Luminosity Measurements with the ATLAS Inner Detector in Run 3 of the LHC

EPS-HEP 2025

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DESY.

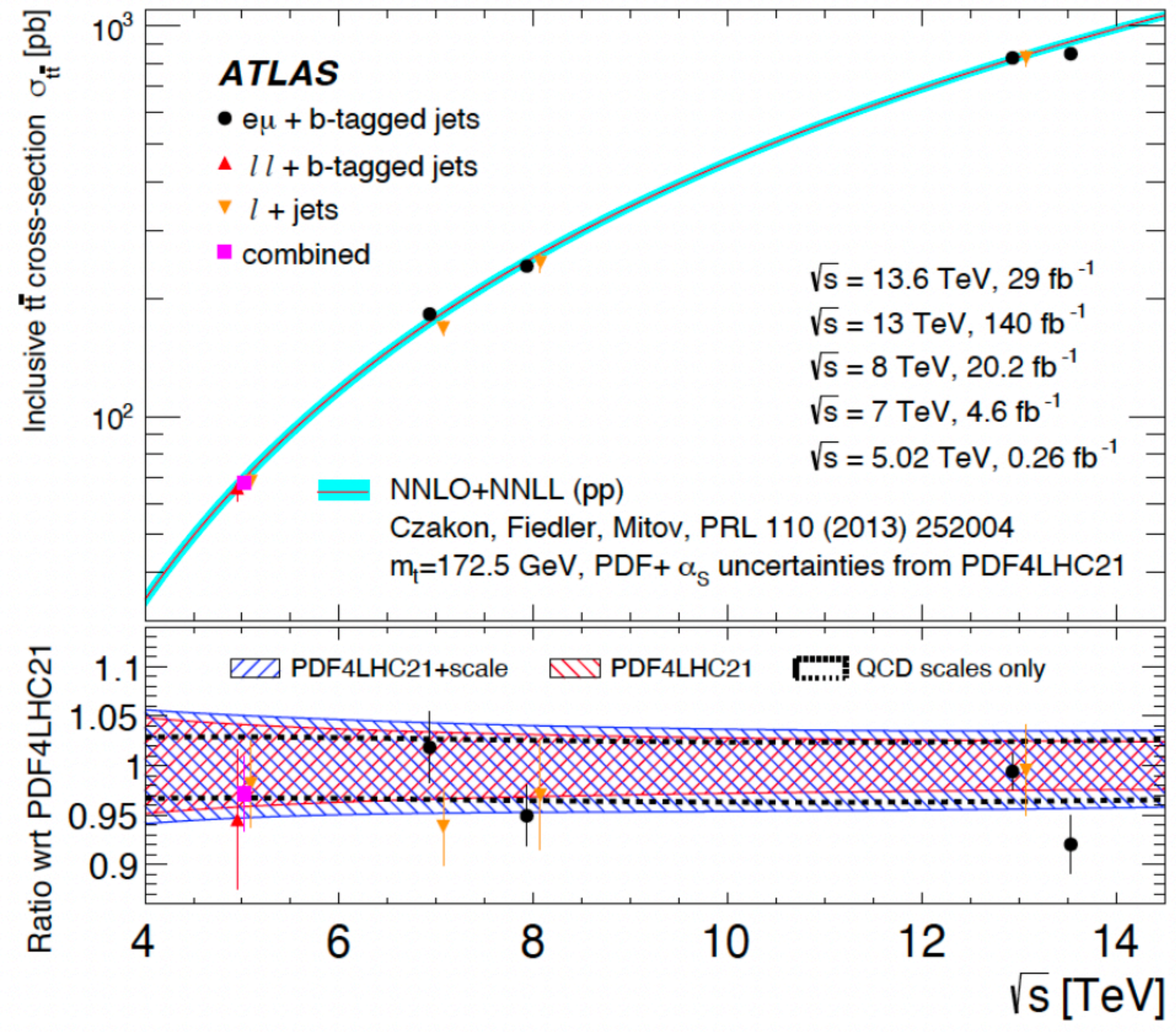
ATLAS EXPERIMENT

Counting collisions

Why luminosity matters

- 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 physics analyses
  - Often the **leading systematic uncertainty** for SM precision measurements

Run 3 $t\bar{t}$ and Z x-sec measurements



$$\sigma_{t\bar{t}} = 859 \pm 4(\text{stat.}) \pm 22(\text{syst.}) \pm 19(\text{lumi.})\text{pb}$$
$$\sigma^{\text{fid.}}_{Z\to\ell\ell} = 751 \pm 0.3(\text{stat.}) \pm 15(\text{syst.}) \pm 17(\text{lumi.})\text{pb}$$

[Phys. Lett. B 848 (2024) 138376]

- ATLAS achieved a **record 0.83% uncertainty** in the full **Run 2** luminosity measurement [Eur.Phys.J.C 83 (2023) 10, 982]
- **Goal for Run 3**: keep final uncertainty **within 1%**

ATLAS luminosity measurement in a nutshell

Measurement strategy

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

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

- 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
- f_r = LHC revolution frequency (11.2 kHz)

- **vdM calibration**
  - Specially-tailored LHC conditions: $\mu \sim 0.5$, no crossing angle, isolated bunches (in *pp* running)
  - Calibration of luminometer σ_{vis}

- **Linearity analysis**
  - Transfer calibration to physics regime
  - **Need detectors linear with luminosity** and/or methods to correct non-linearities

- **Stability analysis**
  - Verify stability of calibration over time
  - **Need stable luminosity detectors** and/or methods to correct for variations in response over time

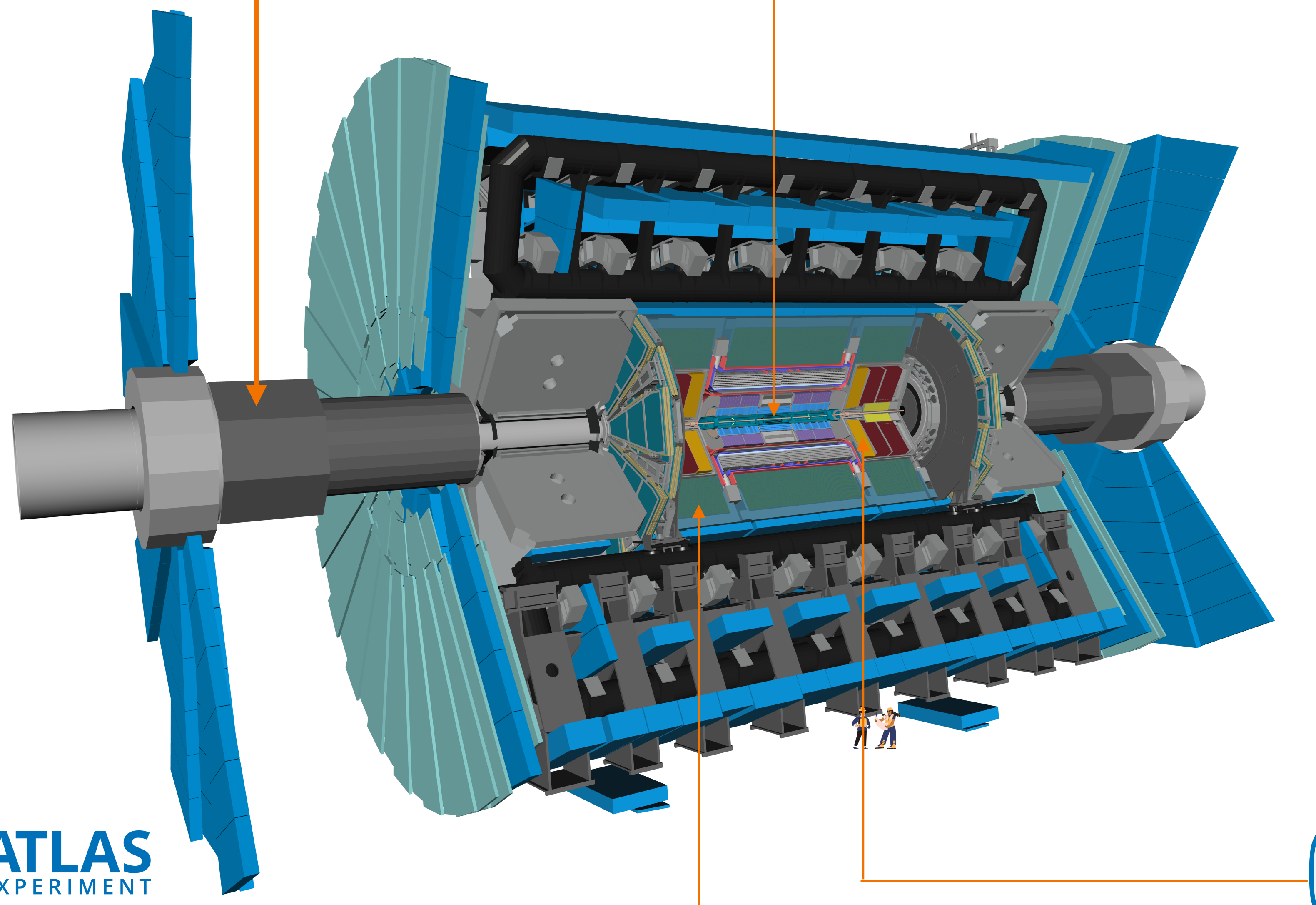
Luminosity detectors and algorithms

ATLAS *luminometers* in Run 3

- **LUCID**
  - **Reference luminometer** usable over full μ range

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

- **Inner Detector**
  - **Track Counting (TC)** counting reconstructed tracks in randomly triggered events
  - **Pixel Cluster Counting (PCC)** counting reconstructed Pixel Clusters in randomly triggered events



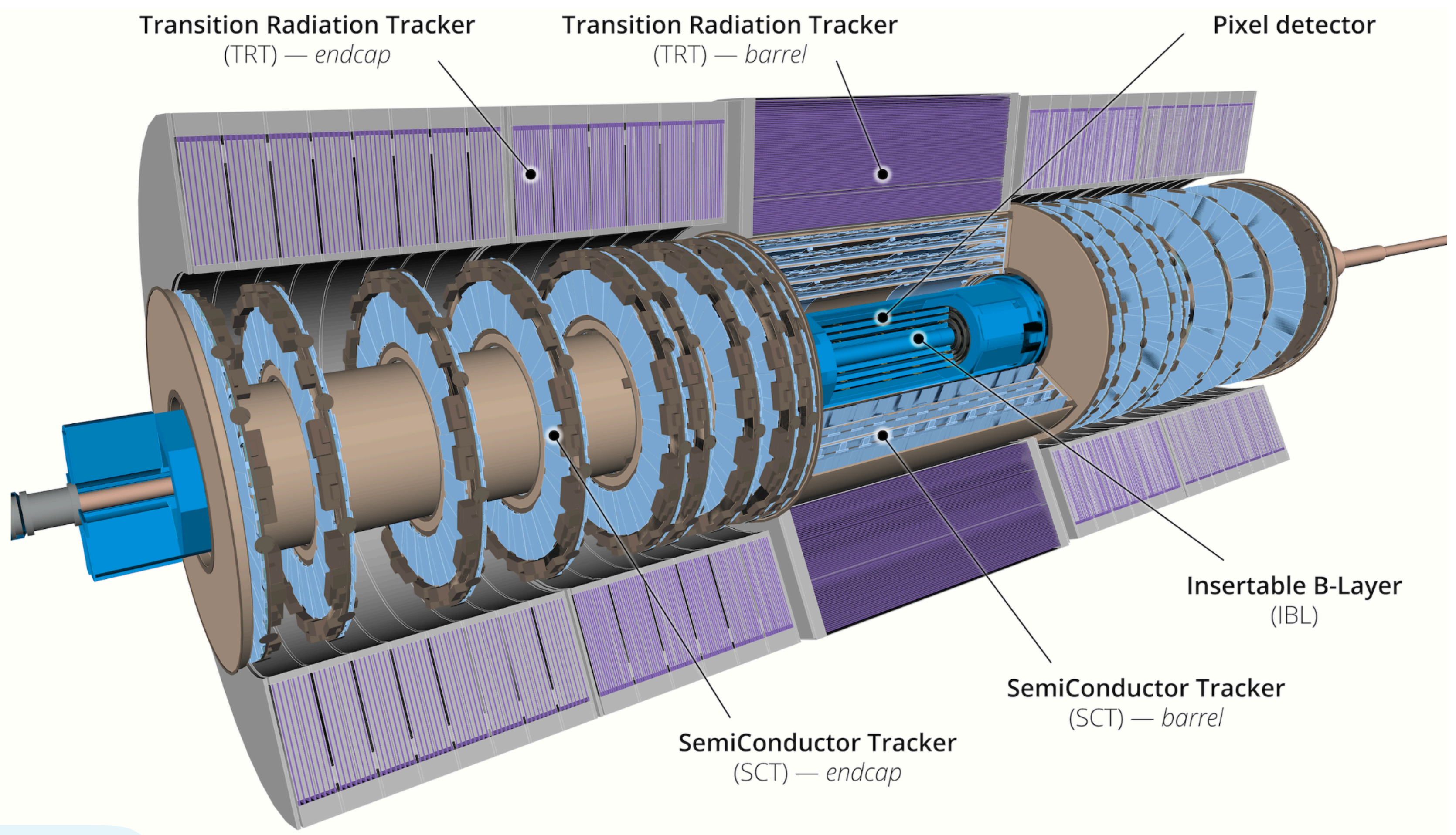
- **LAr calorimeters (EMEC and FCal)**

- **Tile calorimeter**

Luminosity with Track Counting

Counting tracks with the Inner Detector

- Luminosity determined from **mean number of tracks per bunch-crossing**
  - **Dedicated readout stream:** only data from silicon tracking detectors, **Pixel + SCT**
  - 200 Hz **random trigger** in normal physics, up to ~50 kHZ in vdM scans and related runs
- **Dedicated reconstruction + several track selections optimised for luminosity monitoring**



Track selection working points

Criterion	Selection A	Selection B	Selection C
p_T [GeV]	> 0.9	> 0.9	> 0.9
$\|\eta\|$	< 1.0	< 2.5	< 1.0
$N_{\text{hits}}^{\text{Si}}$	≥ 9	≥ 9 if $\|\eta\| < 1.65$ else ≥ 11	≥ 10
$N_{\text{holes}}^{\text{Pix}}$	≤ 1	≤ 1	≤ 1
$\|d_0\|/\sigma_{d_0}$	< 7	< 7	< 7

Nominal selection in Run 2 and 3 (Selection A)

- $\sim$ 1.7 (3.7) tracks/inelastic pp collision in sel. A & C (B)

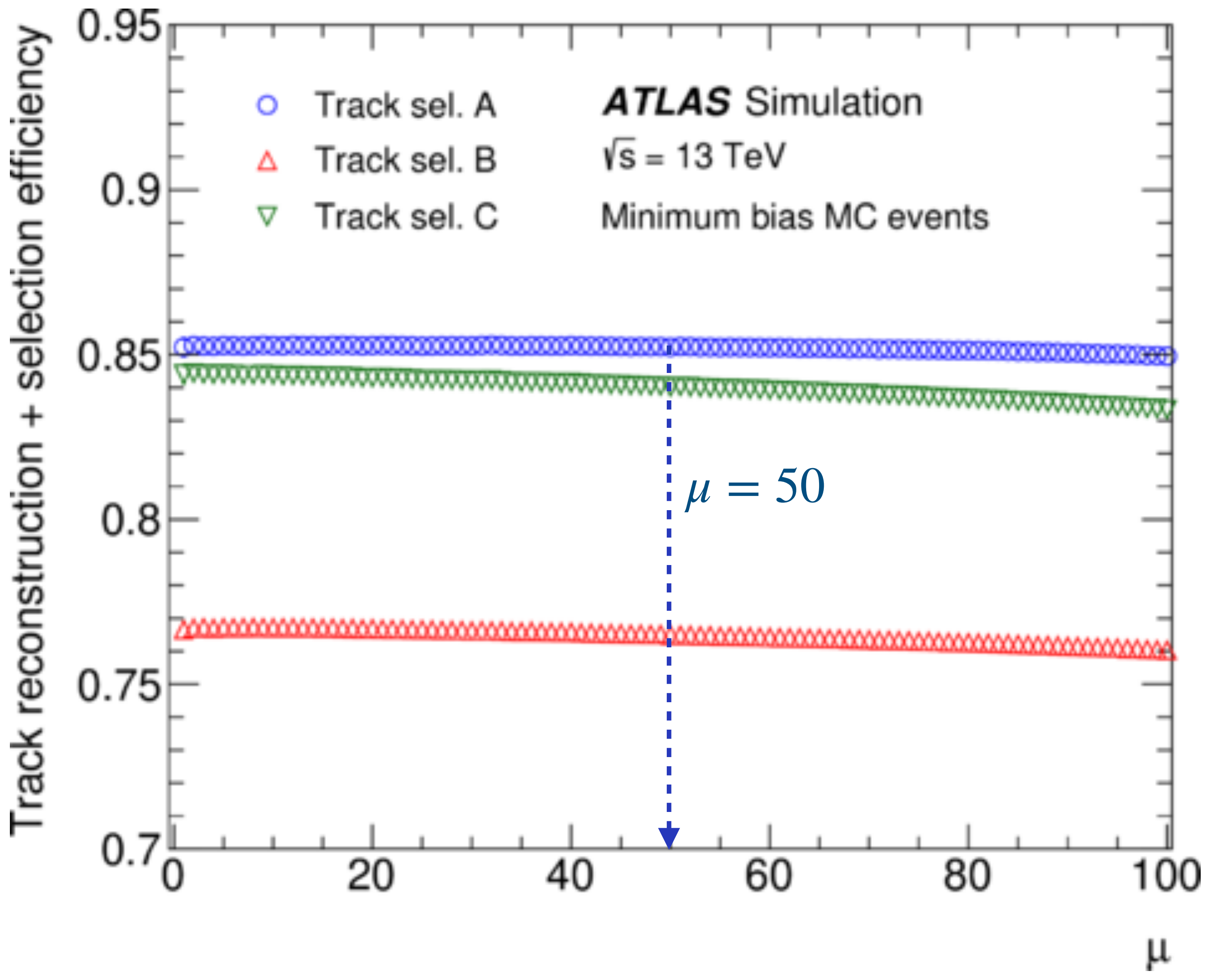
Specific criteria chosen to provide:

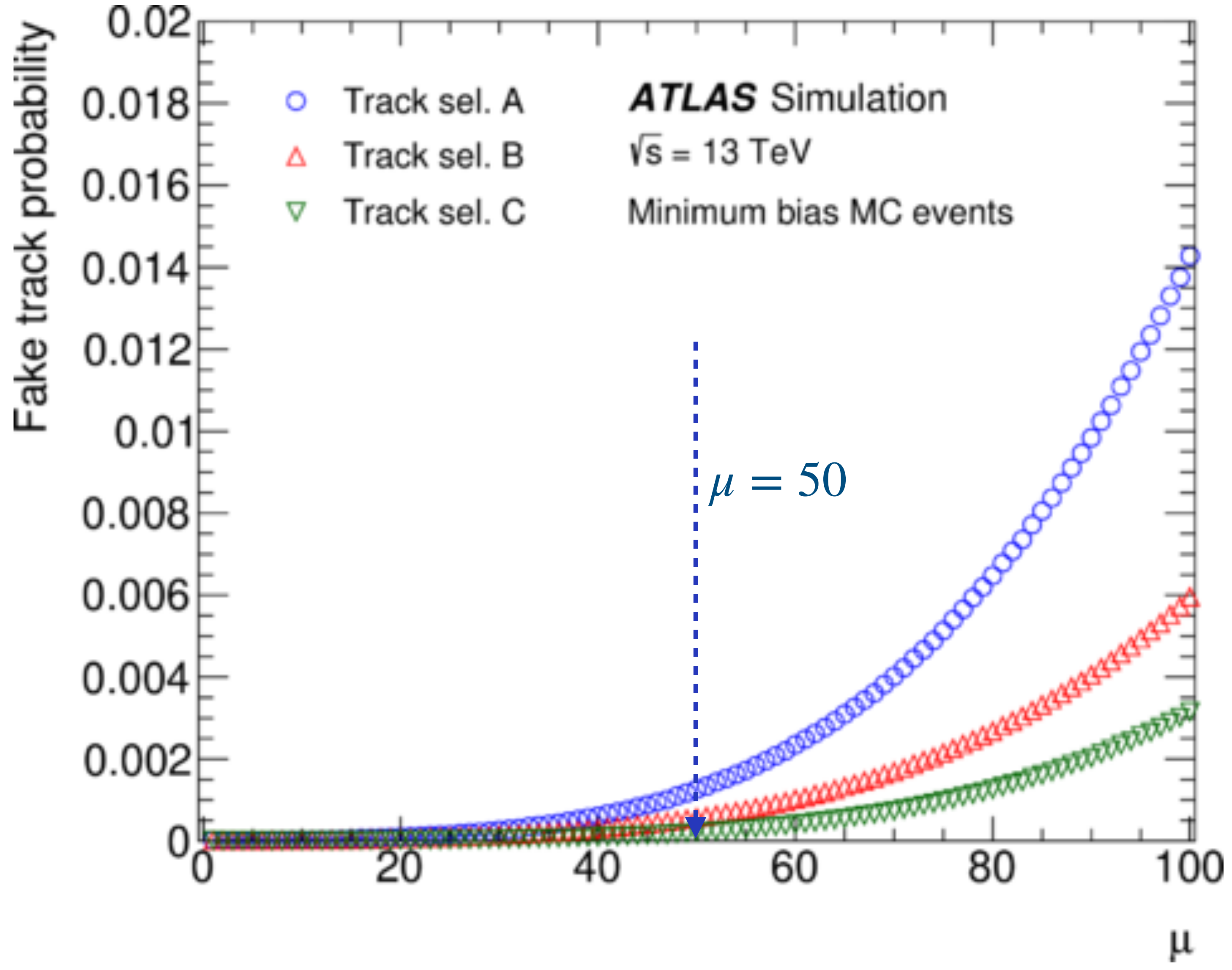
- High quality tracks
- High efficiency
- Low fake rate
- Low μ dependence
- **Operational stability**:
  - E.g., $N_{\text{Holes}}^{\text{Pix}}$ requirement sensitive to Pixel occupancy, data quality, bunch pattern
  - Requires **control down to ~1% level** over long time period

Track Counting performance

Efficiency and fake rates of track selections

- **Track Counting linearity with μ is crucial:**
  - Minimise non-linear effects due to track reconstruction, selection efficiencies, and fake tracks
- Combined track reconstruction + selection efficiency and fake rates studied in Minimum Bias Monte Carlo





- **Sel. A very stable with μ :** 0.1% efficiency decrease and 0.1% fake tracks at $\mu = 50$
- **Sel. B and C:** smaller efficiency but more robust against fake tracks → **alternatives for cross-checks and systematics**

Track Counting in action

Correct LUCID linearity

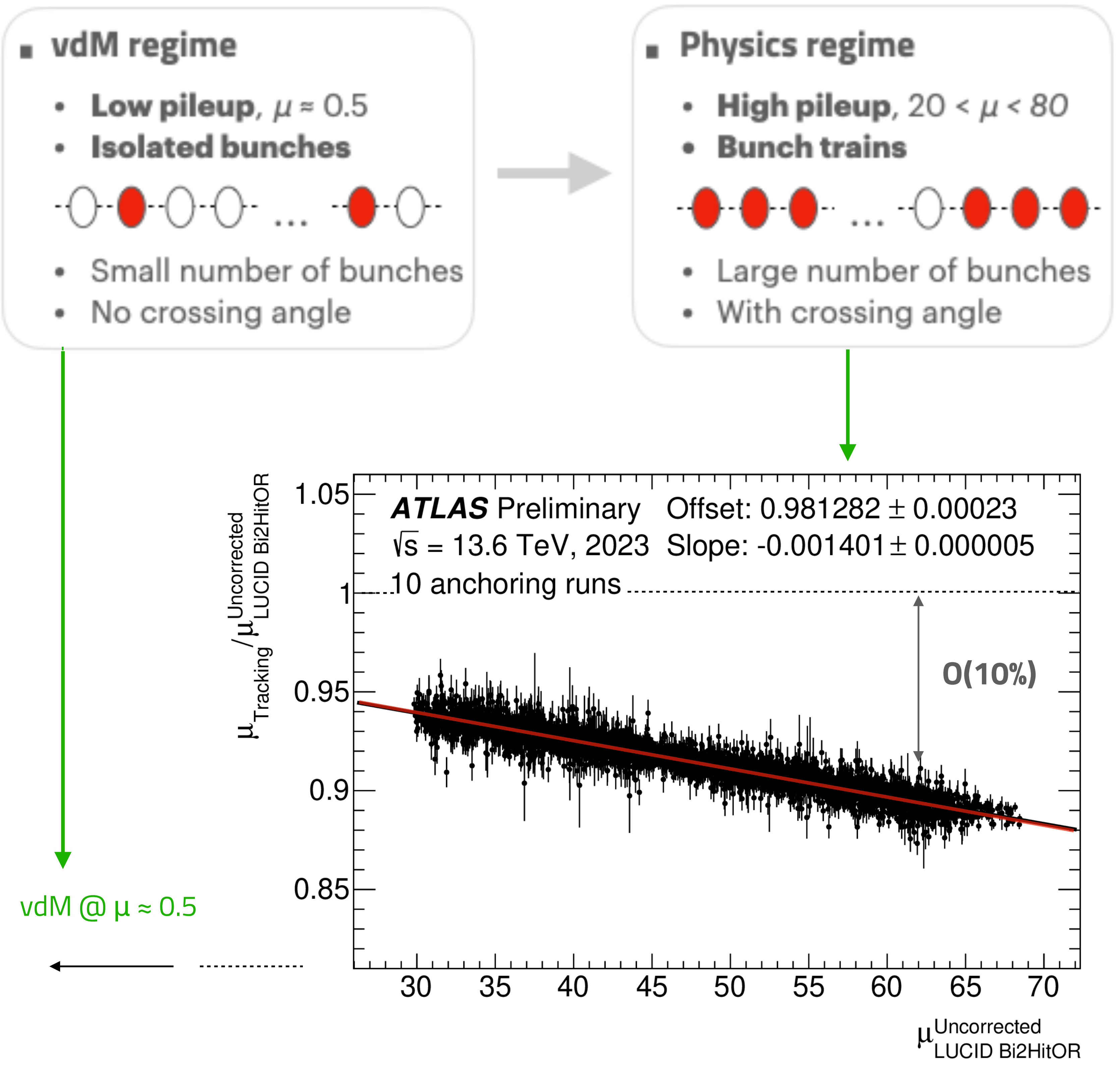
- **Validation of LUCID vdM calibration transfer to physics regime**
  - Normalise (*anchor*) Track Counting to LUCID in head-on parts of vdM fills and compare LUCID vs TC at high-luminosity in physics regime

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

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

→ **correct using Track Counting**

- Linear fit to ratio of <μ> from track-counting and LUCID
- $\langle \mu_{\mathrm{corr}} \rangle = p_0 \langle \mu_{\mathrm{uncorr}} \rangle + p_1 (\langle \mu_{\mathrm{uncorr}} \rangle)^2$
- Correction derived in up to 10 runs around the vdM fill



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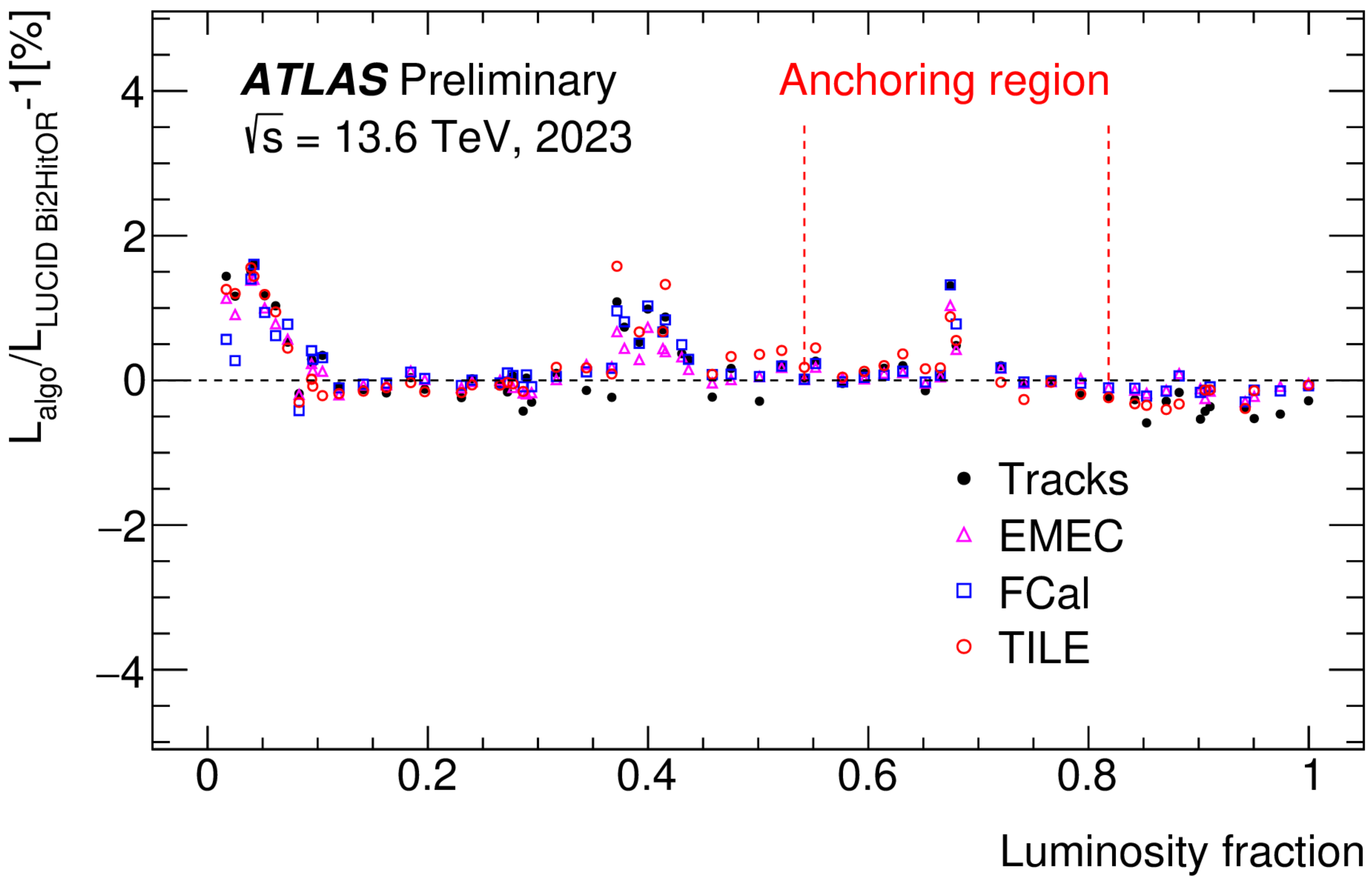
- **Applied to LUCID in all other runs**

  → **TC stability monitored on a ~60 s time basis!**

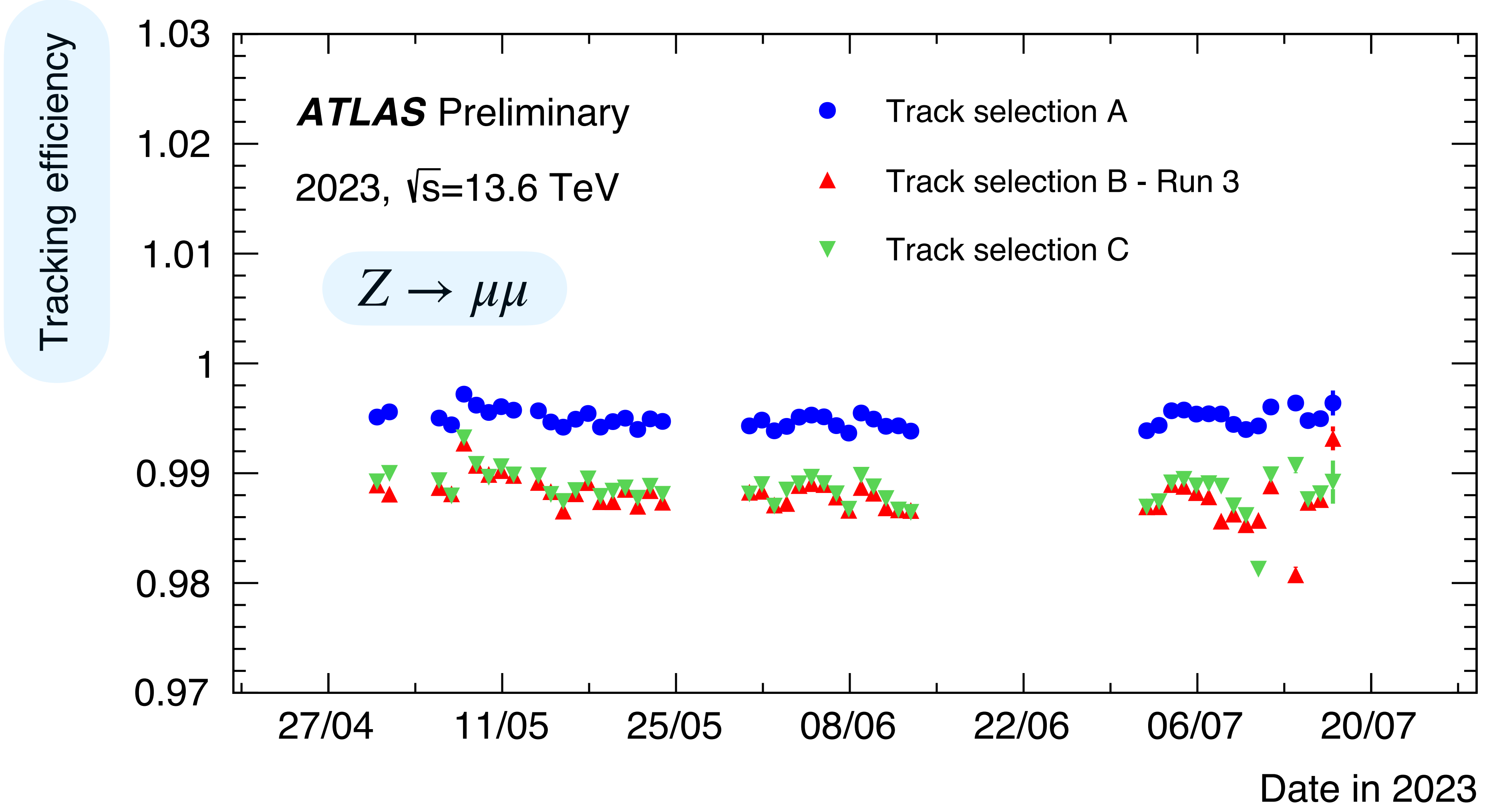
After correction: run-integrated LUCID measurement **typically in agreement** with Track Counting **within ±0.5%**

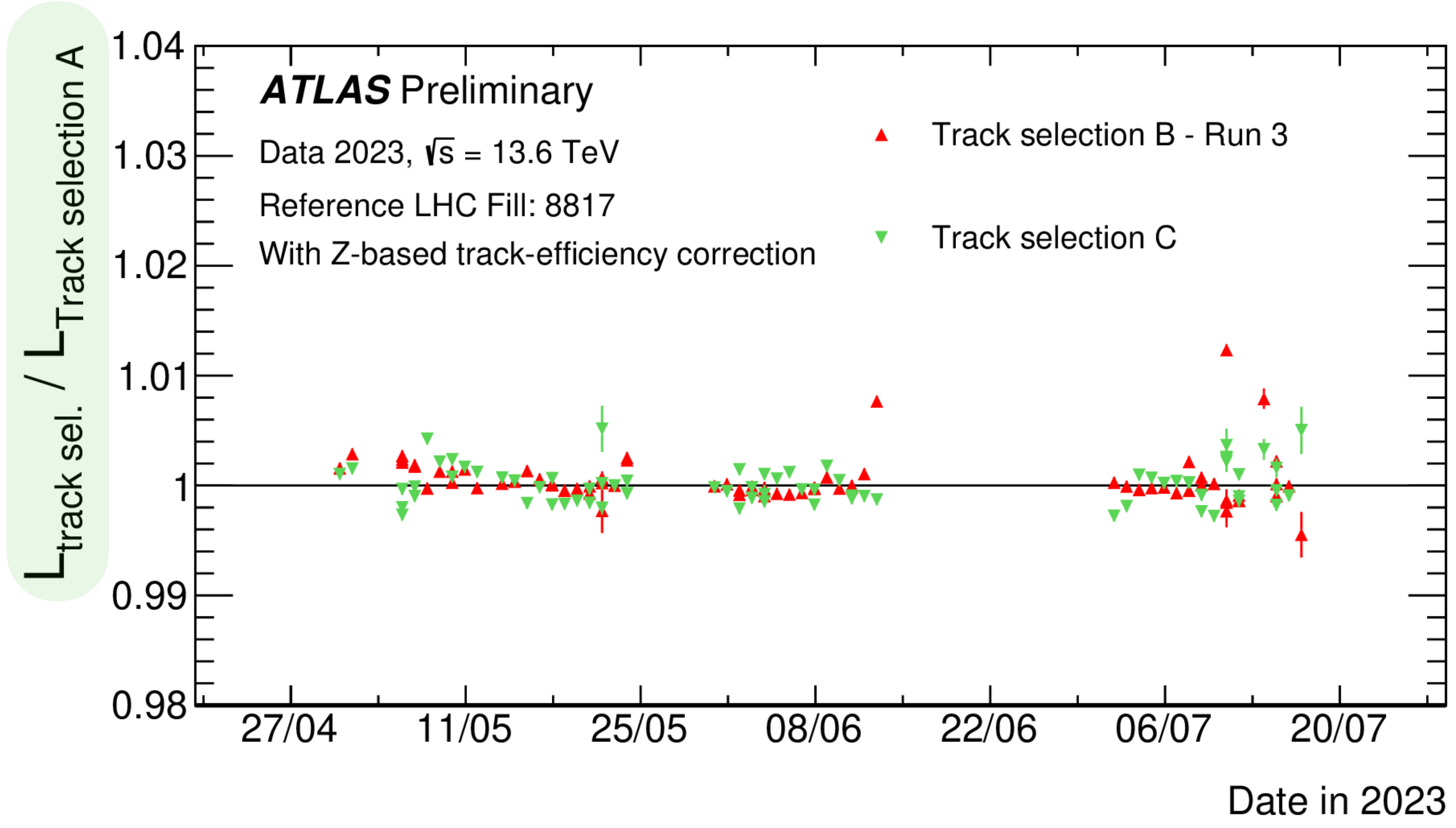


Track Counting in action

Track Counting stability: **over time**

- **Stability of selection working points over time monitored by**
  - Measuring **efficiencies** relative to loose muon selection in $Z \to \mu\mu$ events (then applied as run-by-run corrections)
  - Comparing **ratios of integrated luminosities** of other selection working points wrt to the nominal selection A





- Provides important information about the detector over changing detector conditions and beam configurations
  - **Selections observed to be robust and stable in 2023**: internal agreement within 1%
  - Stability in other Run 3 years under study

Luminosity with Pixel Cluster Counting

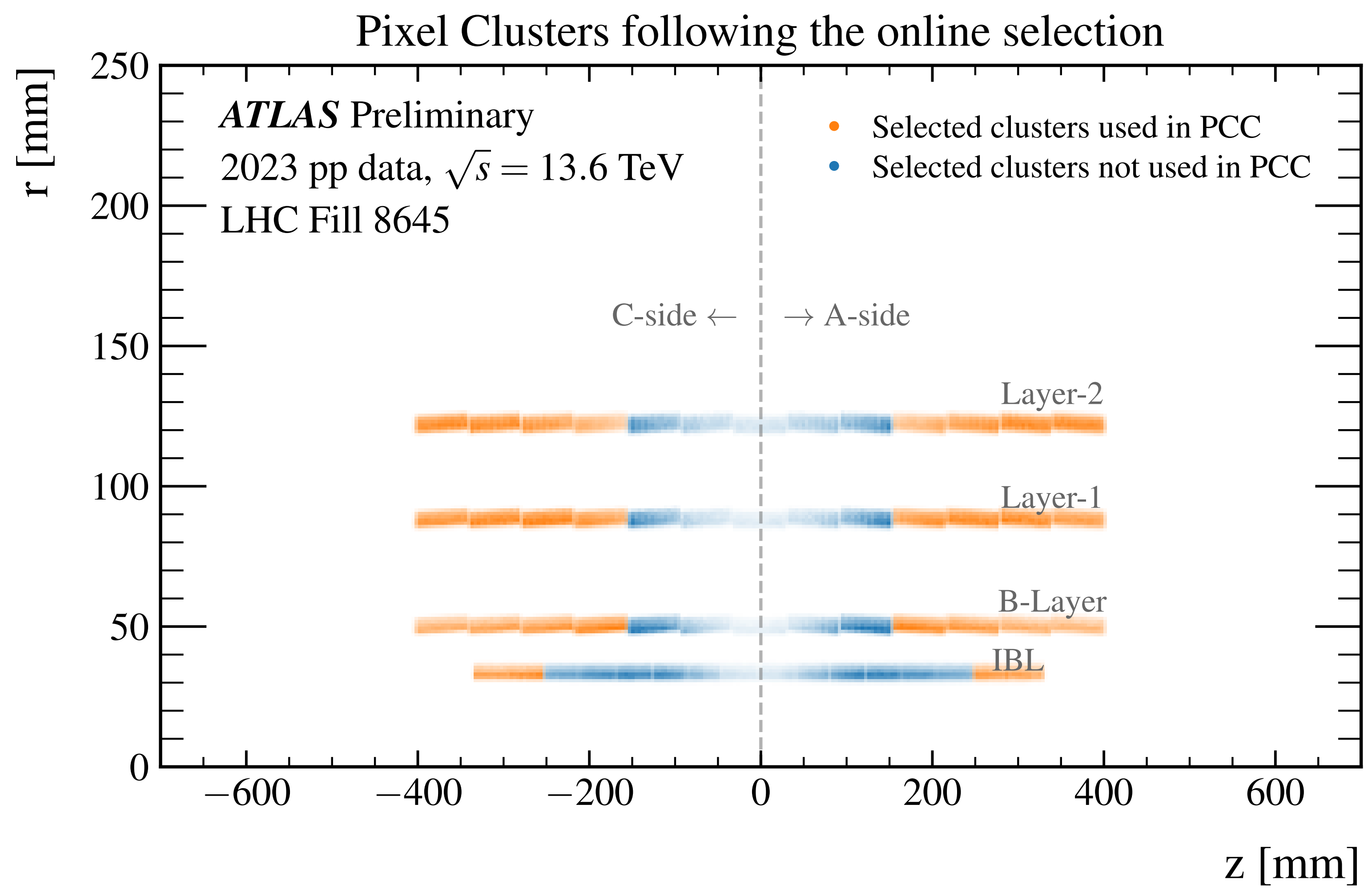
Counting clusters in the Pixel Detector

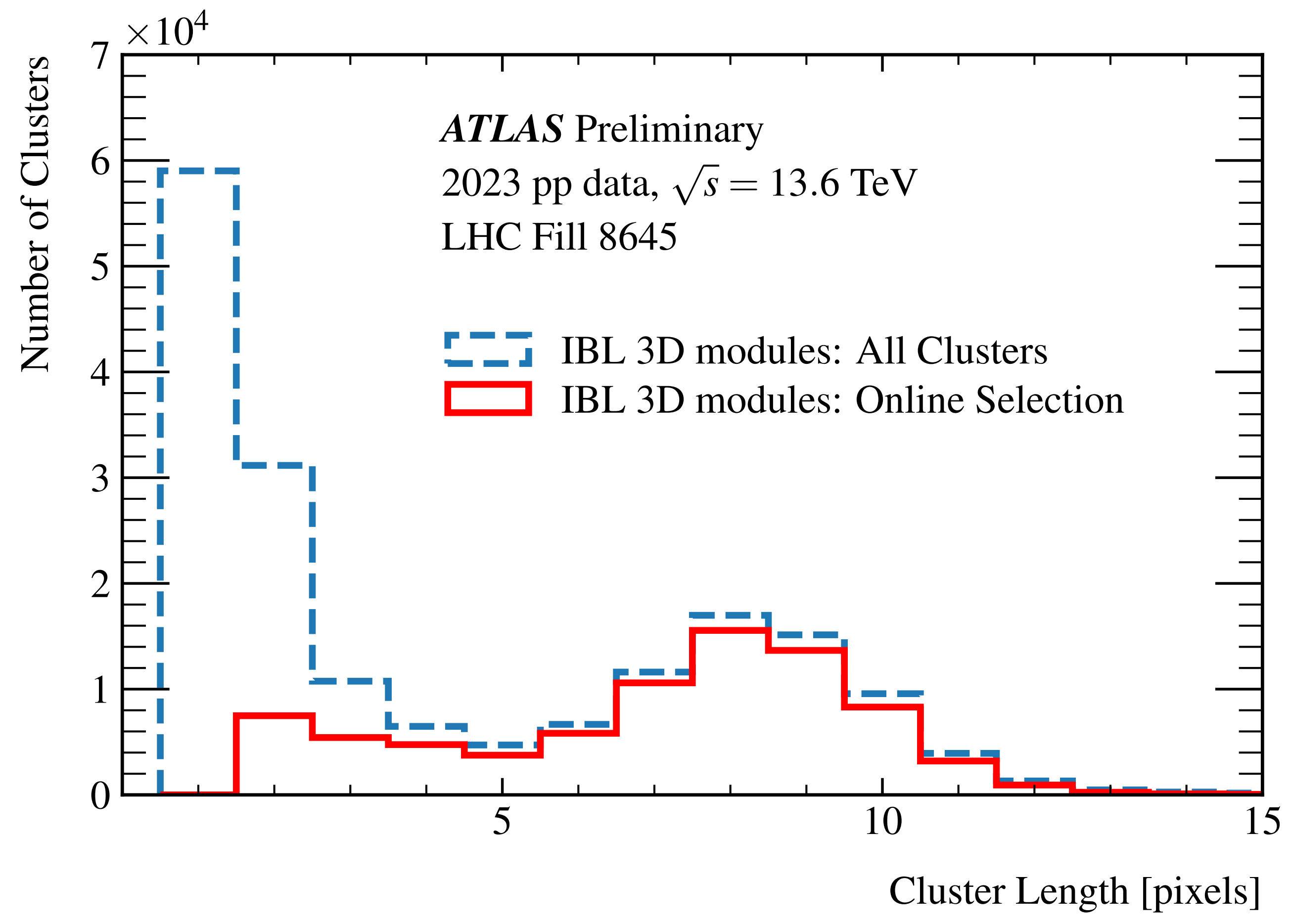
Pixel Cluster = cluster of *n* pixels, close to one another registering a hit

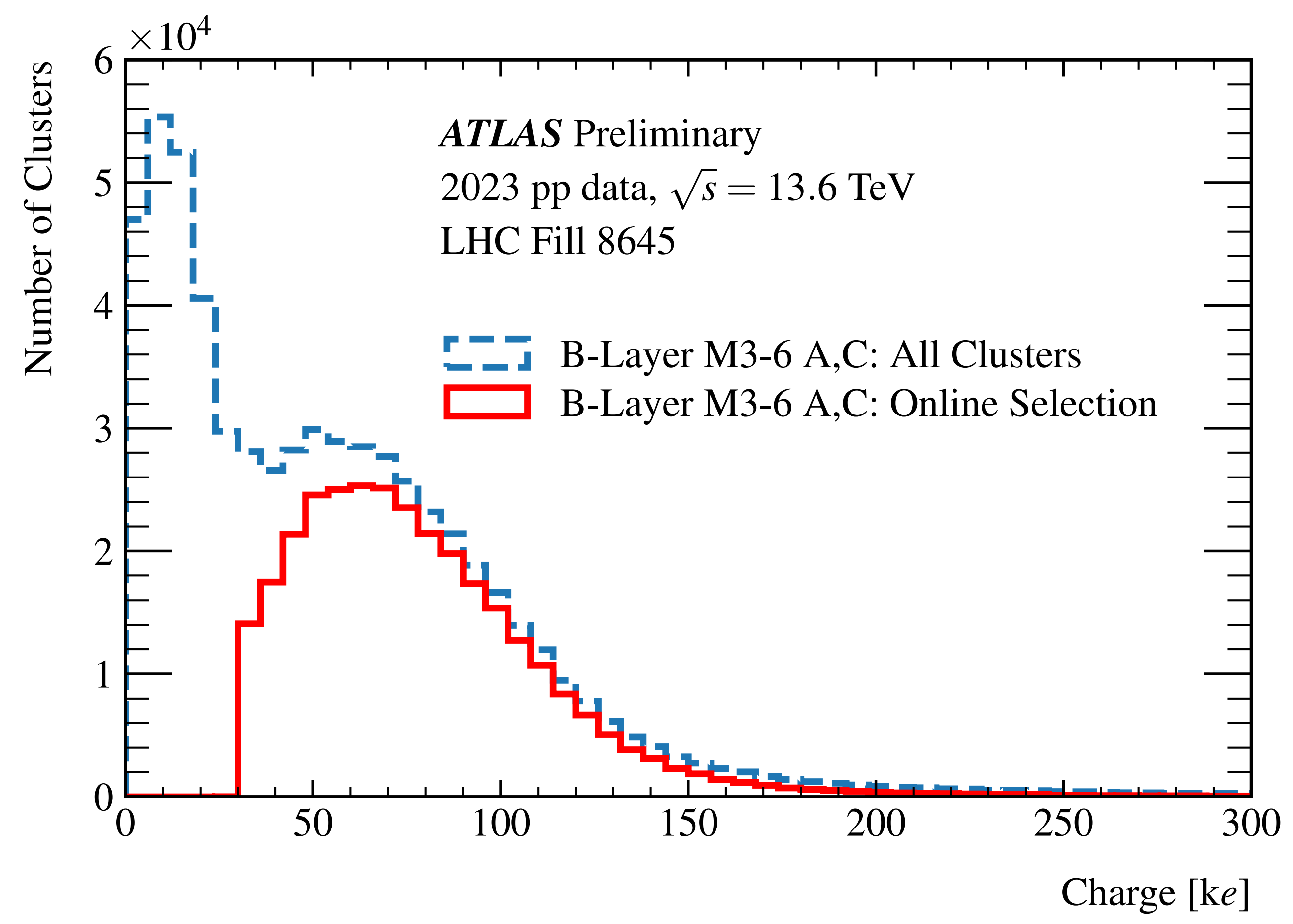
Hit = a threshold-crossing in the sensors

- Luminosity determined from **mean number of Pixel Clusters per bunch-crossing**
  - **Highly linear**: can constrain non-linearities of other luminometers
  - <u>**Preliminary Run-3 analysis in progress**</u>
  - Use same readout stream and random trigger as Track Counting
  - **Online selection mitigating noise and background contamination**
    - Pixel Clusters at high η in the Pixel barrel
    - Shape + charge requirements

Good separation between luminosity-associated (signal) and background clusters



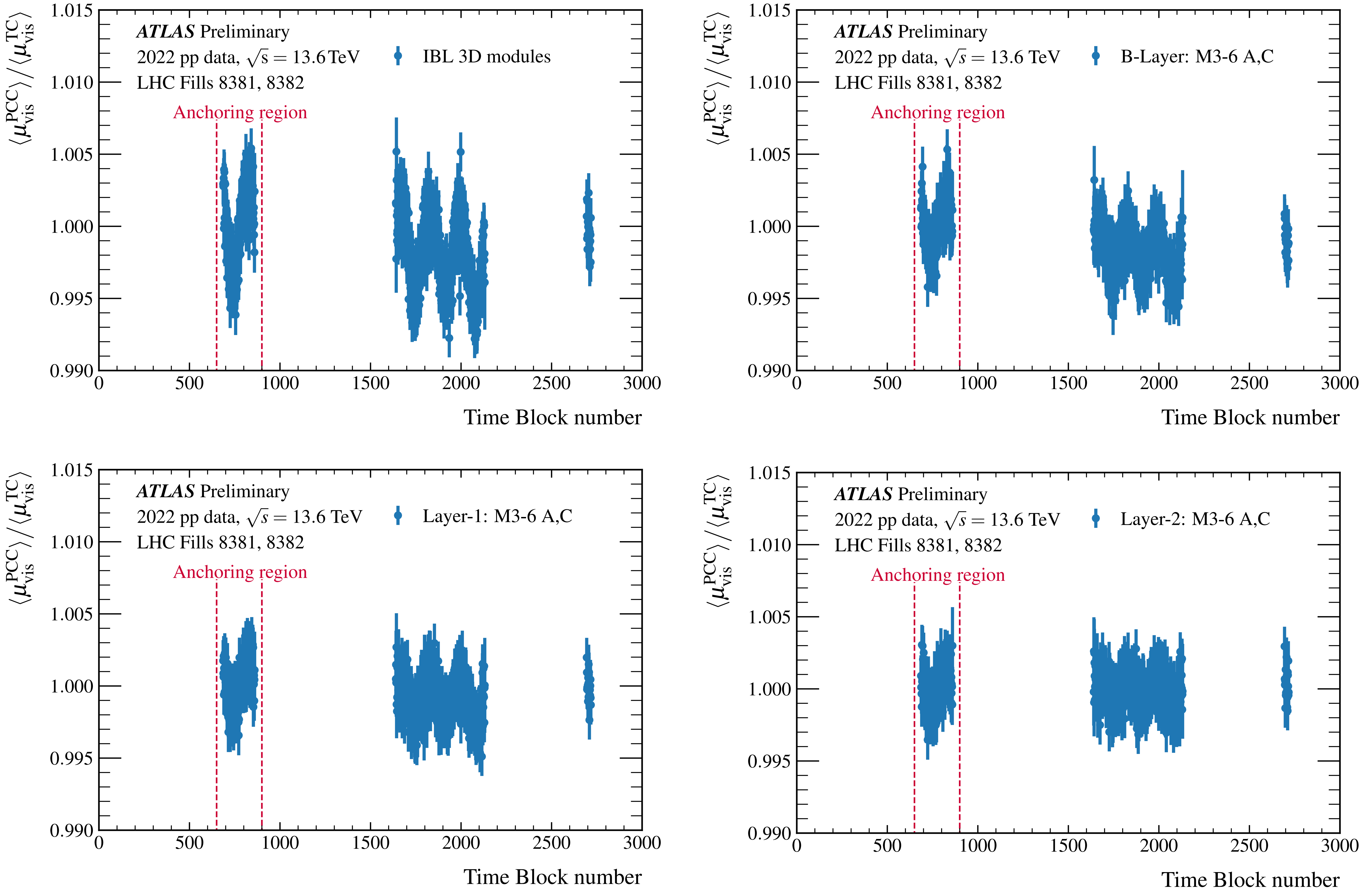




Pixel Cluster Counting in action

Pixel Cluster Counting stability

- Preliminary study of **PCC stability over time for all Pixel layers** in periods of stable head-on collisions in vdM fills
  - Normalise TC to PCC (*anchoring*) in the initial period and check stability of PCC/TC ratio vs Time Block number (1 Time Block ~ 60 s)
  - Sensitive to variations of average **longitudinal Beam Spot position** over considered Time Block numbers



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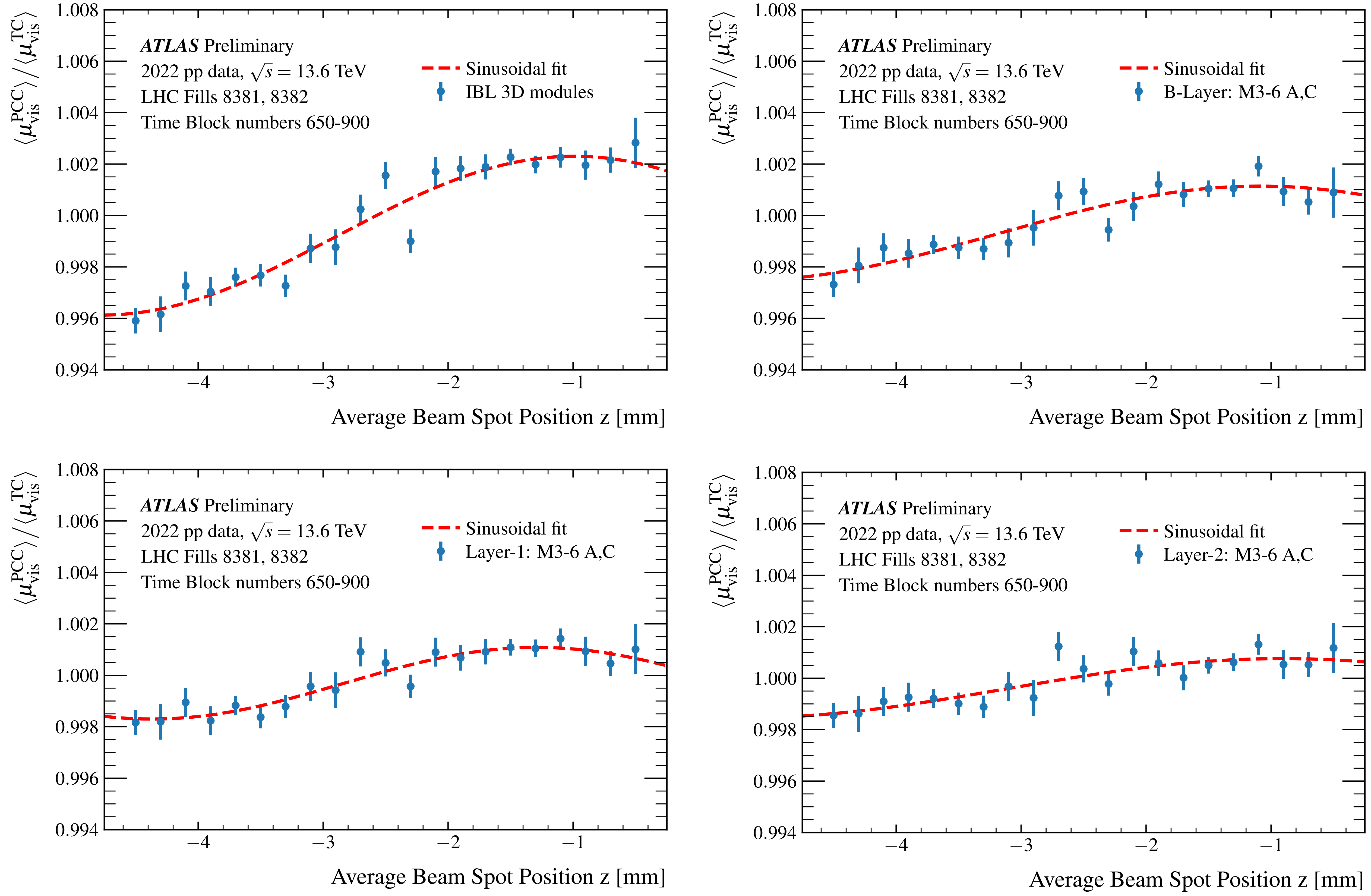

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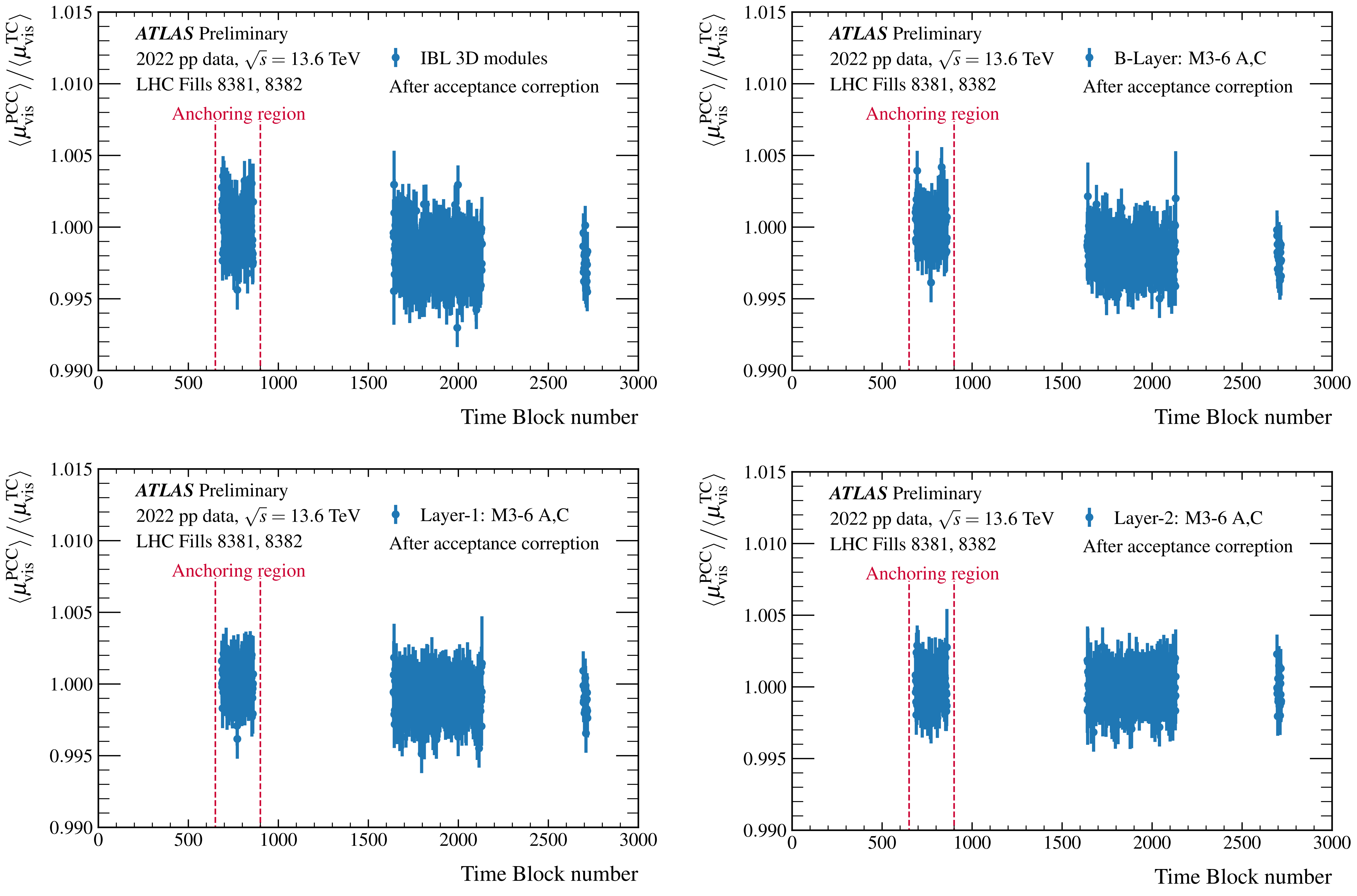

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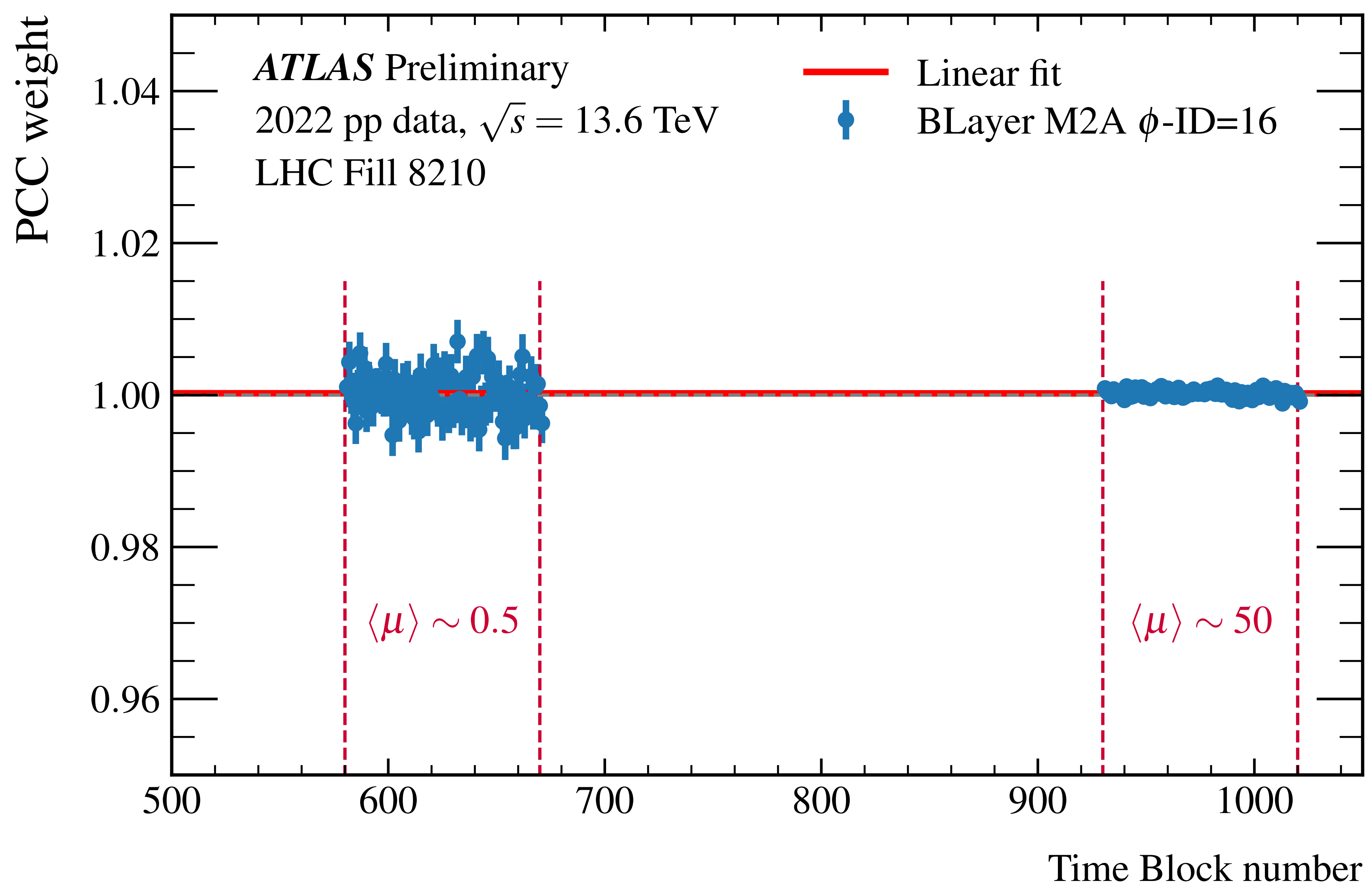
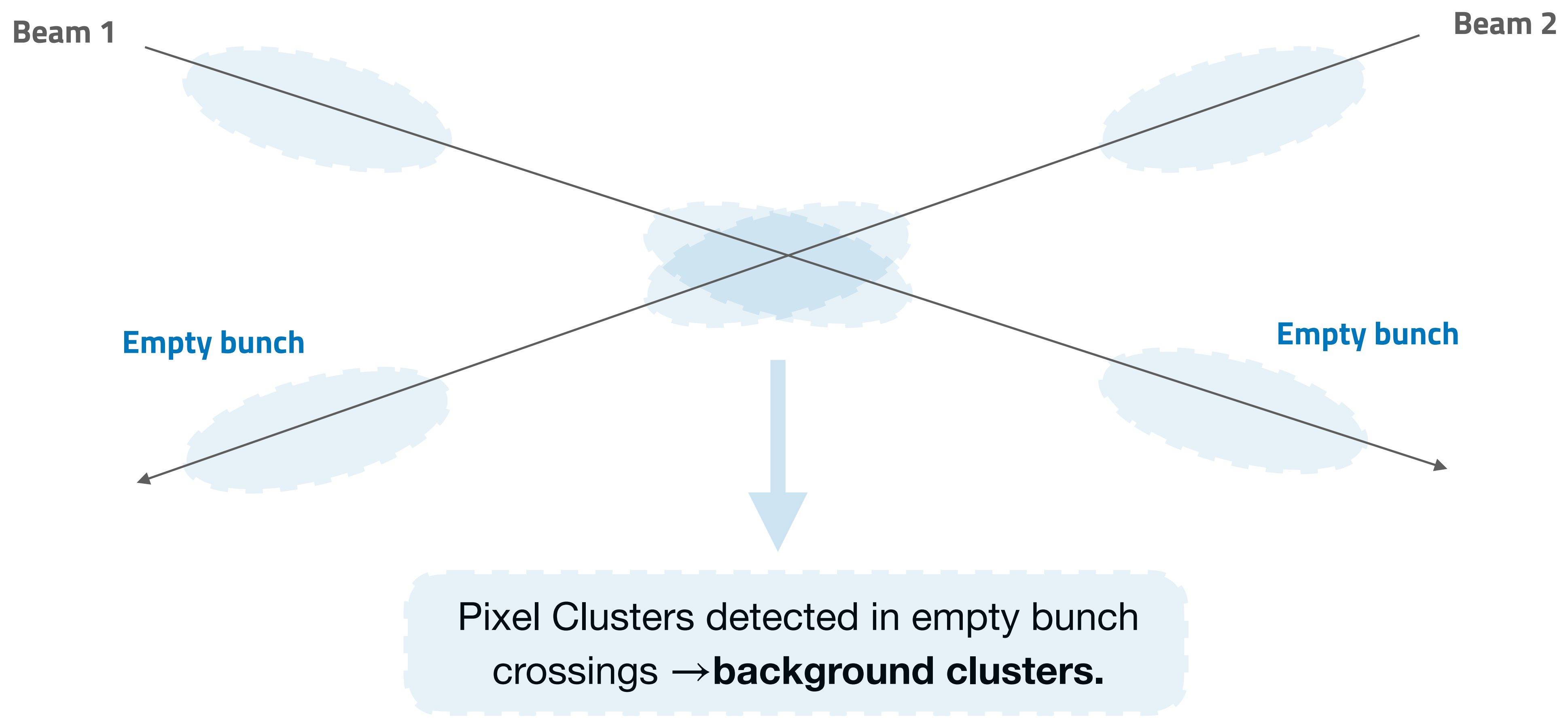
- Procedure to validate **single module stability based on PCC weight**
  - **PCC weight** ≡ normalised ratio of the number of Pixel Clusters in single azimuthal module to total number of Pixel Clusters in the corresponding ring
  - tested in LHC fills with changing pileup conditions: low-μ and a high-μ periods

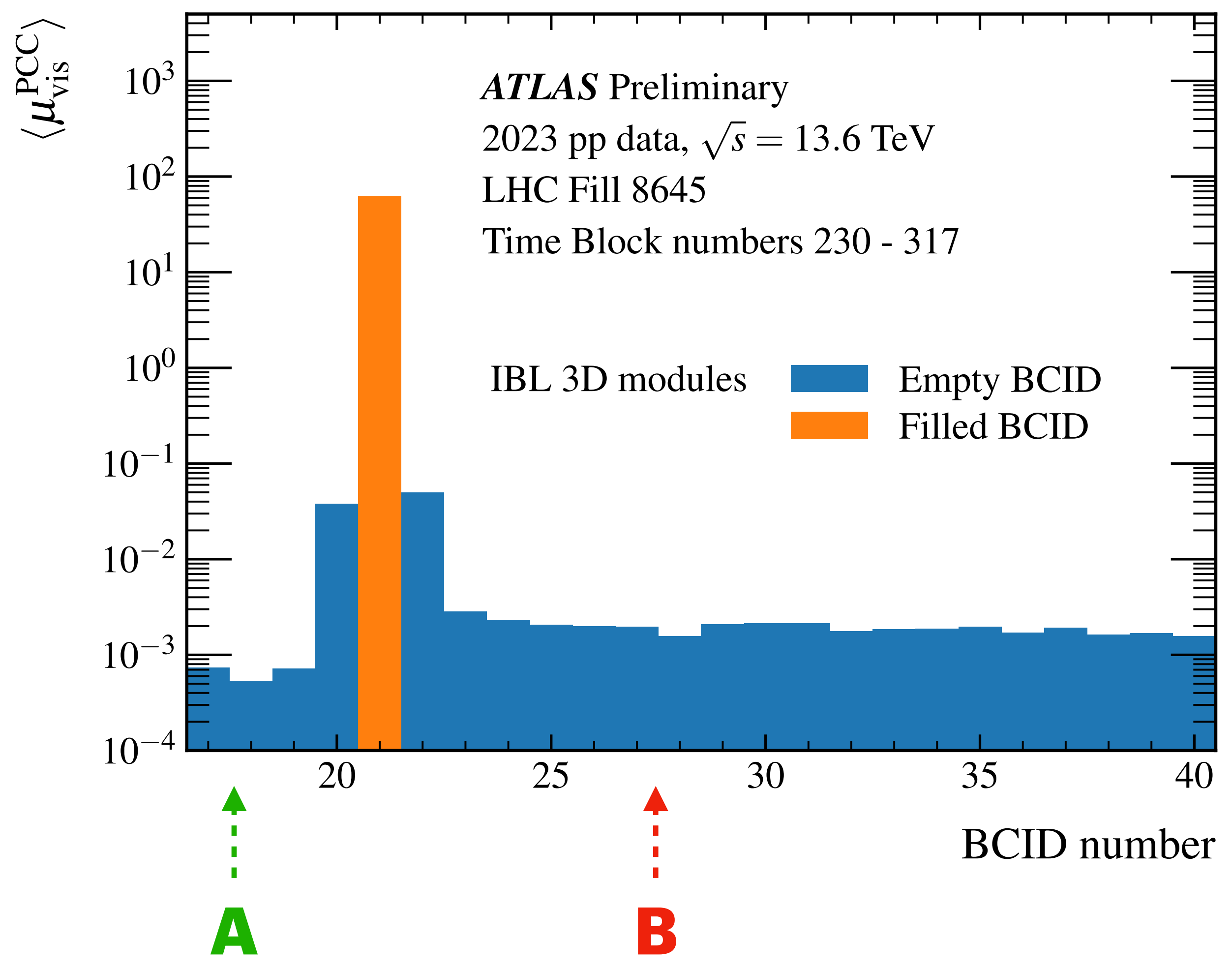


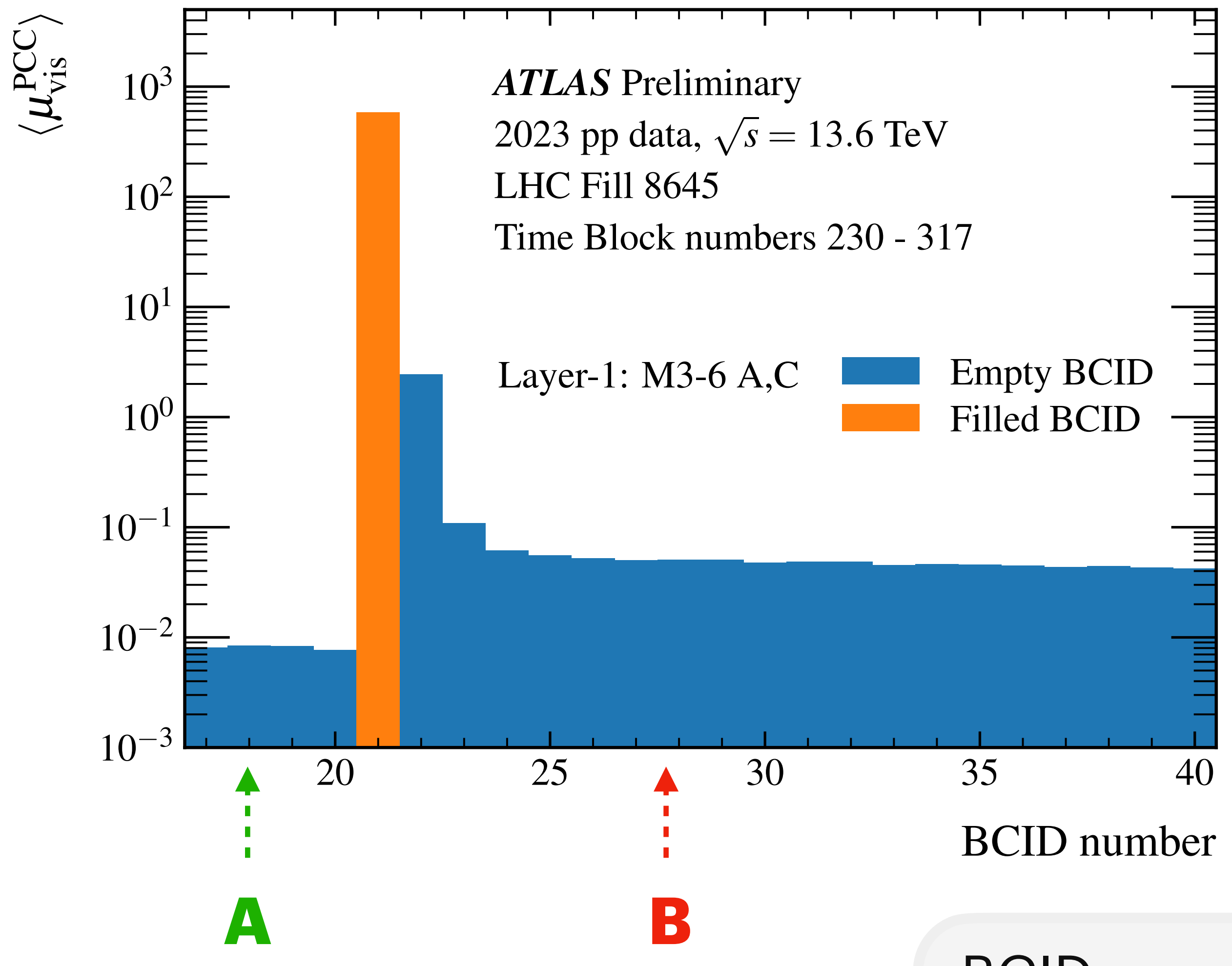
Background contamination in Pixel Cluster Counting

Characterisation of background

- Background contamination in PCC studied in tailored conditions
  - Exploit LHC ramp-up fills: few and isolated filled and colliding bunches
  - 1 kHz **random trigger: samples also crossings of empty bunches**
- **Main background is *afterglow*:** out-of-time clusters induced by previous collisions due to long lived tails of particle cascades and material activation
- Background studied in empty bunches around **isolated** filled bunch







A. Pure *intrinsic* background, e.g. noise

B. Afterglow induced by single bunch crossing + intrinsic background

BCID number ≡ bunch crossing identifier

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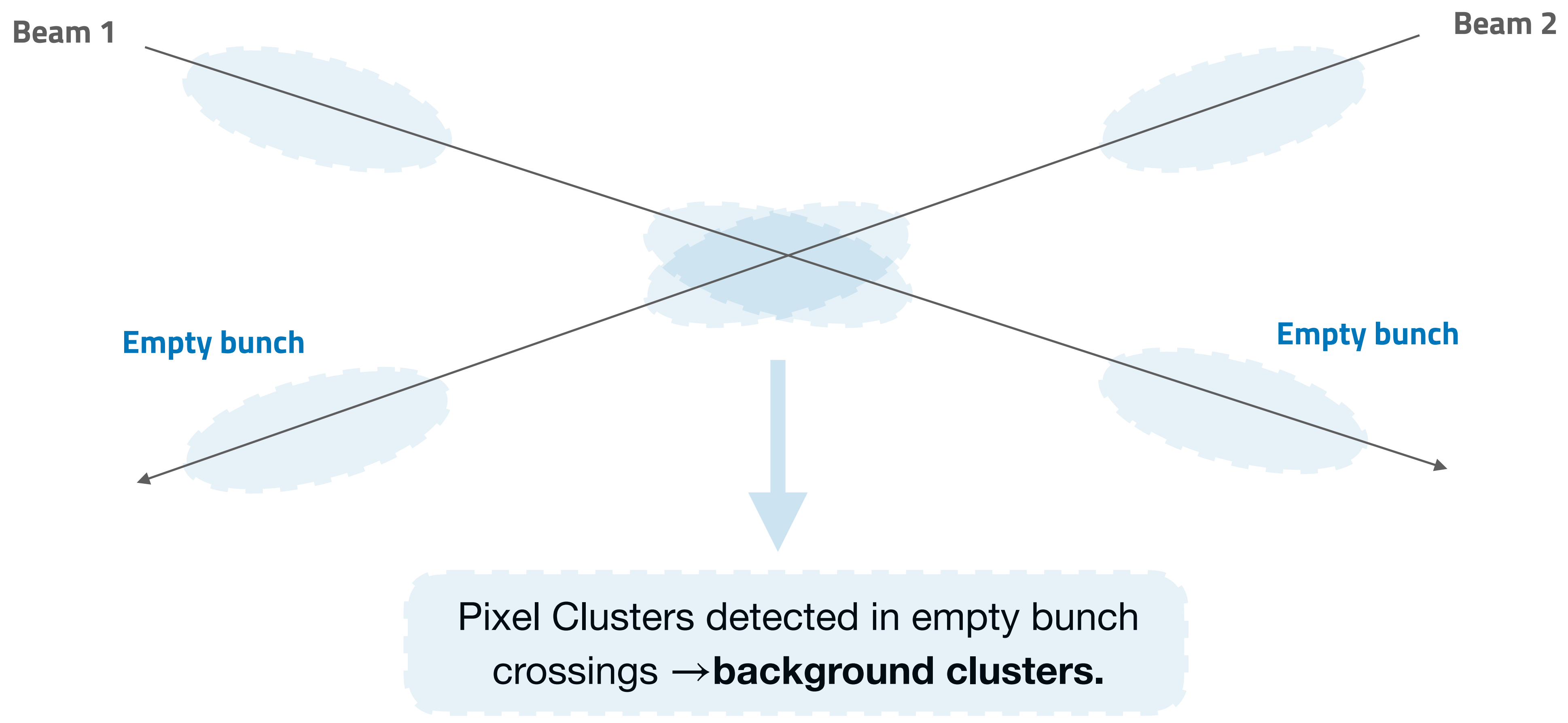
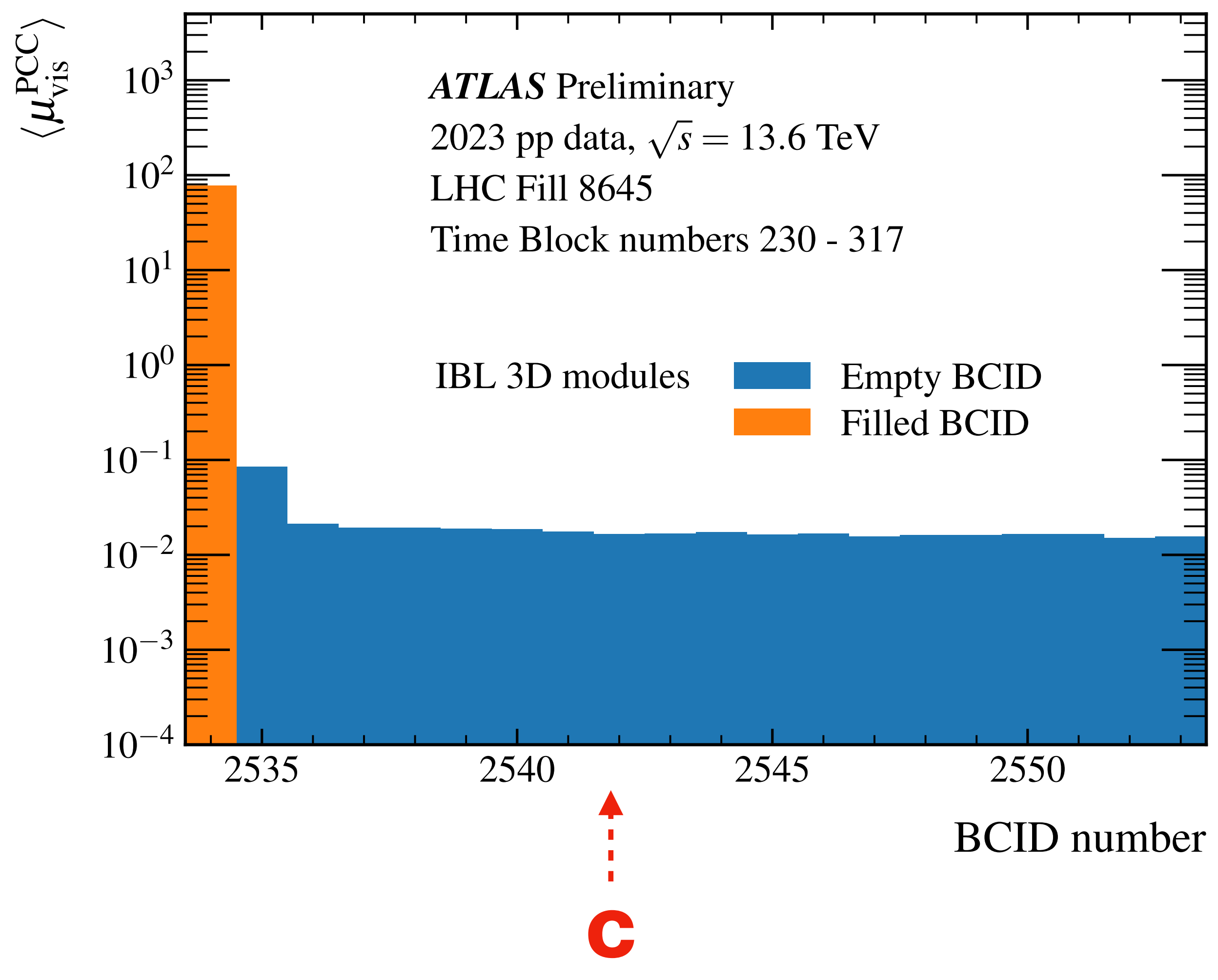
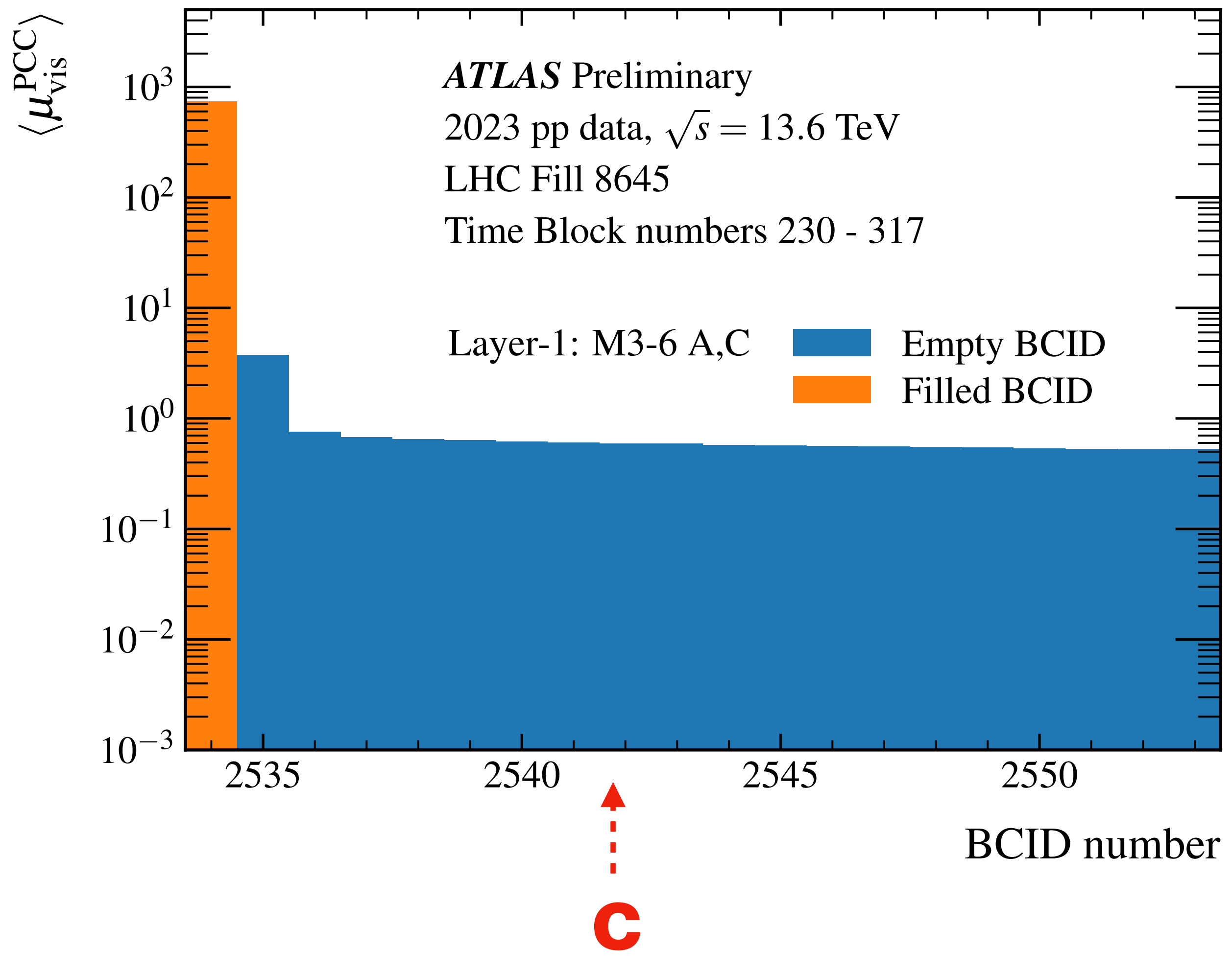
  - 1 kHz **random trigger: samples also crossings of empty bunches**
- **Main background is *afterglow*:** out-of-time clusters induced by previous collisions due to long lived tails of particle cascades and material activation
- Background studied in empty bunches after the last bunch in a **train** of 12 filled bunches





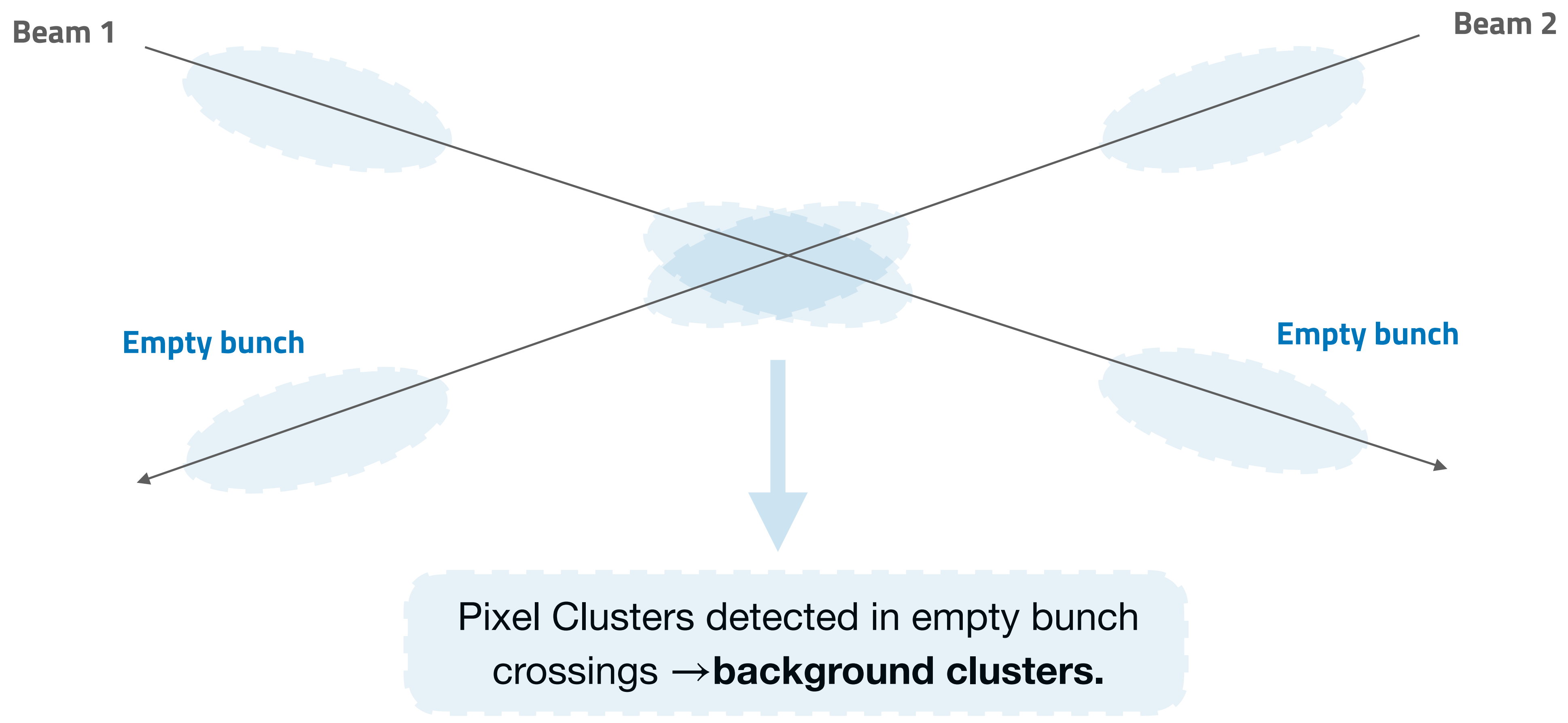


- Relative afterglow activity at **~ permille level**
- **Fast afterglow decay**: within few bunch crossings

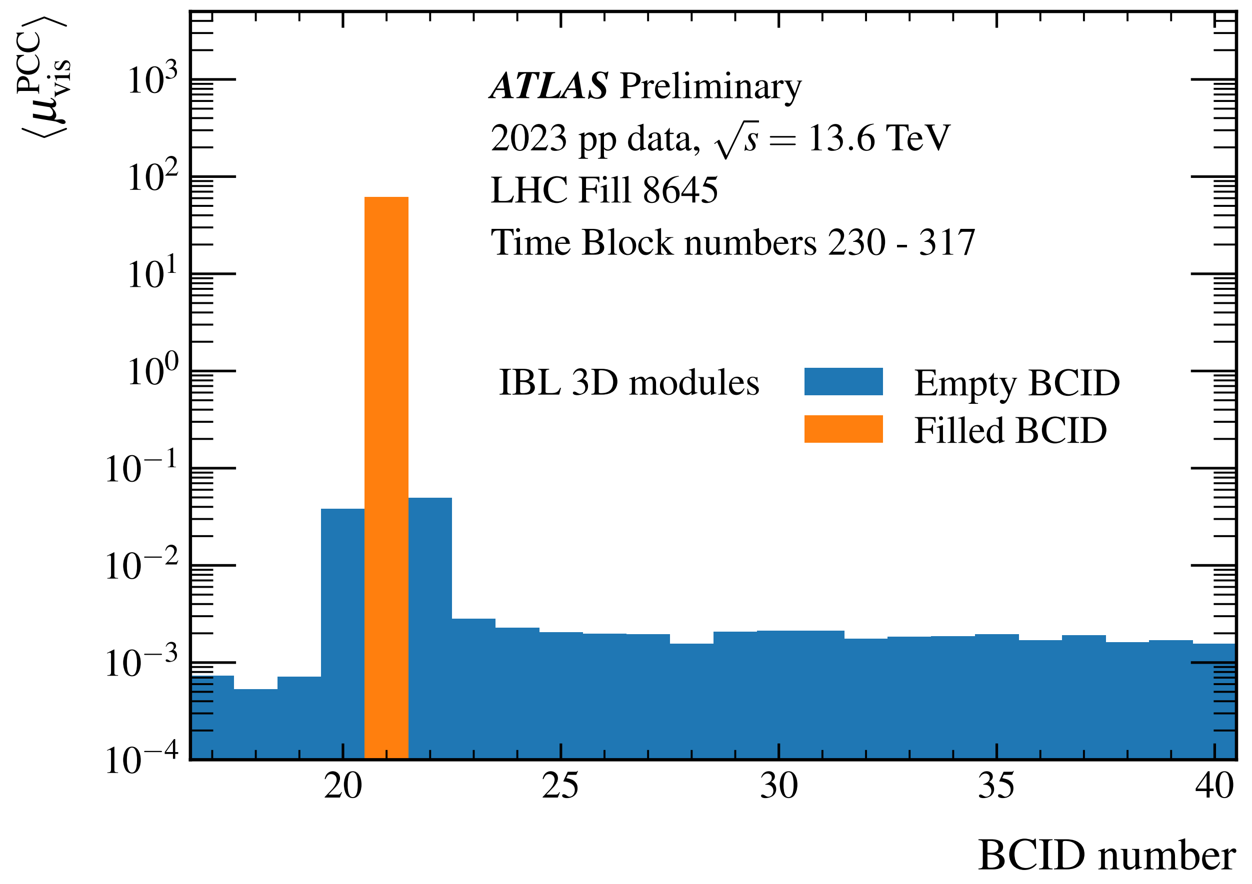
C. Afterglow induced by 12-bunch train
+ intrinsic background

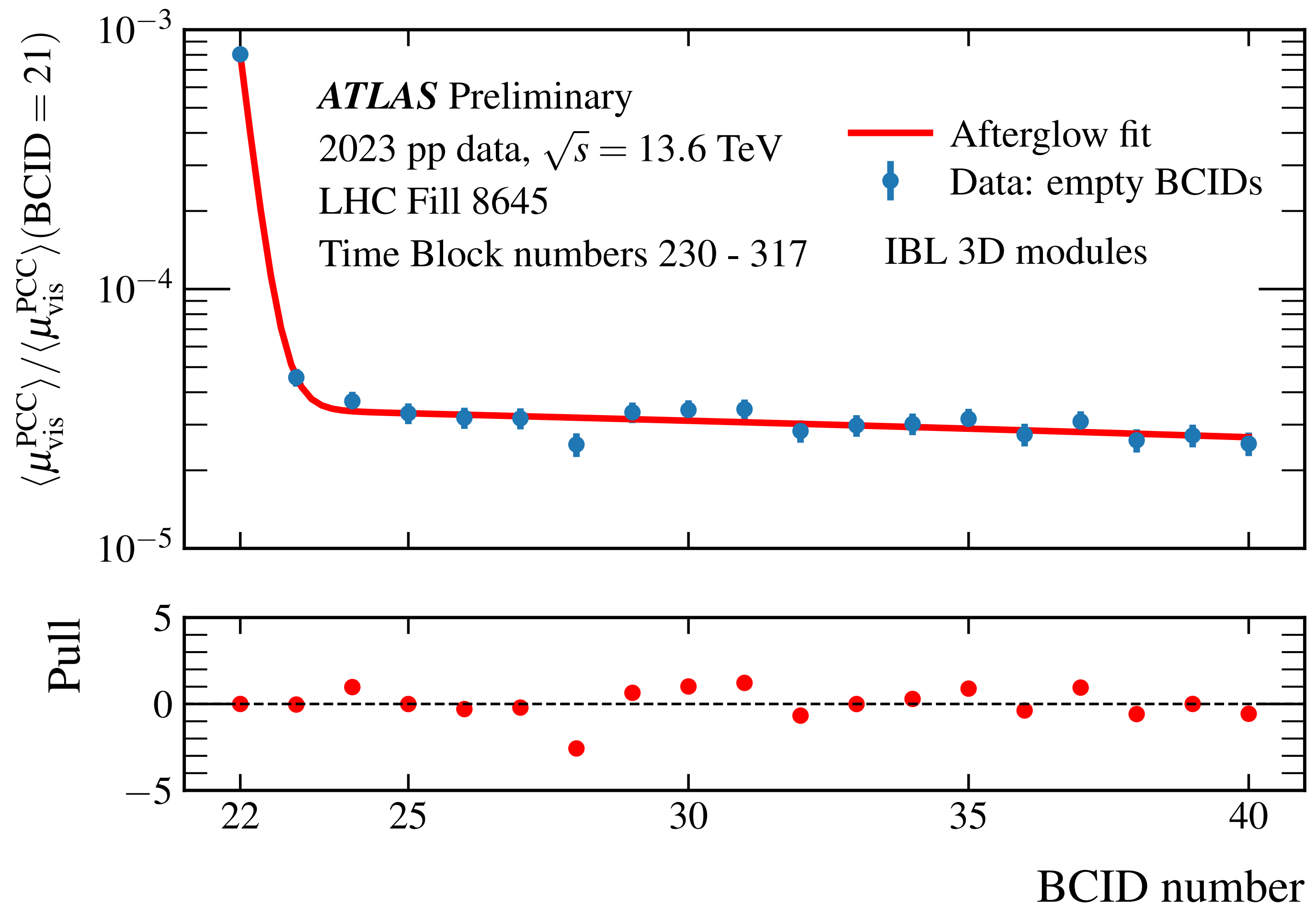
Background contamination in Pixel Cluster Counting

Characterisation of background



- Background contamination in PCC studied in tailored conditions
  - Exploit LHC ramp-up fills: few and isolated filled and colliding bunches
  - 1 kHz **random trigger: samples also crossings of empty bunches**
- **Main background is *afterglow*:** out-of-time clusters induced by previous collisions due to long lived tails of particle cascades and material activation
- Afterglow induced by isolated filled bunch well modelled by exponential (pure afterglow) plus linear function (intrinsic background + longer lived residual activity)





- First step towards the implementation of a **complete afterglow correction procedure** for PCC in normal physics conditions

Putting it all together

Summary and outlook

- The accurate measurement of luminosity is a key component of the ATLAS physics programme

[Eur. Phys. J. C 83 (2023) 982]

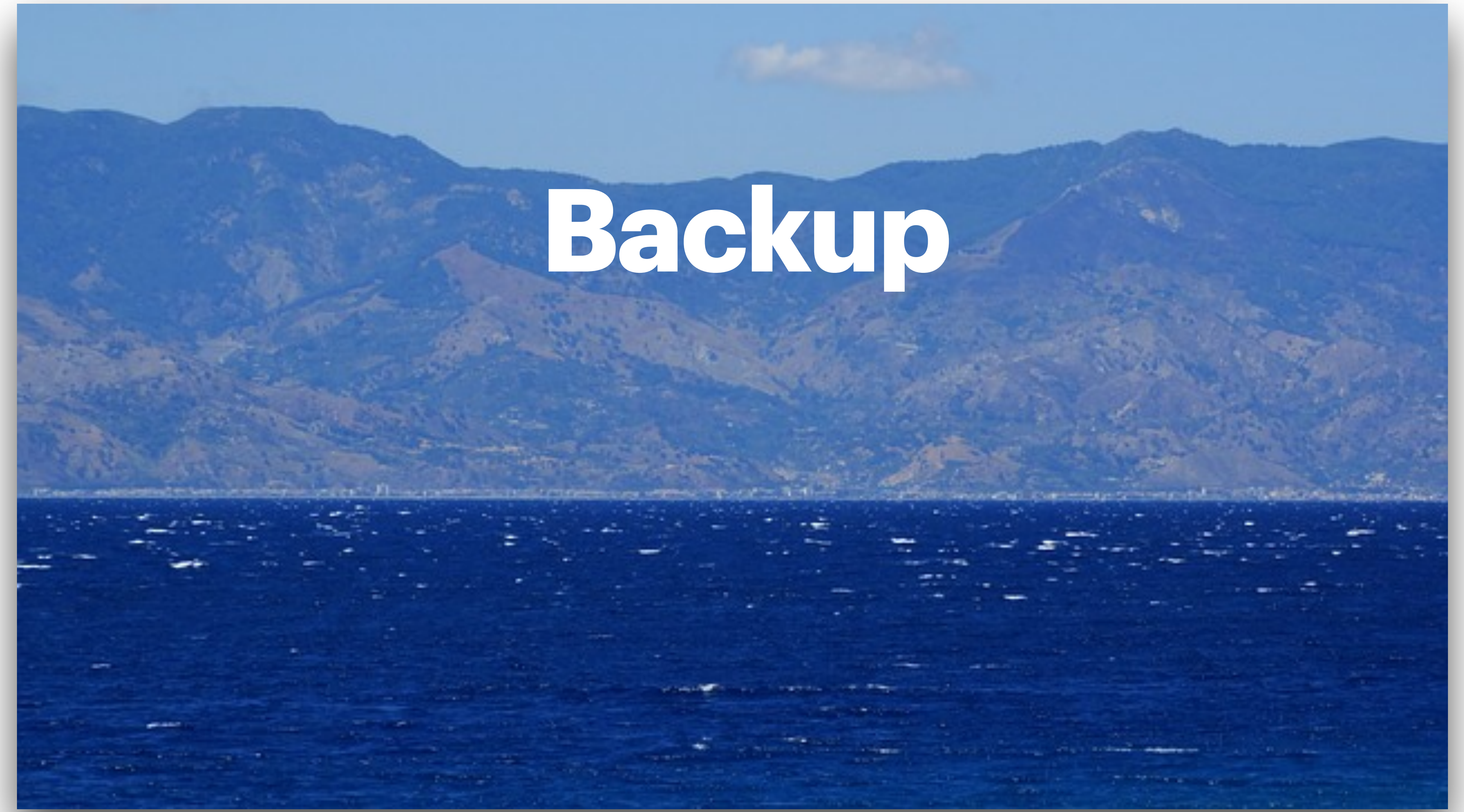
- ATLAS luminosity measurement relies on multiple independent luminometers
  - **Inner Detector → Track Counting and Pixel Cluster Counting**
- **Track Counting established algorithm**
  providing crucial input in to the ATLAS luminosity measurement
  - **Good and stable performance in Run 3**
- First implementation of **Pixel Cluster Counting in development in Run 3**
  - Main ingredients for a Pixel Cluster Counting analysis in place
  - **Promising preliminary studies**: good performance with Run 3 data

Preliminary 2022+2023 estimate

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
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

[ATL-DAPR-PUB-2024-001]

- Redundancy of stable and linear luminometers crucial for an ultra-precise final luminosity measurement in Run 3


Backup

Preliminary Run 3 results

Combination of 2022 and 2023 luminosity uncertainties [ATL-DAPR-PUB-2024-001]

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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
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Track Counting in action

Track Counting stability: **against changing running conditions**

- **Stability of Track Counting tested against varying number of colliding bunches and crossing angle**
  - **Bunch-number dependence** evaluated by **stability of slope** in linear fits of Track Counting/LUCID ratios measured over wide range of pileup variation in beam-separation scans
  - Variations of **Track Counting/LUCID ratios** studied over time periods **with changing crossing angle ($\theta_c/2$) configurations**