Sub-percent precision: Charting new frontiers in measuring luminosity at colliders

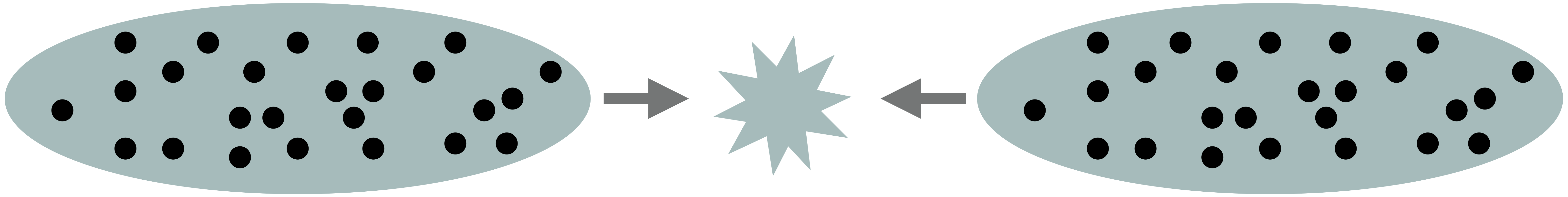
Experimental Particle and Astro-Particle Physics Seminar
Universität Zürich, February 19th, 2024

Claudia Seitz

What is luminosity?

- Important quantity for a collider at its center-of-mass energy
  - Measurement of the **number of collisions** that can be produced in a detector **per cm^2 and per second**

bunch slots every 25ns (or with 40 MHz)



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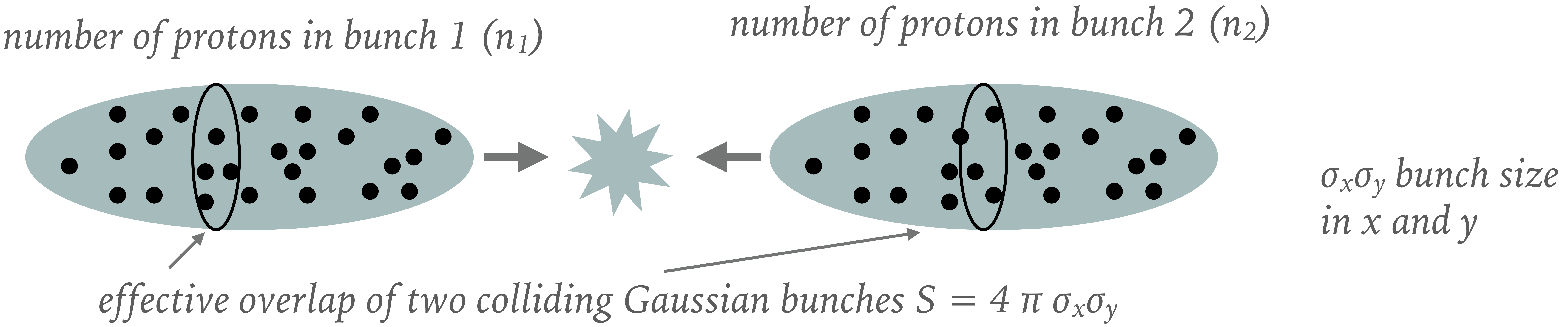
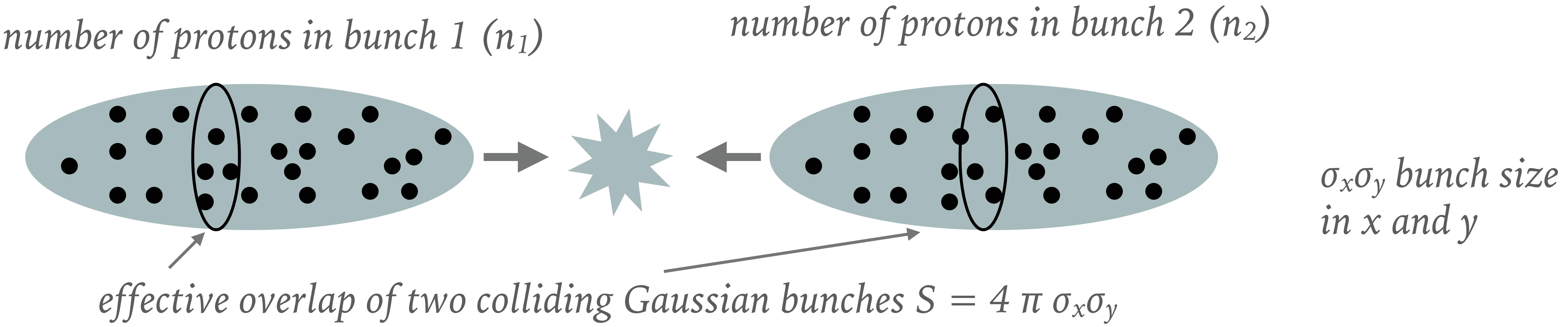


What is luminosity?

1 barn = 10^{-24}cm^2

- Important quantity for a collider at its center-of-mass energy
  - Measurement of the **number of collisions** that can be produced in a detector **per cm² and per second**



Simplified calculation for ***instantaneous luminosity****:*

$n = 1.1 \times 10^{11}$
$t = 25\ ns = 25 \times 10^{-6}\ s$
$\sigma_x = \sigma_y = 16$ microns $= 16 \times 10^{-4}$ cm

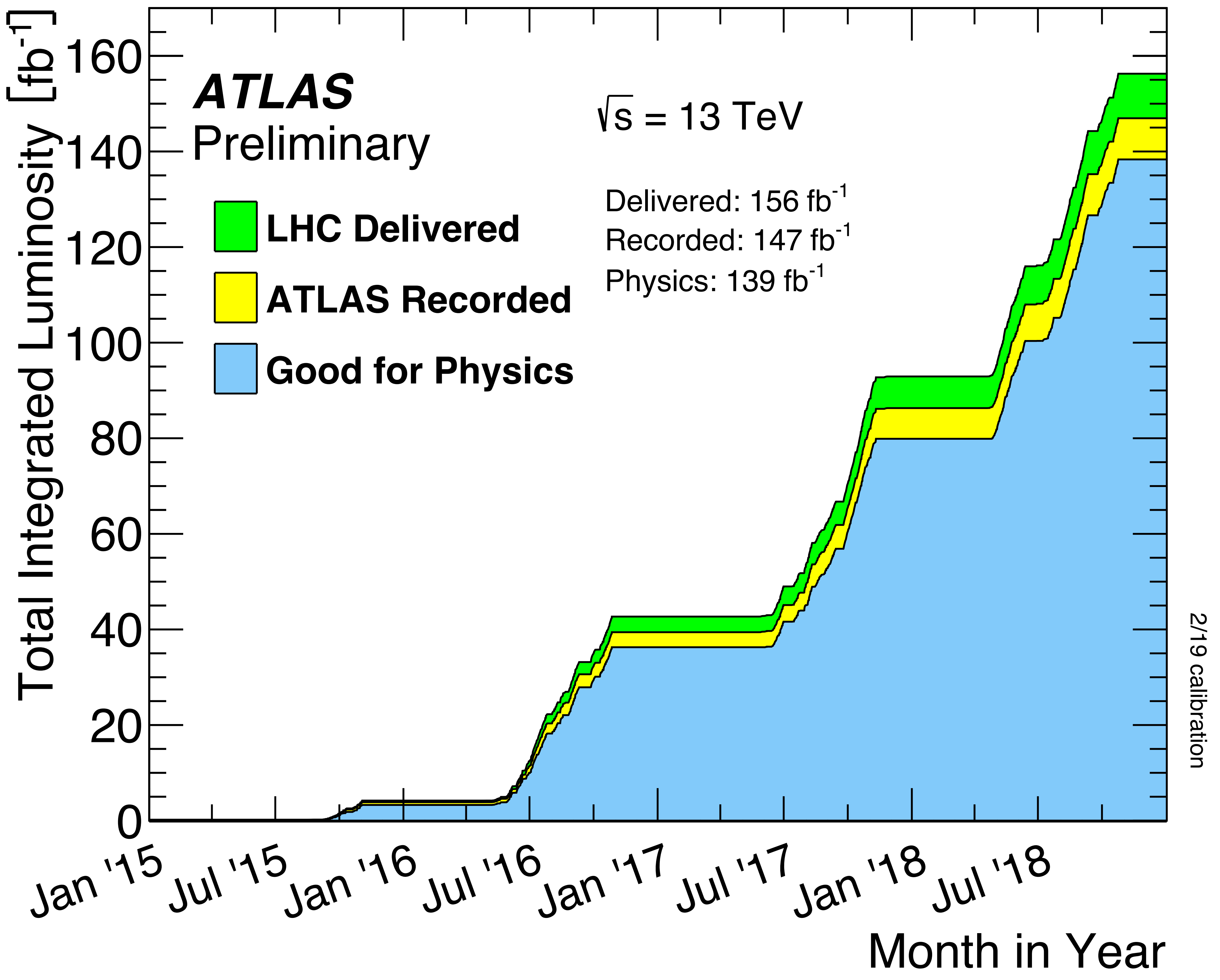
$$\mathcal{L} = n^2/(t \times S)$$
$$\approx 10^{34}\ cm^{-2}\ s^{-1}$$

Why measure luminosity?

- Important quantity for a collider at its center-of-mass energy
  - **Integrated luminosity: how many collisions in a dataset**

$$N_{obs} = \sigma_{inel} L$$

- L = integrated luminosity



ATLAS Run2 Preliminary luminosity

was ***139 ± 2.3 fb^{-1} (1.7%)***

CMS Run2 partial legacy measurement 2016

arxiv:2104.01927

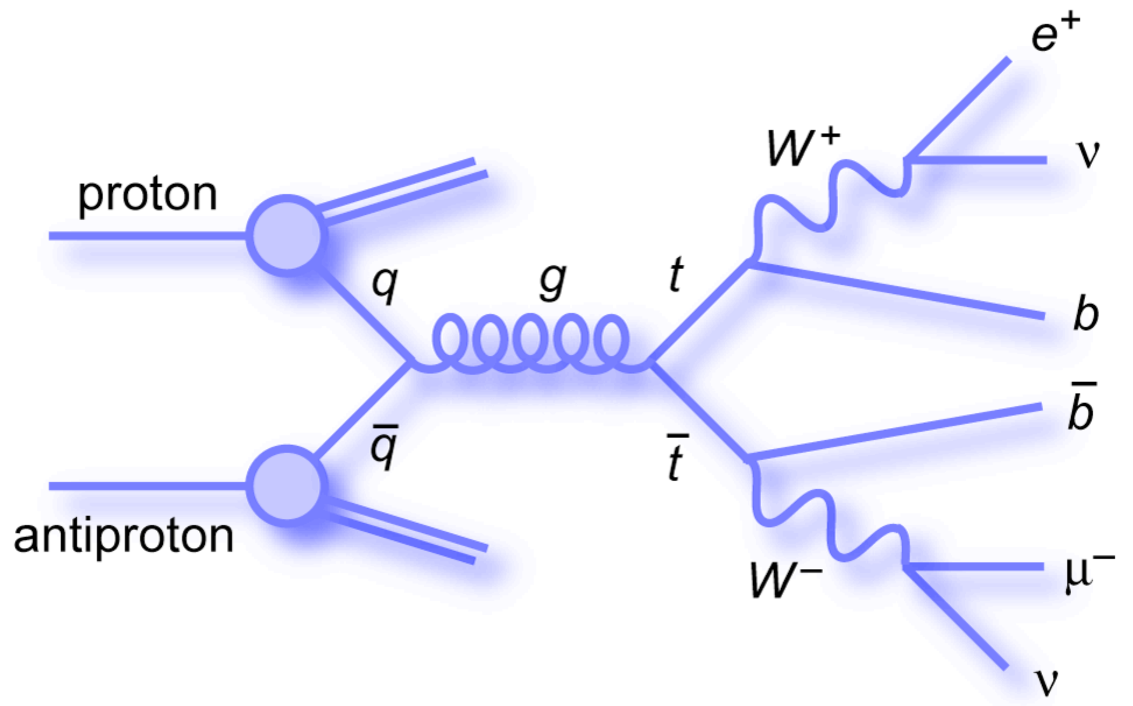
was ***36.3 ± 0.44 fb^{-1} (1.2%)***

Why measure luminosity?

- Important quantity for a collider at its center-of-mass energy
  - **Integrated luminosity: how many collisions in a dataset**
- Goal: provide precision measurement of luminosity for physics analyses
  - Leading systematic uncertainty for some measurements i.e. $t\bar{t}$/W/Z cross section

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

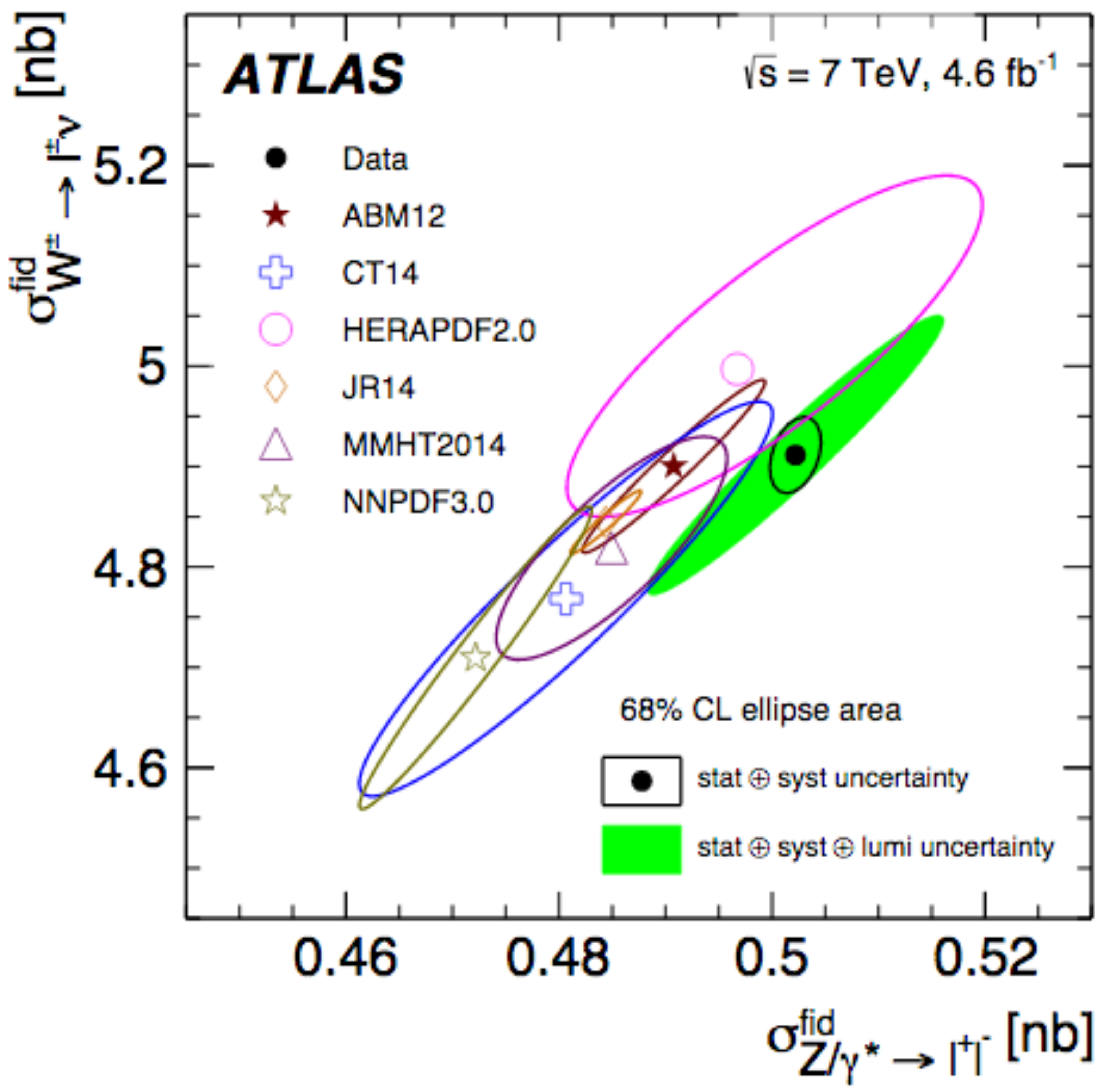
$$\sigma_{t\bar{t}} = 826.4 \pm 3.6\,(\text{stat}) \pm 11.5\,(\text{syst}) \pm 15.7\,(\text{lumi}) \pm 1.9\,(\text{beam})\,\text{pb},$$



$t\bar{t} \to e\mu bb$

at 13 TeV with 36 fb^{-1}

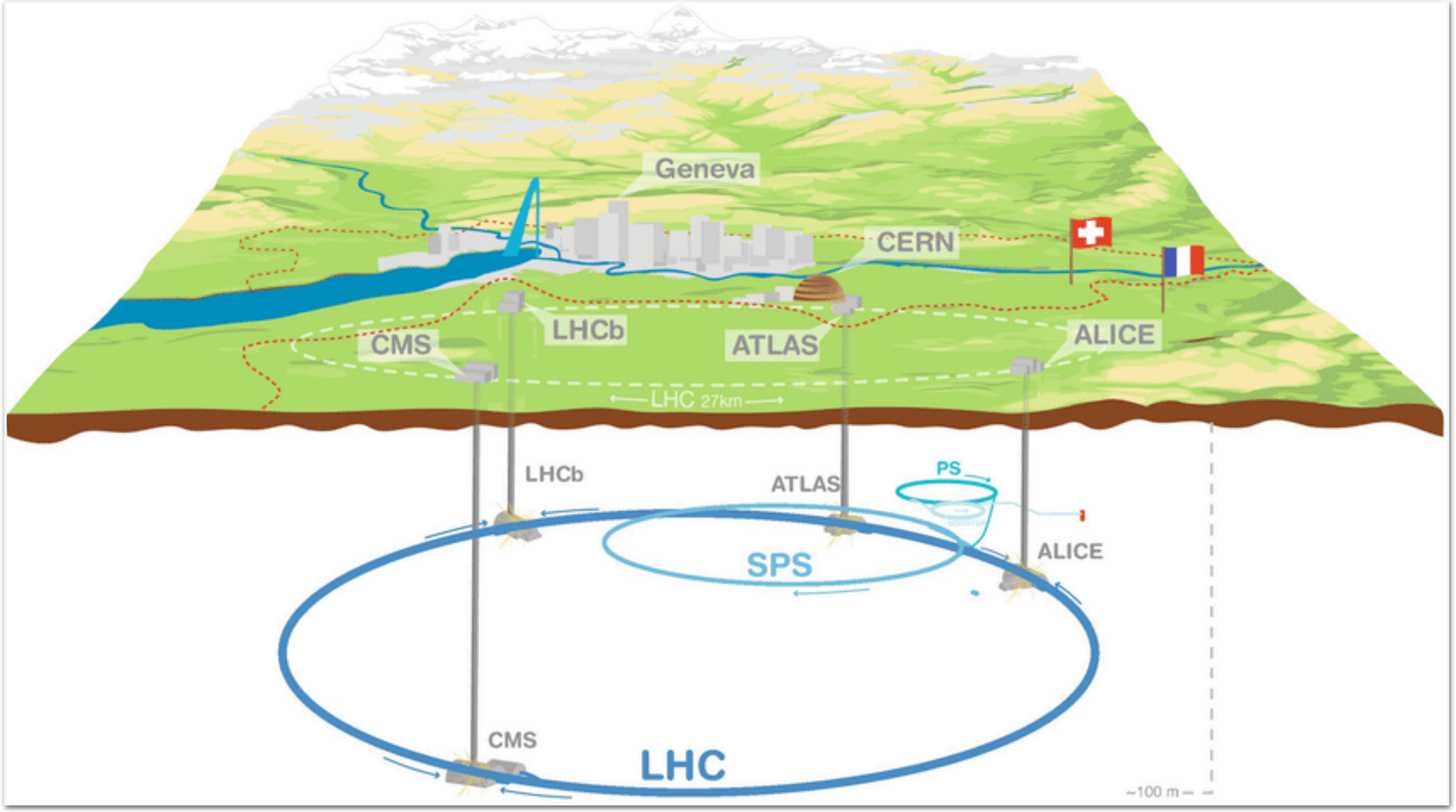
Eur. Phys. J. C 77 (2017) 367

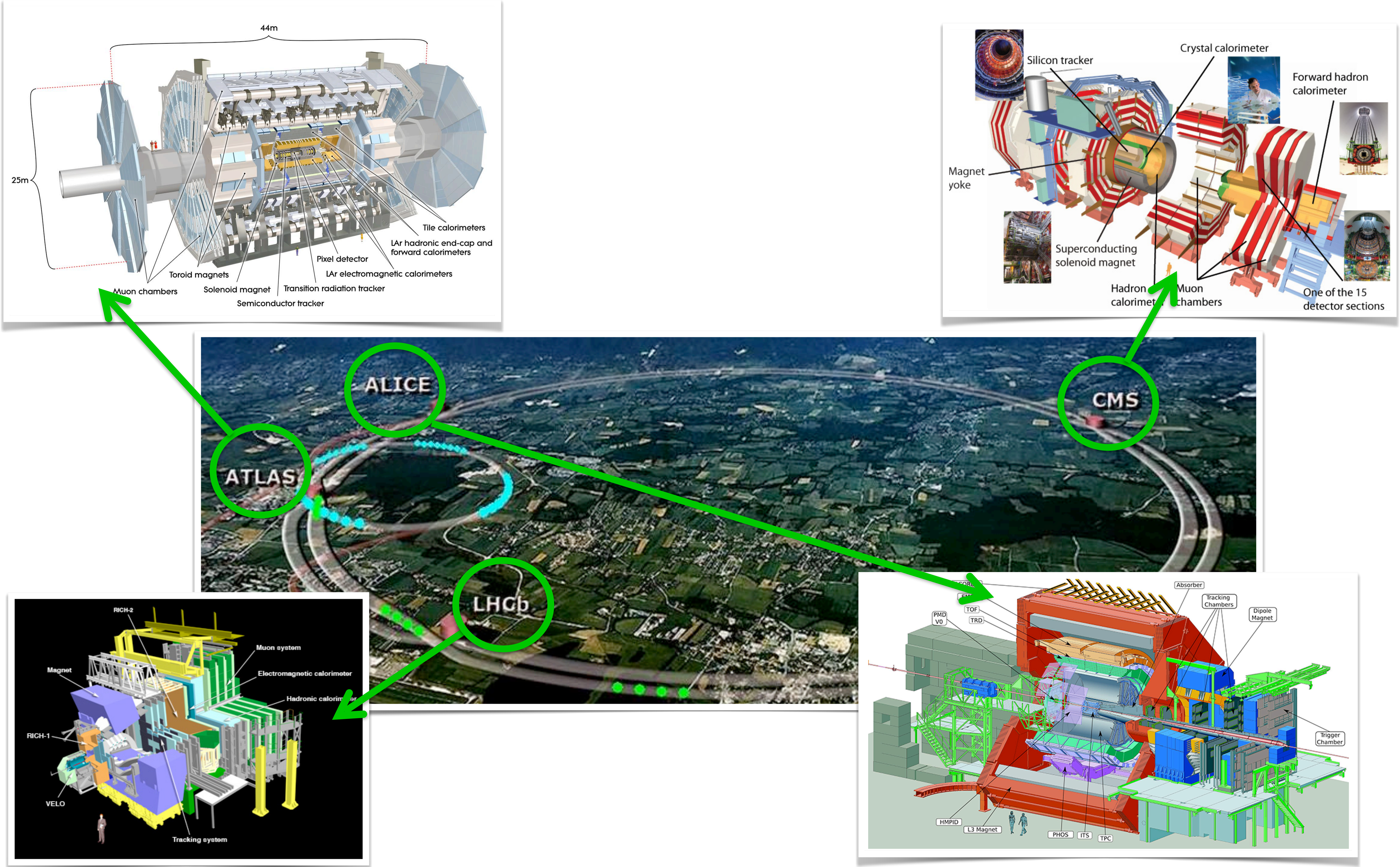


7 TeV dataset: 1.8% luminosity uncertainty

The Large Hadron Collider

- Proton-proton (proton-ion) collider with a circumference of 27 km located under the Swiss-French border near Geneva
- Center-of-mass energy 13 TeV (recently 13.6 TeV achieved)
- Over 1200 dipole magnets to keep proton beams on circular path




44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
Silicon tracker
Crystal calorimeter
Forward hadron calorimeter
Magnet yoke
Superconducting solenoid magnet
One of the 15 detector sections
ALICE
ATLAS
CMS
LHCb
RICH-2
Muon system
Magnet
Electromagnetic calorimeter
RICH-1
VELO
Tracking system
Absorber
Tracking Chambers
Dipole Magnet
PMD V0
TOF
TRD
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC

Luminosity and LHC beam parameters

- Goal: provide precision measurement of luminosity for physics analyses
  - From rate of observed events for a given process cross section
    - Example: $Z \rightarrow ll$ cross section known only to a few %

$$N_{obs} = \sigma \mathcal{L} \Delta t$$

- Δt = luminosity block (LB ~ 60 s)
- $\mathcal{L}$ = instantaneous luminosity

Luminosity and LHC beam parameters

- Goal: provide precision measurement of luminosity for physics analyses
  - From rate of observed events for a given process cross section
    - Example: $Z \rightarrow ll$ cross section known only to a few %
  - From LHC machine parameters
    - Allows more precise measurements

$$N_{obs} = \sigma \mathscr{L} \Delta t$$

- Δt = luminosity block (LB ~ 60 s)
- $\mathscr{L}$ = instantaneous luminosity

- μ_b = number of inelastic pp collisions per bunch crossing
- σ_{inel} = inelastic pp cross section

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

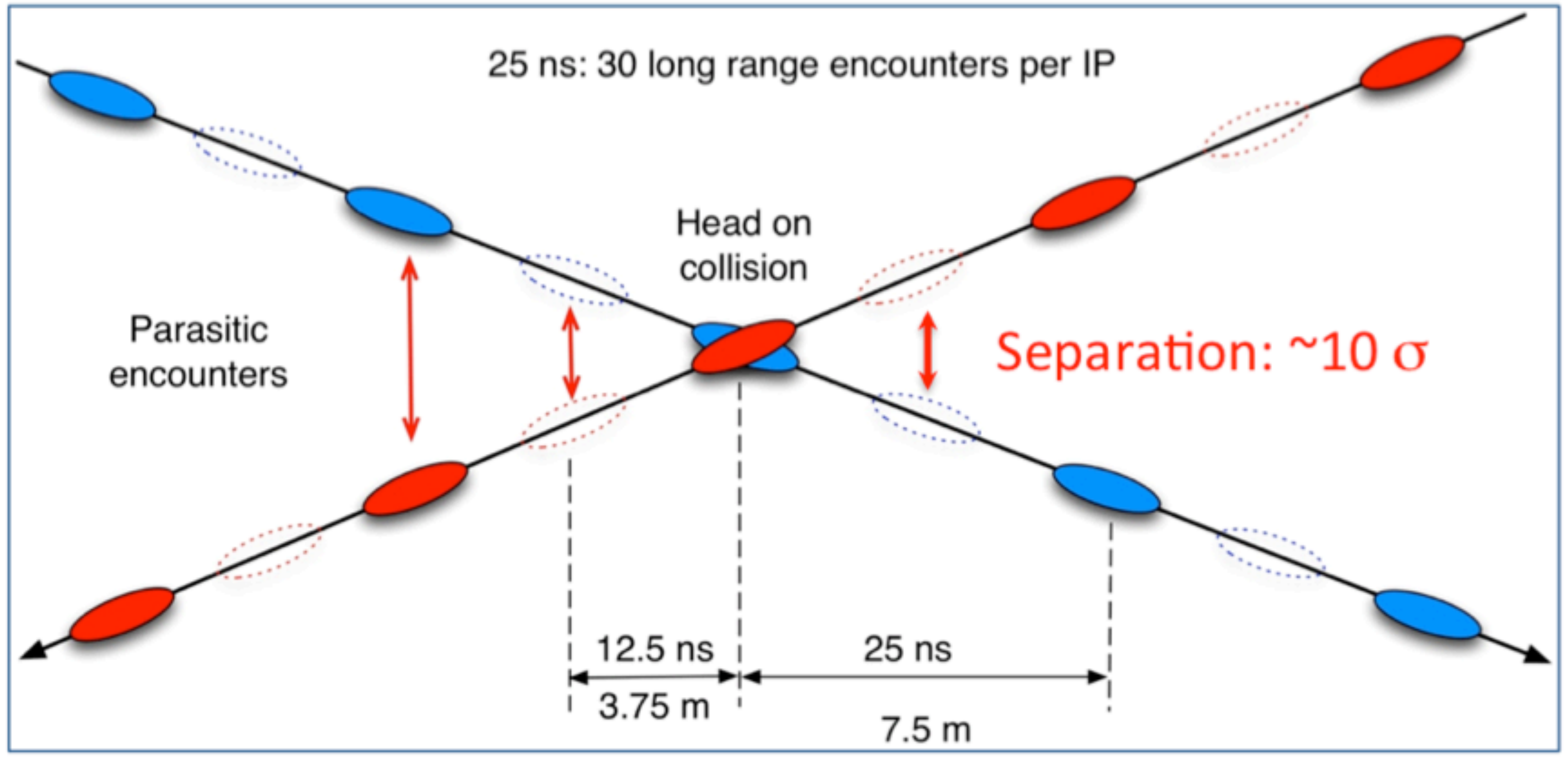
LHC beam parameters

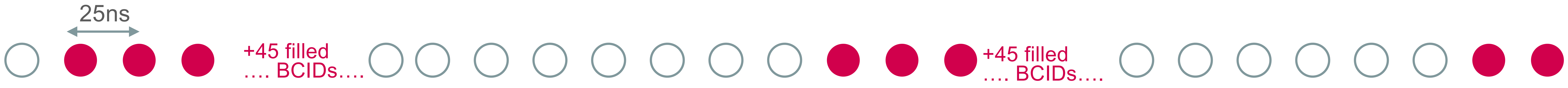
Can also be expressed by
- μ_{vis} = visible interaction rate of a given algorithm or luminometer
- σ_{vis} = visible cross section of that algorithm or luminometer

How do LHC beams look like?

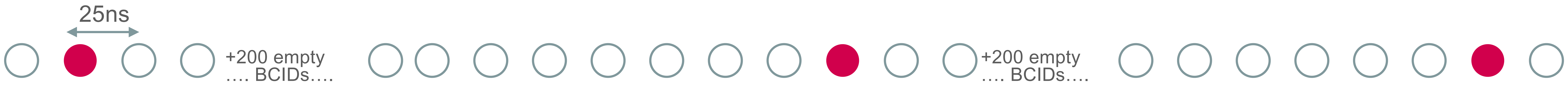
2018 beam parameters (physics regime)

- revolution frequency: $f_r = 11246/s$
- #bunches: n_b up to 2544
- #protons / bunch: $n_i = (1.1\text{-}0.9) \times 10^{11}$
- Width of beams overlap: $\Sigma y > \Sigma x \approx$ 10-20 μm





- *string of several consecutive filled slots in both beams =* ***train***



- *individual filled bunches with several empty ones before and after in both beams =* ***indivs***

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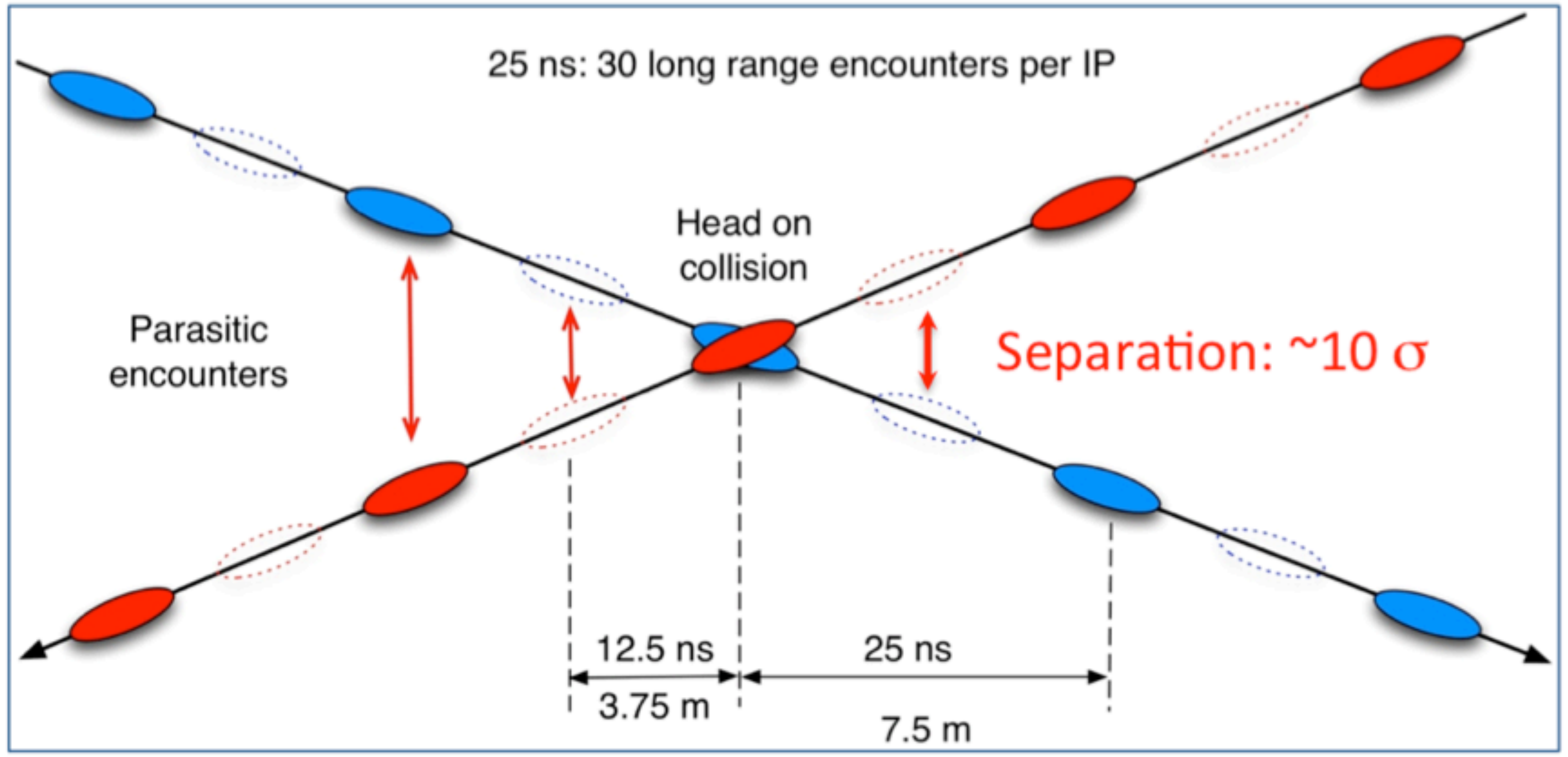
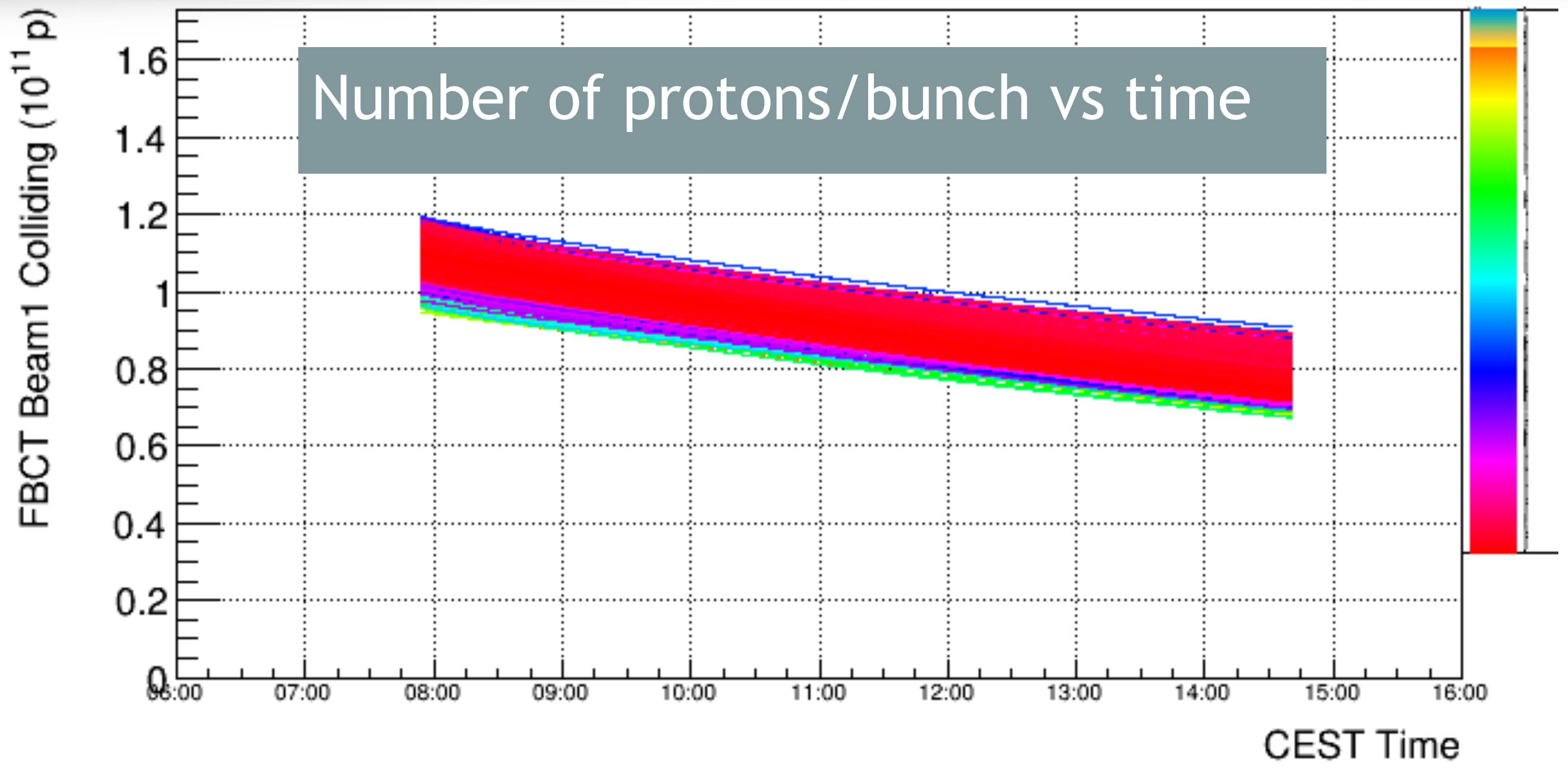
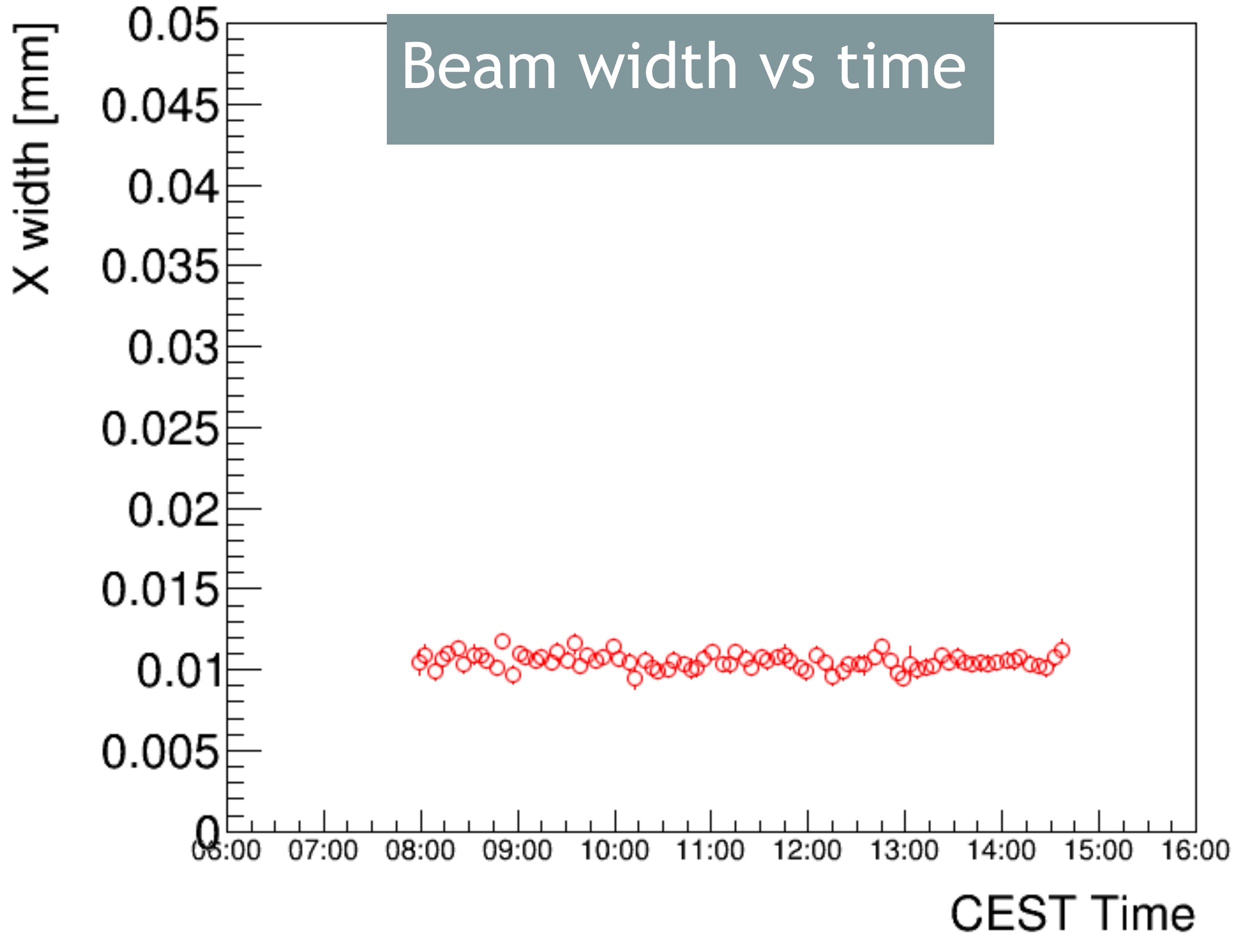
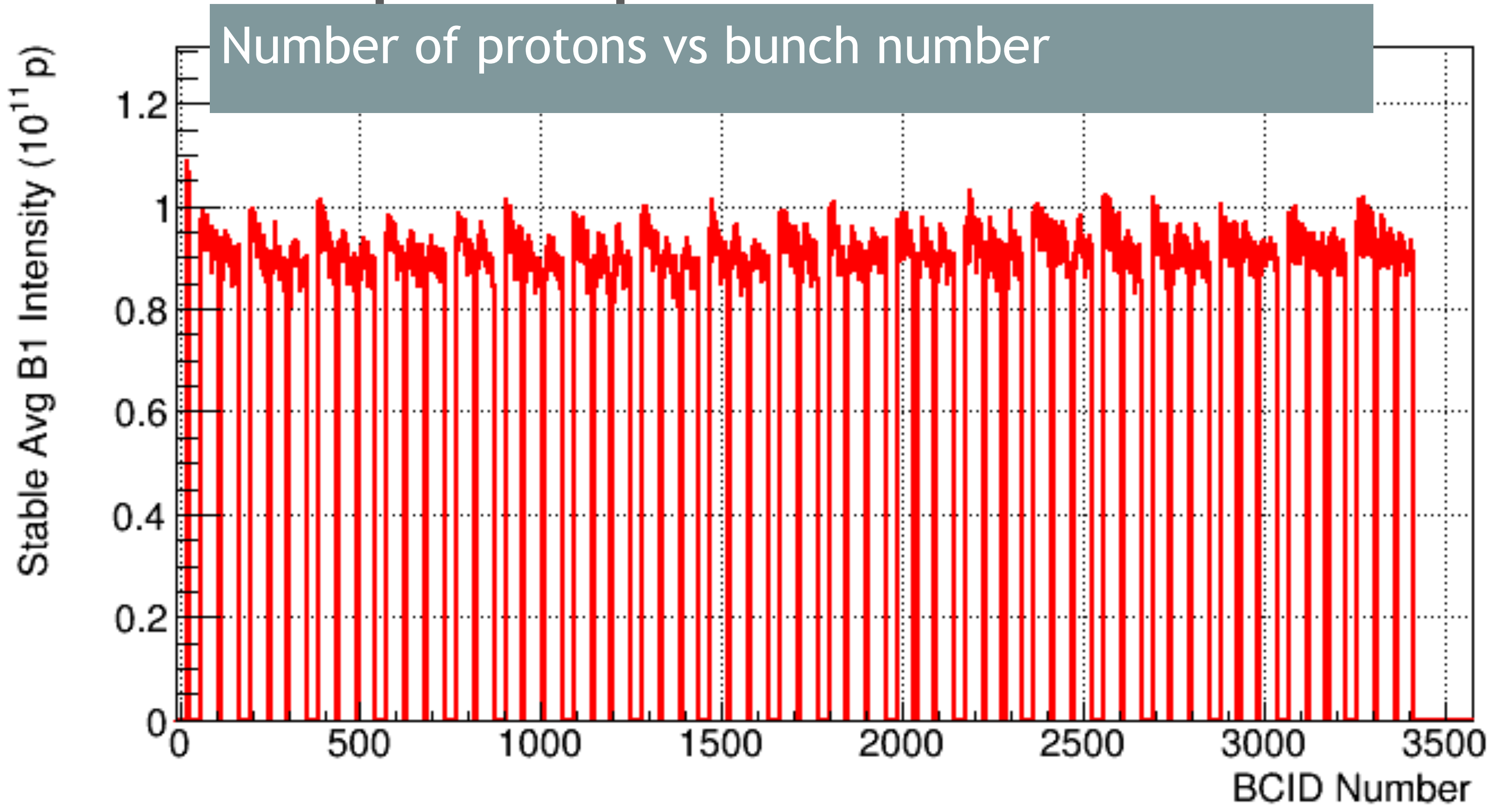






Example fill Sep 4th, 2018



*Each position gets assigned a Bunch Crossing Identifier = **BCID***

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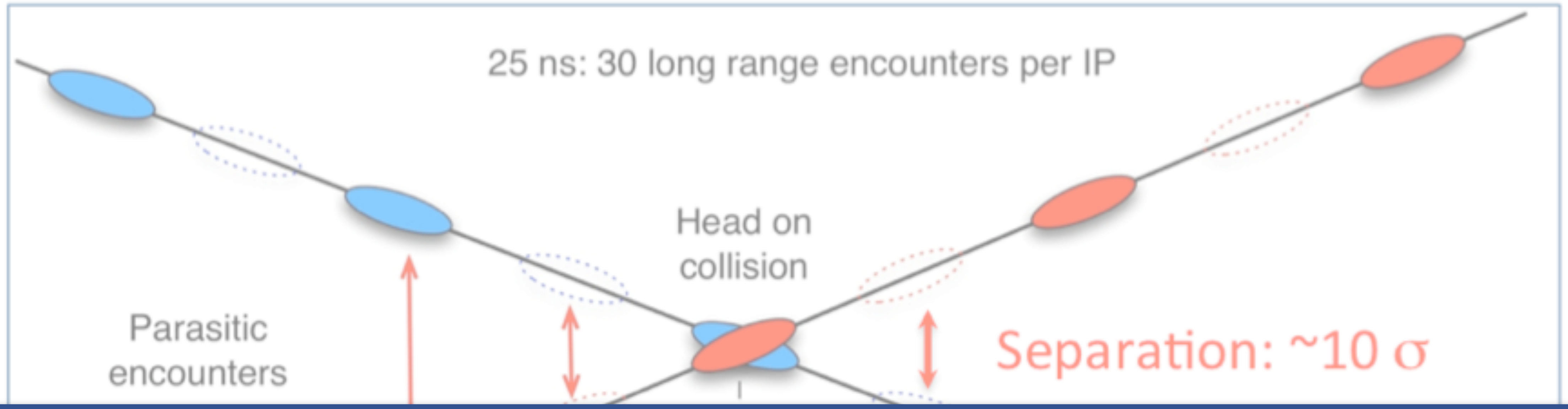
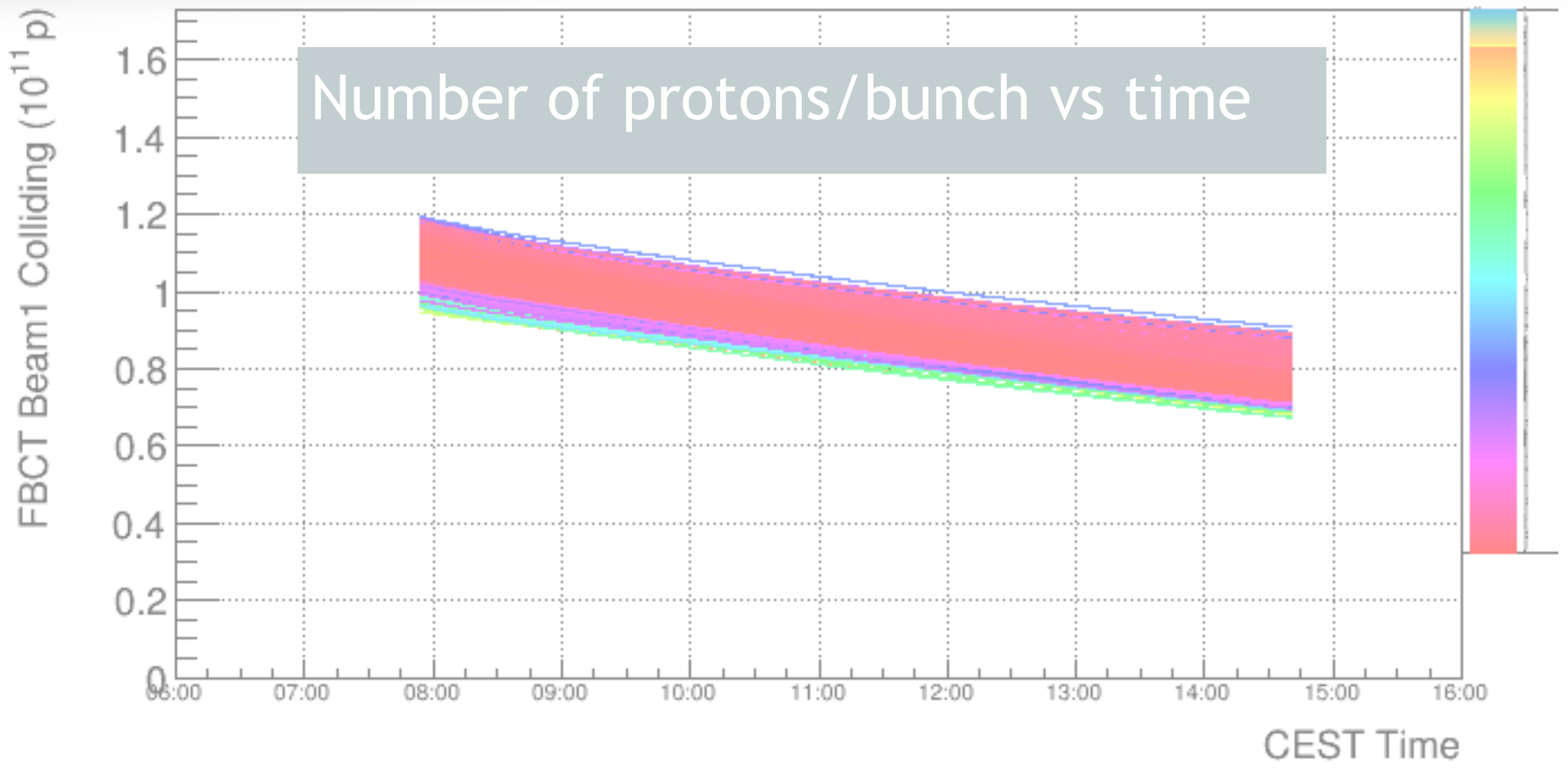
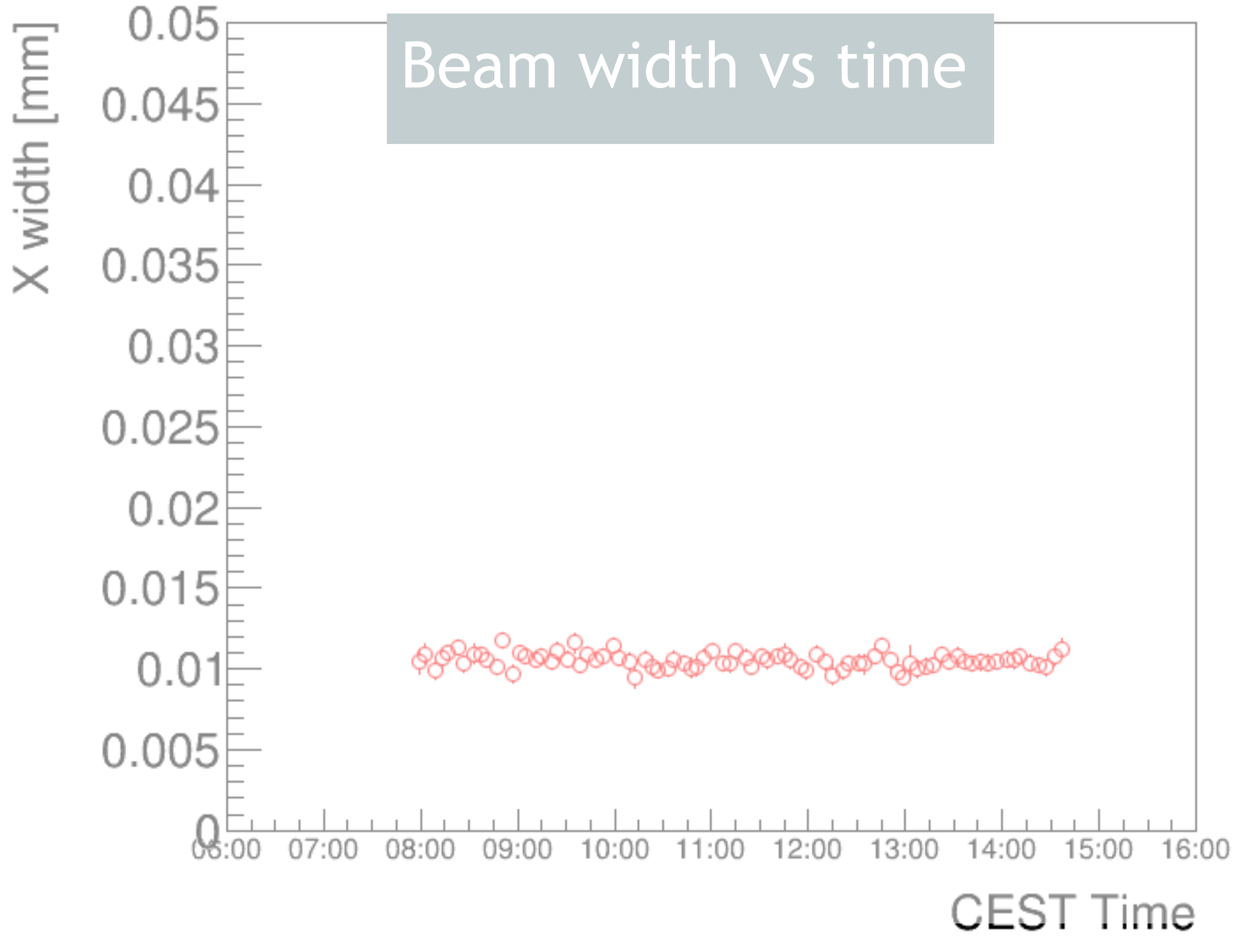
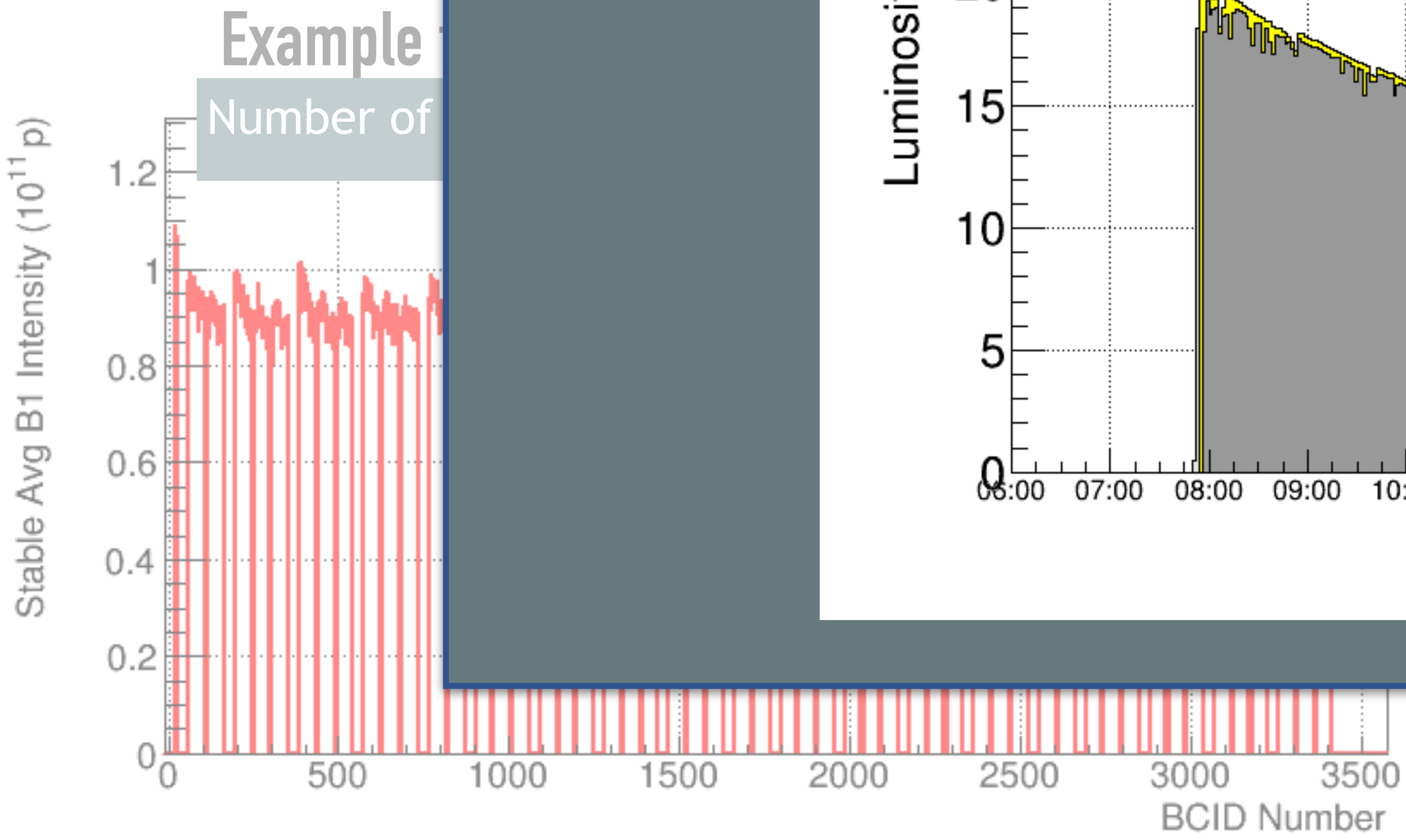
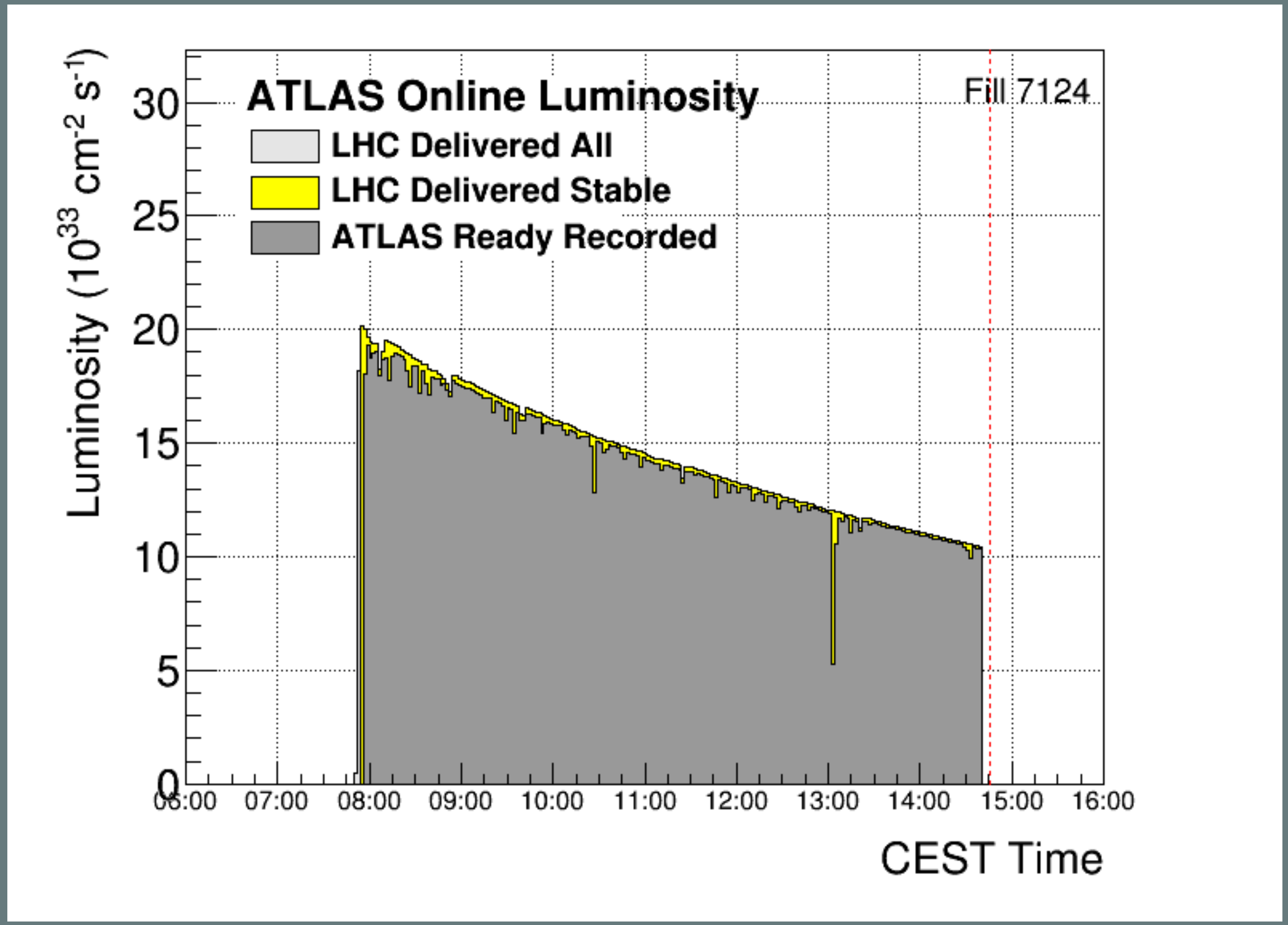




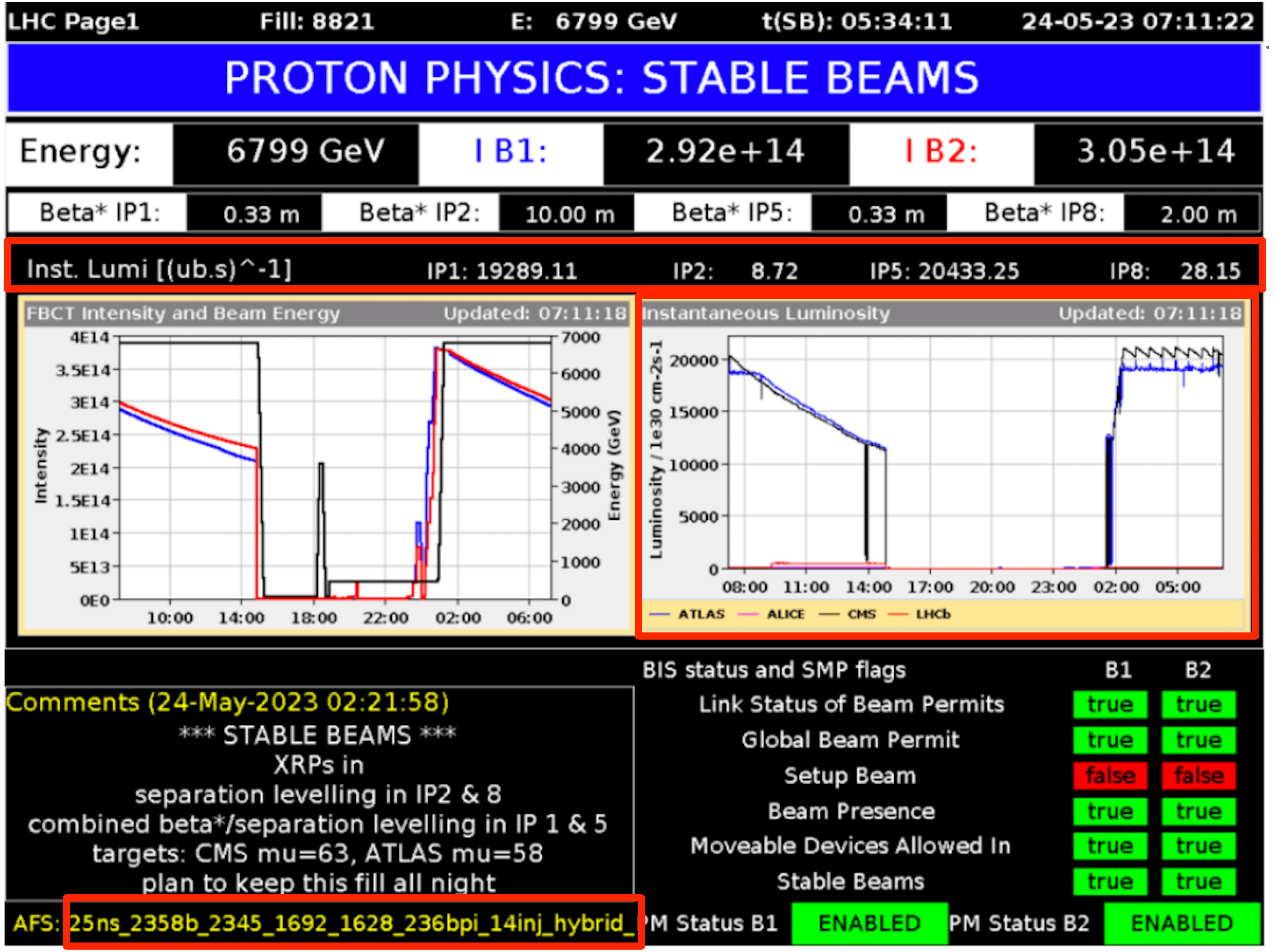




Online luminosity measurement



https://op-webtools.web.cern.ch/vistar/



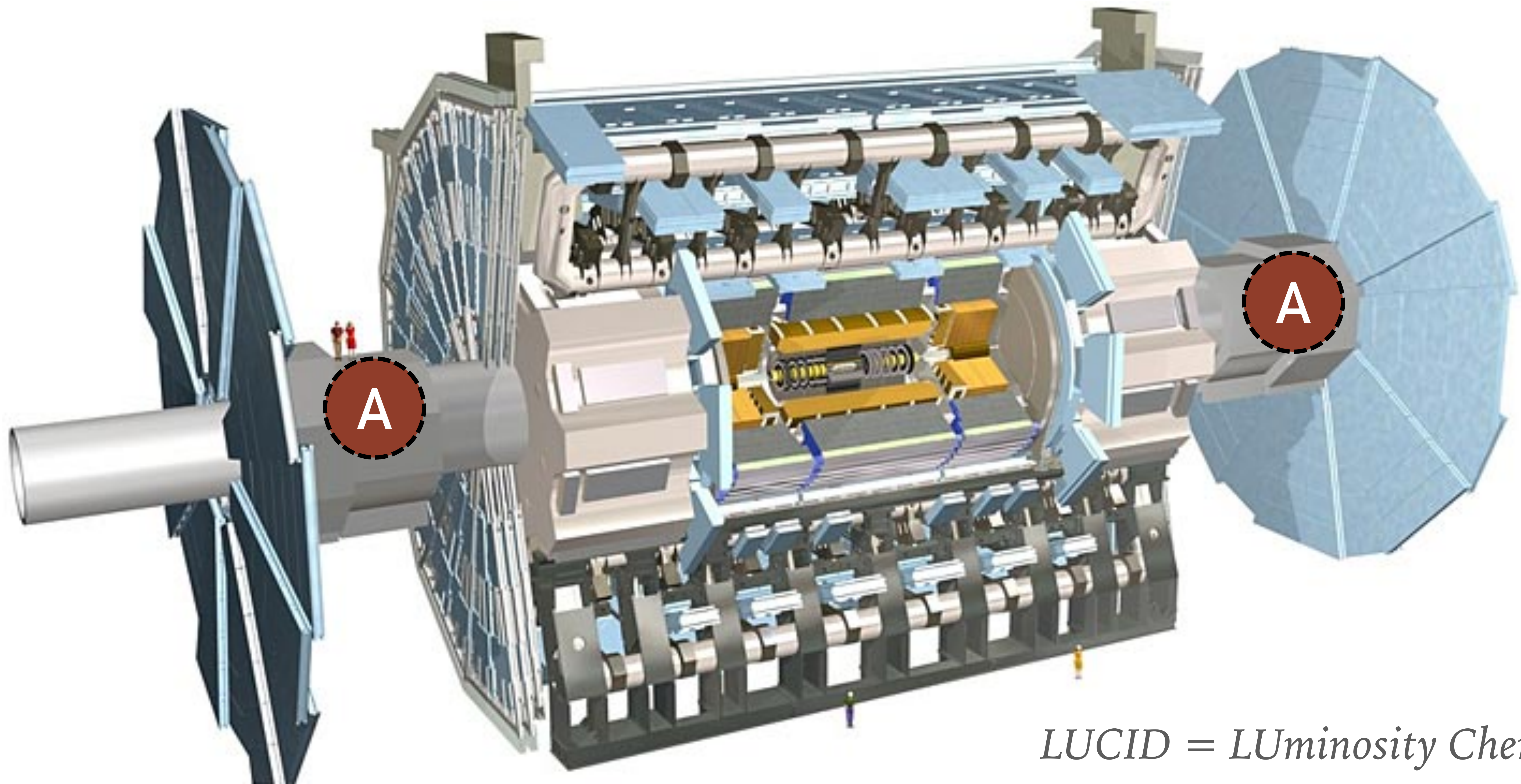
shows the filling scheme

- Online instantaneous luminosity gets reported back to the LHC
- Allows direct comparisons between the different interaction points (IP)

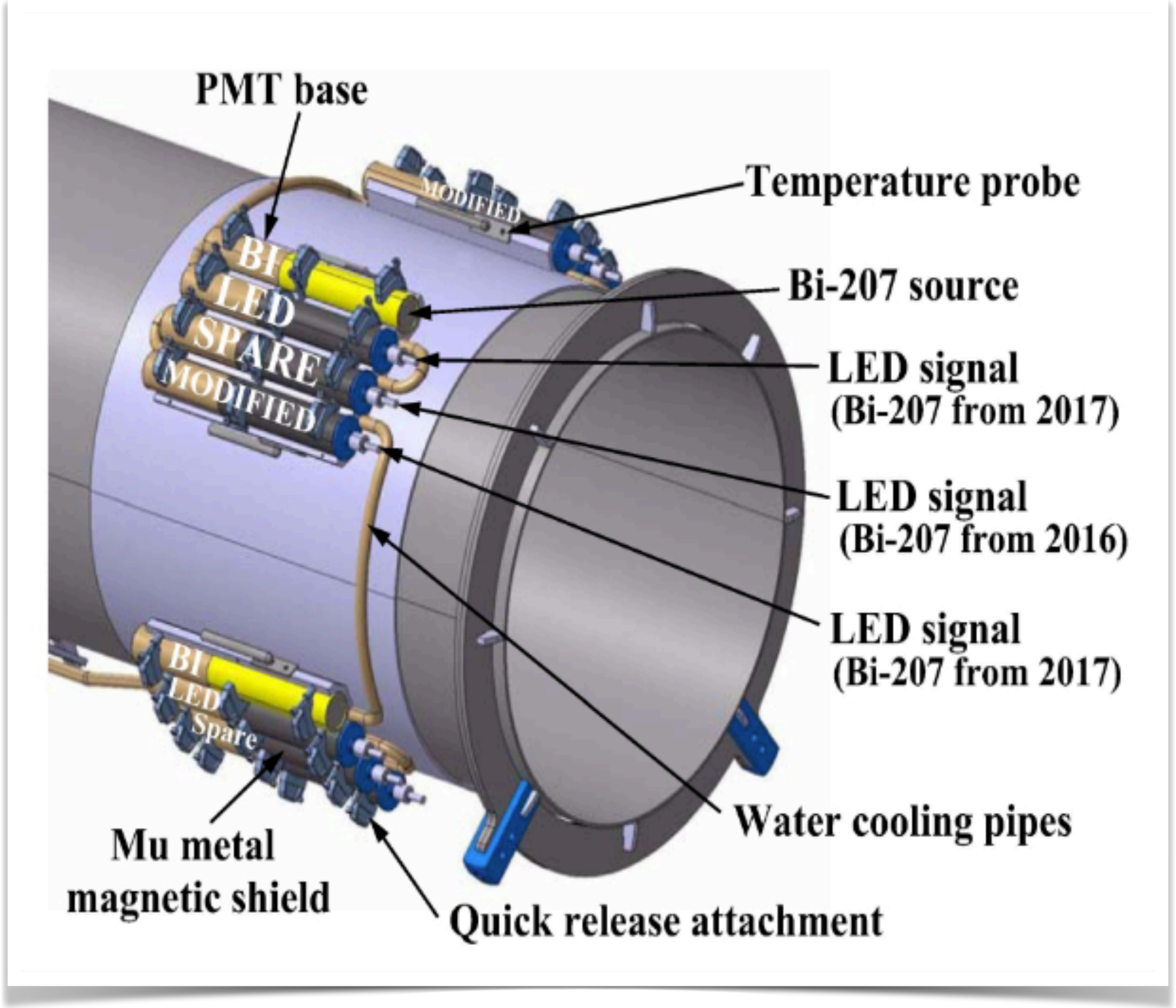
ATLAS Luminosity detectors and algorithms

A **LUCID**

- Baseline luminometer for Run 2, Cherenkov light detector with 2x16 PMTs at z = ± 17 m from IP
- Bunch-by-bunch luminosity through hit counting → different algorithms in use



C



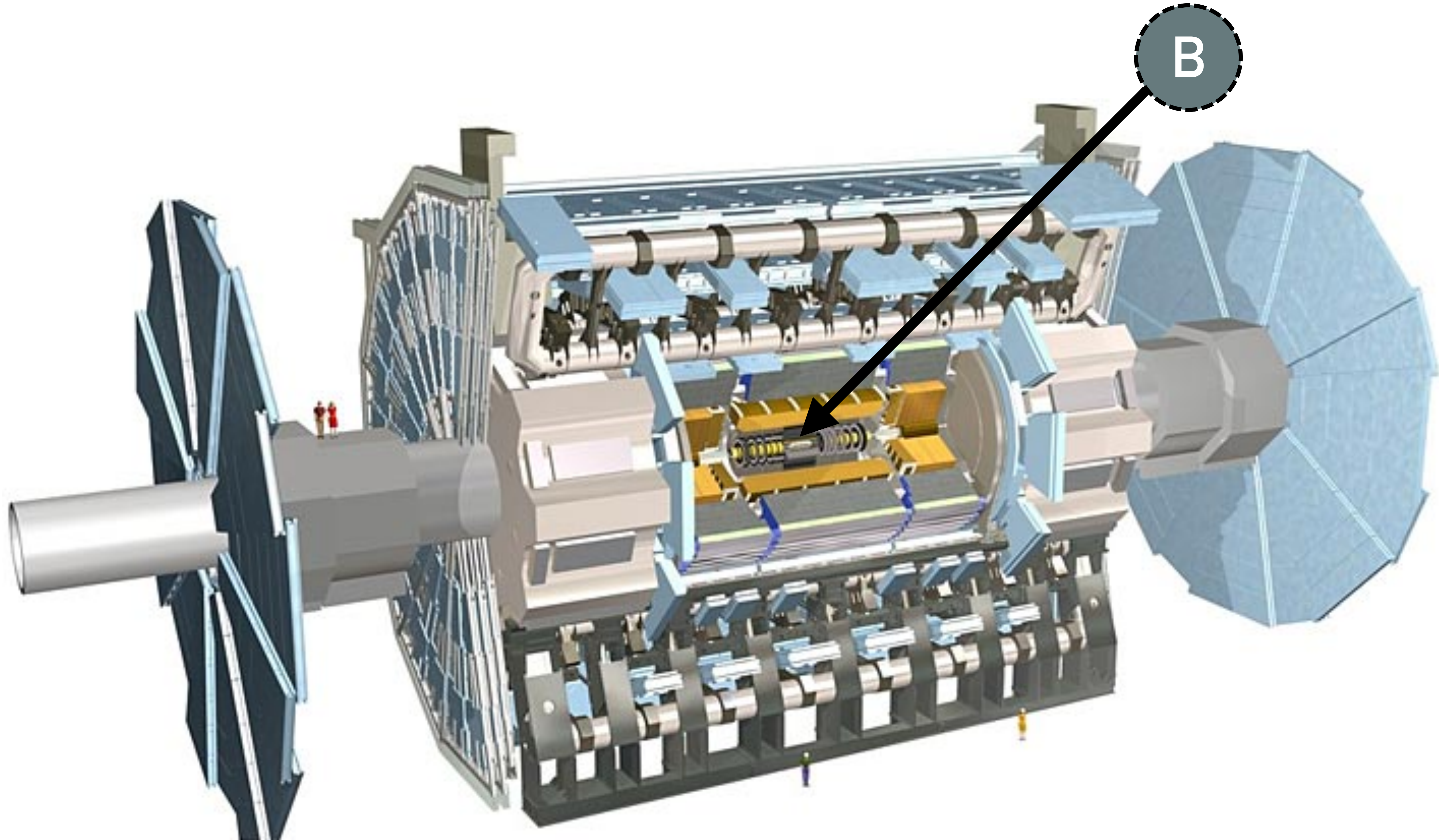
2018 JINST 13 P07017

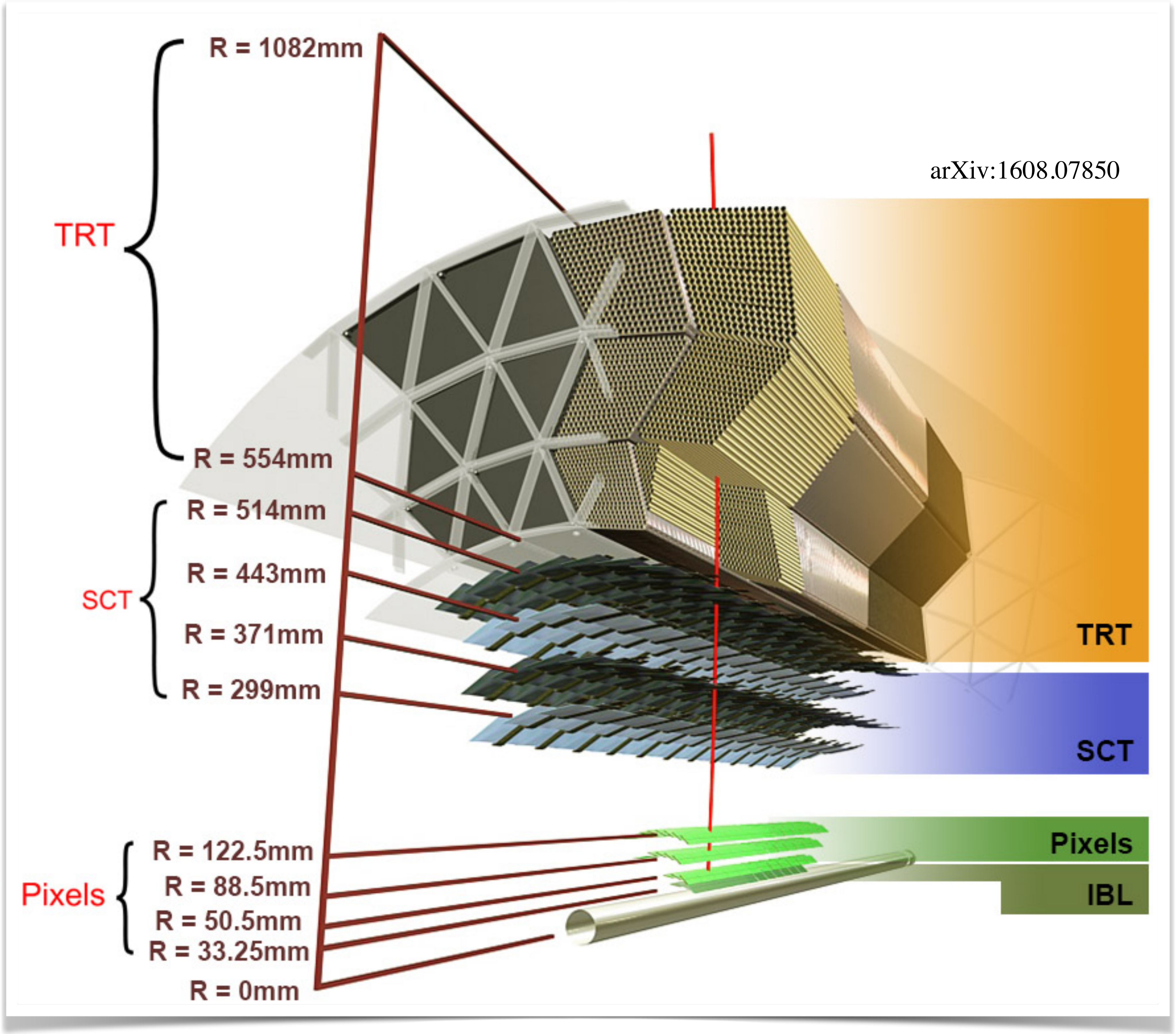
LUCID = LUminosity Cherenkov Integrating Detector

ATLAS Luminosity detectors and algorithms

B Track counting (TC)

- ➤ Counting tracks in the inner detector (ID)
- ➤ Bunch-by-bunch capabilities
- ➤ Bunch-integrated for physics runs
  → different track selections in use

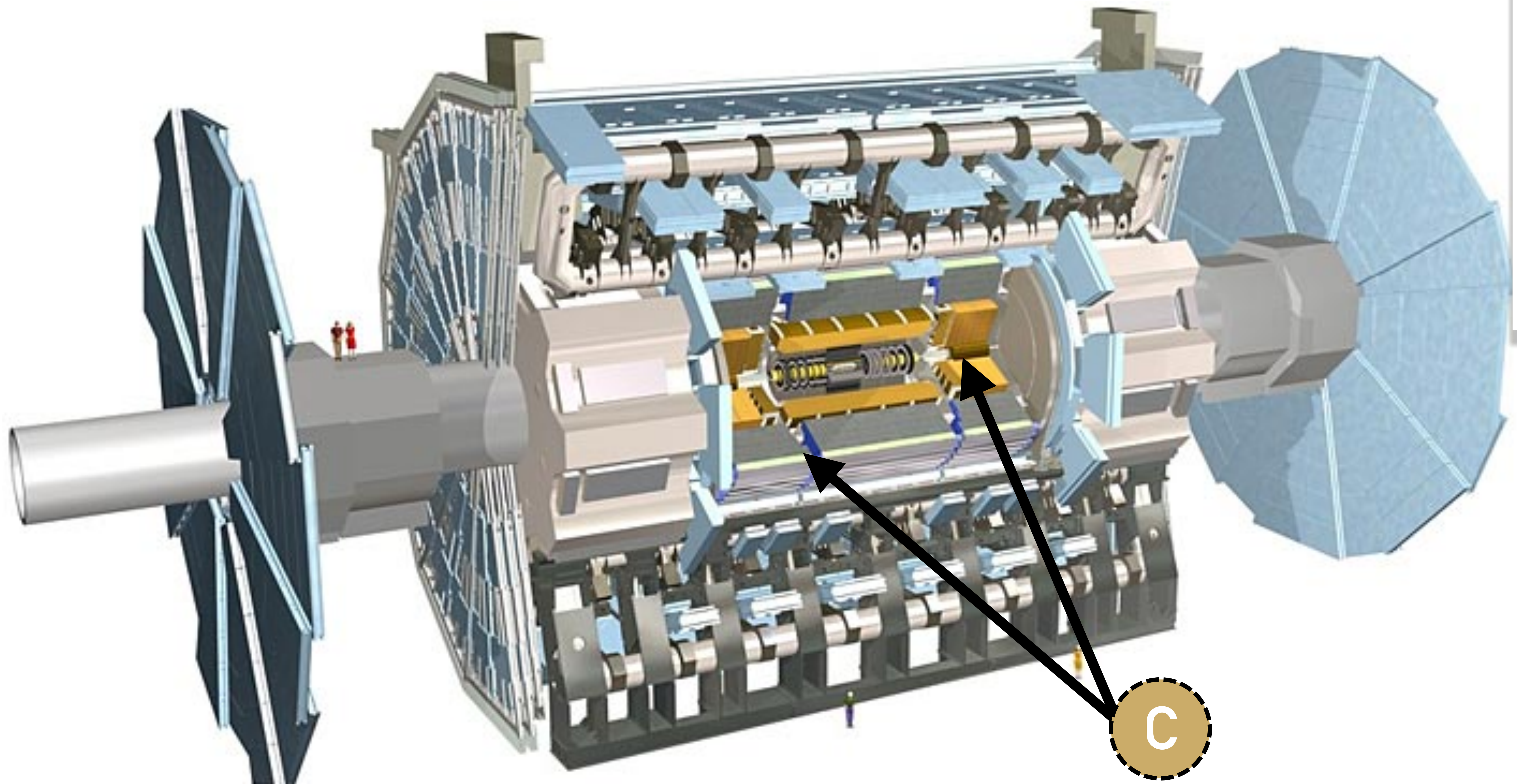


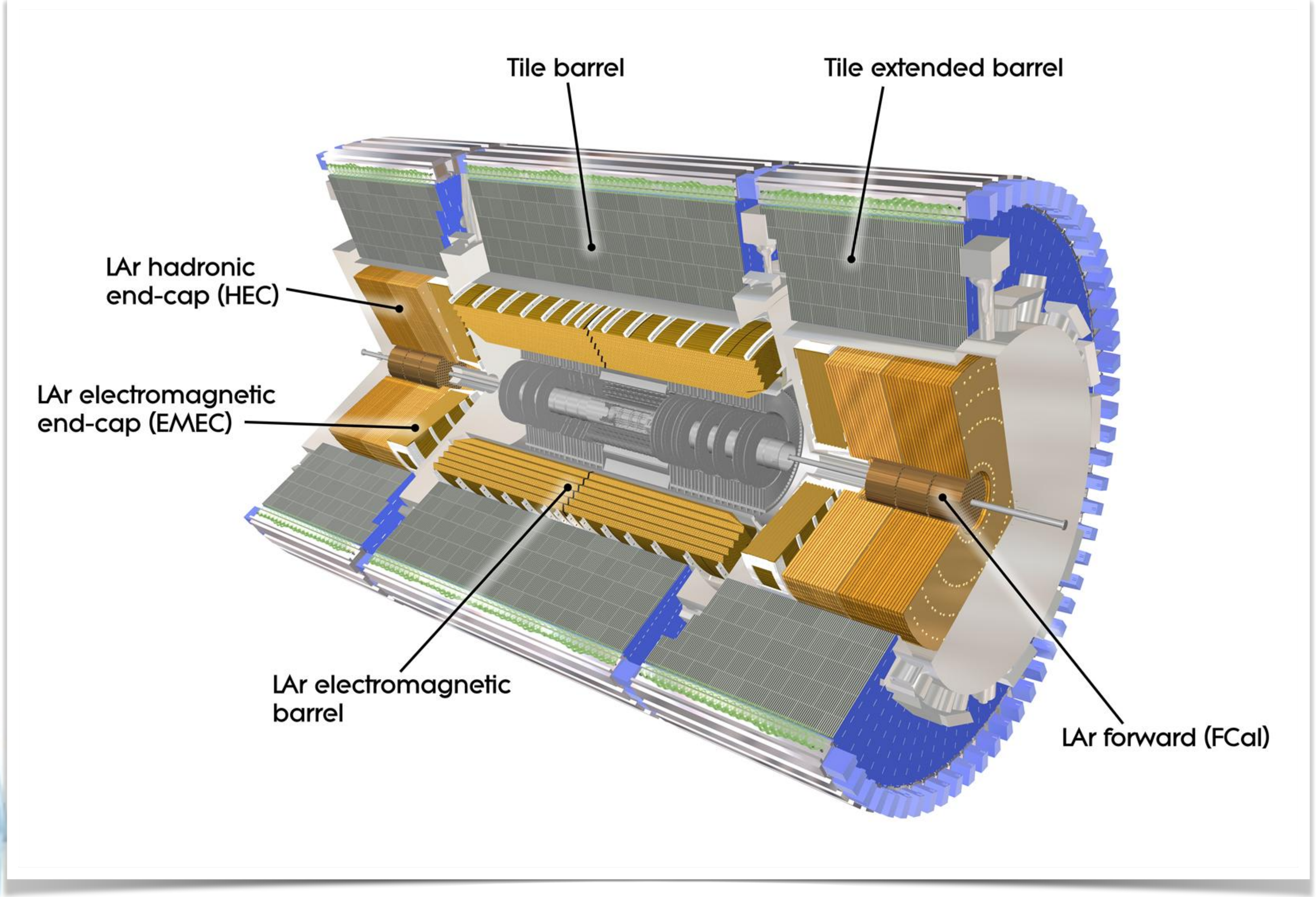


ATLAS Luminosity detectors and algorithms

C **Calorimeter measurements**

- Liquid argon calorimeters (EMEC and FCAL)
  → luminosity proportional to gap current
- Tile calorimeter
  → luminosity proportional to current drawn by PMT
- Only bunch integrated measurement





ATLAS Luminosity measurement strategy in Run 2

1. vdM calibration

- van der Meer scan typically performed once per year
- Calibration of LUCID σ_{vis} in specially tailored beam conditions

2. Calibration transfer

- Extrapolation of LUCID measurement from vdM regime to physics regime
- Track counting used to correct LUCID
- Cross-checked with Tile measurement for uncertainties

3. Long-term stability

- Check of Run-to-Run stability throughout each year
- Comparison of run-integrated luminosity of LUCID wrt Tile, EMEC, FCAL

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Will discuss today final precision Run 2 results: ***Eur. Phys. J. C 83 (2023) 982***

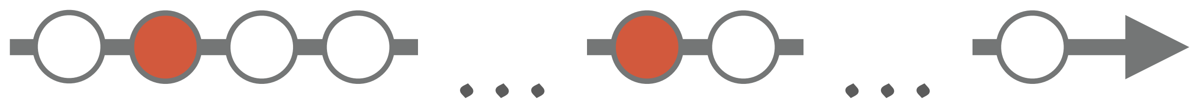
Van der Meer scans

- Method originally developed by Simon van der Meer (vdM) at the Intersecting Storage Ring (ISR)

Specialized beam conditions:

low average pile up (μ~0.6)

isolated bunches



small number of bunches

no crossing angle ….

Van der Meer scans

- Method originally developed by Simon van der Meer (vdM) at the Intersecting Storage Ring (ISR)
- Measure visible interaction rate μ_{vis} vs beam separation
- μ_{vis} related to visible cross section $\sigma_{vis} = \mu_{vis}^{MAX} \frac{2\pi\Sigma_x\Sigma_y}{n_1 n_2}$

Specialized beam conditions:

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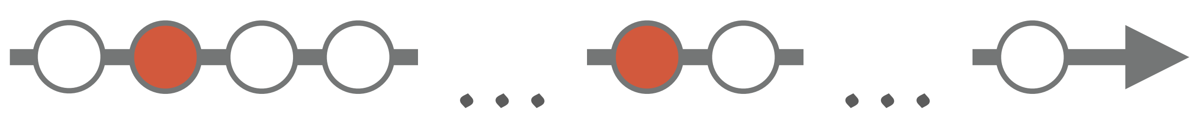

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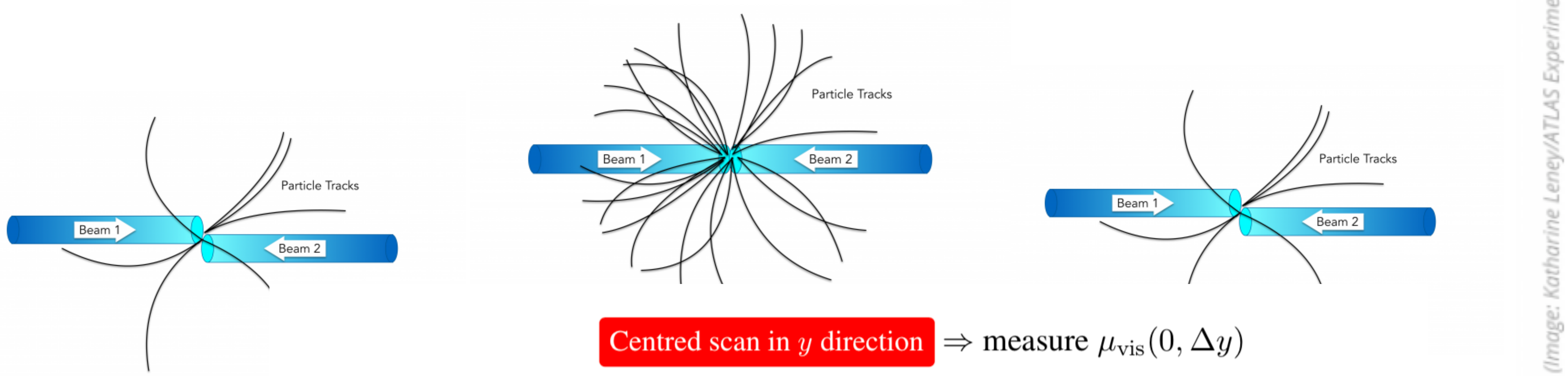
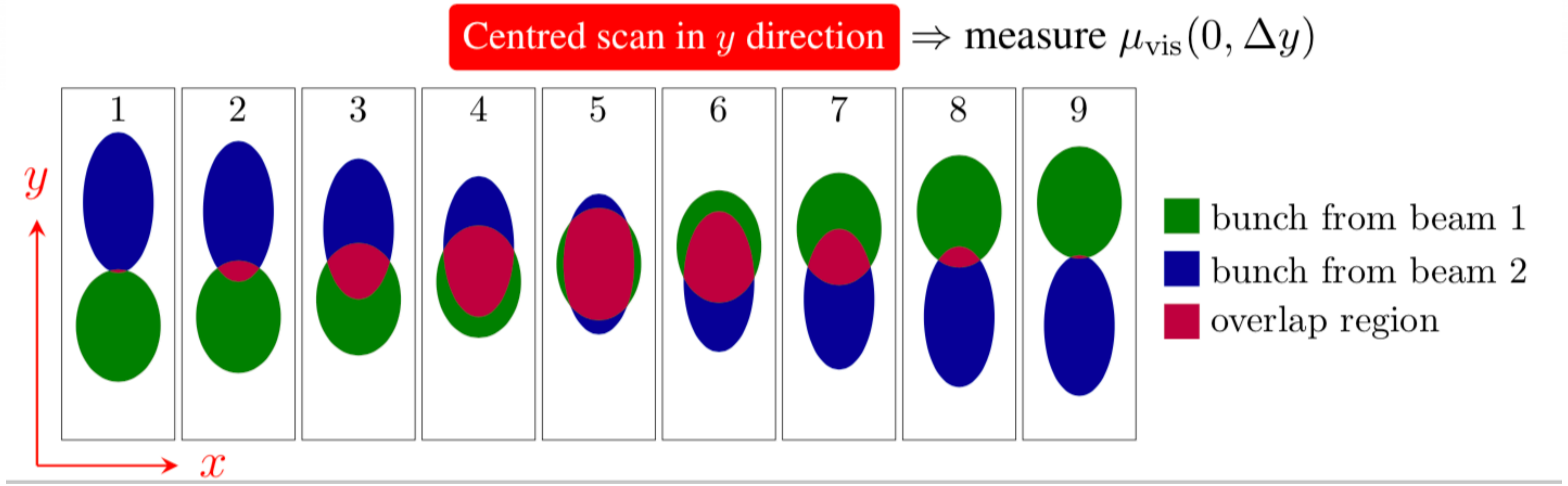




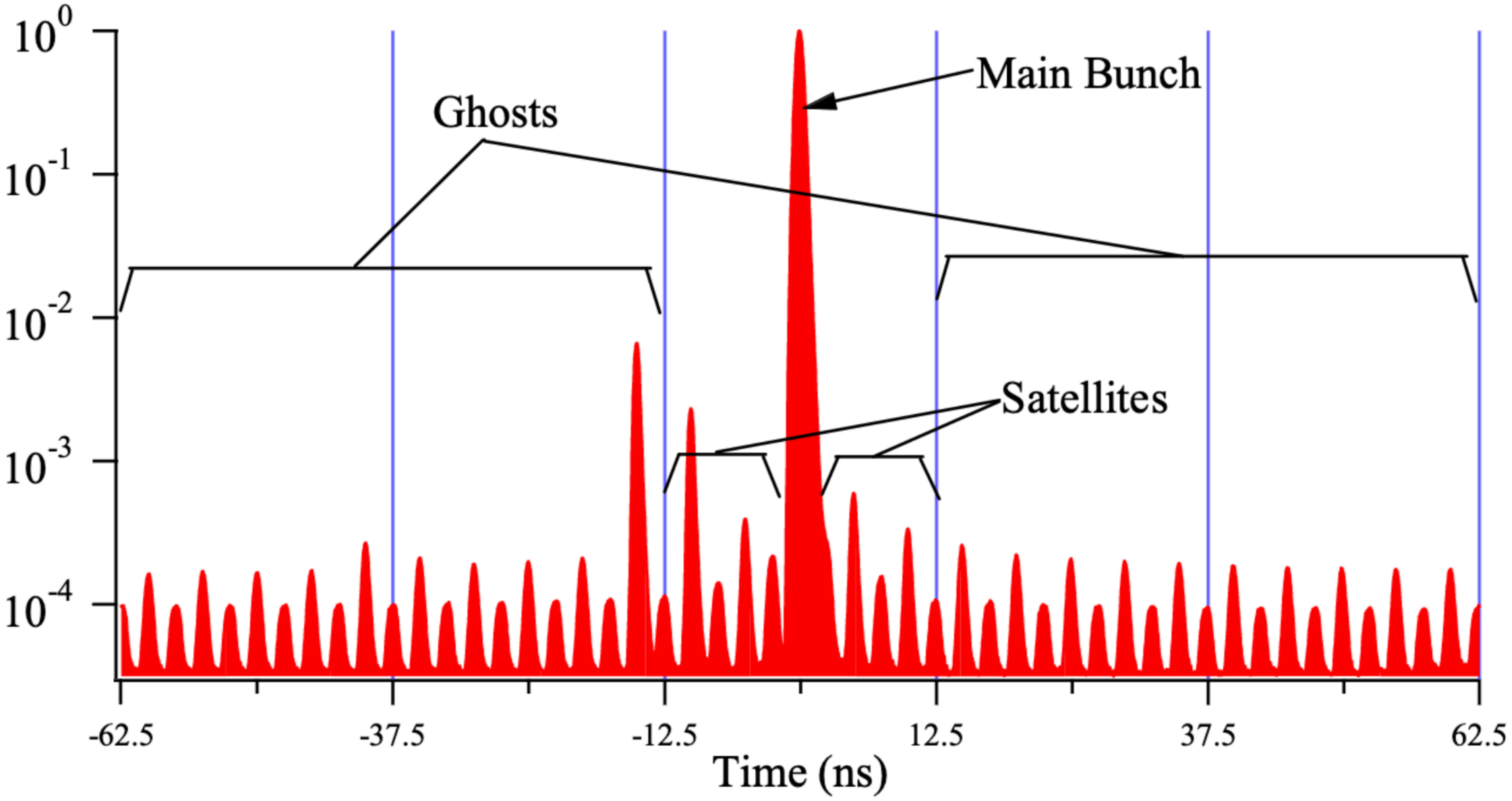
Bunch current product – $n_1 n_2$

DCCT

- LHC instrumented to measure currents of bunches using current transformers
  - DC current transformers: integrated current
  - Fast beam current transformers: relative bunch population

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

- Needs corrections for:
  - Ghost charge (<2.5%):
    - Circulating unbunched beam
  - Satellite bunches
    - Bunches in other RF-buckets

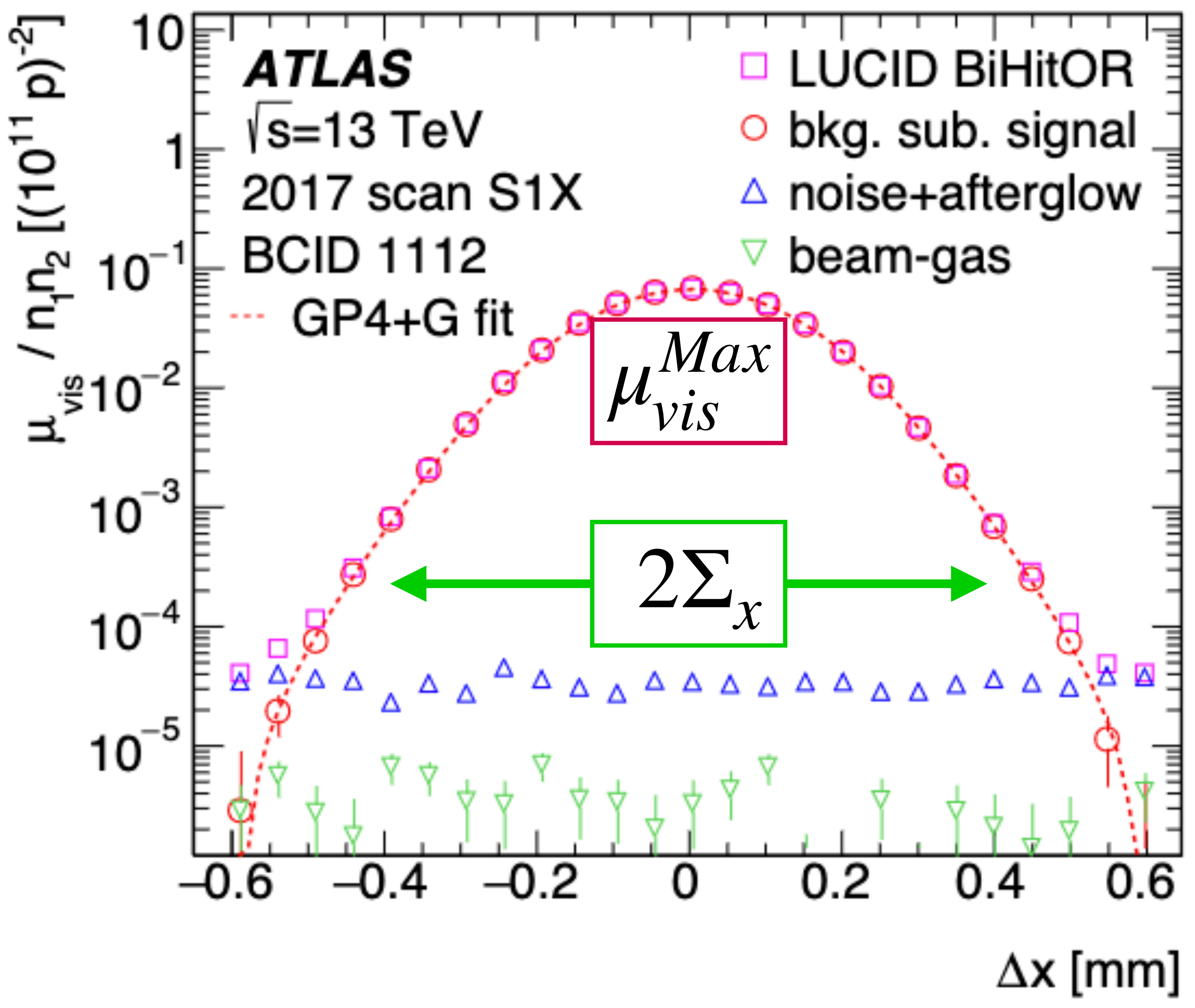


https://cds.cern.ch/record/2649532/

1. vdM calibration – van der Meer scans

- vdM analysis determines the visible cross section σ_{vis} for each bunch
- vdM fit extracts μ_{vis}^{Max} Σ_x Σ_y

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



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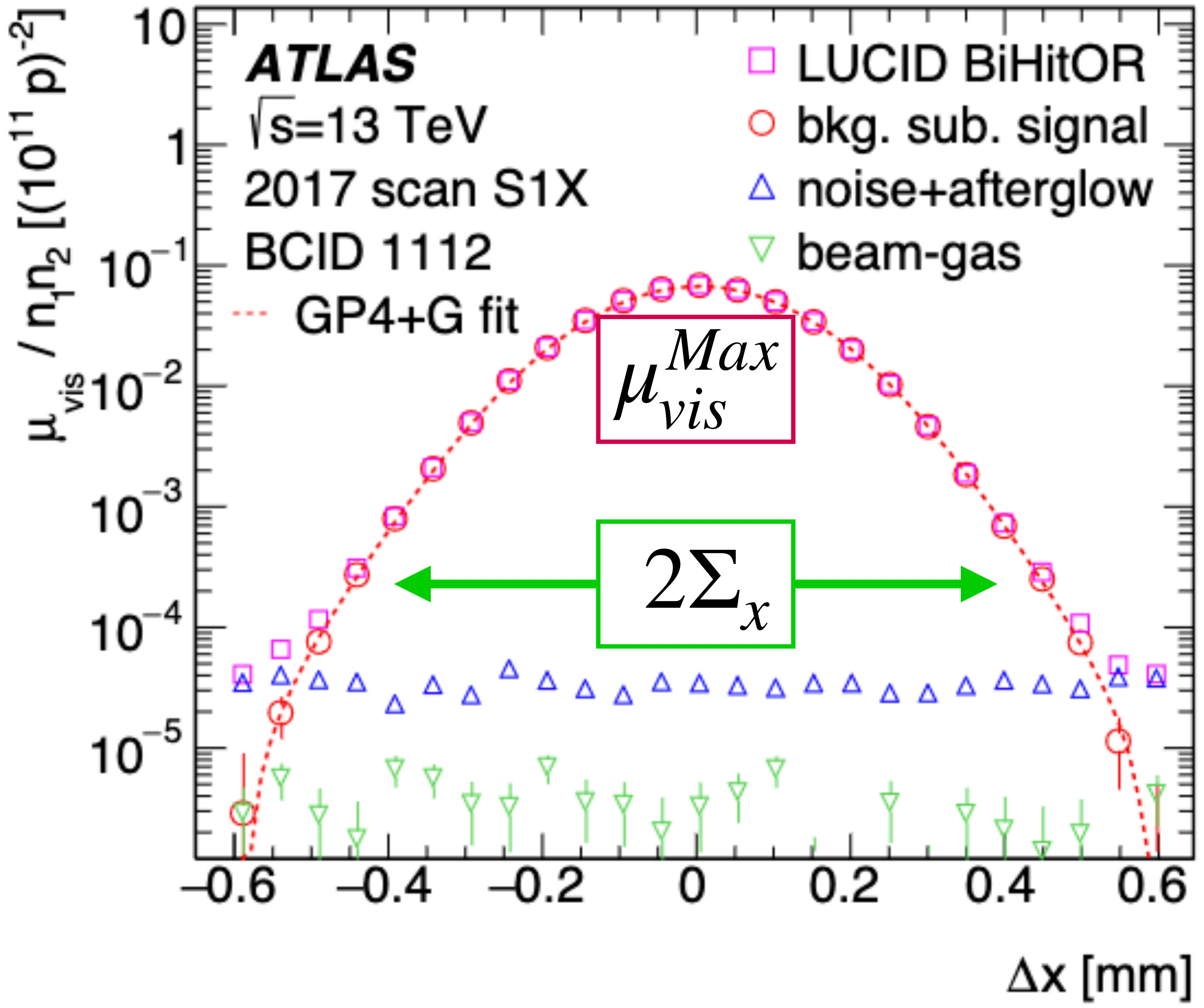
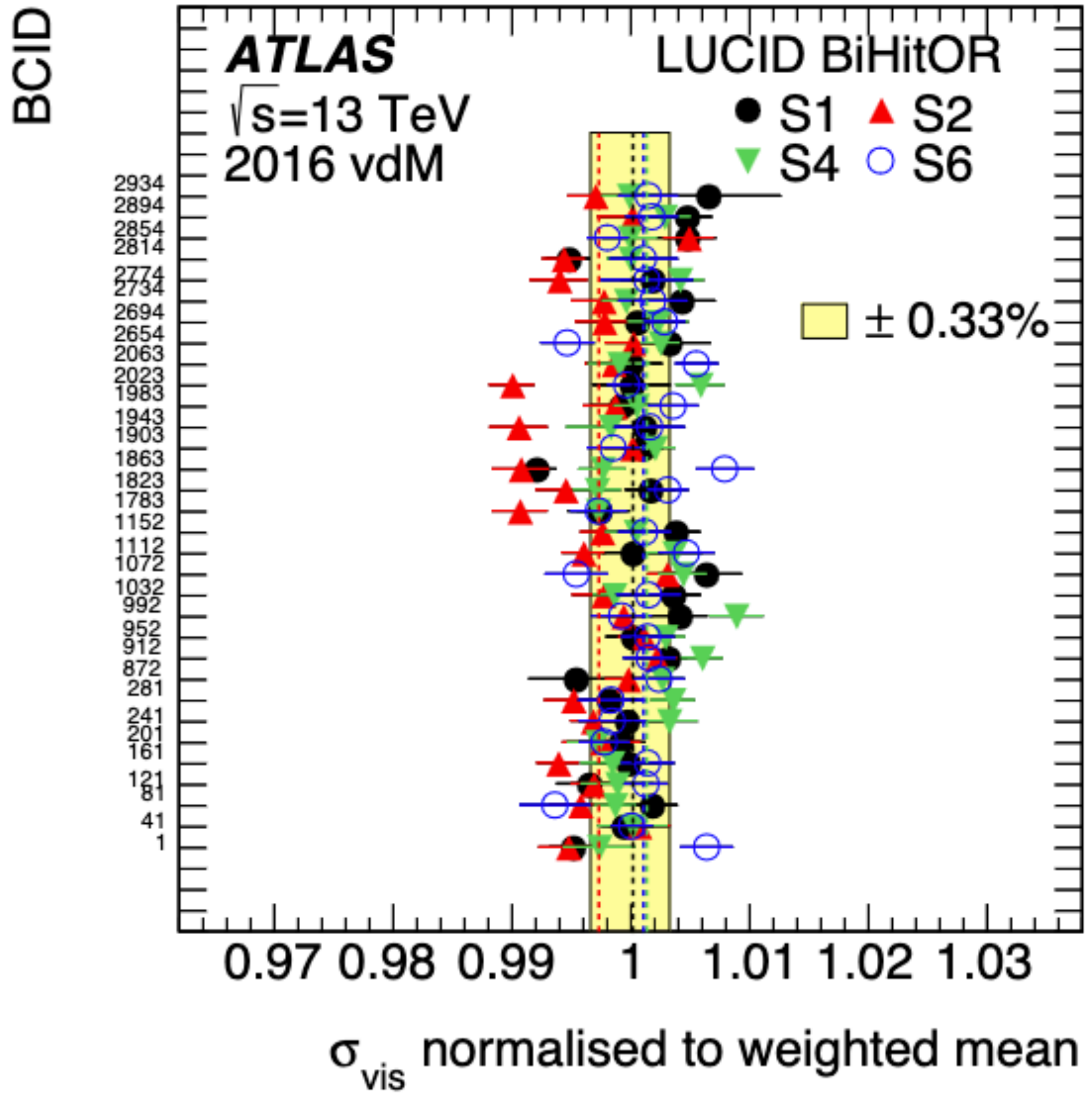
- Several scans performed ⇒ check for scan-to-scan reproducibility





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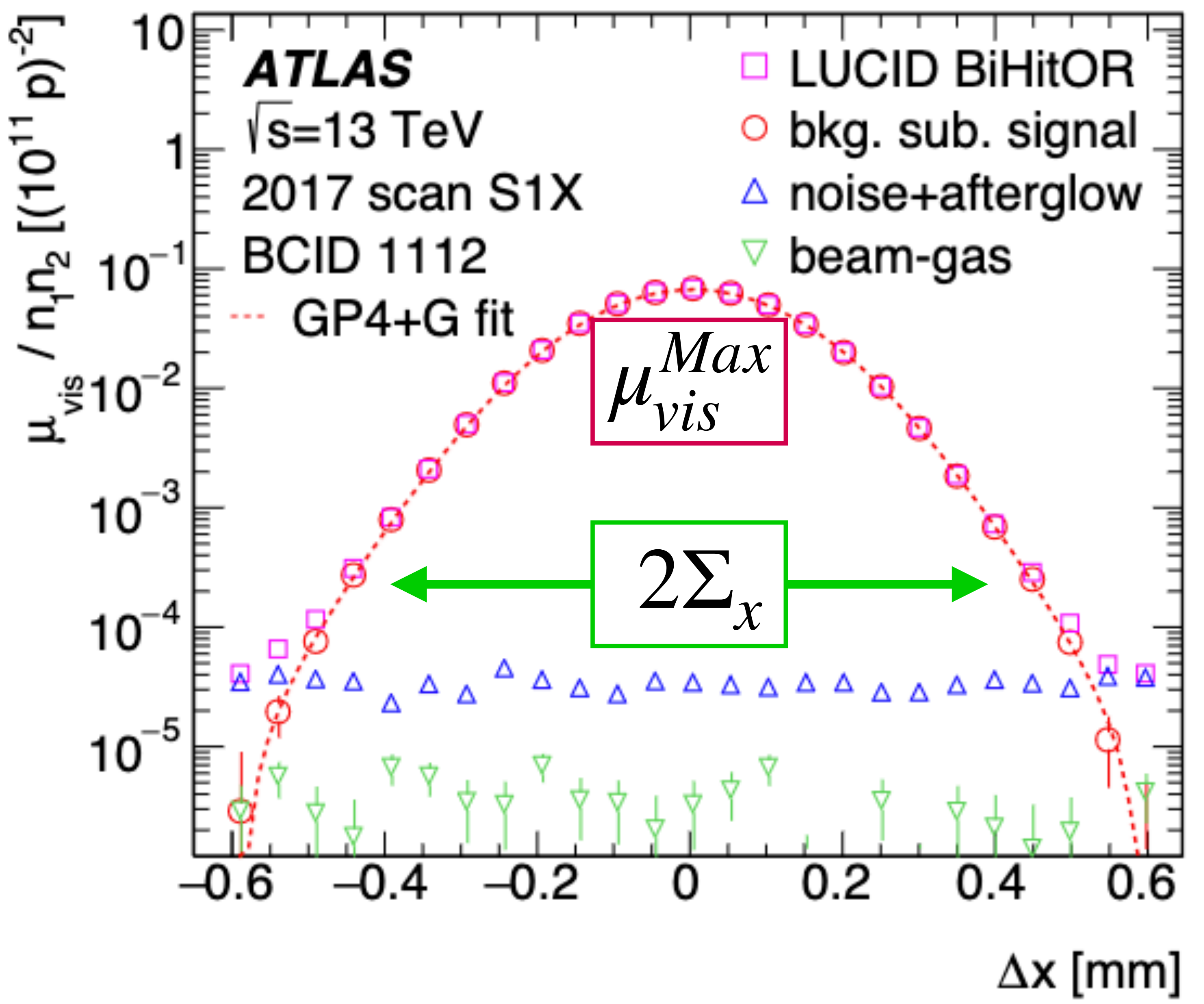
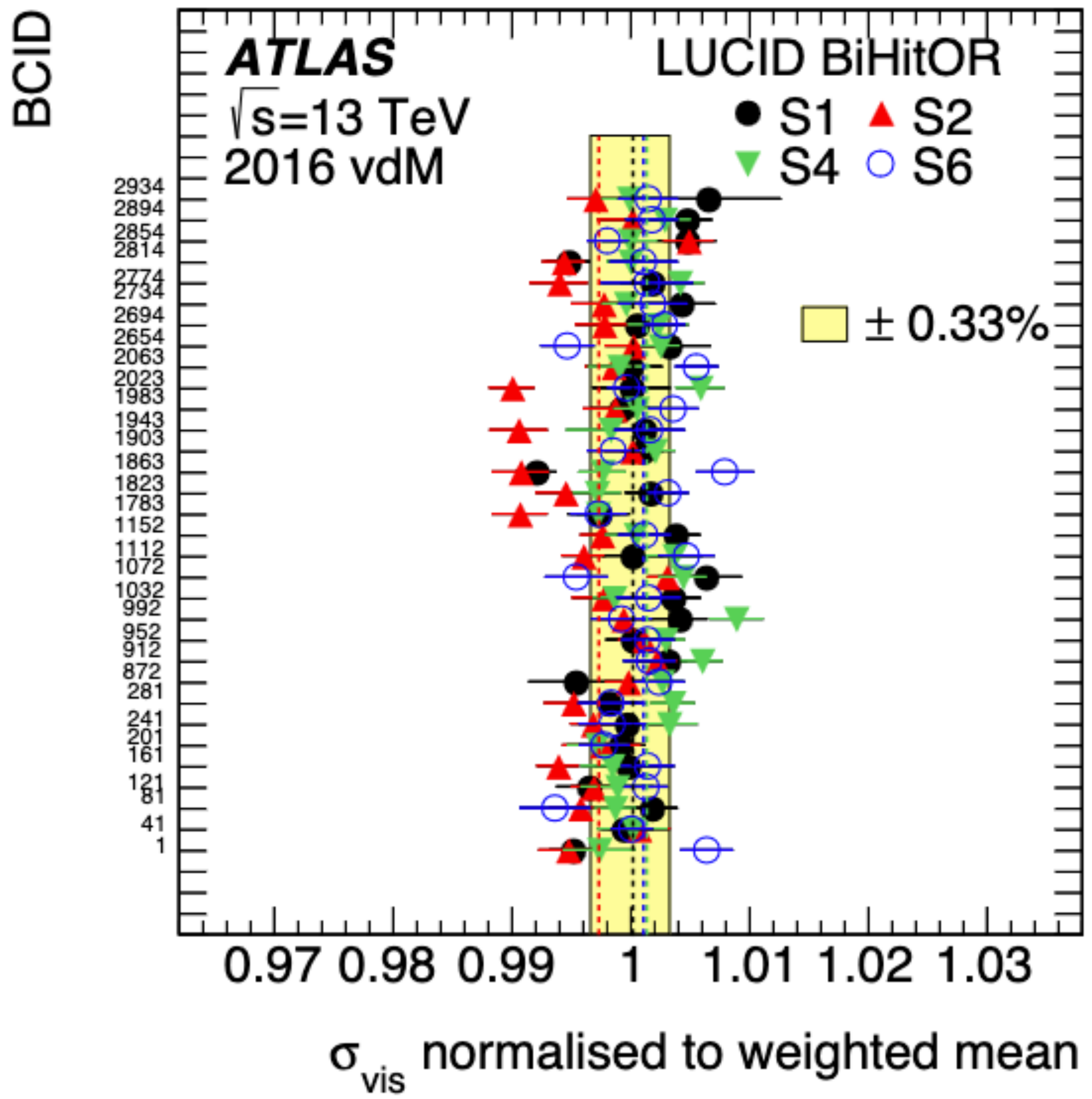
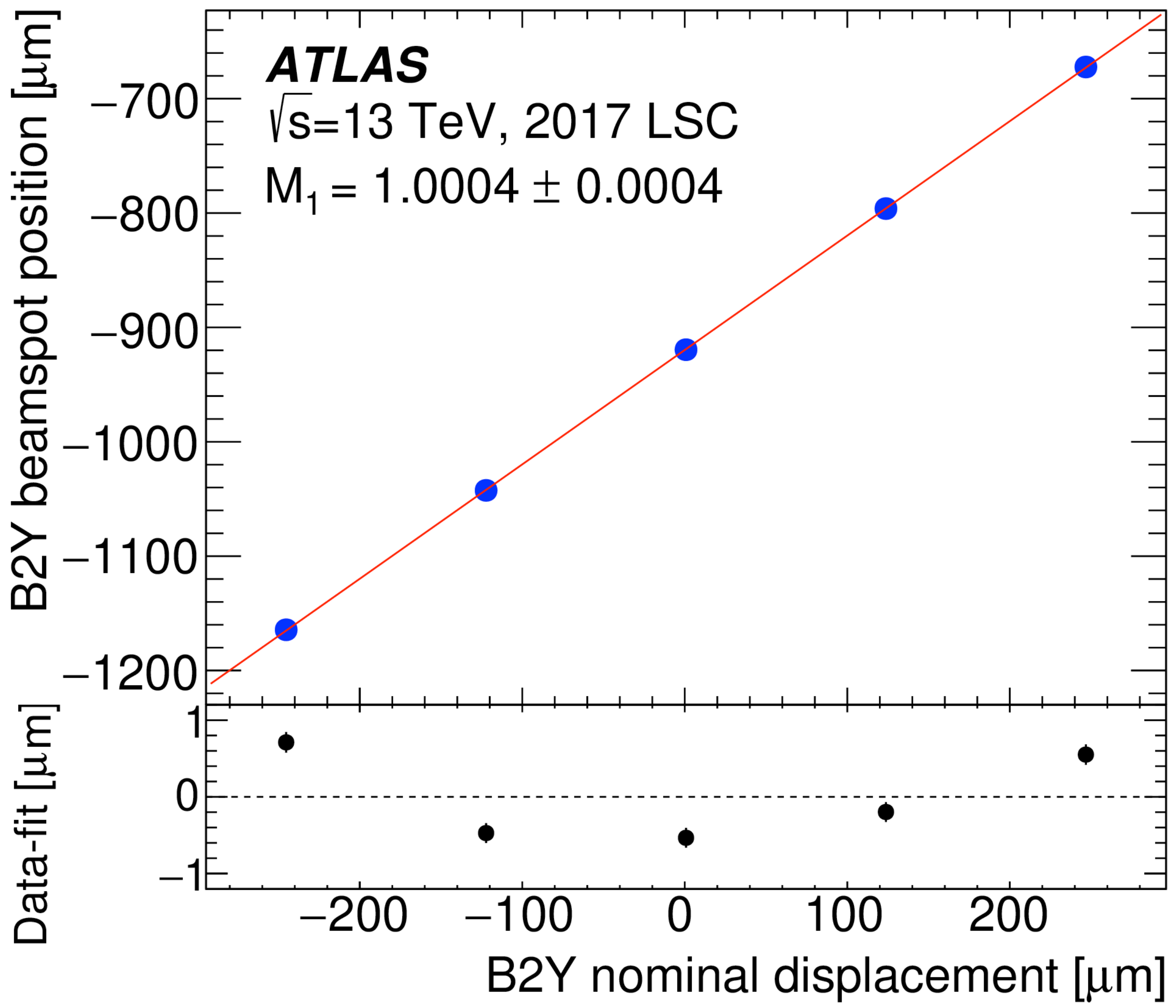




- Various corrections to consider
  - Orbit drifts – beams do not stay still during scans
  - Emittance growth and **non-factorization** – beam sizes change with time, transverse profiles in x and y do not factorize
  - **Length scale** and magnetic non-linearity (arXiv:2304.06559v1, A. Chmielińska et al.) – the steering correctors are not perfect
  - **Beam-beam effects**

Length scale calibration and non-factorization

- **Length scale**: relation between requested and real beam displacement
  - Calibrated in dedicated 5-point scans in x an y
  - True beam displacement measured from beamspot positions reconstructed from tracks



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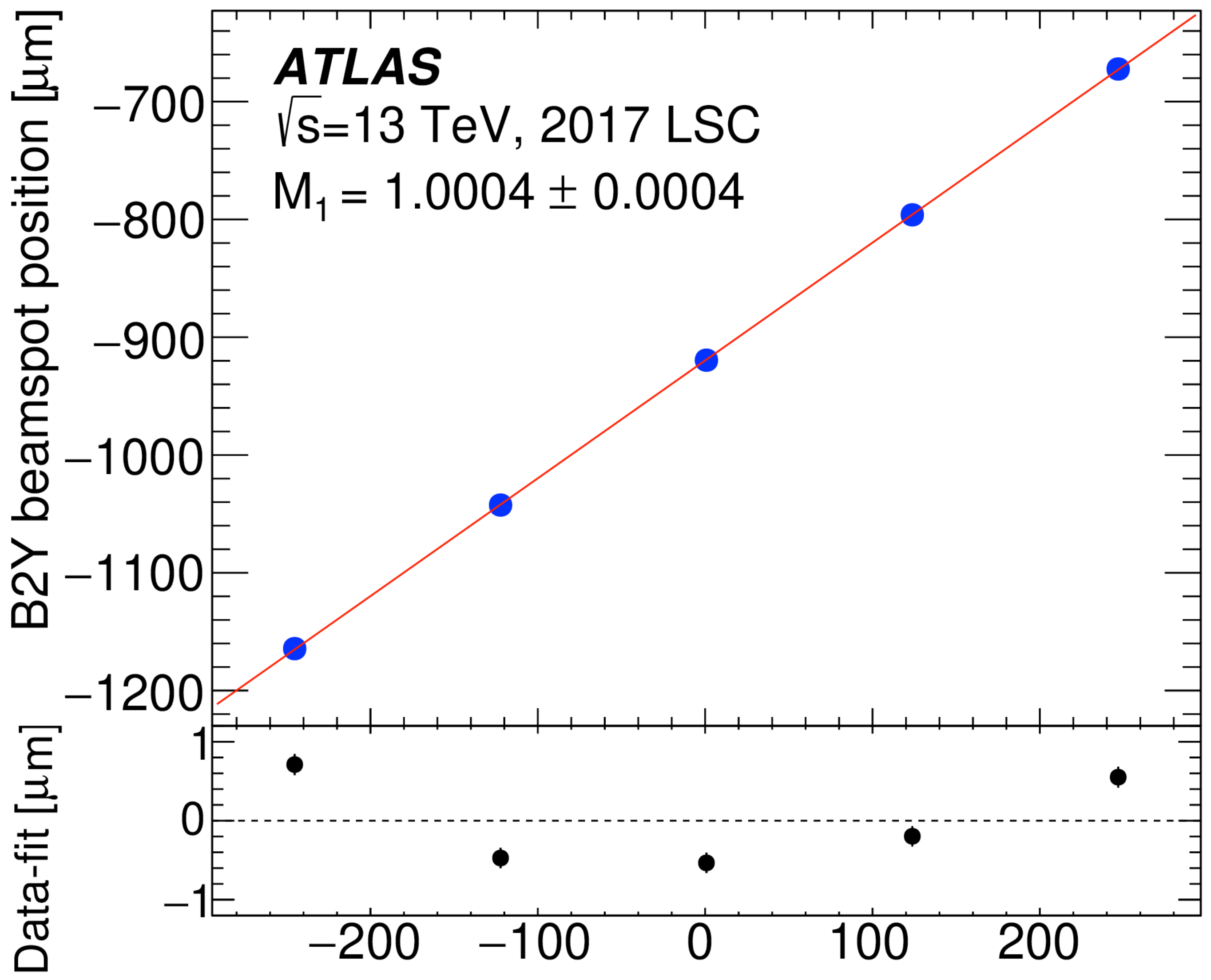
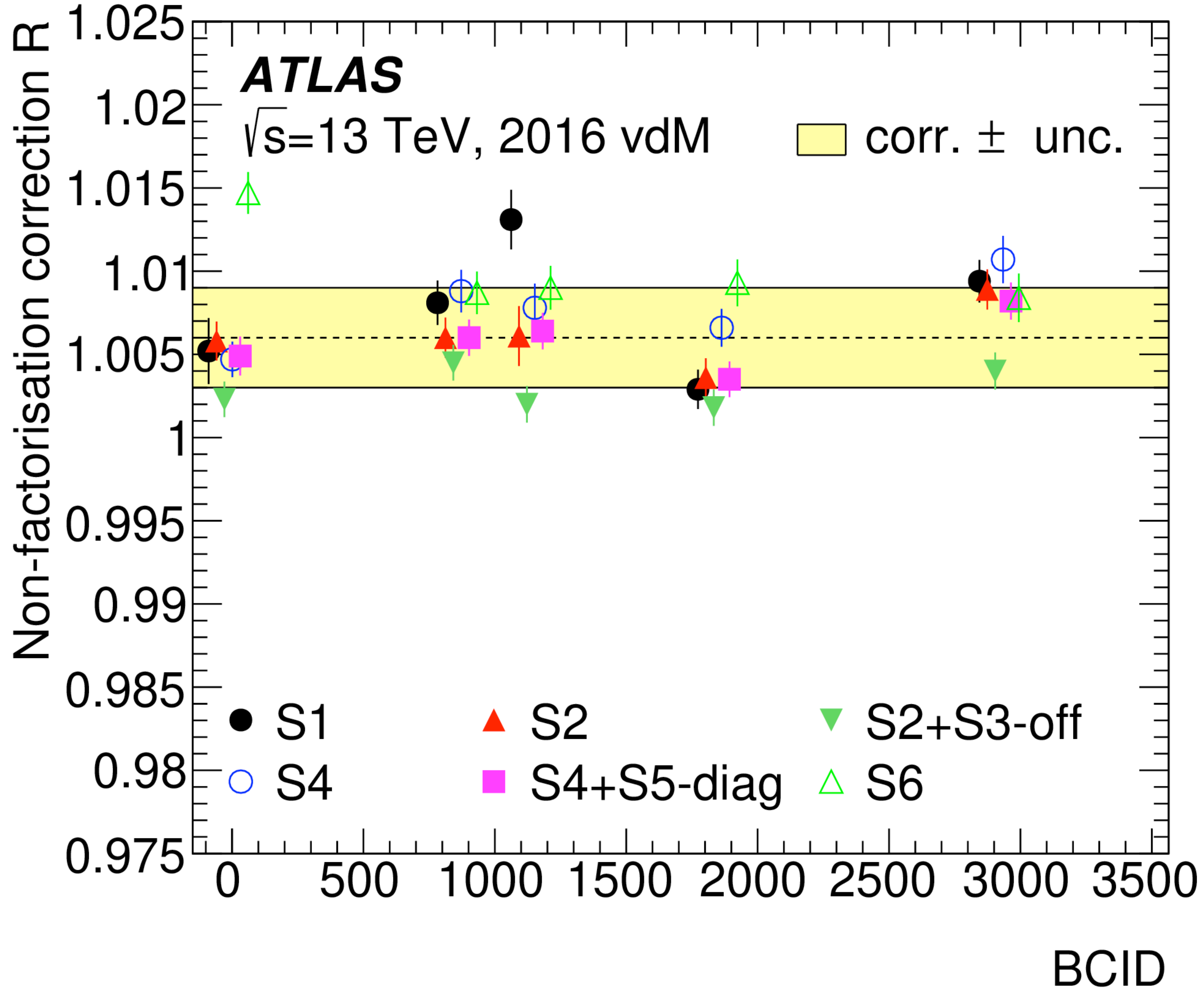


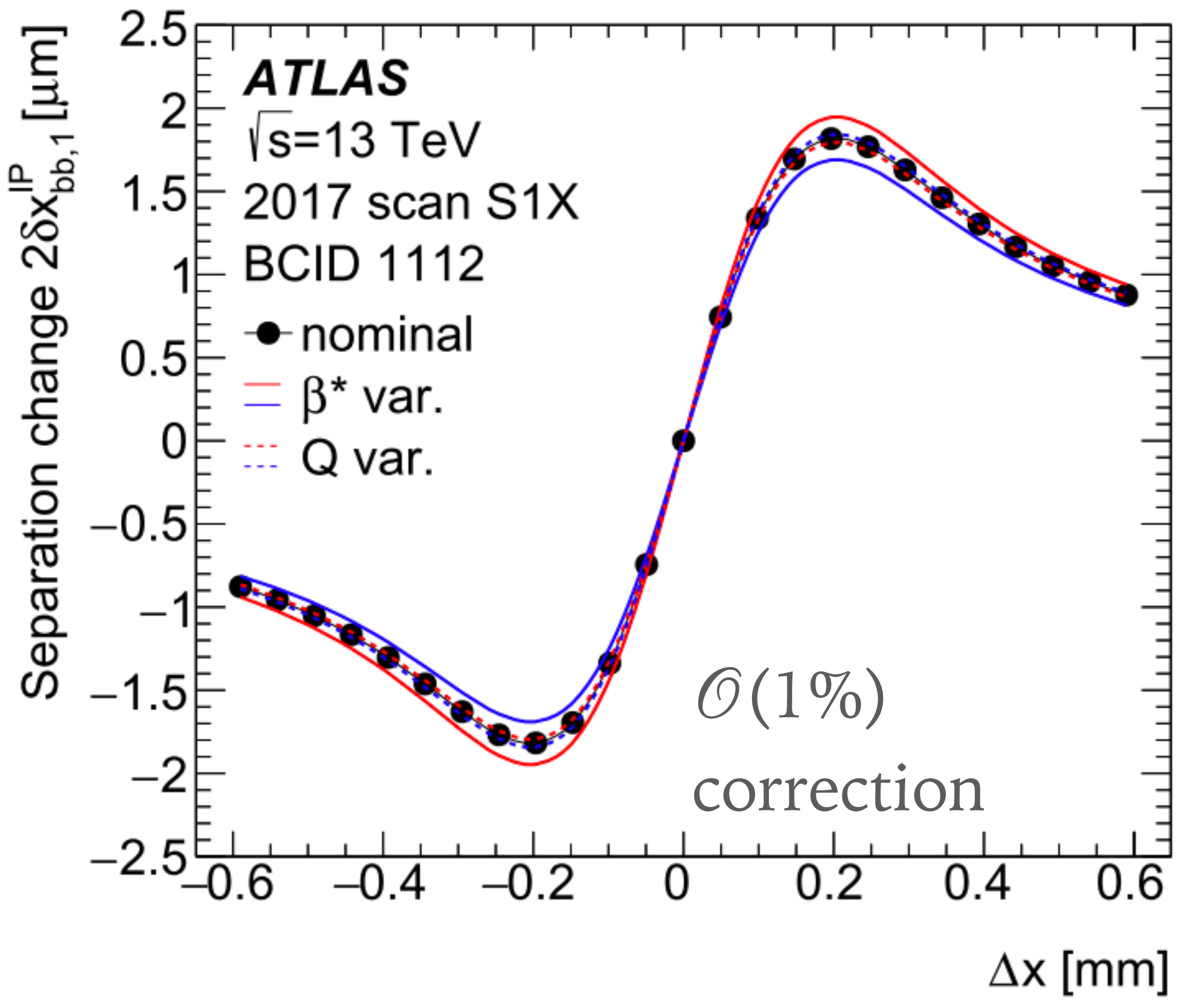
- **Non-factorization:** vdM formalism assumes that beam profiles in x and y factorize
- Deviation from factorization characterized using primary vertex distribution at each scan step
  - Check size, shape, and orientation of luminous region



Beam-Beam effects

➤During vdM scans two distinct effects exist

- ➤ **Beam-beam deflection**
  - ➤Each B1 bunch (as a whole) repels the companion B2 bunch →orbits change
  - ➤Increases the **beam separation** Δ by a different amount at each vdM-scan step



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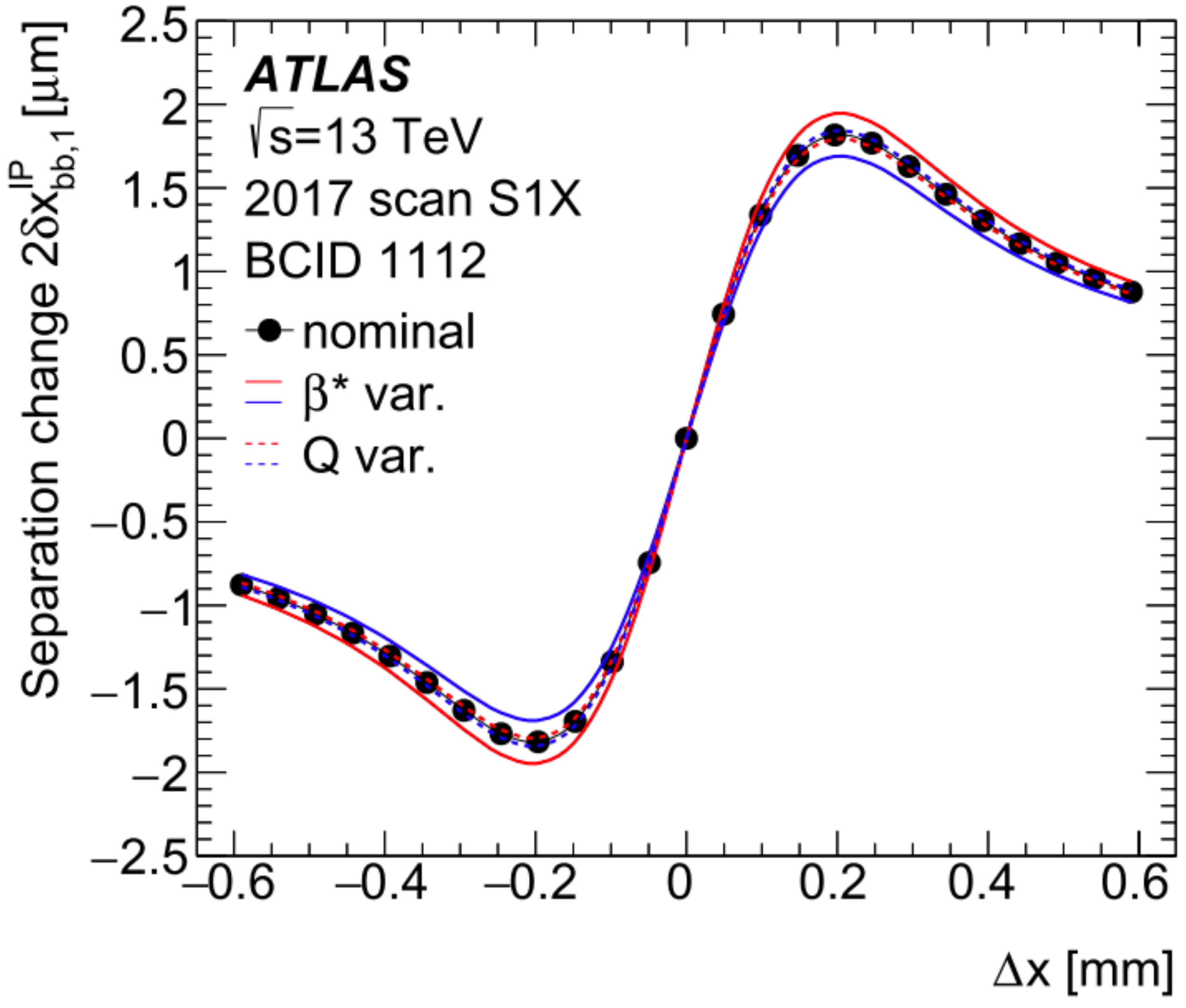
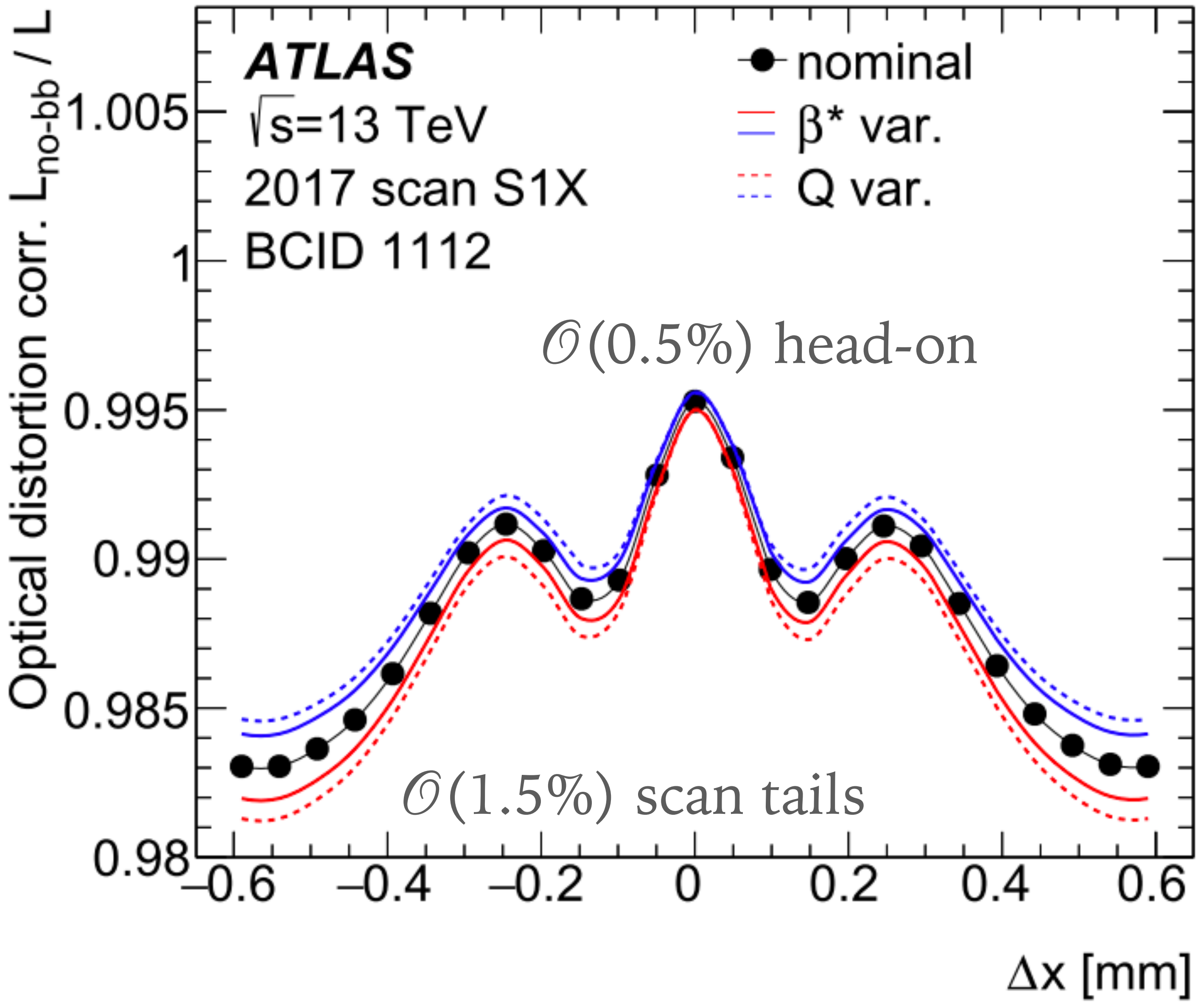
  - **Optical distortion**
    - Each B1 bunch (de)focuses the companion B2 bunch (& vice-versa)
    - Modifies the **beam shapes** by a different amount at each vdM-scan step

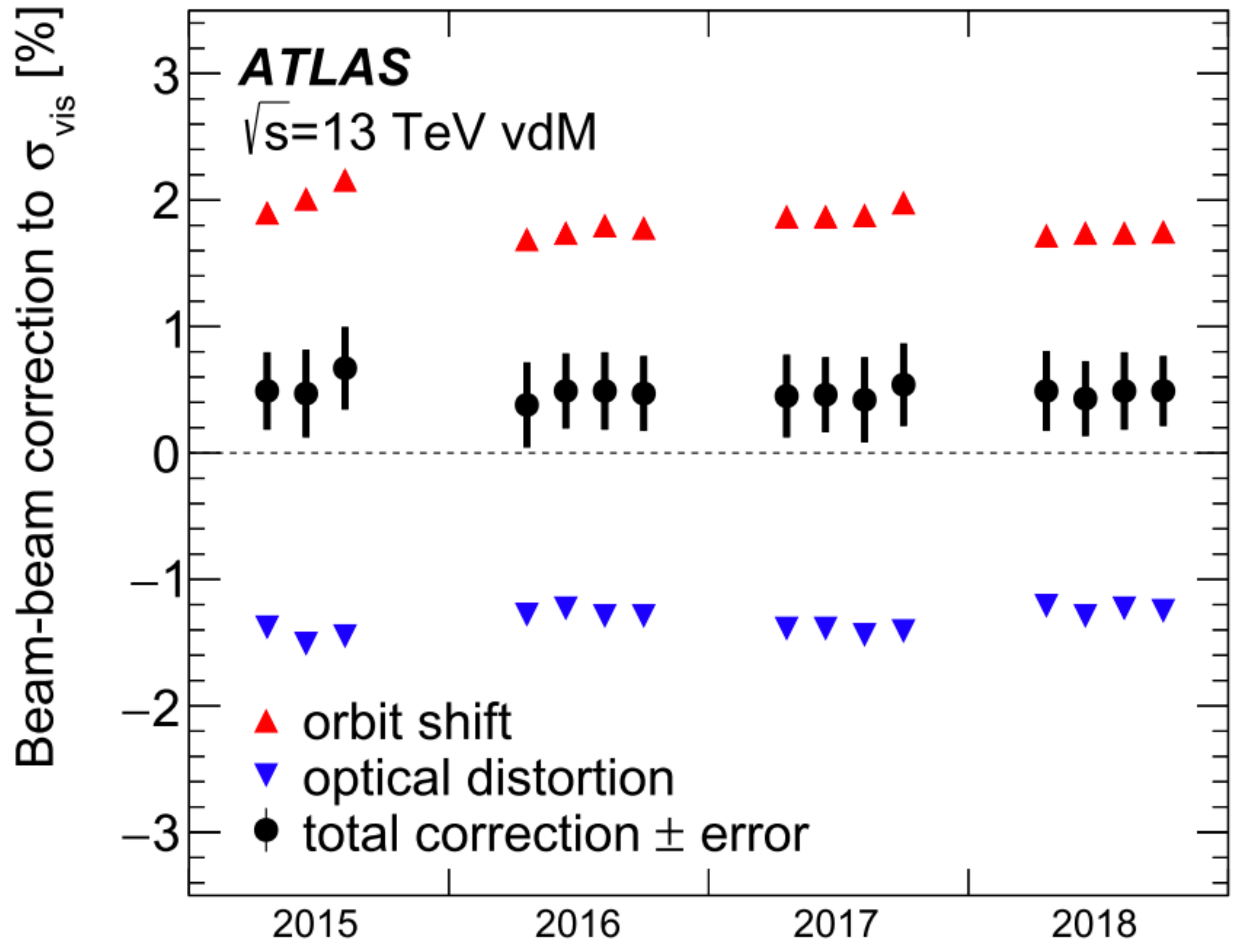




Beam-beam force is non-linear; proton in center of the bunch feels a different force to one at the edge

Beam-Beam effects

- During vdM scans two distinct effects exist
  - **Beam-beam deflection** +1.5 to + 2%
    - Each B1 bunch (as a whole) repels the companion B2 bunch →orbits change
    - Increases the **beam separation** Δ by a different amount at each vdM-scan step
  - **Optical distortion** - 1.5 to -1%
    - Each B1 bunch (de)focuses the companion B2 bunch (& vice-versa)
    - Modifies the **beam shapes** by a different amount at each vdM-scan step



Total correction to σ_{vis} **+0.5 %** with an uncertainty of 0.3%

New treatment developed in LHC lumi WG (LLCMWG) arxiv:2306.10394 (A. Babaev et al.)

ATLAS Luminosity measurement strategy in Run 2

2. Calibration transfer

- Extrapolation of LUCID measurement from vdM regime to physics regime
- Track counting used to correct LUCID
- Cross-checked with Tile measurement for uncertainties

ATLAS Luminosity measurement strategy in Run 2

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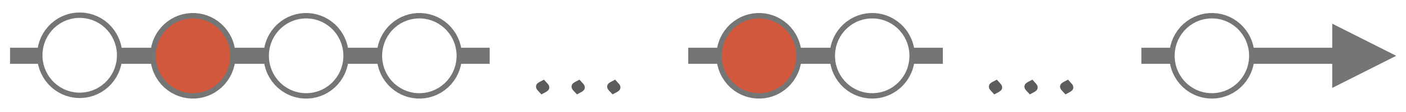
vdM regime

low average pile up (μ~0.6)

isolated bunches



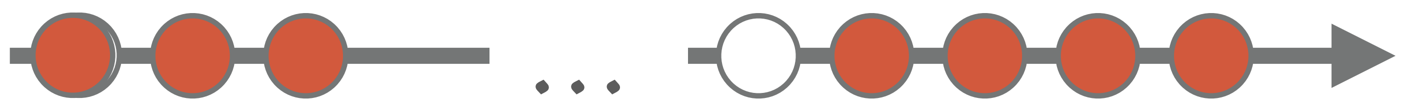
small number of bunches

no crossing angle

Physics regime

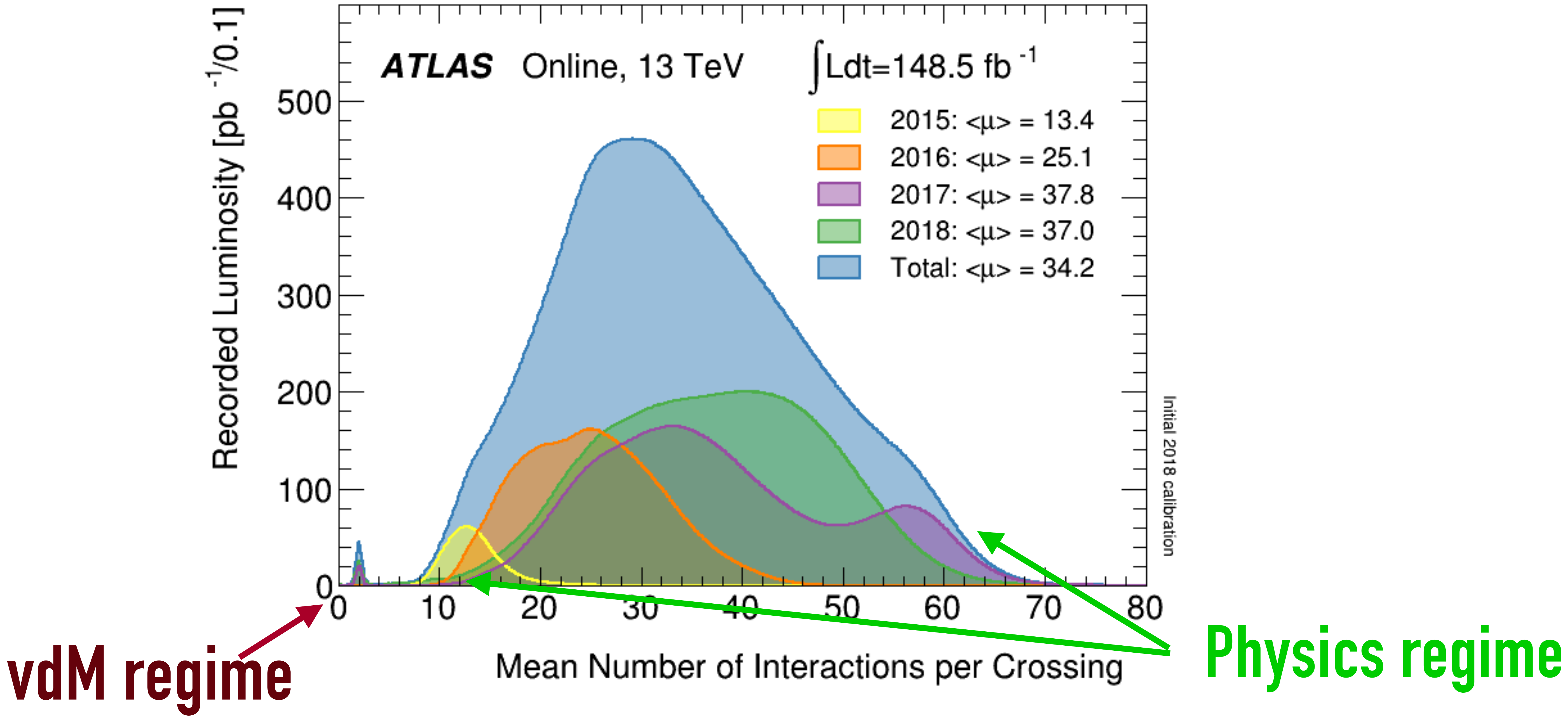
high pile up (20 < μ < 60)

bunch trains



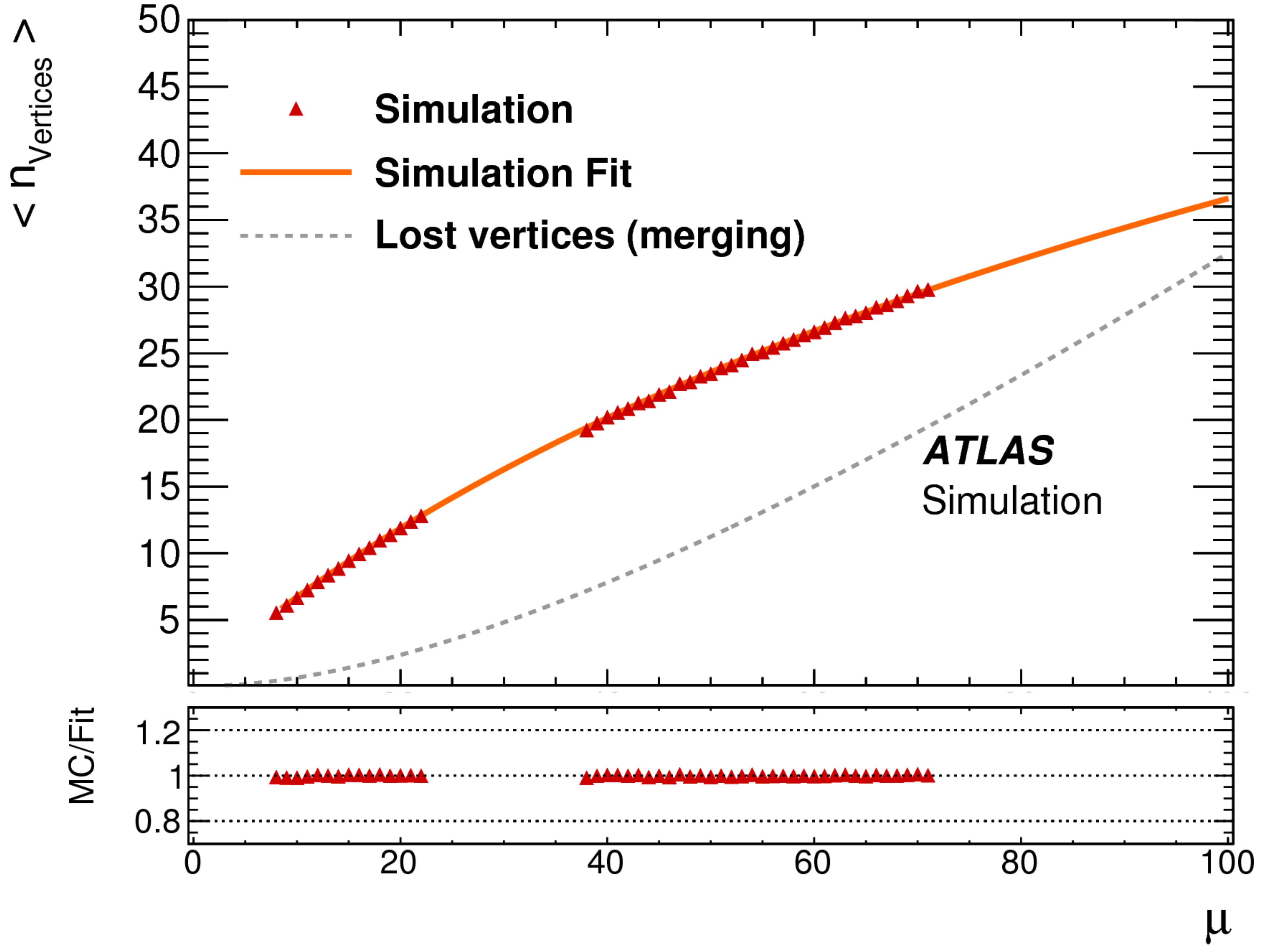
high number of bunches

with crossing angle

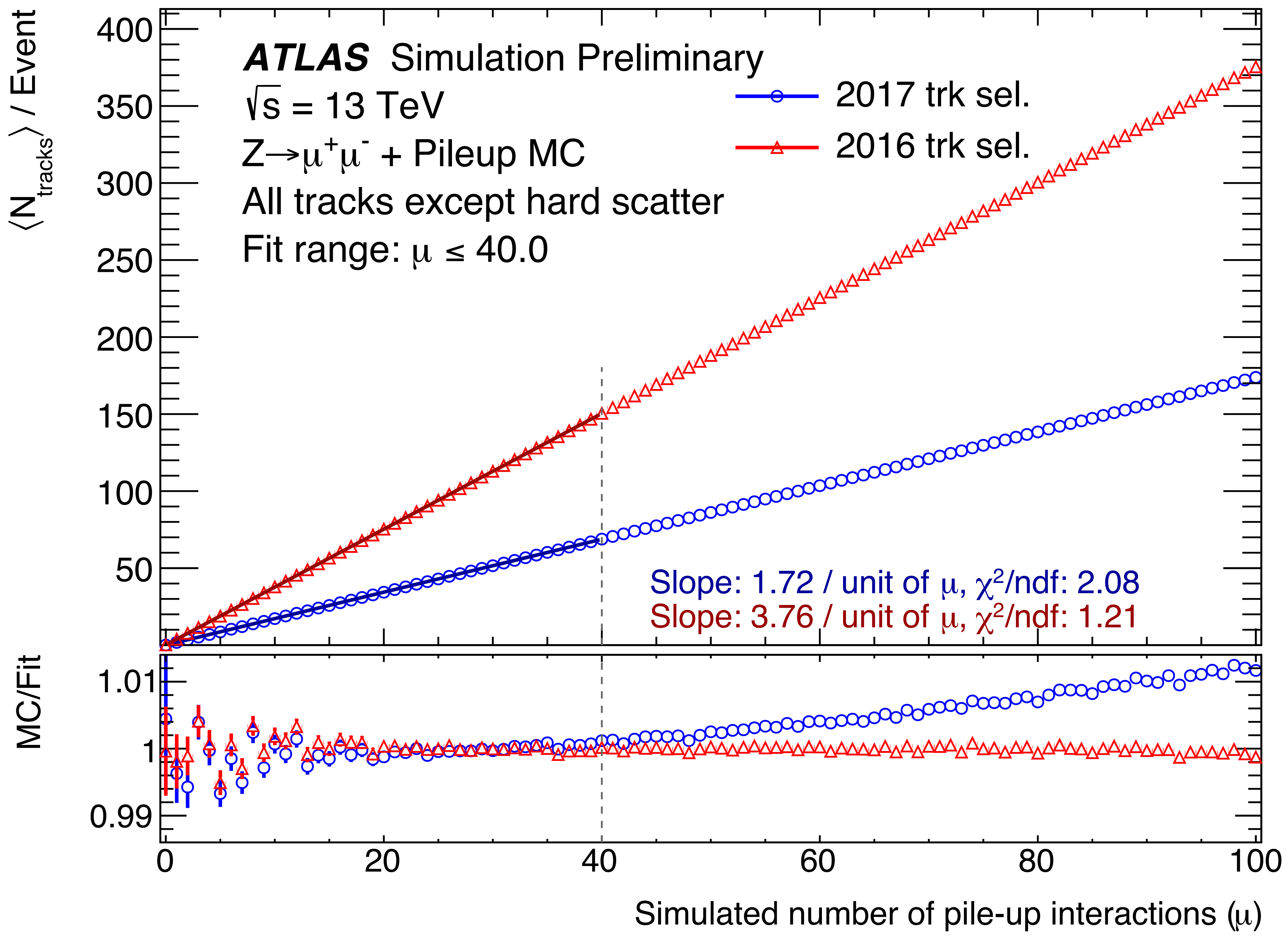


Could we just count vertices?

- **Number of vertices does not scale linearly with μ** due to vertex-merging



- But: **number of tracks** grows ~ linearly with μ
  - **use "track counting"**

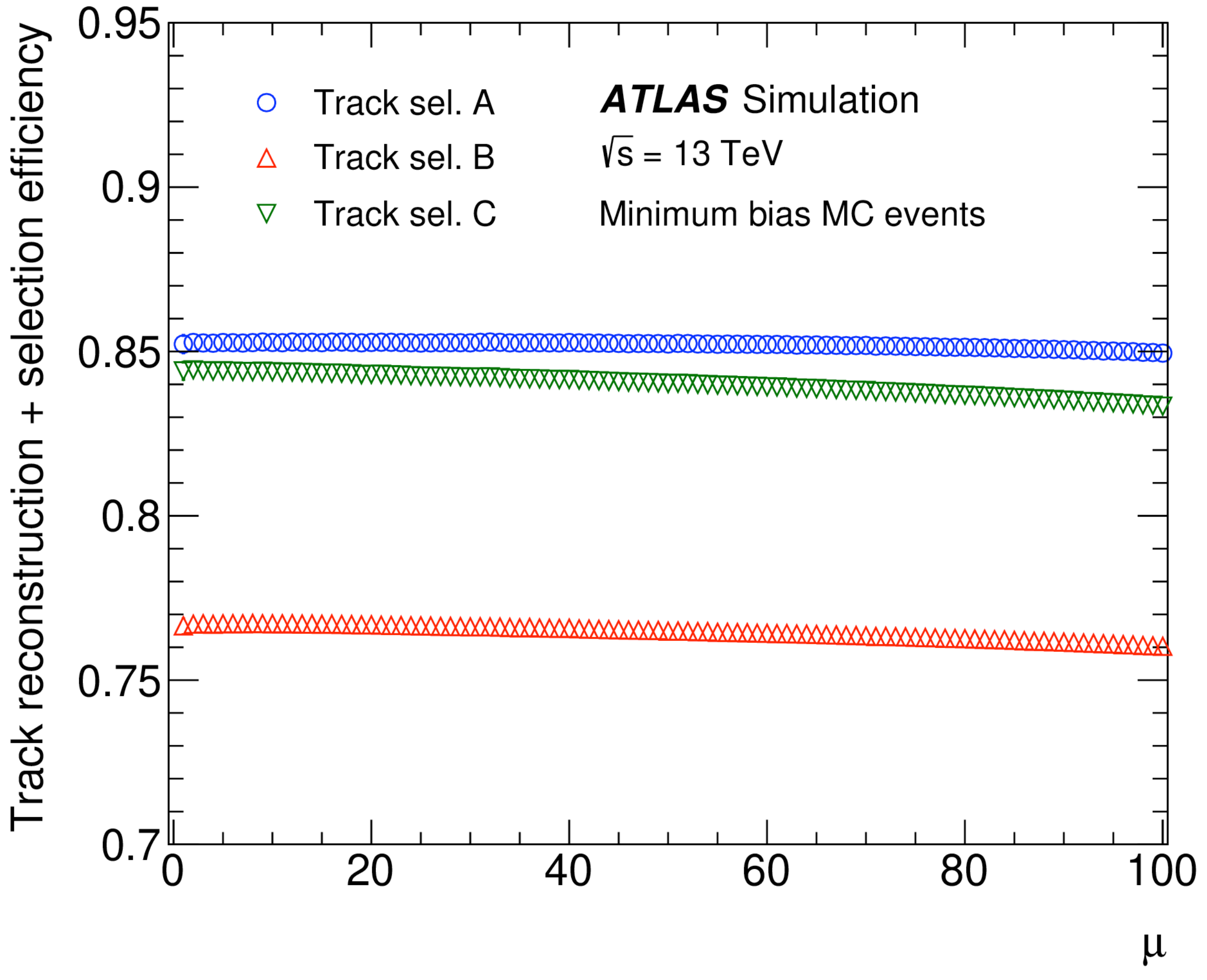


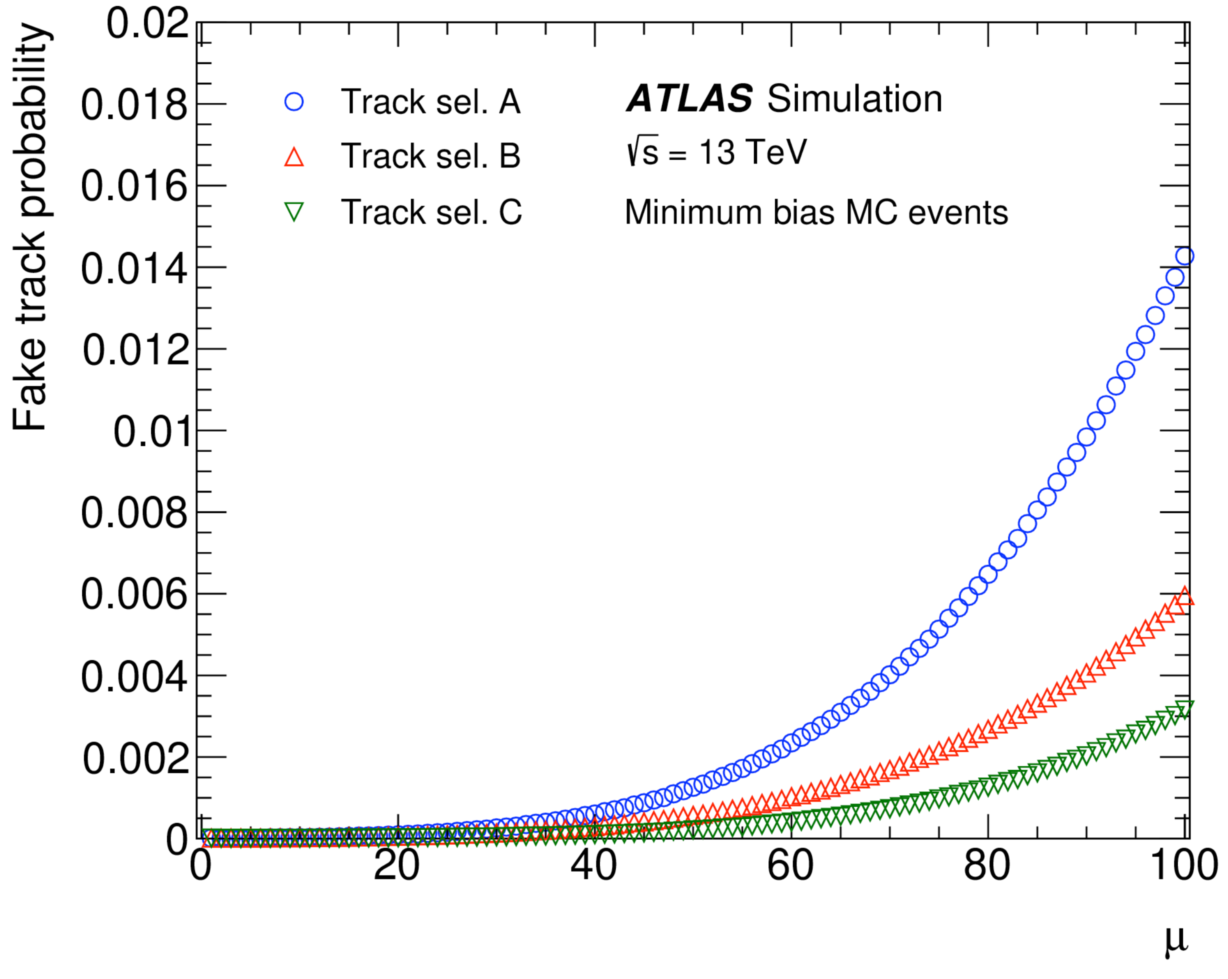
Interlude: Track counting

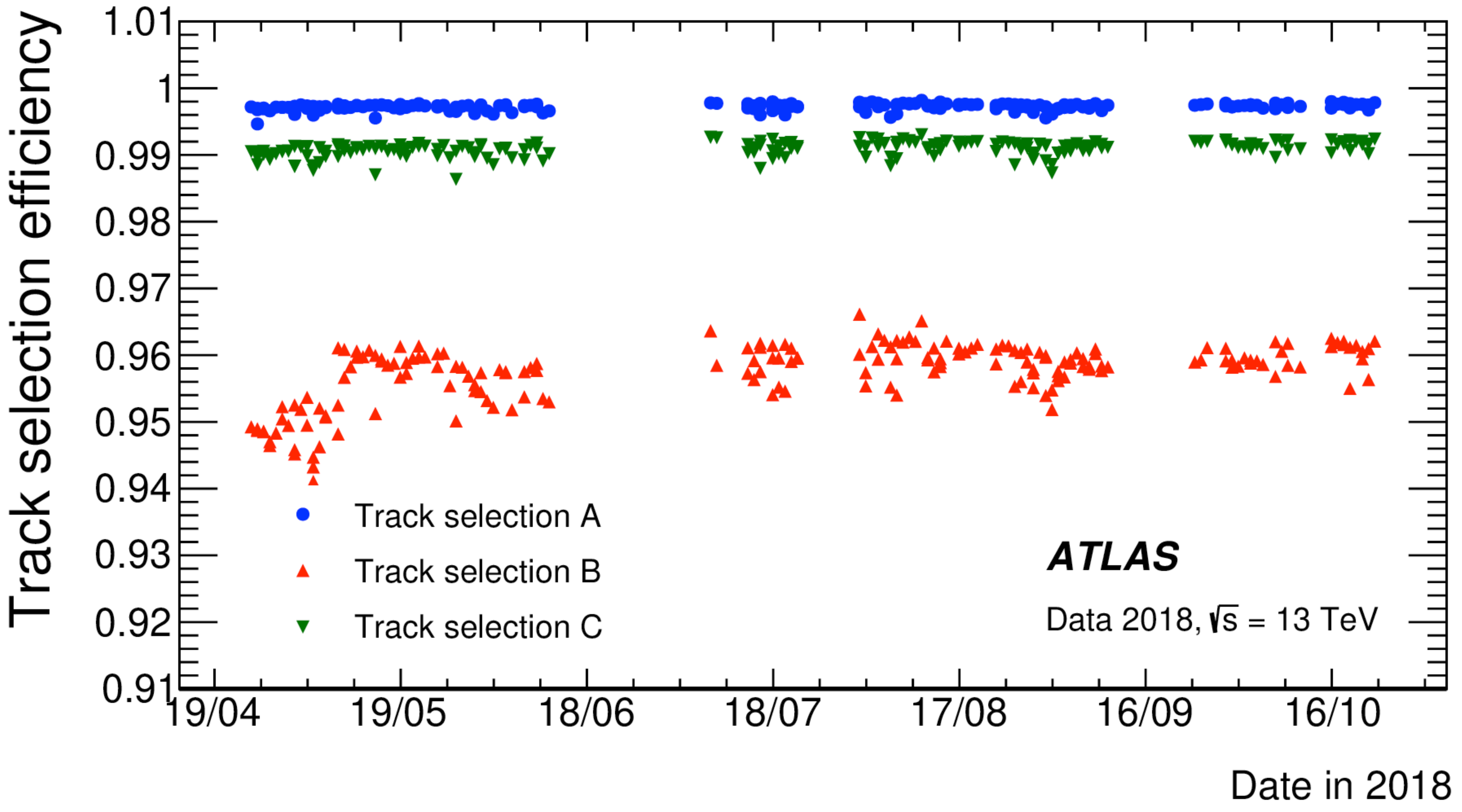
- ➤ Different track selections in use with varying efficiency and fake rates
- ➤ **Selection A** baseline measurement for Run 2

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	$= 0$	≤ 1
$\|d_0\|/\sigma_{d_0}$	< 7	< 7	< 7

- ➤ Stability monitored with $Z \to \mu\mu$ events, measured the track selection efficiency

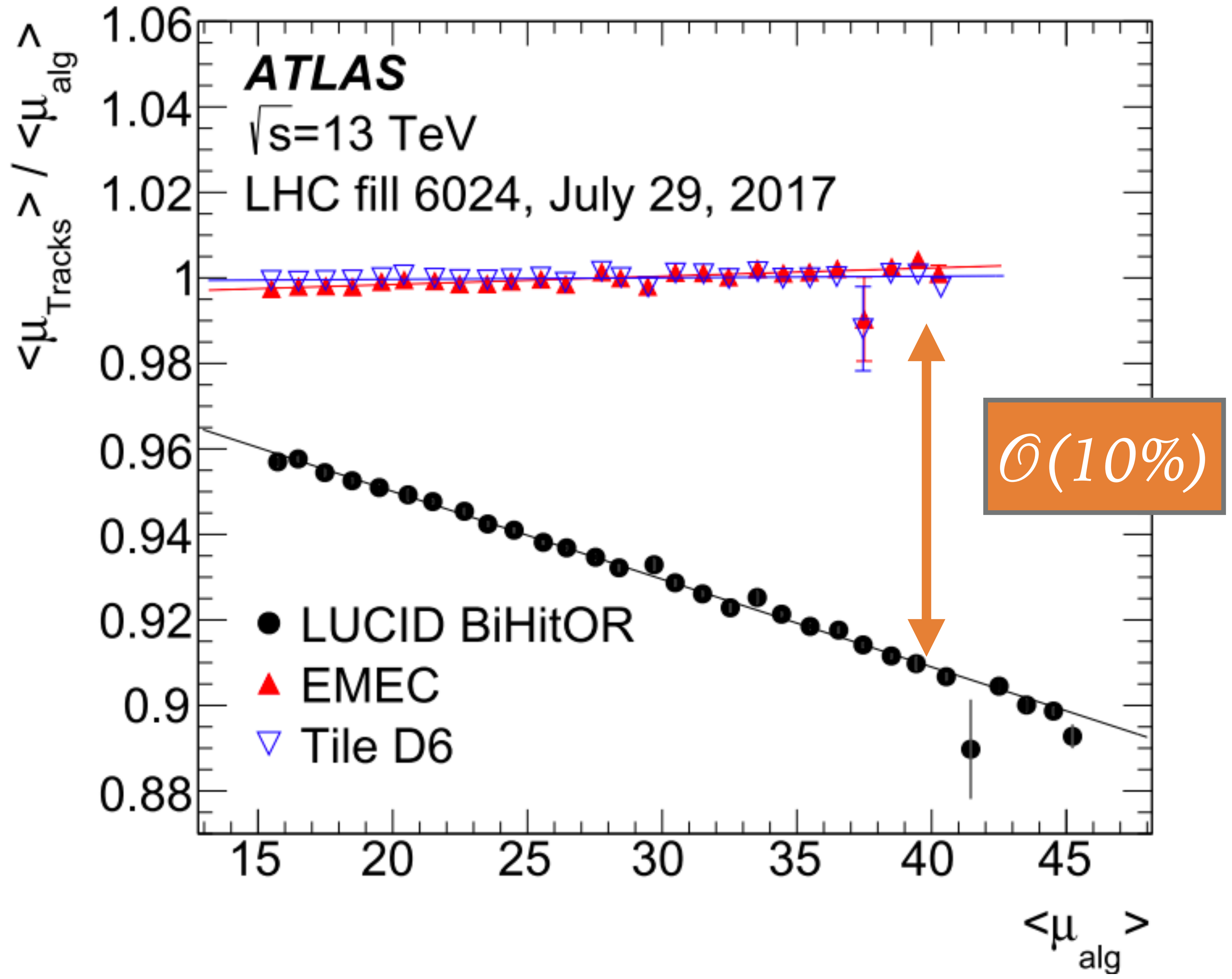






2. Calibration transfer

- LUCID overestimates luminosity at high μ
  - Use track counting to derive correction factor
- Caveat: track counting is only relativ measurement
  - Track counting **normalized** to LUCID in head-on part of vdM fill
  - $\mu-$correction derived in long physics run with natural luminosity decay
    - $\mathcal{O}(10\%)$ at $\langle\mu\rangle$ of 45



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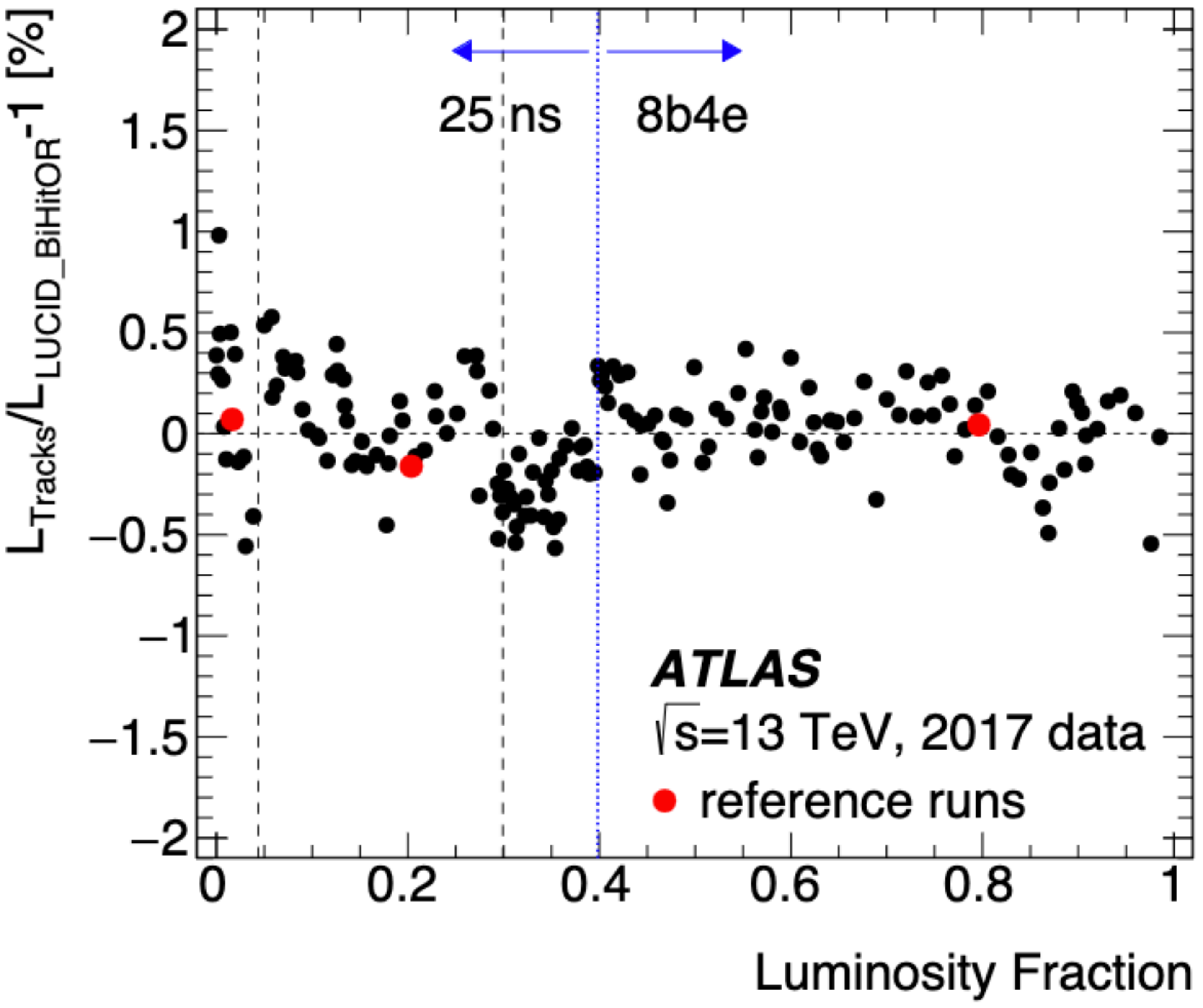
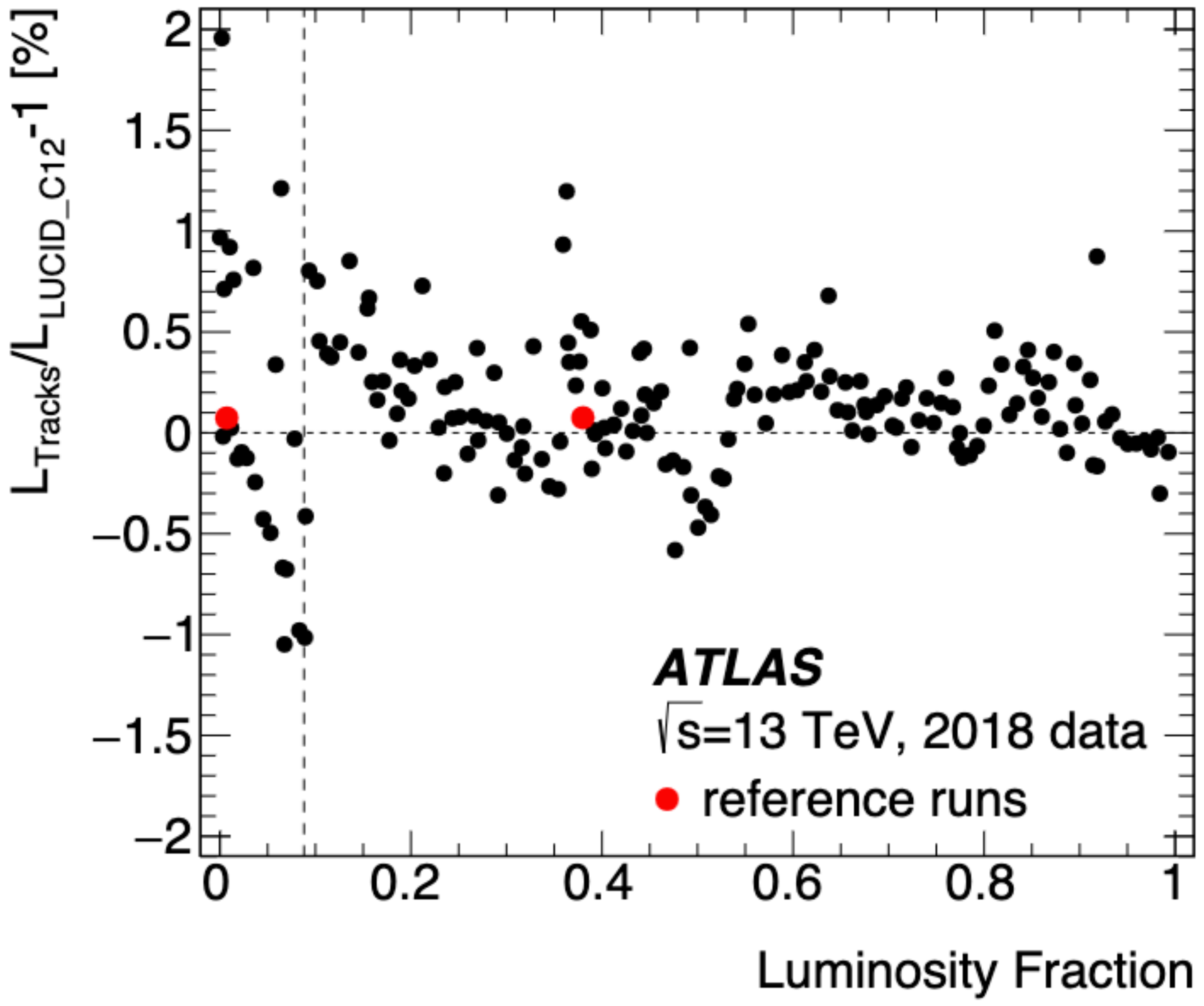




- Data is divided into periods with similar conditions
  - Startup, bulk, 8b4e running in 2017

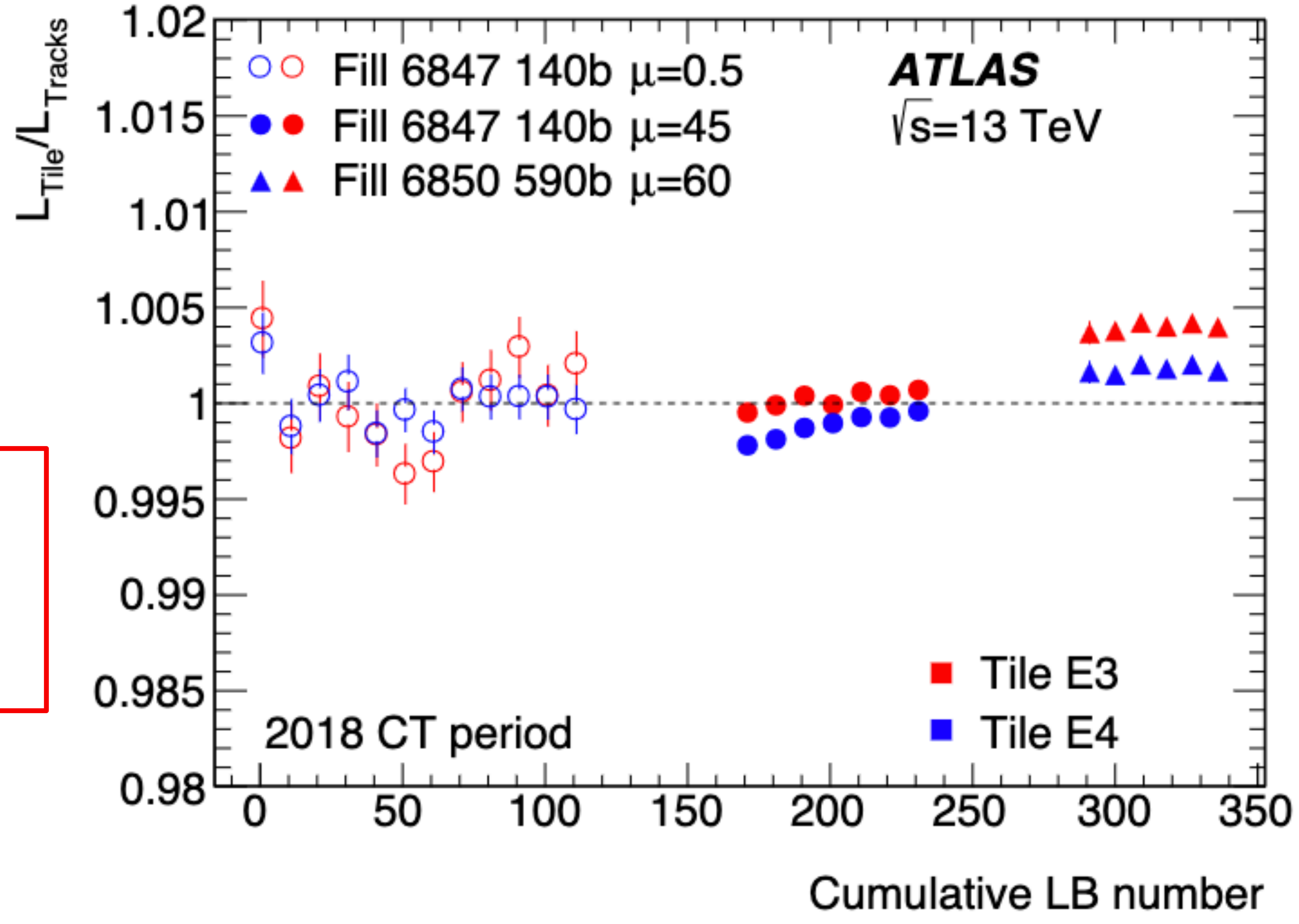
Luminosity fraction ≙ time in year

***Result**: Corrected LUCID luminosity* $\mathbf{L_{corr}}$ *for each LB in each physics run*

2. Calibration transfer uncertainty

- LUCID correction assumes that track counting is perfectly linear from vdM to physics regime
  - Check this assumption with alternative Tile data measurement
    - Sophisticated activation corrections to Tile data need to be applied

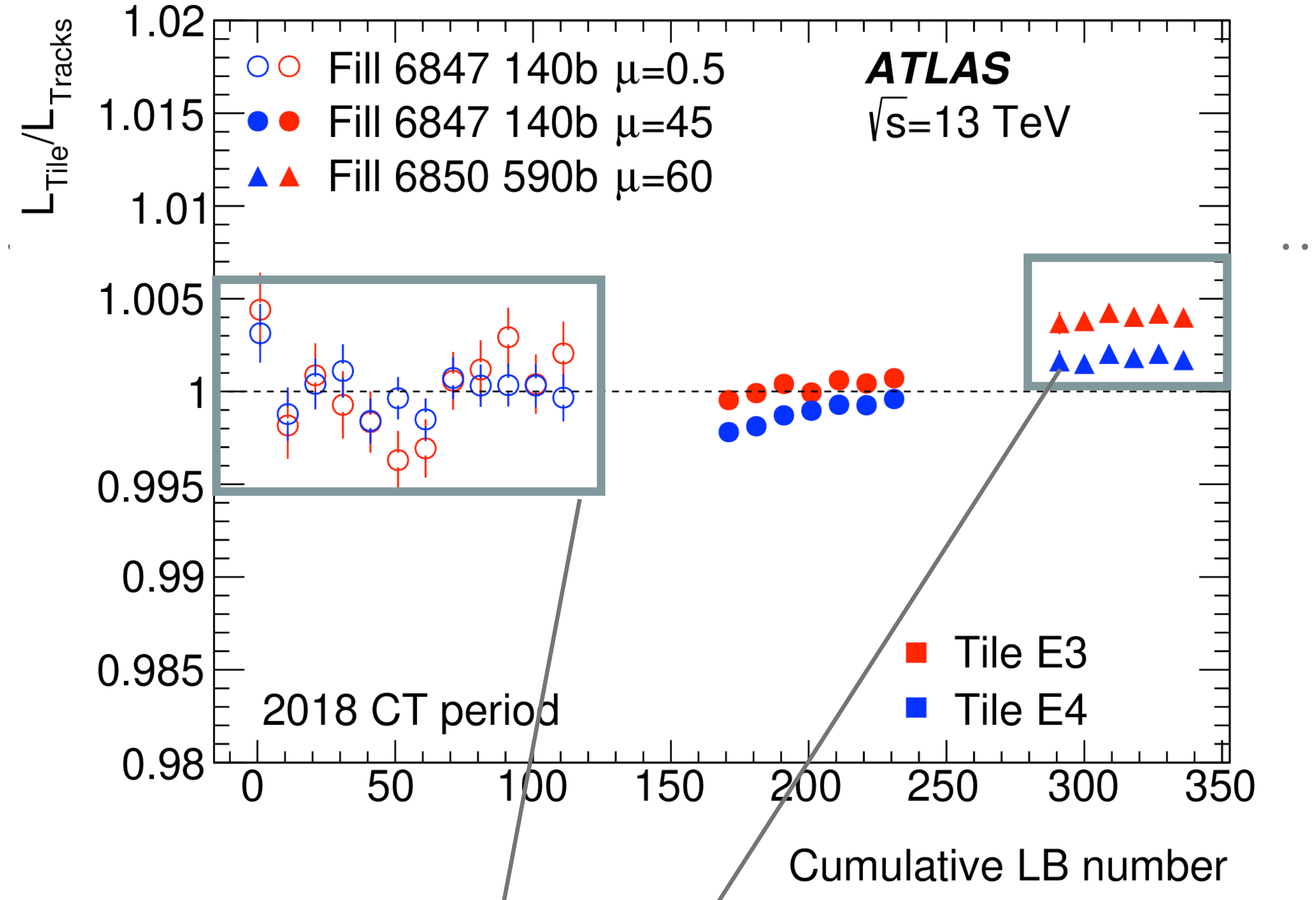
Check Tile/TC ratio in vdM conditions



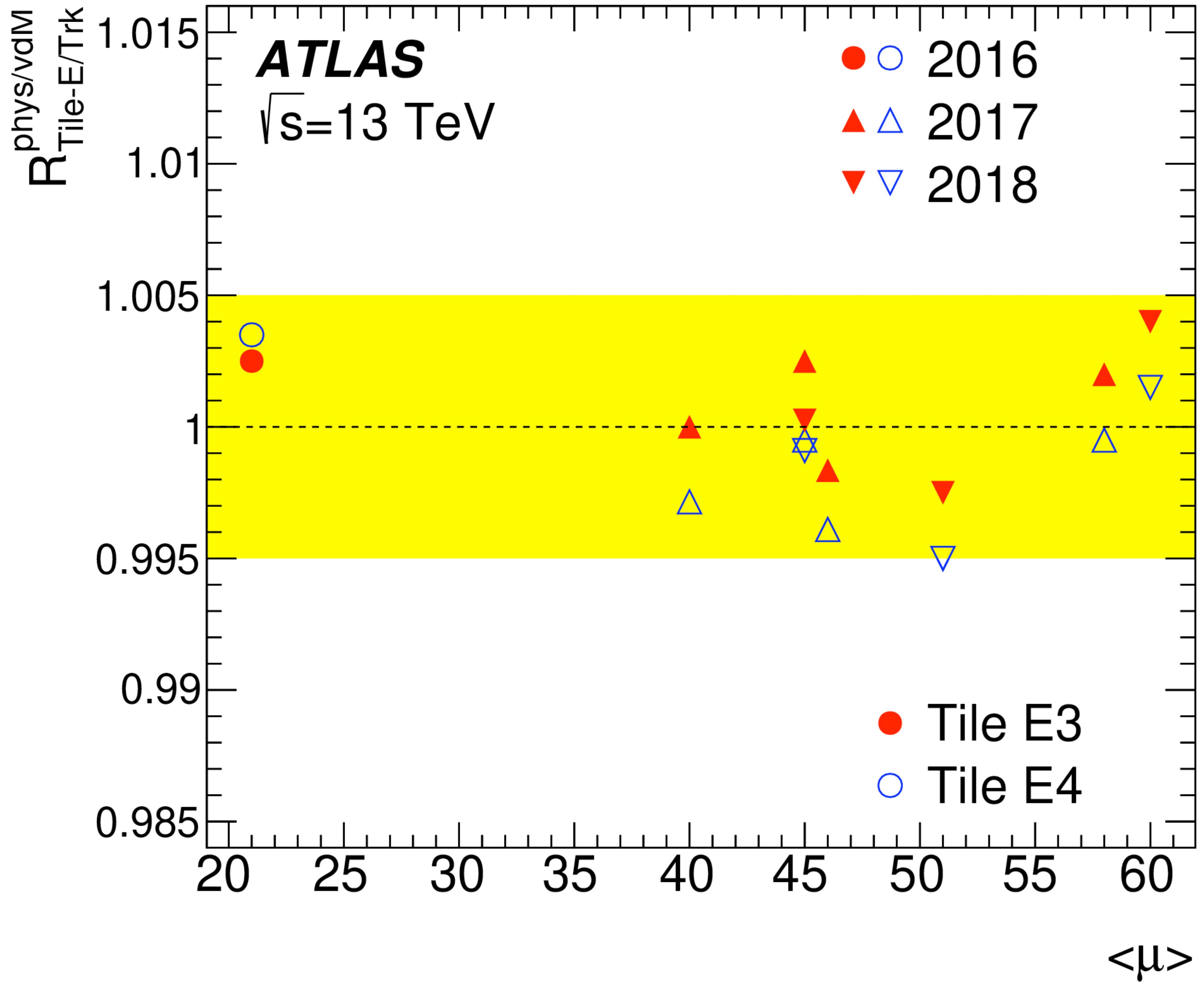
Compare to Tile/TC ratio in physics fill scheduled shortly after vdM

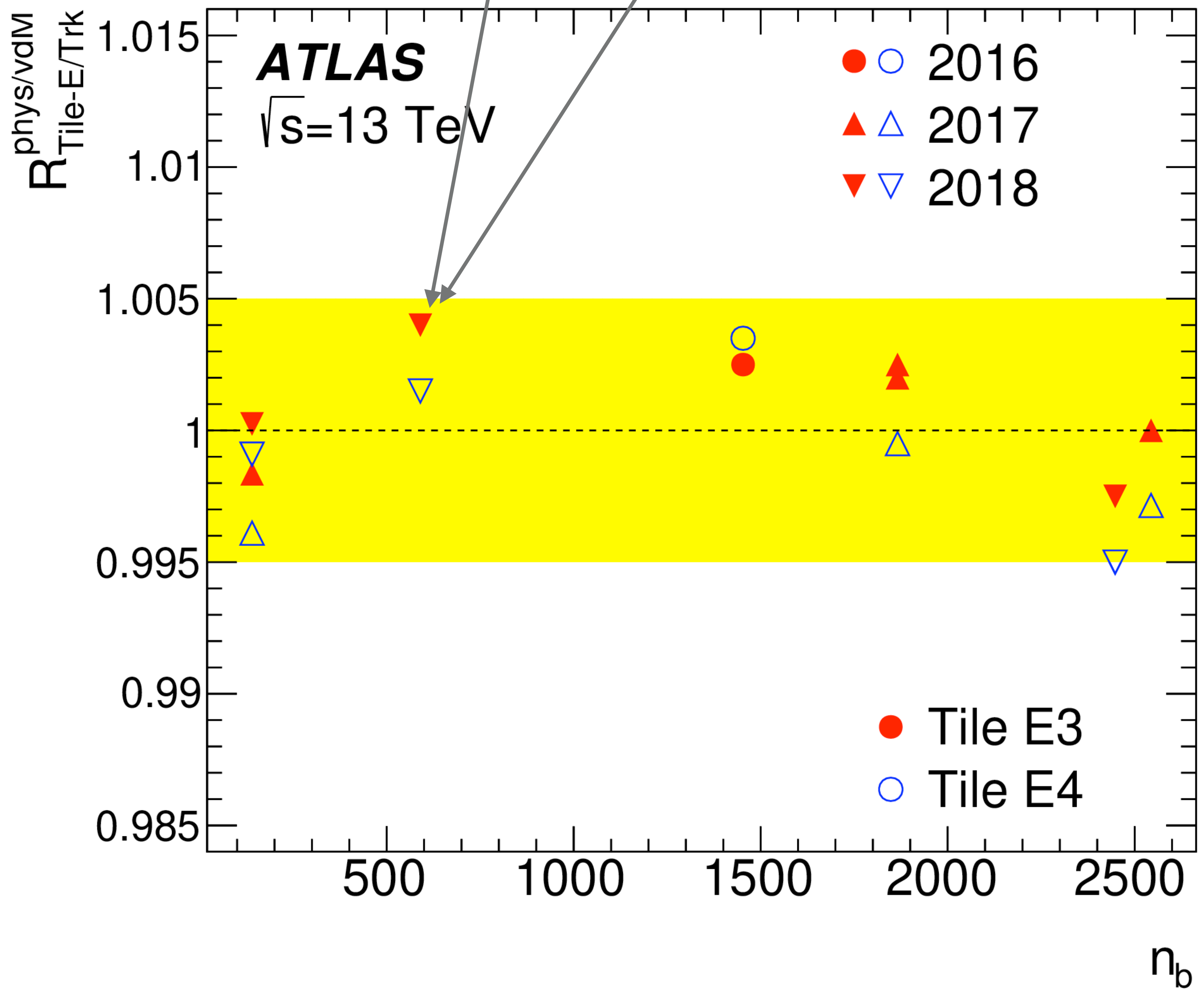
2. Calibration transfer uncertainty

➤ 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 %**





ATLAS Luminosity measurement strategy in Run 2

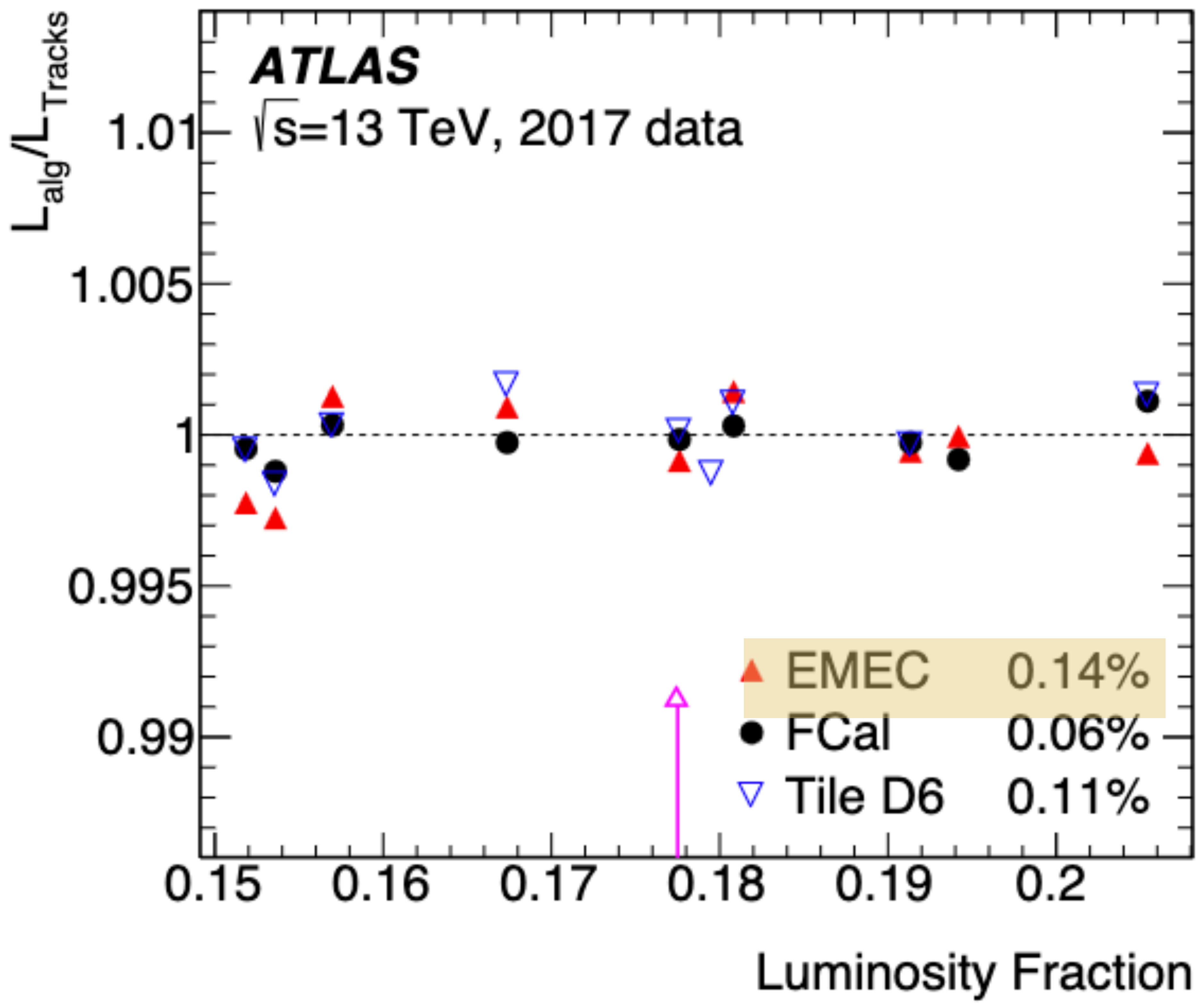
3. Long-term stability

- Check of Run-to-Run stability throughout each year
- Comparison of run-integrated luminosity of LUCID wrt Tile, EMEC, FCAL

➤ Luminosity measurements needs to be monitored throughout the year by comparing corrected LUCID $\mathbf{L}_{\mathbf{corr}}$ with calorimeter measurements

3. Long term stability

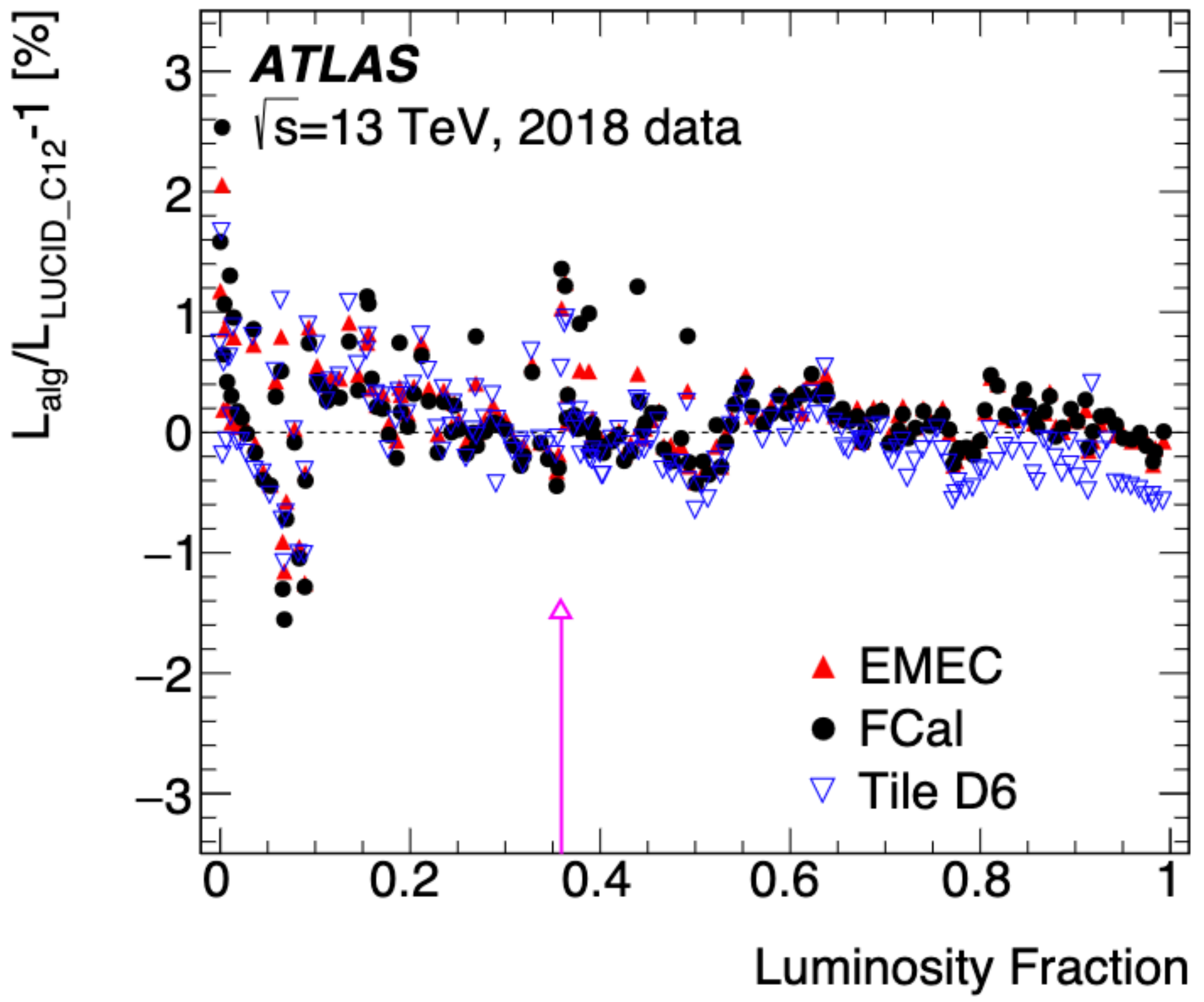
- **Calorimeter anchoring**
  - Calorimeter measurements are not calibrated in vdM fill
    ⇒ need to be “anchored” to track counting in physics run close to vdM fill
  - Using average of 10 runs around vdM fill
  - RMS of run-to-run variations assigned as uncertainty ⇒ **0.1% to 0.3% per year**

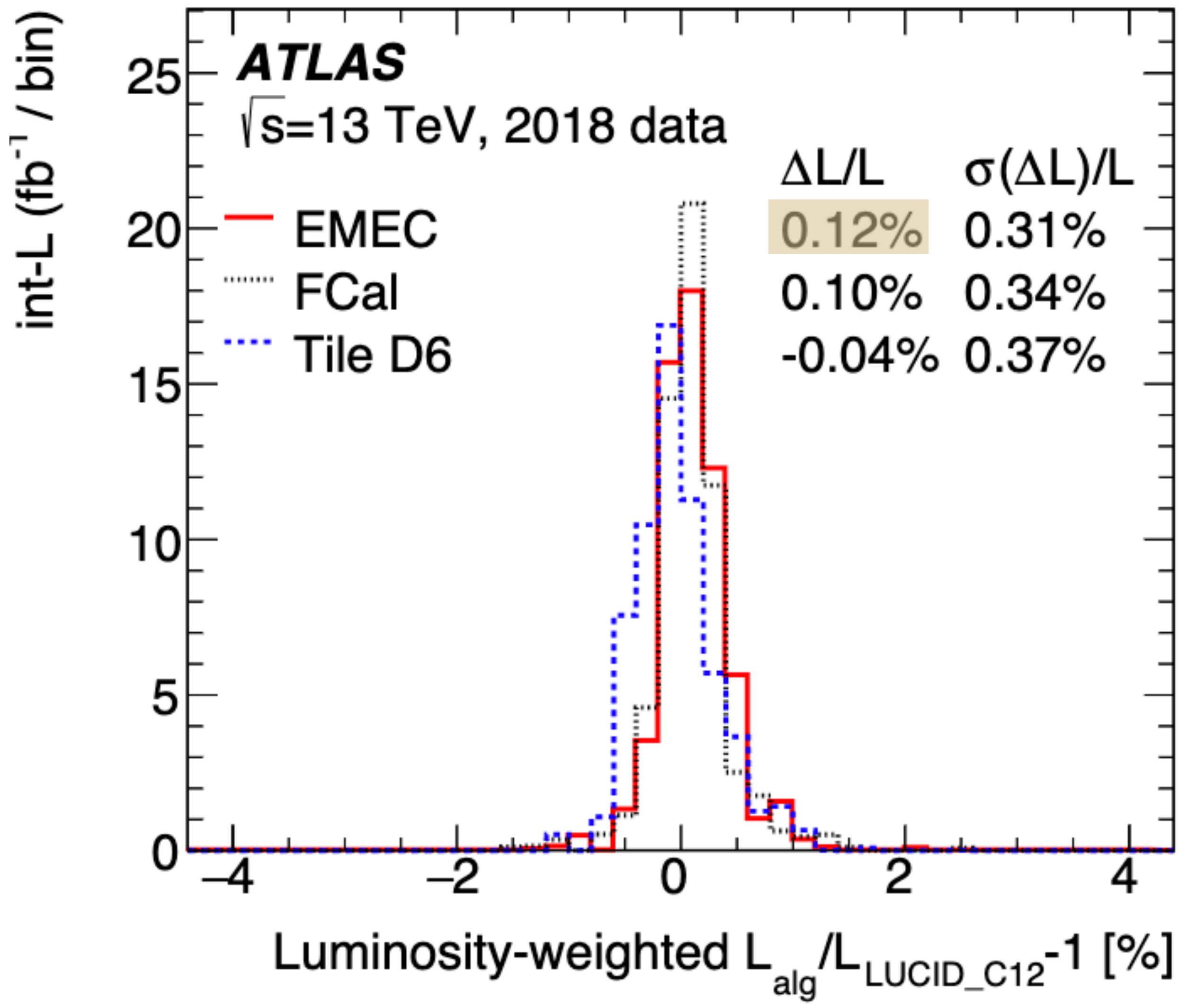


3. Long term stability

- ➤ **Long-term stability**
  - ➤ Comparison of run-integrated luminosity of LUCID wrt Tile, EMEC, FCAL throughout the whole data taking year
  - ➤ **Target: uncertainty on the integrated luminosity not** individual runs
    ⇒ 0.1 to 0.2% per year uncertainty

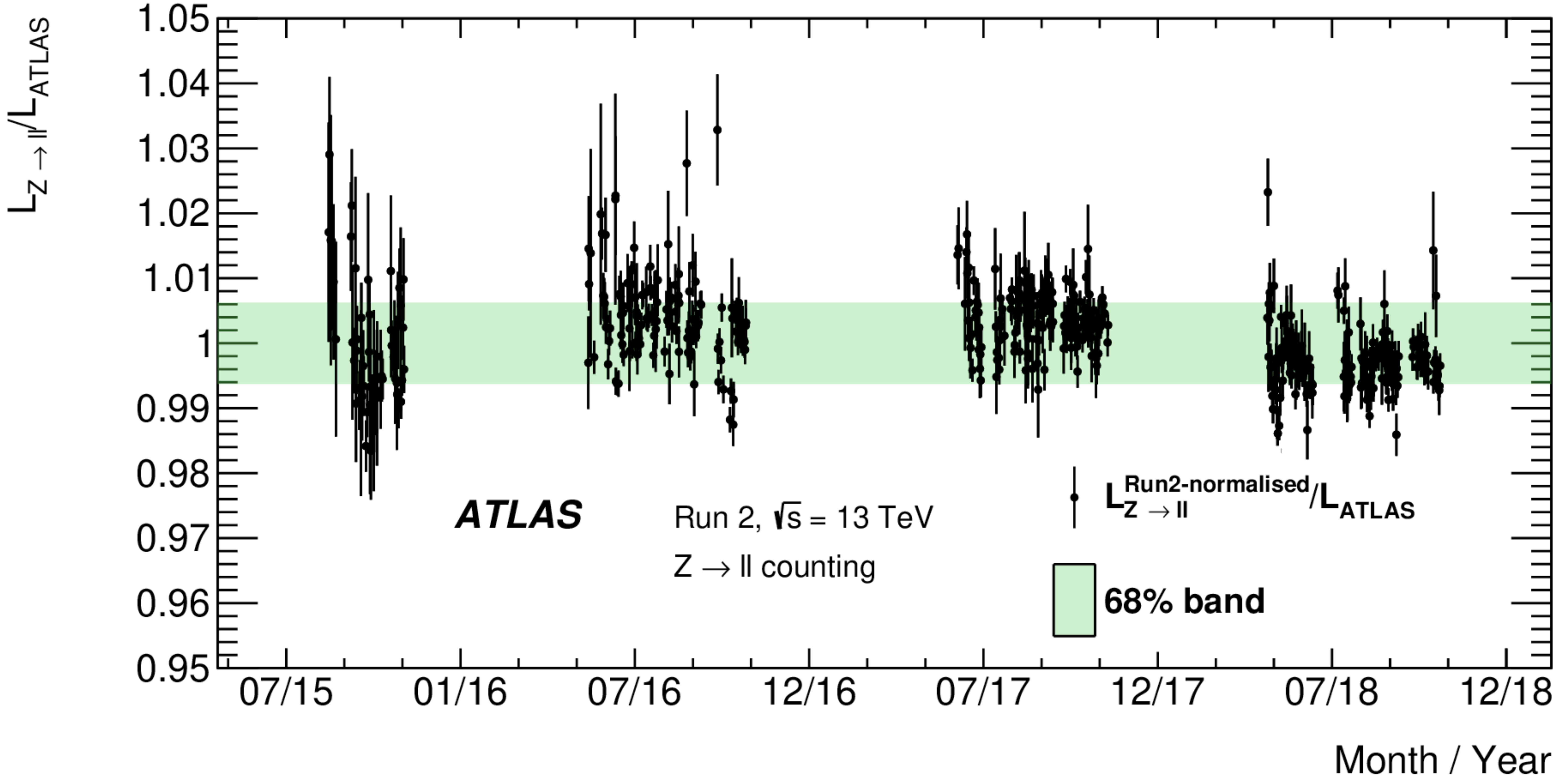
Take largest mean from EMEC, FCal, Tile to define long-term stability uncertainty





Z-counting

- $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ counting can be used to relative luminosity measurements and comparisons between CMS and ATLAS
  - Absolute measurement not precise enough -> PDF uncertainties on Z-cross section too large
- To check inter-year calibration compare L_Z/L_{ATLAS}



Summary

per year

1. vdM calibration
0.7-0.99%

2. Calibration transfer
0.5%

3. Long-term stability
0.2% - 0.3 %

*correlated

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

https://arxiv.org/abs/2212.09379

Summary

per year

1. vdM calibration	2. Calibration transfer	3. Long-term stability
0.7-0.99%	0.5%	0.2% - 0.3 %

- Luminosity measurement for full Run 2 ATLAS pp dataset finalized

140.1 ±1.2 fb^{-1} corresponds to 0.83% uncertainty

  - Highest precision achieved at the LHC

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Ghost-charge and satellite bunches*	0.04	0.04	0.02	0.09	0.05
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  - **Highest precision achieved at the LHC**
  - Dominant uncertainties
    - vdM calibration
      - beam-beam effects
      - non-factorization
      - magnetic-non linearity
      - scan-to-scan reproducibility
    - calibration transfer uncertainty

- Crucial inputs for ongoing Run 3 measurement and ultimate sub-percent precision goal for HL-LHC

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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
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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
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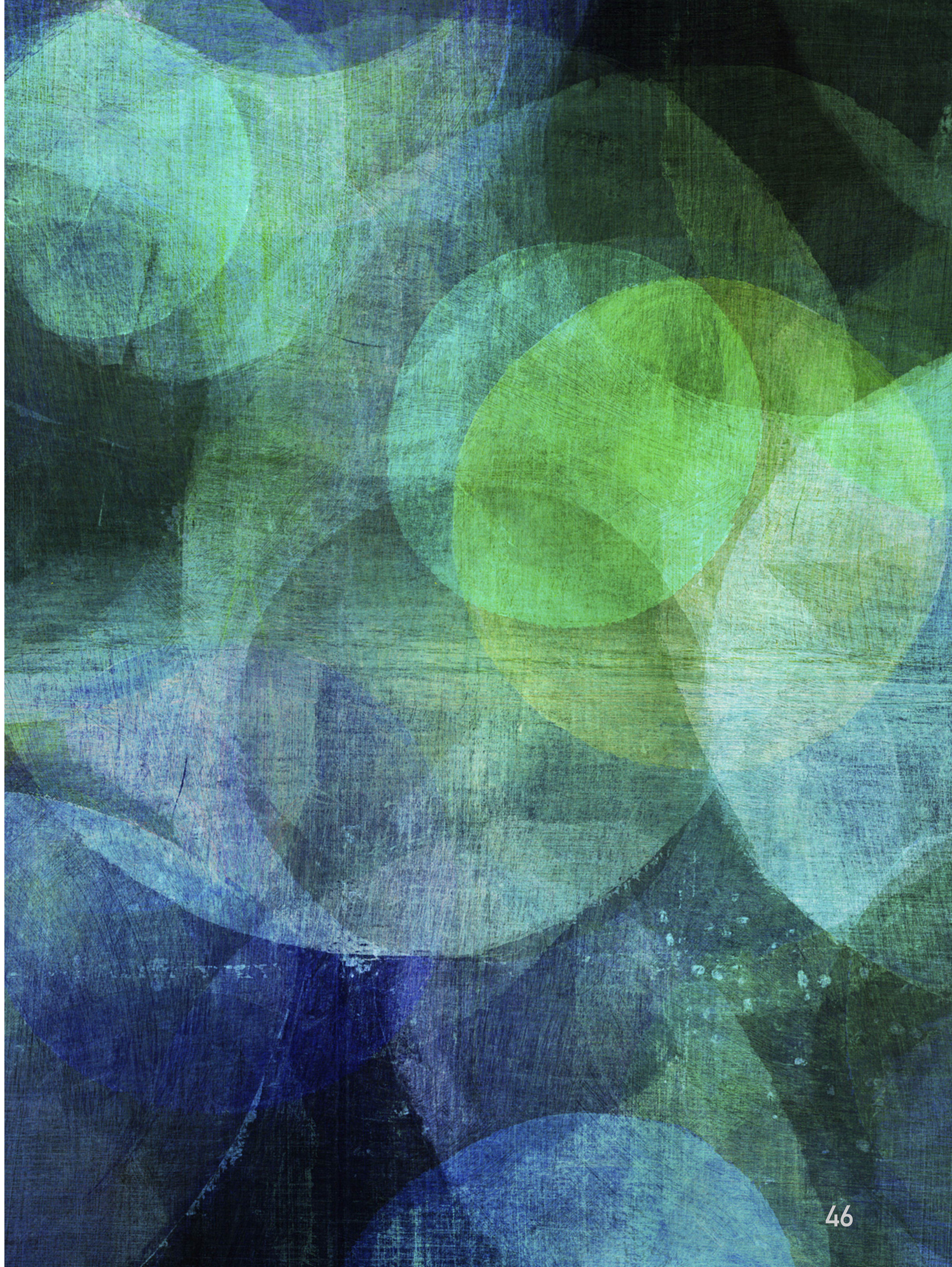
BACKUP

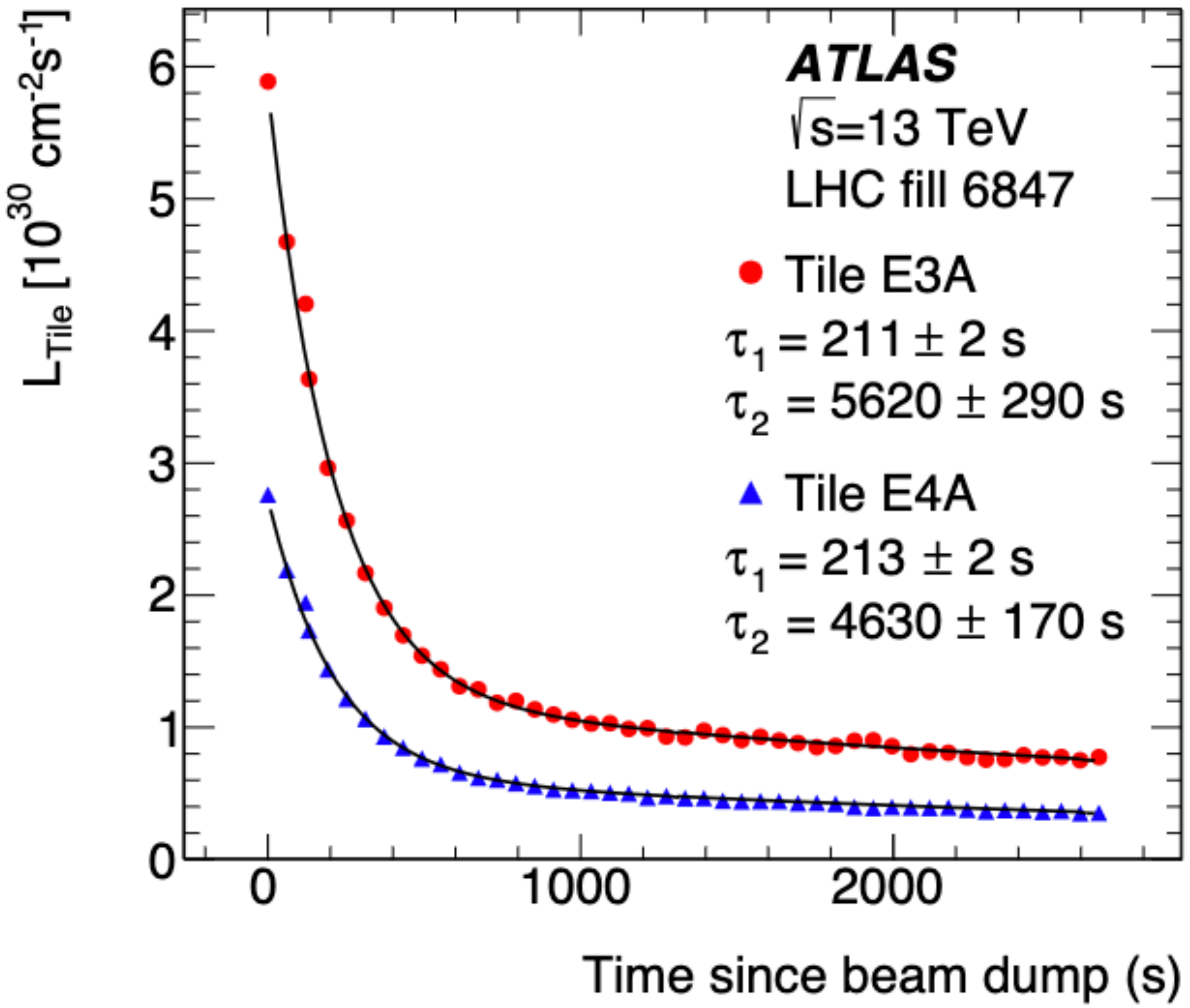


Calibration transfer uncertainty – activation correction

- LUCID correction assumes that track counting is perfectly linear from vdM to physics regime
  - Check this assumption with alternative Tile data measurement
    - Tile data needs **complicated treatment and corrections**

- Residual activation from any high-lumi running just before vdM fill can swamp Tile signal with $\mathcal{O}(10\%)$
  $\Rightarrow$ Needs delicate pedestal subtraction

- PMT response non-linear with luminosity at the 0.5-1.0 % level at high $\langle\mu\rangle$
  $\Rightarrow$ Calibrated out 'in situ' with laser pulses into the PMTs during LHC abort gap



2023 – things are only gonna get better

Preliminary

139 ± 2.3fb^{-1} (1.7%)

140.1 ±1.2 fb^{-1} (0.83%)

NEW

Data sample	2015+16	2017	2018	Comb.
Integrated luminosity (fb^{-1})	36.2	44.3	58.5	139.0
Total uncertainty (fb^{-1})	0.8	1.0	1.2	2.4
Uncertainty contributions (%):				
DCCT calibration†	0.2	0.2	0.2	0.1
FBCT bunch-by-bunch fractions	0.1	0.1	0.1	0.1
Ghost-charge correction*	0.0	0.0	0.0	0.0
Satellite correction†	0.0	0.0	0.0	0.0
Scan curve fit model†	0.5	0.4	0.5	0.4
Background subtraction	0.2	0.2	0.2	0.1
Orbit-drift correction	0.1	0.2	0.1	0.1
Beam position jitter†	0.3	0.3	0.2	0.2
Beam-beam effects*	0.3	0.3	0.2	0.3
Emittance growth correction*	0.2	0.2	0.2	0.2
Non-factorization effects*	0.4	0.2	0.5	0.4
Length-scale calibration	0.3	0.3	0.4	0.2
ID length scale*	0.1	0.1	0.1	0.1
Bunch-by-bunch σ_{vis} consistency	0.2	0.2	0.4	0.2
Scan-to-scan reproducibility	0.5	1.2	0.6	0.5
Reference specific luminosity	0.2	0.2	0.4	0.2
Subtotal for absolute vdM calibration	1.1	1.5	1.2	-
Calibration transfer†	1.6	1.3	1.3	1.3
Afterglow and beam-halo subtraction*	0.1	0.1	0.1	0.1
Long-term stability	0.7	1.3	0.8	0.6
Tracking efficiency time-dependence	0.6	0.0	0.0	0.2
Total uncertainty (%)	2.1	2.4	2.0	1.7

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https://arxiv.org/abs/2212.09379

Many similar size uncertainty ⇒ needs a lot of work to improve on all fronts

Calibration transfer to higher pile up

- Calibration may depend on μ due to **non-linearity of method vs μ**
  - Achieving linearity with μ not trivial at high μ!
- Example **event counting:**
  - Probability to observe at least one "event" in bunch crossing (BC)

$$P_{OR} = \frac{N_{OR}}{N_{BC}} = 1 - e^{-\mu_{vis}}$$

  - At high μ suffers from "zero-starvation"
  - Detector efficiency may also depend on μ

$\mu_{vis} = \varepsilon\mu$	$1-P_{OR}$ (%)	Number of 0s/LB
0.5	61.7	5×10^{10}
5	0.7	6×10^{8}
15	3×10^{-5}	2×10^{6}
30	9×10^{-12}	0.75

You need something that scales linearly with μ!