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Precision luminosity measurement

with proton-proton collisions at the CMS experiment in Run 2

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on behalf of the CMS Collaboration

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Luminosity at LHC Run 2

What is luminosity?

- **Instantaneous** luminosity is a measure of collision rate

$$R(t) = \mathscr{L}(t) \cdot \sigma_{vis}$$

Measured online and delivered to control rooms to optimise beam conditions

Determined from Van der Meer scans

- **Integrated** luminosity is a crucial input to cross section measurements $\sigma(\mathrm{pp} \rightarrow \mathrm{X}) = \dfrac{N(\mathrm{pp} \rightarrow \mathrm{X})}{\int \mathscr{L} dt}$
  - Target precision: ≲1%

More in Hamed Bakhshiansohi's talk

- Units of luminosity: (area · time)$^{-1}$
  - Instantaneous luminosity: Hz/μb
  - Integrated luminosity: fb^{-1}

Luminosity at LHC Run 2

How to measure luminosity @ hadron colliders?

- **Instantaneous** luminosity is a measure of collision rate

$$R(t) = \mathscr{L}(t) \cdot \sigma_{vis}$$

Measured online and delivered to control rooms to optimise beam conditions

Determined from Van der Meer scans

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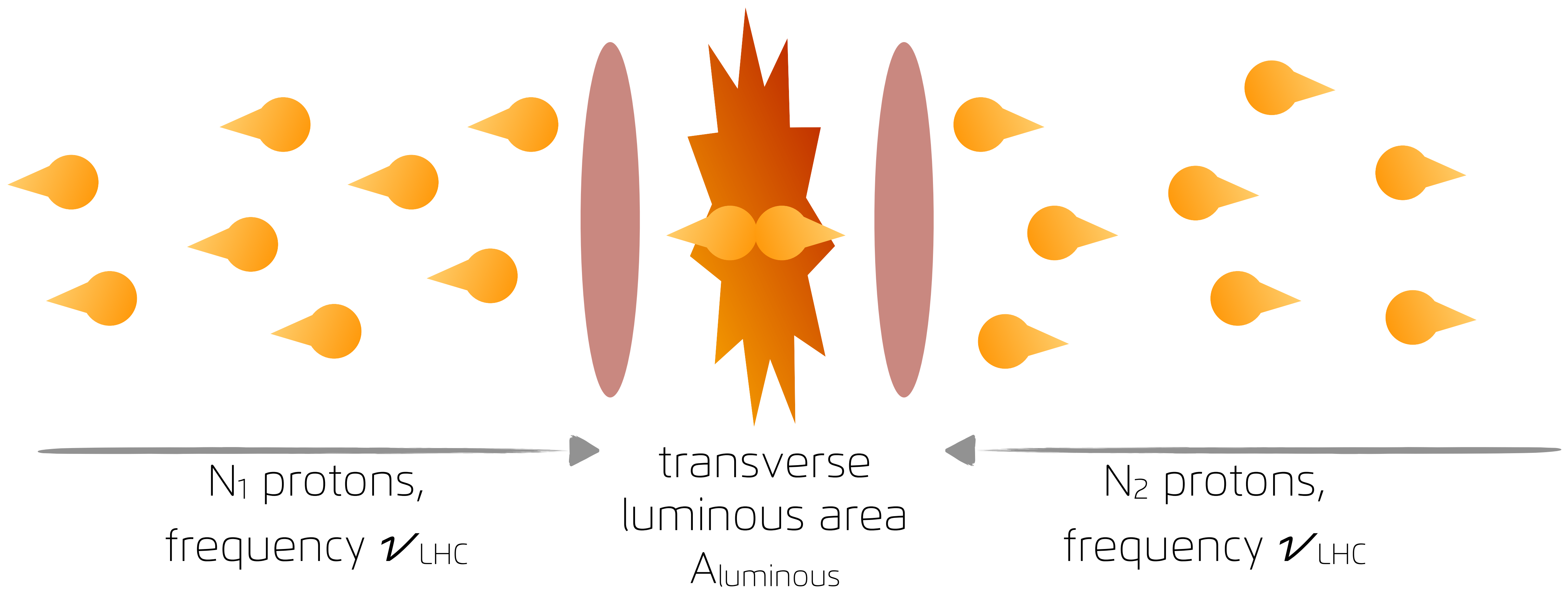
More in Hamed Bakhshiansohi's talk

- Units of luminosity: (area · time)$^{-1}$
  - Instantaneous luminosity: Hz/µb
  - Integrated luminosity: fb^{-1}

- Luminosity from **beam parameters**

$$\mathscr{L}(t) = \frac{\nu_{\mathrm{LHC}} \mathrm{N}_1 \mathrm{N}_2}{\mathrm{A}_{\mathrm{luminous}}}$$



- Luminosity measurement at **hadron colliders**
  - Calibration of predicted reference $\sigma(\mathrm{pp} \rightarrow \mathrm{X})$
  - Integration of rate measurement

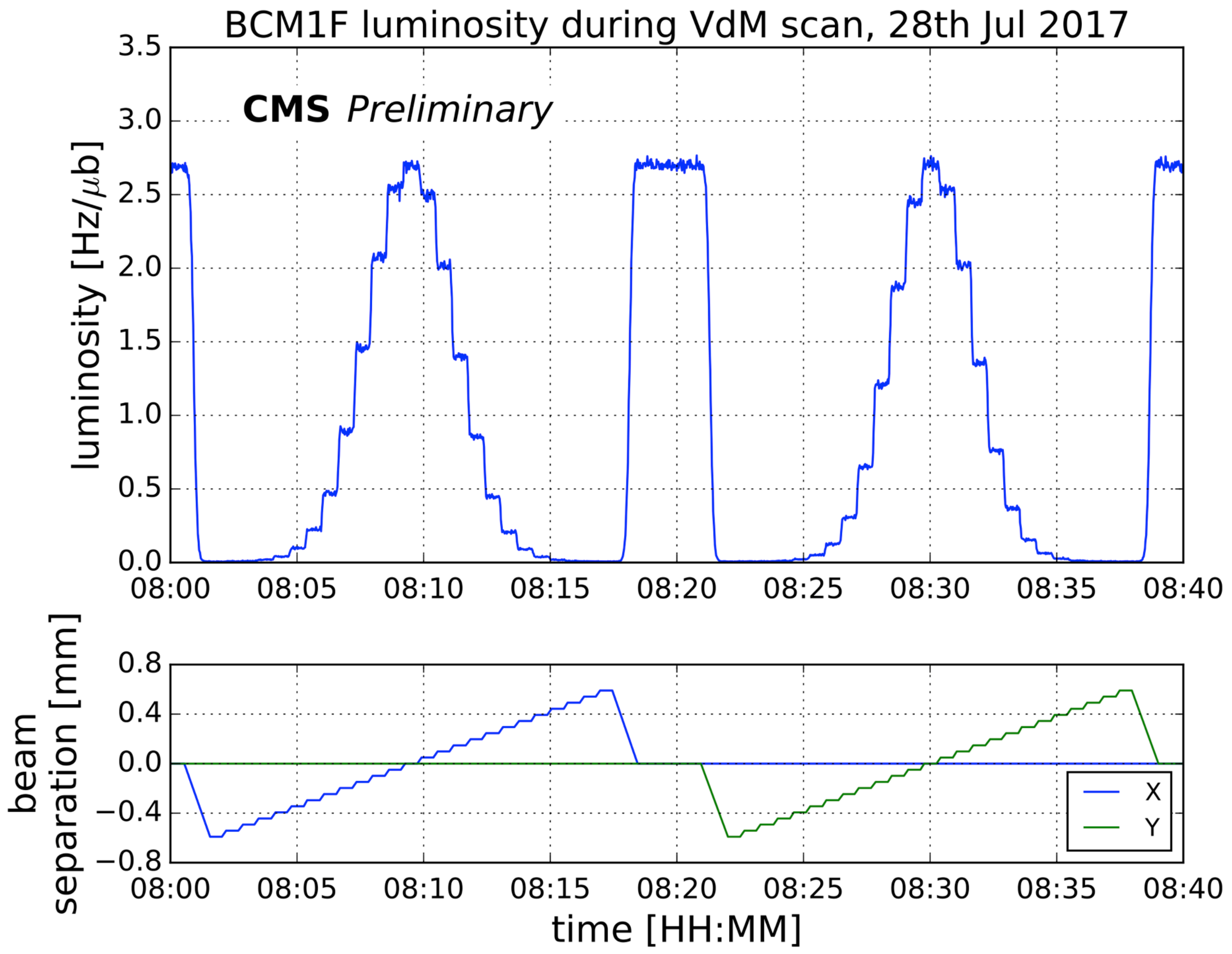
Van der Meer Method

How to calibrate luminosity at CMS?

$$\mathscr{L}(t) = \frac{R(t)}{\sigma_{vis}}$$

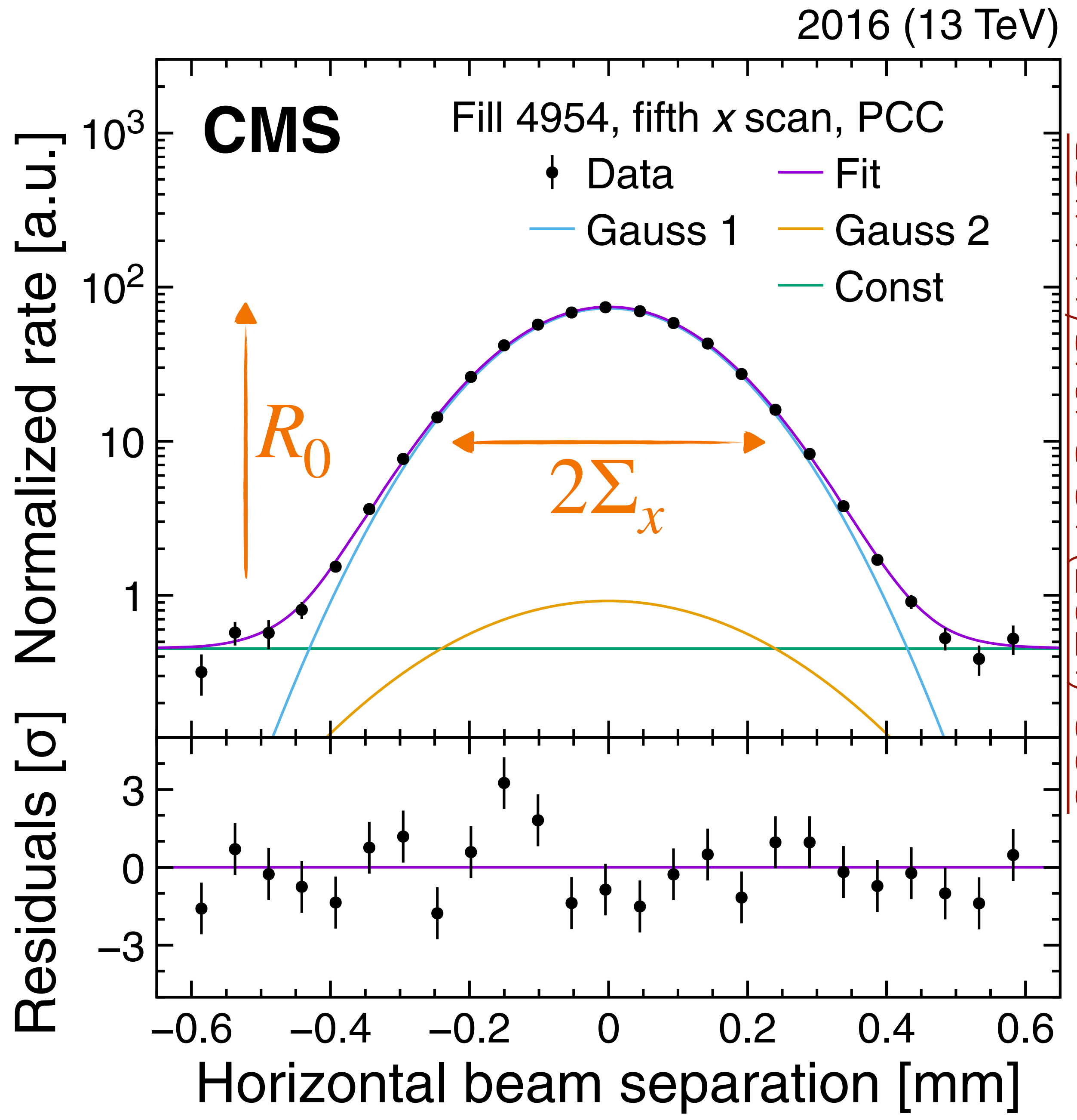
- **Van der Meer (VdM) scans**: beams scanned across each other transversely under special run conditions
  - Determine the beam shapes in x and y from scan of rates for different transverse beam separations

Luminosity during a scan pair in the 2017 VdM fill



CMS-DP-2018-062

Normalized rate as function of the beam separation in the x direction



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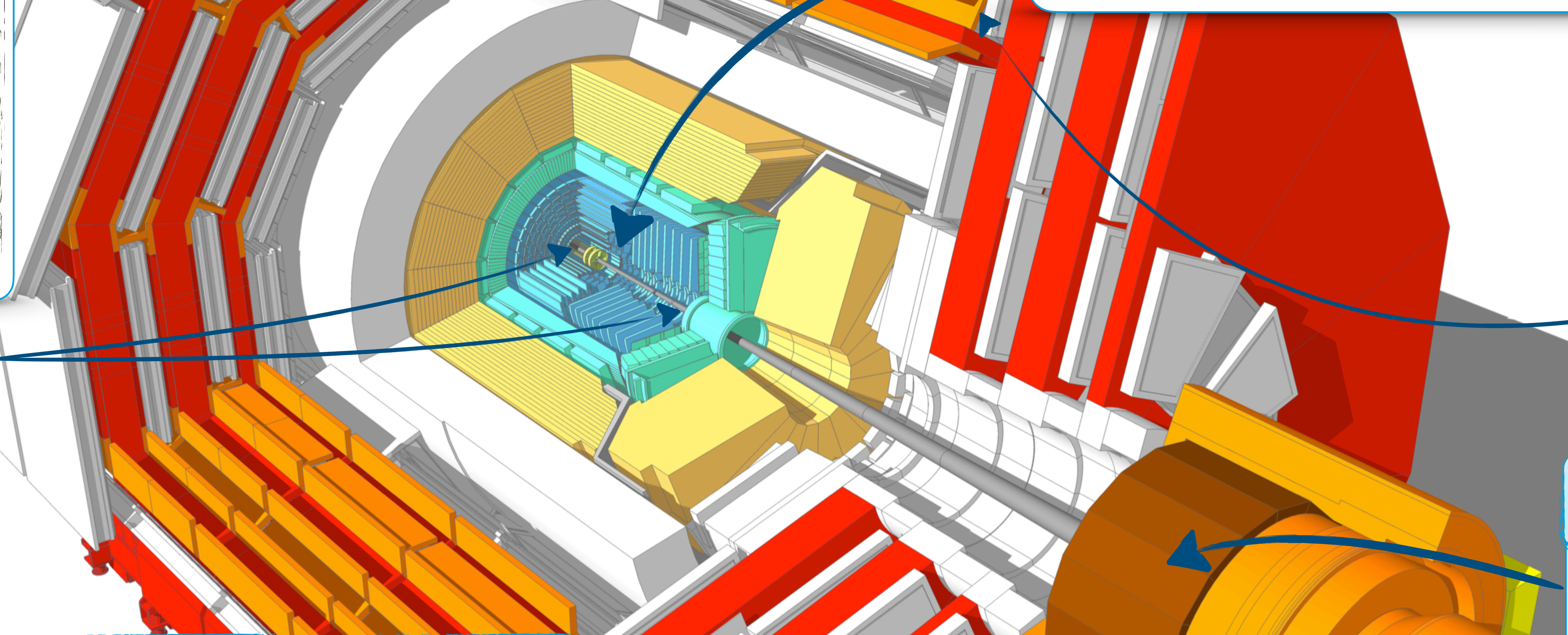
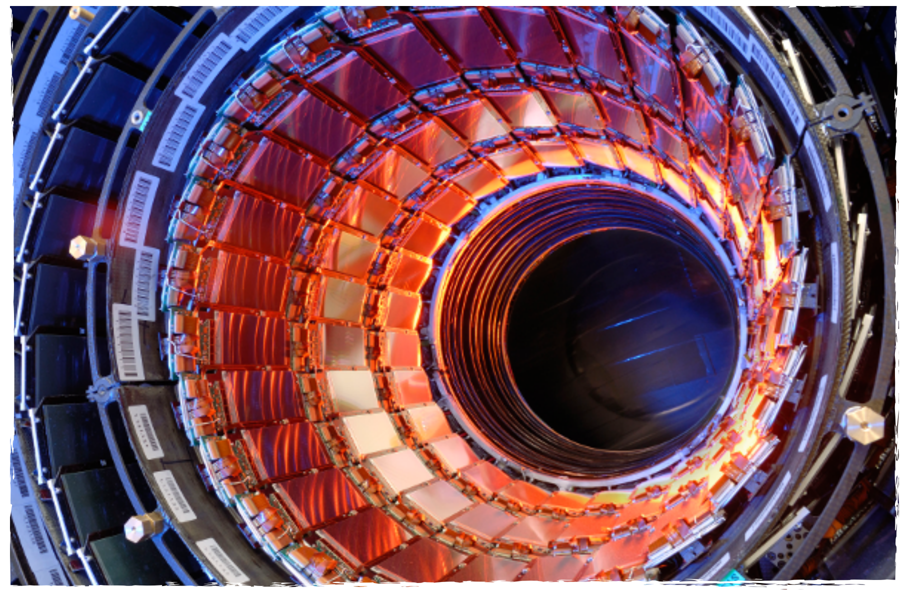
- For each luminometer, derive $\sigma_{vis} = \dfrac{\overset{A_{luminous}}{\boxed{2\pi\Sigma_x\Sigma_y}}}{N_1 N_2 \nu_{LHC}} \cdot R_0$
  - N_1 N_2 from beam intensities and bunch currents data
  - Σ_x , Σ_y evaluated as widths of fitted distributions, double-Gaussian + constant
  - Rates corrected for backgrounds
- Different sources of systematic uncertainties studied

Luminometers

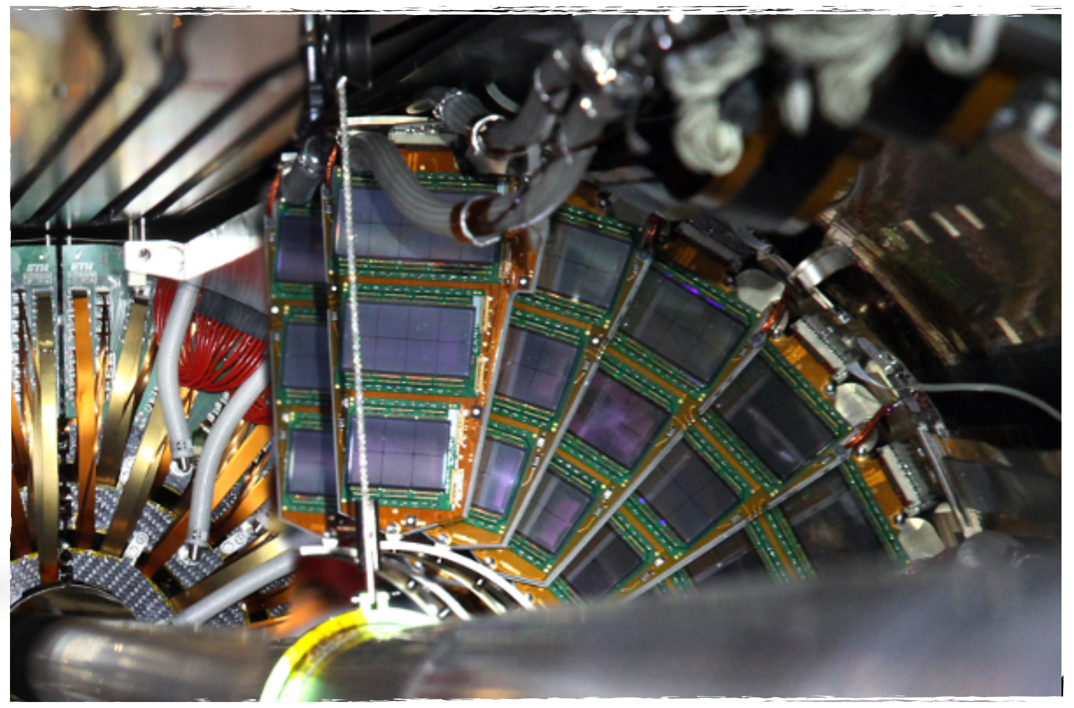
Which detectors?



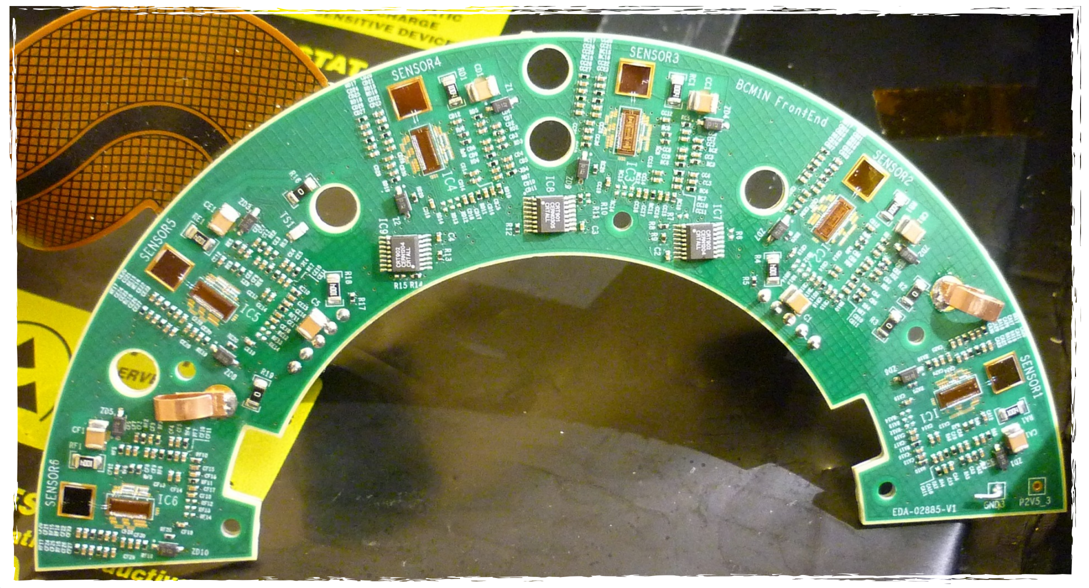
VTX Vertex Counting



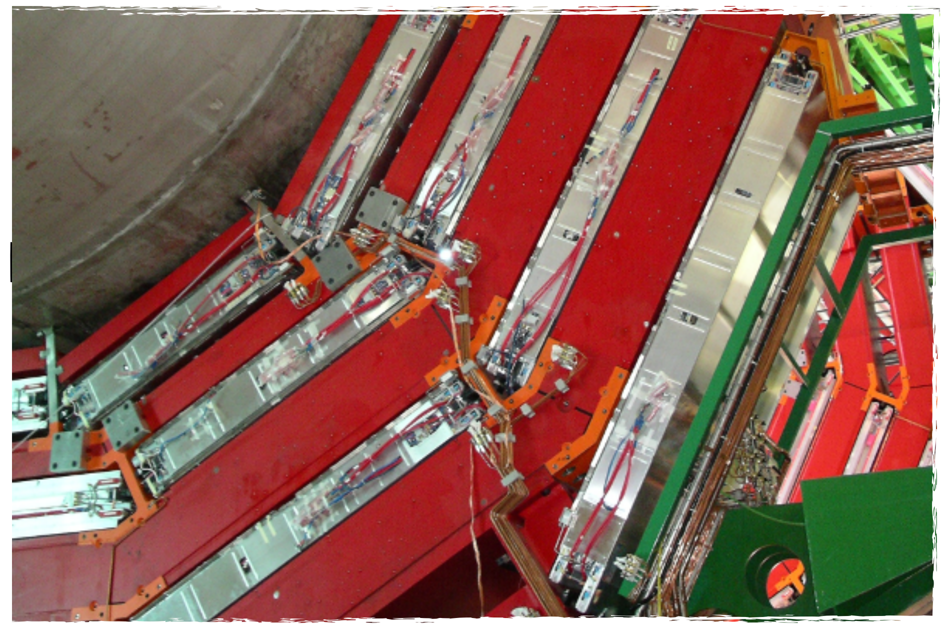
PCC Pixel Cluster Counting



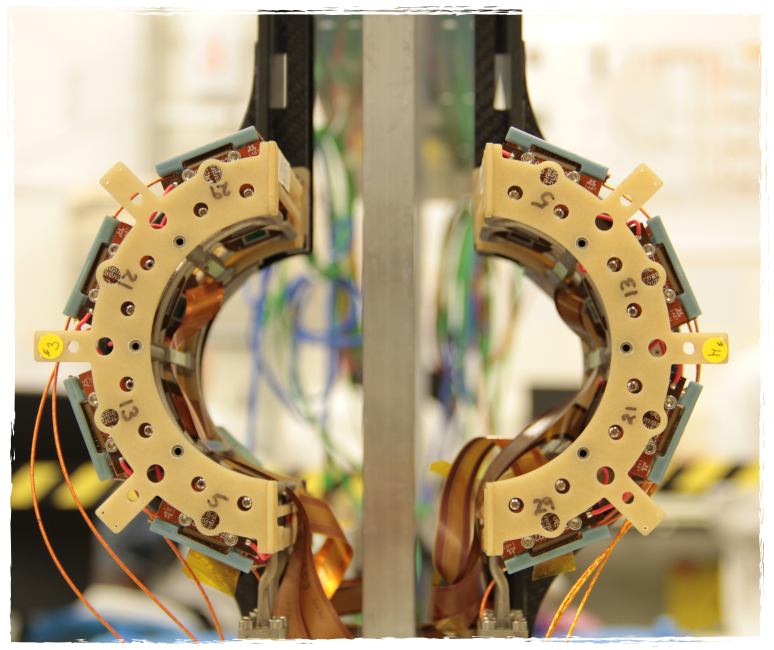
BCM1F Fast Beam Conditions Monitor



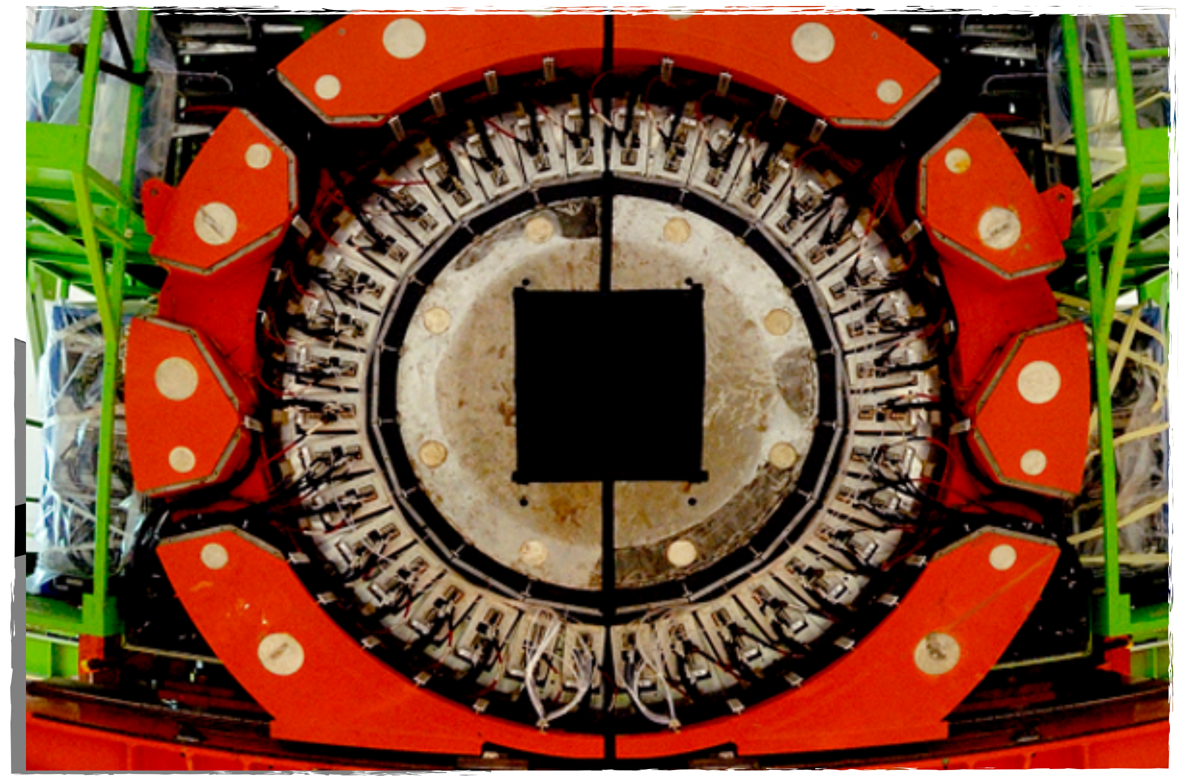
DT Muon Drift Tubes



PLT Pixel Luminosity Telescope



HF Forward Hadron Calorimeter



RAMSES RadiationMonitoring System for Environment & Safety

More
in Nimmitha Karunarathna's
poster

+ LHC devices

Beam Position Monitoring (I)

$$\mathscr{L}(t) = \frac{R(t)}{\sigma_{\text{vis}}}$$

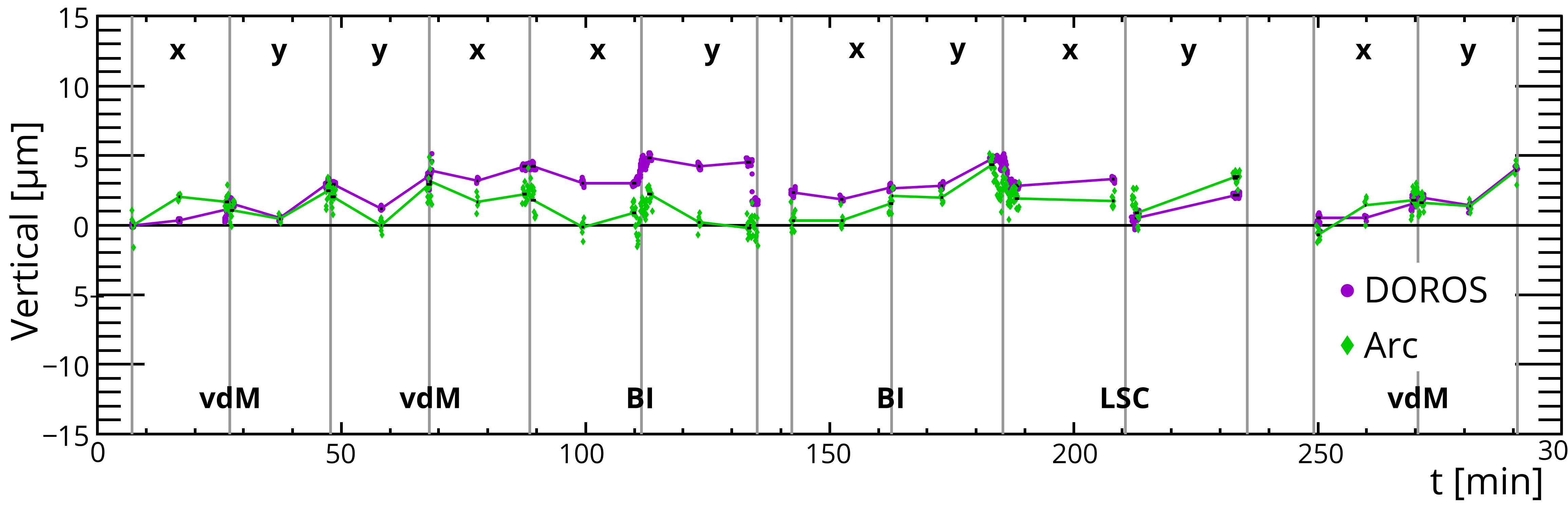
Do we know where the beams are?

- **Orbit drift:** time-dependent movement of beams away from nominal orbit
  - Measured on head-on collisions, before/after each scan
  - Linear interpolation to correct from position monitors (DOROS & ARC)

Correction of σ_{vis}: +0.2 to +1.0%

Uncertainty: 0.1%

Effect of the orbit drift in the horizontal beam-separation



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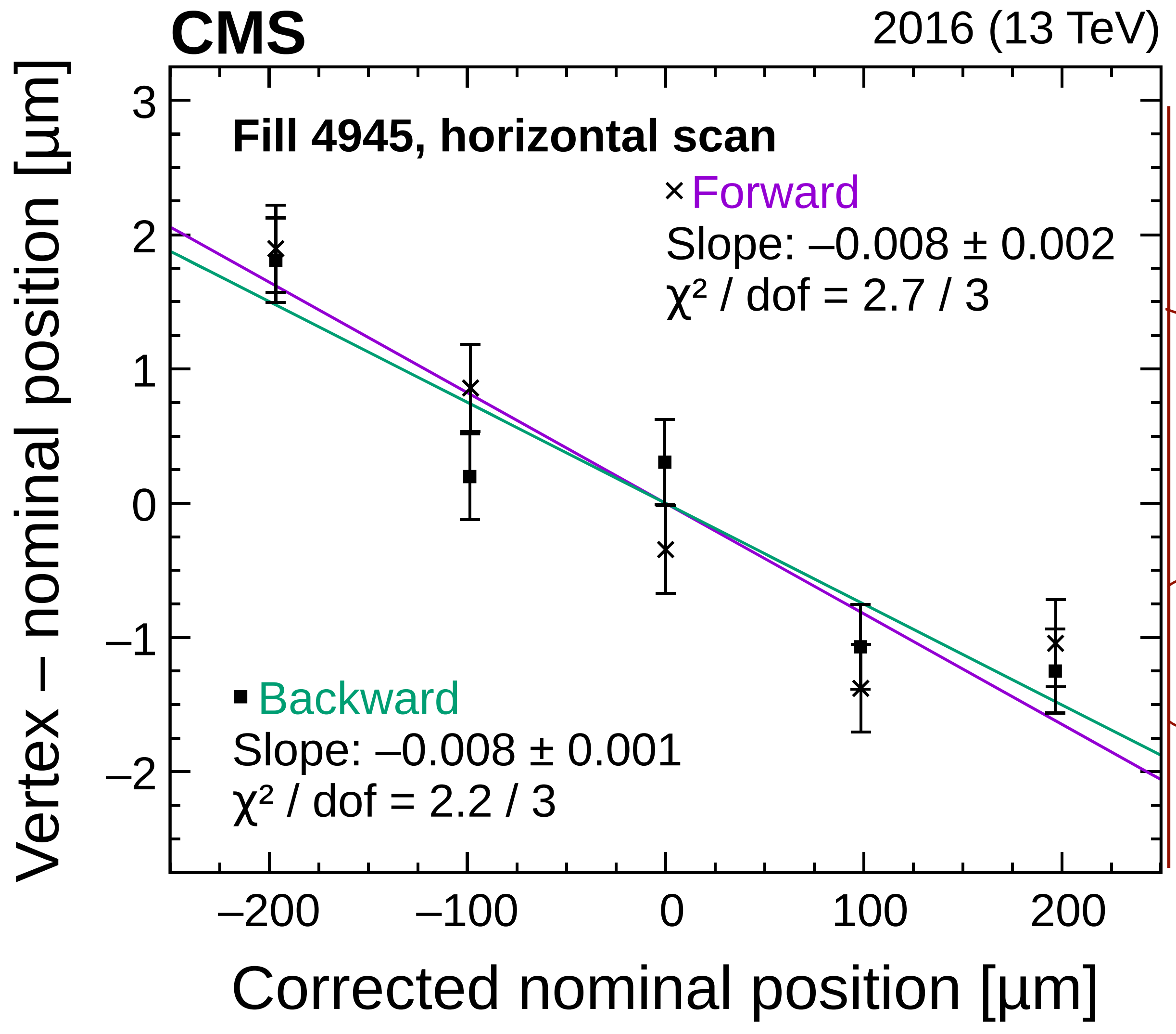
- **Length scale calibration (LSC)** of nominal beamspot position with vertices reconstructed in the tracker
  - Uncertainty on beam separation due to the response of the steering dipoles
  - Linear interpolation of the consistent slope
    - Applied as a scale factor

Correction of σ_{vis}: -1.3%

Uncertainty: 0.3%

Fit to LSC scan data



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Beam Position Monitoring (II)

$$\mathscr{L}(t) = \frac{R(t)}{\sigma_{\text{vis}}}$$

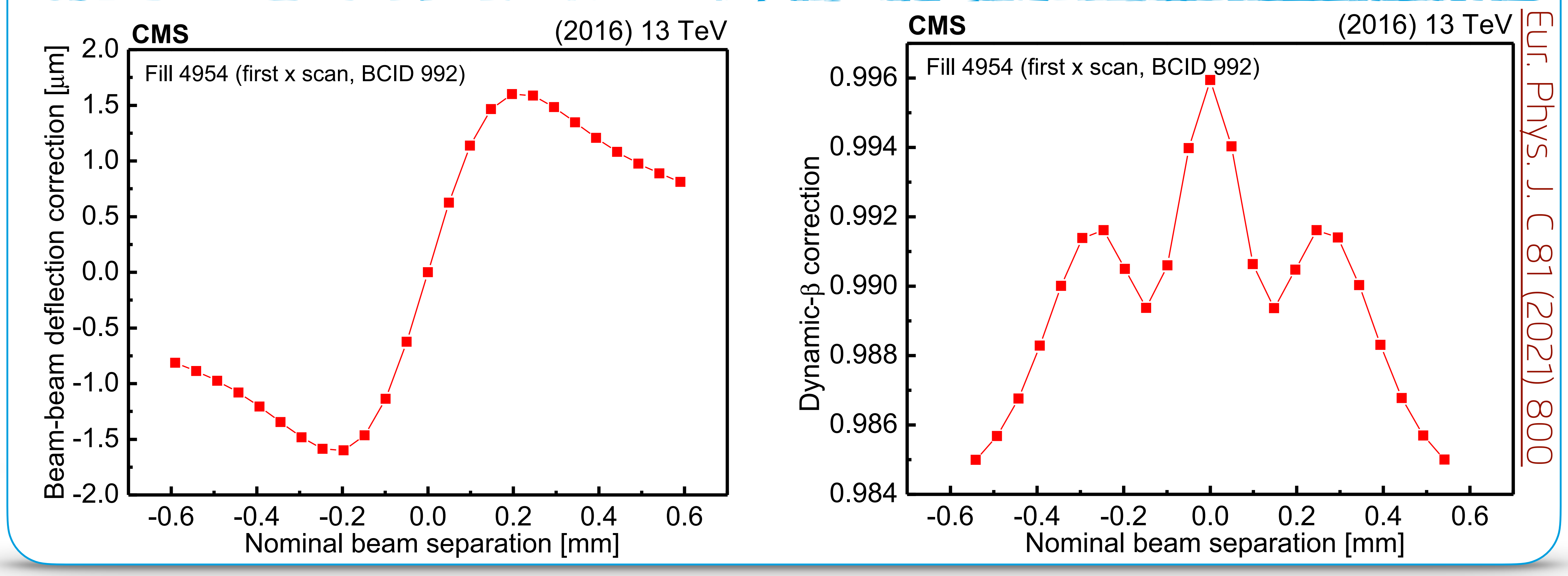
Do we know where the beams are?

- **Electromagnetic beam-beam effects**
  - Deflection: electric repulsion increases separation
  - Dynamic β^*: beam shape change from (de)focusing effect

Correction of σ_{vis}: +0.4%

Uncertainty: 0.5%

Beam-beam deflection and dynamic-β effect correction



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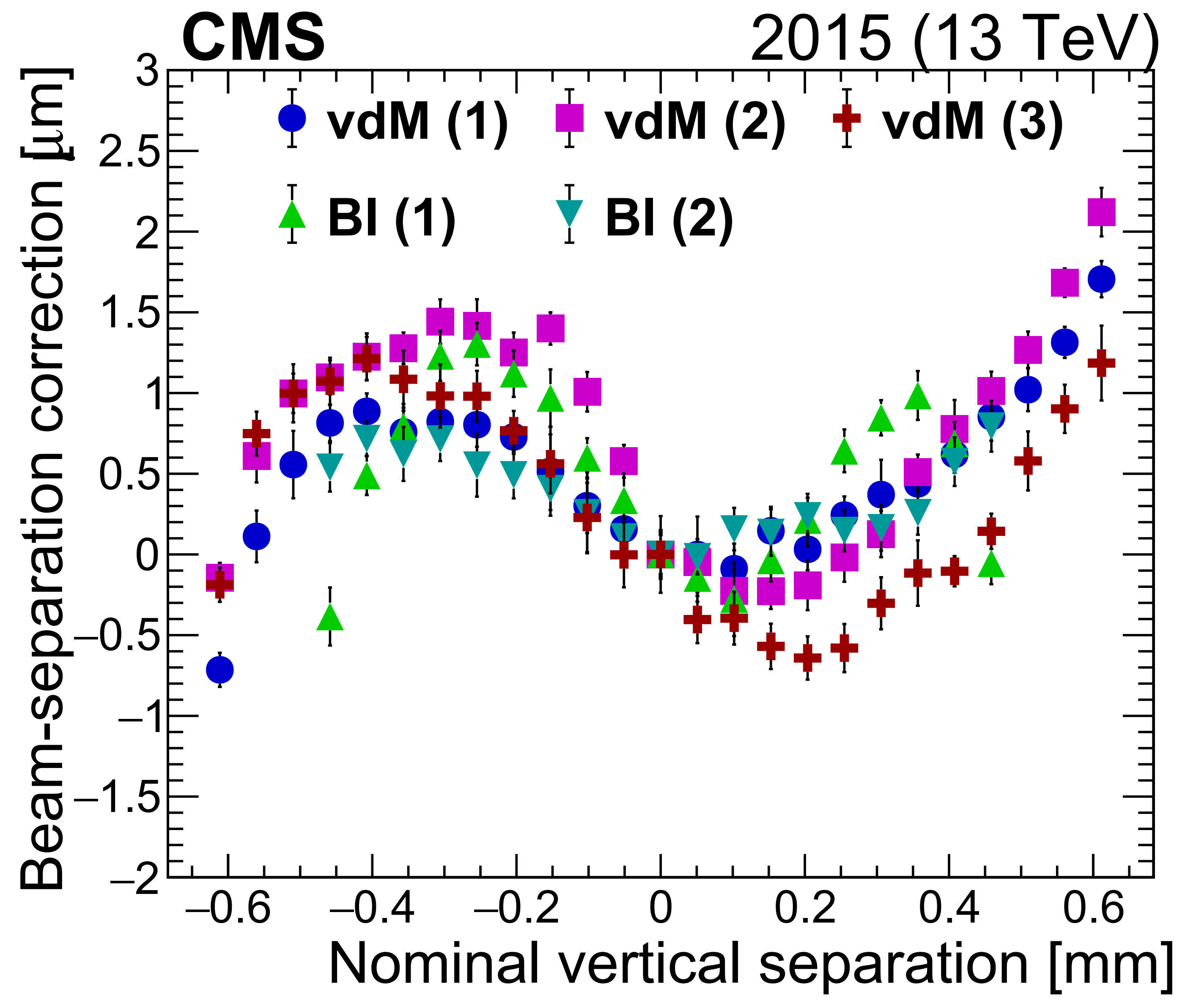
Beam separation residual



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- **Residual beam separation** in case of magnetic effect beyond LHC magnets (e.g. polarisation in iron yokes)
  - All other previous corrections already applied
    - Measured separation - nominal separation x length scale - orbit drift - deflection
  - LHC experiments consistently observe systematic deviations
  - Eur. Phys. J. C 81 (2021) 800, first publication to consider this

Correction of σ_{vis}: -0.5 to 0.2%

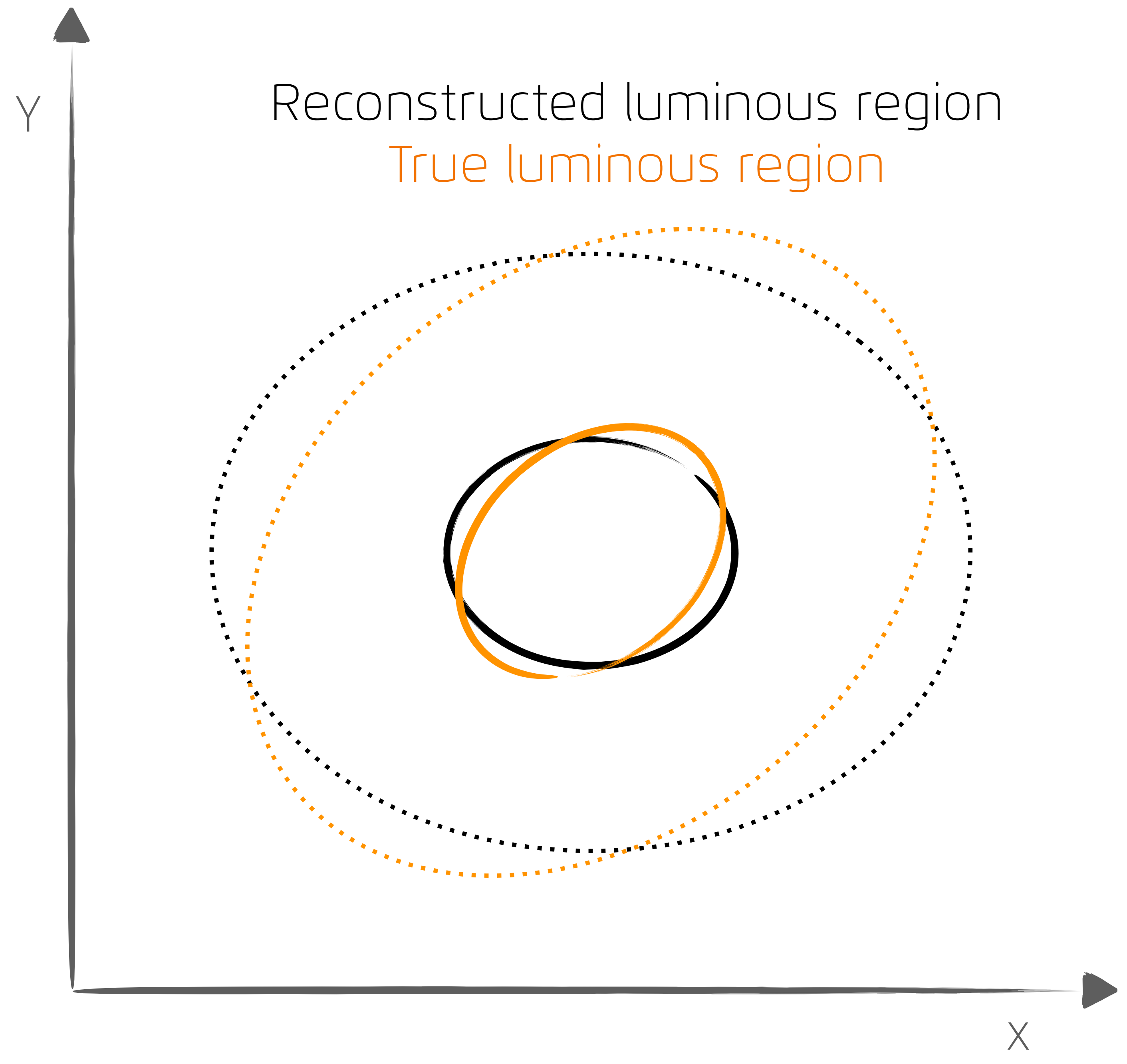
Uncertainty: 0.5%

Factorisation Bias (I)

$$\mathcal{L}(t) = \frac{R(t)}{\sigma_{\mathrm{vis}}}$$

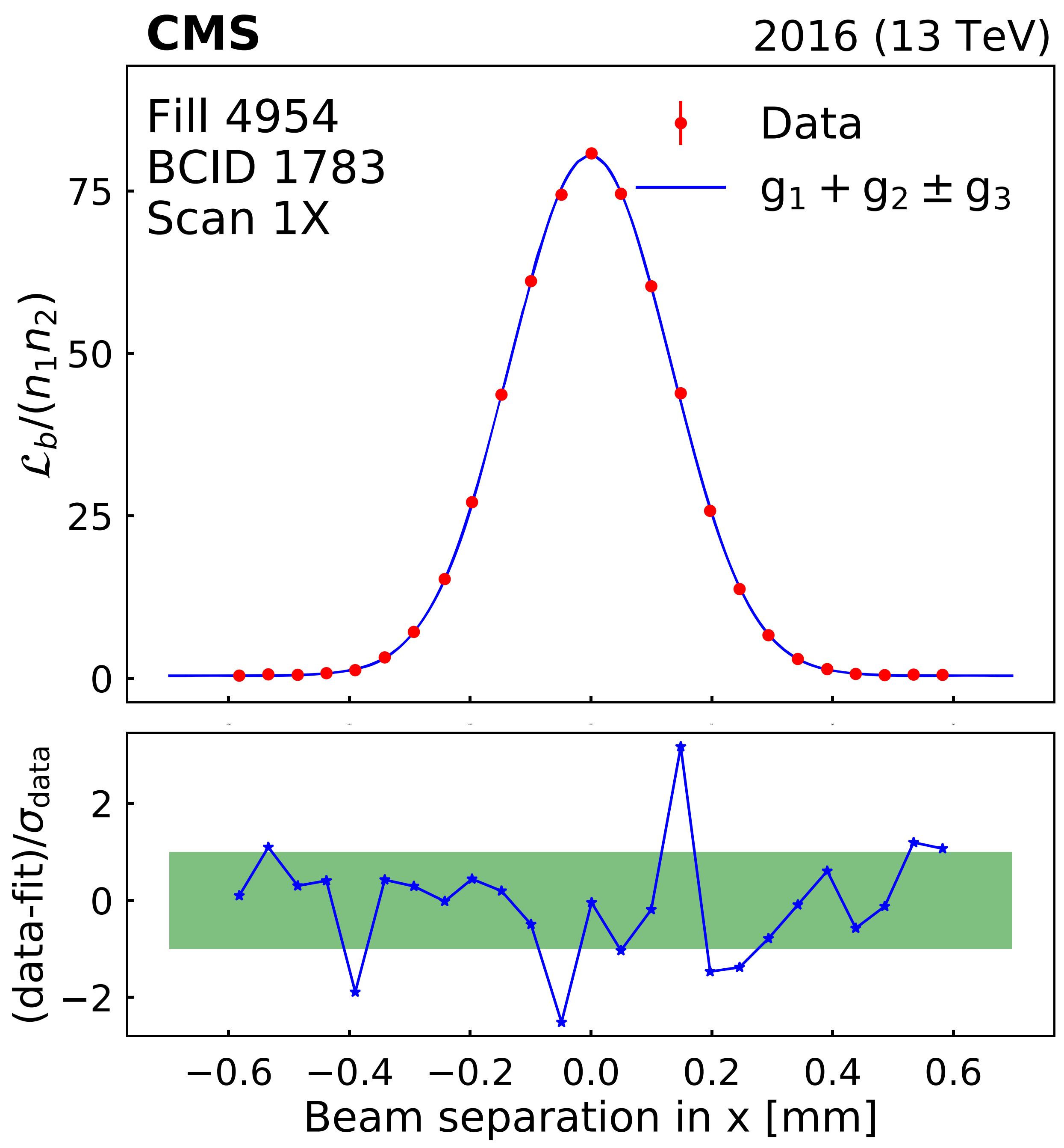
How much we can rely on the VdM scan technique?

- VdM method assumes beam proton densities factories in x and y
  - **Factorization bias:** $A_{\text{luminous}} \neq 2\pi\Sigma_x\Sigma_y$ if beam shapes have x-y correlations
    - Estimated from reconstructed transverse proton beam densities using measured vertices
  - Parametrisation of beam densities to determine the correction to $\boldsymbol{\sigma}_{\mathrm{vis}}$
  - Two methods, used in a combined way



- **Luminous Region Evolution**
  - Rates and 3D-beamspot information from each scan step of any VdM scan
  - Reconstruct 3D bunch proton densities as a function of time from simultaneous unbinned maximum likelihood fit (three-components Gaussian function)

Beam-separation dependance of the rate



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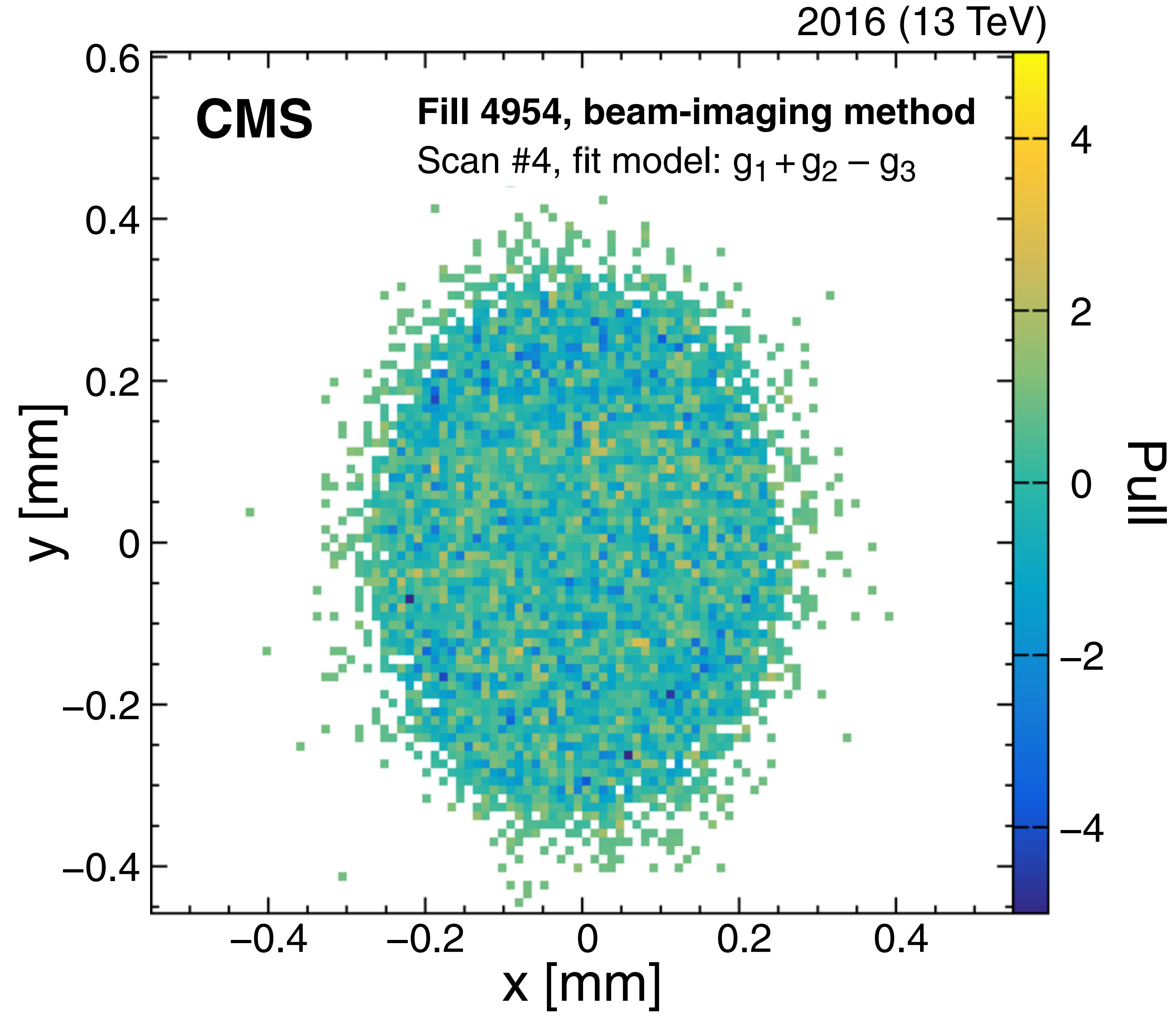
Factorisation Bias (II)

How much we can rely on the VdM scan technique?

- **Beam Imaging Scan**
  - Requires special VdM scans: Beam Imaging (BI) or single-beam scans
    - Only one beam moves at a time with small steps -> four scans: 1X, 1Y, 2X, 2Y
  - Reconstructed vertices from all steps into one cumulative histogram

2D pull distribution of the fit model w.r.t. vertex distribution



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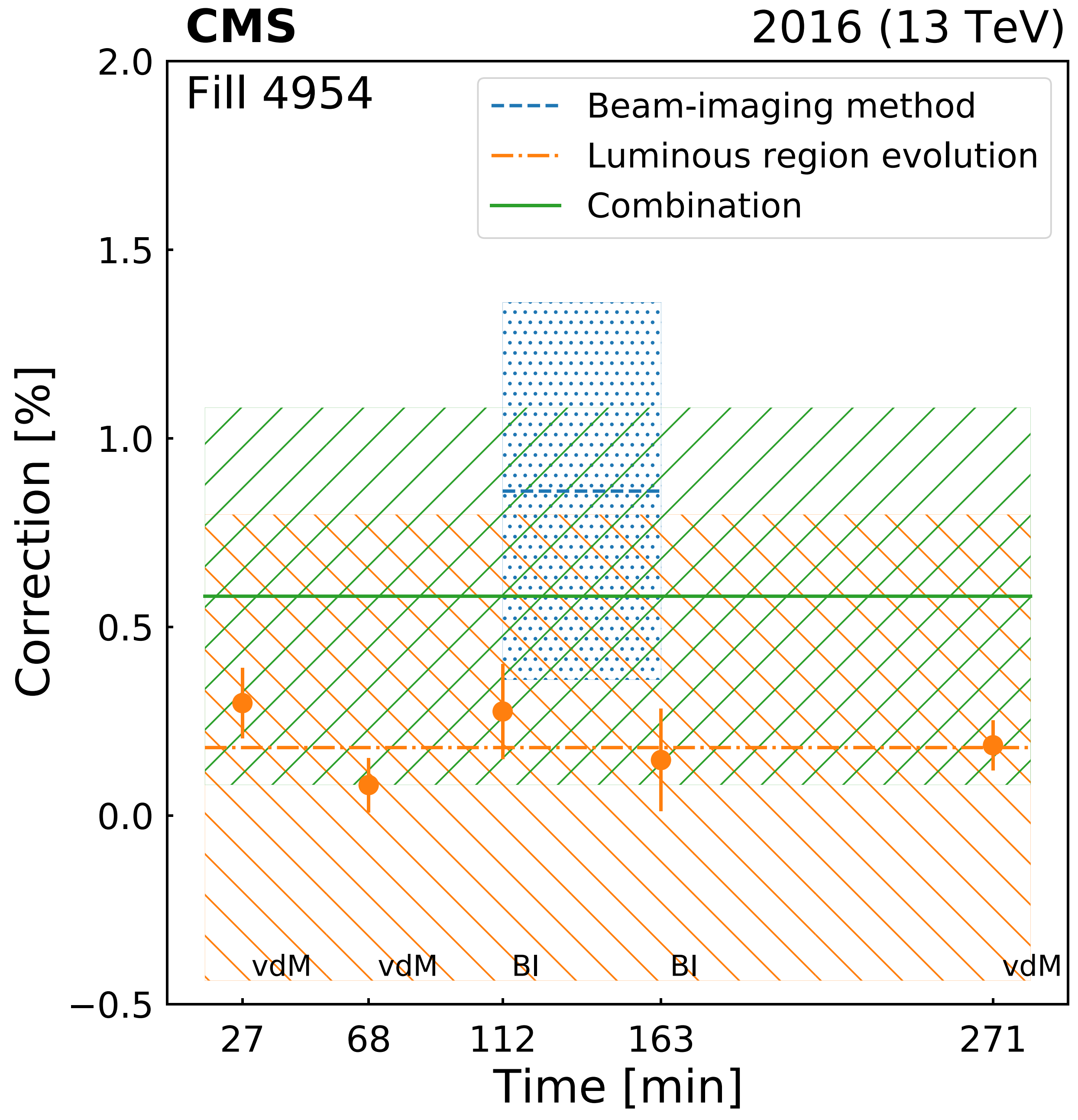
- Fit to transverse bunch profiles integrated over the scanning direction (three-components Gaussian function)
- Correction to σ_{vis} using pseudo-experiments of VdM scans with fitted $\rho(x,y)$

- Two methods provide compatible results

Correction of σ_{vis}: +0.6%

Uncertainty: 0.5%

Correction to σ_{vis} from the two methods and their combination



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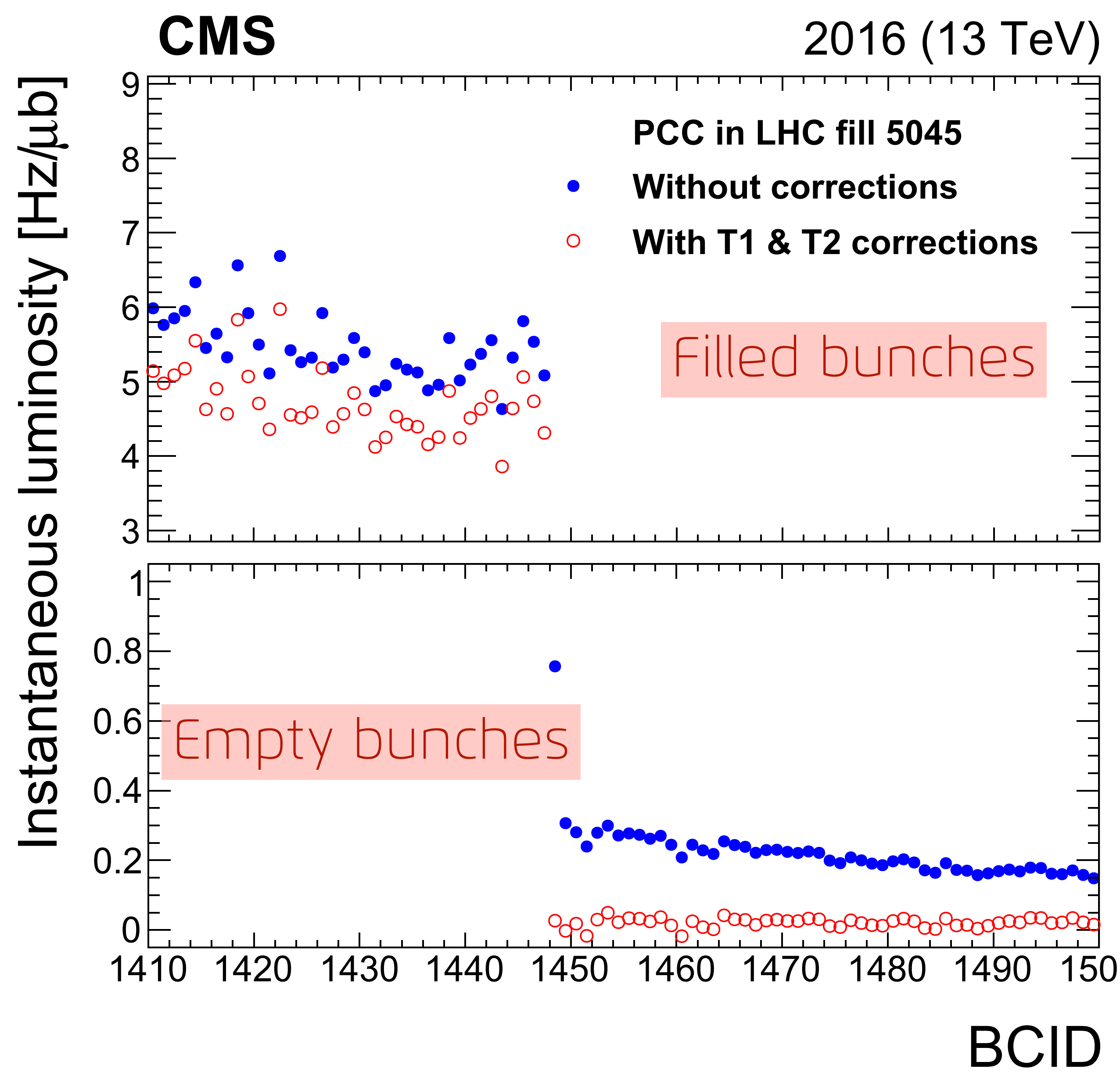
Rate corrections

How to correct uncalibrated luminometers?

- How to ensure accurate final luminosity values in nominal conditions?
- The measurements suffer of **out-of-time pileup contributions**, not arising from pp collisions
  - ✦ Spurious signal from activation of detector material after collisions
  - ✦ Corrections are derived from rate measurements in empty bunches

Instantaneous luminosity before and after corrections also for empty bunches



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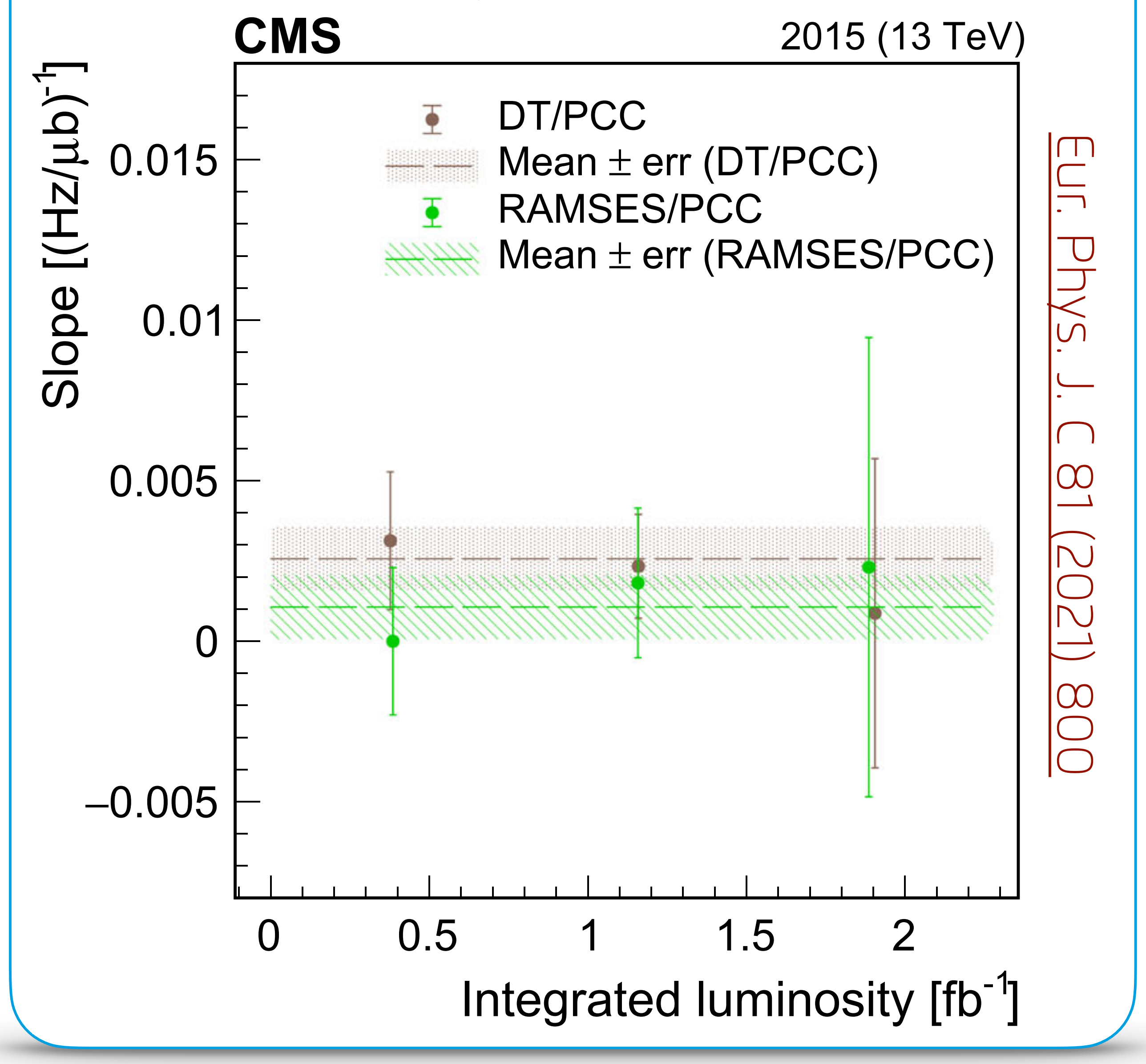
Uncertainty: 0.3%

Linearity summary



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- Comparisons between different luminometers performed to assess any remaining systematics effects
- **Linearity**: change of detector conditions (e.g. pileup)
  - ✦ Slope of ratio as function of instantaneous luminosity in time intervals

Uncertainty: 0.3%

Detector stability and linearity

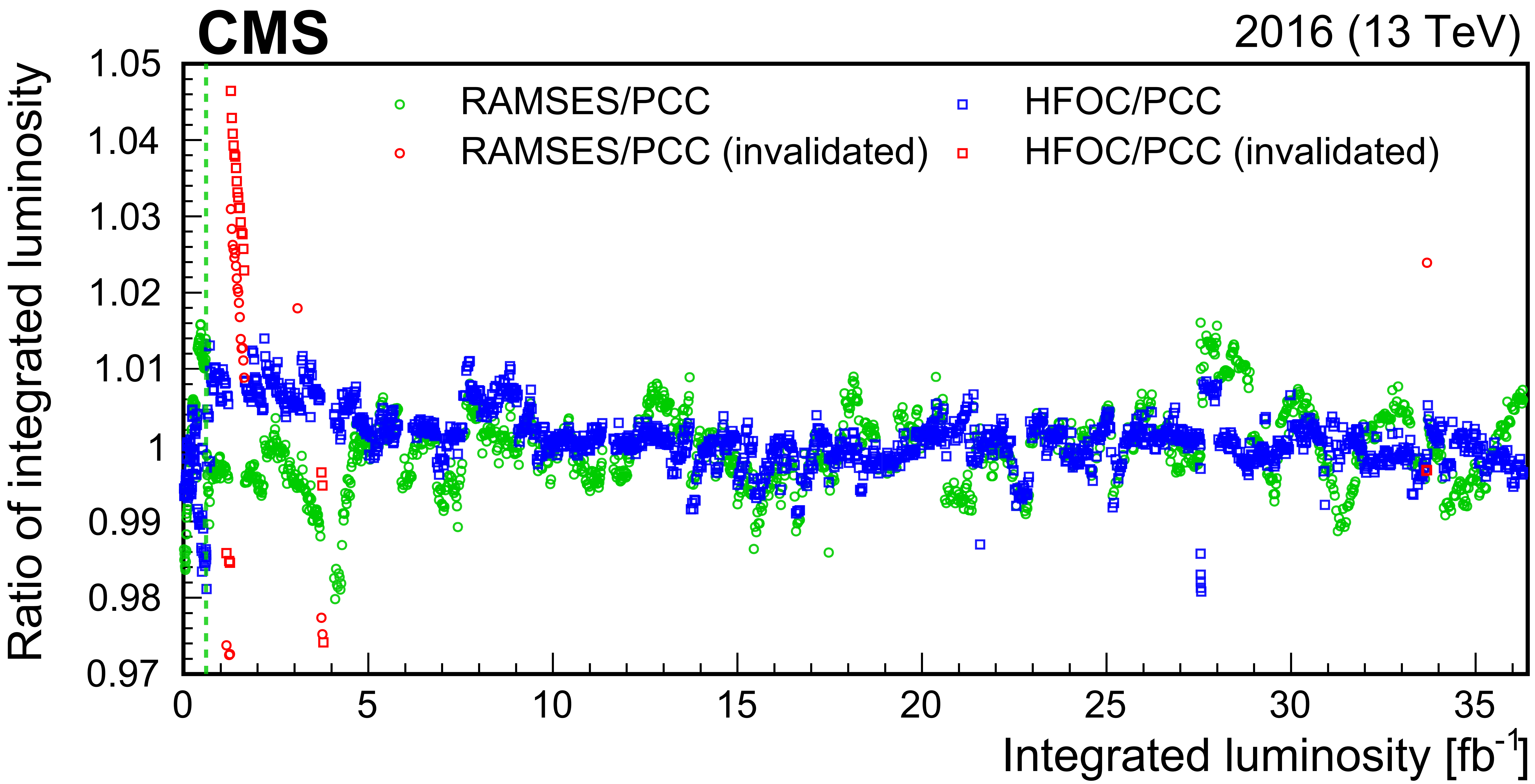
How to assess remaining systematic effects?

$$\mathscr{L}(t) = \frac{R(t)}{\sigma_{\text{vis}}}$$

- **Stability**: change of detector conditions over time
  - Cross-detector stability from independent systems
    - Invalidated data highlighted in red

Uncertainty: 0.45%

The luminosity measurements compared as a function of the integrated luminosity



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Run 2 Luminosity at 13 TeV

pp, 13 TeV		2015	2016	2017 *	2018 *	2016 - 2018
		Eur. Phys. J. C 81 (2021) 800		LUM-17-004	LUM-18-002	
Recorded luminosity	[fb^{-1}]	2.27	36.3	41.5	59.8	138
Total uncertainty	[%]	1.6	1.2	2.3	2.5	1.6
beam currents	[%]	0.2	0.2	0.3	0.2	
orbit-drift	[%]	0.2	0.1	0.2	0.1	
VdM fit & consistency	[%]	0.6	0.3	1.1	0.5	
length scale	[%]	0.2	0.3	0.3	0.2	
beam positions	[%]	0.8	0.5	0.2	0.1	
beam-beam effects	[%]	0.5	0.5	0.6	0.2	
factorisation bias	[%]	0.5	0.5	0.8	2.0	
linearity	[%]	0.5	0.3	1.5	1.1	
stability	[%]	0.6	0.5	0.5	0.6	

* preliminary

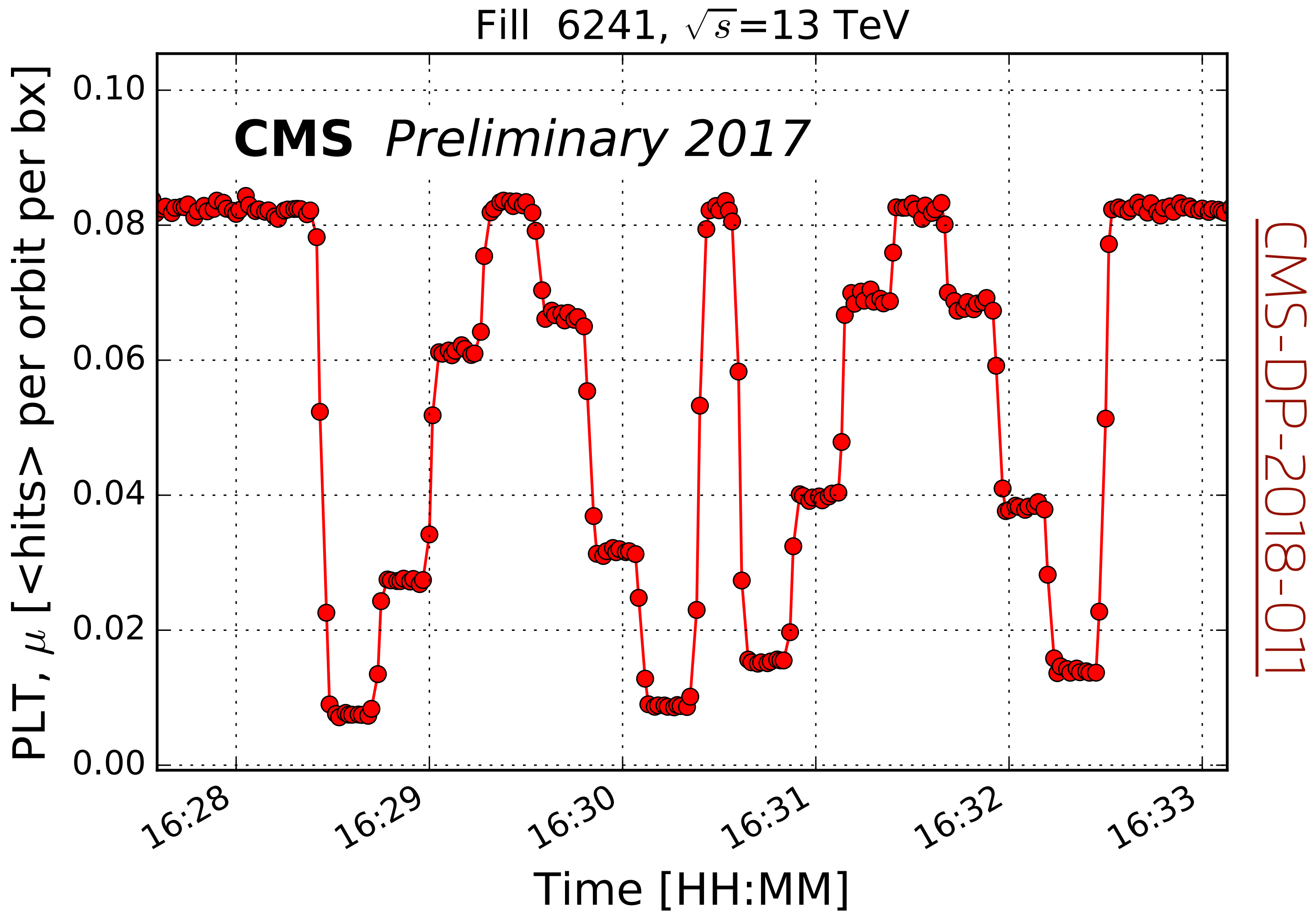
- Eur. Phys. J. C 81 (2021) 800
  - First CMS luminosity paper
  - First Run 2 luminosity paper
    - Matches LHCb Run 1 record of 1.2% precision
  - Key systematic sources ⇒ challenges for final 2017–2018 luminosity

Emittance Scans

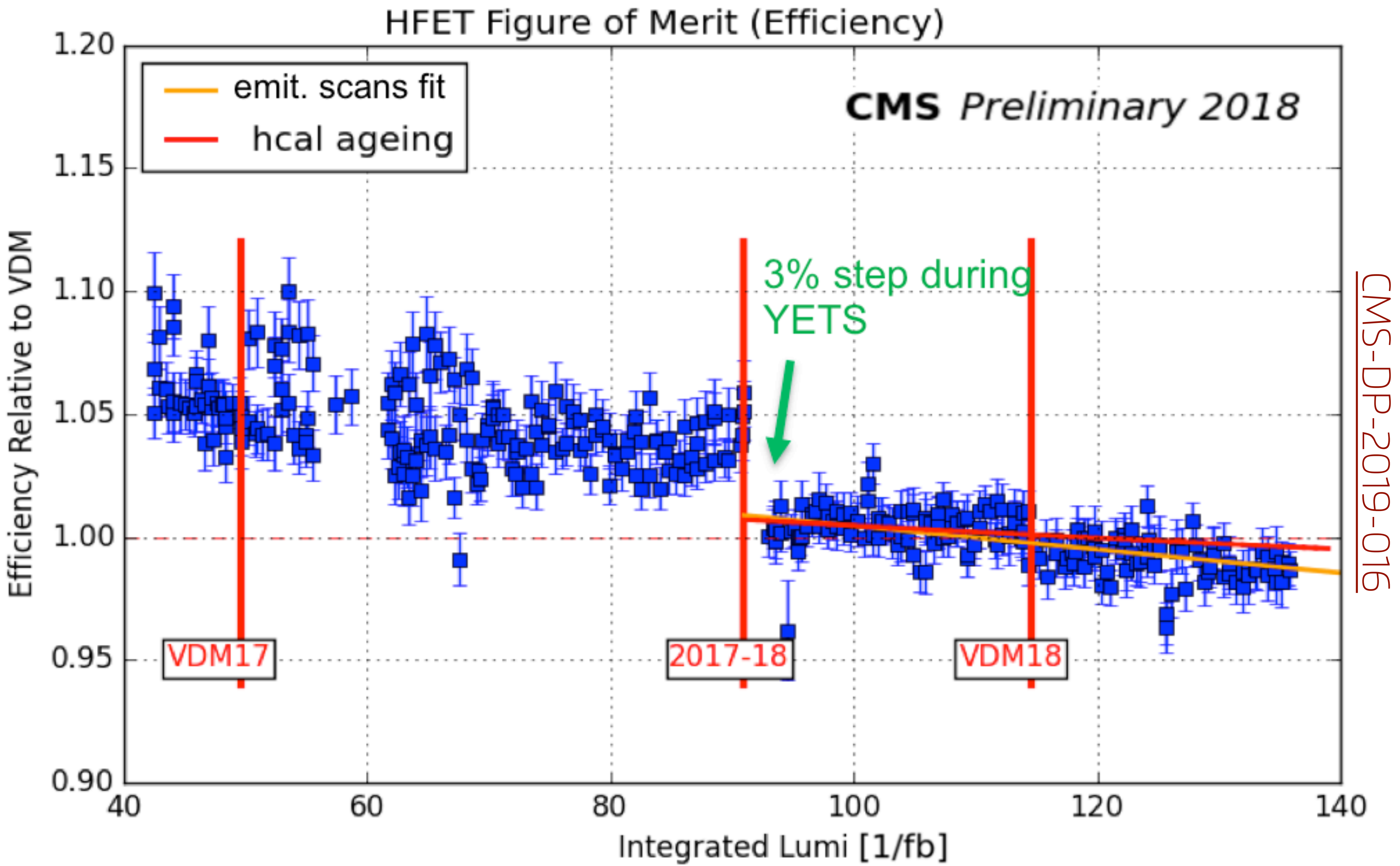
Any other methods for integration?

- **Emittance scans** as powerful tool for LHC diagnostics
  - Short VdM scans at start and (often) at end of physic fill in 2017 & 2018 at CMS
  - Monitor changes in detector efficiency and improve understanding of luminosity measurement during the year
    - Each luminometer is independently calibrated
    - Ratios of luminometers used as a final validation

Measured value of μ in the late emittance scan in fill 6241



Efficiency as the change of the calibration constant measured in emittance scans with respect to the Van der Meer calibration



Summary

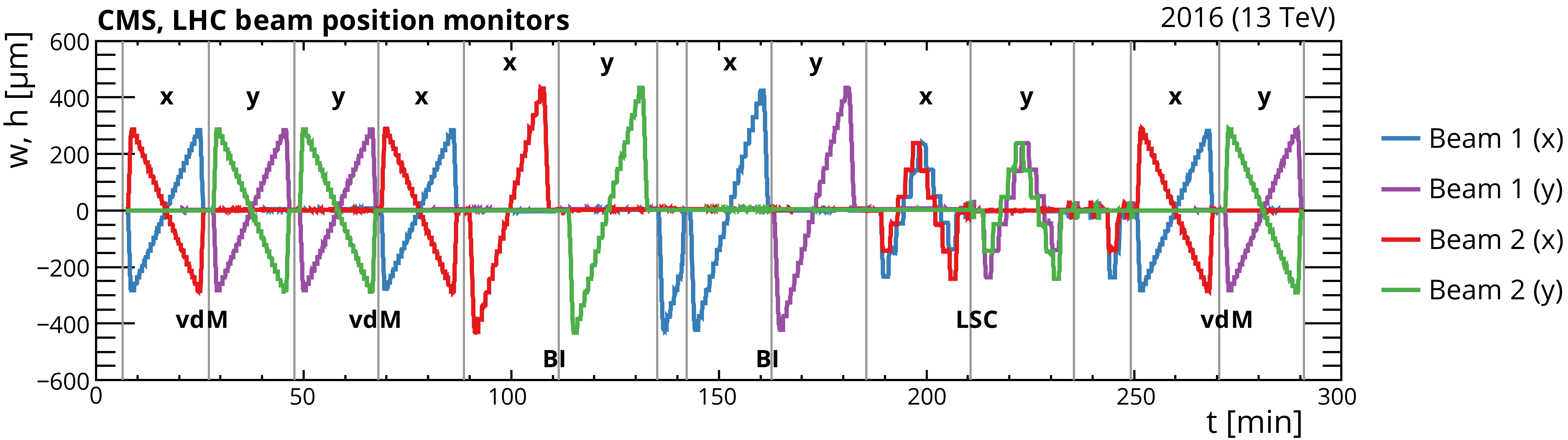
- Luminosity is a measure of the collision rate
  - A precise luminosity measurement is crucial for cross section measurements
- At CMS, the precise luminosity measurement is calibrated with the Van der Meer method using beam-separation scans, and integrated over time and pileup
  - Many sources of systematic effects studied in details to achieve a high precision
- The CMS luminosity measurement for the 2016 data with a precision of 1.2% in the most precise Run 2 result to date
- Improved luminosity measurement with proton-proton collision for 2017-2018 data soon!
- Results for other datasets available
  - PbPb, etc...

More in Krisztián Farkas's poster

More in Nimmitha Karunarathna's poster

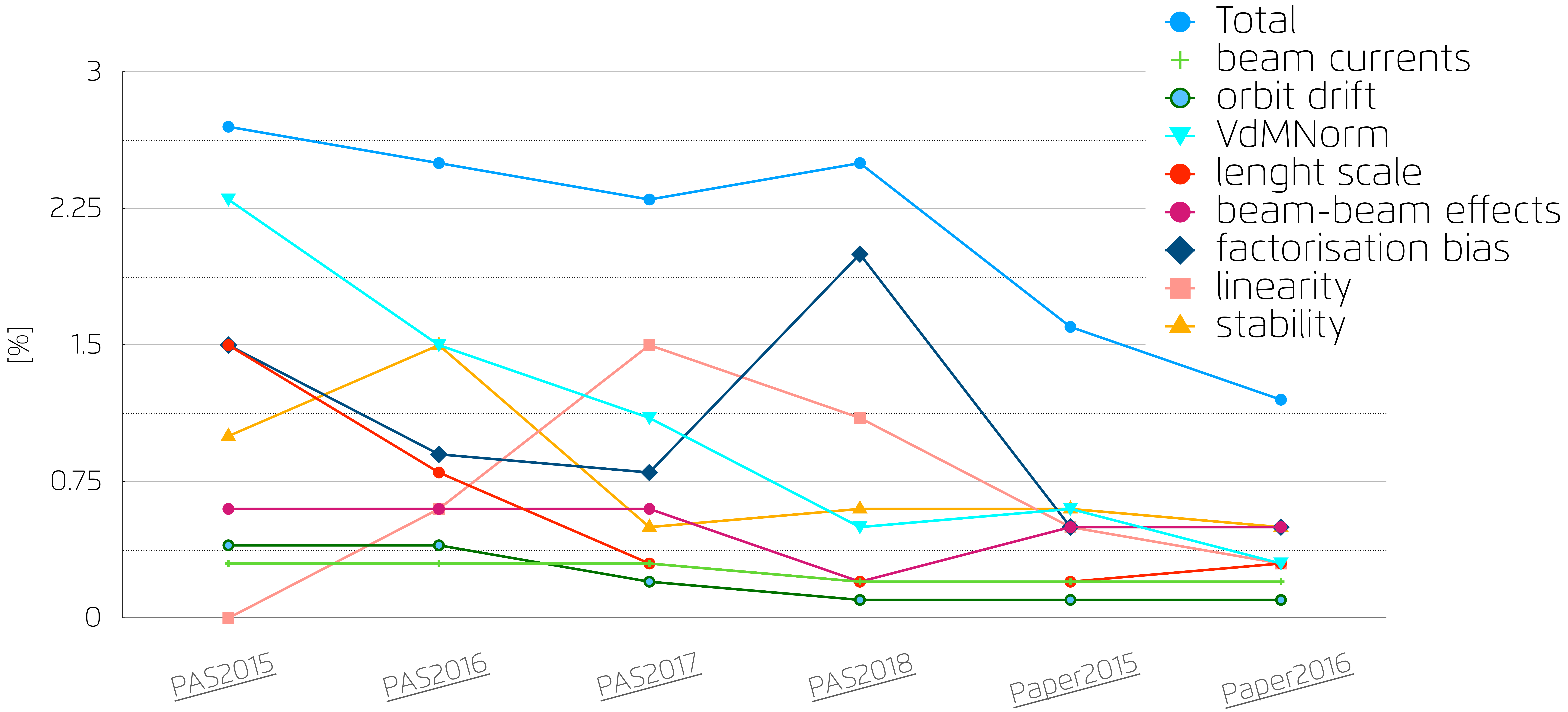
Additional Material

VdM Scan program



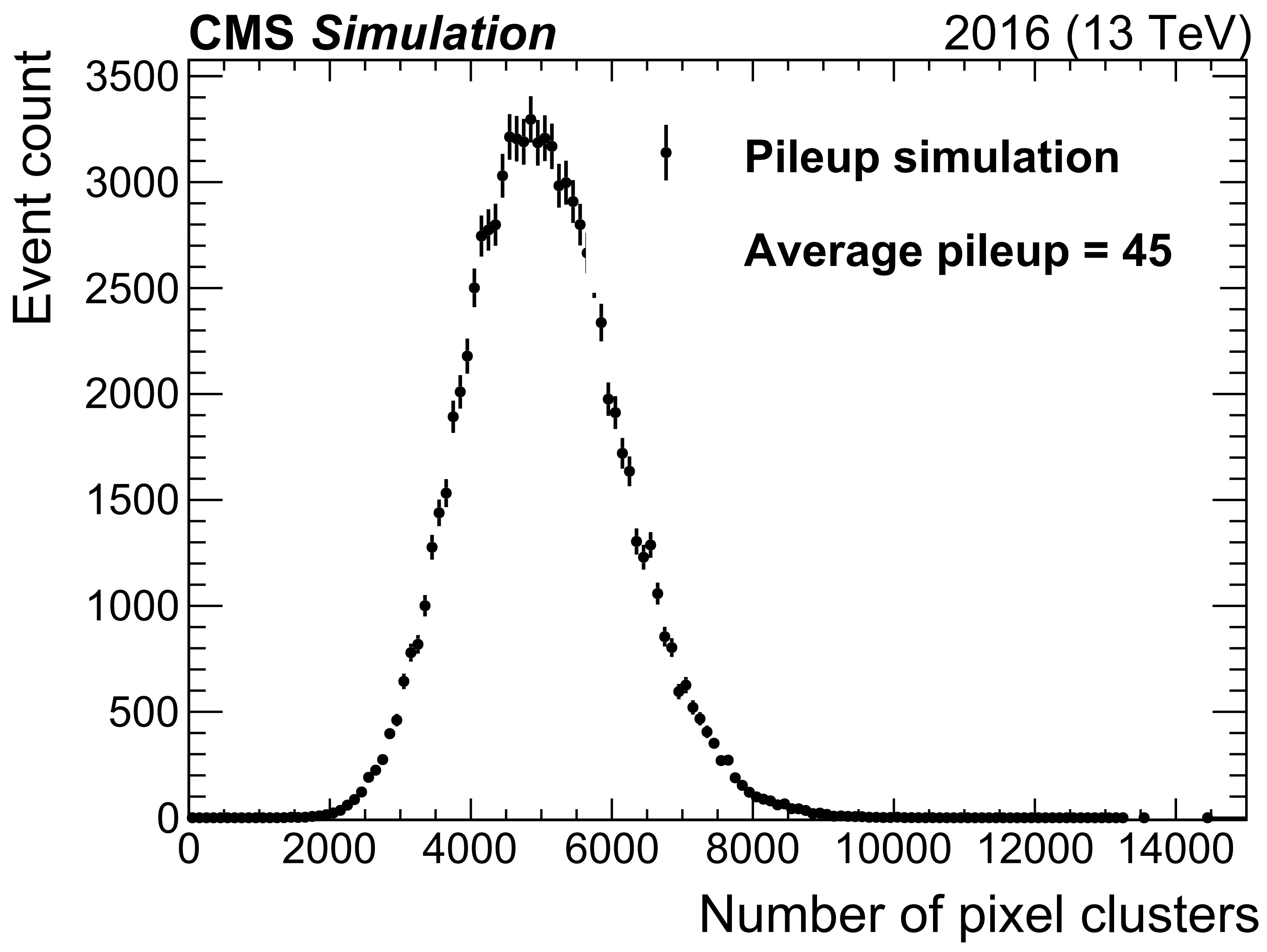
Fill	$\sqrt{s}$ (TeV)	Date	n_b	ϕ (µrad)	β^* (cm)	μ	$\mathcal{L}_{init}$ ($\times 10^{30}$ cm^{-2} s^{-1})	No. of scans		
								vdM	BI	LSC
4266	13	Aug. 2015	30	0	1917	0.6	2.7	6	4	3
4945	13	May 2016	32	0	1917	0.6	2.5	–	–	2
4954	13	May 2016	32	0	1917	0.6	2.5	6	4	2

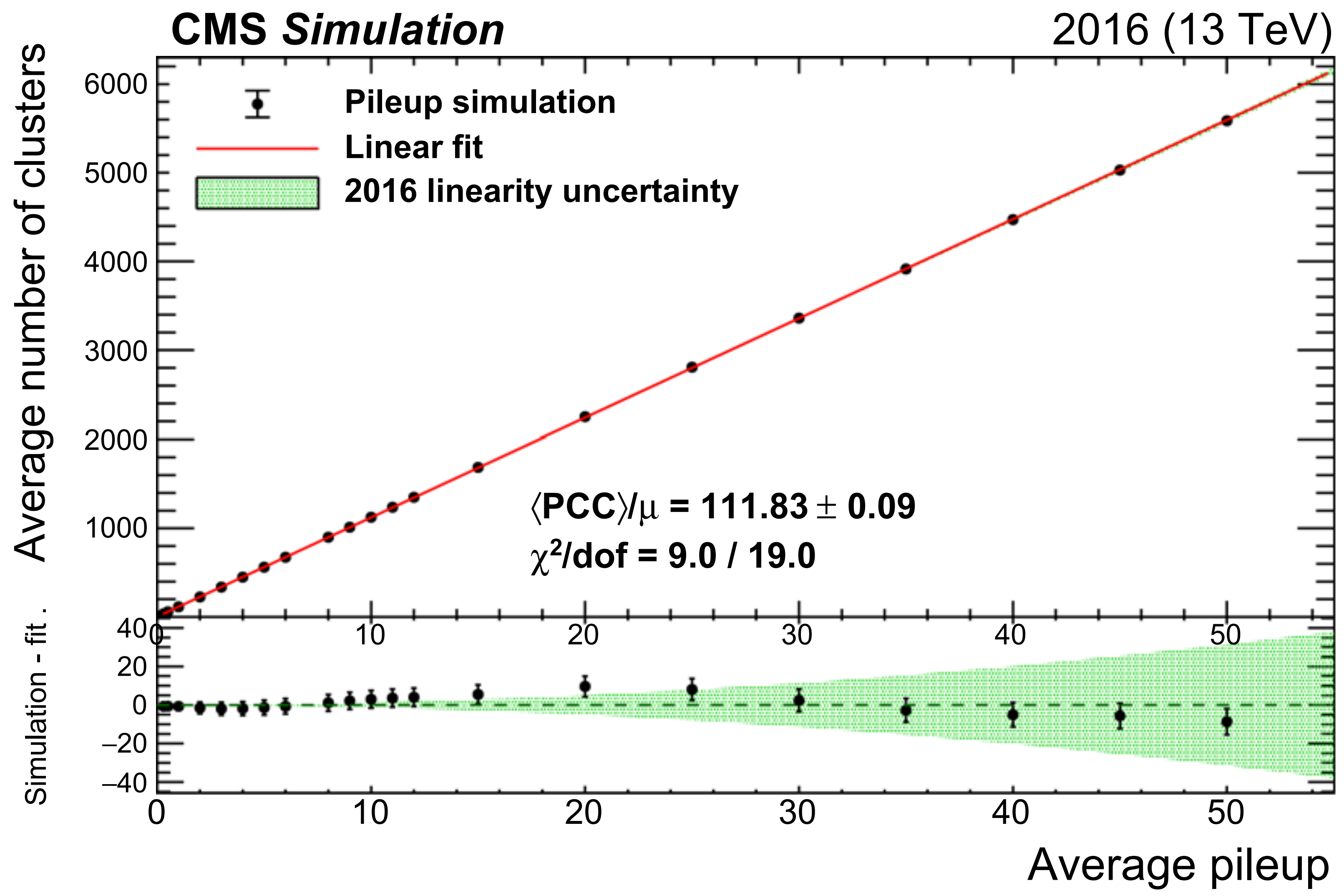
Run 2 Luminosity at 13 TeV



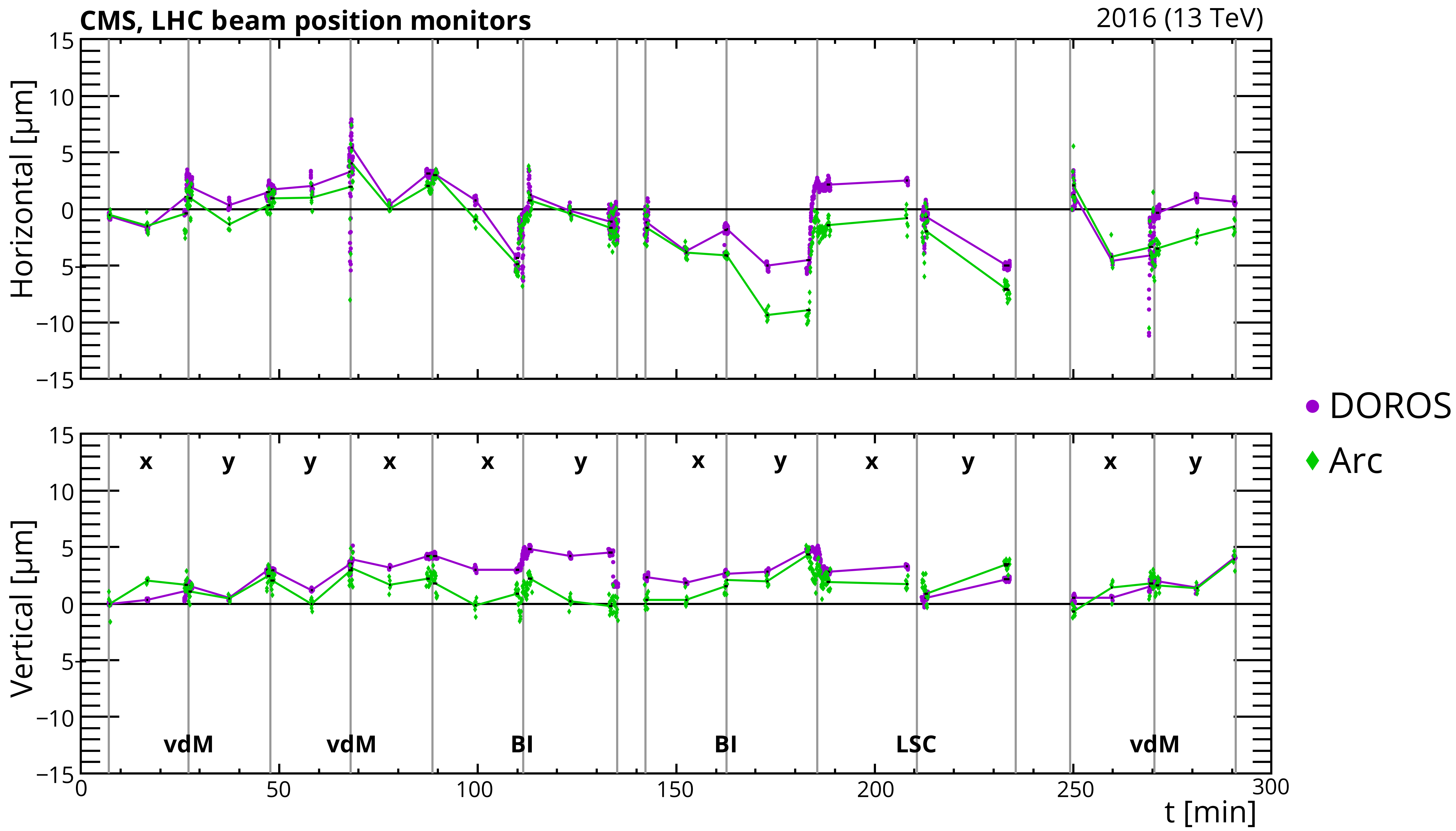
Luminometers: Pixel Cluster Counting

- Very large number of pixel
  - Very small probability for two charged particles to hit same pixel
    - Response very linear to pileup (studied also in MC)
  - Only use pixel modules that were fully operational during full data-taking period
    - Do not use innermost pixel layer due to large dynamic inefficiency





Calibration: Orbit Drift



- DOROS BPMs near CMS behind steering magnets
- ARC BPMs in LHC arcs adjacent to CMS
- Measure beam positions during head-on collisions: before & after scans, at central steps

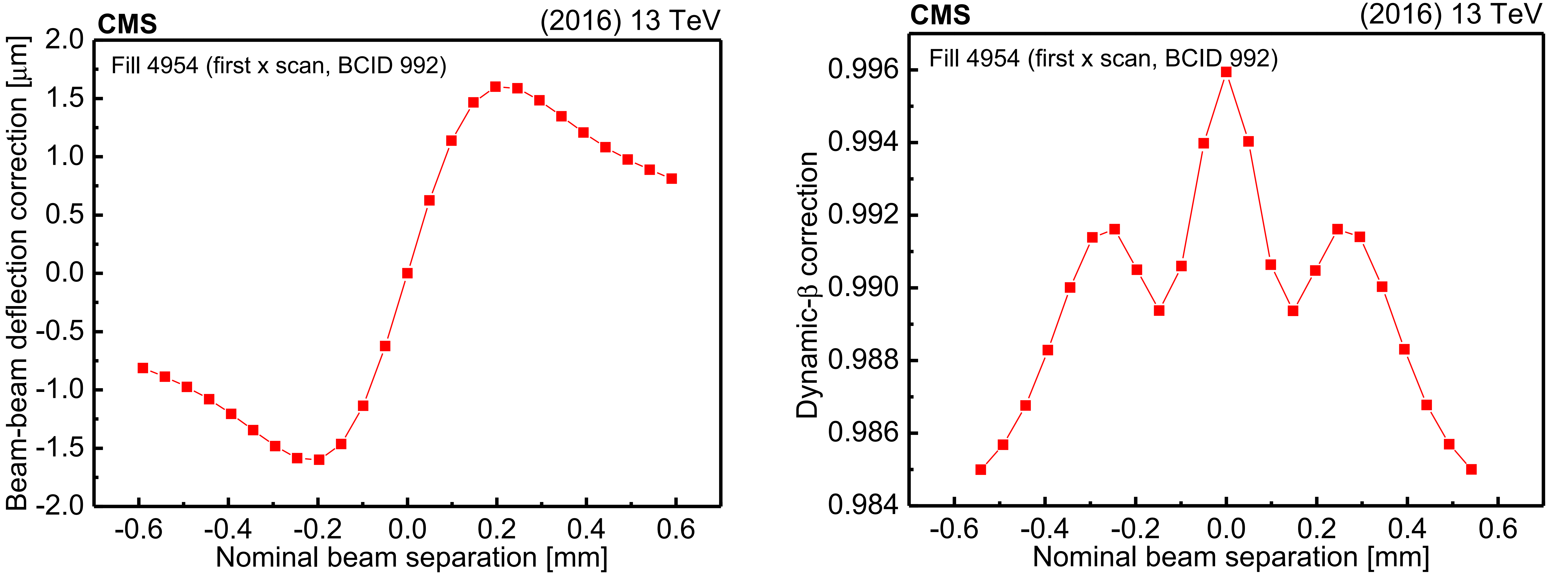
- Linear interpolation to correct nominal positions during VdM scans
- Impact on sigma_vis from DOROS/ARC average: +0.2% up to 1.0%
- Uncertainty from DOROS/ARC difference: 0.2% (2015), 0.1% (2016)

Calibration: Beam-beam effects

Electromagnetic interactions between the proton beams

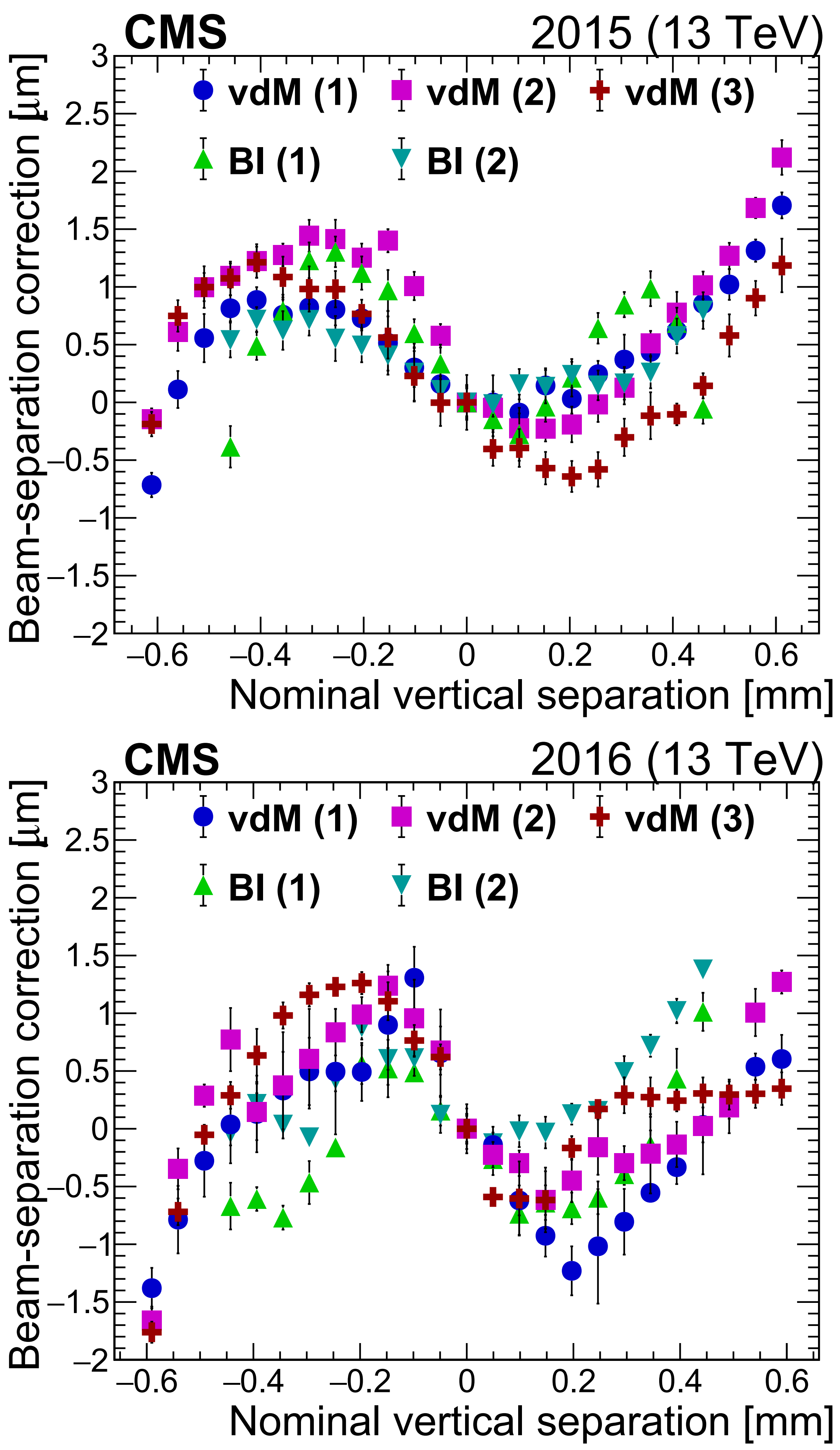
- Coherent deflection of beams away from each other due to electric repulsion
  - calculated analytically
  - impact on sigma_vis: +2.0% (2015), +1.6% (2016)

- Incoherent deflection at per-particle level impacts proton distributions
  - dynamic evolution of beta star -> changes measured luminosity
  - calculated numerically with dedicated particle tracking simulation
  - impact on sigma_vis: -1.7% (2015), -1.4% (2016)



Calibration: Residual Beam Movements

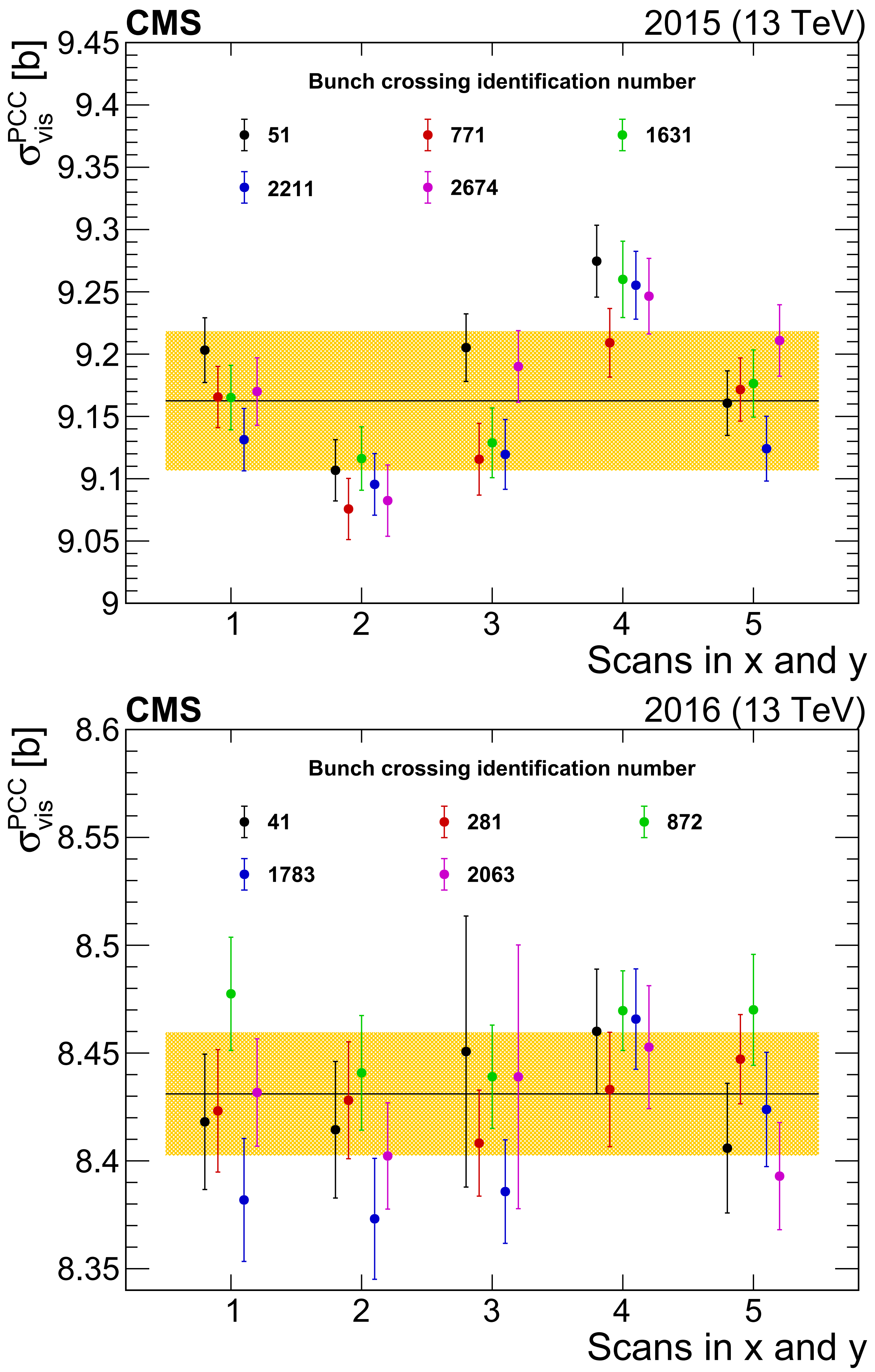
- Evaluate beam positions after all known effects were taken into account
- Separate measurements for both beams
  - Observe antysimmetric systematic structure between two beams
- Study performed for first time
- Relevant for sigma_vis: systematic change of beam separation



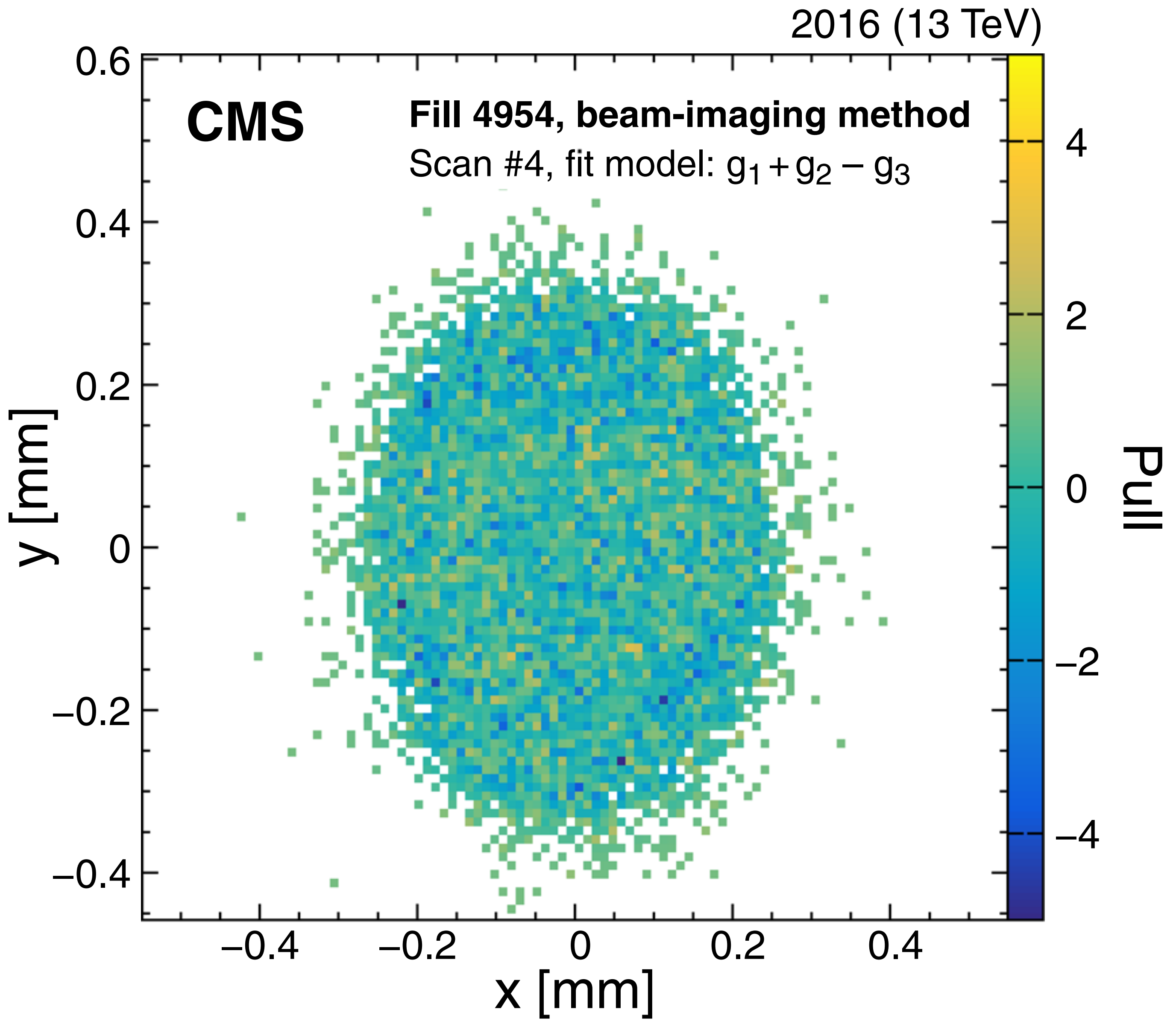
Calibration: Visible cross section

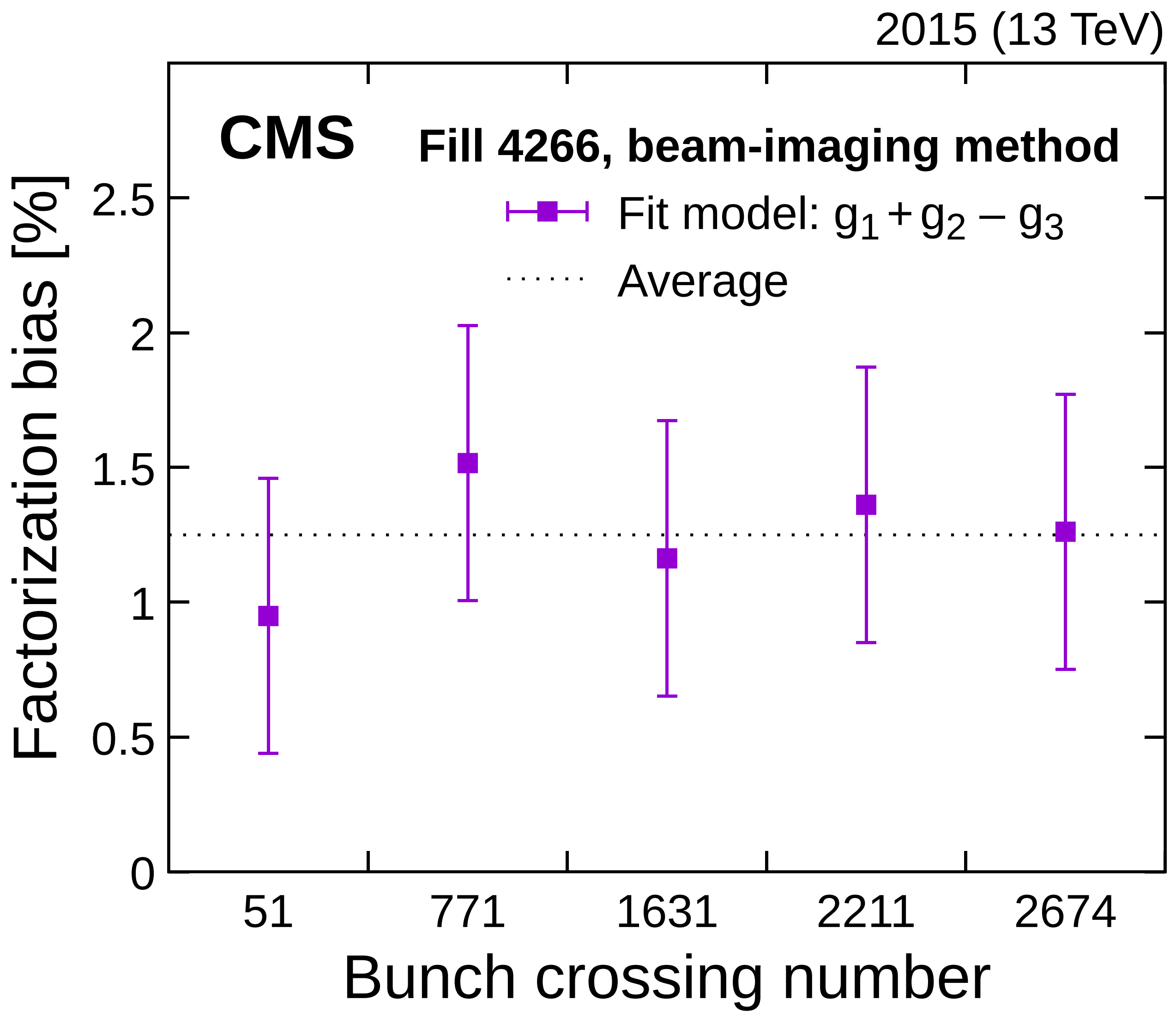
- Good consistency of sigma_vis measured for different bunch crossings and scan pairs
- Calibration uncertainty dominated by residual beam movement

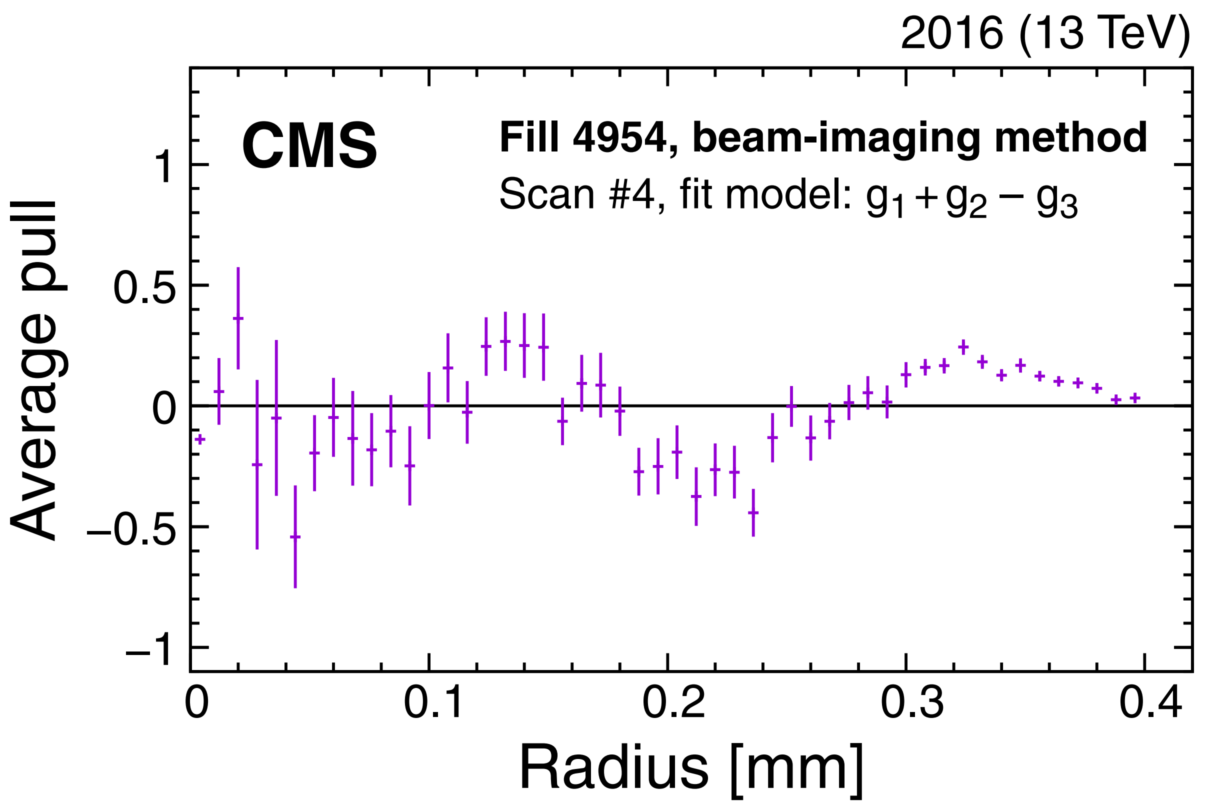
Source	2015 (%)	2016 (%)	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
Beam position monitoring			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
Beam overlap description			
Beam-beam effects	0.5	0.5	Yes
Length scale calibration	0.2	0.3	Yes
Transverse factorizability	0.5	0.5	Yes
Result consistency			
Other variations in σ_{vis}	0.6	0.3	No

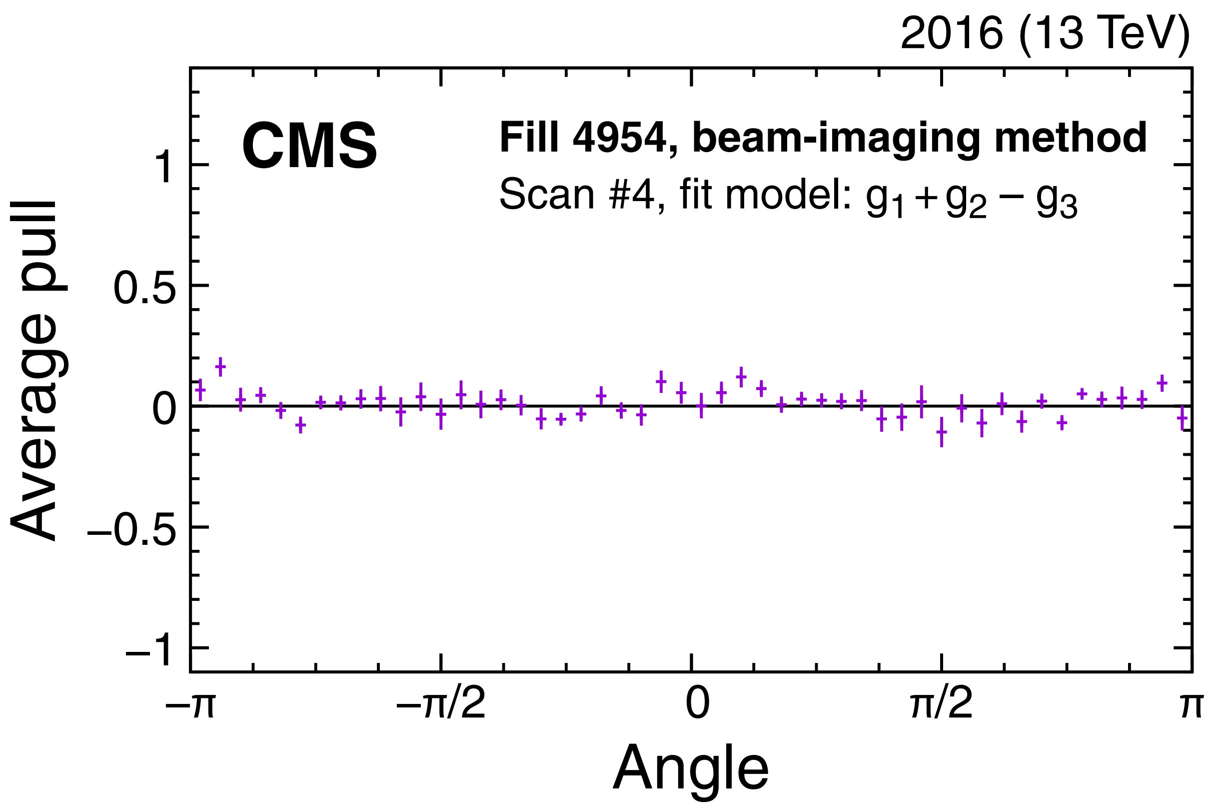


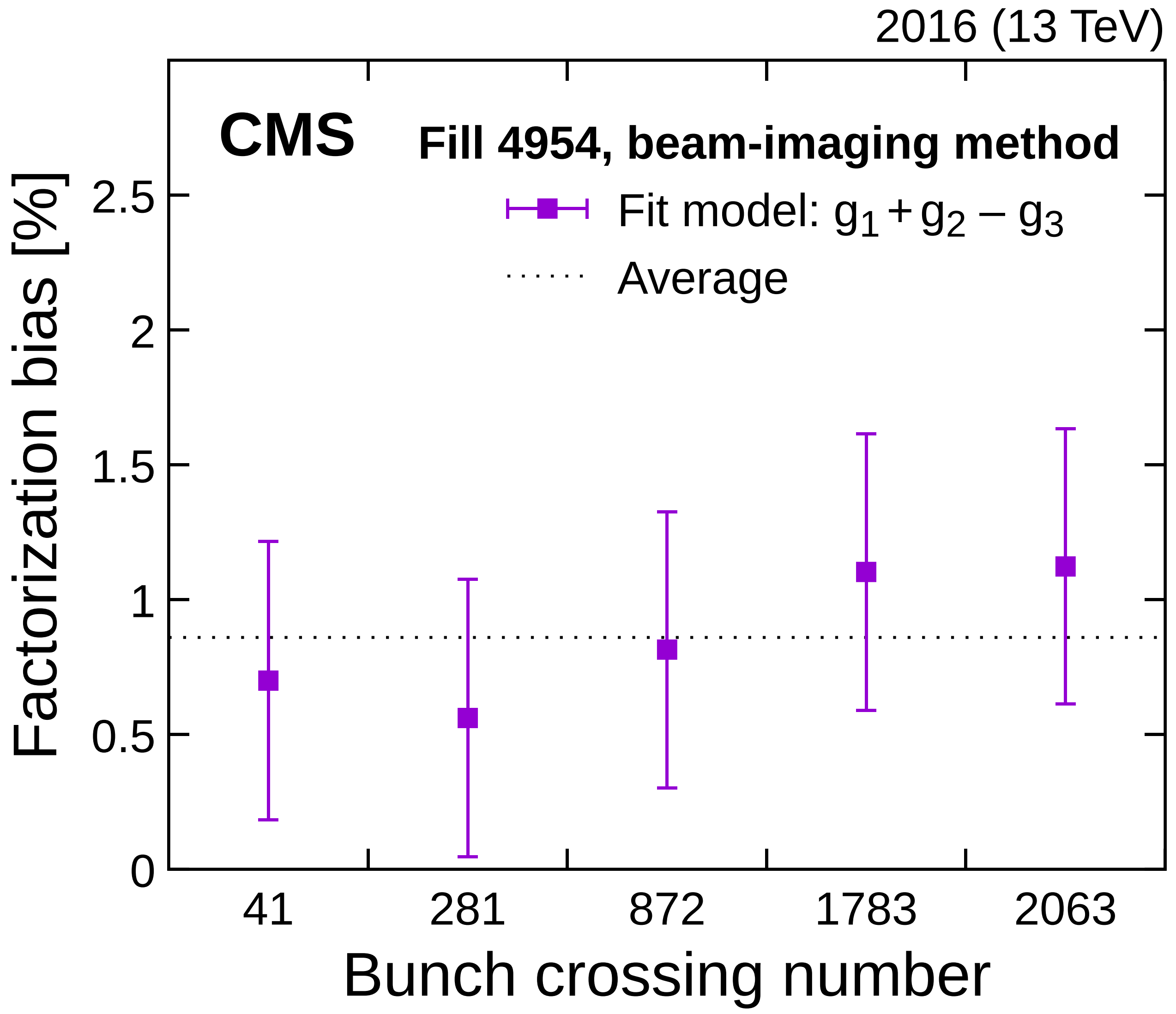
Beam Imaging Results



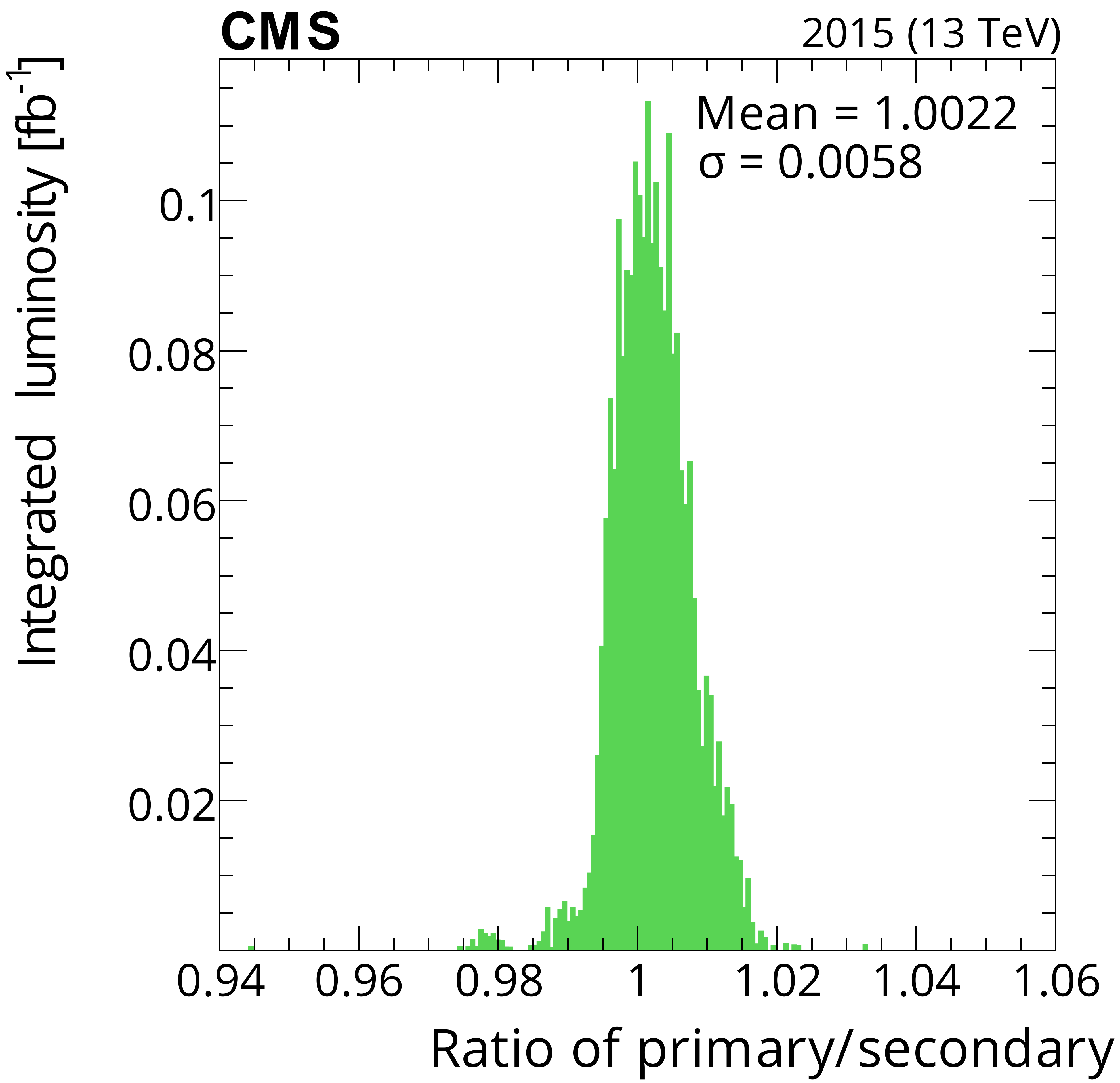


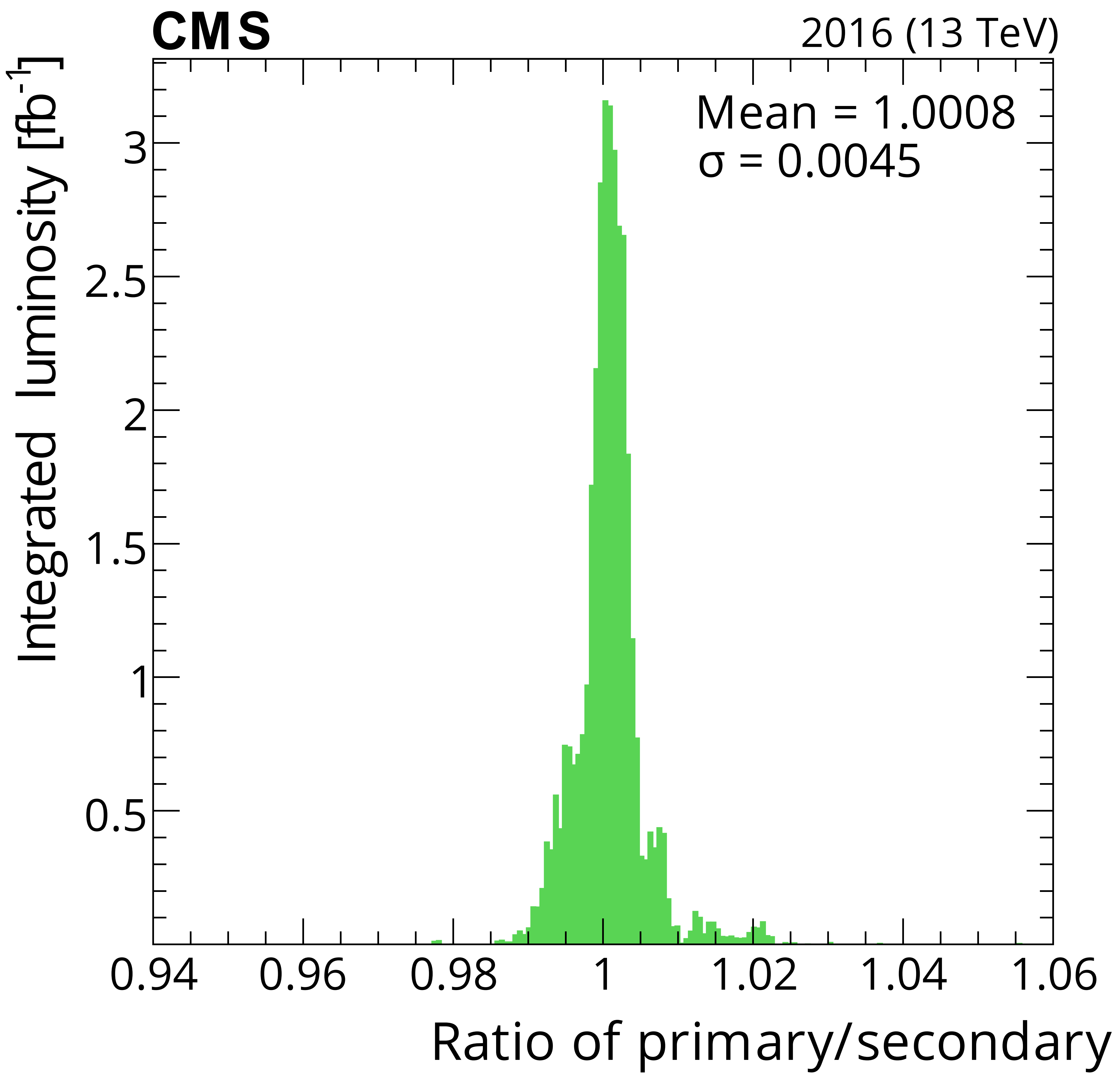






Stability & Linearity





Efficiency Scans

- Emittance scans at the beginning and at the end of LHC fills were used to monitor the stability of the luminometers over time.
- Efficiency is defined as the change of the calibration constant measured in emittance scans with respect to the Van der Meer (VdM) calibratioon.
- The plot shows all 2017 pp data and 2018 pp data for HFET (forward hadron calorimeter (HF), transverse energy (ET) counting algorithm for luminosity).
  - Due to improved beam quality and more consistent filling schemes during operation in 2018 spread between the points is minimized (in 2017 filling scheme was changed couple of times).
  - The 3% step-like change in the efficiency is detector performance change after the extended end of year technical stop (YETS).
    - The observed slope is due to a radiation damage of the detector. The slope measured from emittance scans (orange line) is slightly steeper than it was predicted in the HCAL aging model (red line).