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

DESY FH Discussion, October 23rd, 2023

Claudia Seitz

Luminosity definition

- 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

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

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

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    - LHC machine parameters

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

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

- μ_b = number of inelastic pp collisions per bunch
- 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

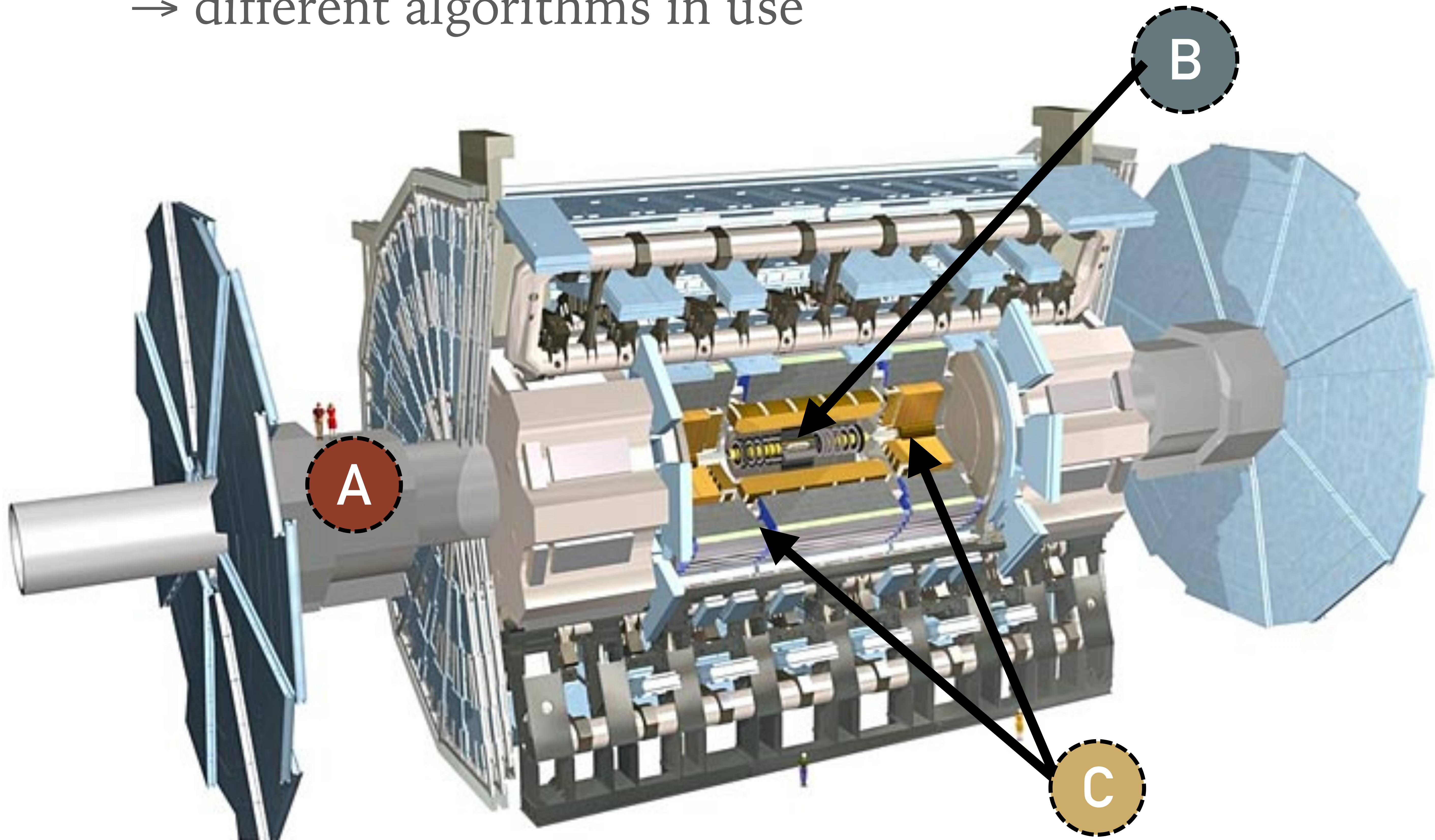
Luminosity detectors and algorithms

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 $\rightarrow$ different algorithms in use

B **Track counting (TC)**

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



C **Calorimeter measurements**

- LAr (EMEC and FCAL) $\rightarrow$ proportional to gap current
- Tile calorimeter $\rightarrow$ 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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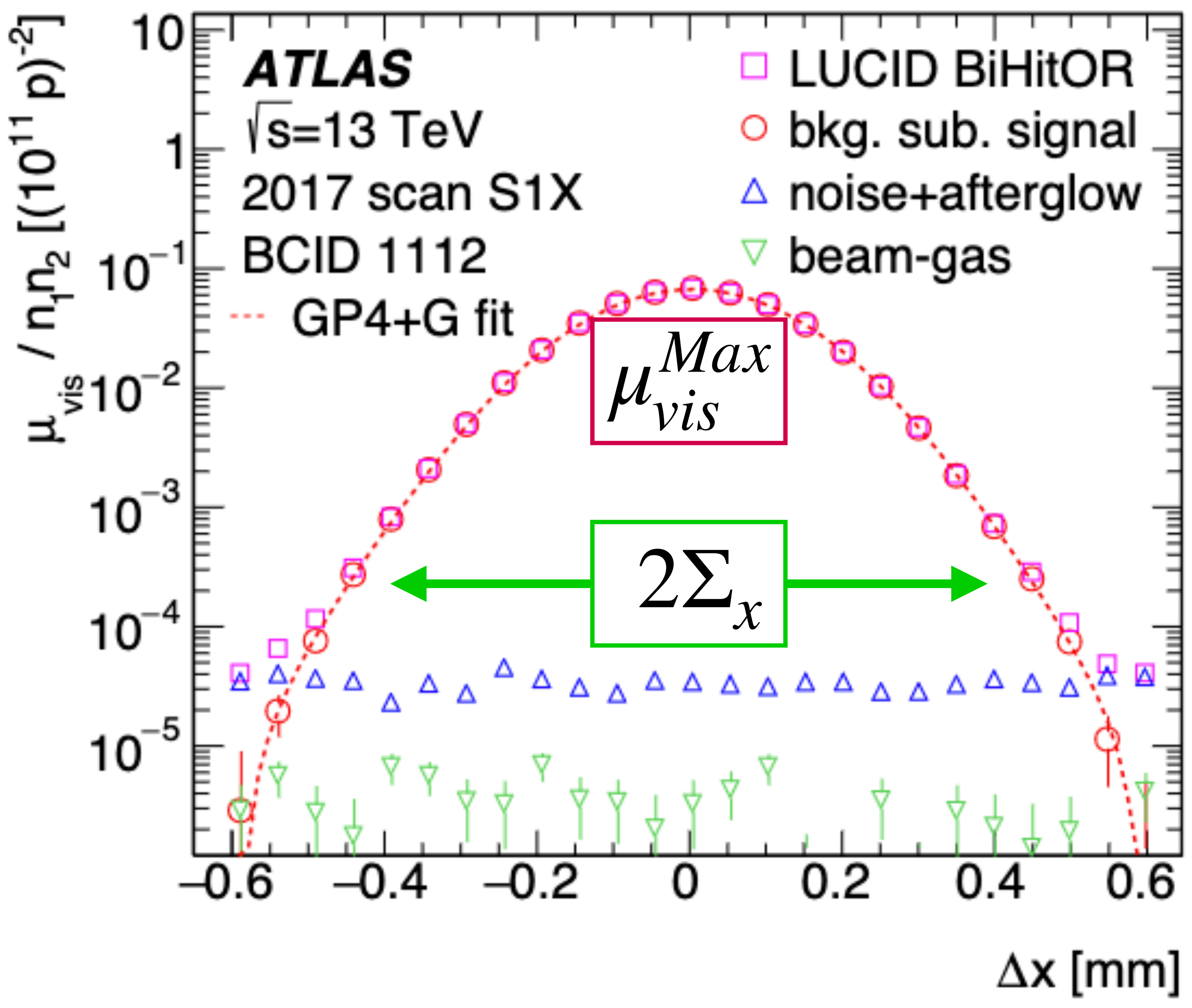
Will discuss today final precision Run 2 results: https://arxiv.org/abs/2212.09379

1. vdM calibration – van der Meer scans

- vdM analysis determines the visible cross section σ_{vis} for each bunch

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

- vdM fit extracts μ_{vis}^{Max} Σ_x Σ_y
- Beam current product ($n_1 n_2$) determined by LHC current measurement devices (±0.2%)



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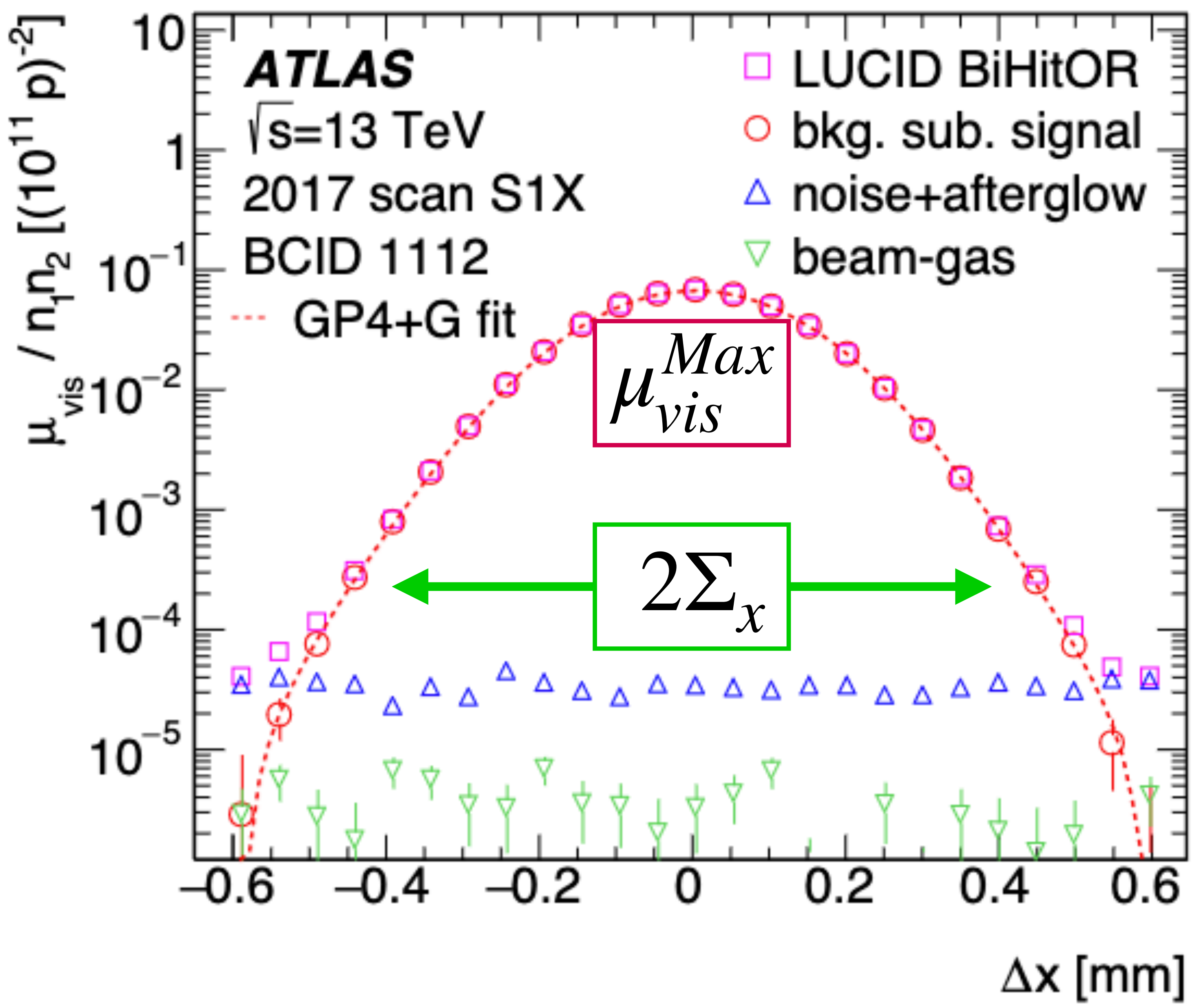

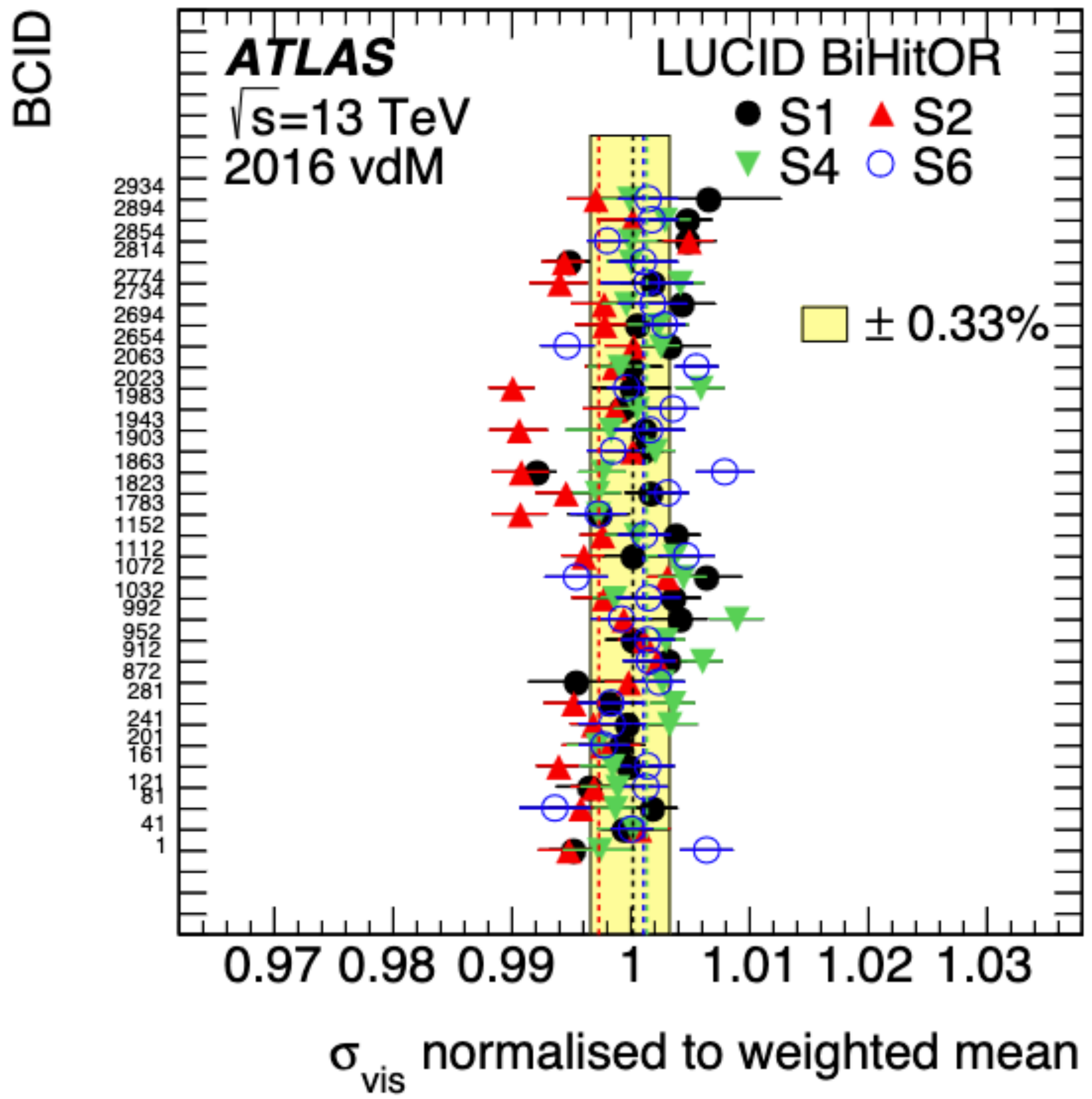

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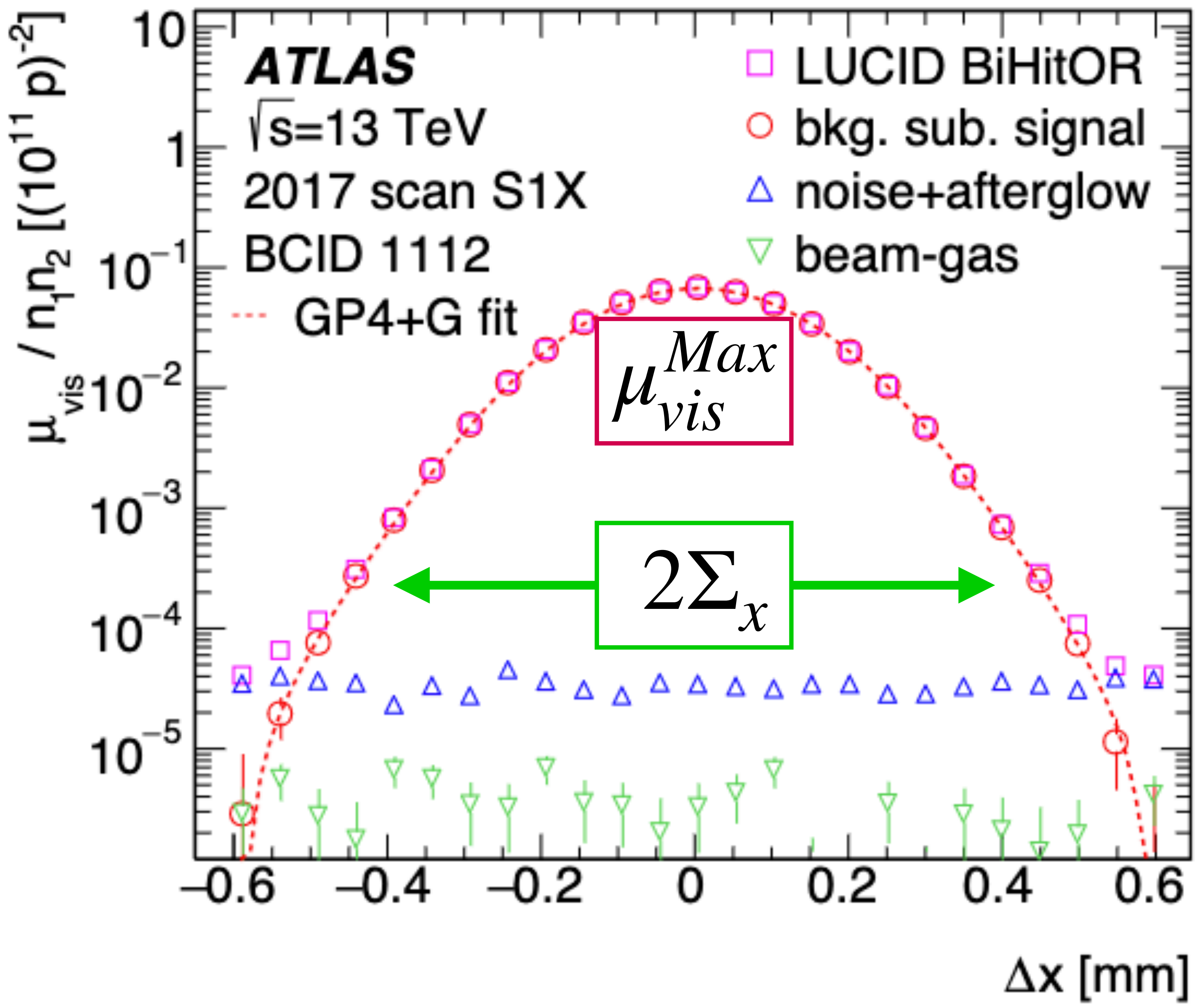
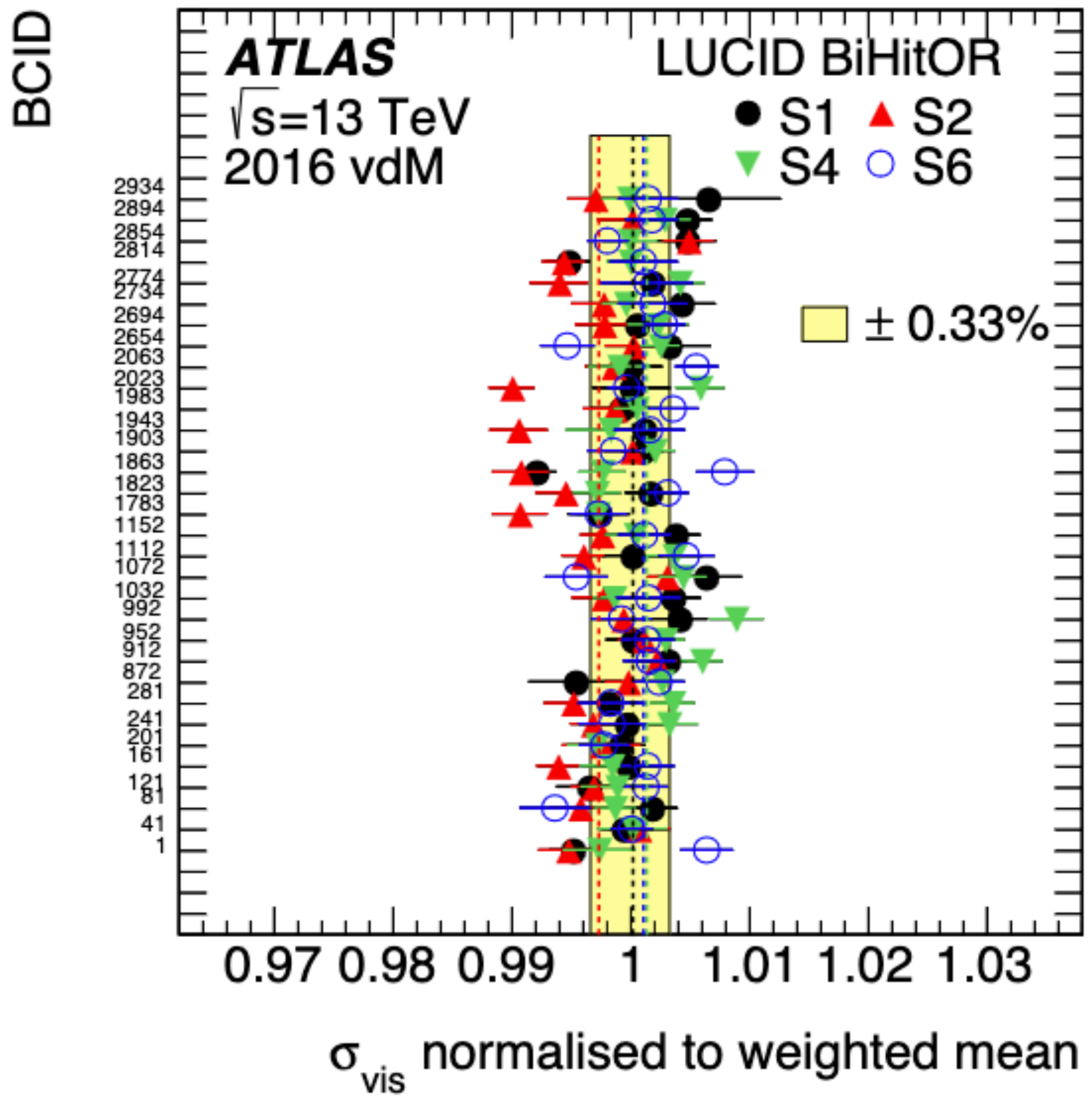
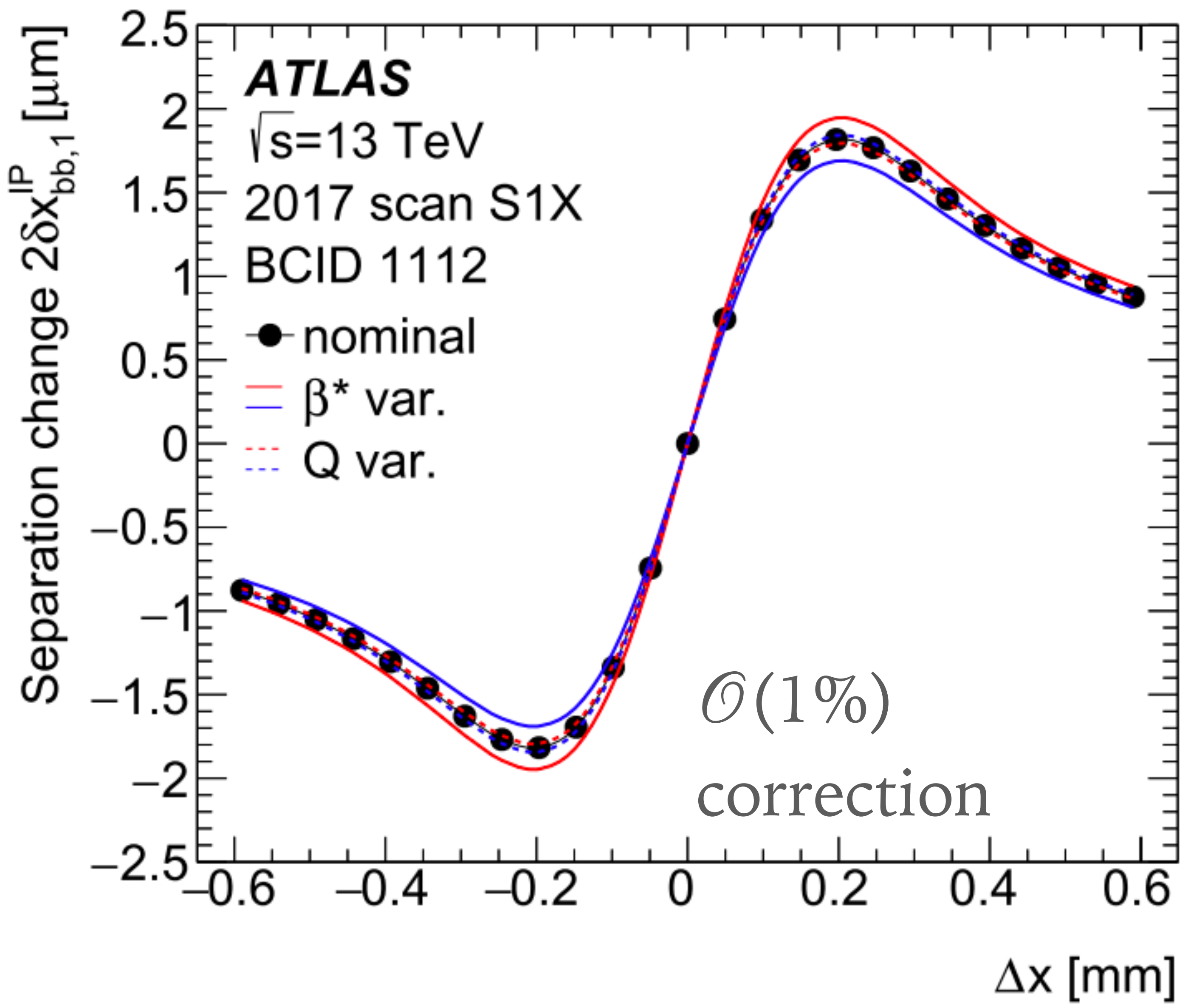




- Various corrections to consider
  - Orbit drifts – beams do not stay still during scans
  - Emittance growth and non-factorization – beam sizes change with time, transverse profiles in x and y do not factorize
  - Length scale and magnetic non-linearity (arXiv:2304.06559v1, A. Chmielińska et al.) – 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** Δ by a different amount at each vdM-scan step



$\mathcal{O}(1\%)$ correction

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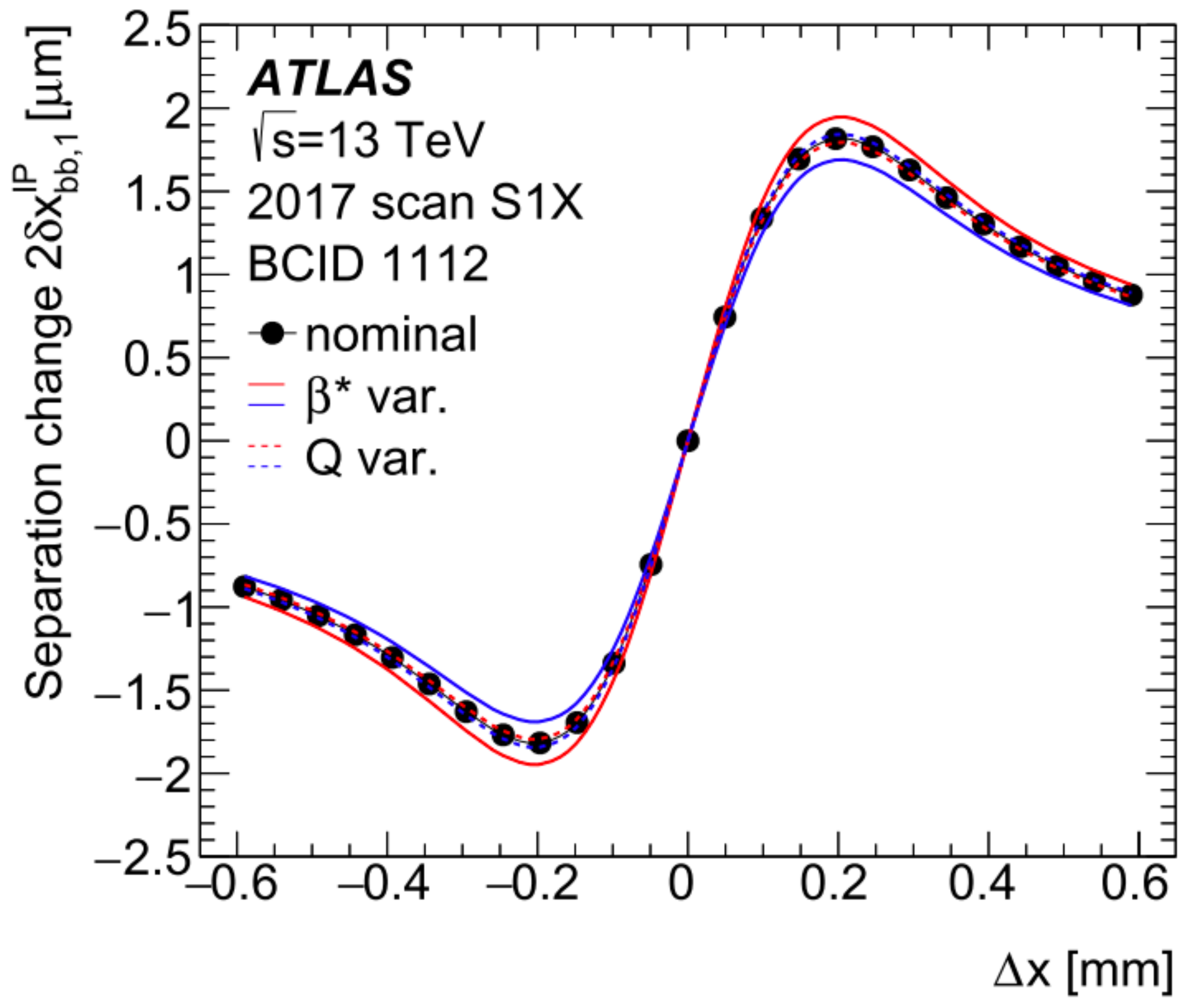
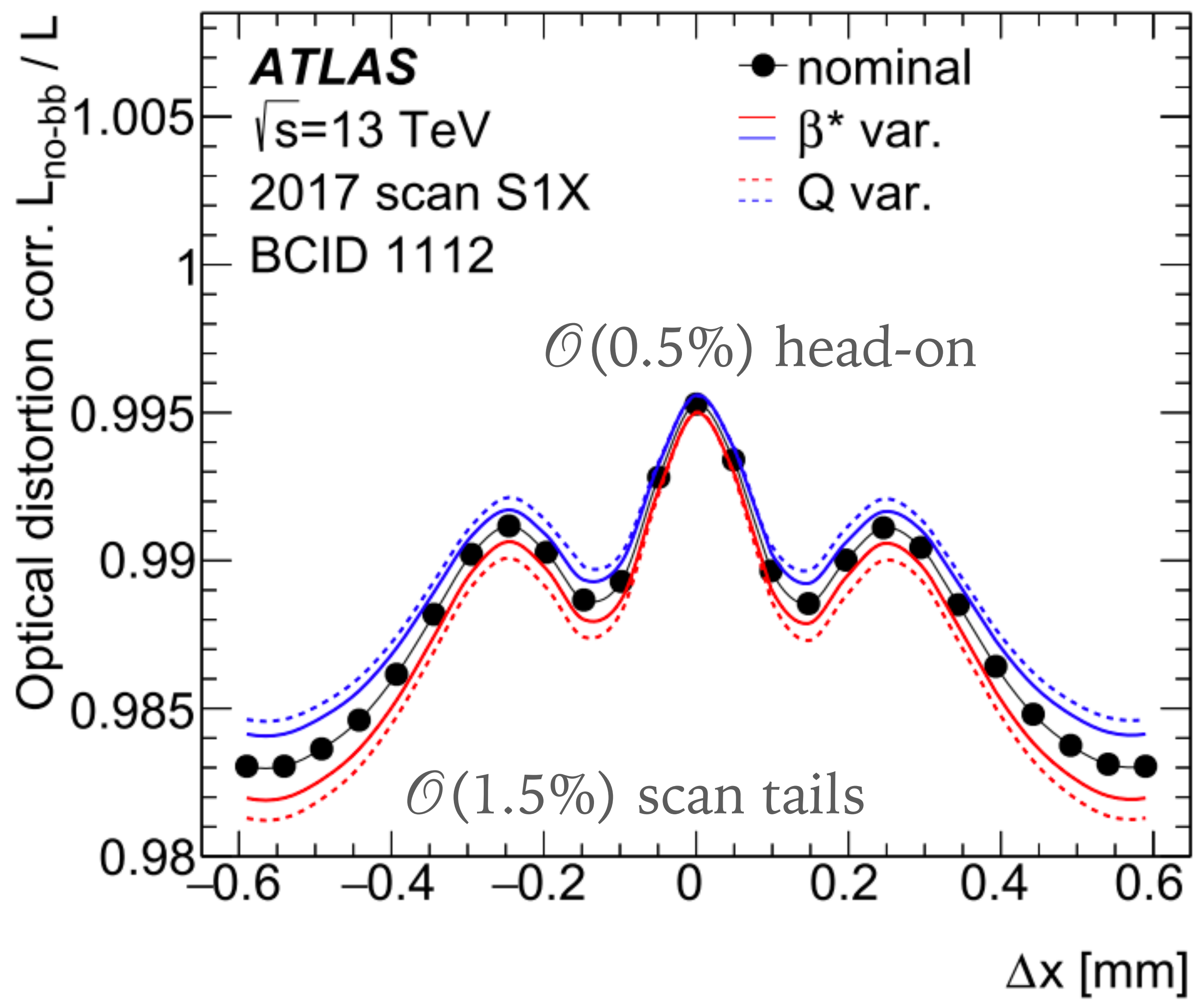
  - ➤ **Optical distortion**
    - ➤Each B1 bunch (de)focuses the companion B2 bunch (& vice-versa)
    - ➤Modifies the **beam shapes** by a different amount at each vdM-scan step

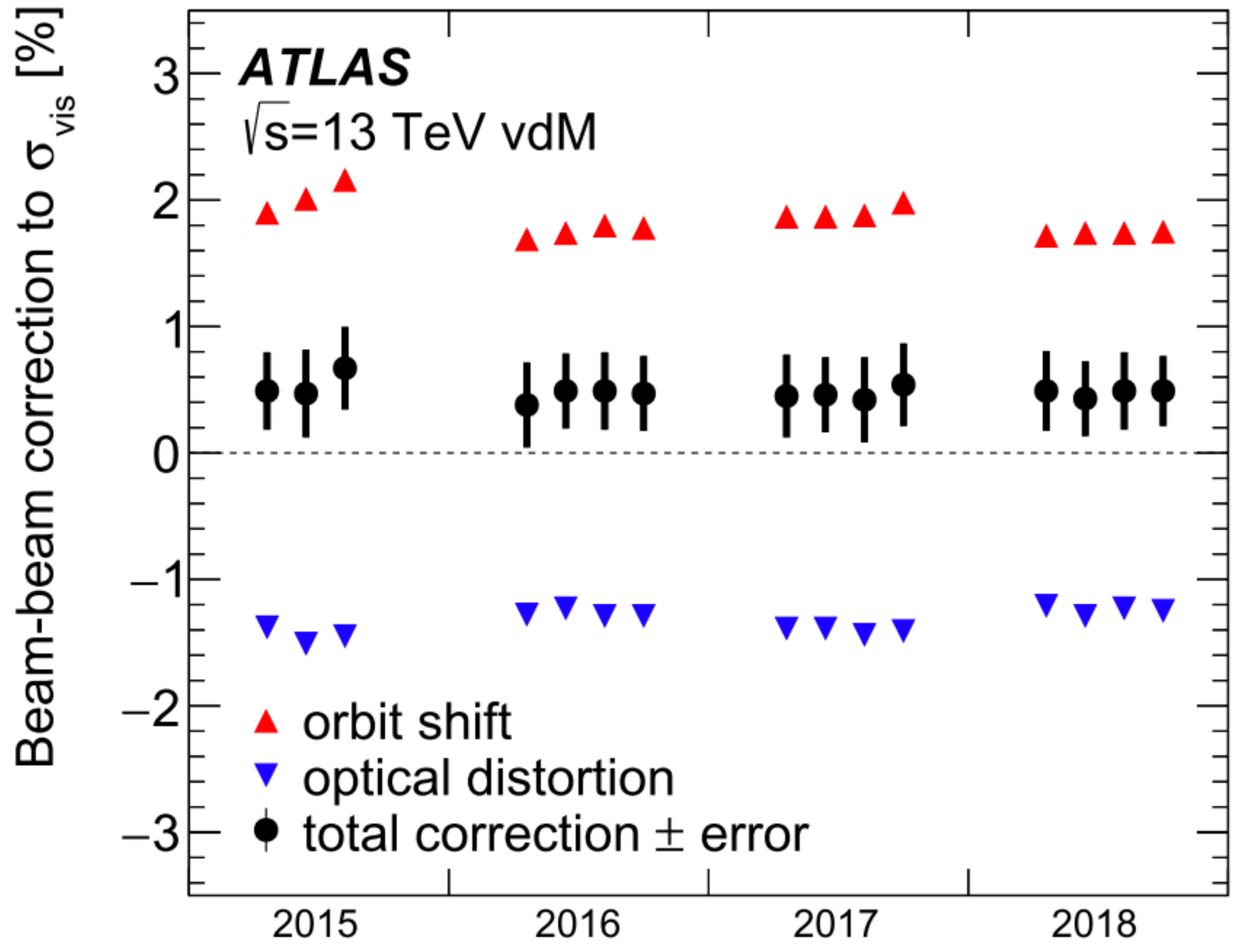




Beam-beam force is non-linear; proton in center of the bunch feels a different force to one at the edge

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%

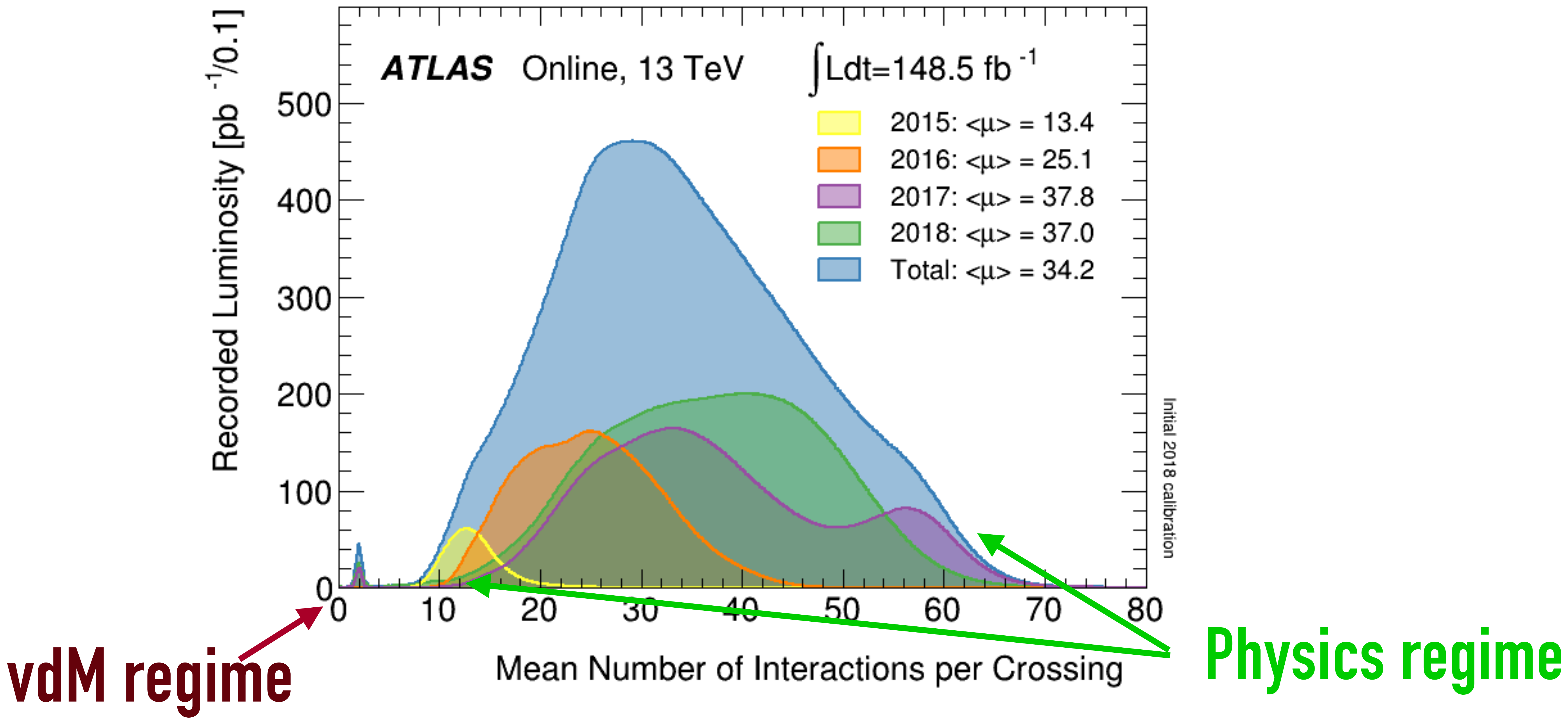
New treatment developed in LHC lumi WG (LLCMWG) **arxiv:2306.10394 (A. Babaev et al.)**

ATLAS Luminosity measurement strategy in Run 2

2. Calibration transfer

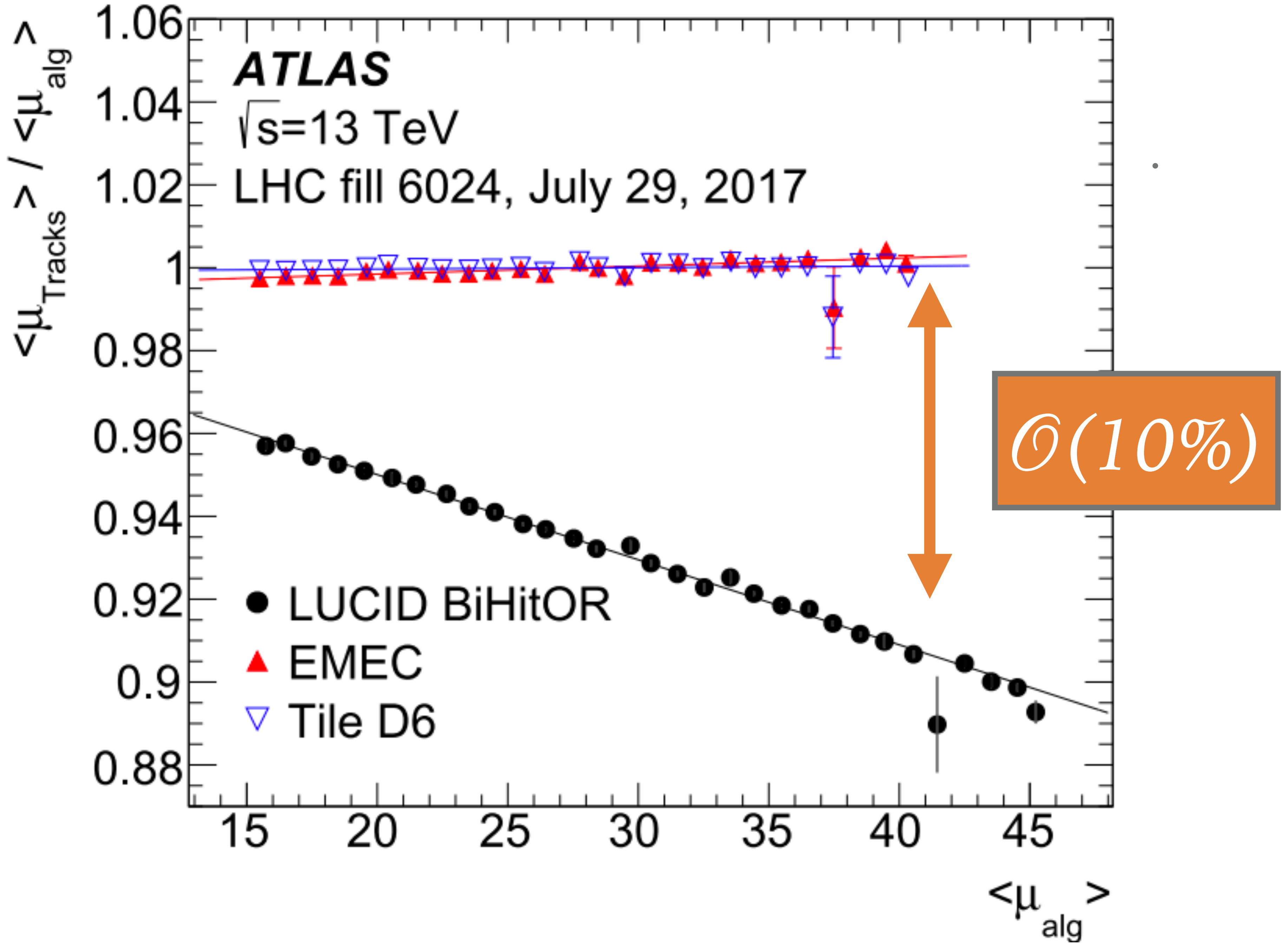
- Extrapolation of LUCID measurement from vdM regime to physics regime
- Track counting used to correct LUCID
- Cross-checked with Tile measurement for uncertainties

vdM regime	Physics regime
low average pile up ($\mu \sim 0.6$)	high pile up ($20 < \mu < 60$)
isolated bunches	bunch trains
small number of bunches	high number of bunches
no crossing angle	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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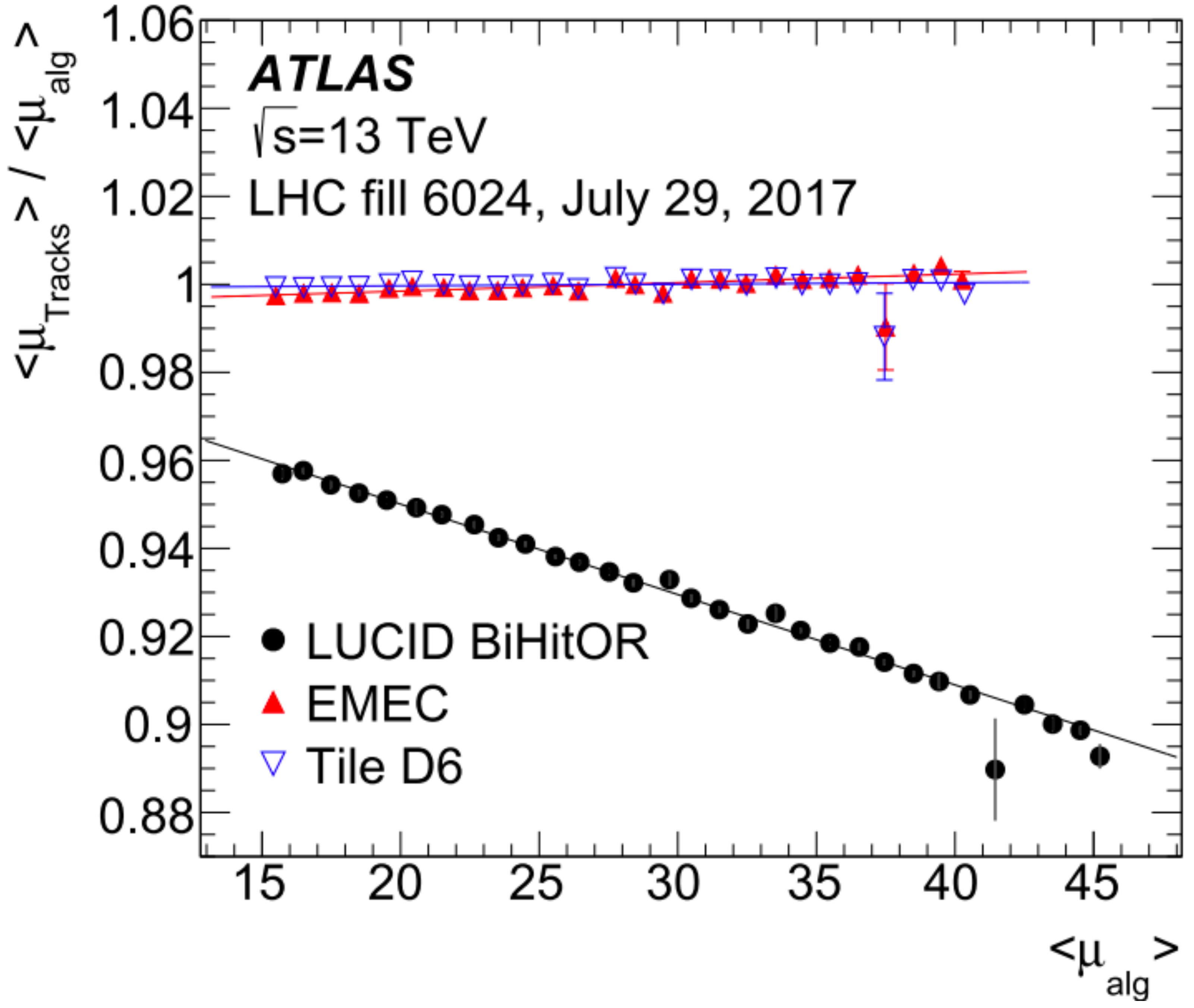
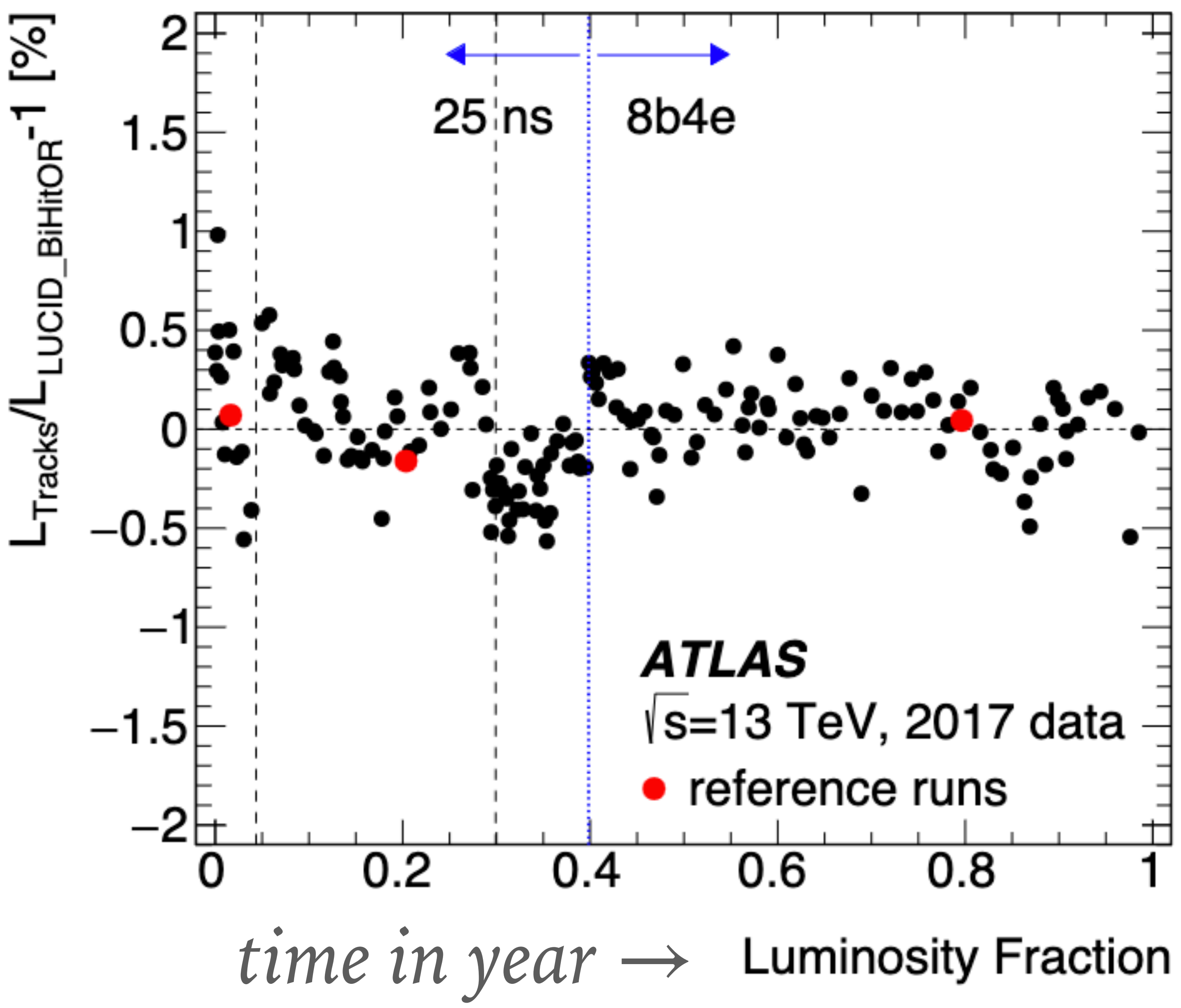
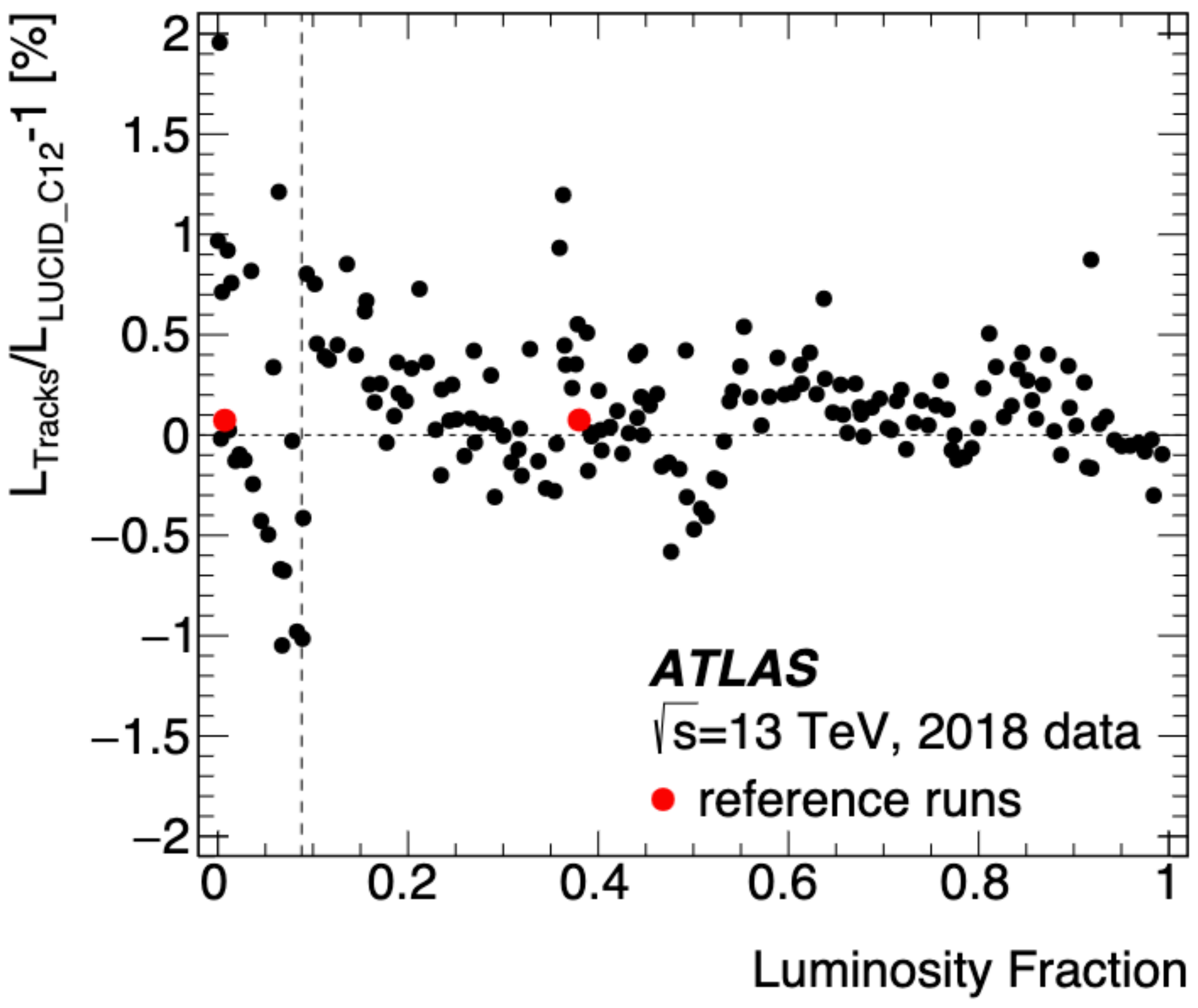




time in year →



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

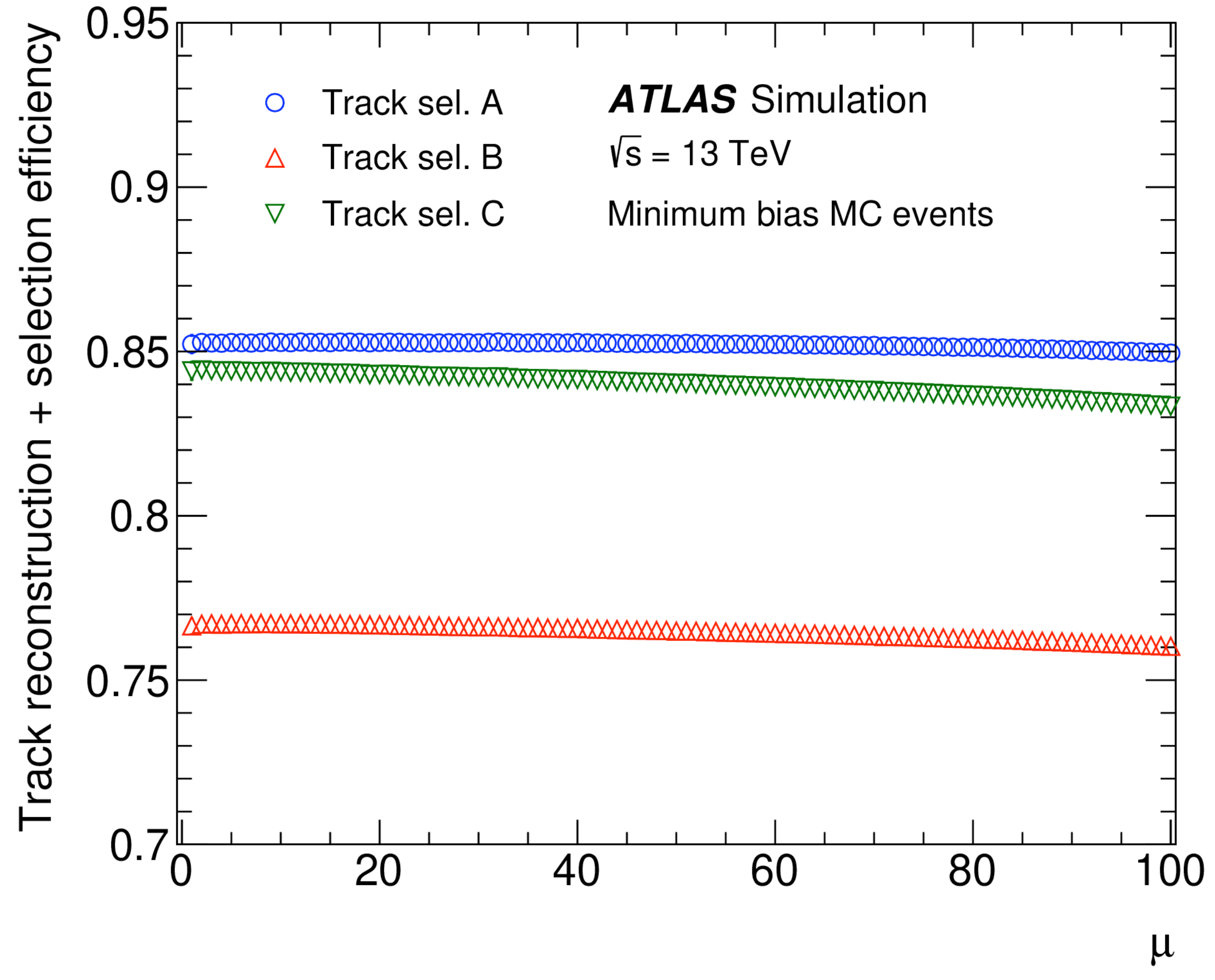
***Result**: Corrected LUCID luminosity* $\mathbf{L_{corr}}$ *for each LB in each physics run*

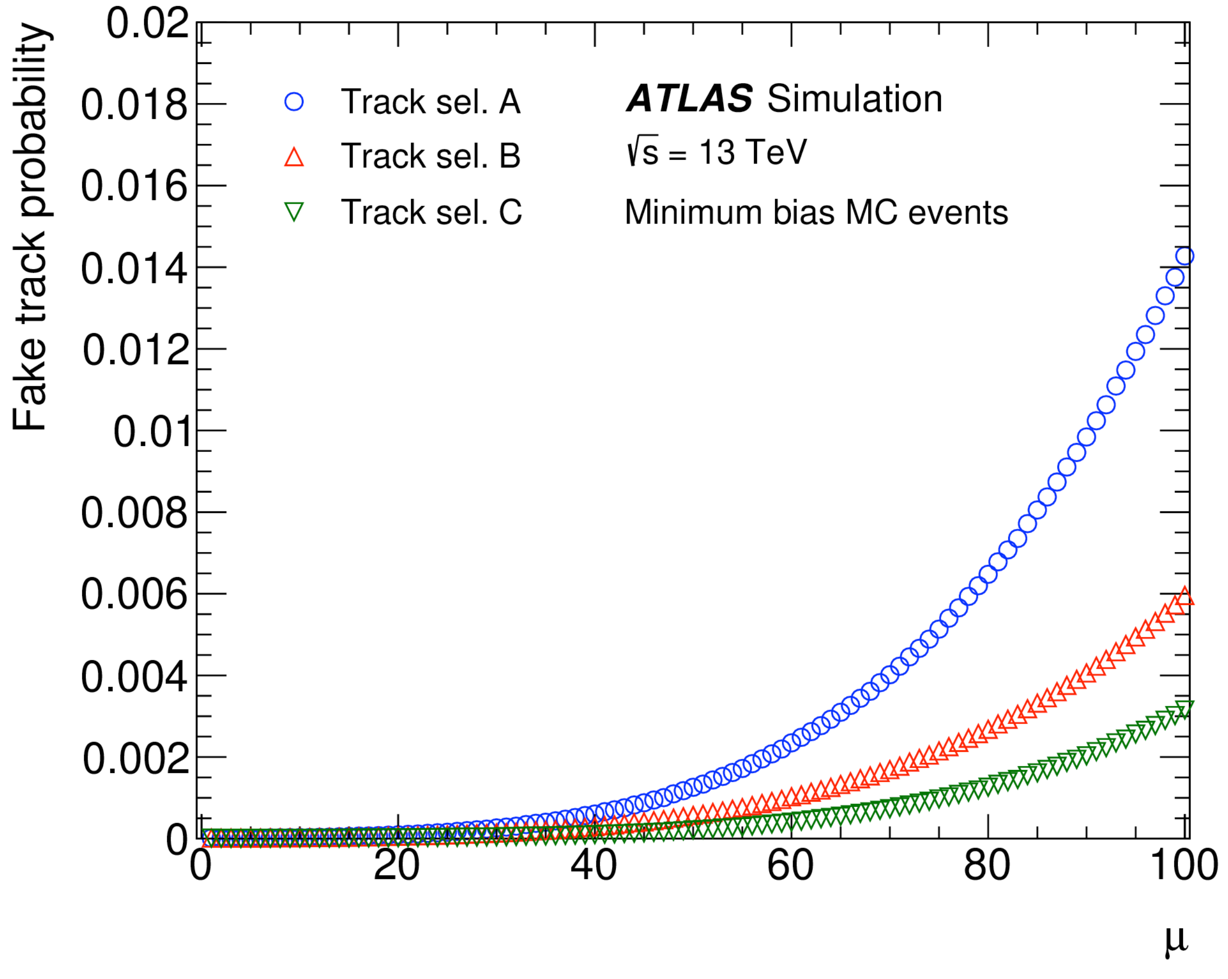
Interlude: Track counting

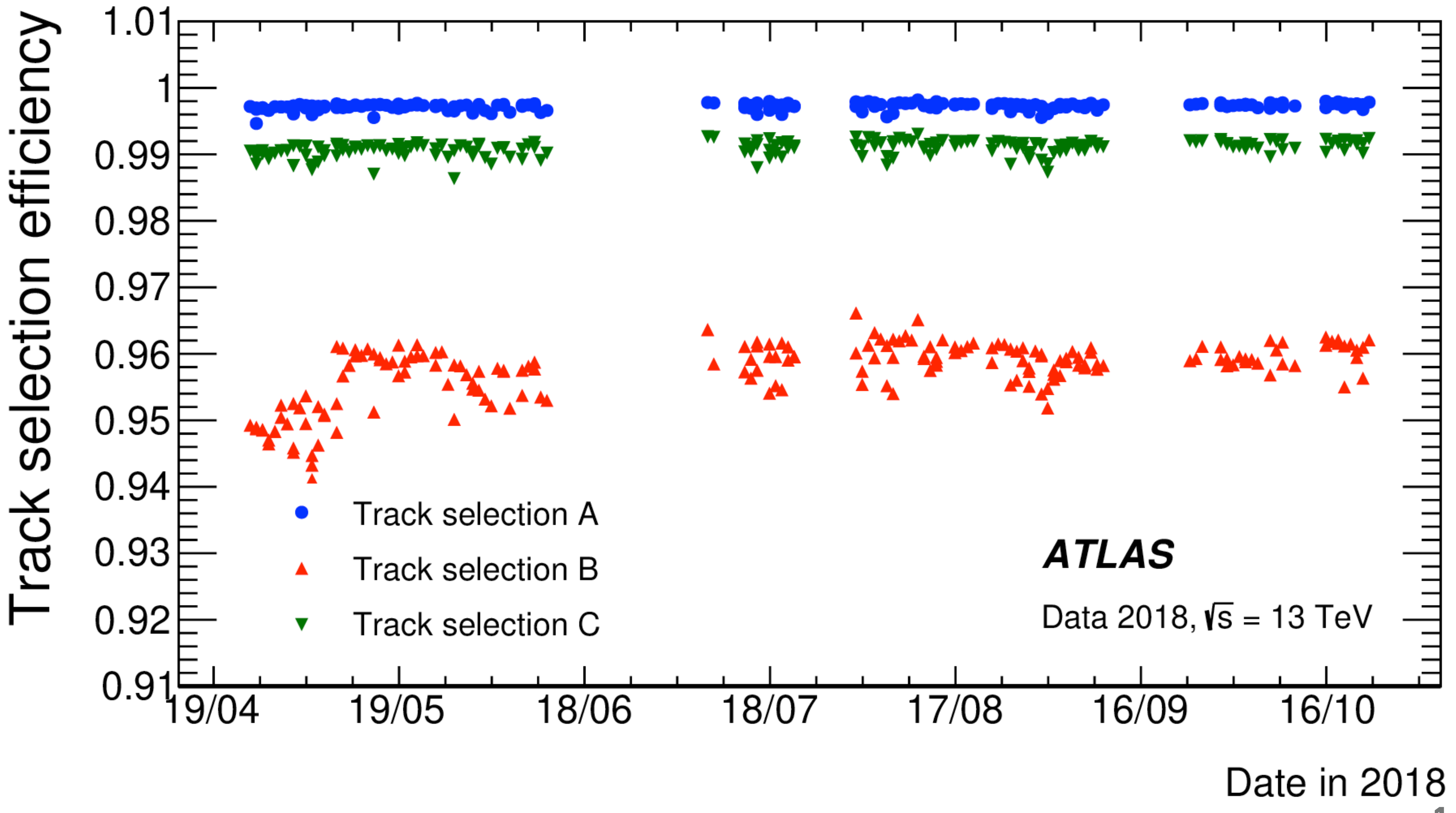
- Different track selections in use with varying efficiency and fake rates
- **Selection A** baseline measurement for Run 2

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



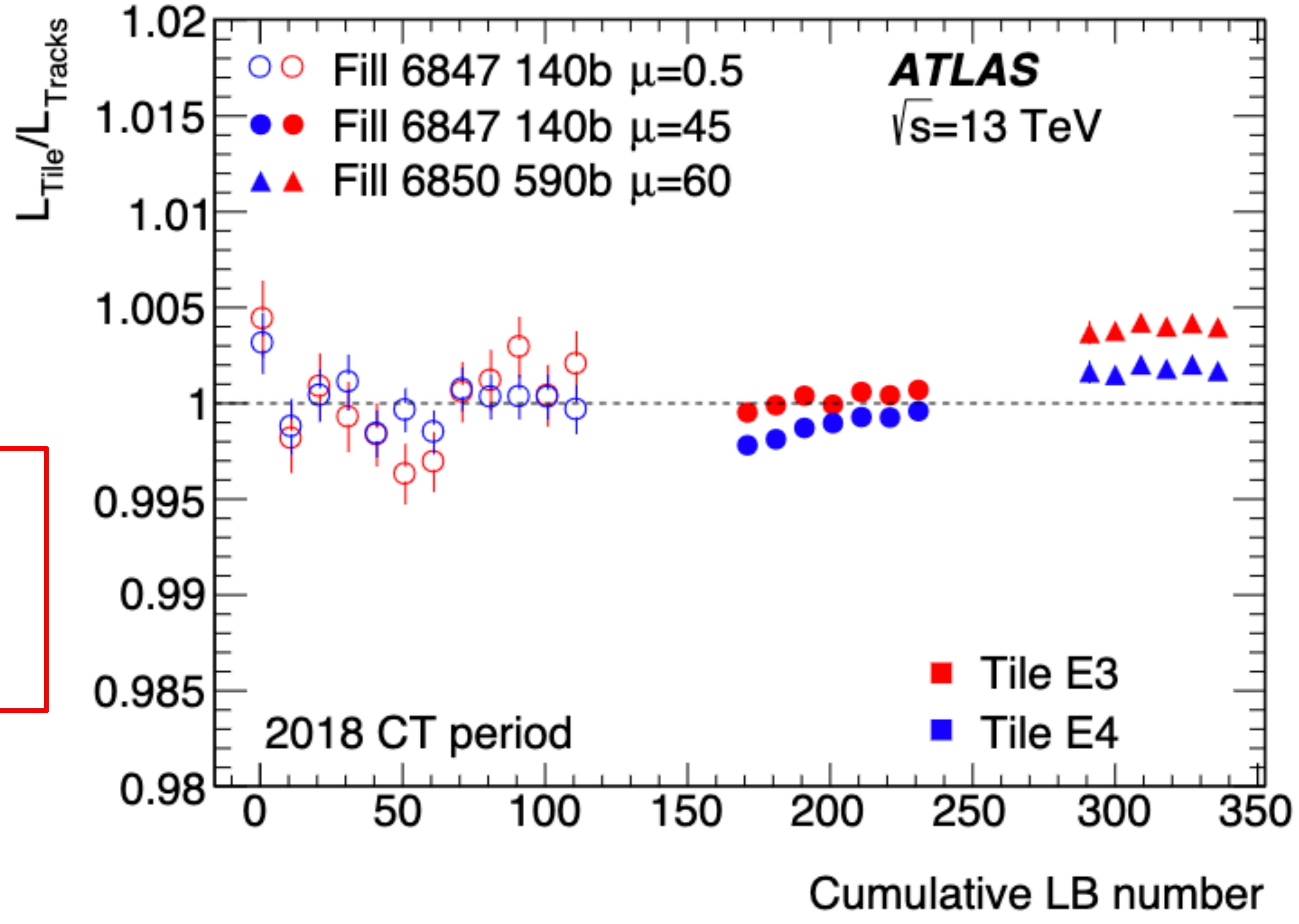




2. Calibration transfer uncertainty

- 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

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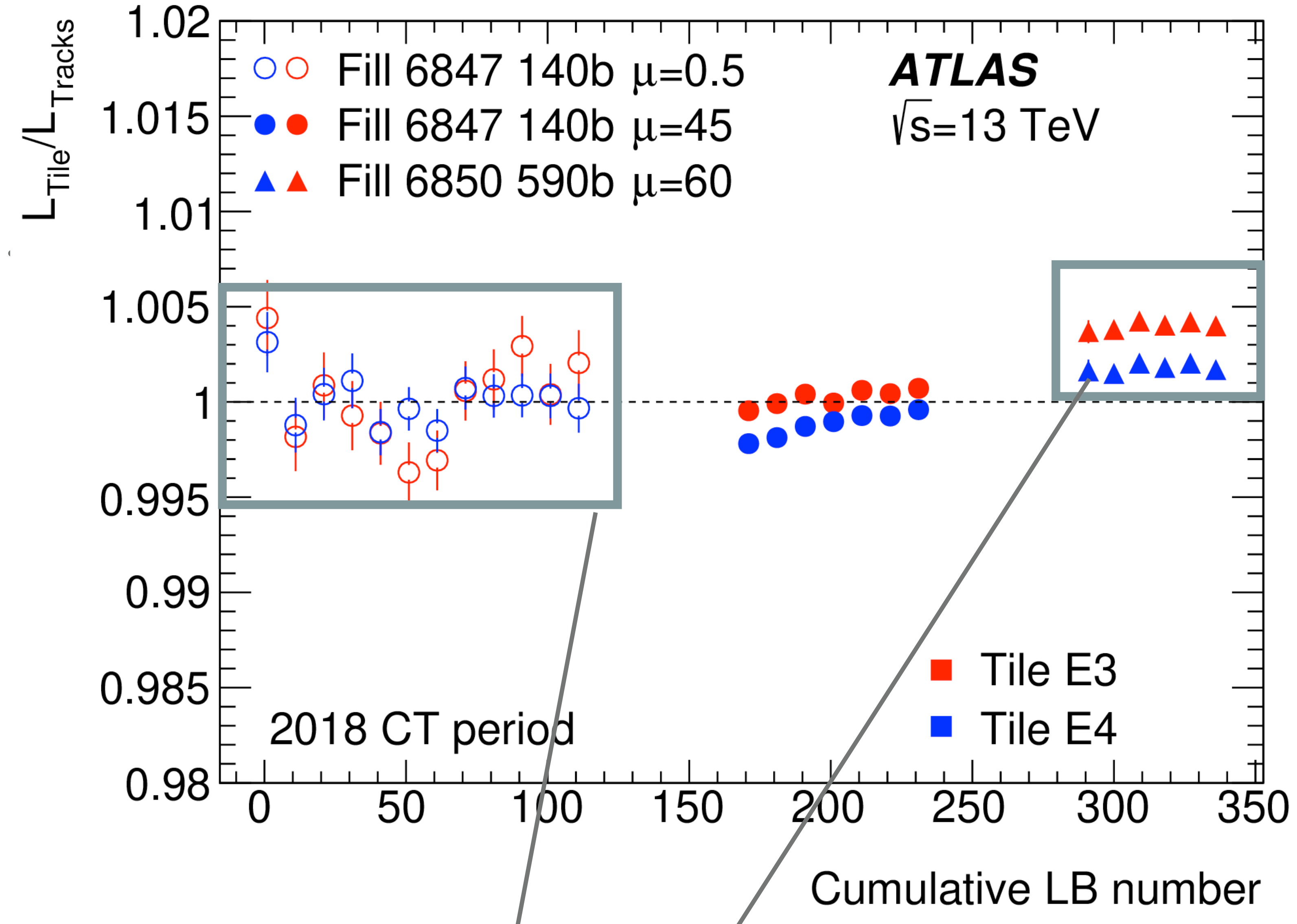
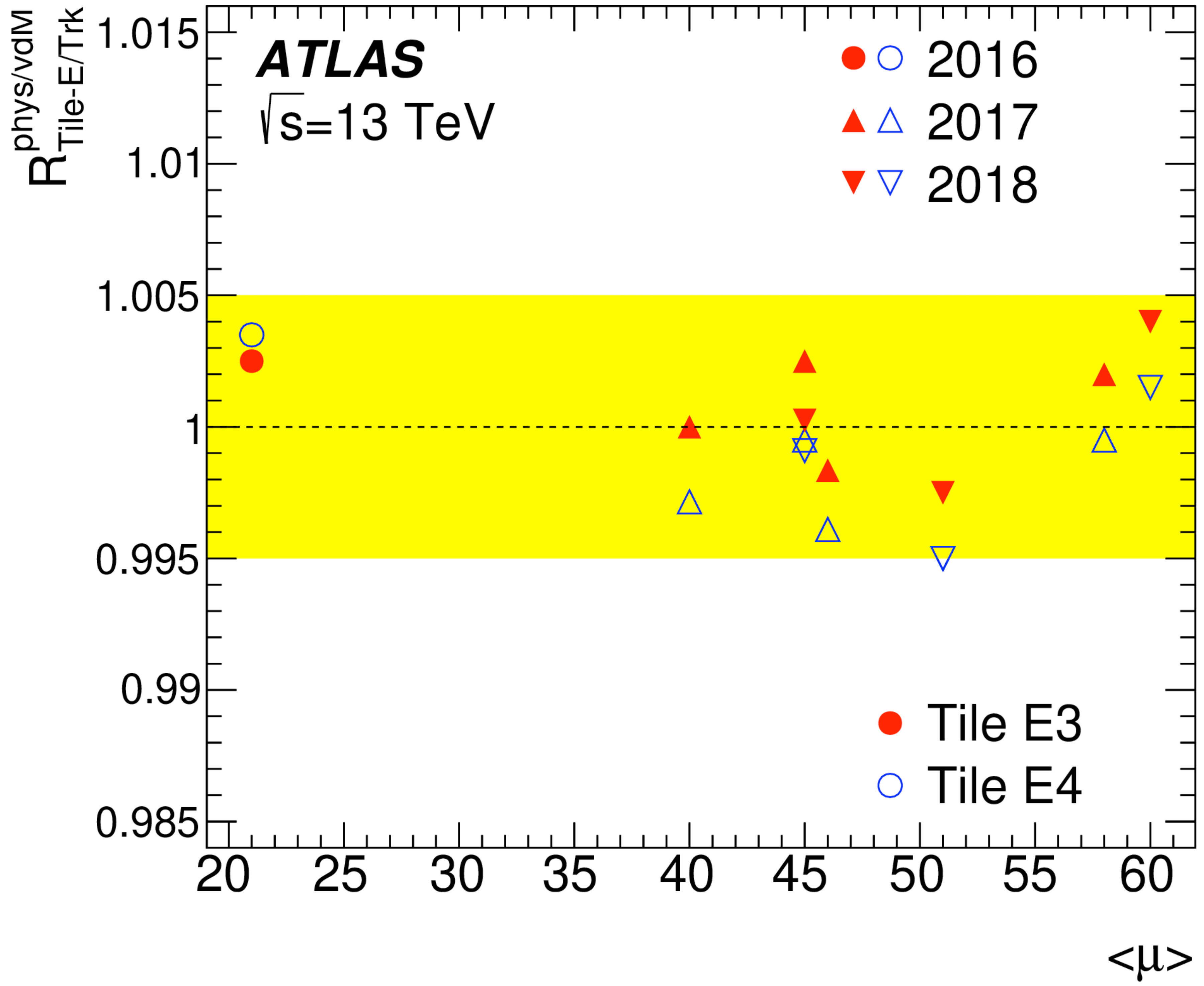
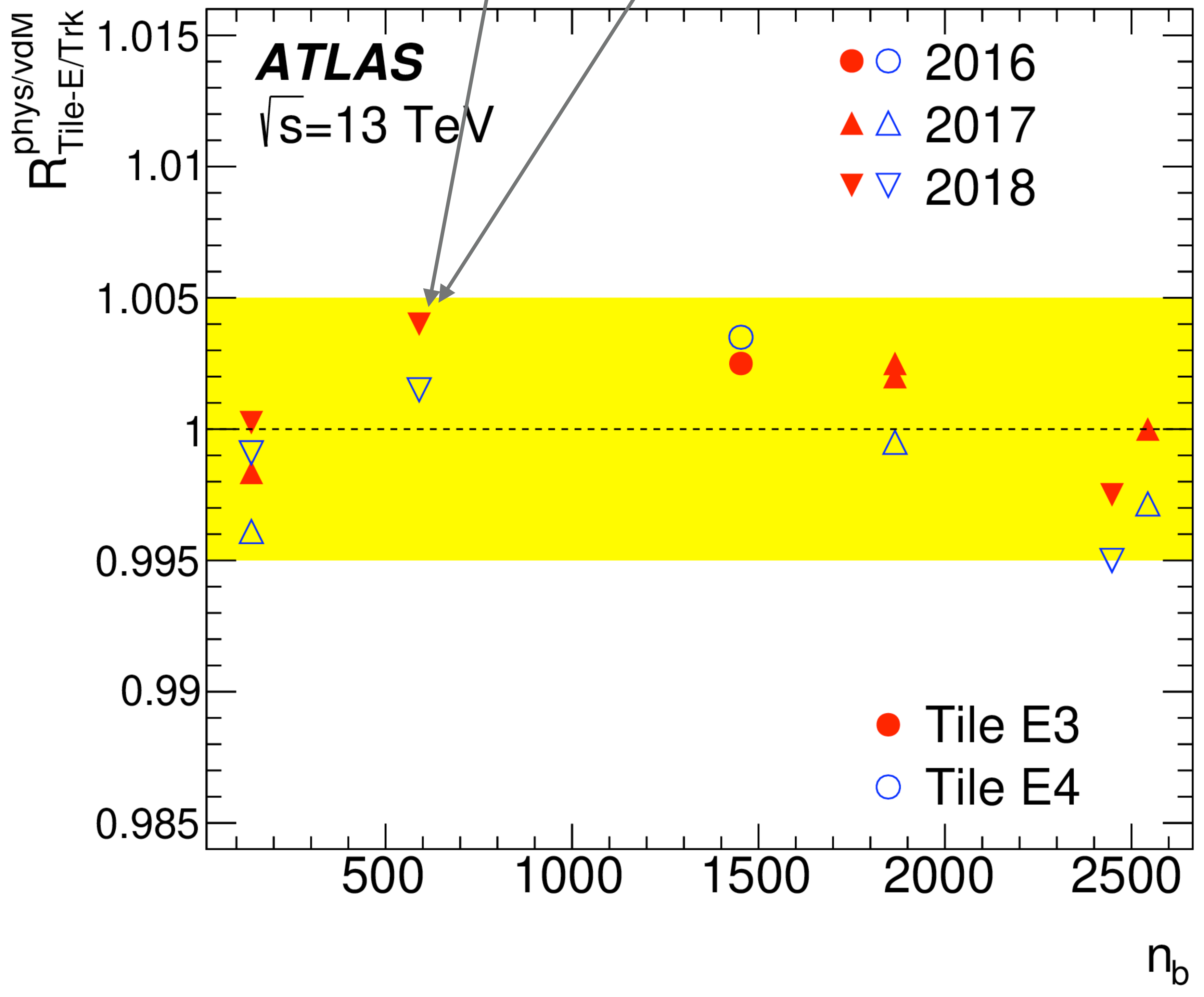


- ➤ Check double ratio of $R_{Tile-e/TC}$ in physics vs vdM conditions as a function of $\langle \mu \rangle$ and the number of bunches

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





ATLAS Luminosity measurement strategy in Run 2

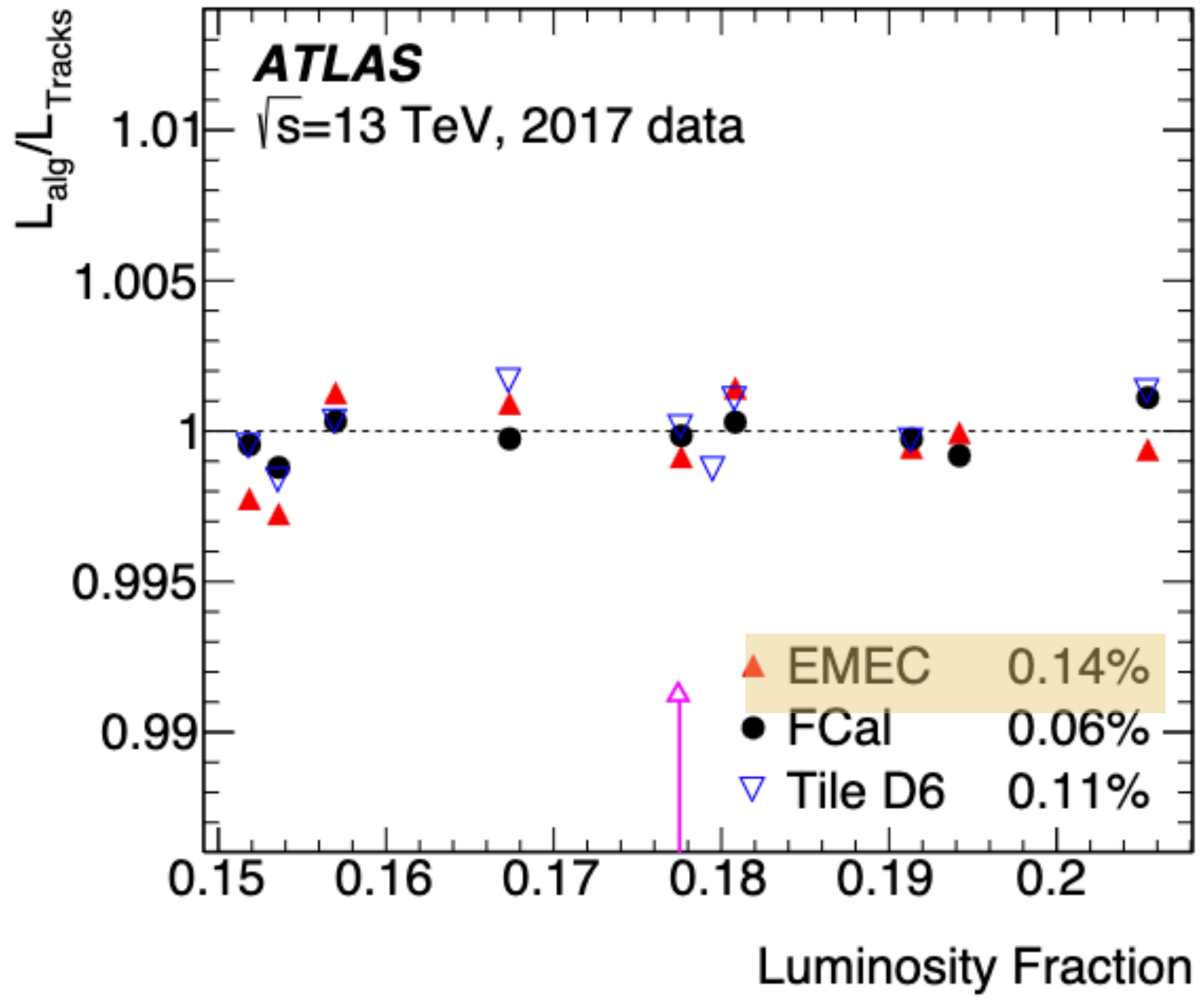
3. Long-term stability

- 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 $\mathbf{L_{corr}}$ 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 fill
    - RMS of run-to-run variations assigned as uncertainty
      ⇒ **0.1% to 0.3% per year**



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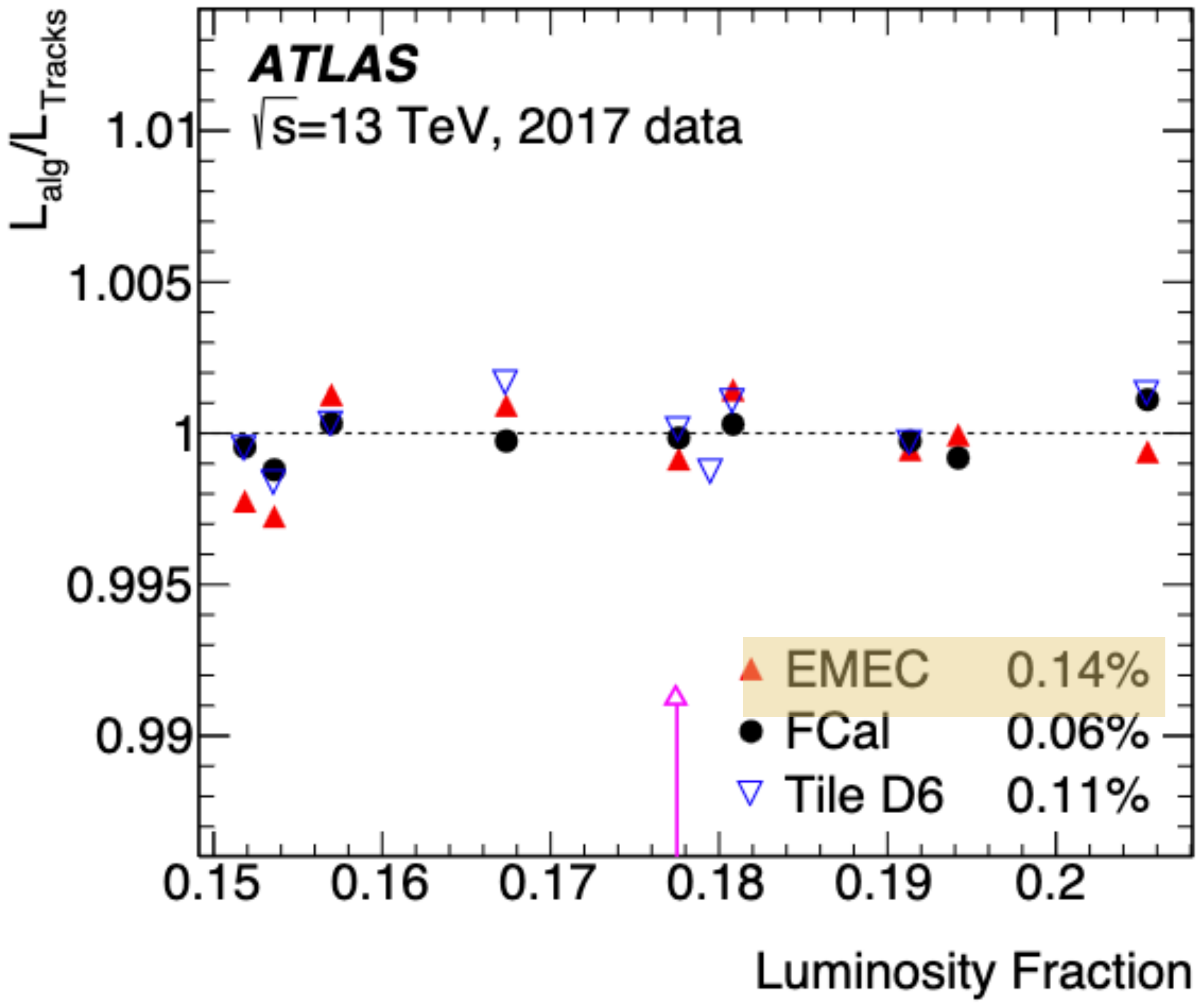
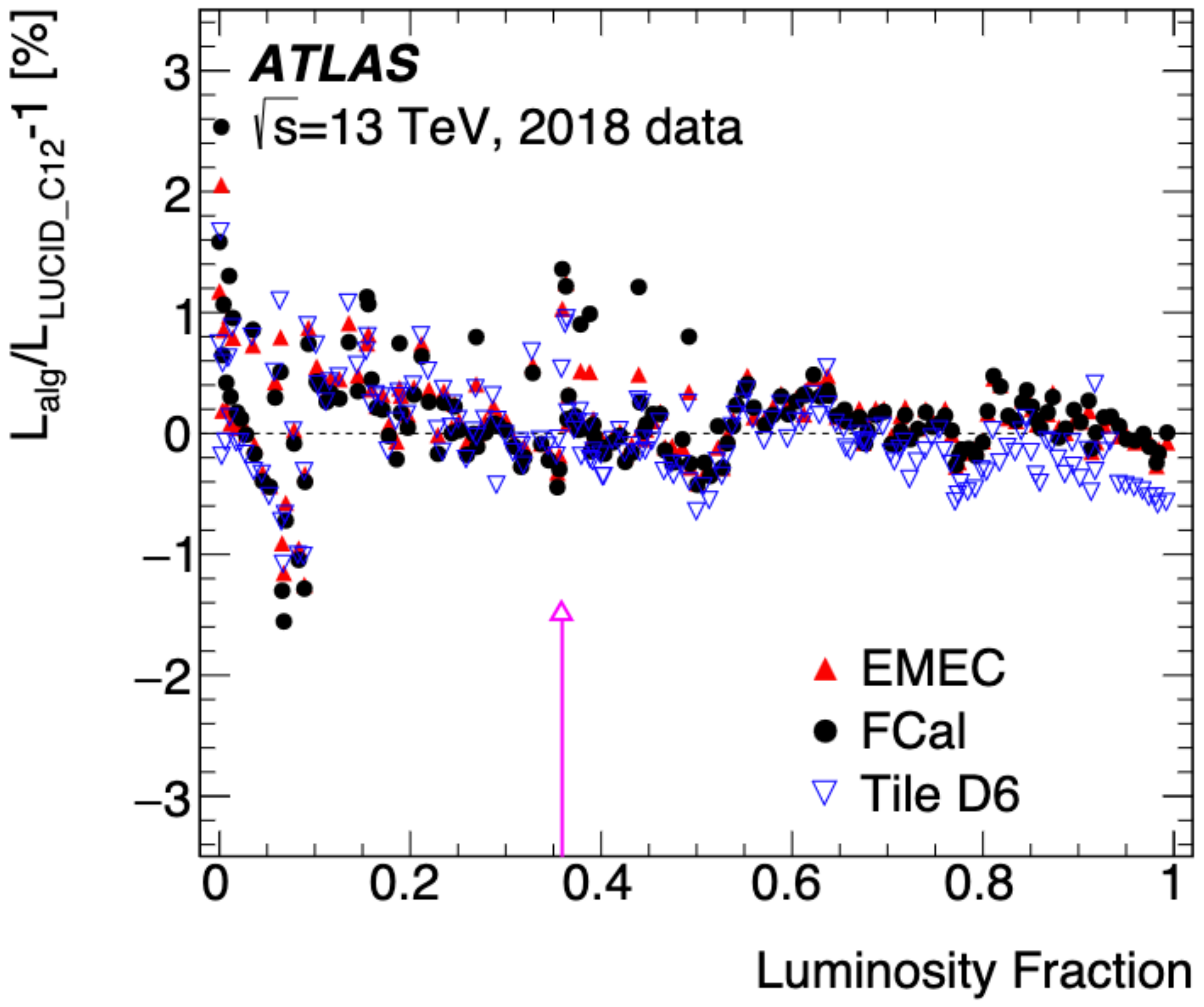
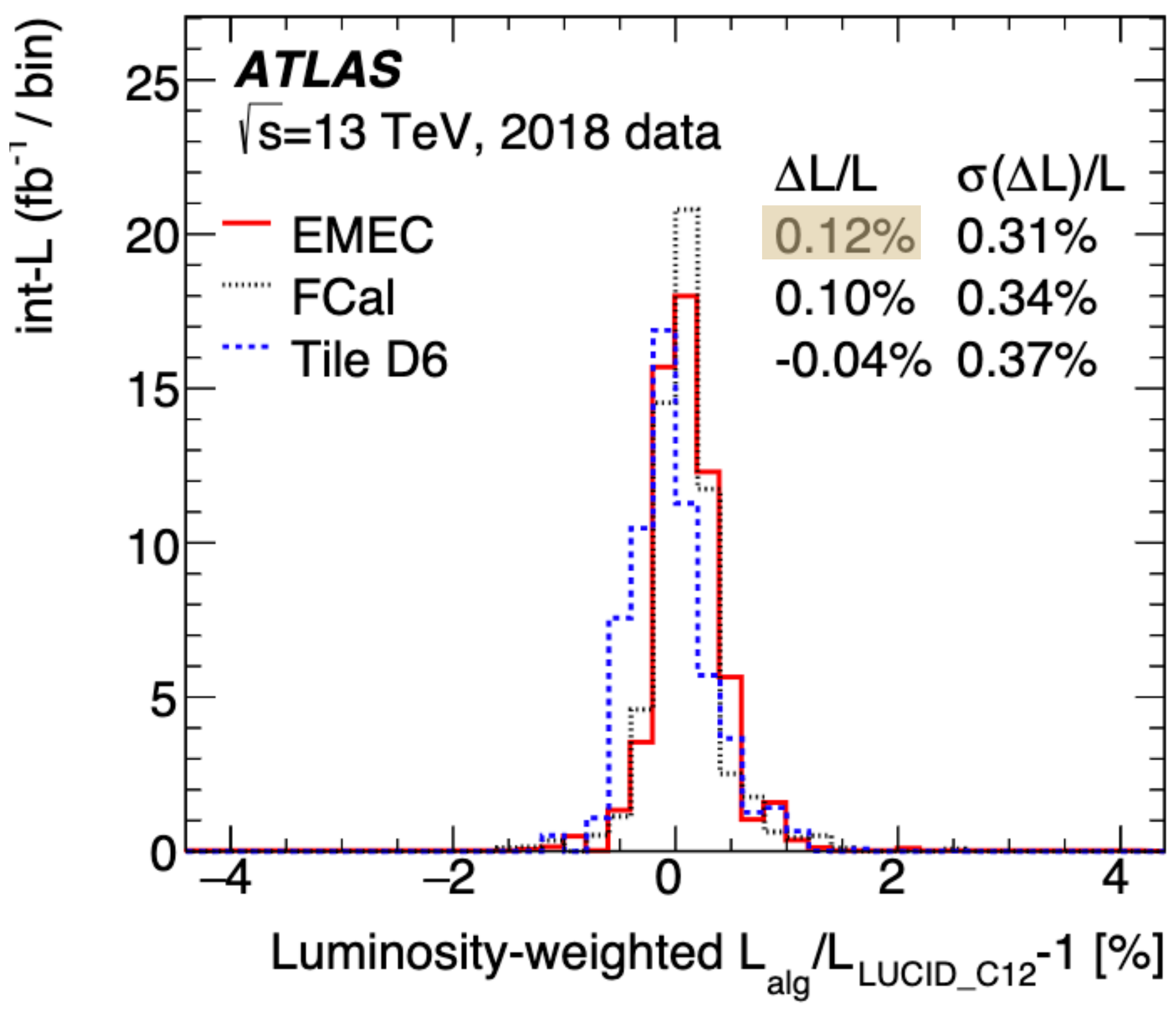


Take largest mean from EMEC, FCal, Tile to define long-term stability uncertainty



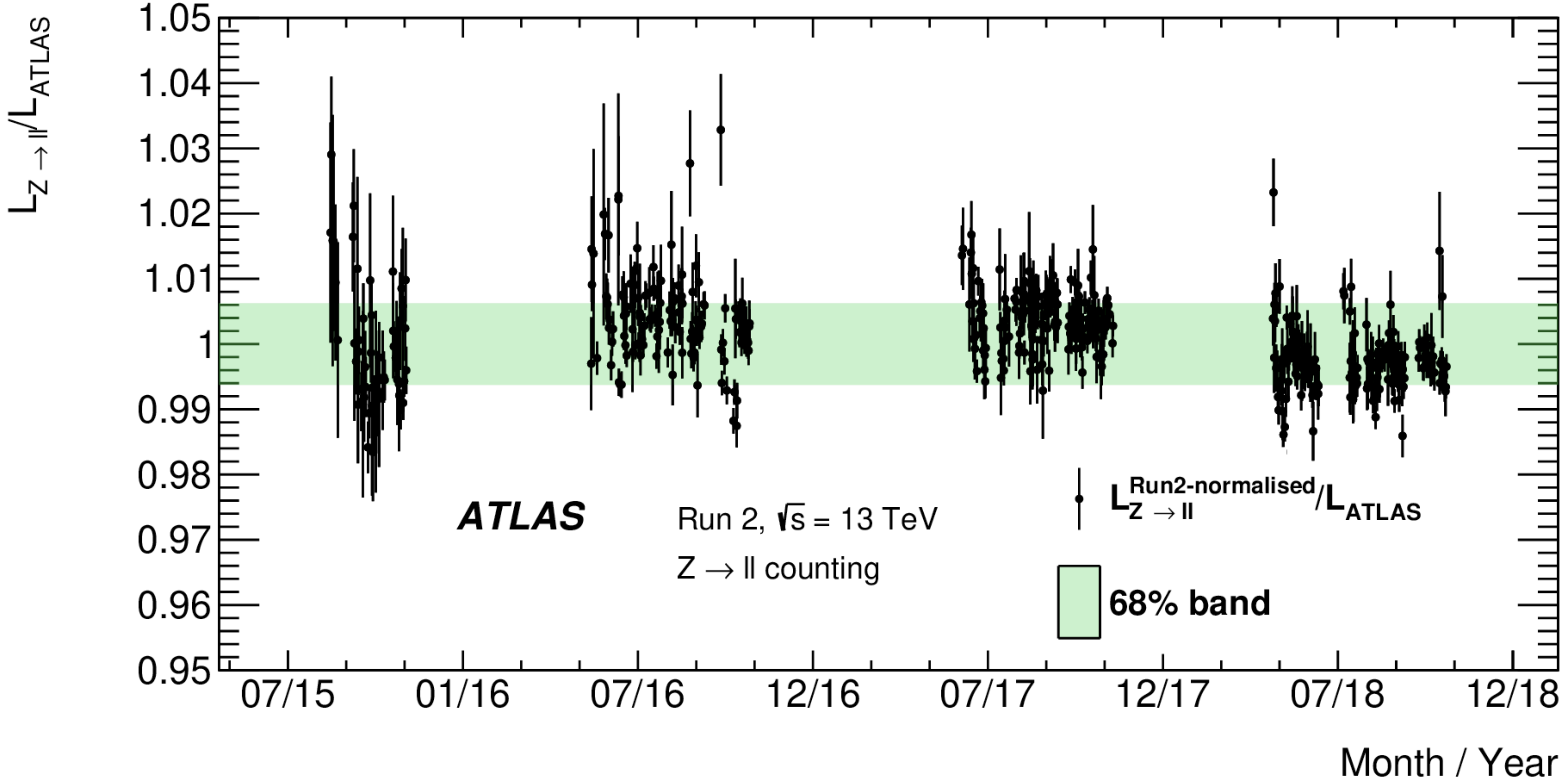


- **Long-term stability**
  - Comparison of run-integrated luminosity of LUCID wrt Tile, EMEC, FCAL throughout the whole data taking year
  - **Target: uncertainty on the integrated luminosity not** individual runs
    ⇒ **0.1 to 0.2% per year uncertainty**

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}



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

**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

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- Luminosity measurement for full Run 2 ATLAS pp dataset finalized

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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

*correlated

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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
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
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Emittance growth correction*	0.04	0.02	0.09	0.02	0.04
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Subtotal vdM calibration	0.96	0.70	0.99	0.93	0.65
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Long-term stability	0.23	0.12	0.16	0.12	0.08
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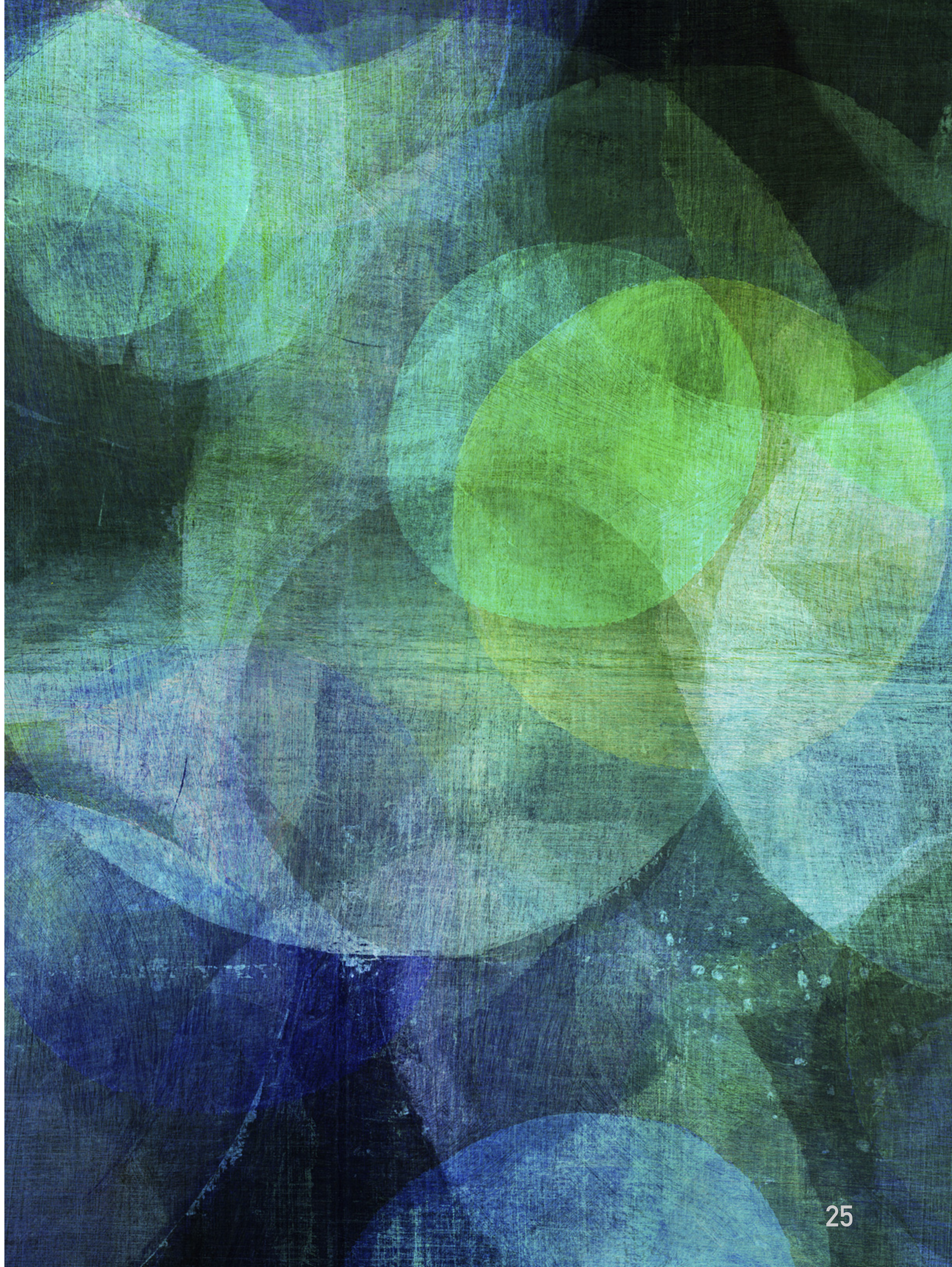
https://arxiv.org/abs/2212.09379

BACKUP



Comparison between Preliminary and Final Run 2 result

Preliminary 139 ± 2.3fb^{-1} (1.7%)

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

ATLAS-CONF-2019-021

NEW

140.1 ±1.2 fb^{-1} (0.83%)

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

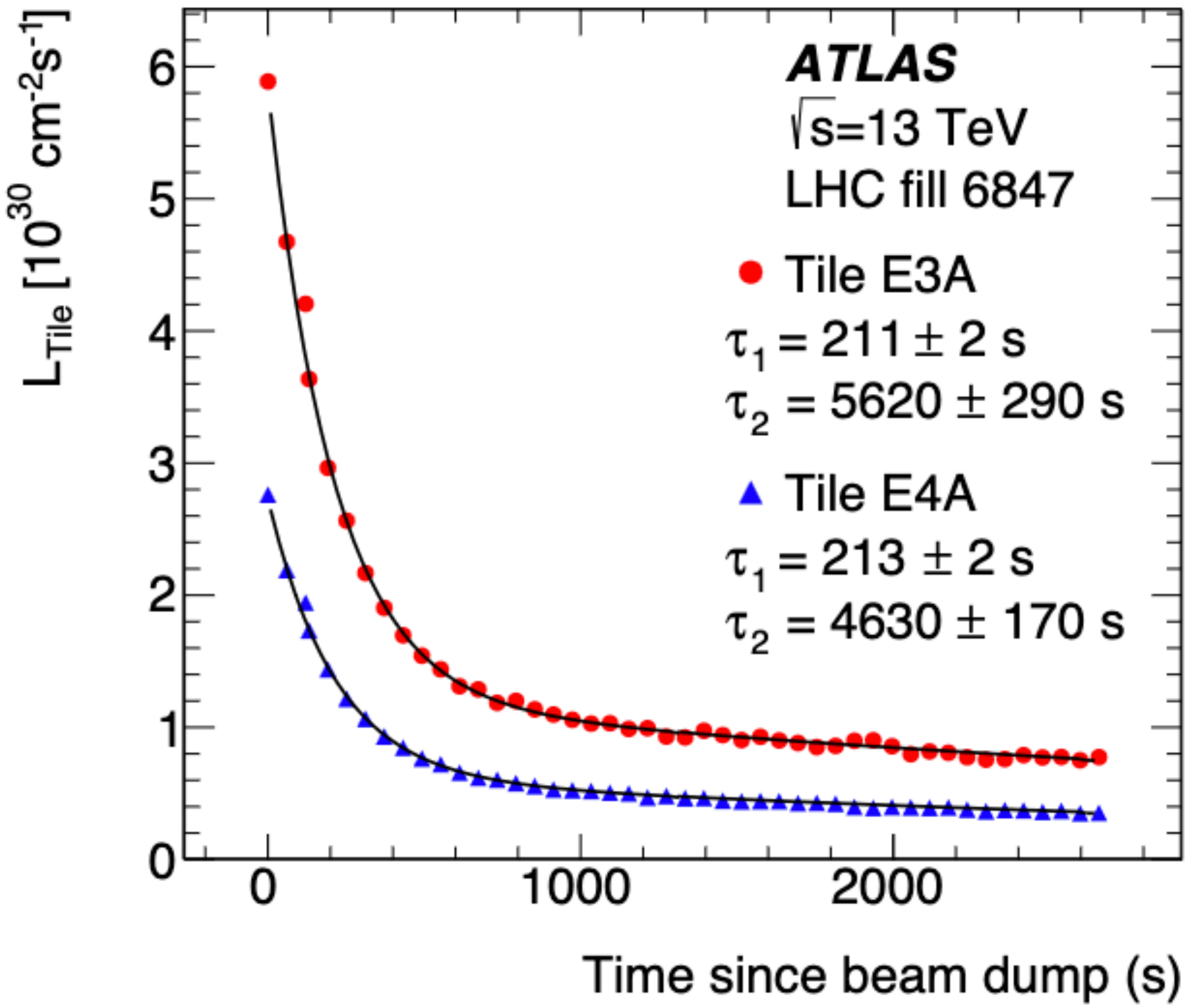
➤ https://arxiv.org/abs/2212.09379

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**

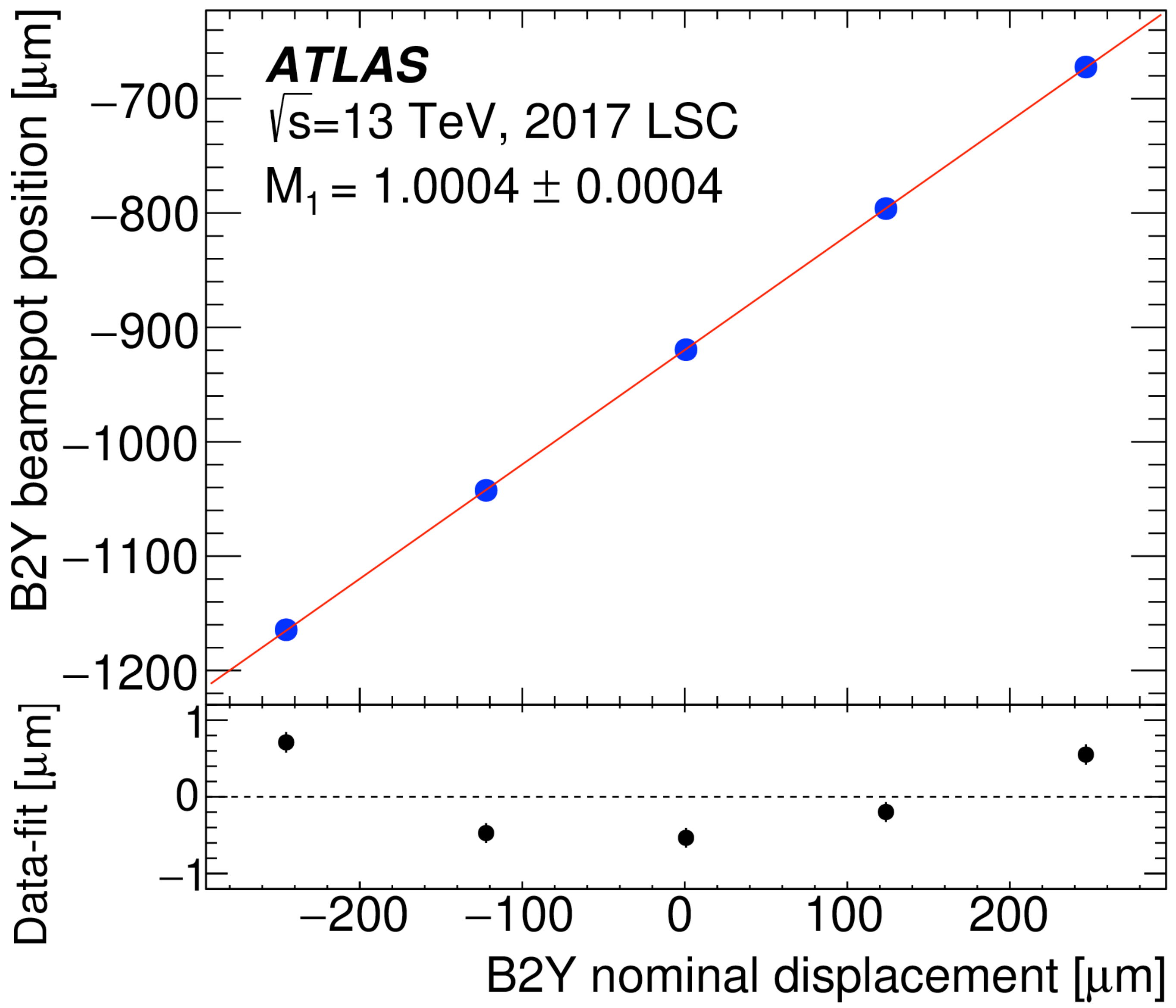
- Residual activation from any high-lumi running just before vdM fill can swamp Tile signal with $\mathcal{O}(10\%)$
  $\Rightarrow$ Needs delicate pedestal subtraction

- 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

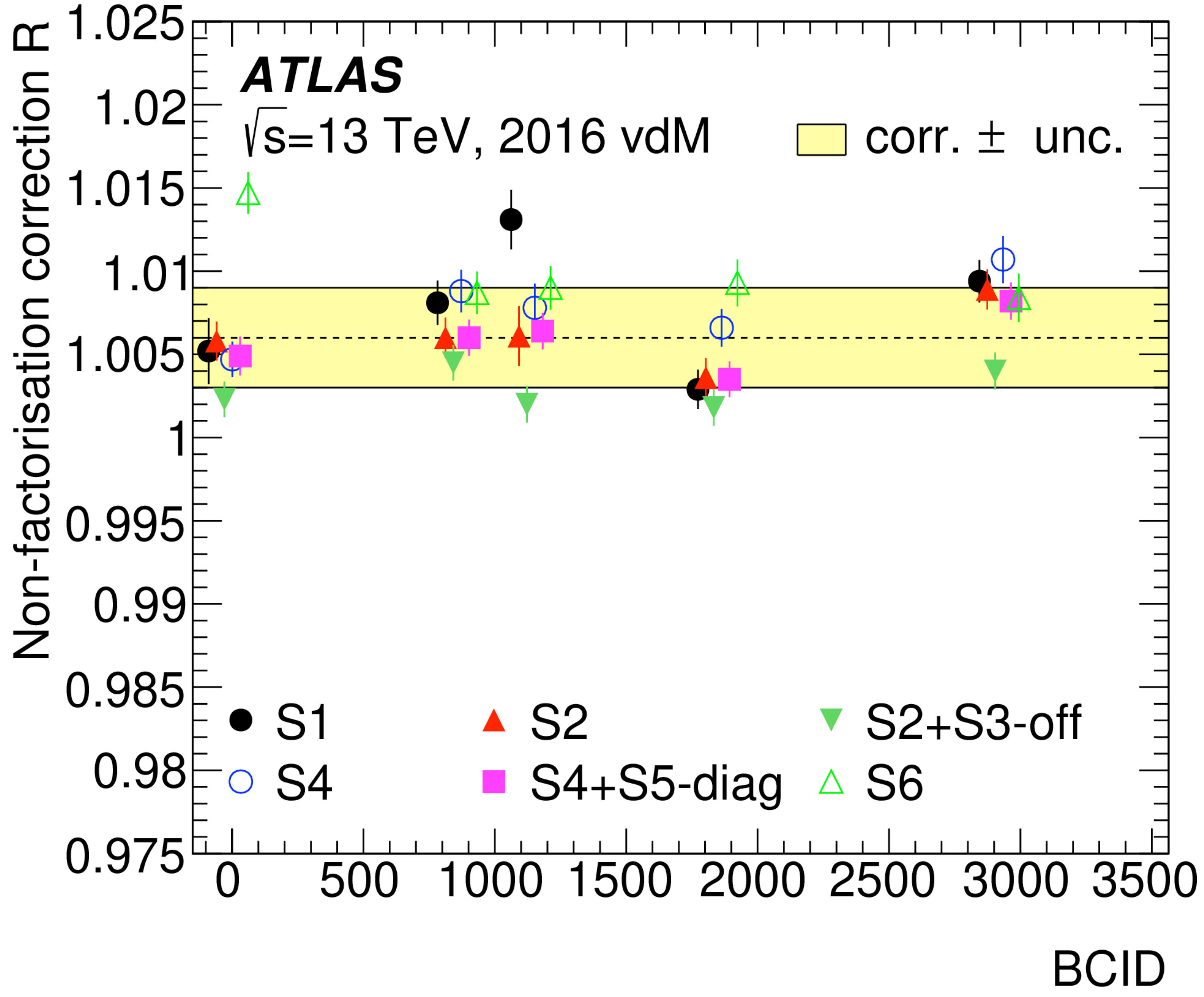


Length scale calibration and non-factorization

- 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 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

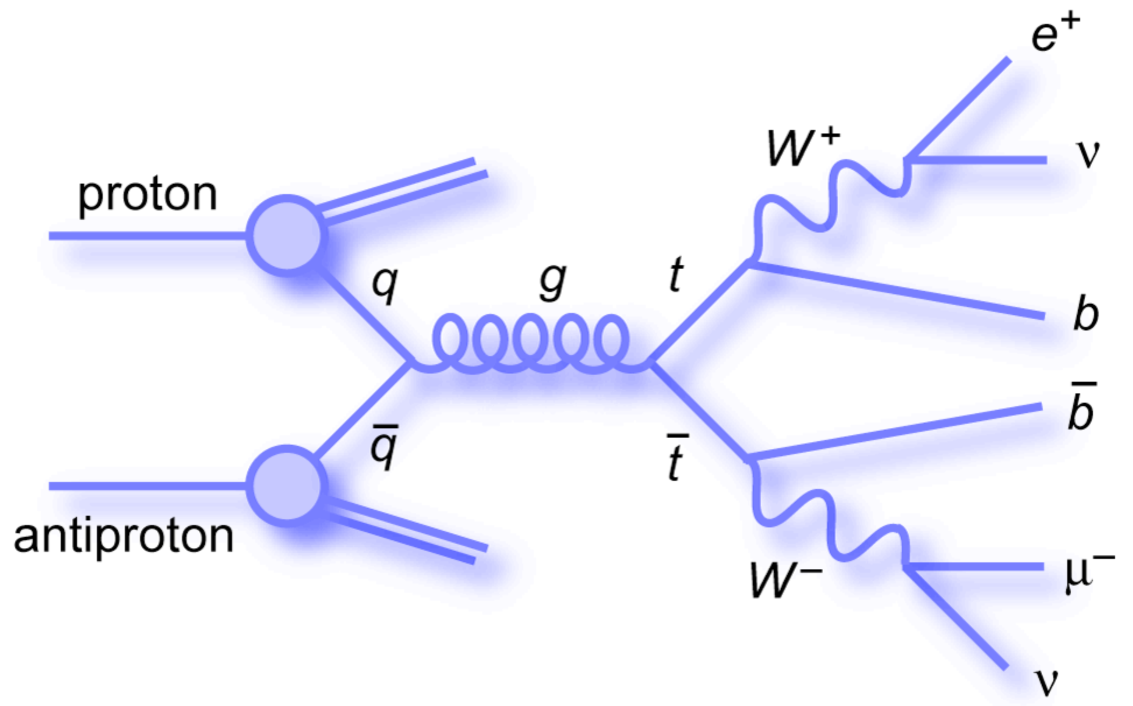


Why measure luminosity?

- 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

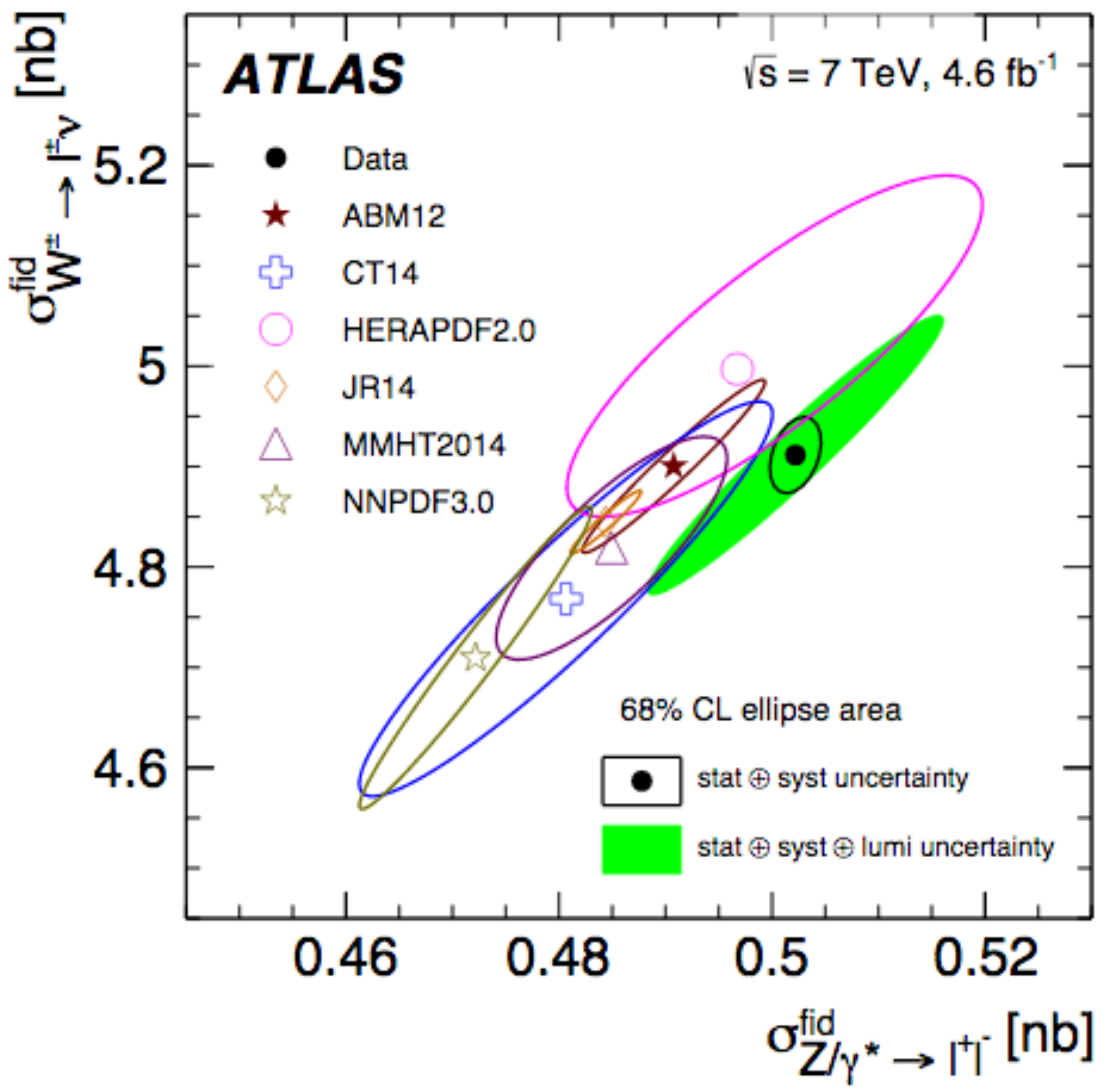
$$\sigma_{t\bar{t}} = 826.4 \pm 3.6\,(\text{stat}) \pm 11.5\,(\text{syst}) \pm 15.7\,(\text{lumi}) \pm 1.9\,(\text{beam})\,\text{pb},$$



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

at 13 TeV with 36 fb^{-1}

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



7 TeV dataset: 1.8% luminosity uncertainty