



# Luminosity determination in pp collisions at 13 TeV with the ATLAS detector

*Lepton Photon Conference, Melbourne, July 19th, 2023*

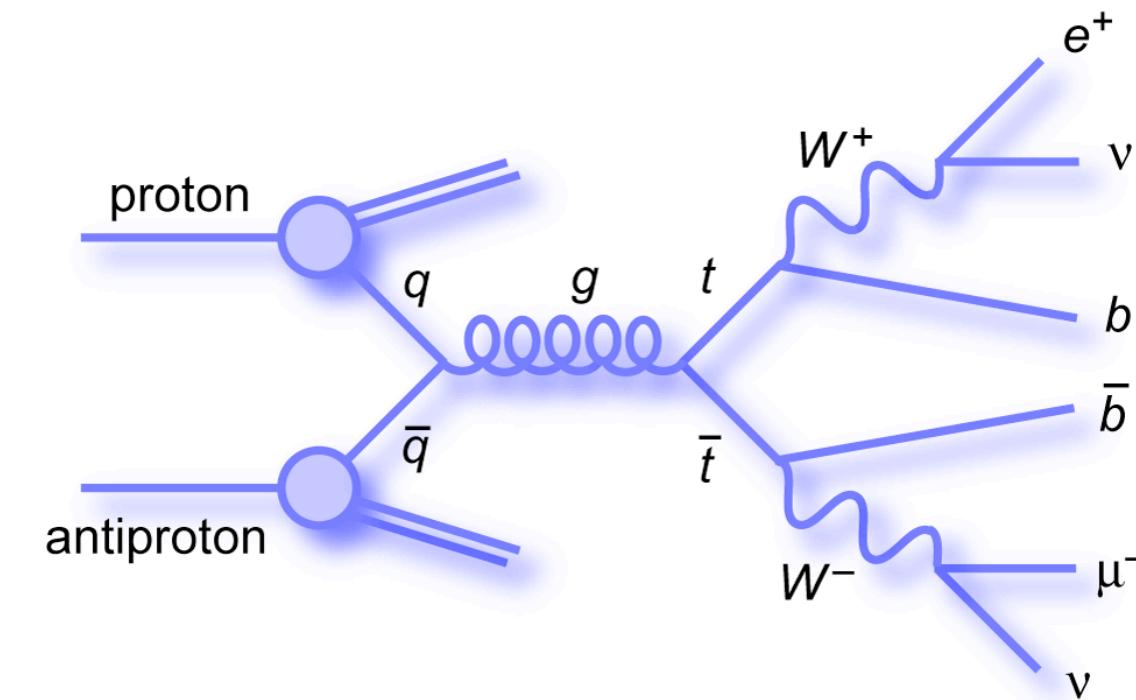
*Claudia Seitz on behalf of the ATLAS Collaboration*

# 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](#)

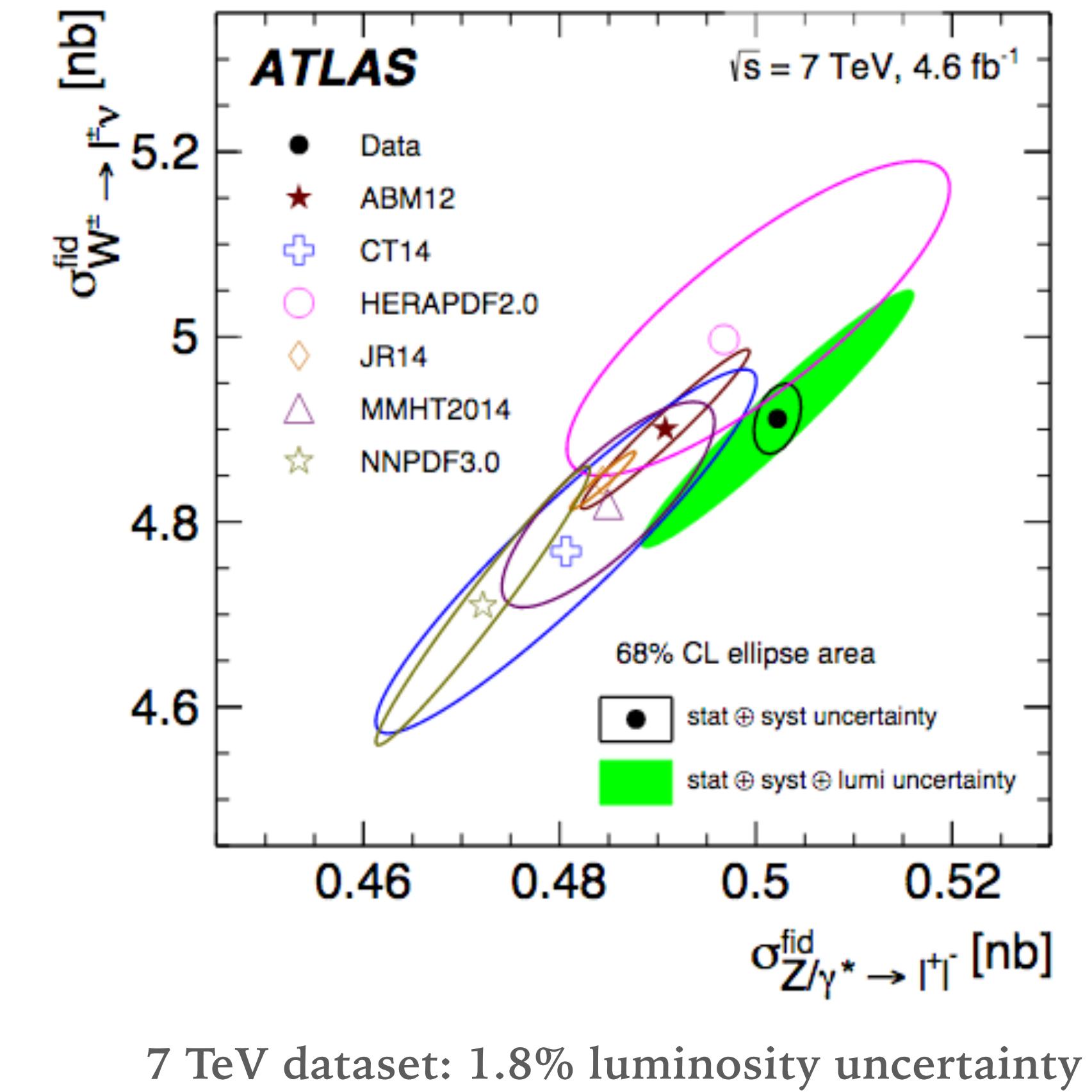
$$\sigma_{t\bar{t}} = 826.4 \pm 3.6 \text{ (stat)} \pm 11.5 \text{ (syst)} \pm 15.7 \text{ (lumi)} \pm 1.9 \text{ (beam)} \text{ pb},$$



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

at 13 TeV with  $36 \text{ fb}^{-1}$

[Eur. Phys. J. C 77 \(2017\) 367](#)



# Luminosity definition

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- 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
- Related to
  - Rate of observed events

$$R = \frac{N_{obs}}{\Delta t} = \sigma_{inel} \mathcal{L}$$

- $\Delta t$  = luminosity block ( $LB \sim 60$  s)
- $\mathcal{L}$  = instantaneous luminosity

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- Integrated luminosity: how many collisions in a dataset
- Goal: provide precision measurement of luminosity for physics analyses
- Related to
  - Rate of observed events
  - LHC machine parameters

$$R = \frac{N_{obs}}{\Delta t} = \sigma_{inel} \mathcal{L}$$

-  $\Delta t$  = luminosity block (LB  $\sim$  60 s)  
-  $\mathcal{L}$  = instantaneous luminosity

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

LHC beam parameters

-  $\mu_b$  = number of inelastic pp collisions per bunch  
-  $\sigma_{inel}$  = inelastic pp cross section

Can also be expressed by

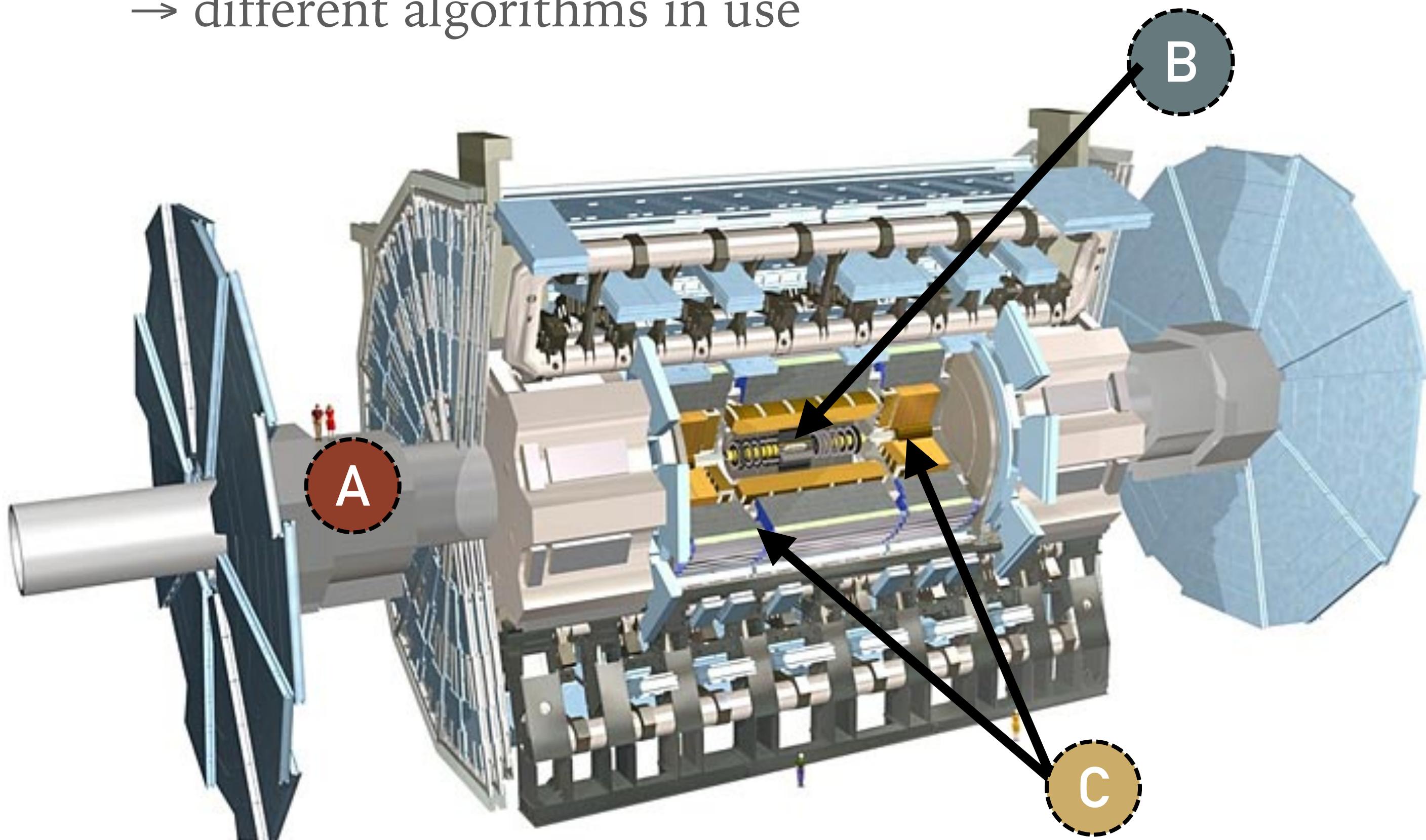
-  $\mu_{vis}$  = visible interaction rate of a given algorithm or luminometer  
-  $\sigma_{vis}$  = visible cross section of that algorithm or luminometer

# Luminosity detectors and algorithms

A

## LUCID

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



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

C

## Calorimeter measurements

- LAr (EMEC and FCAL)
  - proportional to gap current
- Tile calorimeter
  - 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  $\sigma_{\text{vis}}$  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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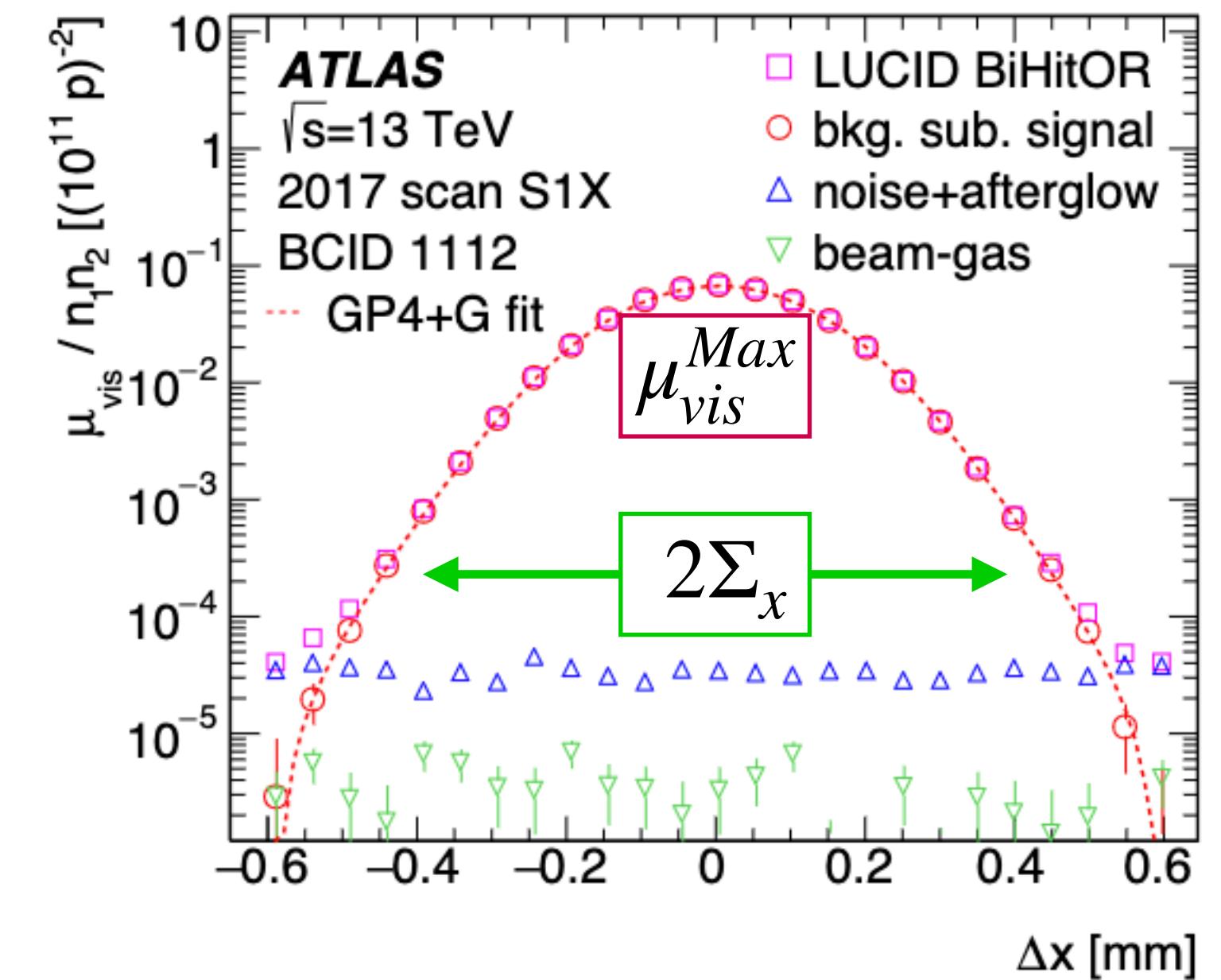
Will discuss today final precision Run 2 results: <https://arxiv.org/abs/2212.09379>

# 1. vdM calibration – van der Meer scans

- vdM analysis determines the visible cross section  $\sigma_{vis}$  for each bunch

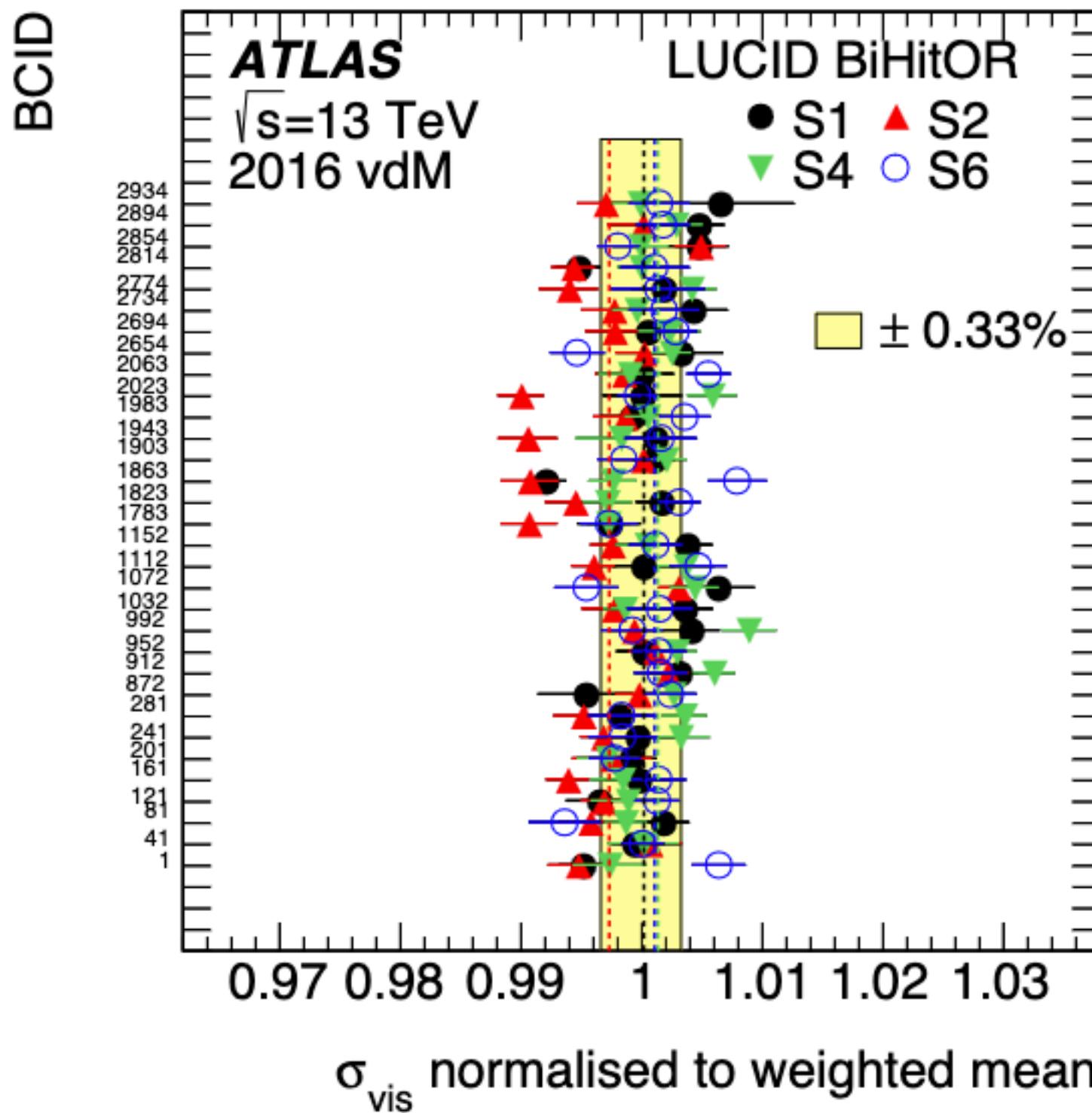
$$\sigma_{vis} = \mu_{vis}^{Max} \frac{2\pi \Sigma_x \Sigma_y}{n_1 n_2}$$

- vdM fit extracts  $\mu_{vis}^{Max}$   $\Sigma_x$   $\Sigma_y$
- Beam current product ( $n_1 n_2$ ) determined by LHC current measurement devices ( $\pm 0.2\%$ )

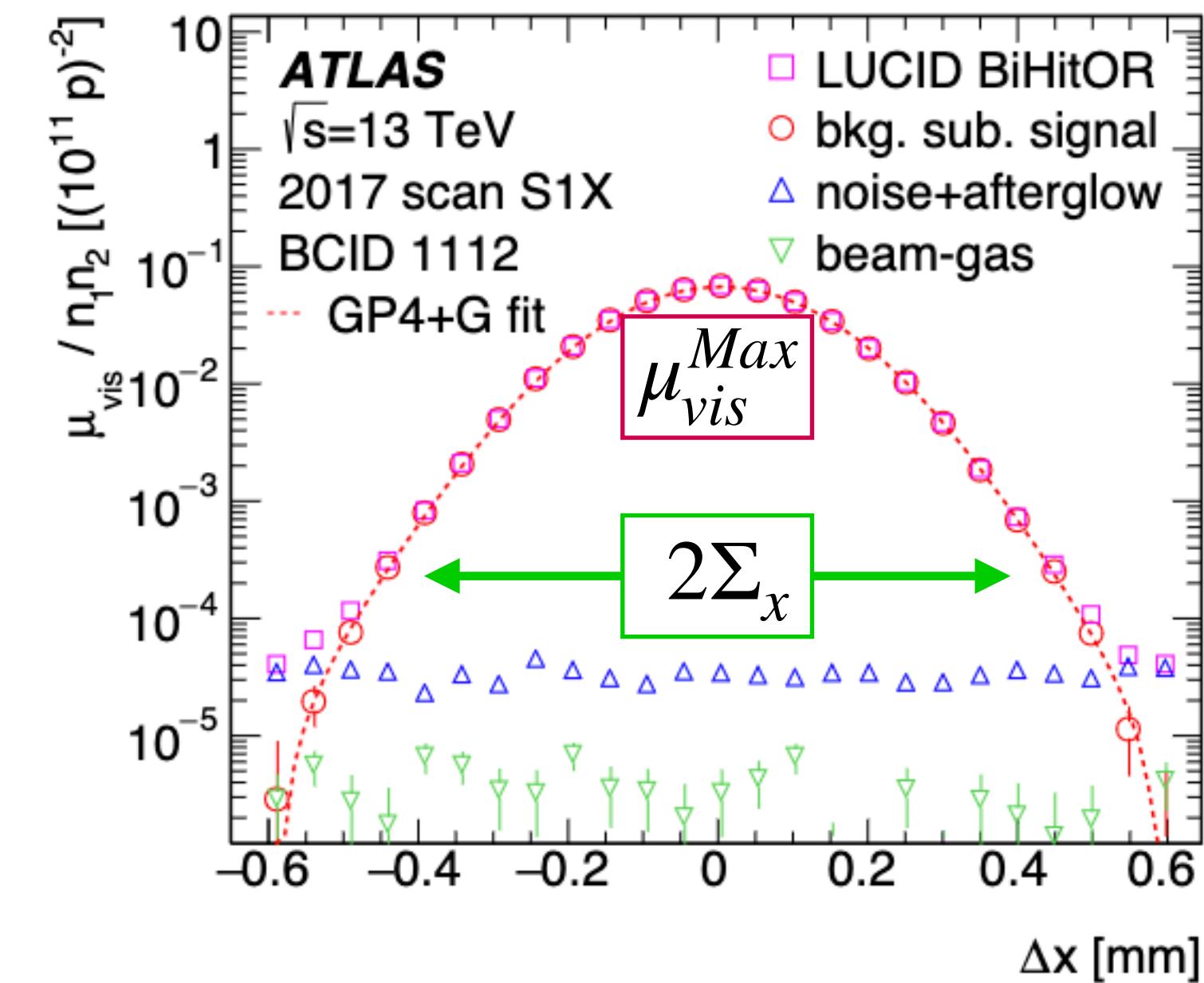


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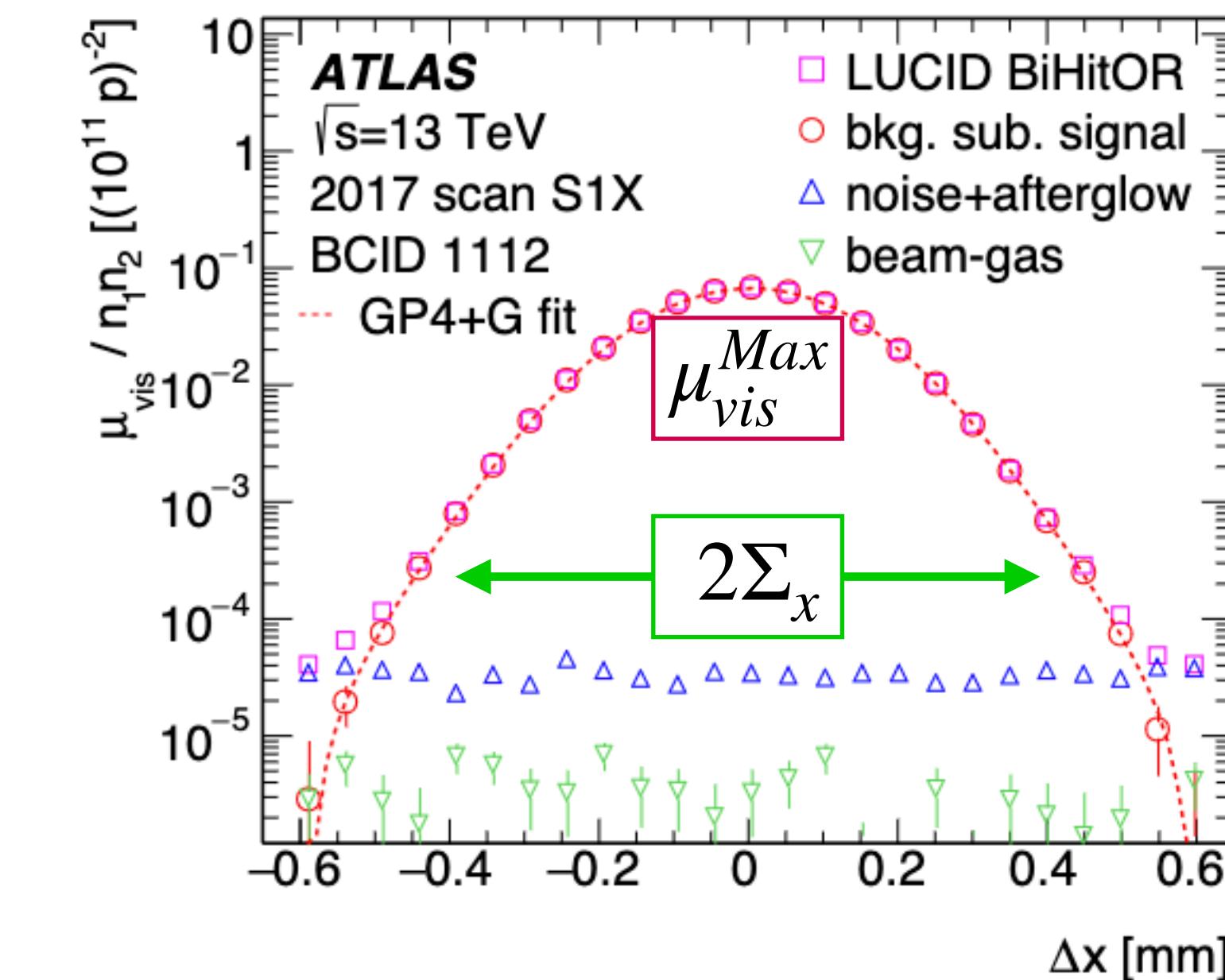
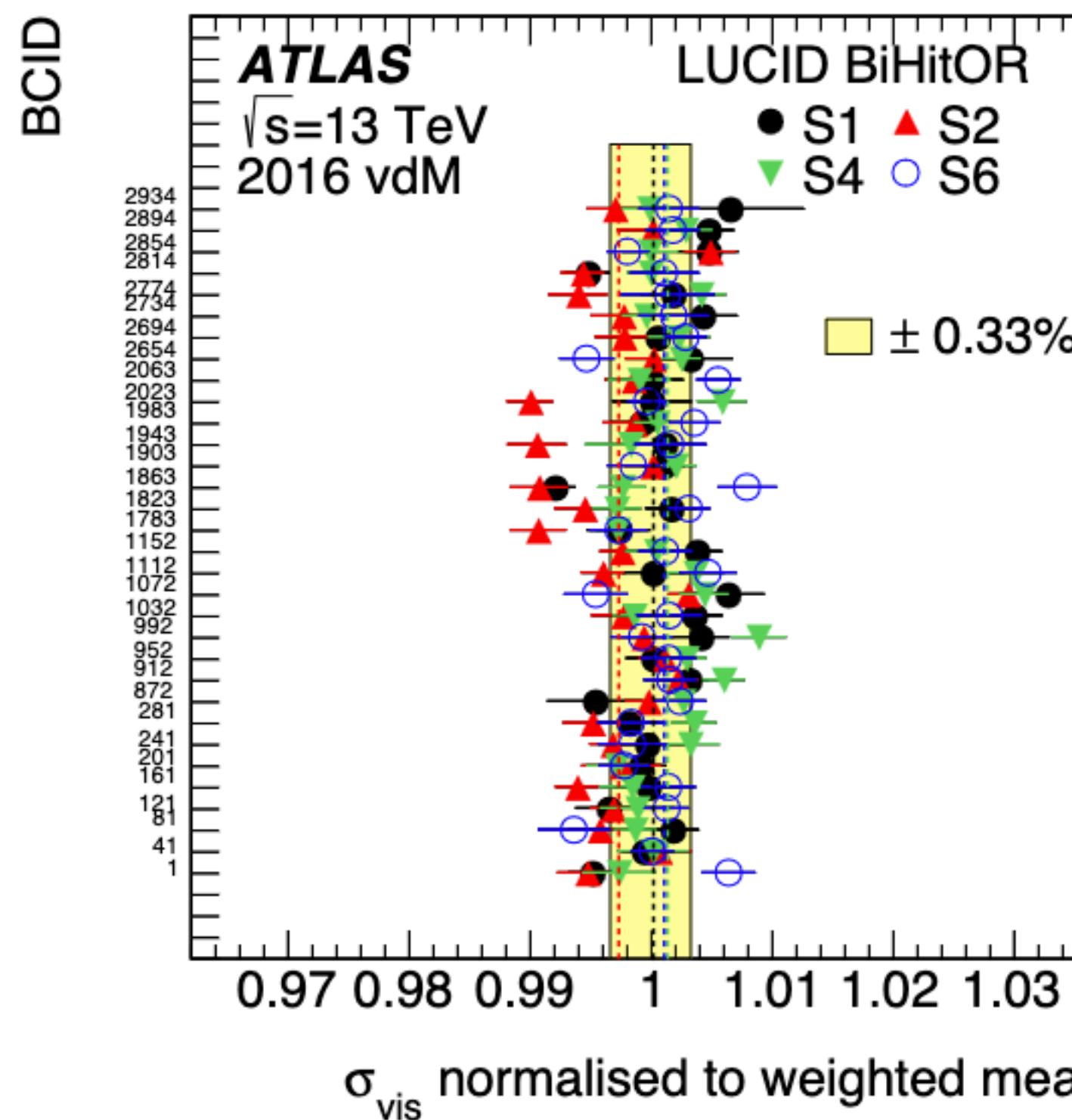


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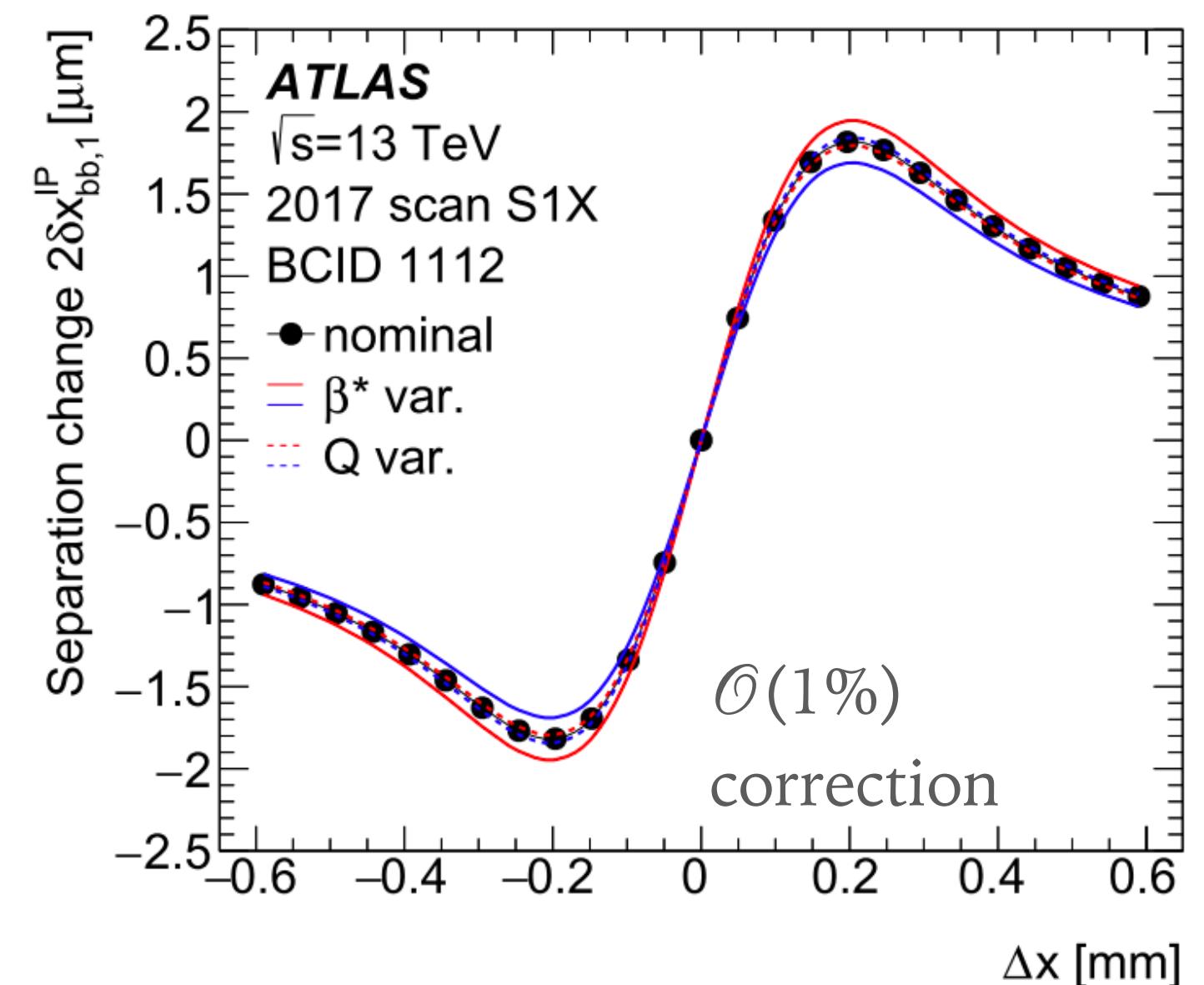
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- Various corrections to consider
  - Orbit drifts – beams do not stay still during scans
  - Emittance growth and non-factorization – beam sizes change with time, transverse profiles in x and y do not factorize
  - Length scale and magnetic non-linearity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

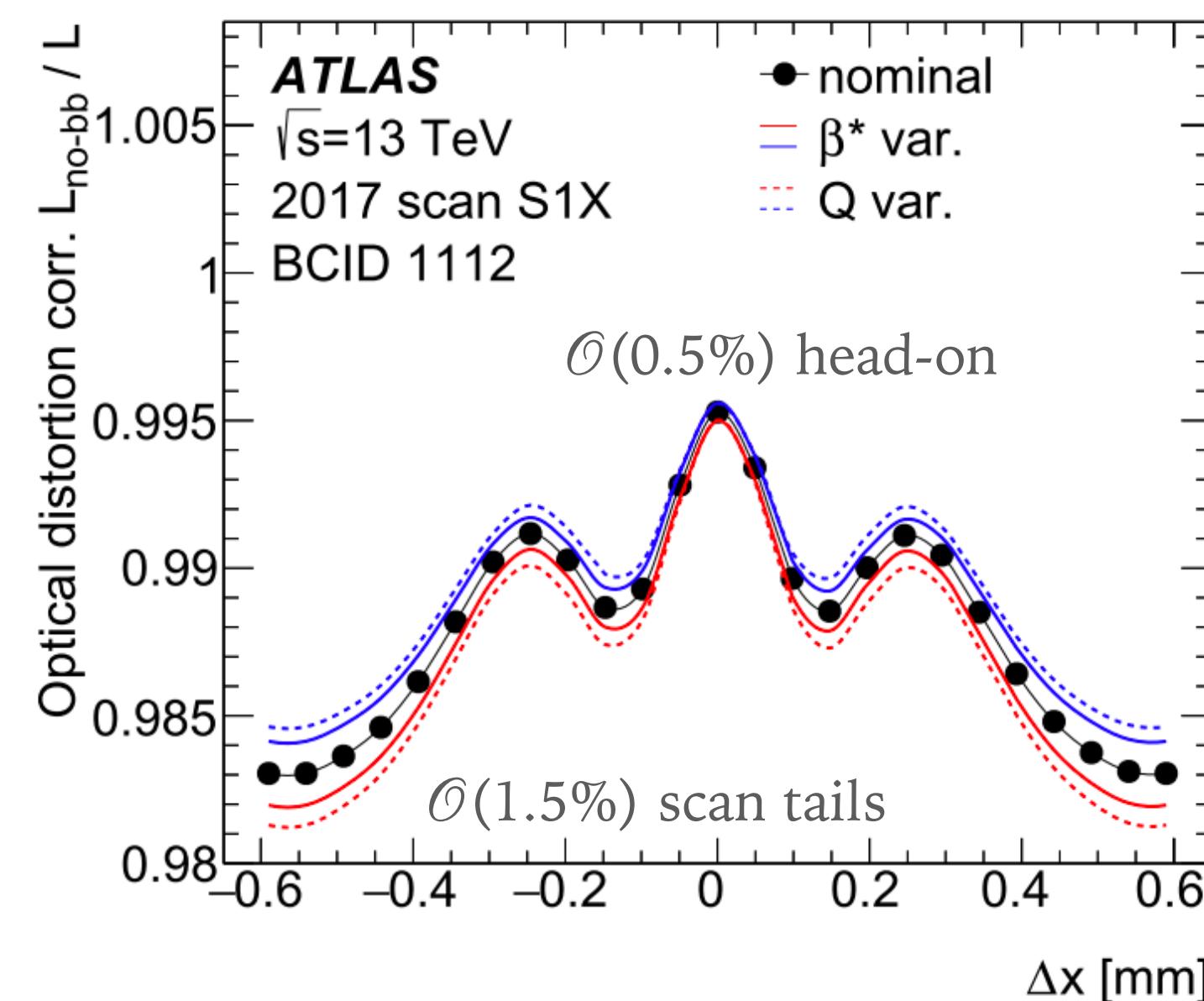
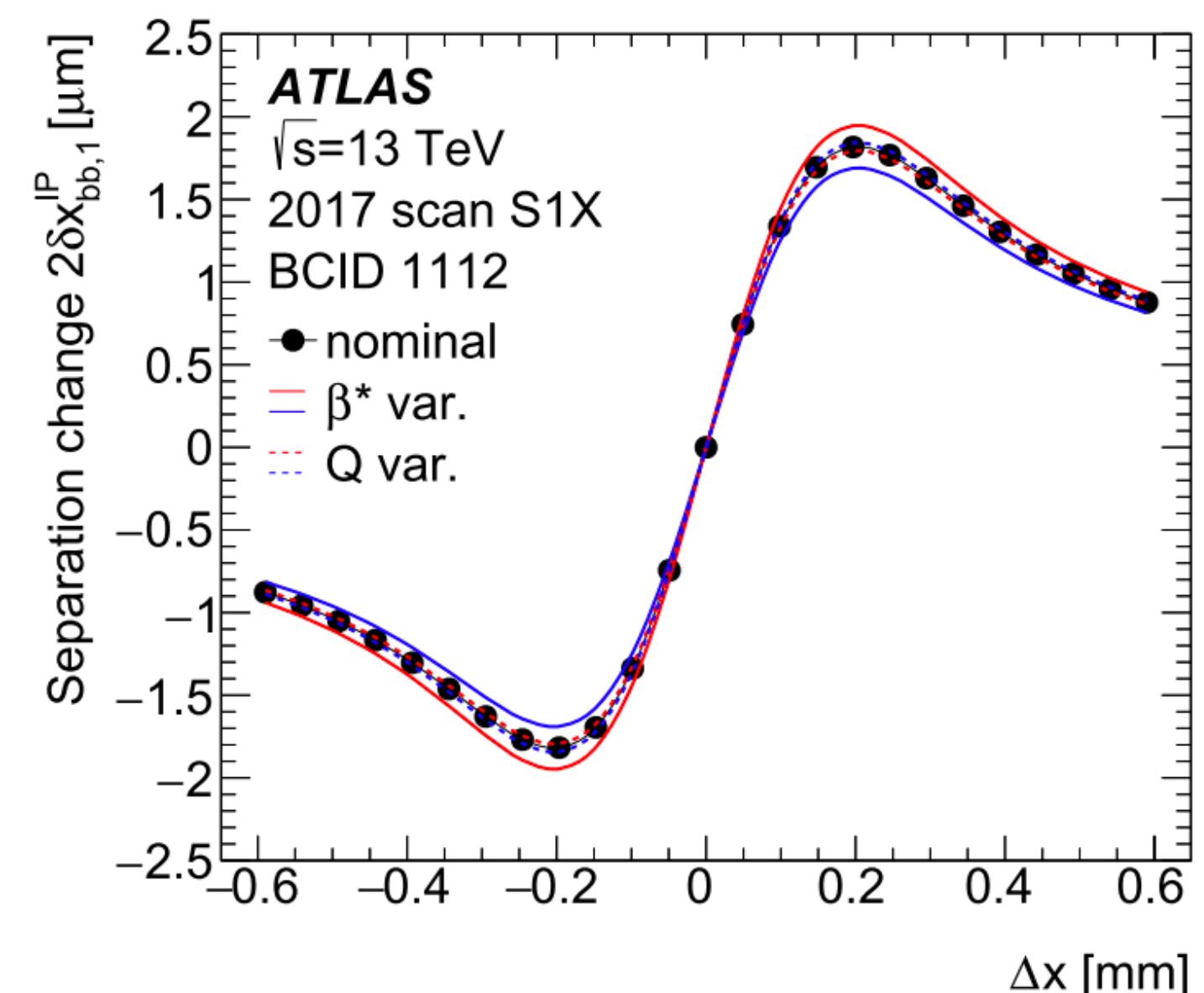
# Beam-Beam effects

- 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  $\Delta$  by a different amount at each vdM-scan step



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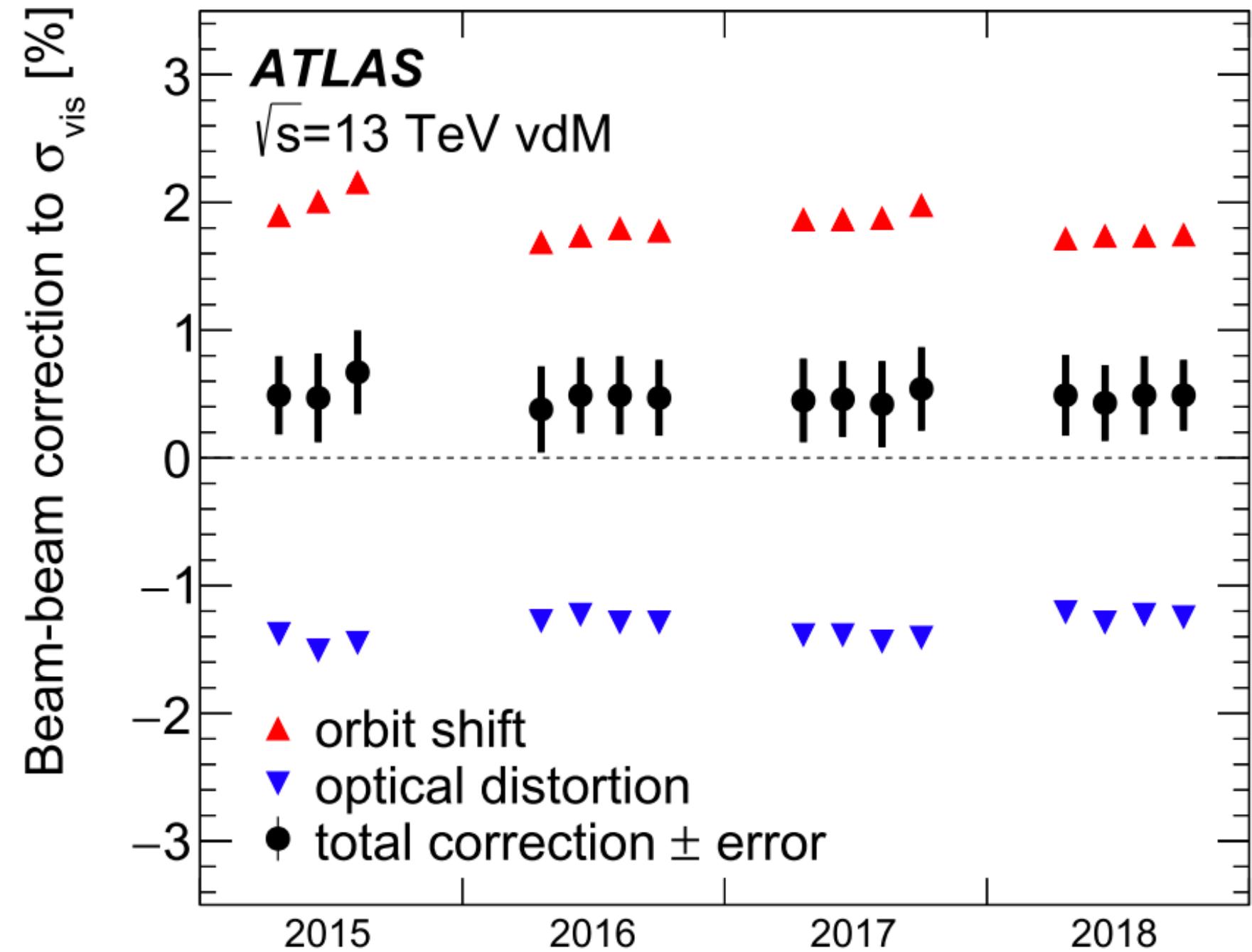
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- Optical distortion
  - Each B1 bunch (de)focusses the companion B2 bunch (& vice-versa)
  - Modifies the **beam shapes** by a different amount at each vdM-scan step



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  $\Delta$**  by a different amount at each vdM-scan step
- Optical distortion **- 1.5 to -1%**
  - Each B1 bunch (de)focusses the companion B2 bunch (& vice-versa)
  - Modifies the **beam shapes** by a different amount at each vdM-scan step



Total correction to  $\sigma_{\text{vis}} +0.5 \text{ \%}$  with an uncertainty of 0.3%  
New treatment developed in LHC lumi WG (LLCMWG)  
[arxiv:2306.10394](https://arxiv.org/abs/2306.10394) (A. Babaev et al.)

# ATLAS Luminosity measurement strategy in Run 2

## 2. Calibration transfer

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### vdM regime

low average pile up ( $\mu \sim 0.6$ )

isolated bunches



small number of bunches

no crossing angle

### Physics regime

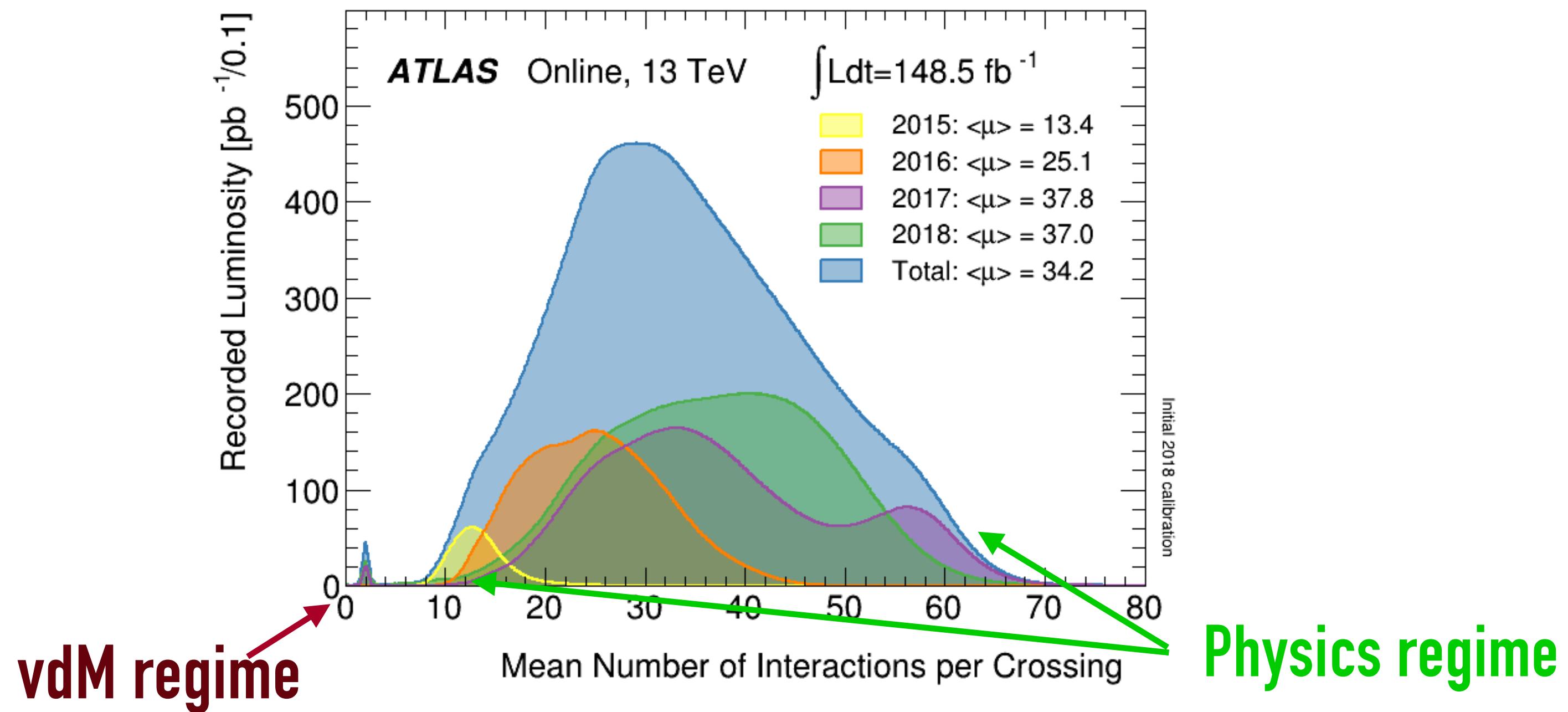
high pile up ( $20 < \mu < 60$ )

bunch trains



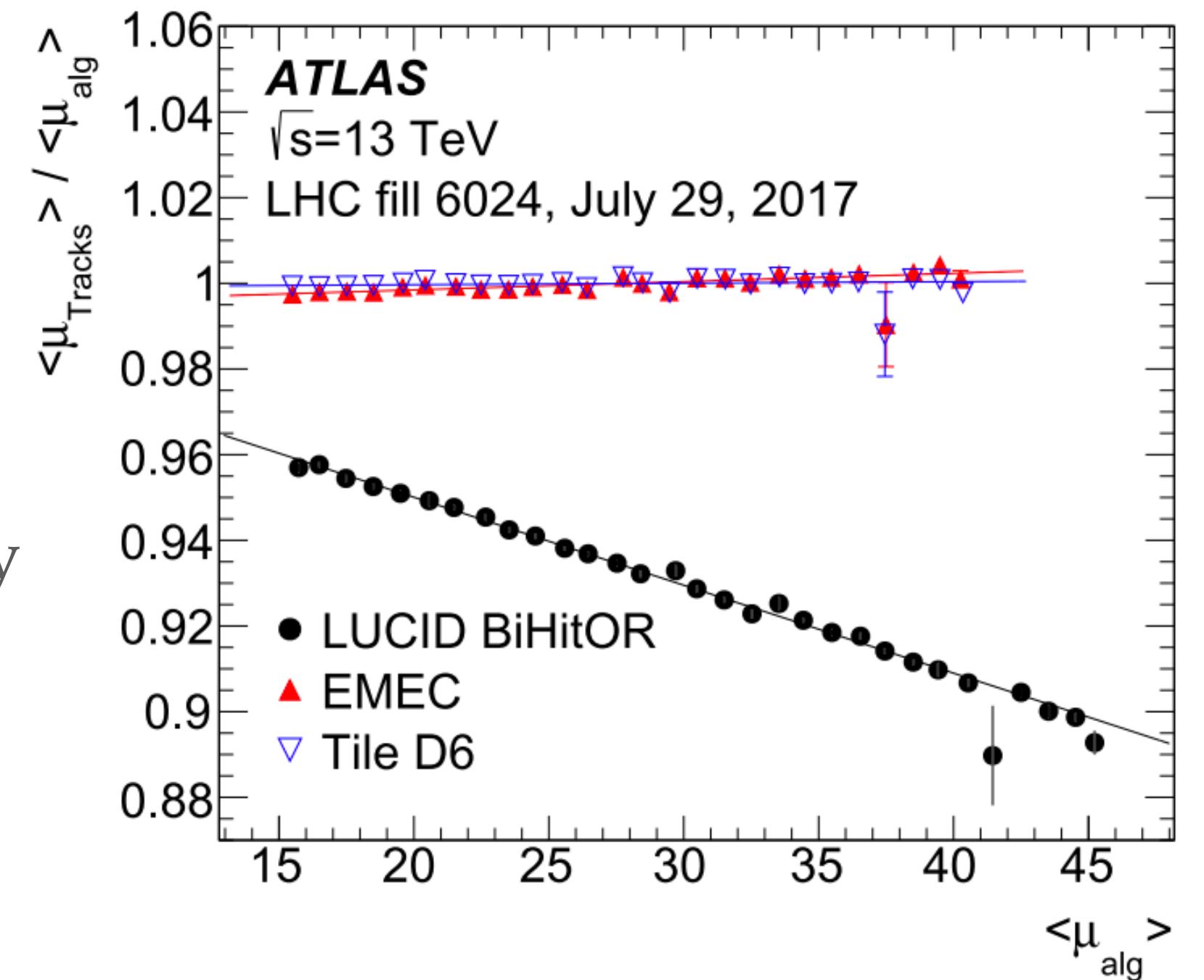
high number of bunches

with crossing angle



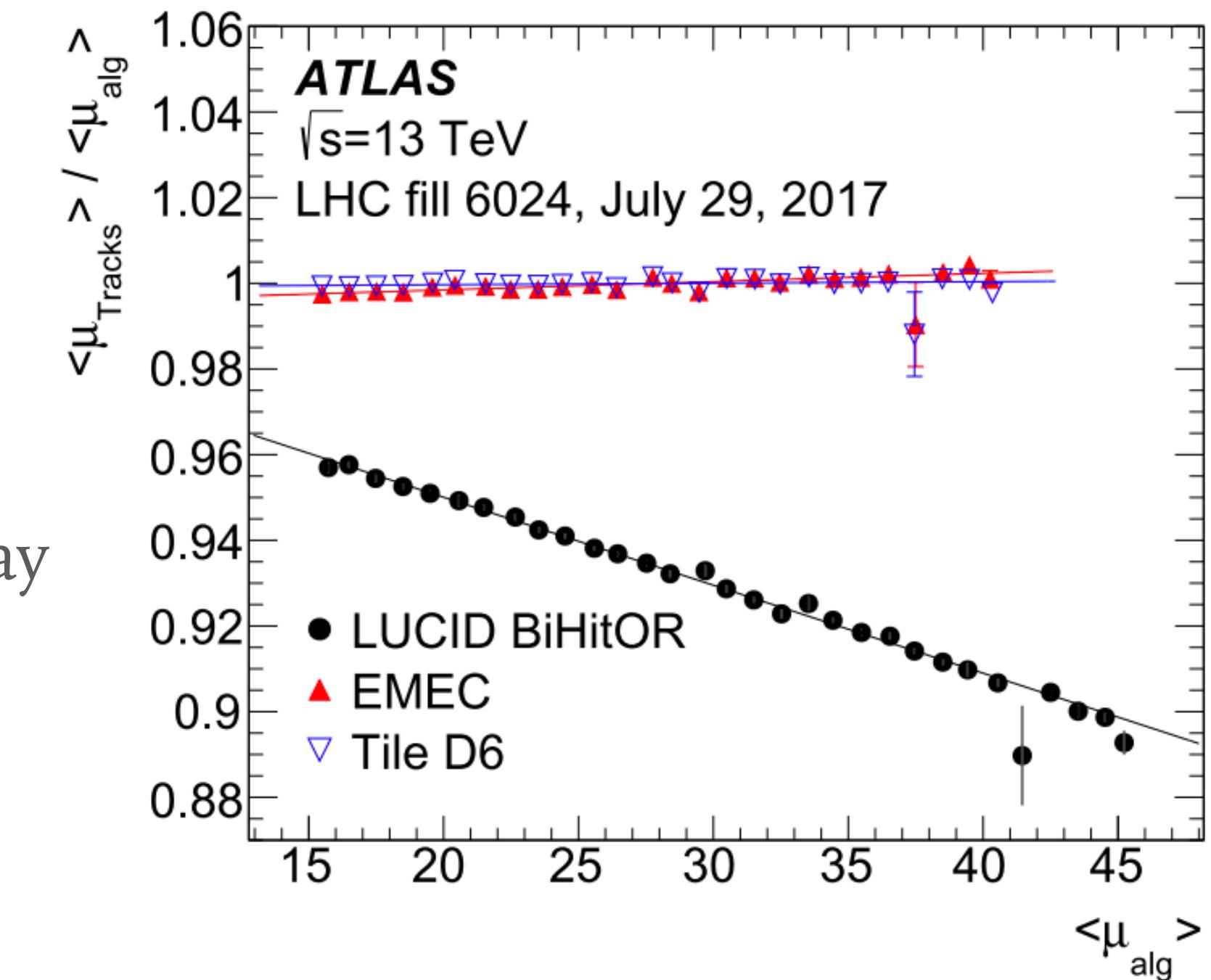
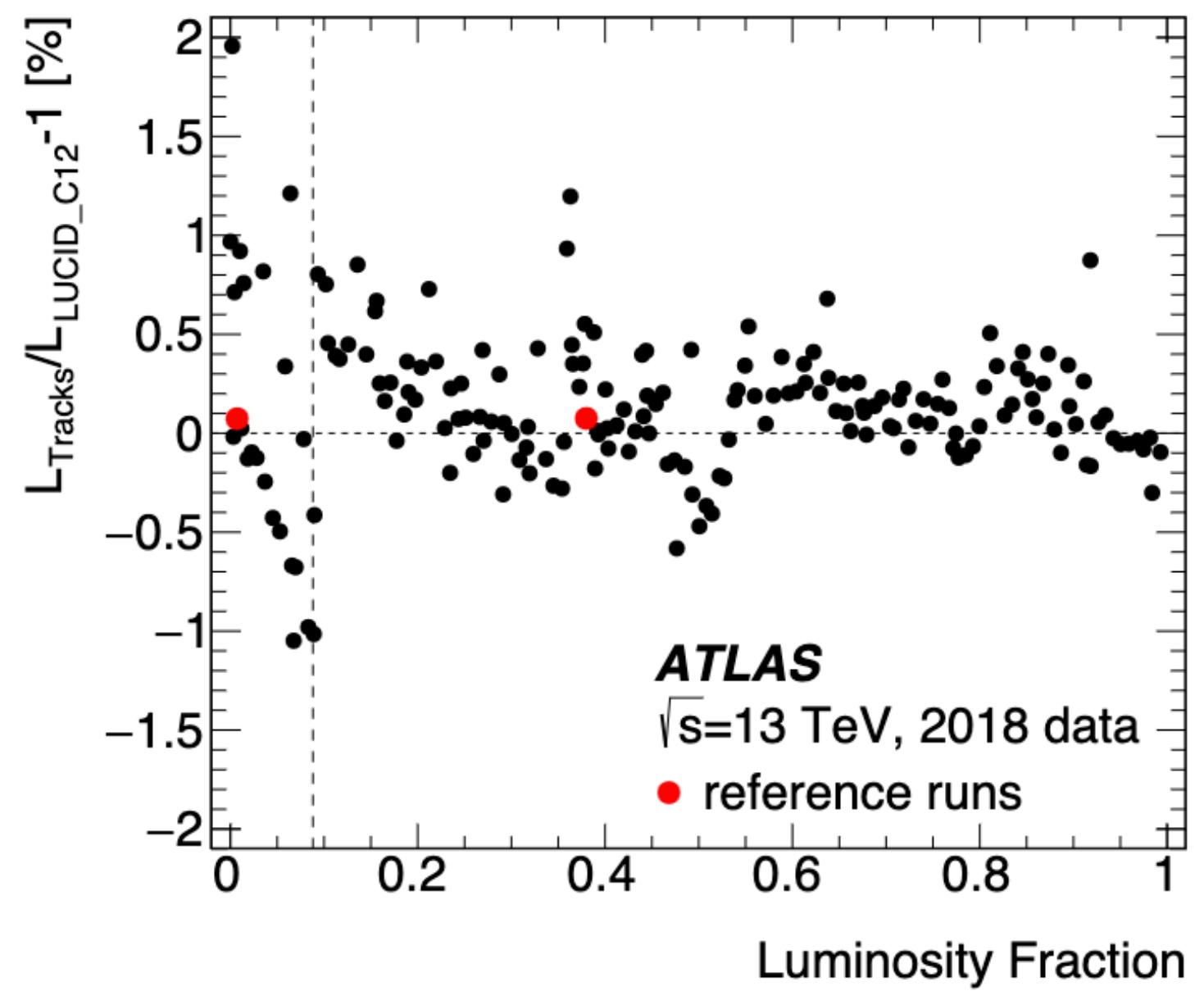
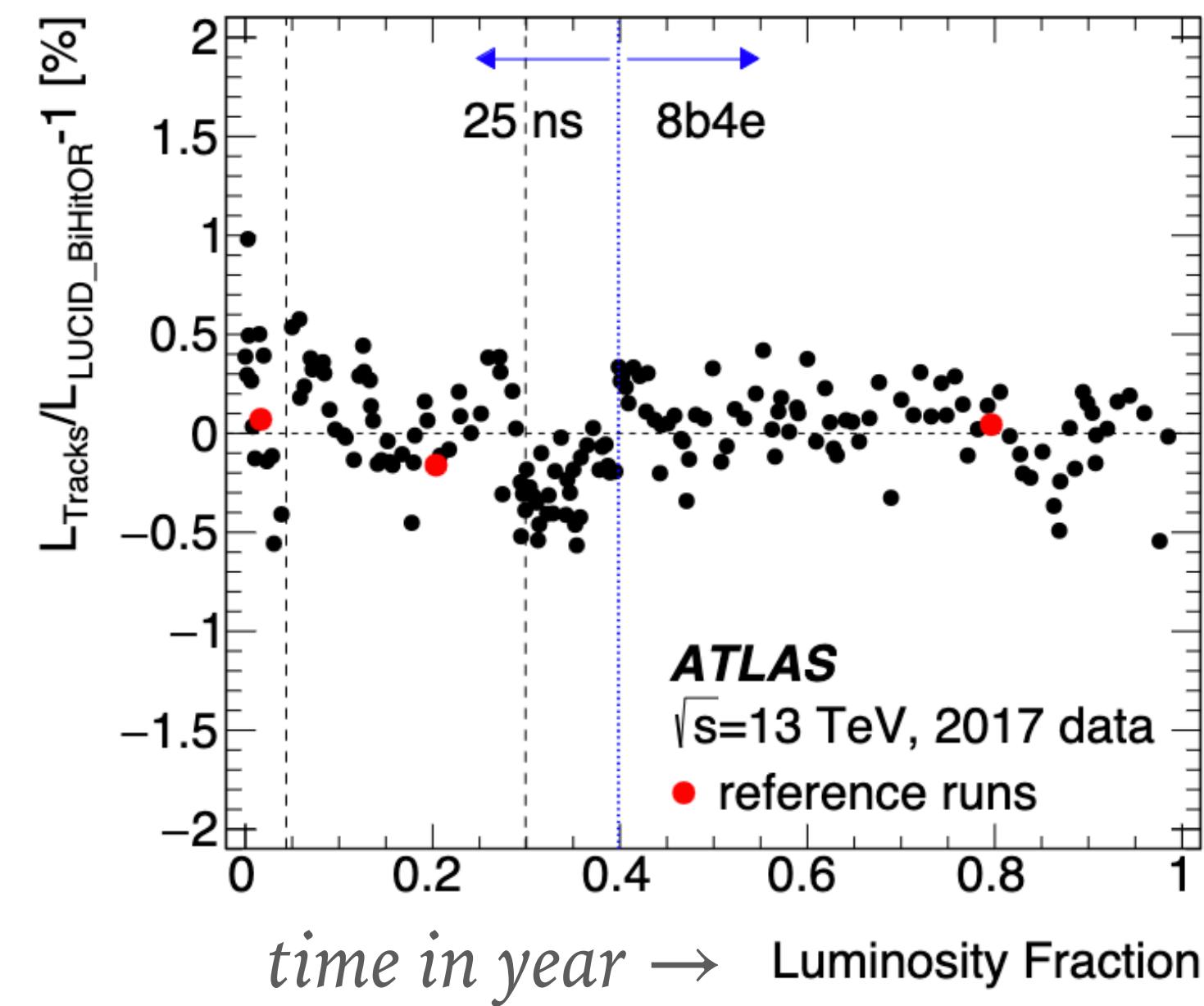
# 2. Calibration transfer

- LUCID needs correction derived from track counting 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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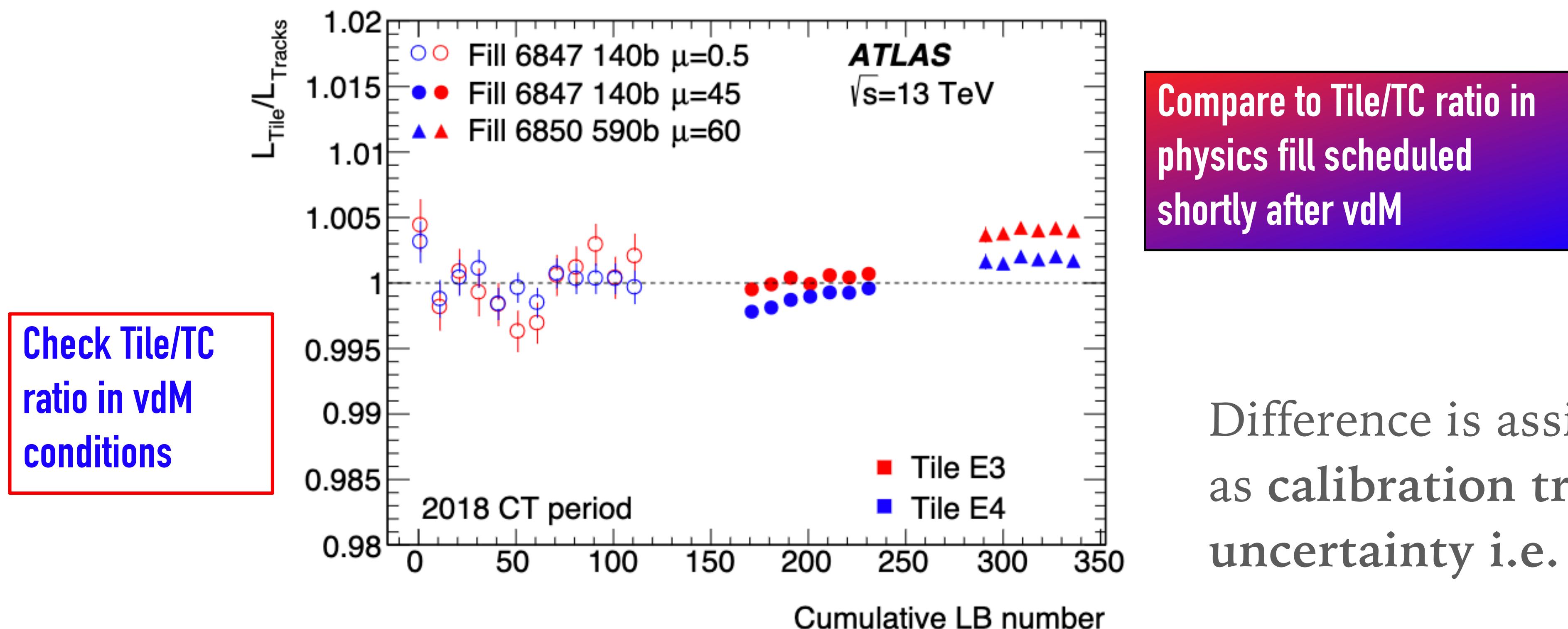


- Data is divided into periods with similar conditions
- Startup, bulk, 8b4e running in 2017

*Result: Corrected LUCID luminosity  $L_{\text{corr}}$  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



Difference is assigned  
as calibration transfer  
uncertainty i.e. 0.5 %

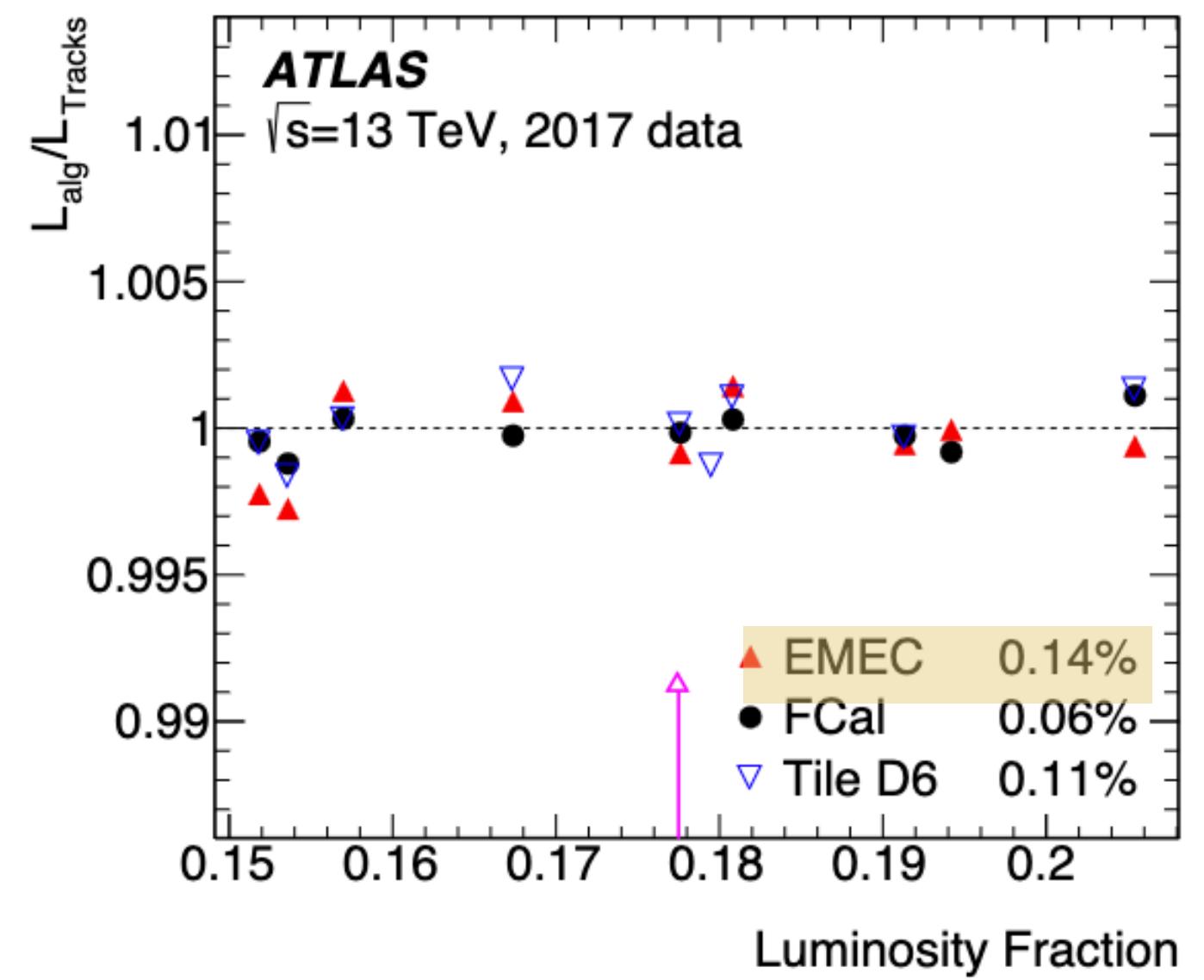
# ATLAS Luminosity measurement strategy in Run 2

## 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  $L_{corr}$  with calorimeter measurements

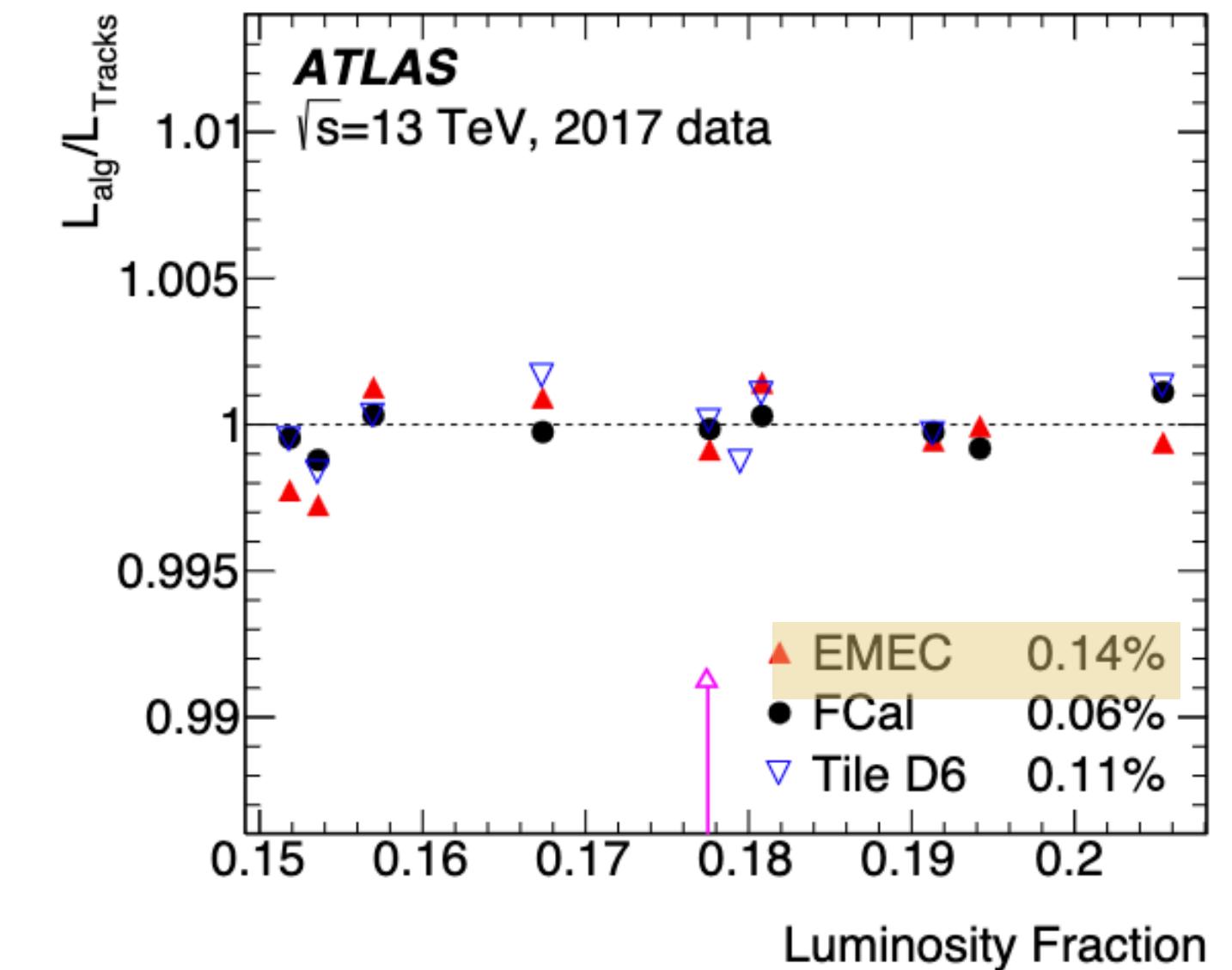
# 3. Long term stability

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

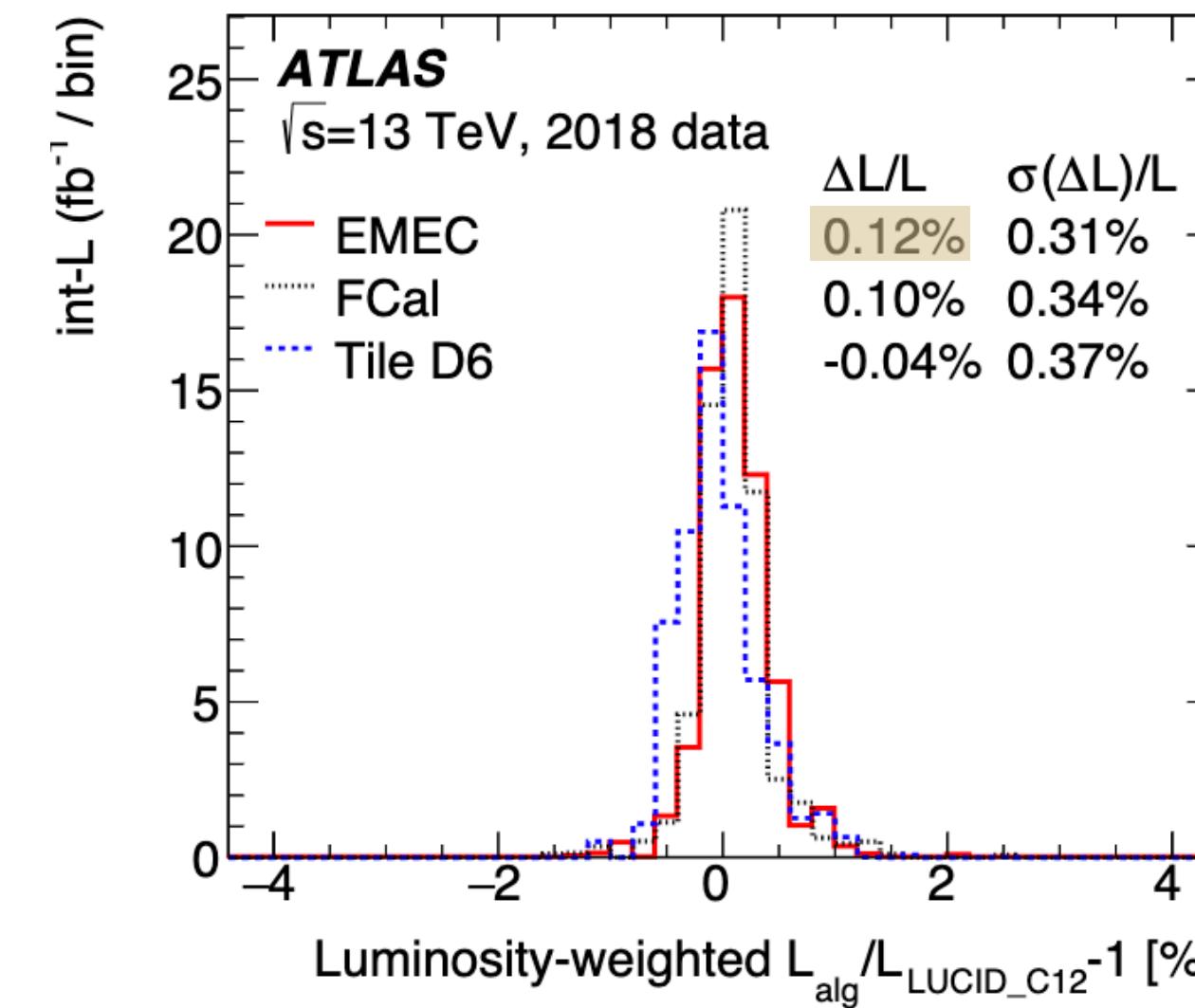
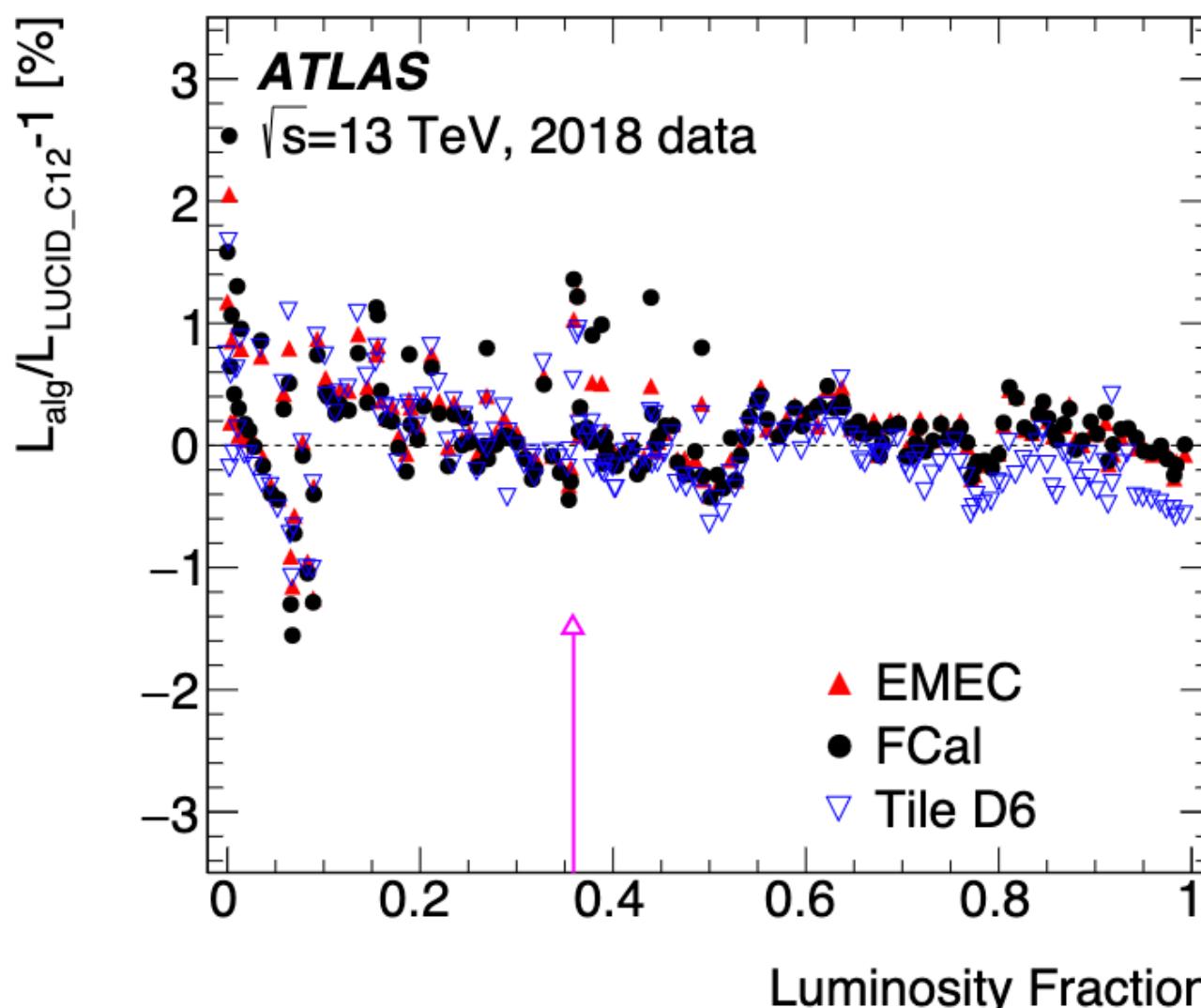


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Take largest mean from EMEC, FCal, Tile to define long-term stability uncertainty



- 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

# Summary

per year

## 1. vdM calibration

0.7-0.99%

## 2. Calibration transfer

0.5%

## 3. Long-term stability

0.2% - 0.3 %

- Luminosity measurement for full Run 2 ATLAS pp dataset finalized

**$140.1 \pm 1.2 \text{ fb}^{-1}$  corresponds to 0.83% uncertainty**

- Highest precision achieved at the LHC

\*correlated

Data sample	2015	2016	2017	2018	Comb.
Integrated luminosity [ $\text{fb}^{-1}$ ]	3.24	33.40	44.63	58.79	140.07
Total uncertainty [ $\text{fb}^{-1}$ ]	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 $\sigma_{\text{vis}}$ 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

# Summary

per year

## 1. vdM calibration

0.7-0.99%

## 2. Calibration transfer

0.5%

## 3. Long-term stability

0.2% - 0.3 %

- Luminosity measurement for full Run 2 ATLAS pp dataset finalized

**$140.1 \pm 1.2 \text{ fb}^{-1}$  corresponds to 0.83% uncertainty**

- 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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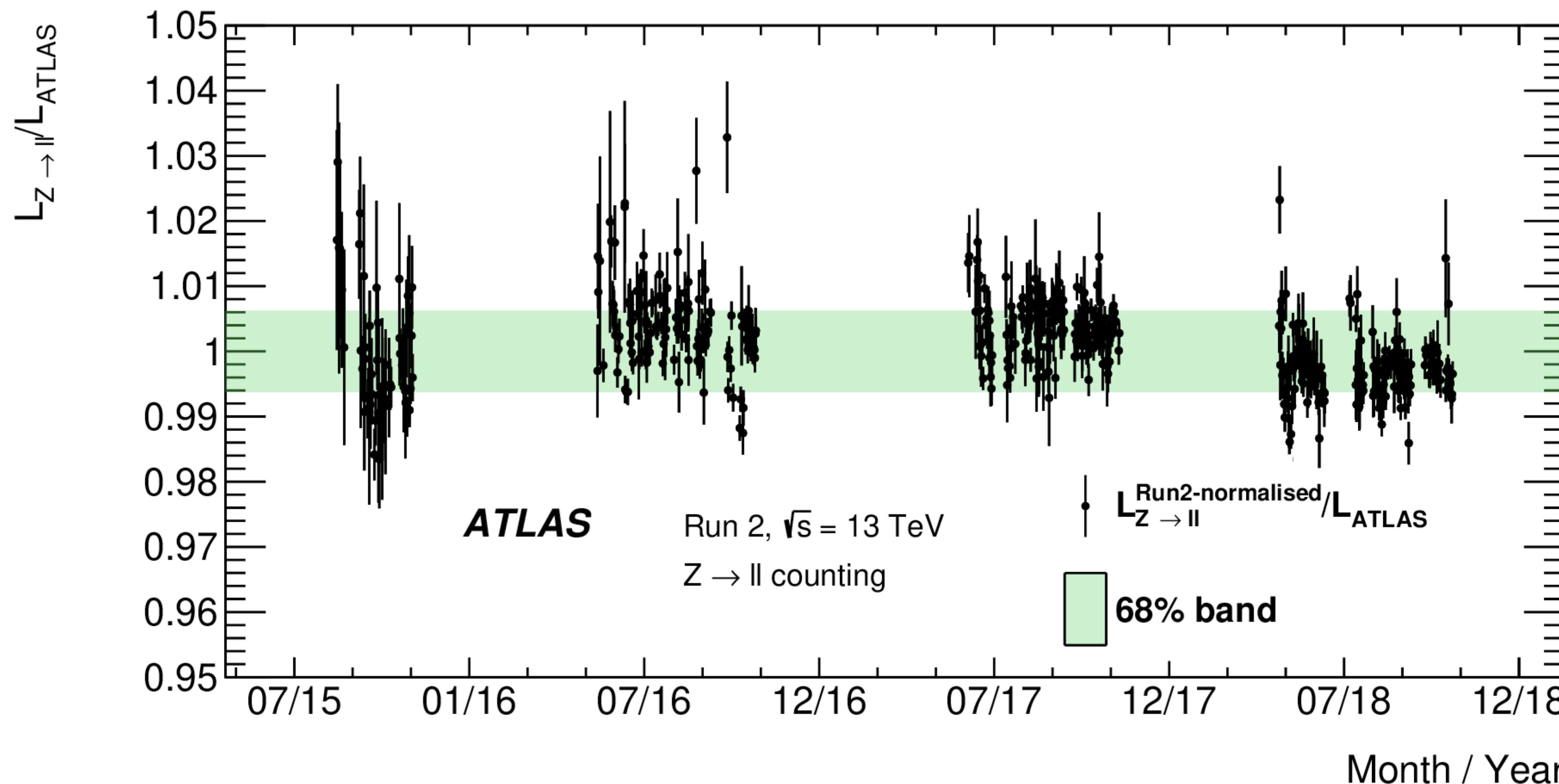
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# BACKUP

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# Z-counting

- $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  counting can be used to relative luminosity measurements and comparisons between CMS and ATLAS
- To check inter-year calibration compare  $L_Z/L_{ATLAS}$



# Comparison between Preliminary and Final Run 2 result



Preliminary

$139 \pm 2.3 \text{ fb}^{-1}$  (1.7%)

Data sample	2015+16	2017	2018	Comb.
Integrated luminosity ( $\text{fb}^{-1}$ )	36.2	44.3	58.5	139.0
Total uncertainty ( $\text{fb}^{-1}$ )	0.8	1.0	1.2	2.4
Uncertainty contributions (%):				
DCCT calibration <sup>†</sup>	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 <sup>†</sup>	0.0	0.0	0.0	0.0
Scan curve fit model <sup>†</sup>	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 <sup>†</sup>	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 $\sigma_{\text{vis}}$ 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 <sup>†</sup>	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

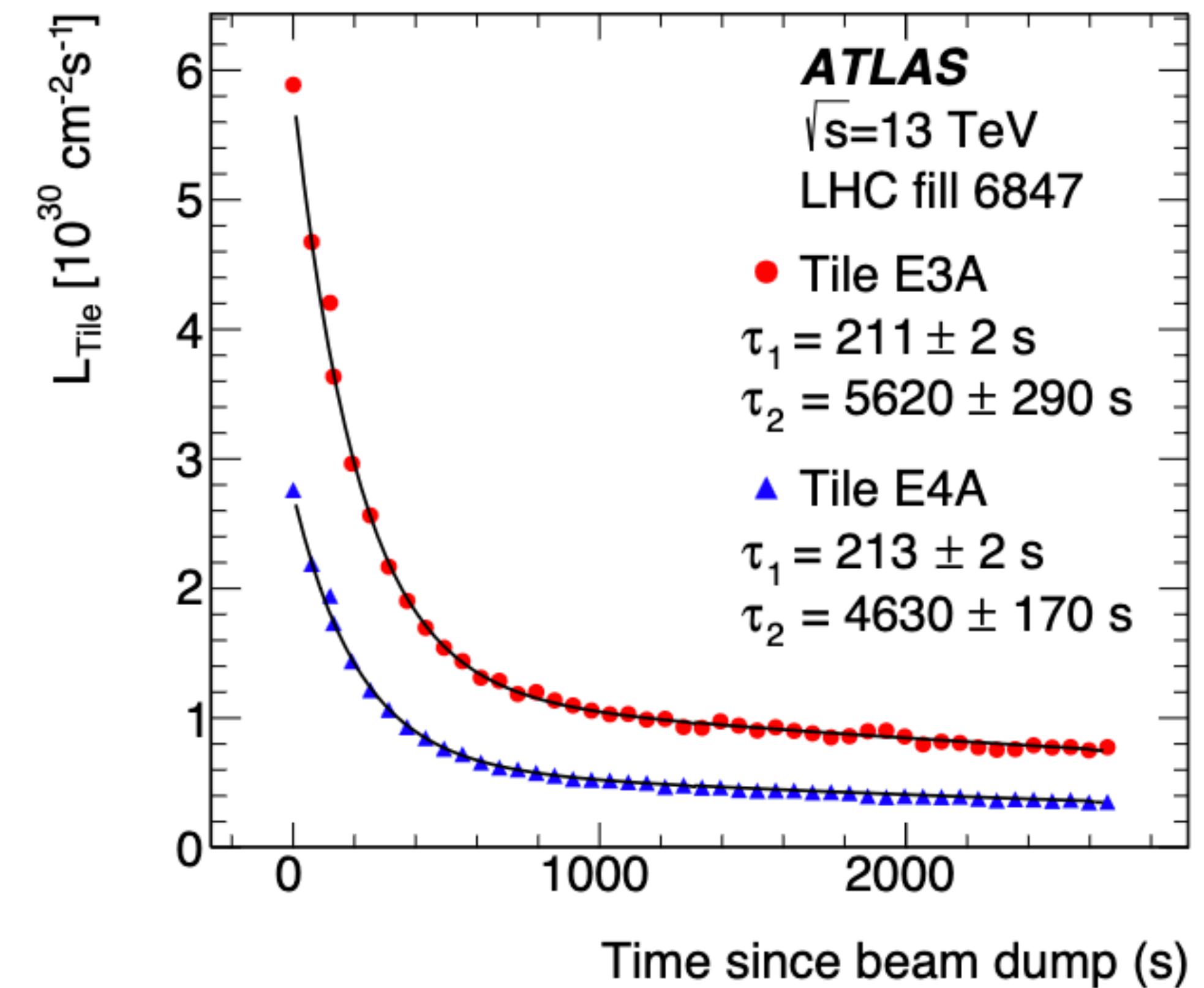
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Subtotal vdM calibration	0.96	0.70	0.99	0.93	0.65
Calibration transfer*	0.50	0.50	0.50	0.50	0.50
Calibration anchoring	0.22	0.18	0.14	0.26	0.13
Long-term stability	0.23	0.12	0.16	0.12	0.08
Total uncertainty [%]	1.13	0.89	1.13	1.10	0.83

# Calibration transfer uncertainty - activation correction

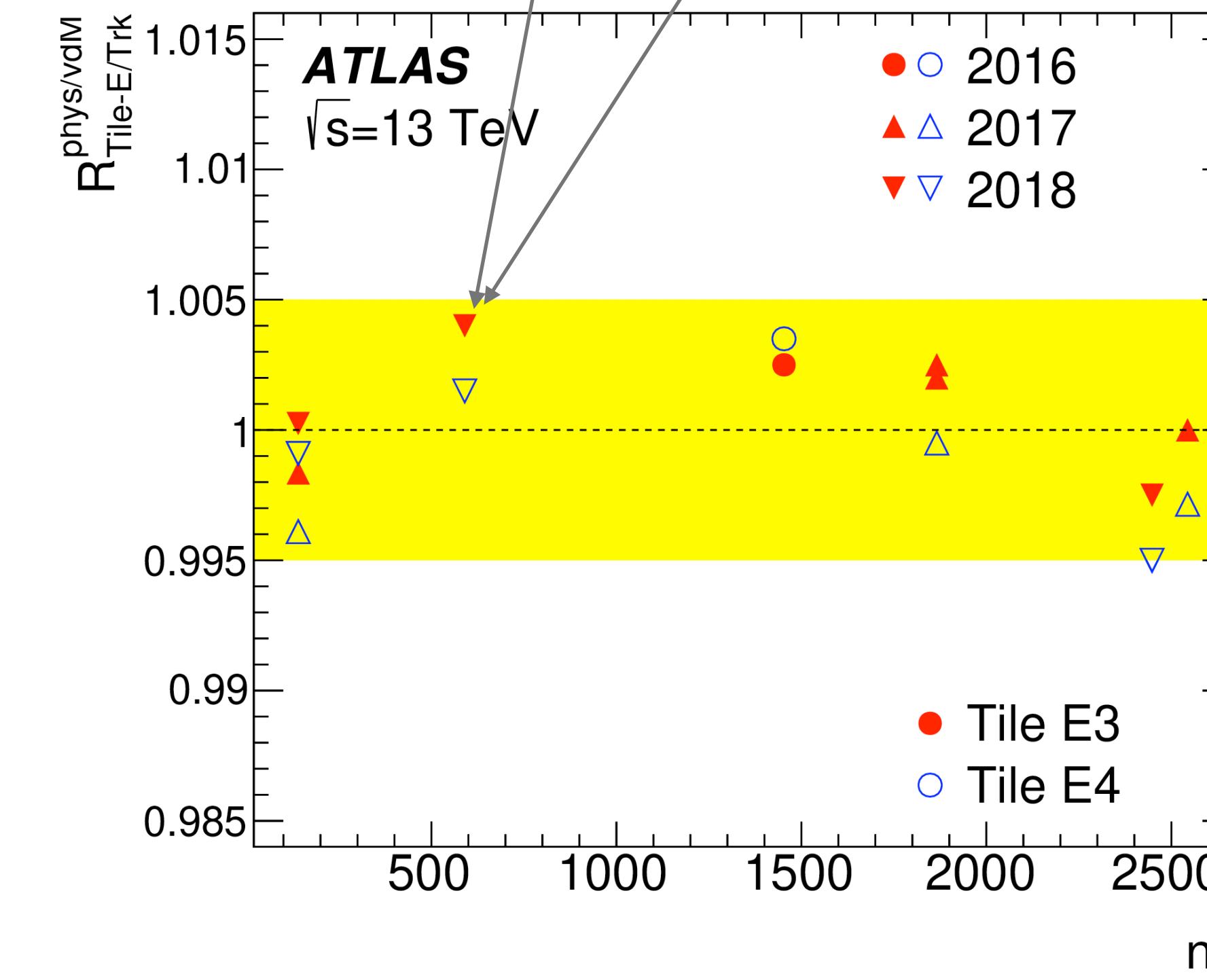
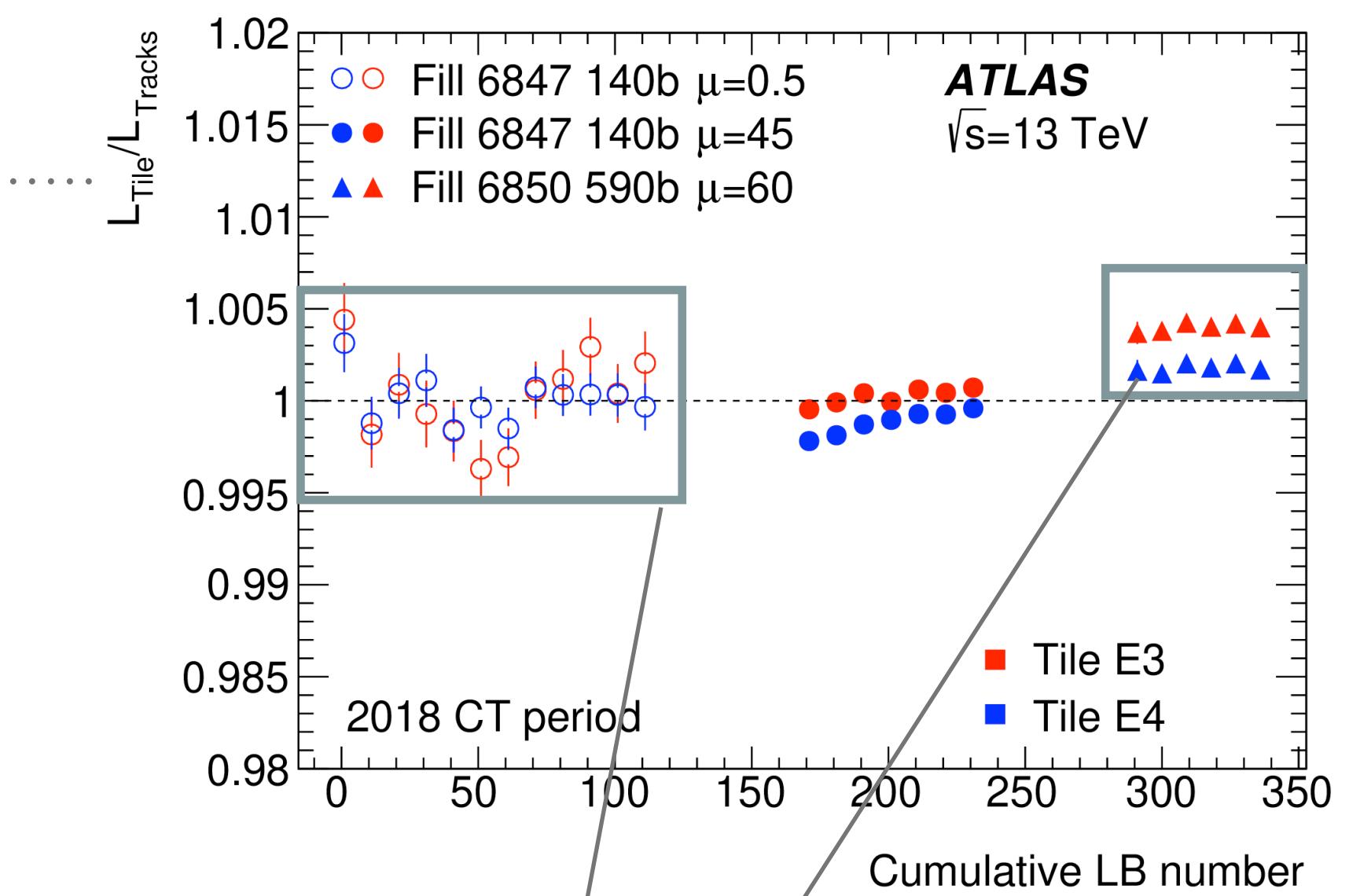
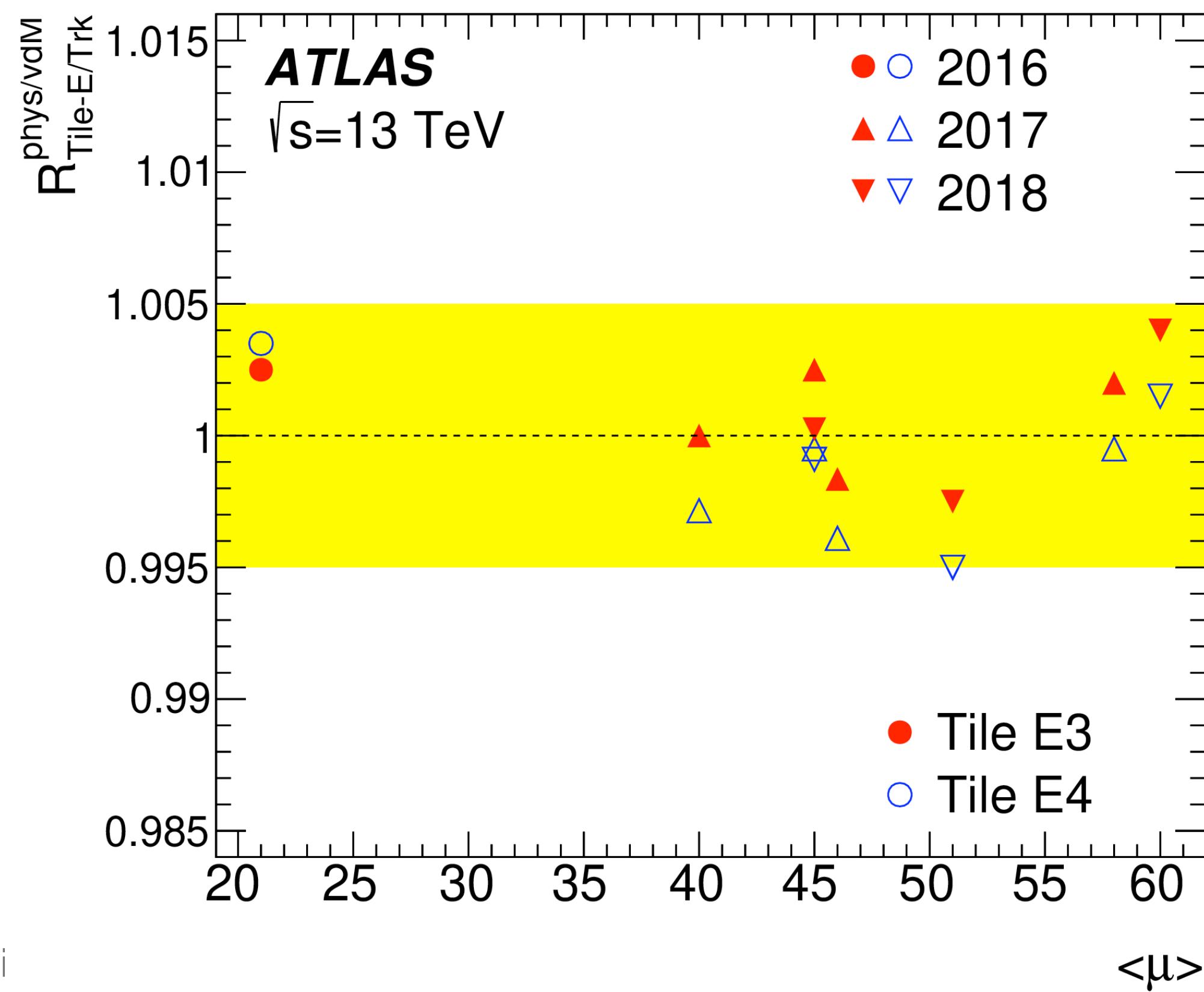
- LUCID correction assumes that track counting is perfectly linear from vdM to physics regime
  - Check this assumption with alternative Tile data measurement
    - Tile data needs **complicated treatment and corrections**

- Residual activation from any high-lumi running just before vdM fill can swamp Tile signal with  $\mathcal{O}(10\%)$ 
  - ⇒ Needs delicate pedestal subtraction
- PMT response non-linear with luminosity at the 0.5-1.0 % level at high  $\langle \mu \rangle$ 
  - ⇒ Calibrated out ‘in situ’ with laser pulses into the PMTs during LHC abort gap



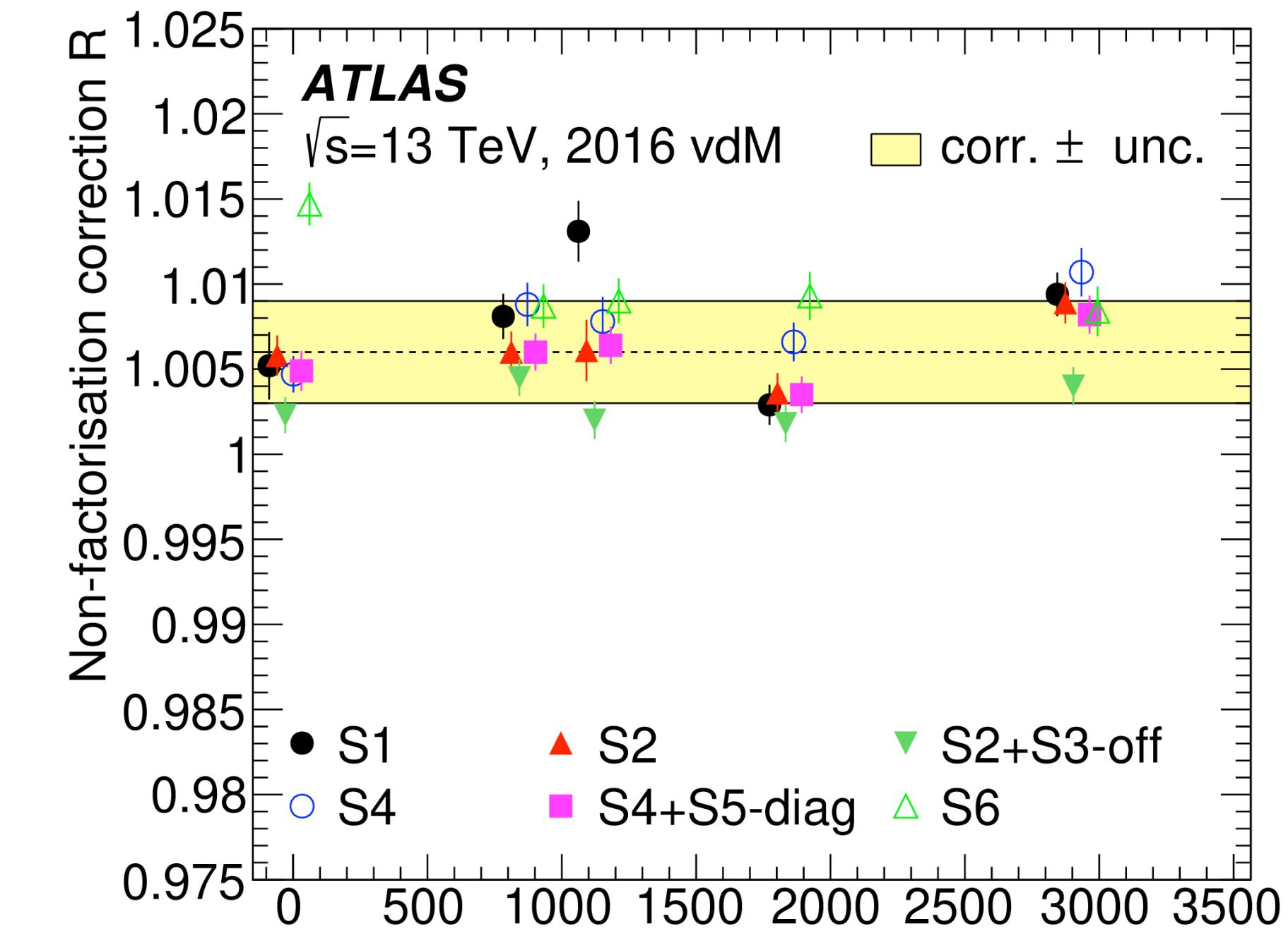
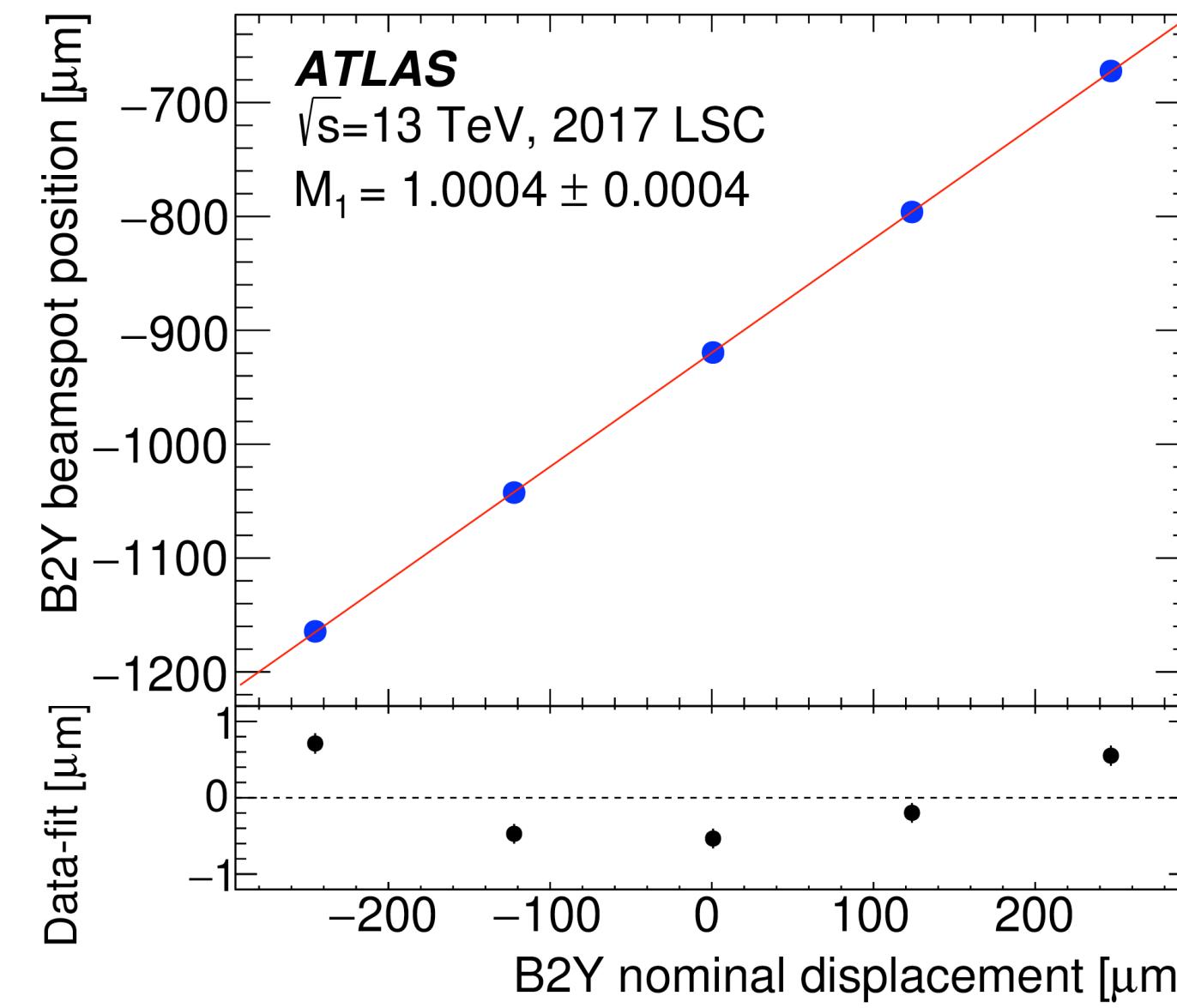
# Calibration transfer uncertainty

- Check double ratio of  $R_{\text{Tile}-e/\text{TC}}$  in physics vs vdm conditions as a function of  $\langle \mu \rangle$  and the number of bunches
- Yellow band covers scatters  $\rightarrow 0.5\%$  uncertainty



# Length scale calibration and non-factorization

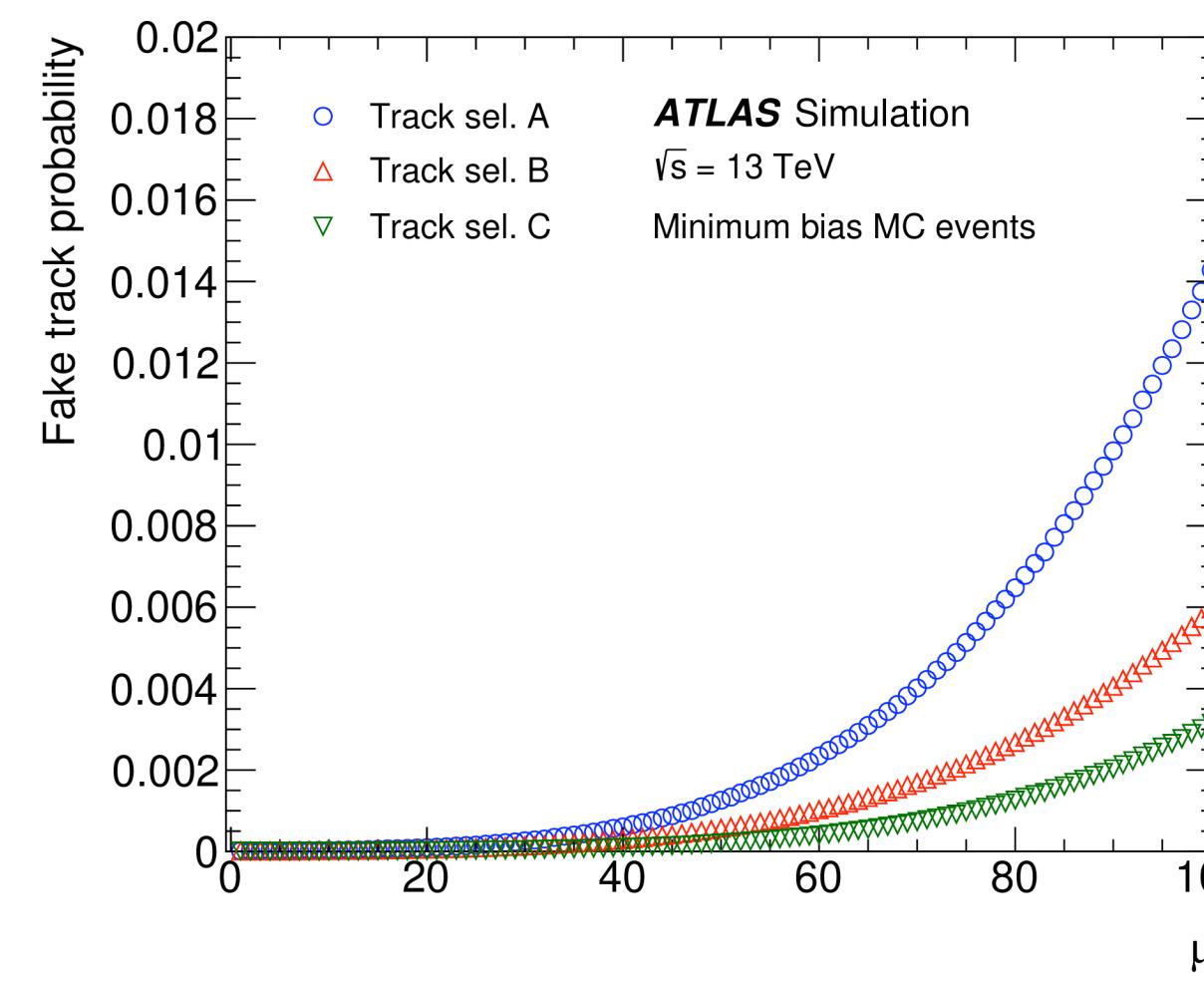
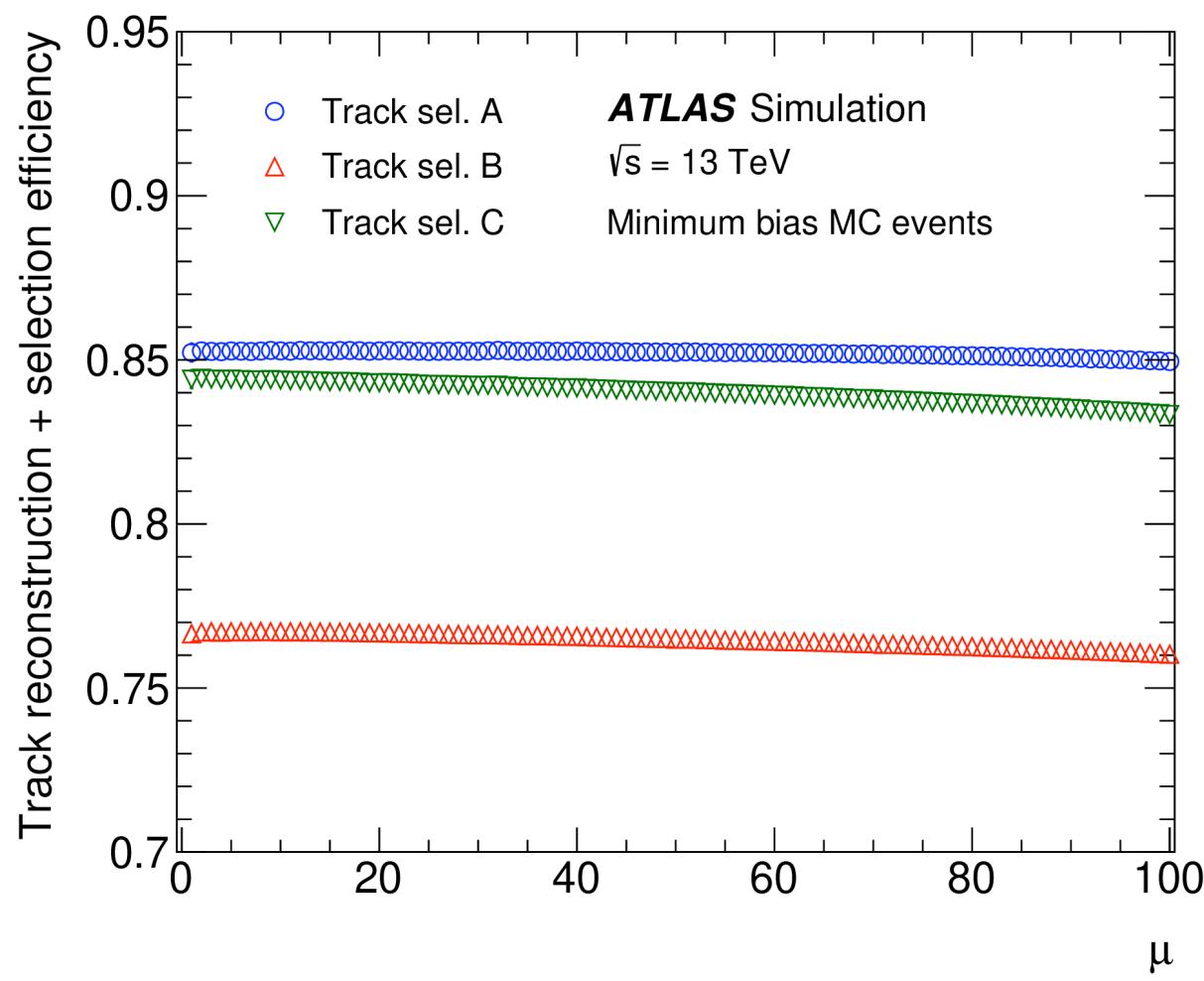
- Length scale: relation between requested and real beam displacement
  - Calibrated in dedicated 5-point scans in x and y
  - True beam displacement measured from beamspot positions reconstructed from tracks in ATLAS ID
- Non-factorization: vdM formalism assumes that beam profiles in x and y factorize
  - Deviation from factorization characterized using primary vertex distribution at each scan step
  - Check size, shape, and orientation of luminous region



# 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
$N_{\text{hits}}^{\text{Si}}$	$\geq 9$ if $ \eta  < 1.65$ else $\geq 11$	$\geq 9$ if $ \eta  < 1.65$ else $\geq 11$	$\geq 10$
$N_{\text{holes}}^{\text{Pix}}$	$\leq 1$	$= 0$	$\leq 1$
$ d_0 /\sigma_{d_0}$	< 7	< 7	< 7



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

