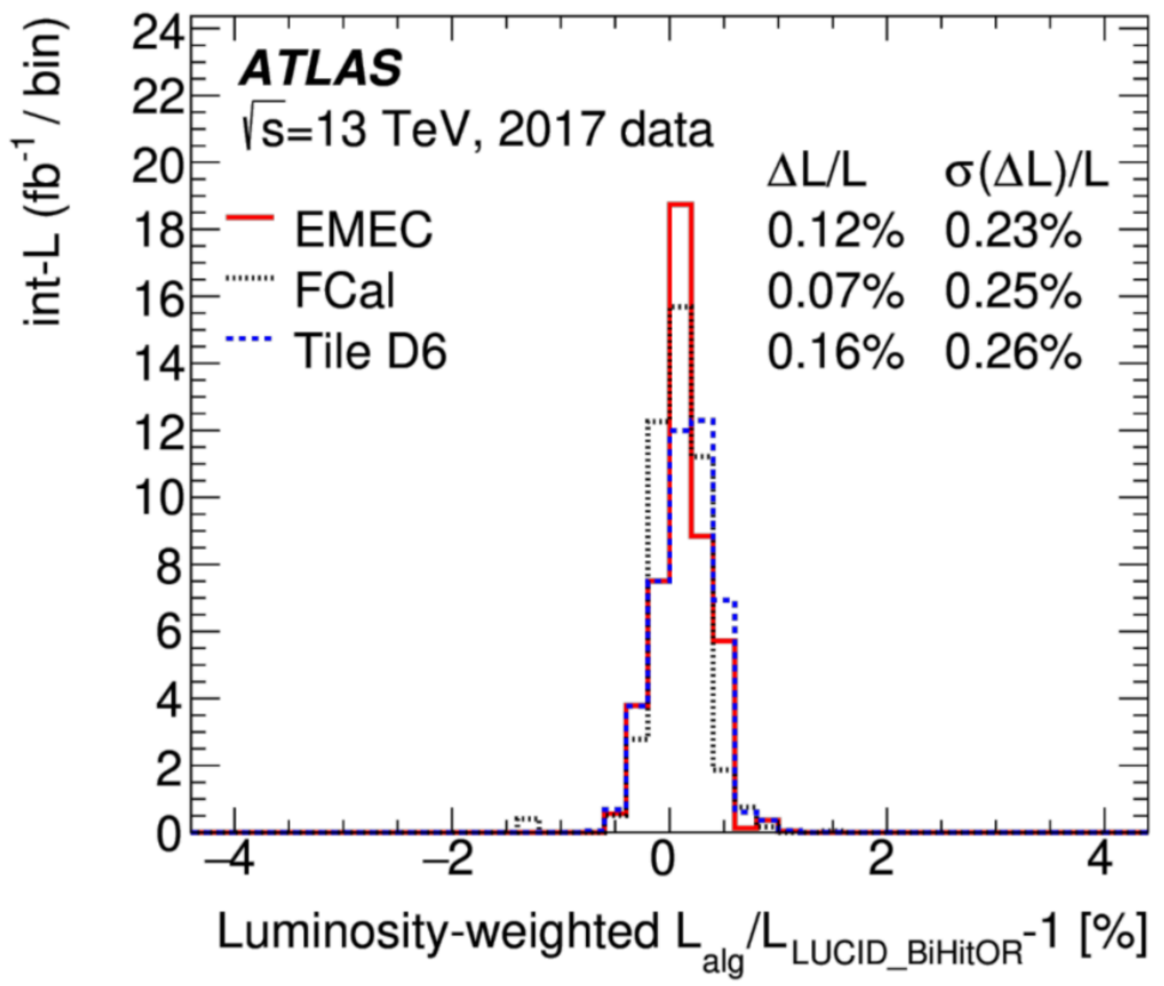
Methodology

[R. Hawkings]

Long-term stability – methodology

- Now study calorimeter/LUCID differences for each run, for EMEC, FCal, Tile
  - ΔL/L typically within 0.5% for long runs, apart from start-up period with low n_b
    - Outliers tend to be short runs with low L_{int}
  - Integrated-luminosity-weighted histogram of per-run ΔL/L is more representative





- Physics analyses interested in possible deviations of L_{int} for whole sample
  - Mean of ΔL/L histogram captures this – take largest mean from EMEC, FCal, Tile to define long-term stability uncertainty (equiv. to taking L_{calo} instead of L_{LUCID})

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Z-Counting

The Method

[J. Newell]

- Use the decays of Z bosons to electrons or muons to determine luminosity:

$$\mathcal{L}_Z = \frac{N_Z}{\sigma_Z}$$

Monte Carlo correction factors and data-driven efficiencies are applied

$$\mathcal{L}_Z(\Delta t) = \frac{N_{Z\to l^+l^-}(\Delta t) \times (1 - f_{bkg})}{F^{\mathrm{MC}}(\mu) \times A^{\mathrm{MC}} \times \epsilon^{T\&P}_{Z\to l^+l^-}(\Delta t) \times \sigma_{theory} \times \Delta t}$$

- Theoretical cross-section does not affect plots shown (Cancels in $\mathcal{L}_{e^+e^-}/\mathcal{L}_{\mu^+\mu^-}$ and $\mathcal{L}_{Z\to l^+l^-}/\mathcal{L}_{ATLAS}$ ratios)

In-situ Z-event-level Efficiency per time (LB):

$$\varepsilon^{T\&P}_{Z\to l^+l^-} = \left(1 - (1 - \varepsilon_{\mathrm{trig},\,1l})^2\right) \times (\varepsilon_{\mathrm{reco},\,1l})^2$$

- Broken down into single-lepton reconstruction (tag-and-probe) and trigger efficiencies

Pileup-dependent Monte Carlo correction factor:

$$F^{\mathrm{MC}} = \frac{N^{\mathrm{reco,fiducial,MC}}_{Z\to l^+l^-}(\mu)}{N^{\mathrm{generated,MC}}_{Z\to l^+l^-}(\mu) \times A^{\mathrm{MC}}} \times \frac{1}{\varepsilon^{T\&P,MC}_{Z\to l^+l^-}(\mu)}$$

- Accounts for non-closure between data-driven reconstruction and trigger efficiencies and the true Z-event level efficiency given by Monte Carlo simulation

3

Oxygen Run

p-O Details

[E. Torrence]

- LHCf is one of the physics priorities for the p-O data, driving IP1 parameters
- Target 1.5 nb^{-1} at $\mu \sim 0.01$ (0.03 for 10%) (~36h of stable beams)
- Max IP1/5 μ not clear, but $\mu \lesssim 0.05$-0.1 was mentioned by Roderik in `21 talk
- LHCf prefers $\beta^* \sim$ 10-20m, probably will get more like 1m (unsqueezed)
- Likely fill pattern with ~24 colliding bunches, > 200 ns spacing
- Vertical (negative) crossing angle (bad for ZDC)

Physics motivation is measuring cosmic-ray cross-sections, needed by astrophysics community, need ~3% precision on lumi uncertainty to match other expected uncertainties

Oxygen Run

O-O Details

[E. Torrence]

- Parameters here are expected to be more HI-like
- Expect something like 0.5 nb^{-1} in one day (one long fill) or 2 days
- Energy requested to match PbPb nucleon-nucleon energy
- μ_{max} ~ 0.6 has been mentioned, may need to be levelled for physics
- May keep β* ~ 1m to save setup time - decided to keep at β* ~ 0.5m
- Vertical (positive) crossing for ZDC, Roderik wants to go to 0 xangle
- Probably 8 bunches colliding (12b_8_8_8) - optimal for all IPs

ATLAS luminosity target probably around 5% to match expected statistics

Oxygen Run

Tentative plan

[E. Torrence]

- For p-O we really want a 5-point LSC - non-linearity significant issue in ‘24 PbPb, large risk if we go to 3 points
- For O-O optics identical to 2024 PbPb - don’t need additional LSC, can argue we roughly know this without too much of a systematic penalty
- Can achieve similar results with 1 head-on + grid as 2 head-on + diagonal, similar time estimates, choose between these internally
- For p-O, believe we can achieve something like 3% in 4 hours (Silver)
- For O-O, believe we can achieve something like 5% in 2.5 hours (Bronze), but with a bit more risk, 1.5 hours would be in the range of 5-7%. Depends on whether LRE analysis alone can constrain NF at all in this data.

2018 ALFA runs at 900 GeV

Dataset composed of 14 runs at $\sqrt{s}$ = 900 GeV + dedicated vdM scans

[V. Maksimovic]

ALFA runs: notable characteristics

- **$\langle\mu\rangle$ = 0.01 - 0.06, β* = 50/100 m**
- No crossing angle
  - 2 runs with with ID ON
  - 3 runs with crystal collimation (CC)
  - 2 runs with β* = 11m
  - Only 5 runs with unpaired bunches

vdM scans: notable characteristics

- Oct 2018: 363514, 363516
  - Fills 7299-7300
  - On-axis scans: S1, S3, S4 (S2 off-axis)
- Nov 2018: 365218, 365219
  - Fills 7406-7407
  - On-axis scans: S5, S6 (S7 off-axis)

- 11 m beam optics
- 150 colliding bunch-pairs
- 2 unpaired bunches per beam
- lucBi2HitOR algorithm used as nominal (using 5 available PMTs)

2018 ALFA runs at 900 GeV

Results

[V. Maksimovic]

LUCID data is used to to estimate the absolute luminosity value for the √s=900 GeV 2018 pp runs

- **Calibrated visible cross-section from vdM: 0.85326 mb ± 0.07%(stat) ± 1.85%(syst)**
  - SigVis value calculated using November session scans only and the lucBi2HitOR algorithm
  - Major contributors to total systematic uncertainty: Reference Specific Luminosity and Non-factorization
- **LUCID and TC data** are analysed to estimate the luminosity value and validate it
- The **main backgrounds** are either subtracted (afterglow + Bismuth) or their contribution is evaluated and accounted for as a systematic uncertainty (single-beam)
- A calibration method for the **LUCID AND** algorithm has been developed, allowing to improve the reliability of the stability uncertainty
- Given that the β*=11m dataset is composed only by 2 runs (only one with unpaired bunches, non with TC available), it was decided to quote the same systematic uncertainty as for the β*=90/100 m dataset

$$\beta^* = 11\,\mathrm{m} \qquad \mathscr{L} = 504.9 \pm 0.4_{stat} \pm 12.5_{sys}\ \mu\mathrm{b}^{-1}$$

$$\beta^* = 50/100\,\mathrm{m} \qquad \mathscr{L} = 932.6 \pm 0.5_{stat} \pm 23.0_{sys}\ \mu\mathrm{b}^{-1}$$

Uncertainty [%]	$\beta^* = 11\,\mathrm{m}$	$\beta^* = 50/100\,\mathrm{m}$
Stability	1.46 (sys)	
vdM calibration	1.85 (sys)	
Single-beam background	0.74 (sys)	
Total systematic	2.47	
Statistical uncertainty	0.079 (stat)	0.053 (stat)
Total uncertainty	**2.47**	**2.47**

2018 ALFA runs at 900 GeV

Track counting data

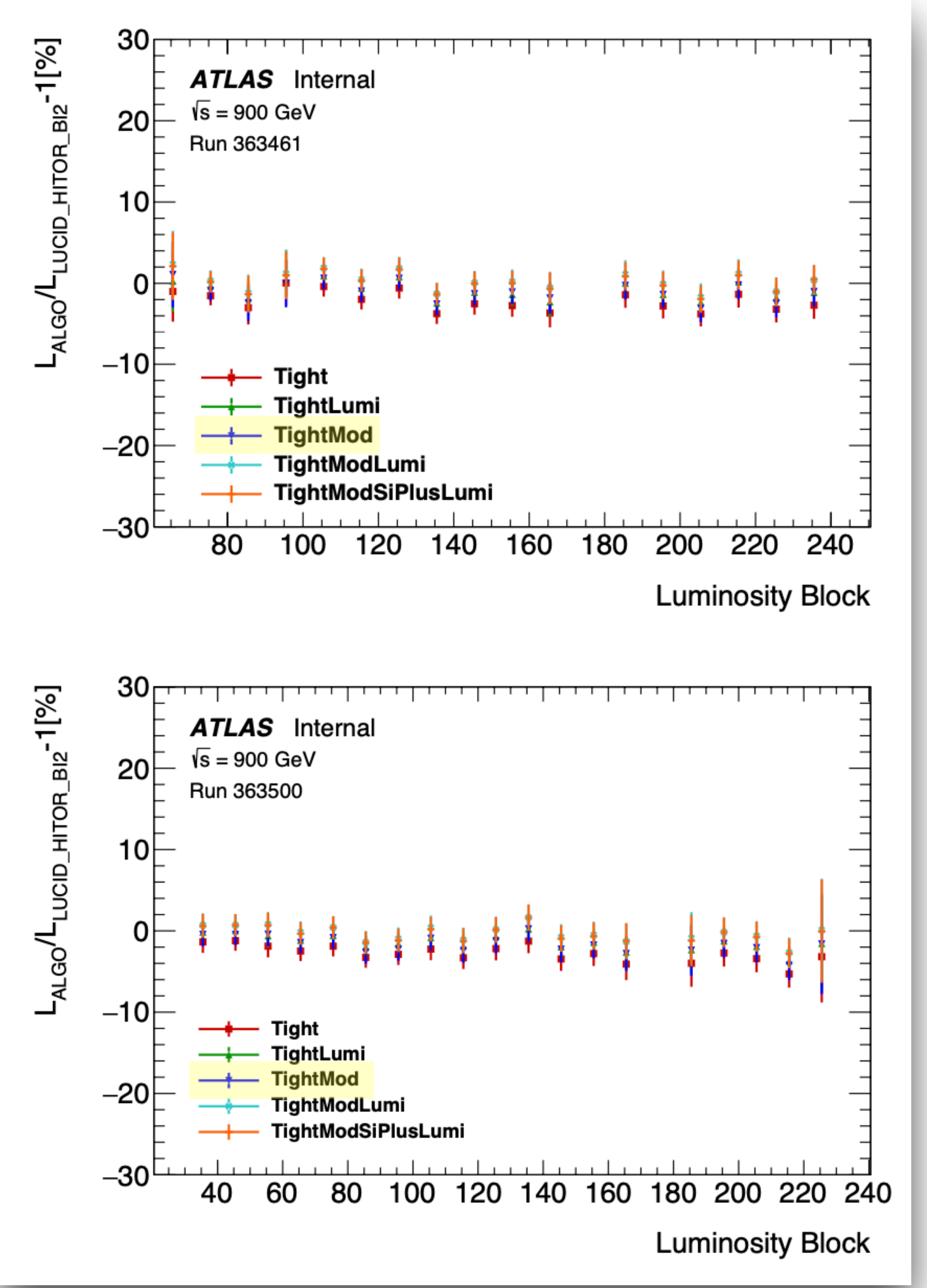
Track counting (TC) data from the Inner Detector is compared to LUCID's measurement **for stability evaluation**

Note: this is the only other detector that could provide a measurement in this regime (Calo has no sensitivity in this low-μ regime)

- Inner Detector data available in 2 runs, with a reduced LB selection
- TC data anchored to reference algo (LUCID HITOR BI2) in non-scan periods of the November vdM runs
- TC selection optimised for low-luminosity: **TightMod**

Algorithm	$\mathscr{L}_{tot}$ [μb^{-1}]	$\Delta\mathscr{L}/\mathscr{L}_{ref}$ [%]
LUCID_HITOR_BI2	154.76 ± 0.22	//
TightMod	152.79 ± 0.20	-1.27 ± 0.19

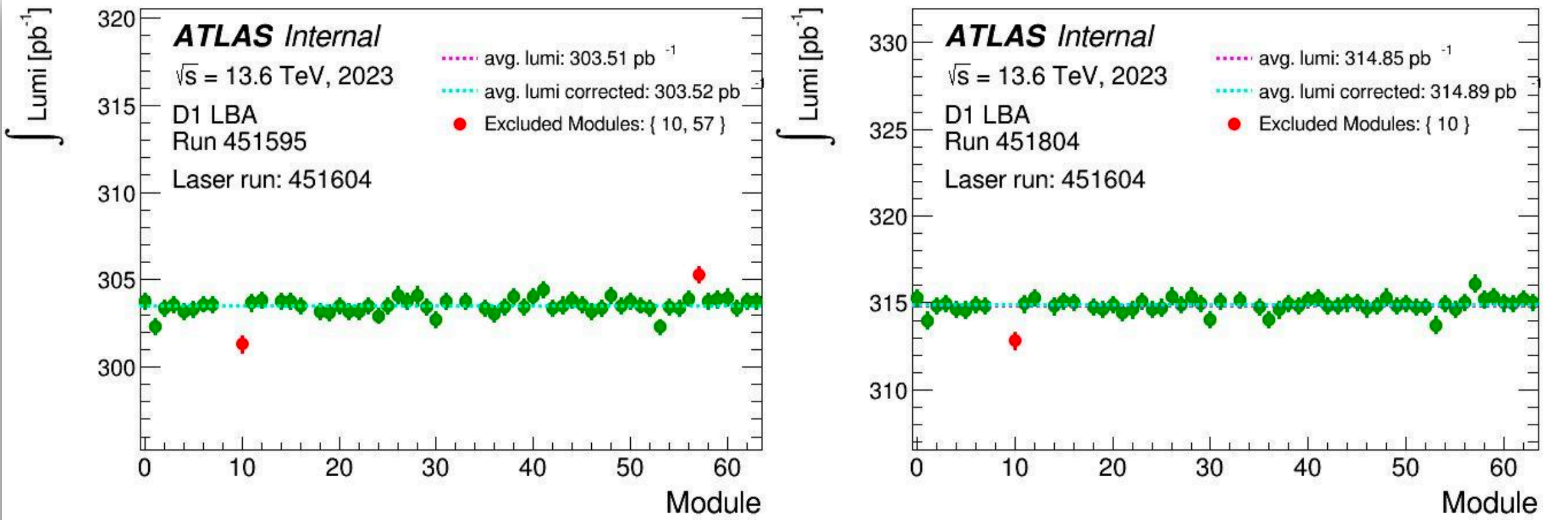
[V. Maksimovic]



Luminosity measurements Using TileCal

Laser corrections

[P. Rapheeha]



- TileCal employs the Laser Calibration to correct for variation in PMT responses
- See Rute's presentation on Laser correction derivation
- After Application of Laser corrections, modules that have luminosities at are 3 std. deviations from the mean are excluded
  - Such modules are typically less than 2 for most runs
  - The Laser run from which the correction are derived is given in the legend
- This exclusion is done on a per-run basis

6

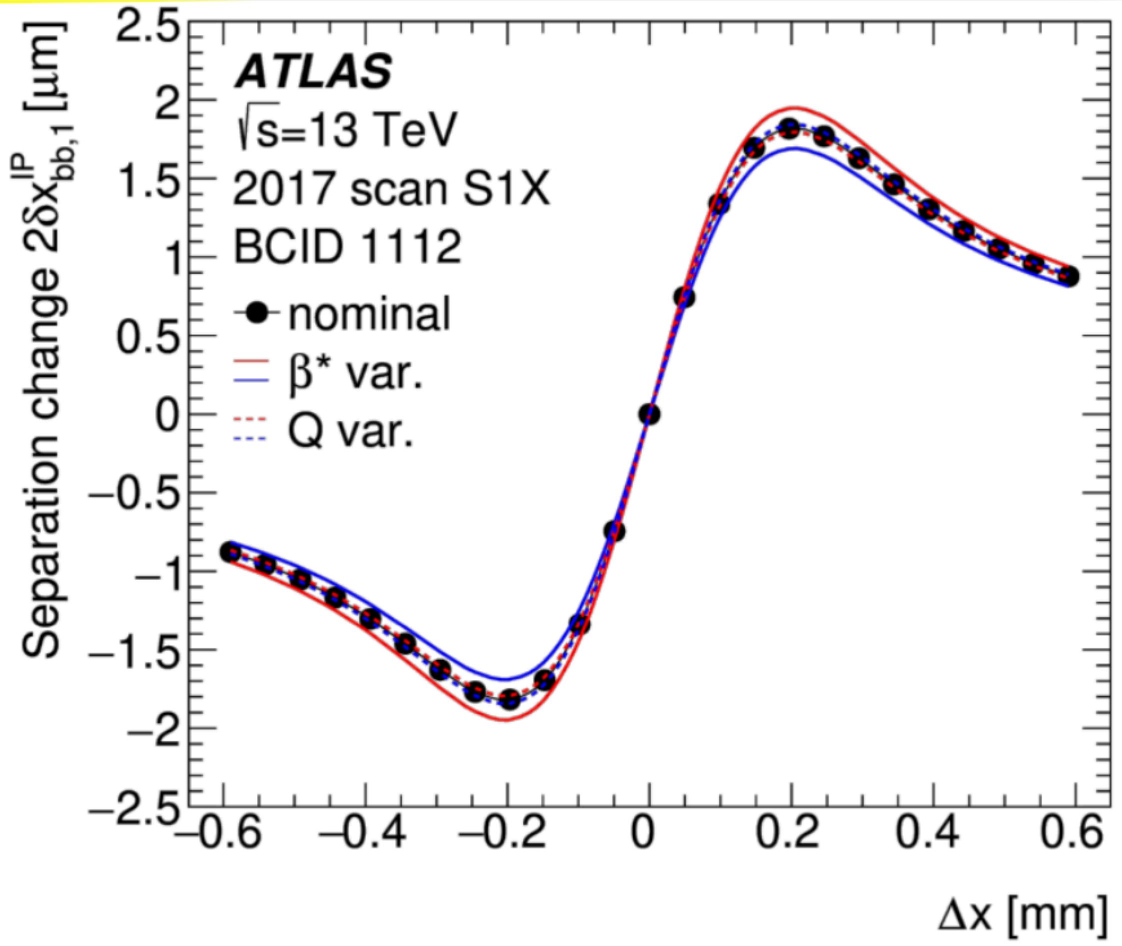
vdM calibration

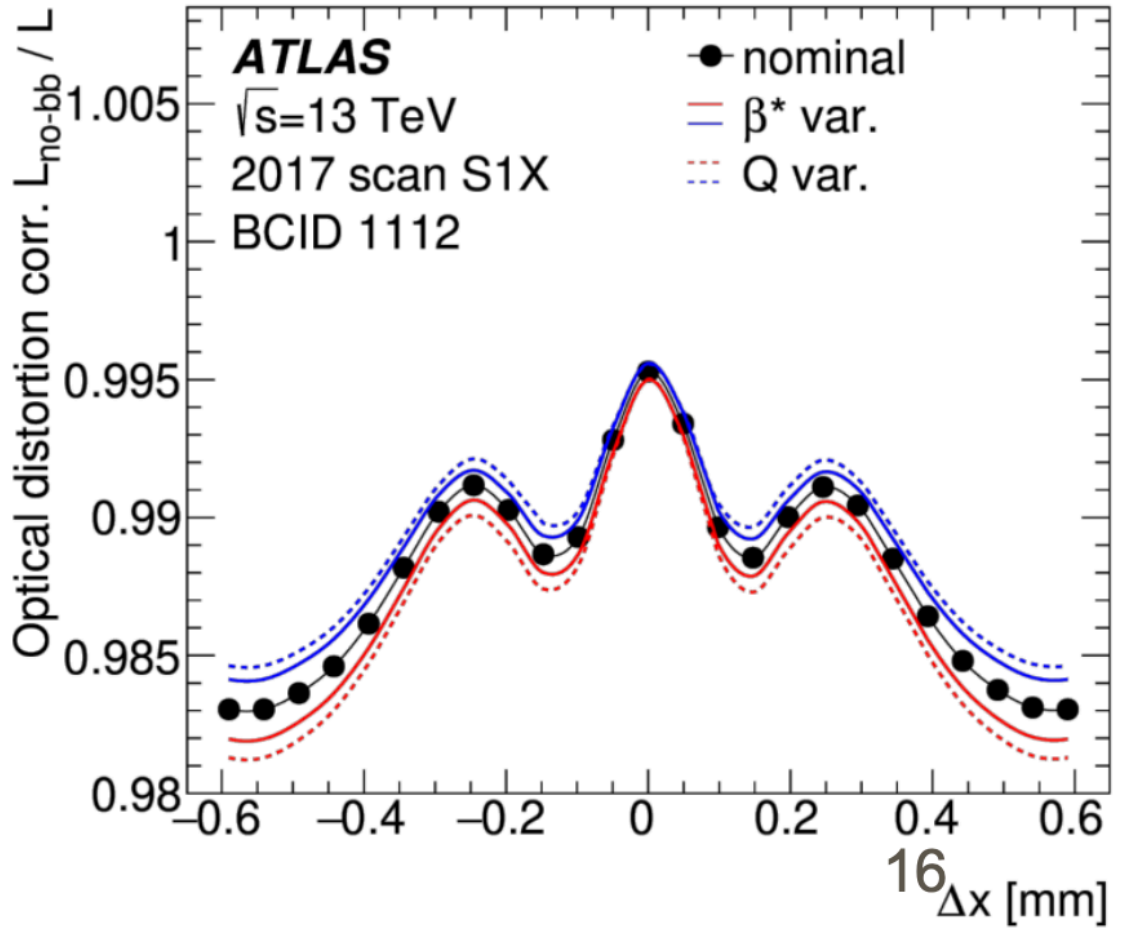
Beam-beam effects

[R. Hawkings]

- Two effects from EM repulsion of colliding bunches
- 1) Separation-dependent beam-beam deflection
  - Beams give each other an angular kick θ_x resulting in an additional separation δ_x above that requested
  - Well-understood, depends on Δx, n_2, Σ_x
  - Corrections to Δx of up to 2 μm at Δx=200 μm
- 2) Optical distortion, aka dynamic β
  - Opposing bunch defocuses the beam, changing its size and shape as a function of Δx, changing L_{inst}
  - Previously handled with a linear approximation
    - Beam-beam force is non-linear; proton in centre of the bunch feels a different force to one at the edge
  - Intensive common study in LHC luminosity WG, with multiparticle tracking codes COMBI and B*B
    - Developed parameterised correction as fn of ξ_R

$$\frac{L_{\text{no-bb}}}{L}(\Delta x) = f(\Delta x, Q_x, Q_y, \xi_R) \qquad \xi_R = \frac{r_p \bar{n} \beta^*}{2\pi\gamma\Sigma_x\Sigma_y}$$





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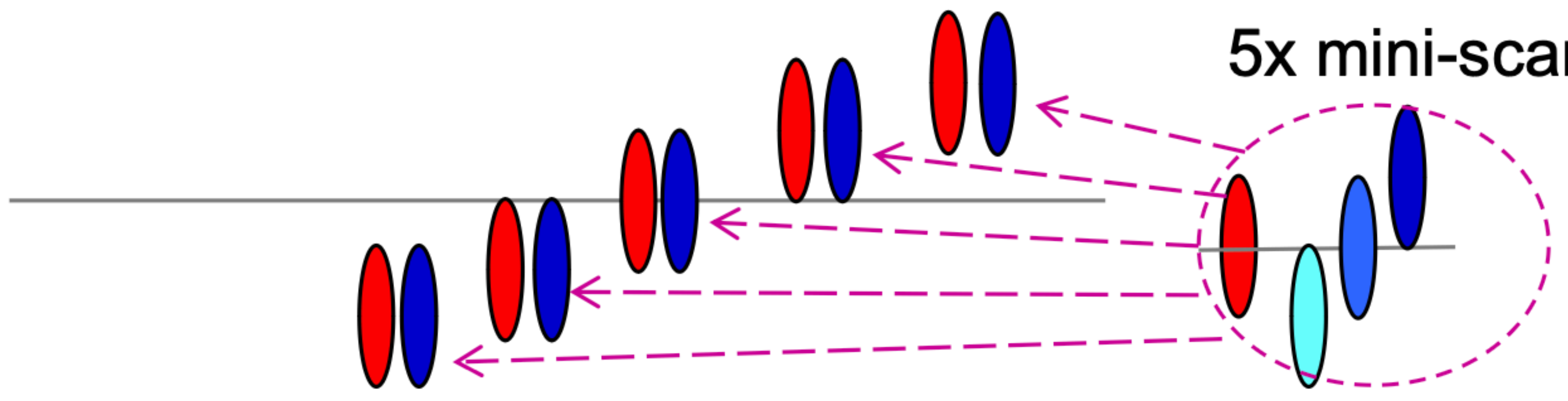
vdM calibration

Length scale calibration

[R. Hawkings]

Relation between requested/real beam displacement

- Calibrated in 5-point LSC scans, per beam, x/y, year



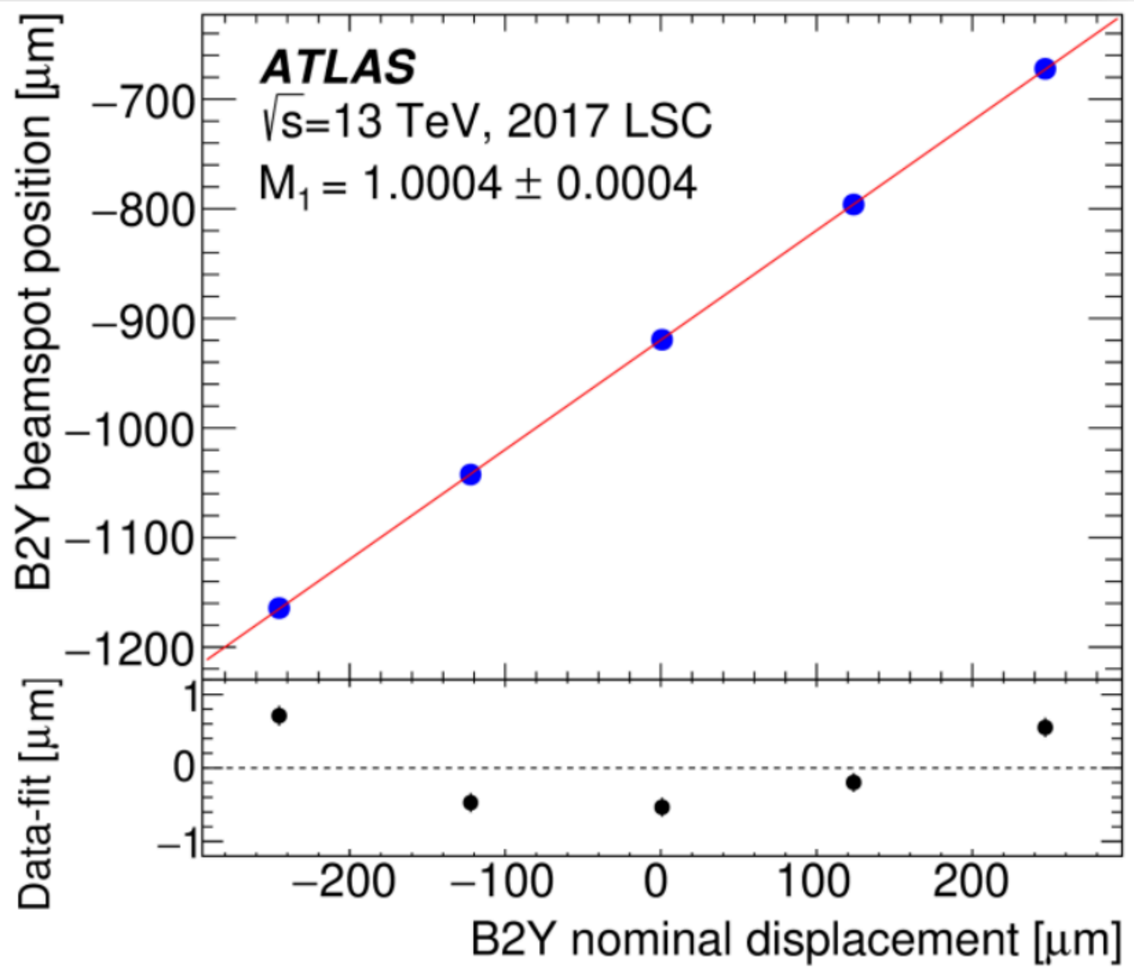
- True beam displacement measured from beamspot positions reconstructed from tracks in ATLAS ID
  - 3-point mini-scan of 'witness' beam around each position to interpolate to head-on collisions

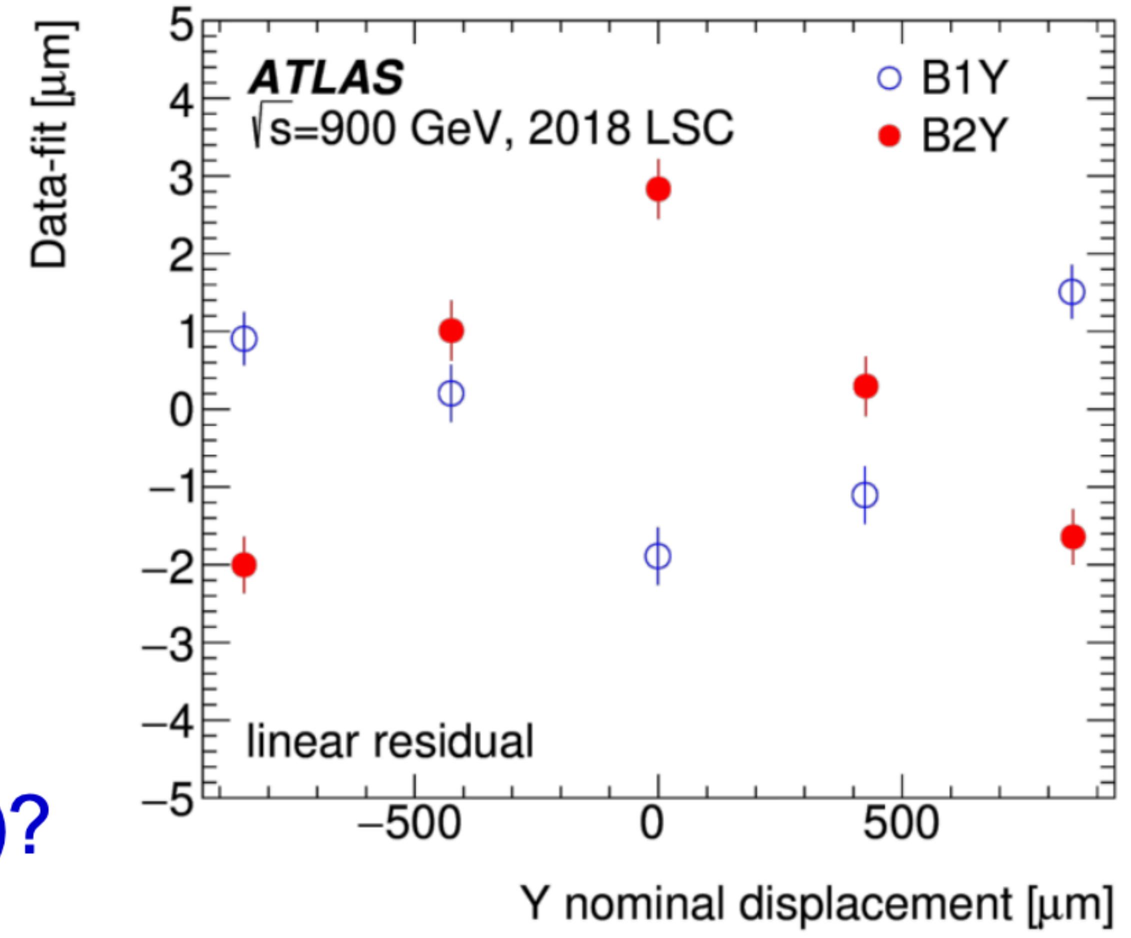
Length scale factors M_1 all within $\pm 0.4\%$ of unity

- With random scatter from year to year
- σ_{vis} scales by L_{xy}: $L_{xy} = (M_1^{x,1} + M_1^{x,2})(M_1^{y,1} + M_1^{y,2})/4$

Fit residuals hint at potential non-linearities

- Much clearer in a LSC scan at 900 GeV in late 2018
- Reproducible? Magnet hysteresis (direction-dependent)?





vdM calibration

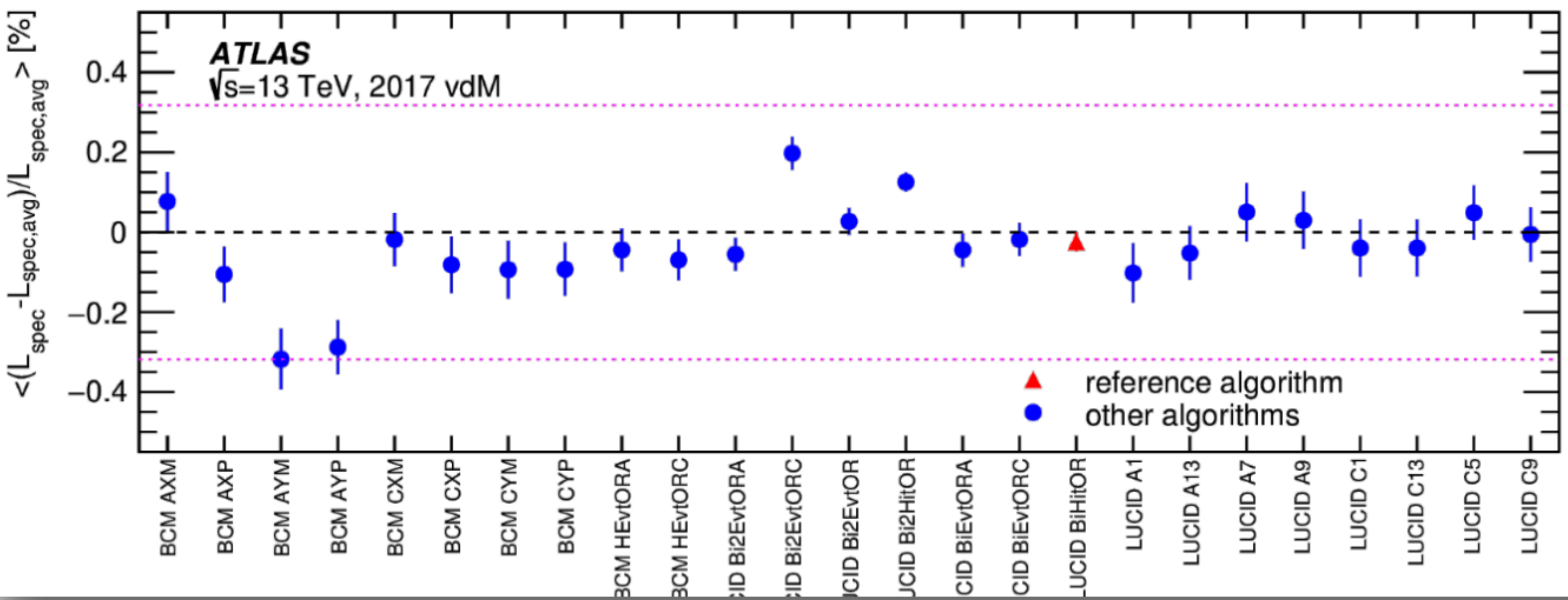
Consistency checks

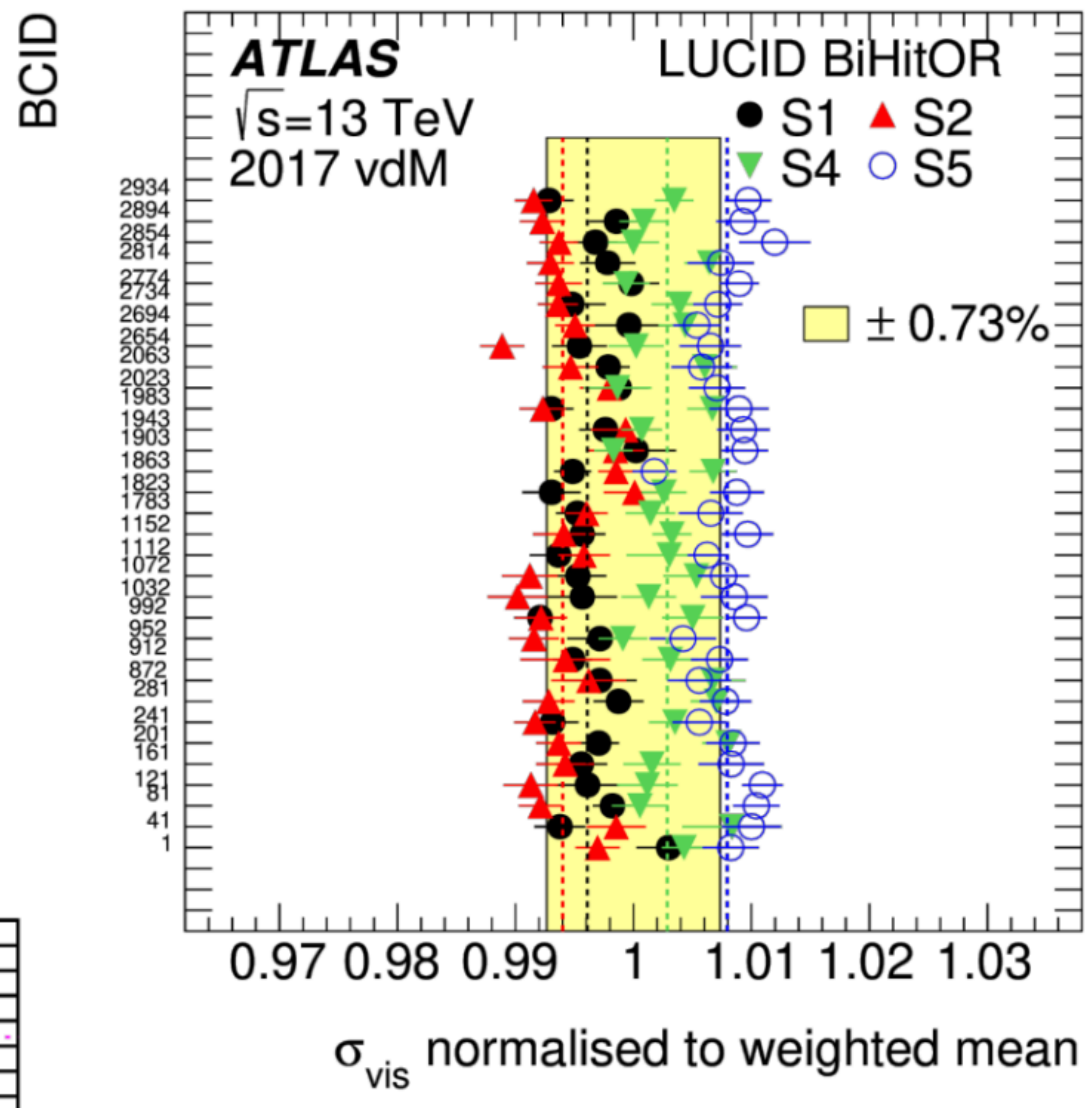
[R. Hawkings]

- Bunch-by-bunch consistency, up to 0.4%
  - Calculate RMS of σ_{vis} over all bunches in each scan, subtract expected spread due to stat. errors
- Scan-to-scan consistency, up to 0.7%
  - Sampling-corrected RMS of all scans in one year
- Reference specific luminosity L_{spec}:

$$\mathcal{L}_{\text{spec}} = \frac{\mathcal{L}_{\text{b}}}{n_1 n_2} = \frac{f_{\text{r}}}{2\pi \Sigma_x \Sigma_y}$$

  - Per-algo. deviation averaged over all bunches/scans





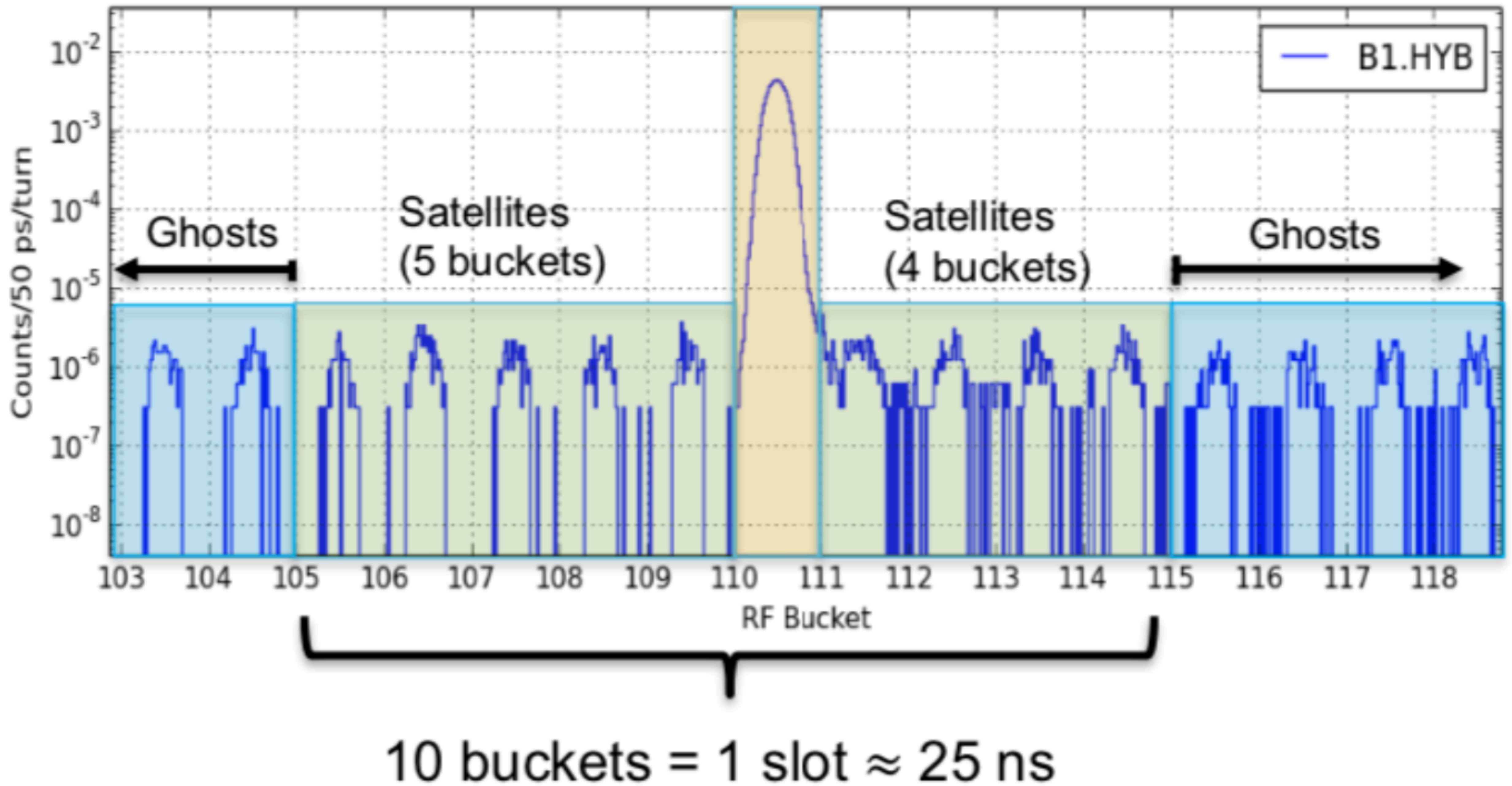
- **Total** per-year uncertainty on σ_{vis}:
  - **0.7-1.0%**

vdM calibration

Bunch population measurements

[R. Hawkings]

- Measuring n_1 and n_2 relies on LHC instrumentation and LHCb SMOG
  - LHC ring has 3564 25ns bunch slots, each divided into 10 RF buckets (400 MHz)
    - Particles circulate stably in all these RF buckets
- Structure as seen by LHC longitudinal density monitor (LDM)



Marcus Palm, LHC lumi days 2019

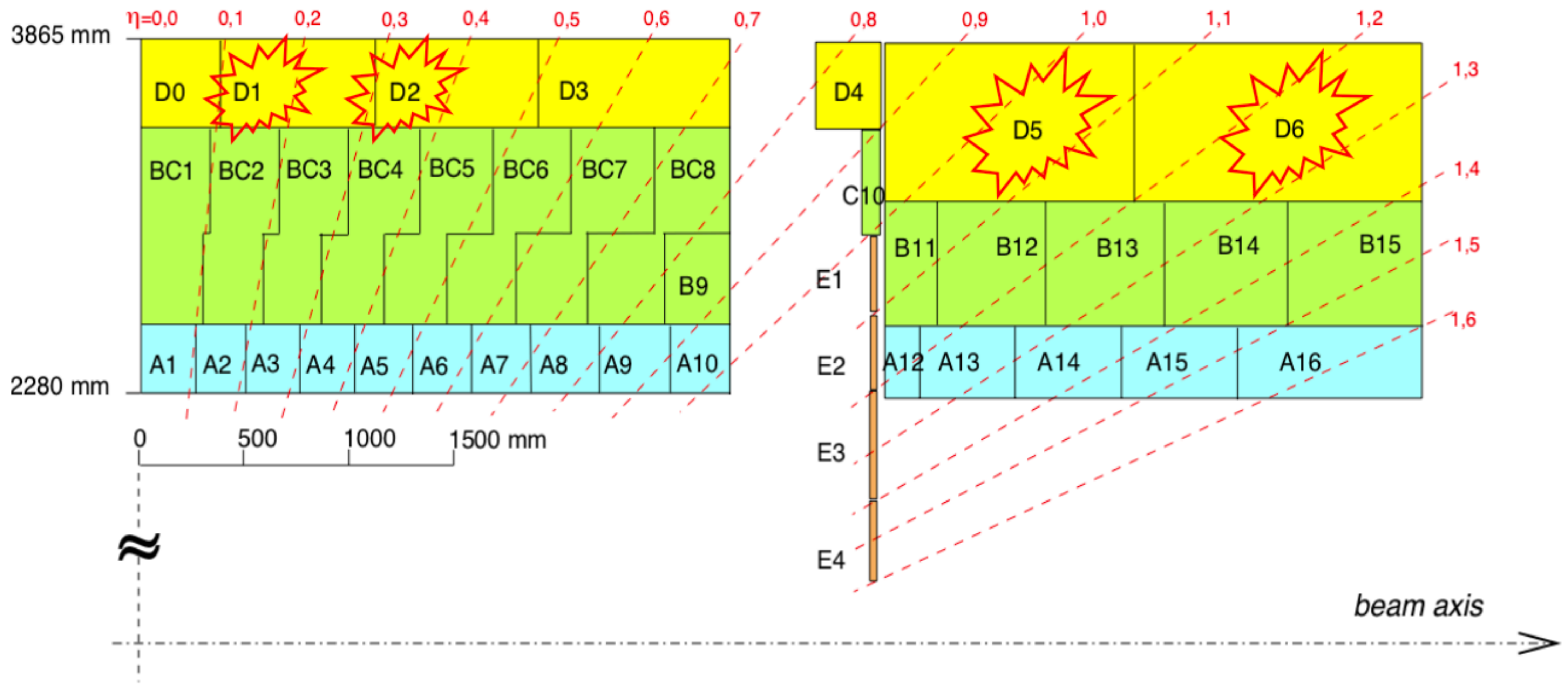
- **Satellites:** charge in filled slot, but in the wrong bucket
- **Ghosts:** charge in nominally-empty bunch slots (unfilled BCIDs)

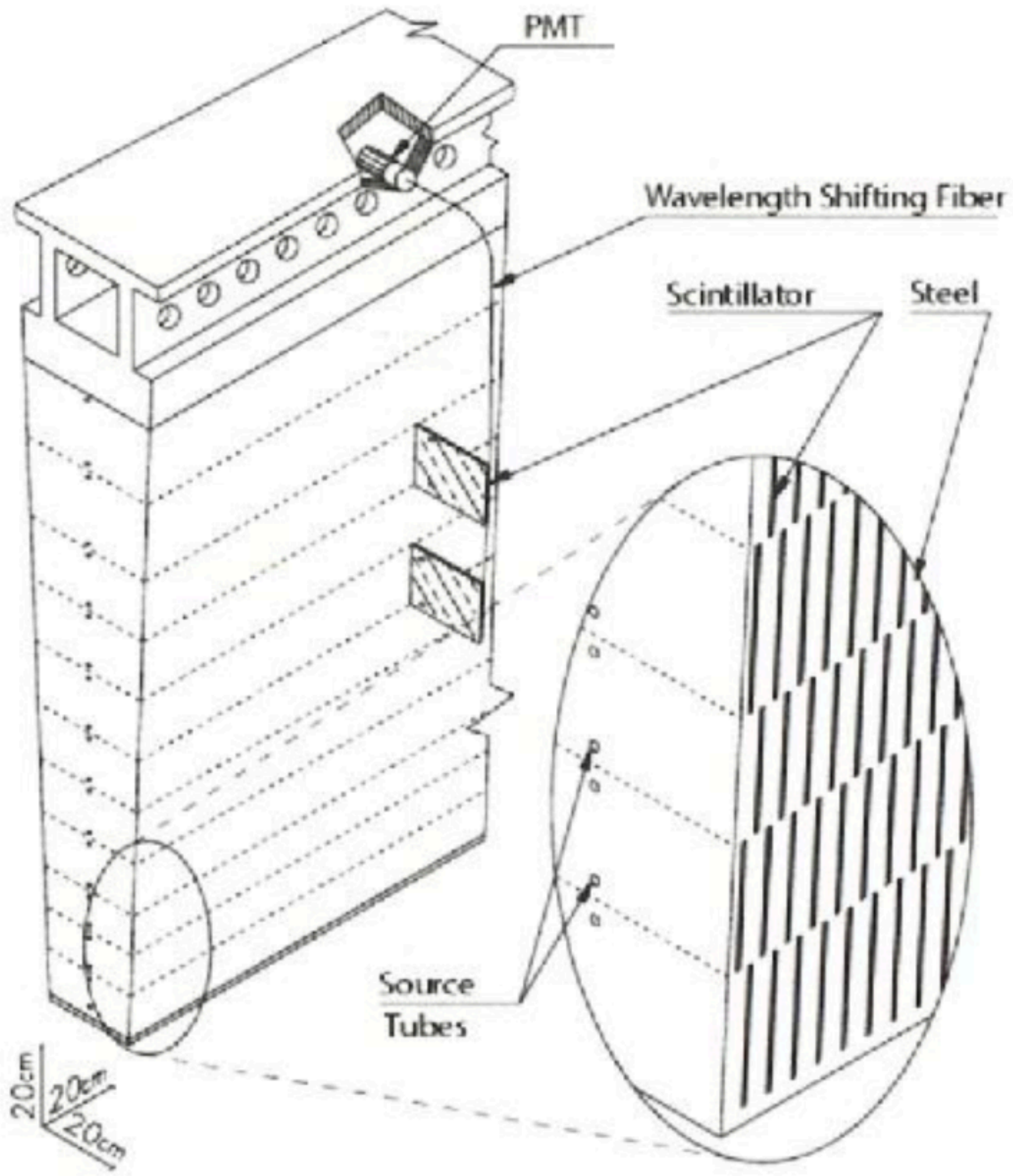
Luminosity measurements Using TileCal

TileCal as Luminometer

[P. Rapheeha]

- The Tile Calorimeter has 64 wedge shaped modules around the beam axis and segmented longitudinal into three sections.





- Primary offline TileCal luminosity measurements for the Long-Term stability studies are obtained from D5/D6 cells
- D1 and cells will be used for systematic comparisons

Luminosity measurements Using TileCal

TileCal as Luminometer

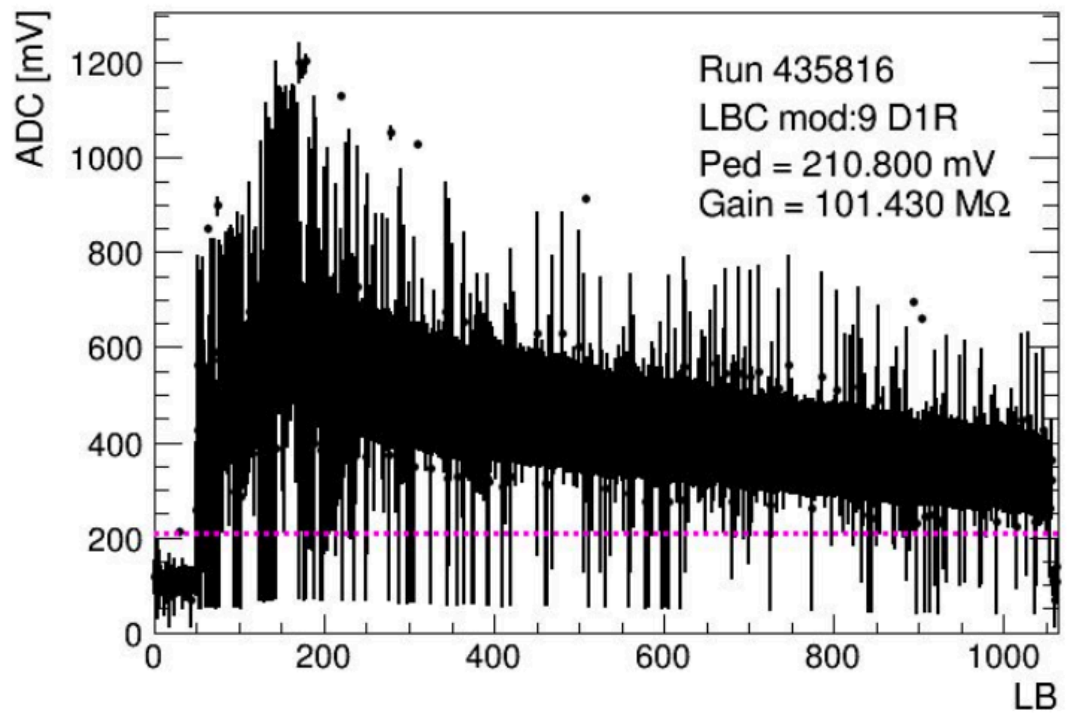
[P. Rapheeha]

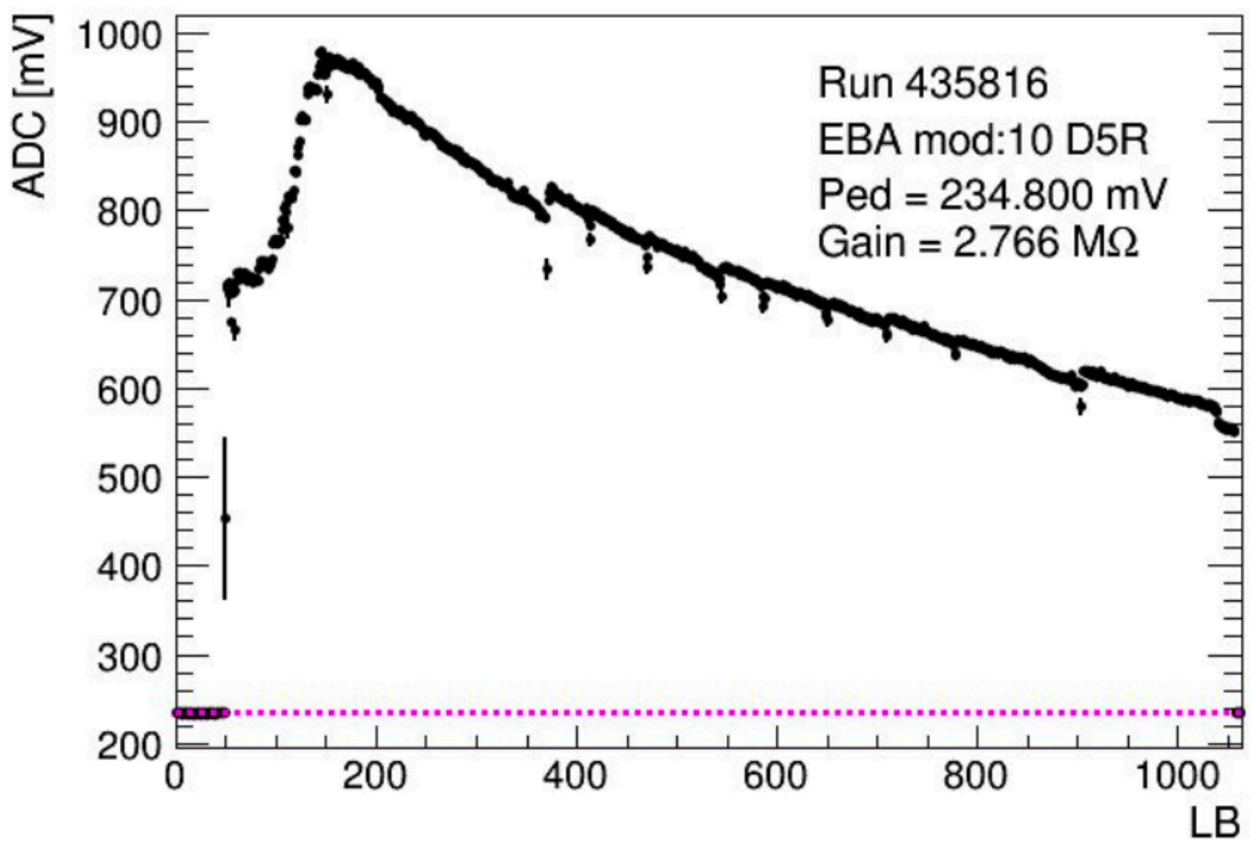
- Each cell is read by two PMTs
- The collision induced PMT current is given by:

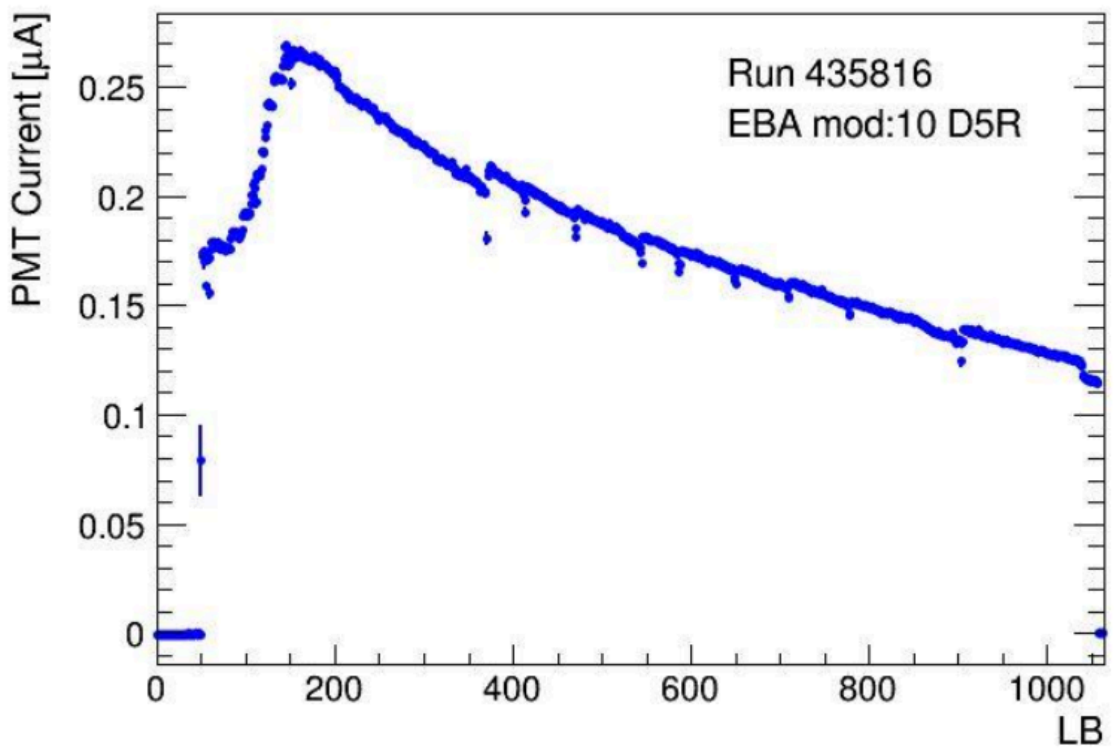
$$I_{PMT} = \frac{ADCs \ - pedestal}{Gain_{PMT}}$$

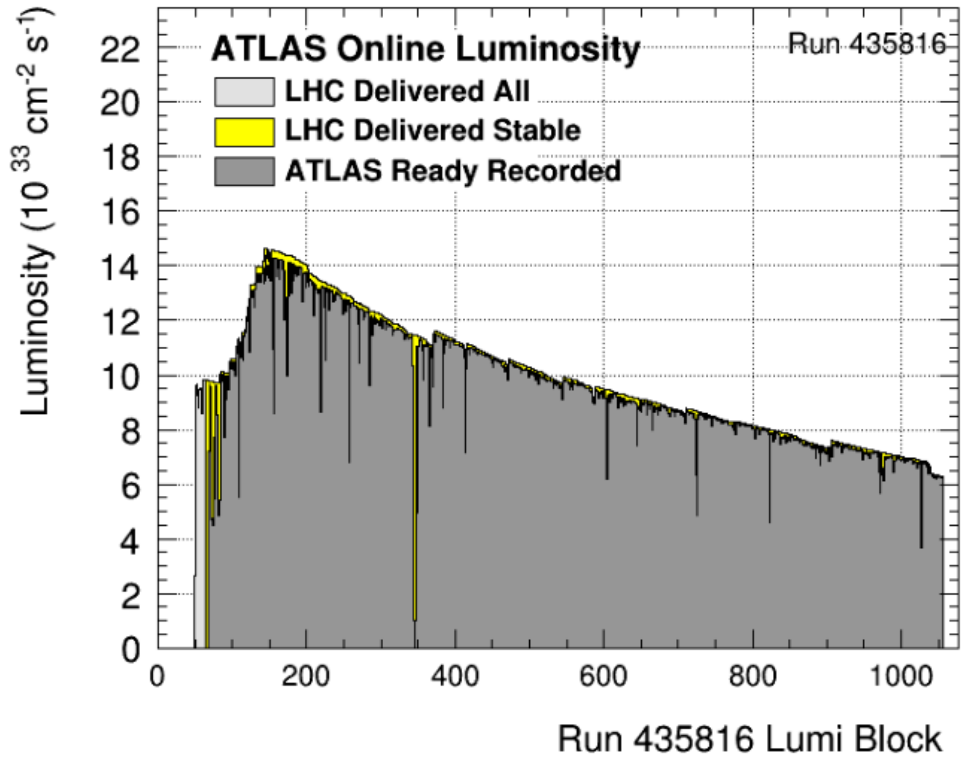
- The pedestal is taken as the average ADCs before collisions
- The PMT current of a given cell is proportional to the number of particles passing through the cell

- Not all modules are used in Luminosity studies
  - Modules that get power-cycled during runs, saturated or noisy modules are excluded









Luminosity measurements Using TileCal

TileCal as Luminometer

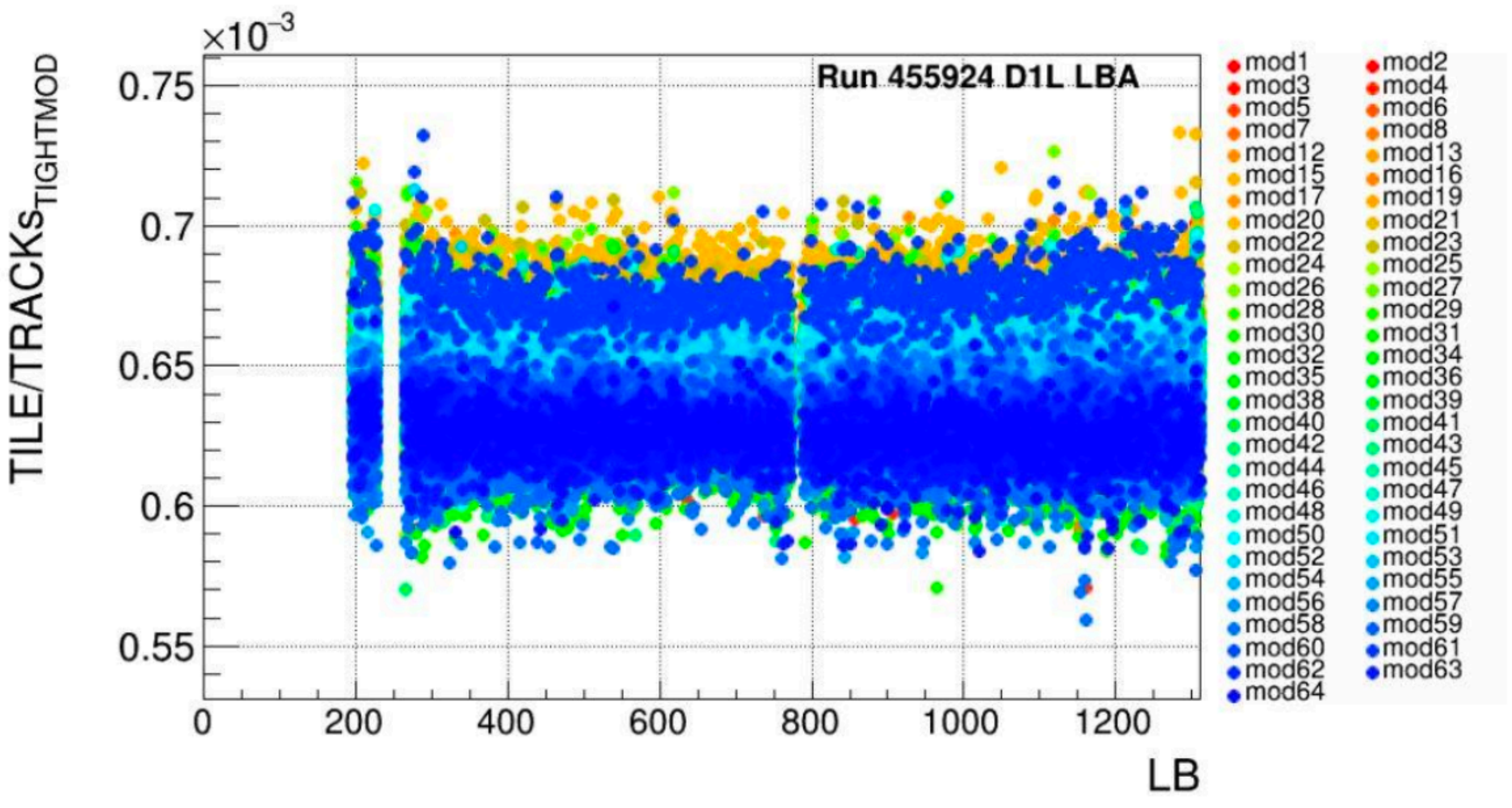
[P. Rapheeha]

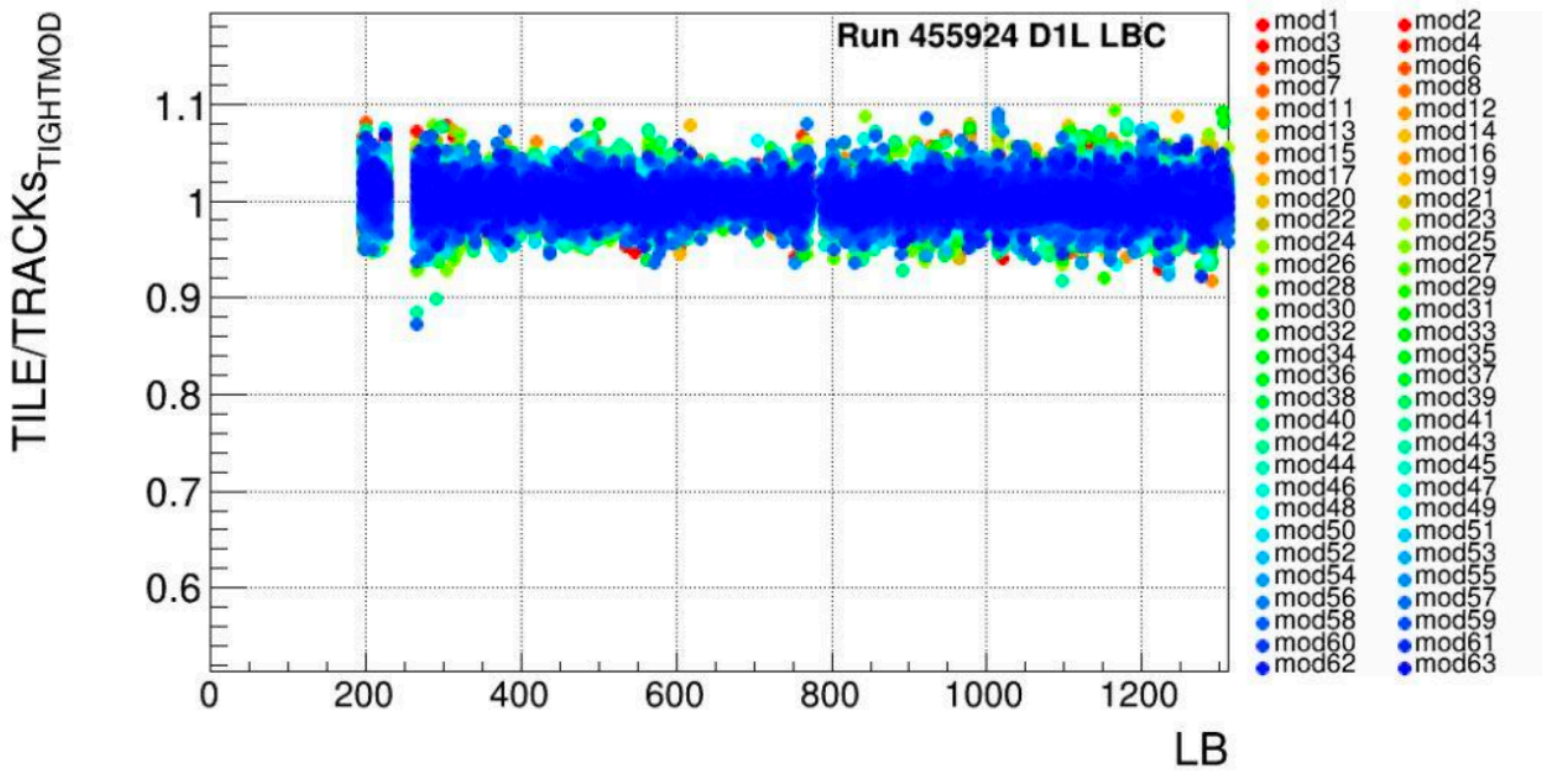
- PMT currents are cross-calibrated to track-counting luminosity to PMT luminosities

$$\alpha_{module} = \frac{L_{Track}}{<I_{PMT}>_{module}}$$

- The calibration constants are determined in an "anchoring run"
- Run 455924 is chosen as the anchoring run for the 2023 dataset
- **LB 675 – 1350 Anchoring range**

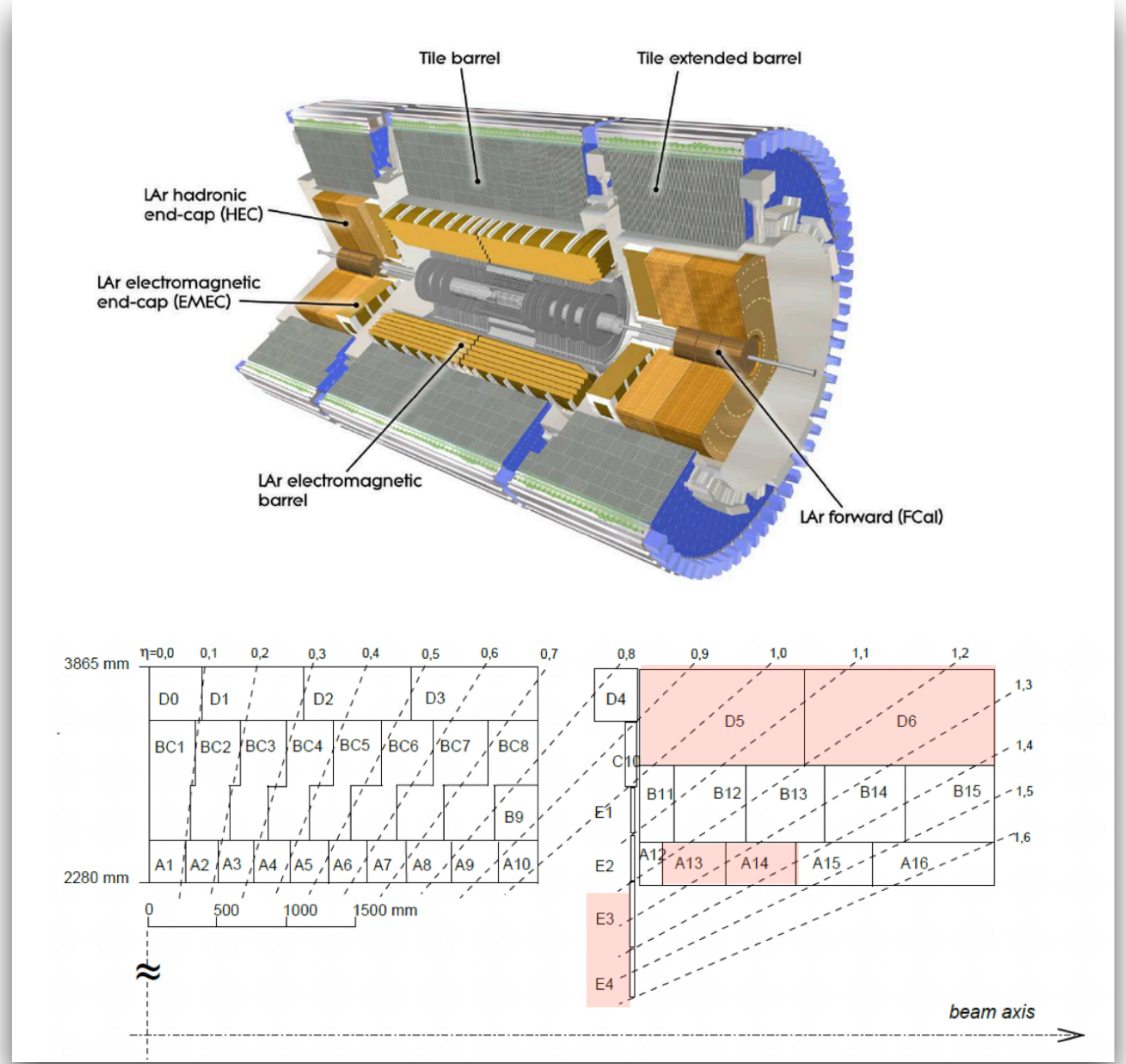
- The TileCal luminosity of a given cell in a given module obtained by taking the average current in the left and right PMTs
- The luminosity of a cell is given by the average luminosity across all good modules





Tile calorimeter

TILE cell division scheme



Combination across years

Standard method

and the absolute uncertainty in the total luminosity, $\sigma_{\mathcal{L}_{\mathrm{tot}}}$, is given by standard error propagation as

$$\sigma^2_{\mathcal{L}_{\mathrm{tot}}} = \mathbf{e}^{\mathrm{T}}\mathbf{V}_{\mathbf{L}}\mathbf{e}\,.$$

Here, $\mathbf{V}_{\mathbf{L}}$ is the covariance matrix of the absolute luminosity uncertainties for the different years, and $\mathbf{e}$ is a column vector with unit entries.[13] The covariance matrix is made up of the sum of terms corresponding to each uncertainty source in Table 8; uncorrelated uncertainties give rise to terms on the diagonal, whilst correlated sources are represented by terms with non-zero off-diagonal entries.

as $\mathbf{V}_{\mathbf{L}} = \boldsymbol{\sigma}_{\mathbf{L}}\mathbf{C}\boldsymbol{\sigma}_{\mathbf{L}}^{\mathrm{T}}$, where the vector $\boldsymbol{\sigma}_{\mathbf{L}}$ of total absolute uncertainties on $\mathcal{L}_i$ and (symmetric) correlation matrix $\mathbf{C}$ are given by

$$\boldsymbol{\sigma}_{\mathbf{L}} = \begin{pmatrix} 0.0367 \\ 0.296 \\ 0.504 \\ 0.644 \end{pmatrix} \mathrm{fb}^{-1}\,, \quad \mathbf{C} = \begin{pmatrix} 1.000 & & & \\ 0.579 & 1.000 & & \\ 0.368 & 0.437 & 1.000 & \\ 0.480 & 0.510 & 0.362 & 1.000 \end{pmatrix}.$$