Nonfactorization and the VdM scan method

Methods applied and lessons learnt at the CMS experiment

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on behalf of the CMS Collaboration

LHC Lumi Days
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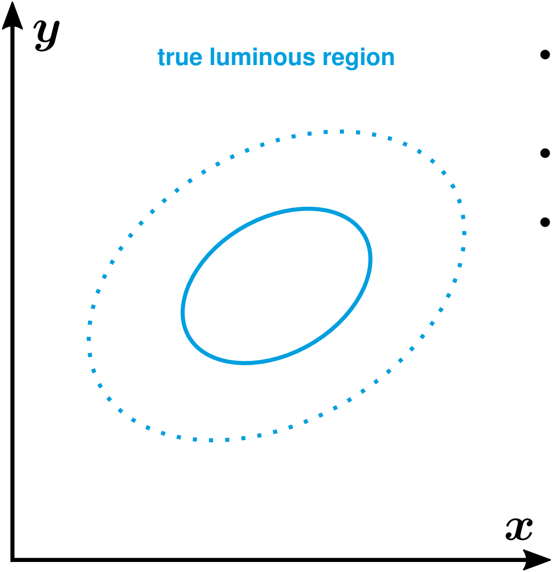
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

About *xy* nonfactorization



- VdM method assumes: beam proton densities factorize in *x* and *y*
- *xy* nonfactorization causes bias
- possible features:
  - “tilt”
    ⇒ correlation parameter ϱ
  - “stretch”
    ⇒ double Gaussian

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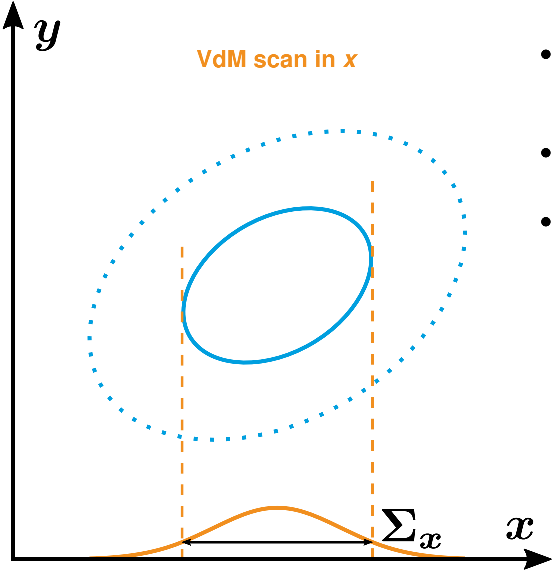

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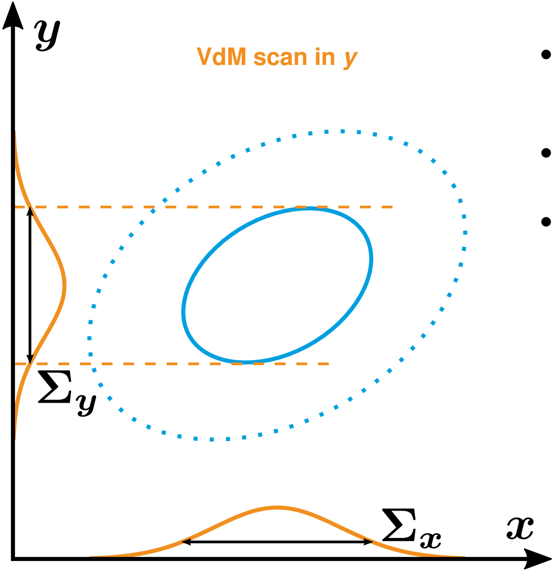

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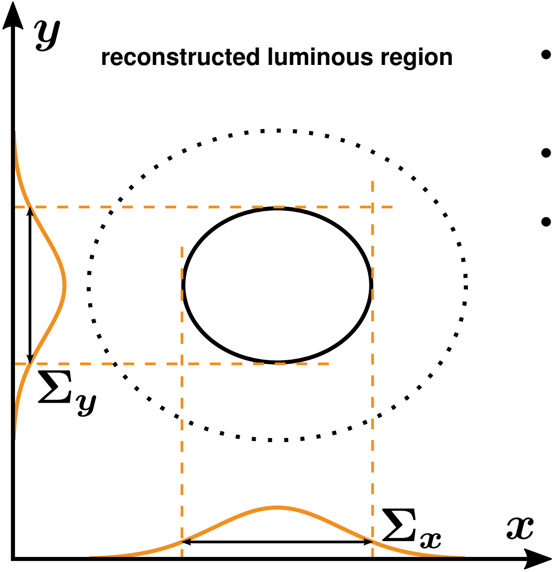

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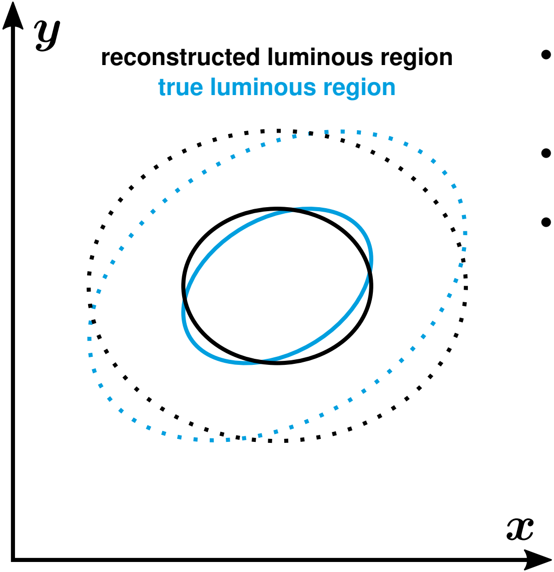

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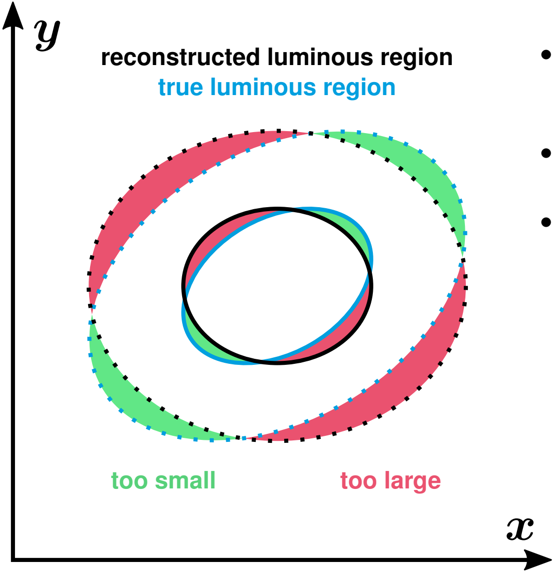

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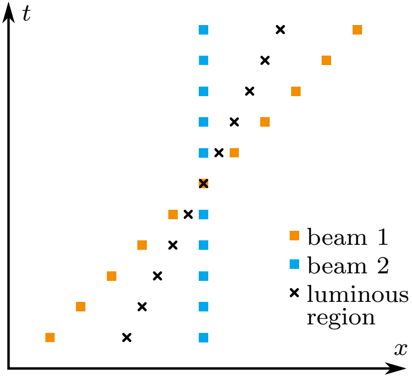
Beam imaging method

Beam imaging analysis

Beam imaging scans & analysis strategy



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  - limited by vertex resolution V

Beam imaging analysis

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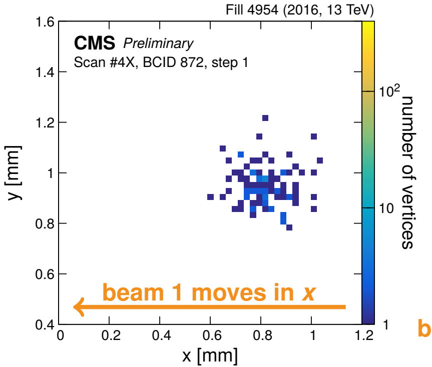

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beam proton densities

$$\underbrace{N_{\text{vertices}}(x, y; \Delta x)}_{\text{vertex distribution}} \propto \left[\rho_1(x + \Delta x, y) \cdot \rho_2(x, y)\right] \otimes V$$

beam separation at each step

Beam imaging analysis

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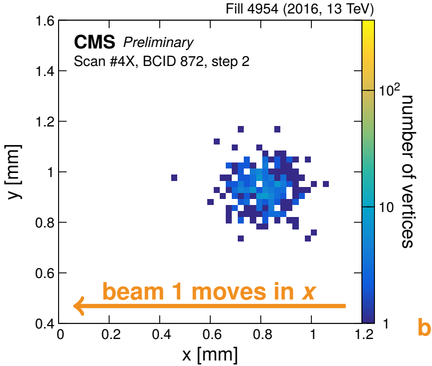

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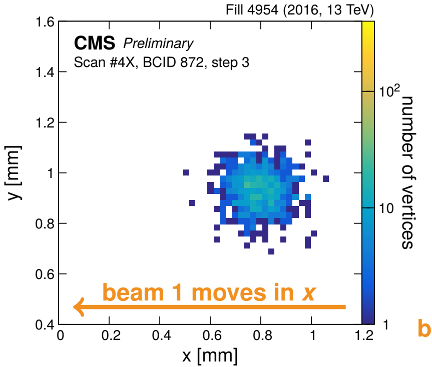

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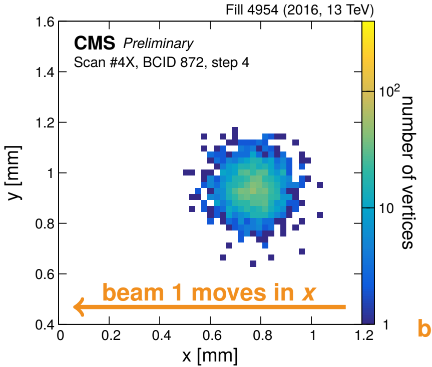

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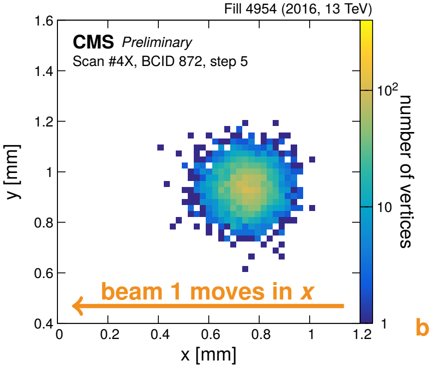

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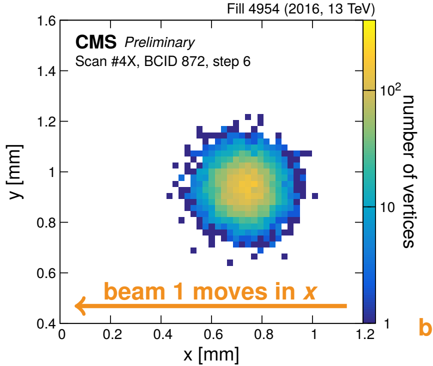

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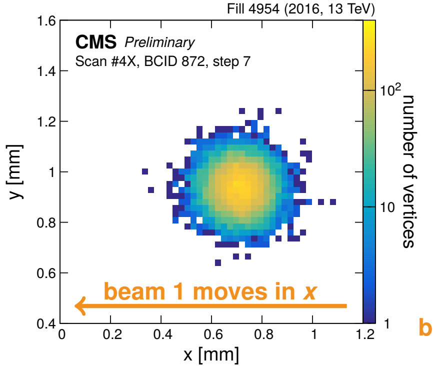

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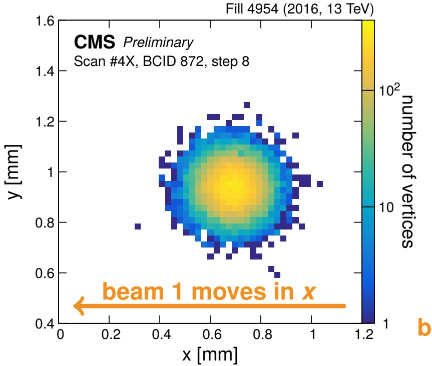

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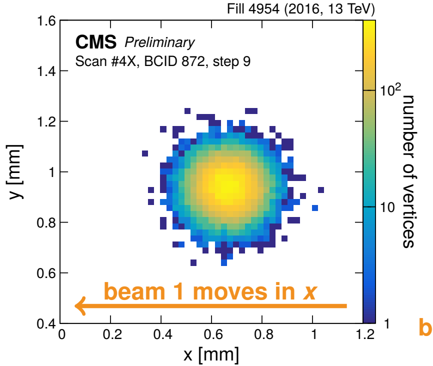

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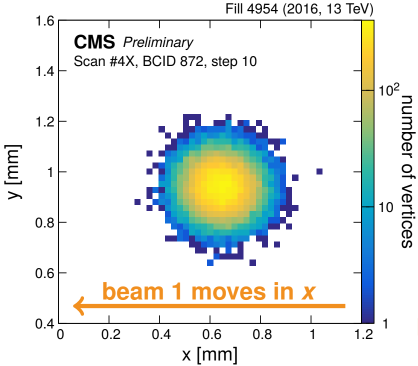

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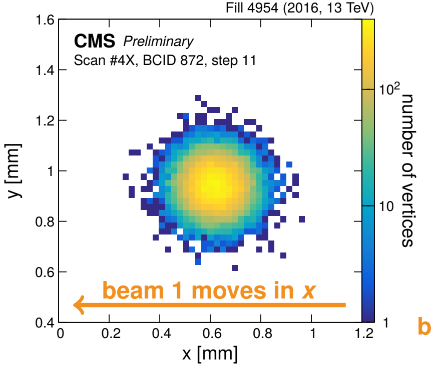

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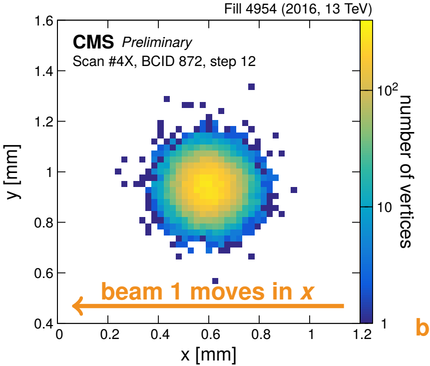

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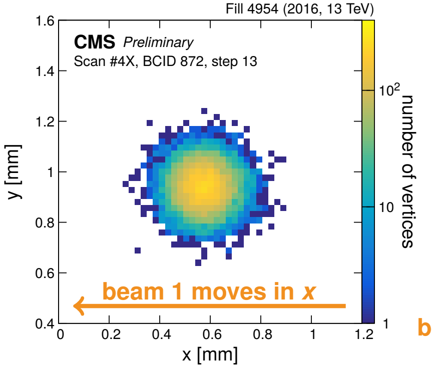

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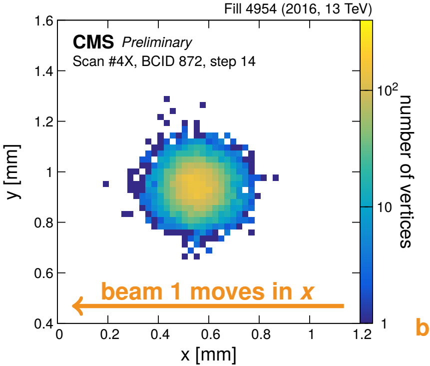

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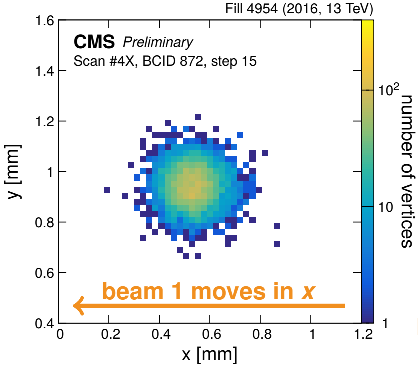

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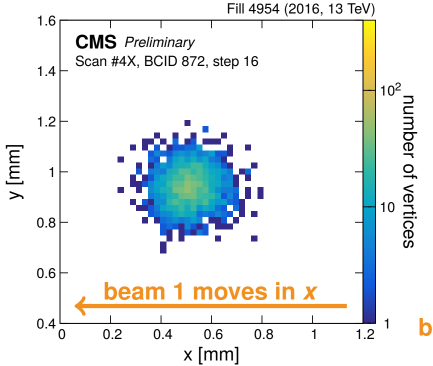

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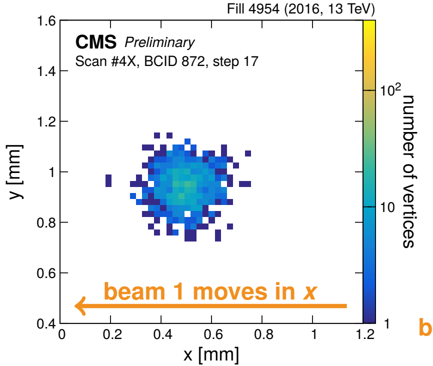

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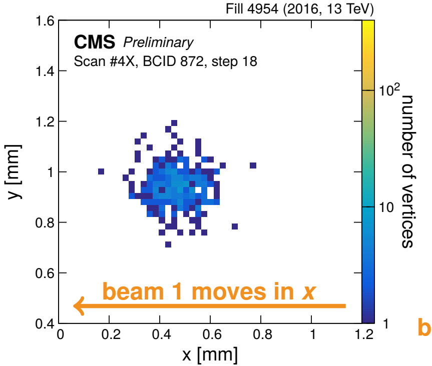

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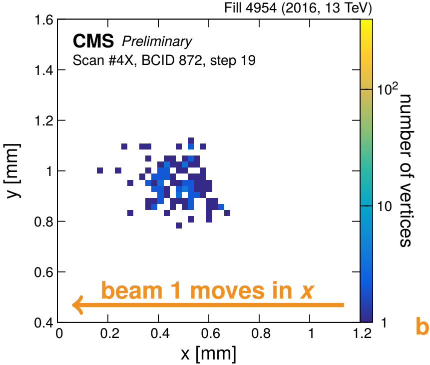

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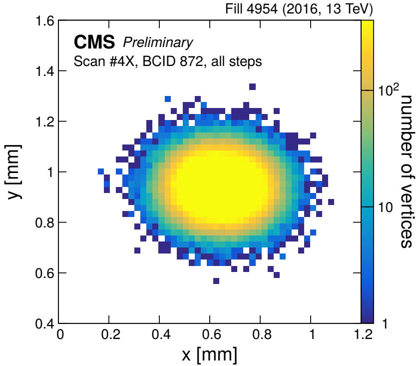

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- reconstruct primary vertices
  - limited by vertex resolution V
- combine all steps

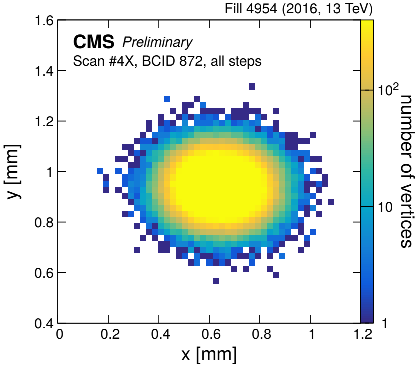
$$\sum_{\Delta x} N_{\text{vertices}}(x, y; \Delta x) \propto \sum_{\Delta x} \left[\rho_1(x + \Delta x, y) \cdot \rho_2(x, y)\right] \otimes V$$

$$\approx \int_{\Delta x} \left[\rho_1(x + \Delta x, y) \cdot \rho_2(x, y)\right] \otimes V \, \mathrm{d}\Delta x$$

valid for small step size ↗

Beam imaging analysis

Beam imaging scans & analysis strategy



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  - repeat: beam 1 and 2, in x and y
- reconstruct primary vertices
  - limited by vertex resolution V
- combine all steps to obtain "beam image" of fixed beam
- choose models for proton densities ρ_1, ρ_2 for simultaneous fit of 4 scans

$$\sum_{\Delta x} N_{\text{vertices}}(x, y; \Delta x) \propto \sum_{\Delta x} \left[\rho_1(x + \Delta x, y) \cdot \rho_2(x, y)\right] \otimes V$$

$$\approx \left[\left(\int_{\Delta x} \rho_1(x + \Delta x, y)\, \mathrm{d}\Delta x\right) \cdot \rho_2(x, y)\right] \otimes V$$

$$= \left[(\mathcal{M}_x \rho_1)(y) \cdot \rho_2(x, y)\right] \otimes V$$

marginalized ↗ can extract this dependence ↖

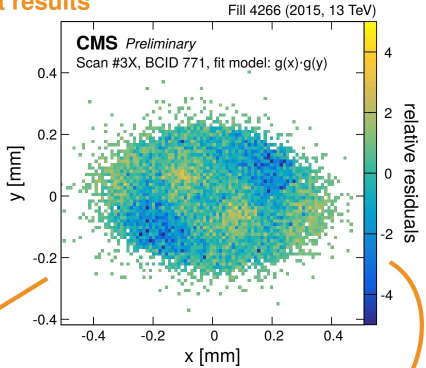
Beam imaging analysis

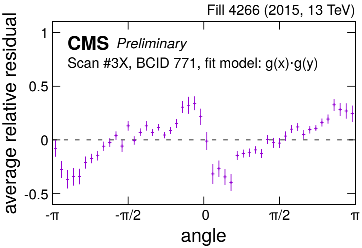
Transverse proton density models and fit results

- analytical convolution $\otimes V$ requires Gaussian-based fit models
- simplest case: **single 1D Gaussians**

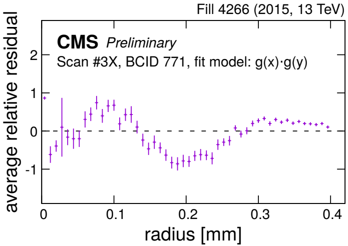
$$g(x) \cdot g(y) = \exp\left[-\frac{1}{2}\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right)\right]$$

$\Rightarrow$ large angular and radial dependency of residuals





angular projection



radial projection

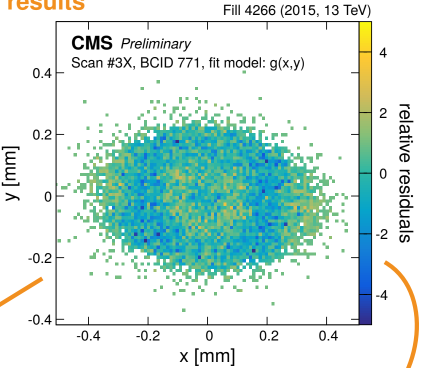
Beam imaging analysis

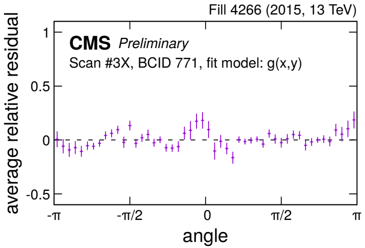
Transverse proton density models and fit results

- analytical convolution $\otimes V$ requires Gaussian-based fit models
- **single Gaussian with correlations**

$$g(x,y) = \exp\left[-\frac{1}{2(1-\varrho^2)}\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}-\frac{2\varrho xy}{\sigma_x\sigma_y}\right)\right]$$

$\Rightarrow$ good angular description, but still clear radial structure





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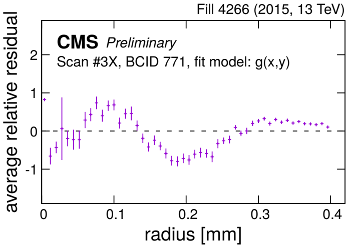

radial projection

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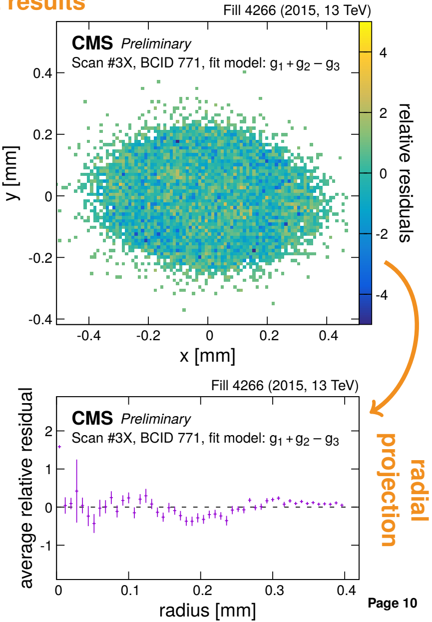
- **normalized sums of Gaussians**
  - add wider Gaussian g_2
    $\Rightarrow$ wider tails
  - subtract narrow Gaussian g_3
    $\Rightarrow$ flattened centre

$\Rightarrow$ best-fit model: $g_1 + g_2 - g_3$
for pp at 13 TeV in 2015, 2016 & 2017,
but no sufficient description in 2018

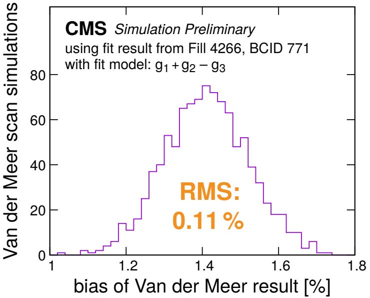


Beam imaging analysis

Determination of VdM bias

Bias from VdM simulations

- unbiased overlap from direct integration of product of fitted proton densities
- biased overlap from repeated MC simulations of VdM scan pairs using fitted proton densities
- VdM results corrected for difference



Beam imaging analysis

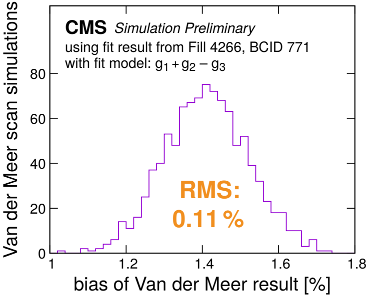
Determination of VdM bias

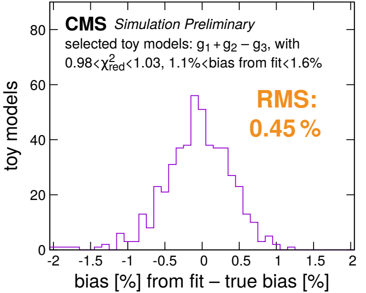
Bias from VdM simulations

- unbiased overlap from direct integration of product of fitted proton densities
- biased overlap from repeated MC simulations of VdM scan pairs using fitted proton densities
- VdM results corrected for difference

Closure test with toy models

- randomly generate toy models, simulate set of beam imaging scans, and apply same fit procedure as for data
- select toys with similar fit properties as data fits, evaluate VdM bias
- reconstruction of VdM bias from good fits with precision $\lesssim 0.5\,\%$ possible

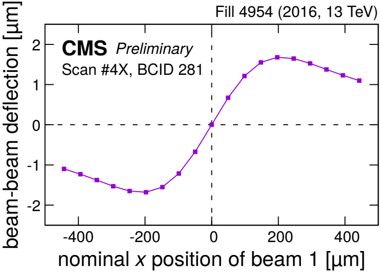




Beam imaging analysis

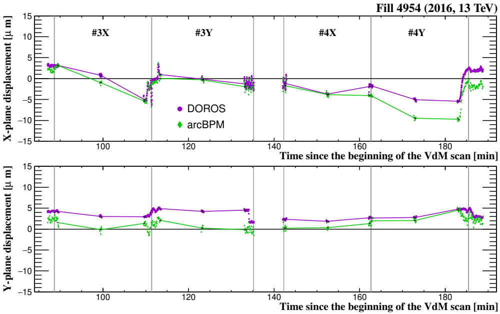
Effects impacting beam position

Beam-beam deflection



- electric repulsion of proton beams, depending on transverse separation
- causes movement of fixed beam

Orbit drift



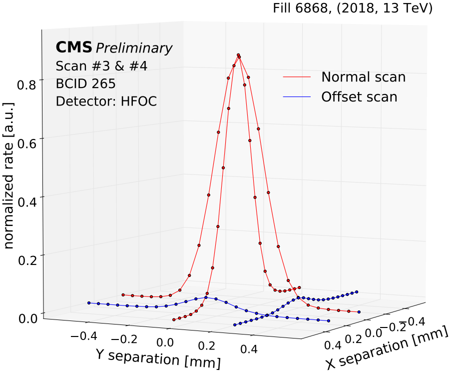
- beams drift away from nominal orbit
- changes beam position within step, and step size among different steps

Length scale doesn't affect fixed beam, doesn't introduce step size variations

Recently implemented methods & developing ideas

Offset scan analysis

Offset scans and general considerations



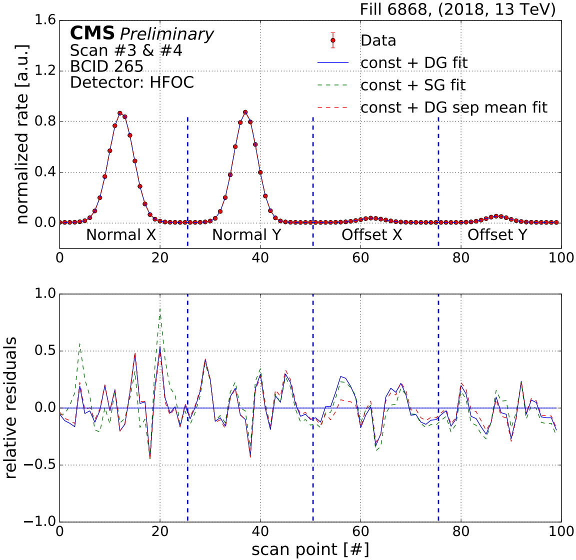
- normal VdM scans
- offset scans with beams at constant separation in non-scanning direction

⇒ differently affected by nonfactorization

- reconstruct luminous region profile (= product of beam proton densities) from fit to rate vs 2D beam separation
- sensitive to beam separation effects: length scale, beam-beam, orbit drift
- four separation configurations shared between two scans
  ⇒ consistency check
- tails limited by low statistics
- can use any luminometer
  ⇒ not limited by central DAQ
- offset scans only done in 2017 & 2018 VdM programmes

Offset scan analysis

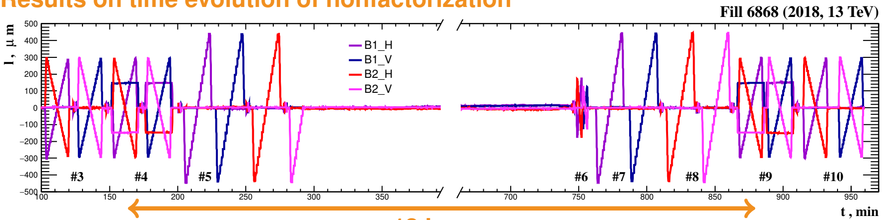
Luminous region modelling and fit results



- ad-hoc position correction to reach rate agreement at coinciding steps
  ⇒ thus correcting for beam position effects
- no limitation on luminous region models
- found good description with single and double Gaussians
  ⇒ main result: ϱ of main Gaussian component

Offset scan analysis

Results on time evolution of nonfactorization

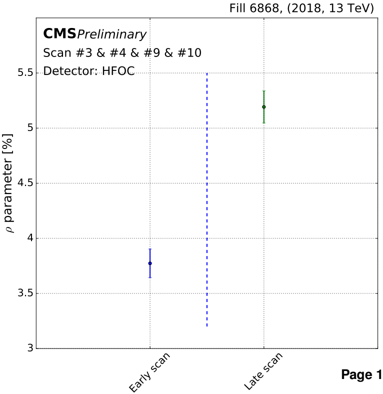


12 hours

- in Fill 6868: two offset scan pairs taken ∼12 hours apart
- separately analysed ⇒ test of time evolution of nonfactorization

⇒ correlation parameter ϱ of luminous region profile increases with time

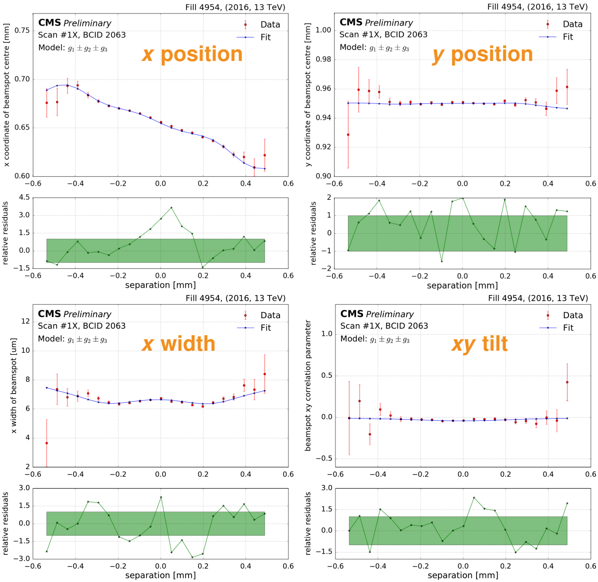
⇒ consistently observed in beam imaging method



fit uncertainties only

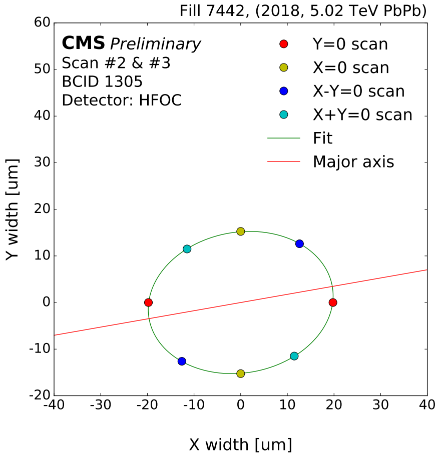
Beamspot evolution analysis

- at each scan step, fit 3D ellipsoid to vertex distribution, including vertex resolution
- extract observables: mean, width, tilt
- analytically compute predictions from models for observables
- fit predictions to rate & beamspot data
- plots: fit results with $g_1 \pm g_2 \pm g_3$ for Scan #1X, Fill 4954 (2016, 13 TeV)



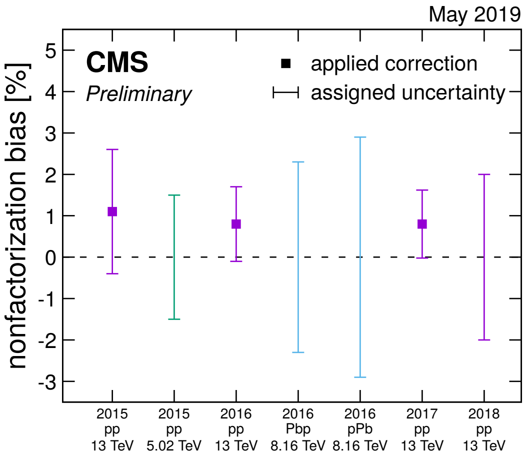
Diagonal scan analysis

- VdM scans in X, Y, X+Y, X−Y, analysed with standard method
  $\Rightarrow$ obtain four widths
- fit ellipse to obtain 1σ contour line of luminous region profile
  $\Rightarrow$ can extract correlation parameter ϱ
- diagonal scans only done in 2018 PbPb VdM programme



Summary

Summary



- In Run 2, beam imaging is the main method of evaluating nonfactorization.
- Complementary methods are being developed:
  - offset scans,
  - beamspot evolution,
  - diagonal scans.
- Improved nonfactorization results are underway.
- Essential next steps:
  - direct comparison of results from different methods,
  - toy simulations including all methods and effects.

References

CMS luminosity measurements

- `CMS-PAS-LUM-15-001`
  (pp 13 TeV 2015)
- `CMS-PAS-LUM-16-001`
  (pp 5.02 TeV 2015)
- `CMS-PAS-LUM-17-001`
  (pp 13 TeV 2016)
- `CMS-PAS-LUM-17-002`
  (Pbp/pPb 8.16 TeV 2016)
- `CMS-PAS-LUM-17-004`
  (pp 13 TeV 2017)
- `CMS-PAS-LUM-18-002`
  (pp 13 TeV 2018)

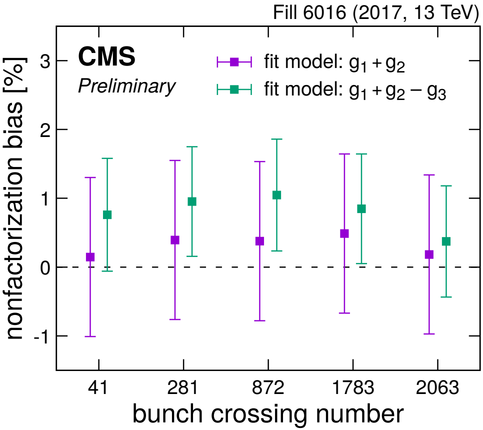
Method descriptions

- Klute, Medlock, and Salfeld-Nebgen,
  JINST **12** (2017) P03018 (beam imaging method)
- Chatrchyan et al. (CMS Collaboration),
  JINST **9** (2014) P10009 (vertex splitting)
- Aaboud et al. (ATLAS Collaboration),
  Eur. Phys J. C **76** (2016) 653
  (offset scan & beamspot evolution analysis)
- CMS Collaboration, `CMS-DP-2016-051`
  (beamspot fits)
- Webb, `CERN-THESIS-2015-054`
  (beamspot evolution analysis)

Backup

Beam imaging analysis

Reconstructed bias for different bunch crossings



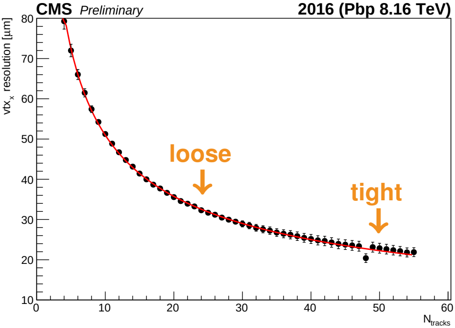
BCIDs for which vertex data was recorded:

- Fill 4266: 51, 771, 1631, 2211, 2674
- Fill 4634: 644, 1215, 2269, 2389, 2589
- Fill 4937: 81, 875, 1610, 1690, 1730
- Fill 4954: 41, 281, 872, 1783, 2063
- Fill 5527: 177, 1420, 2311, 3015
- Fill 5563: 958, 1486, 2032, 2576
- Fill 6016: 41, 281, 872, 1783, 2063
- Fill 6380: 41, 644, 1215, 2269, 2589
- Fill 6868: 265, 865, 1780, 2192, 3380

⇒ we use average of bias from five BCIDs as correction for all BCIDs

Beam imaging analysis

Vertex resolution



- measured with vertex splitting method
- need resolution smaller than beam size
  ⇒ problematic for heavy-ion runs
- 2016 pPb/Pbp: only single Gaussian fit at tightest vertex selection possible