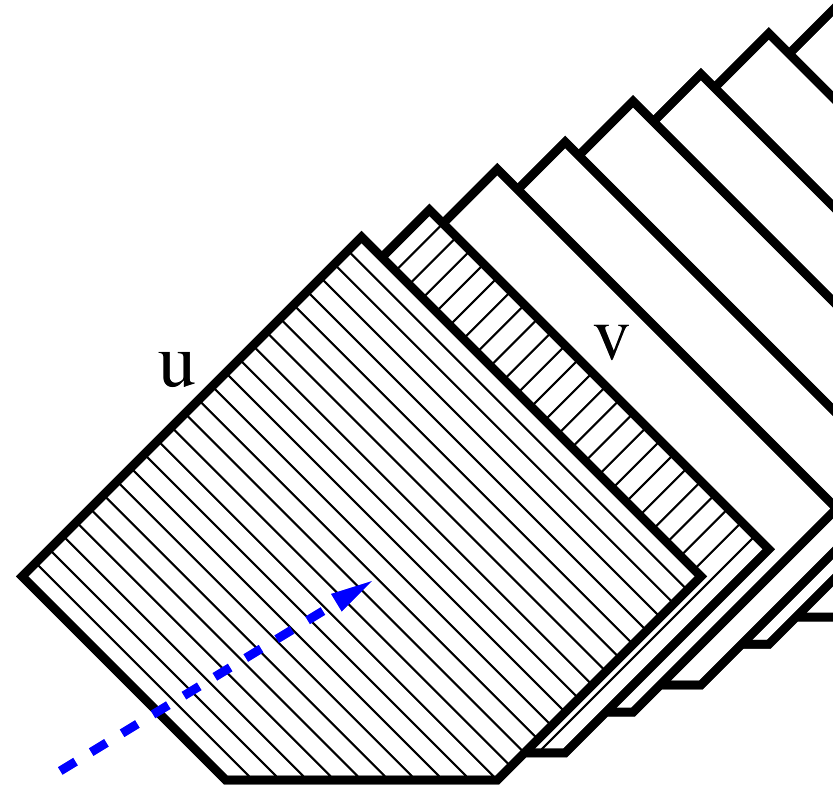
Study of proton reconstruction using the TOTEM Roman pot detectors during the high-β^* data taking period



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Zimányi Winter School

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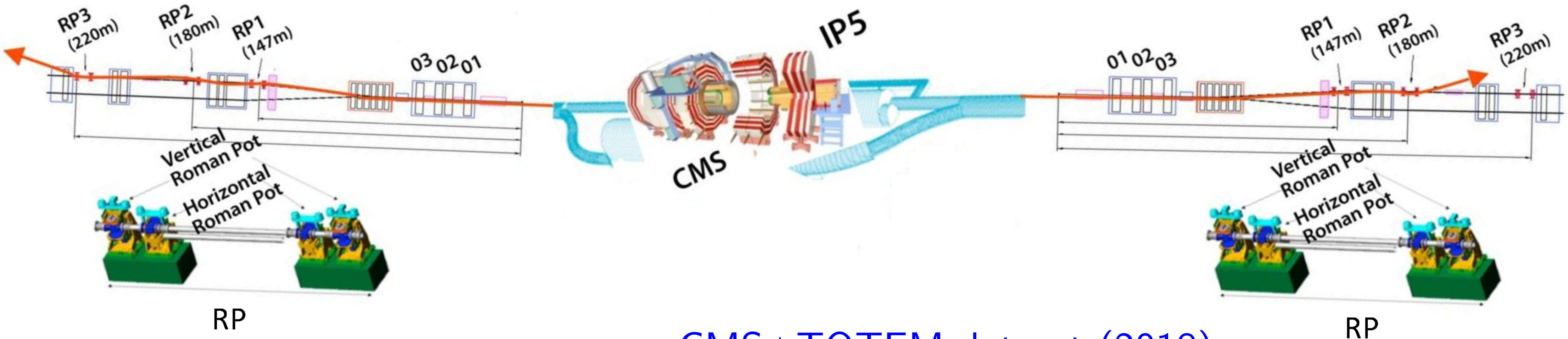
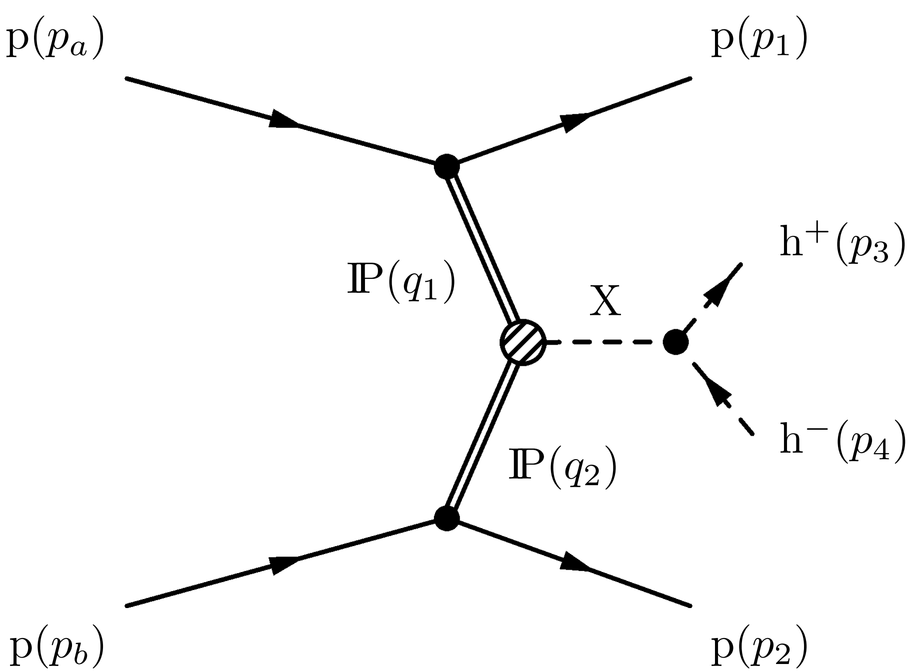
Central exclusive production – data



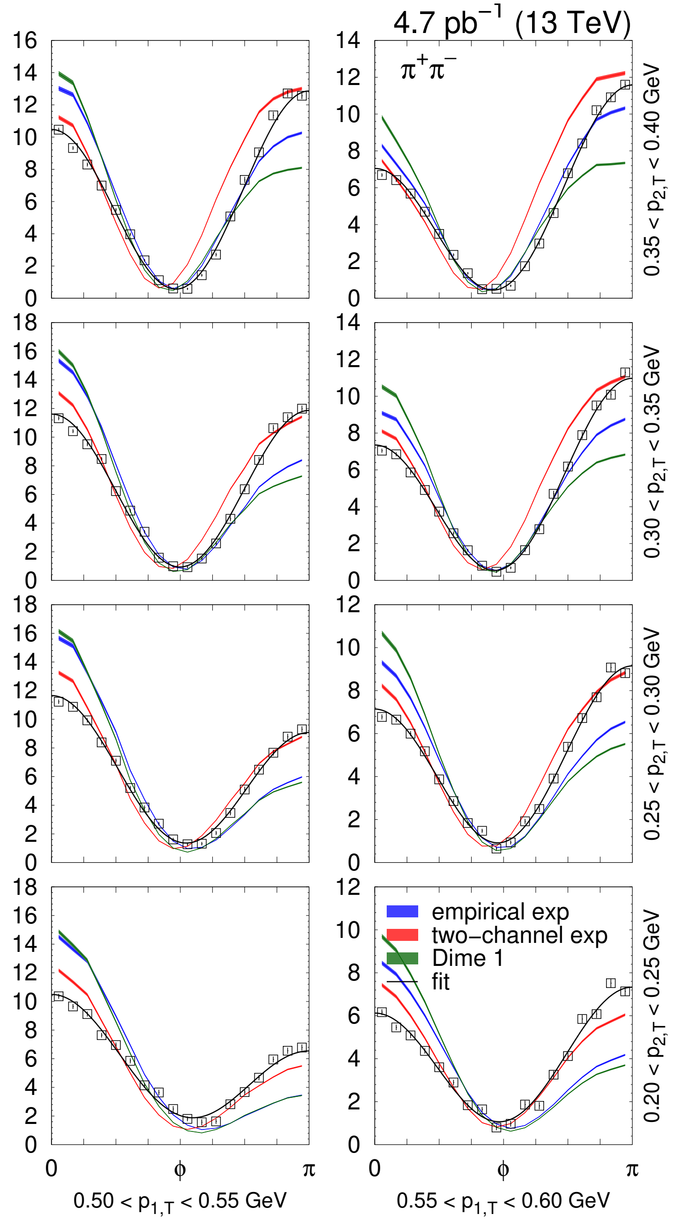


- CMS+TOTEM dataset (2018)
  - about 80 M events with **two scattered protons** and only **two reconstructed central tracks**
  - part of those is double pomeron exchange (DPE), where a central system (X) was created
  - subsequently decayed to particle-antiparticle pair h^+h^-, mostly $\pi^+\pi^-$or K^+K^-, but some $p\bar{p}$

$\mathbb{P}\mathbb{P}$ collider $\rightarrow$ gluon-rich initial state

Competition with ALICE, ATLAS, and LHCb

Physics analysis – from last year



- Analysis
  - double pomeron exchange, charged hadron pairs, 13 TeV
  - now the $\pi^+\pi^-$ final state, resonance-free region
  - differential cross sections in bins of $(p_{1,\mathrm{T}}, p_{2,\mathrm{T}})$
  - azimuthal angle ϕ between the surviving protons
- Results
  - rich structure of nonperturbative interactions
  - **parabolic minimum in the distribution of ϕ** (first)
  - **interference** of the bare and the rescattered amplitudes
  - **model tuning: pomeron-related quantities** (first)
  - good quality fits, **choices of form factors** tested

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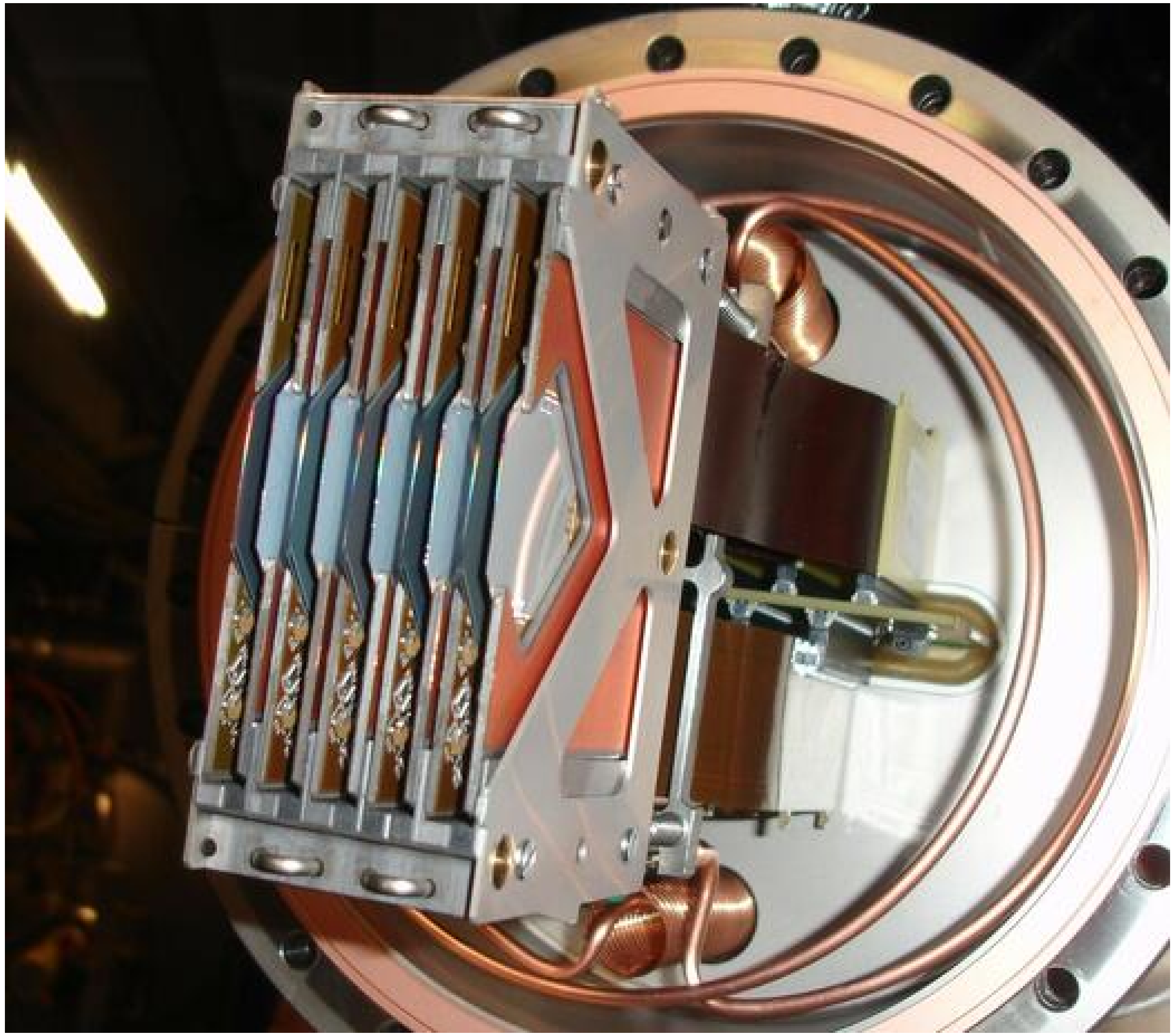
Now: technical details (arXiv:2411.19749), submitted to J Inst

Scattered protons – roman pots



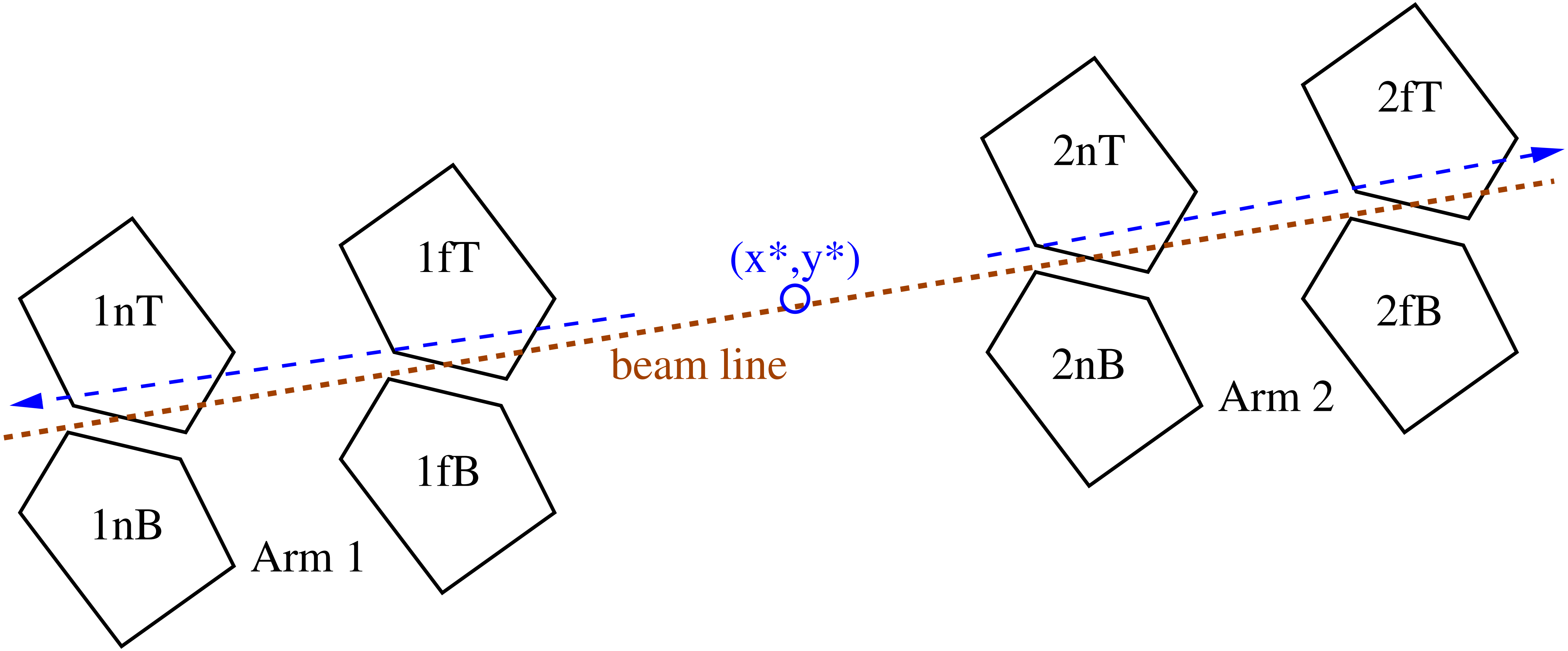
- Details
  - two arms (in sectors 45 and 56)
  - near and far stations (at ≈213 and 220 m)
  - top and bottom pots
  - within a pot:
    5 planes in 'u' and
    5 planes in 'v' directions
    (usually at $\pm 45°$, or 37 vs $-53°$)
  - each plane has: 4 × 128 strips

- Two pots per arm

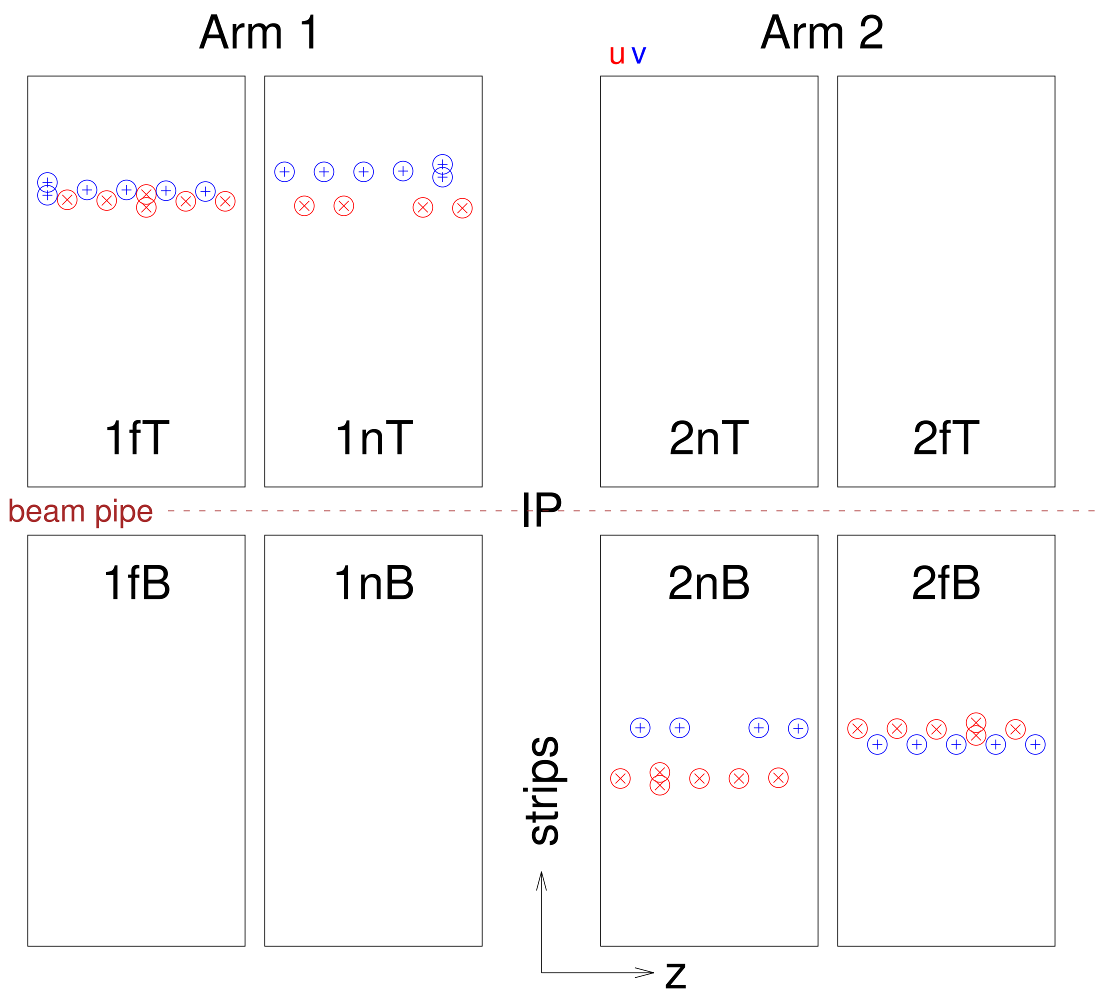
→ two measurements

→ location and momentum at IP

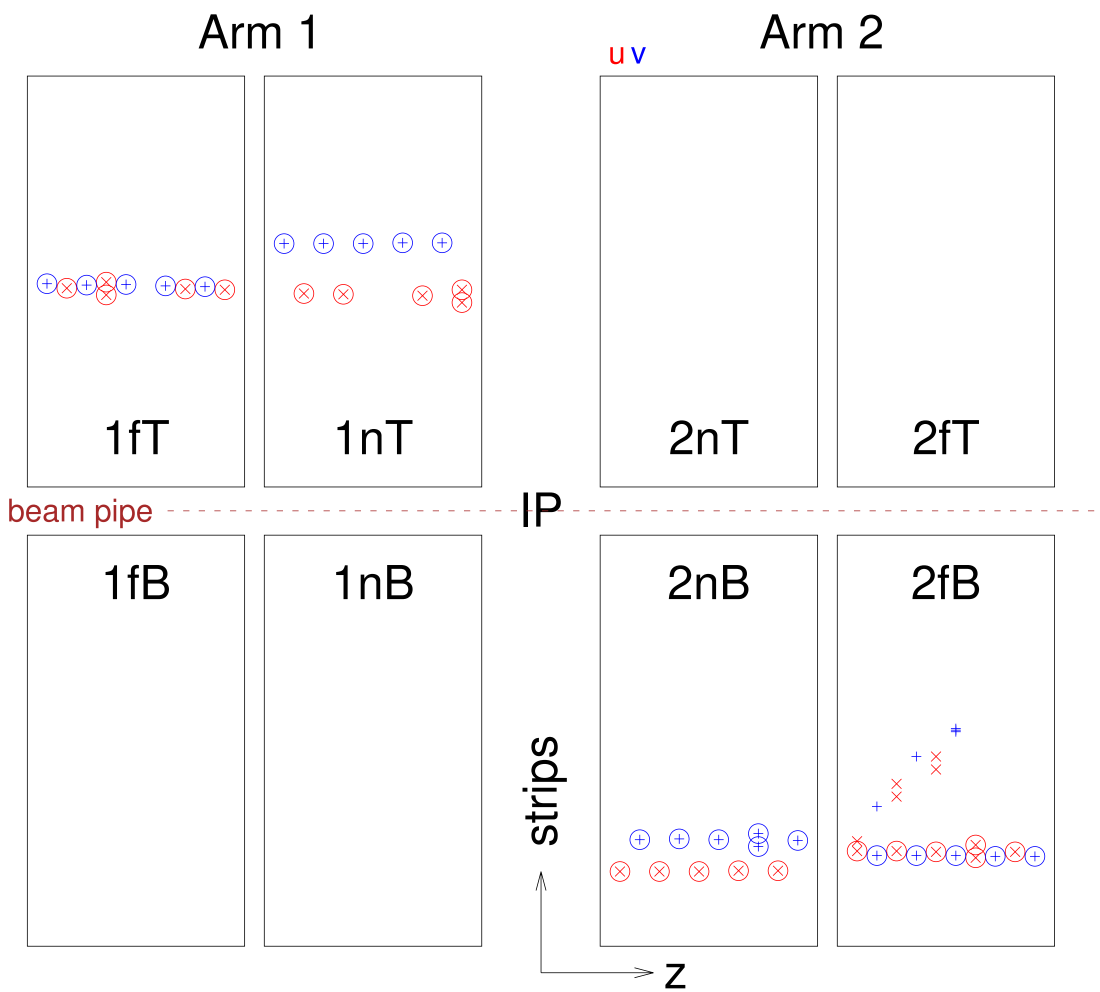
Roman pots (not to scale!)



Roman pots – close look at events (not to scale!)

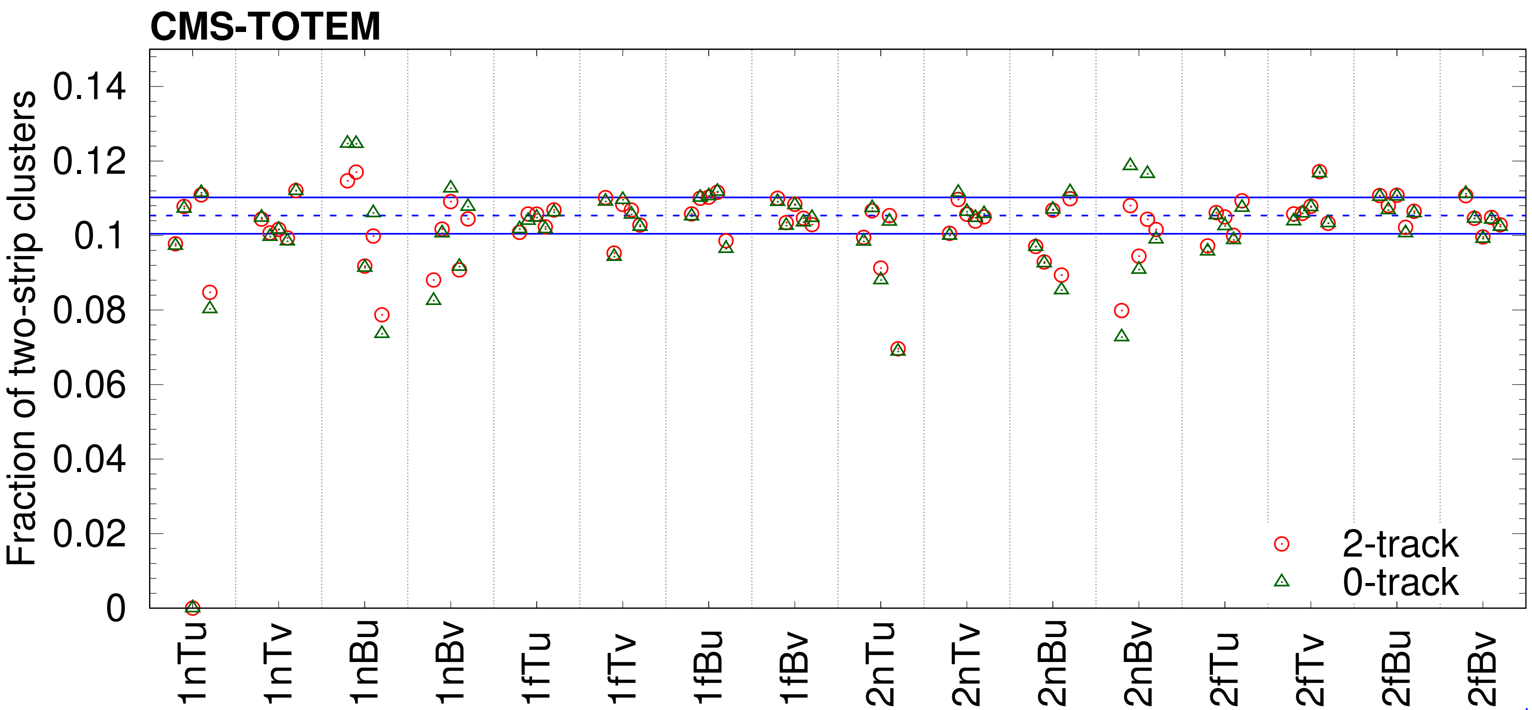


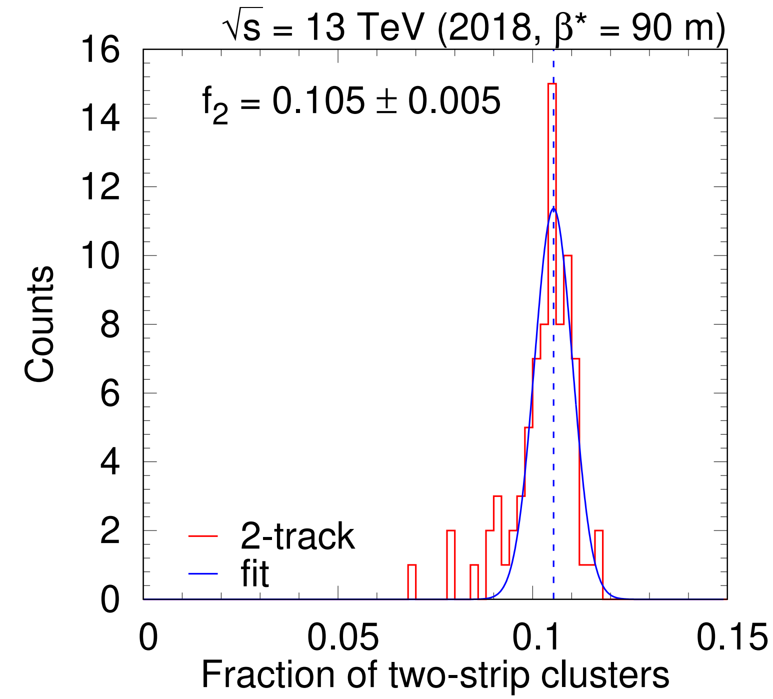
Normal

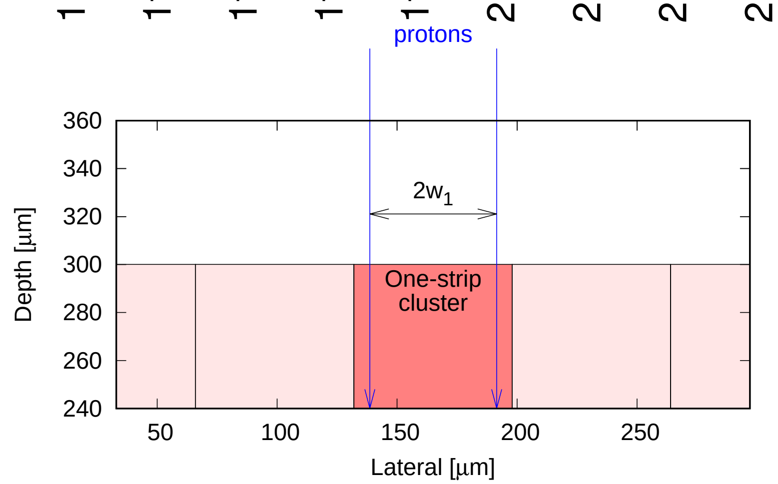


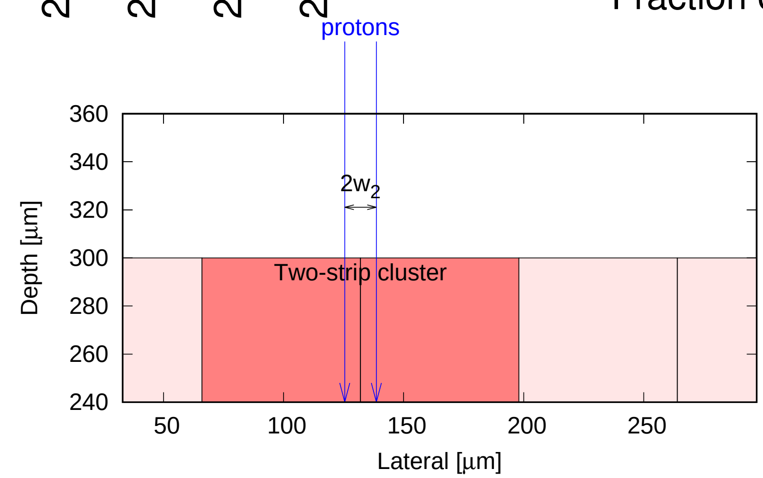
Normal with secondary (1% within a station)

Roman pots – fraction of two-strip clusters



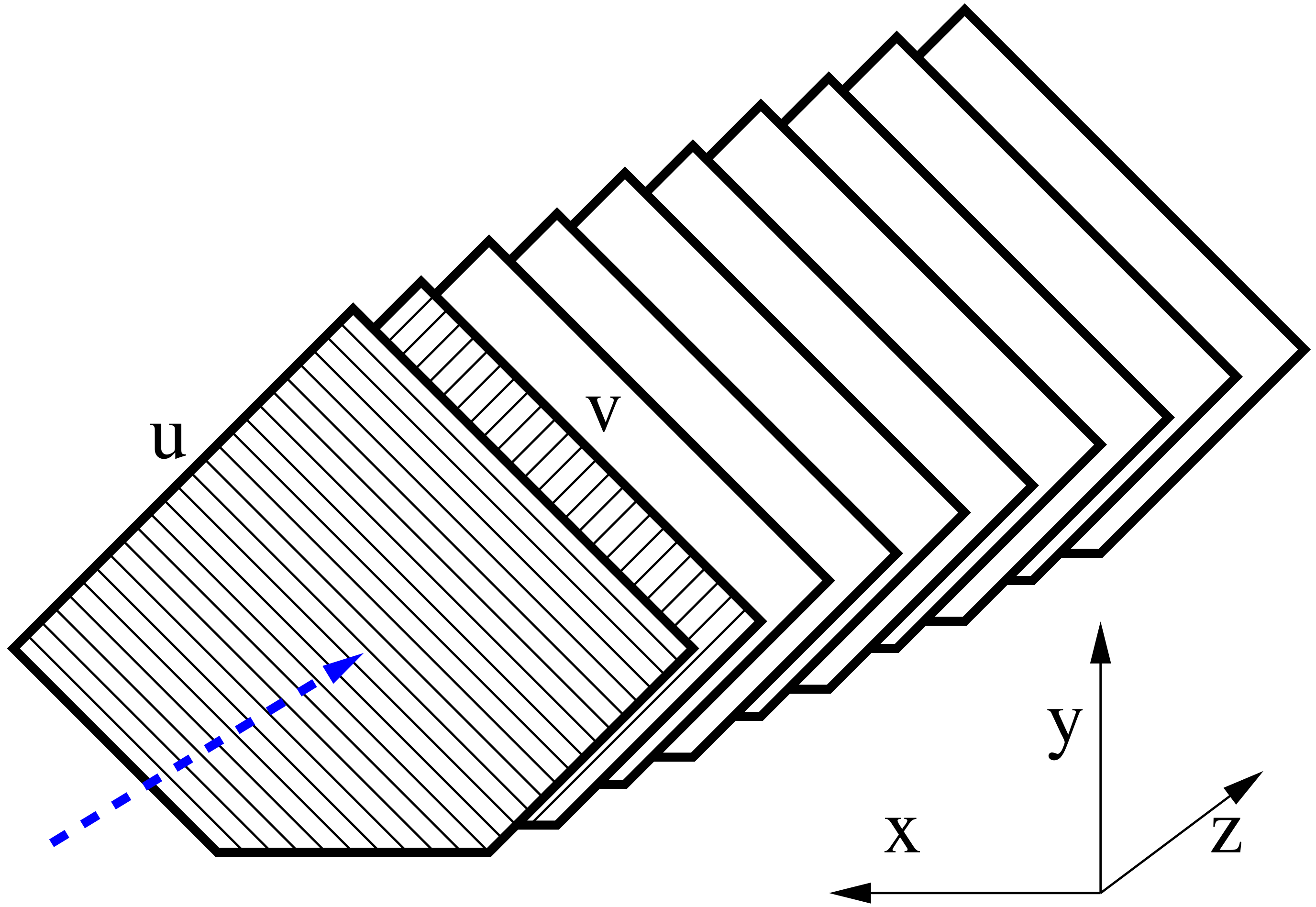






About 10.5% of the clusters are two-strip, precious position information

Roman pots – protons

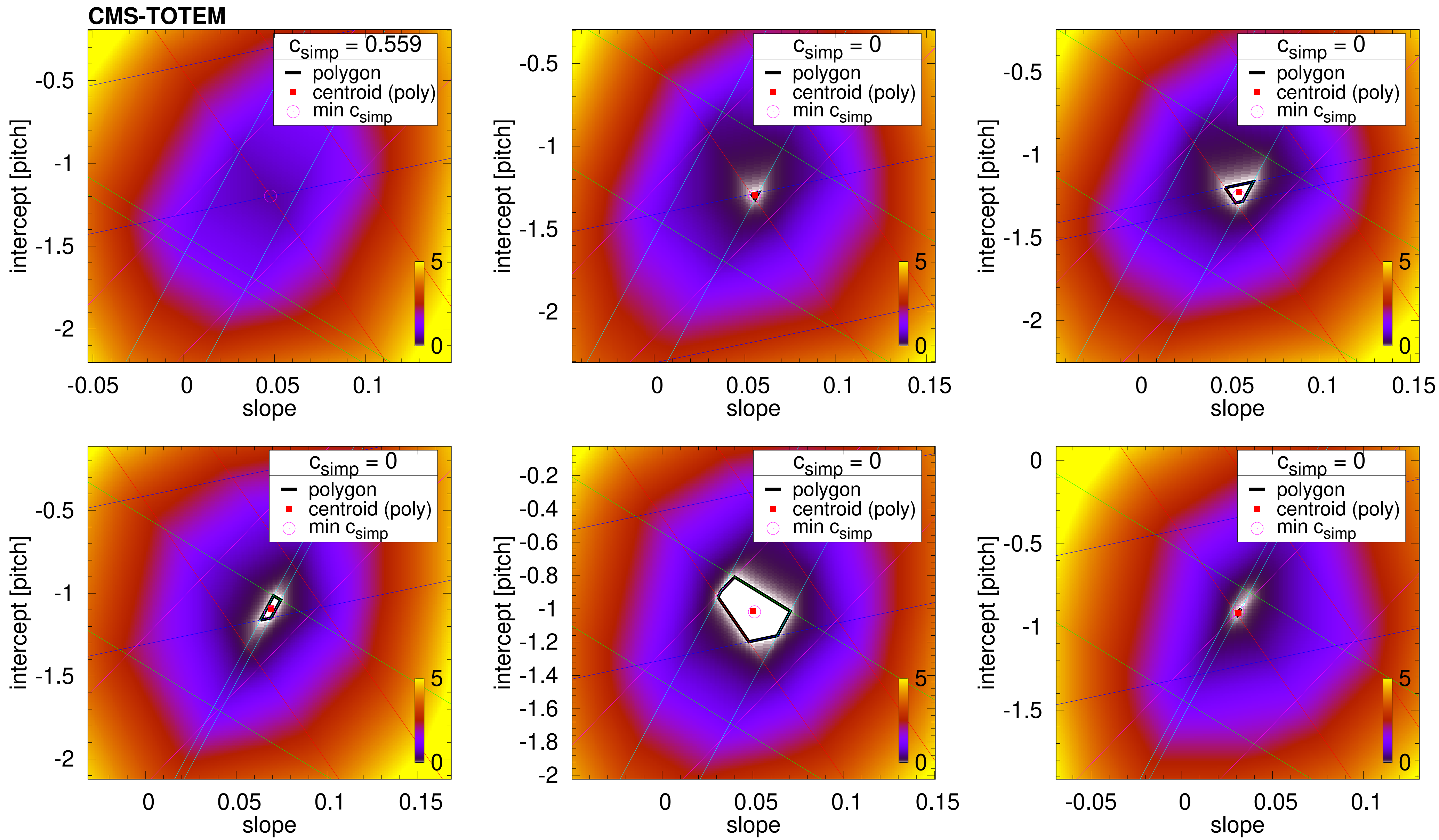


Track model: $u_i = az_i + b + \delta_i$ – how to optimally use/extract information?

We have “digital” hit information (strip number) vs usual normally-distributed uncertainties

Expected location on the ith plane: measured u_i, slope a, intercept b, shift δ_i

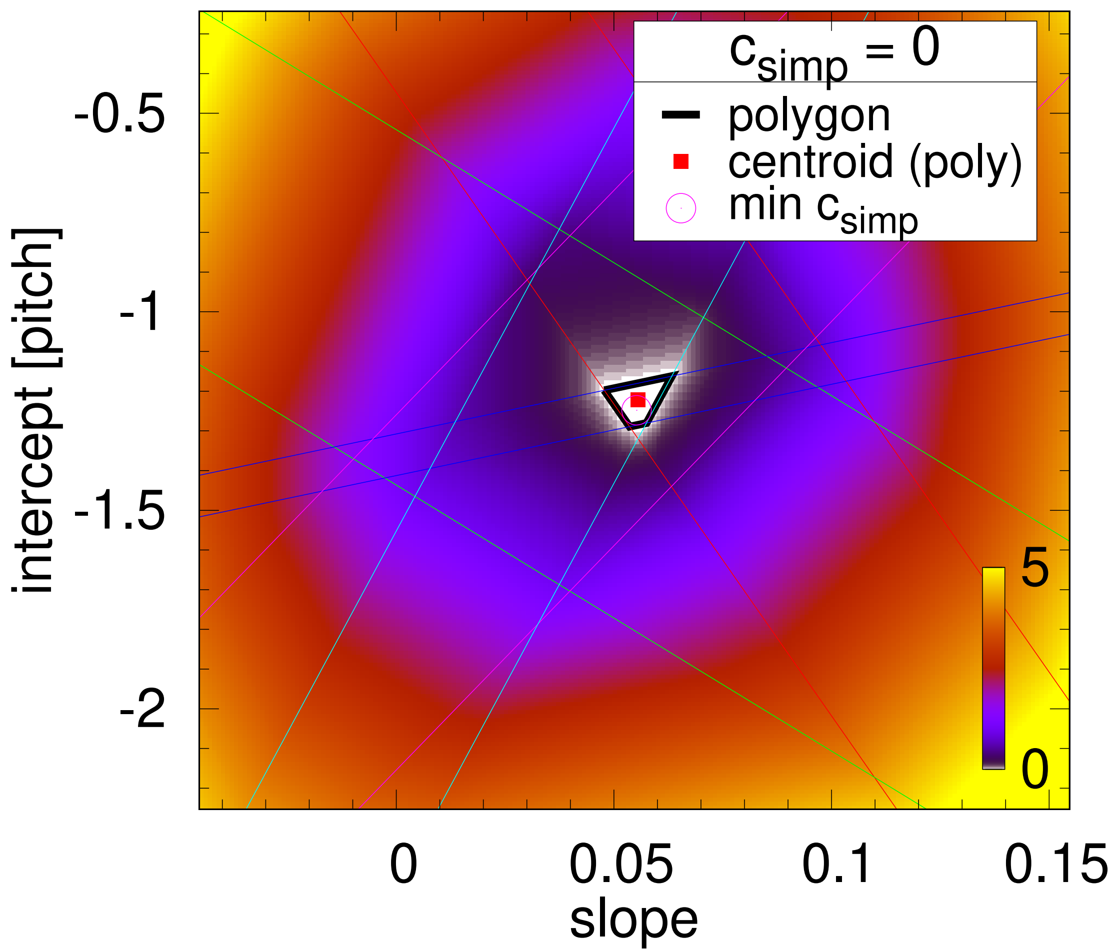
Roman pots – fitting tracklets (5 planes)



Track intercept vs slope (at local $z = 0$)

Find intersection of bands: polygon

Roman pots – fitting tracklets (5 planes)



Bands

$$y_i^{\text{clus}} - az_i - \delta_i - w < b < y_i^{\text{clus}} - az_i - \delta_i + w,$$

Centroid

$$C_x = \frac{1}{6A} \sum_{j=0}^{n-1} (x_j + x_{i+j})(x_j\ y_{j+1} - x_{j+1}\ y_j),$$

$$C_y = \frac{1}{6A} \sum_{j=0}^{n-1} (y_j + y_{i+j})(x_j\ y_{j+1} - x_{j+1}\ y_j),$$

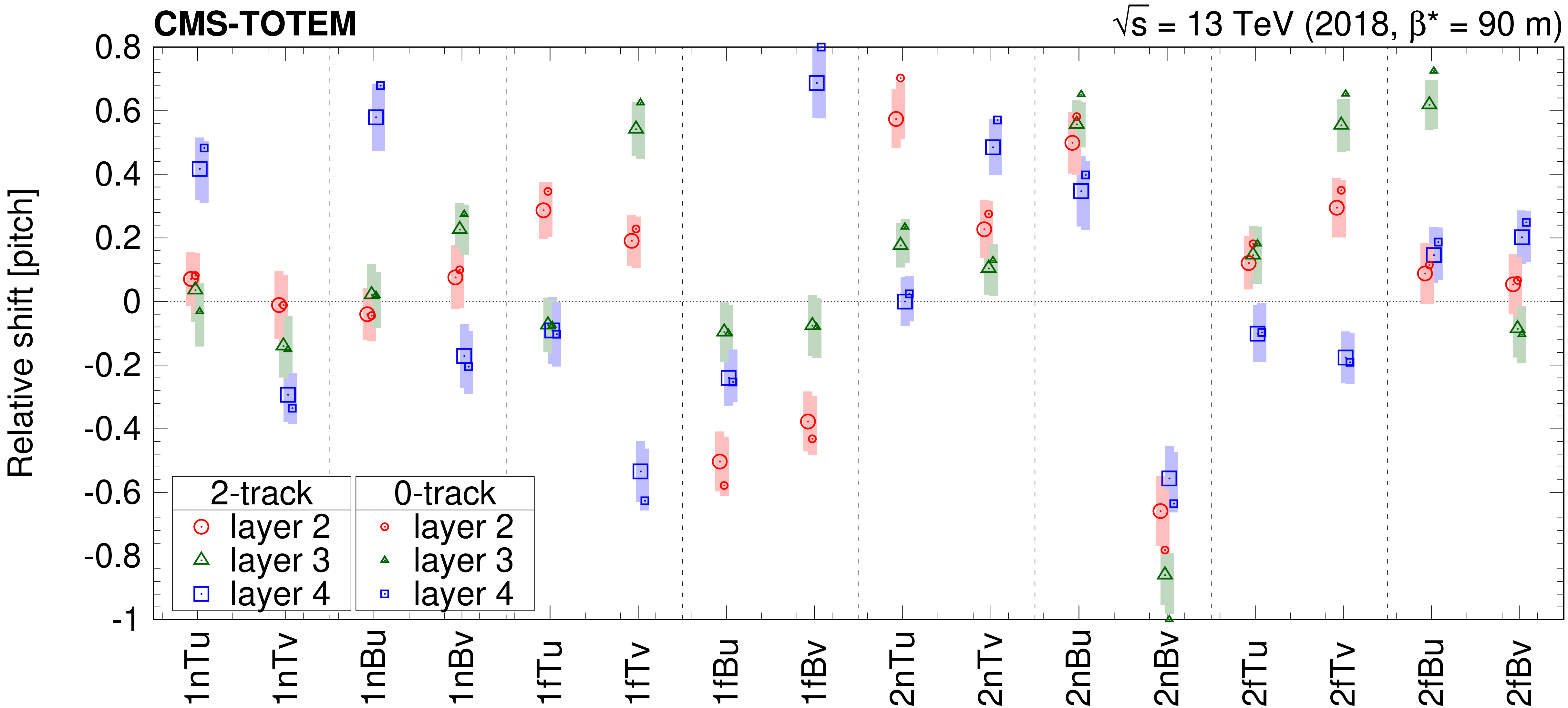
Area of the polygon is $A = \frac{1}{2} \sum_{j=0}^{n-1} (x_j\ y_{j+1} - x_{j+1}\ y_j)$

Variance through the moment of inertia

$$\sigma_y^2 = \frac{1}{12A} \sum_{j=0} (x_j y_{j+1} - x_{j+1} y_j)(y_j^2 + y_j y_{j_1}^2 + y_{j+1}^2)$$

Use global χ^2 of all tracklets to optimize relative shifts

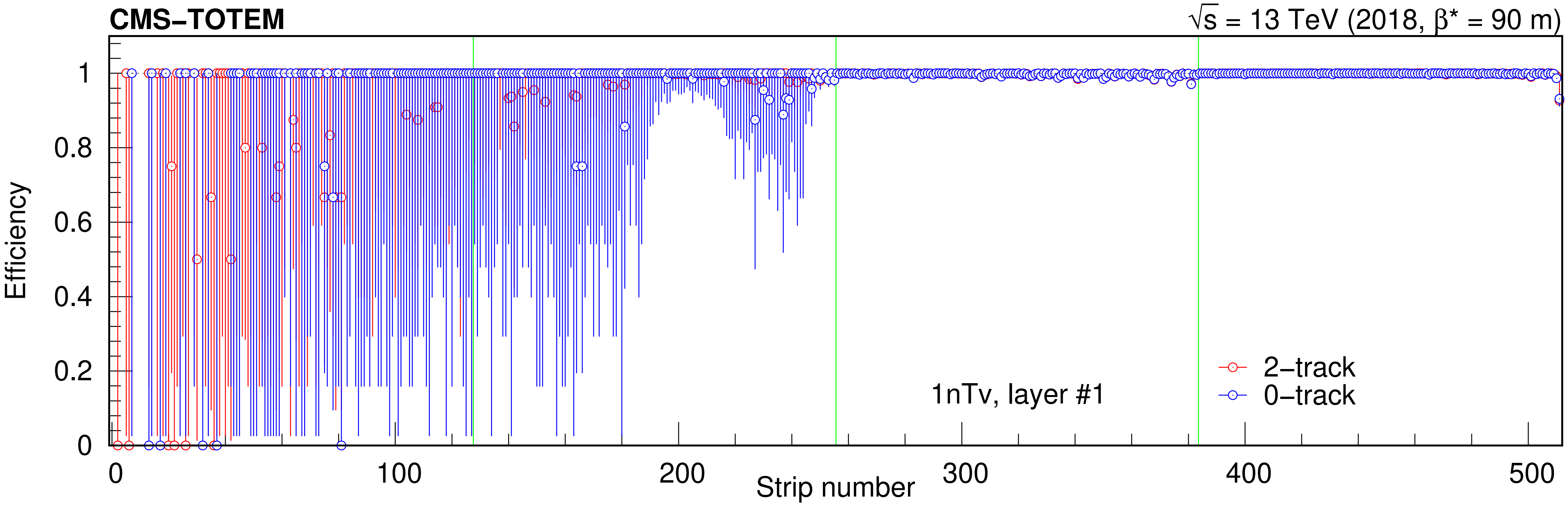
Roman pots – relative alignment of planes



Relative shifts in pitch (66 μm) units, for central exclusive elastic events

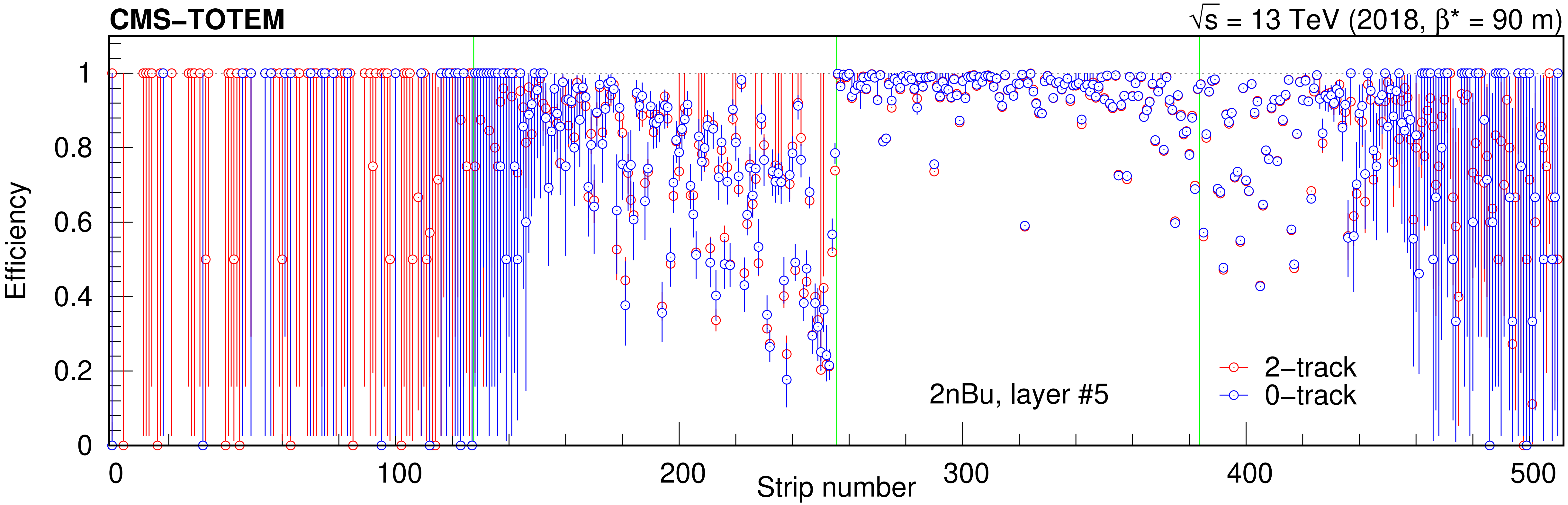
Translation and shear (weak modes)! Planes 1 and 5 are fixed

Roman pots – strip-level efficiencies



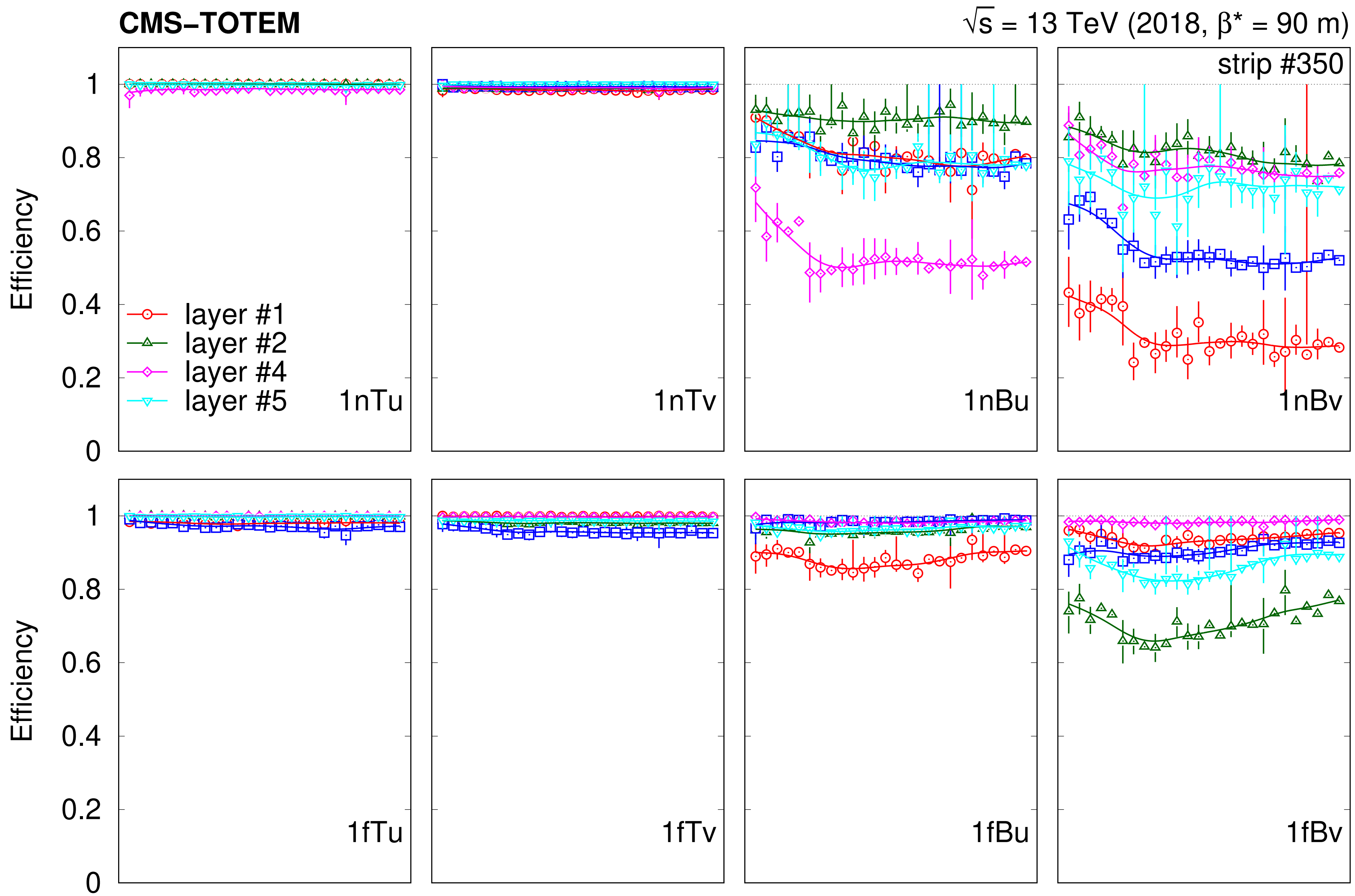
This looks good, but . . .

Roman pots – strip-level efficiencies



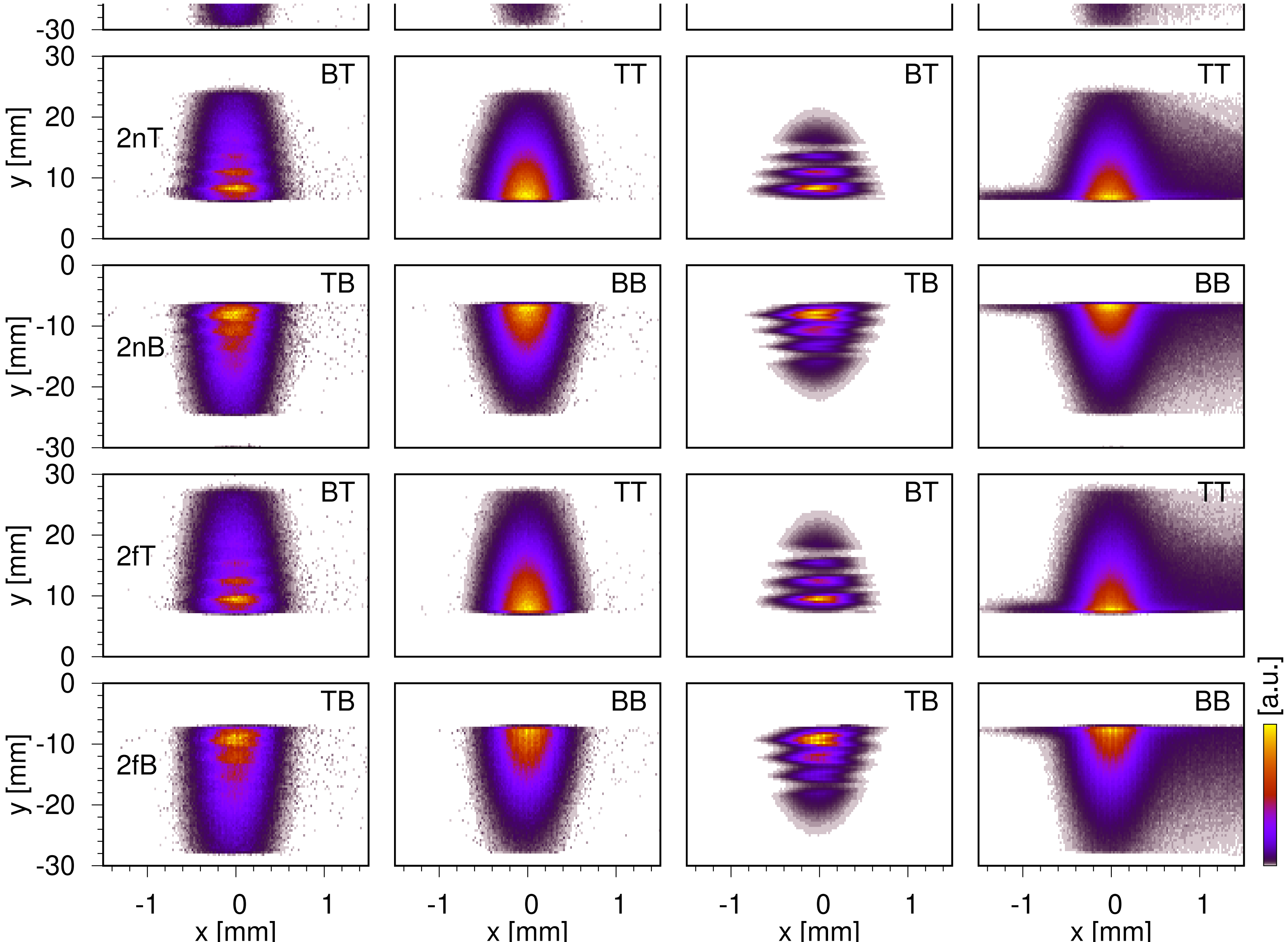
- Inefficiencies seen in data
  - originates at strip-level
  - efficiency can extracted by looking at found tracklets, “tag and probe”

Roman pots – strip-level efficiencies vs run



Changes wrt run number (here, for a given strip #350)

Roman pots – proton hit locations



Efficiency corrected

Beam optics studies – local vs global

The transverse coordinates of a particle (proton) at a path length s

$$x(s) = \sqrt{\beta_x(s)\varepsilon}\,\cos\left[\phi_0 + \Delta\mu(s)\right] + D_x(s)\Delta p/p,$$

with betatron amplitude β, emittance ε, phase offset ϕ_0, phase advance $\Delta\mu$, dispersion function D, relative momentum loss $\Delta p/p$.

The dependencies around a given location can be **linearised**,

$$x_1 = v_{x,1}x^* + L_{x,1}\theta_x^* + D_{x,1}\Delta p/p, \qquad x_2 = v_{x,2}x^* + L_{x,2}\theta_x^* + D_{x,2}\Delta p/p,$$

magnification $v(s) = \sqrt{\beta(s)/\beta^*}\cos\Delta\mu$ and **effective length** $L(s) = \sqrt{\beta(s)\beta^*}\sin\Delta\mu$.

For elastic and central exclusive collisions $|\Delta p/p| \ll 1$, the above equations solved as

$$x^* = (L_{x,2}x_1 - L_{x,1}x_2)/|d|, \qquad \theta_x^* = (v_{x,1}x_2 - v_{x,2}x_1)/|d|,$$

where $|d| = v_{x,1}L_{x,2} - v_{x,2}L_{x,1}$ is the distance between the near and far pots.

Scattered protons – absolute alignment per run – x direction

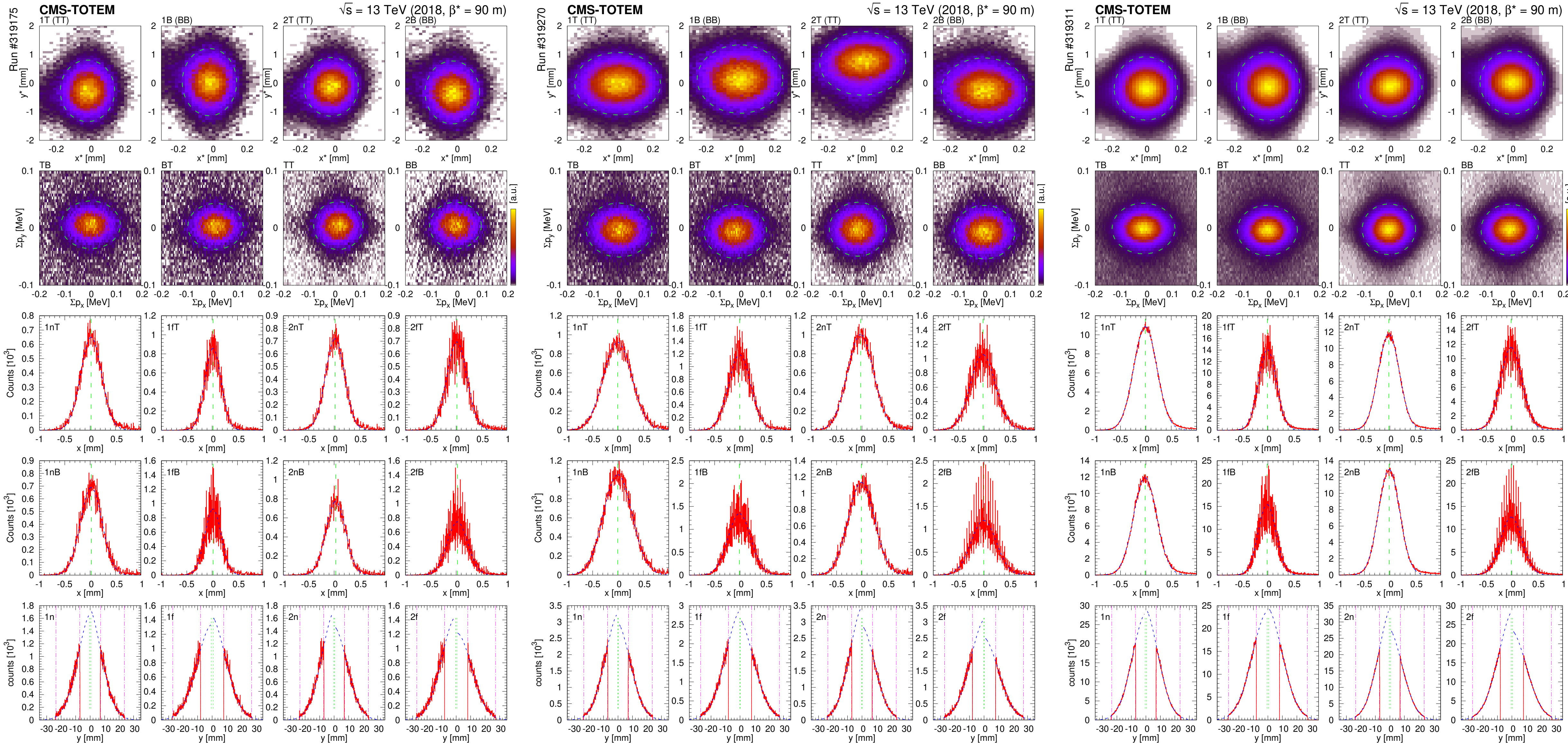
$$A_x = \begin{pmatrix} L_{1f}/d & -L_{1n}/d & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & L_{1f}/d & -L_{1n}/d & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & L_{2f}/d & -L_{2n}/d & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & L_{2f}/d & -L_{2n}/d \\ -pv_{1f}/d & pv_{1n} & 0 & 0 & 0 & 0 & -pv_{2f}/d & pv_{2n}/d \\ 0 & 0 & -pv_{1f}/d & pv_{1n}/d & -pv_{2f}/d & pv_{2n}/d & 0 & 0 \\ -pv_{1f}/d & pv_{1n}/d & 0 & 0 & -pv_{2f}/d & pv_{2n}/d & 0 & 0 \\ 0 & 0 & -pv_{1f}/d & pv_{1n}/d & 0 & 0 & -pv_{2f}/d & pv_{2n}/d \end{pmatrix},$$

where $d = |\det(v, L)|$, p is the beam momentum, and the transformation itself is

$$A_x \begin{pmatrix} \delta x_{1nT} \\ \delta x_{1fT} \\ \delta x_{1nB} \\ \delta x_{1fB} \\ \delta x_{2nT} \\ \delta x_{2fT} \\ \delta x_{2nB} \\ \delta x_{2fB} \end{pmatrix} = \begin{pmatrix} -\overline{x^*}_{1T} \\ -\overline{x^*}_{1B} \\ -\overline{x^*}_{2T} \\ -\overline{x^*}_{2B} \\ -\overline{\sum p_{xTB}} \\ -\overline{\sum p_{xBT}} \\ -\overline{\sum p_{xTT}} \\ -\overline{\sum p_{xBB}} \end{pmatrix}.$$

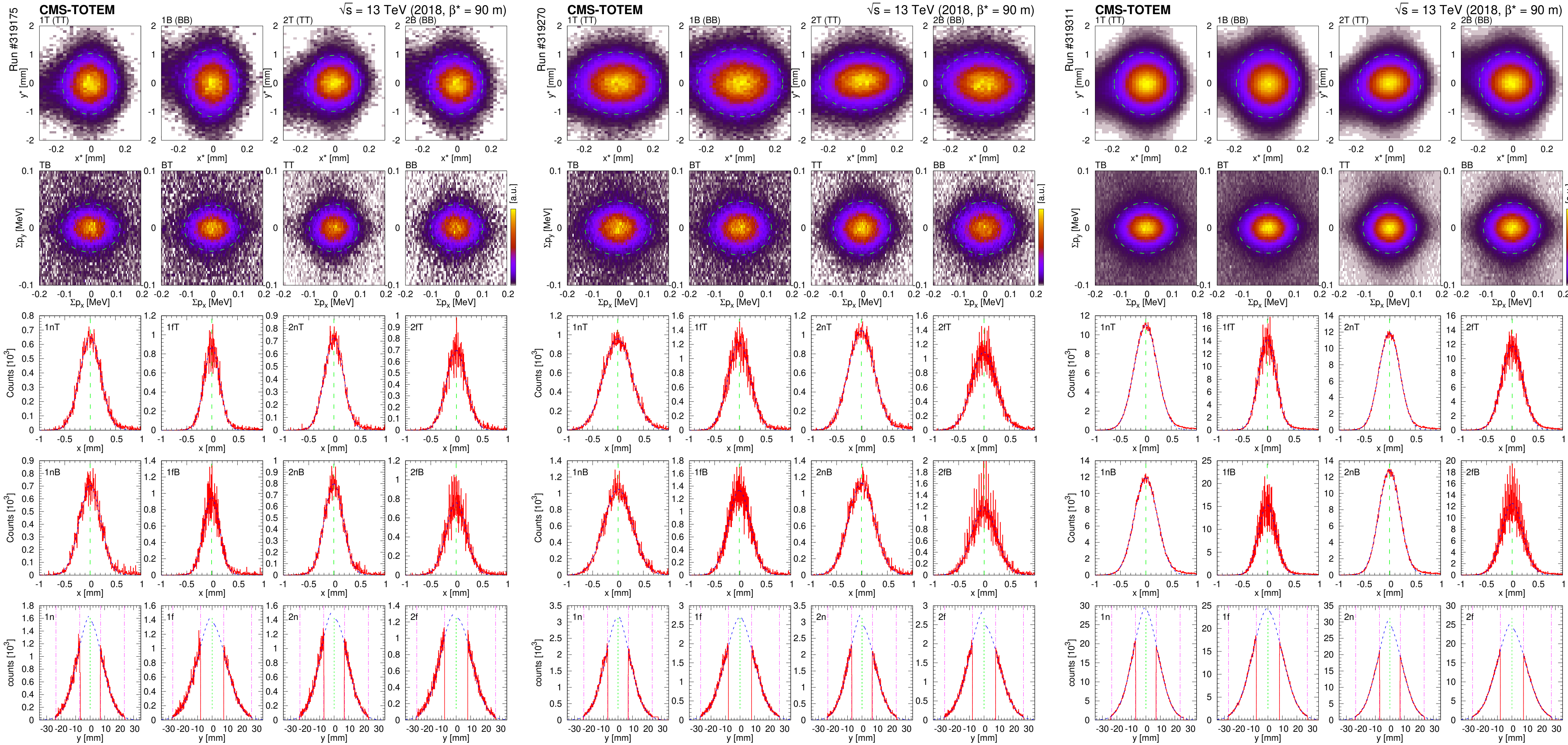
From measured quantities to alignment

Scattered protons – absolute alignment per run



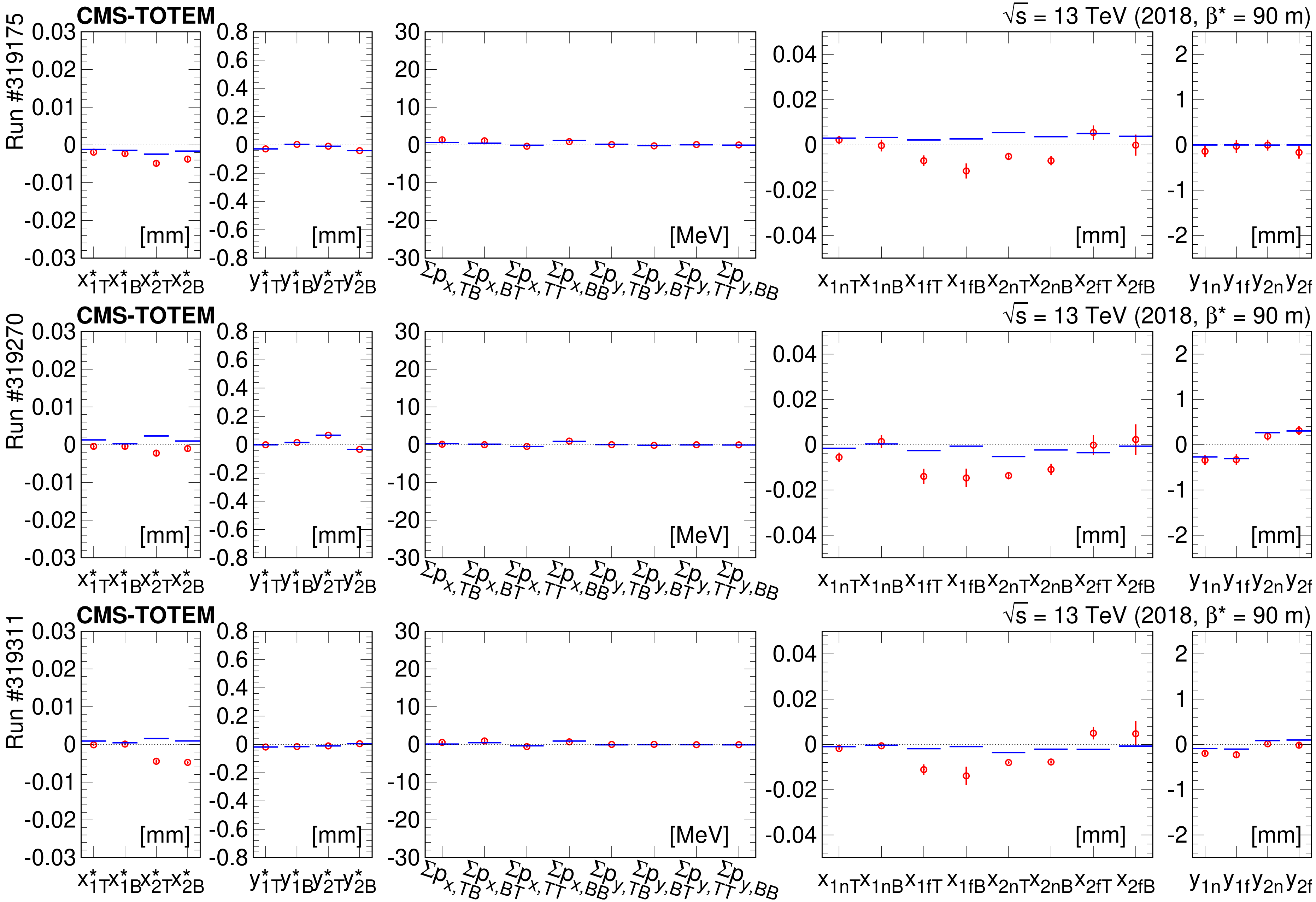
Use symmetries for interaction point (x^*, y^*), momentum sums $(\sum p_x, \sum p_y)$, local hits (x, y)

Scattered protons – absolute alignment per run – aligned

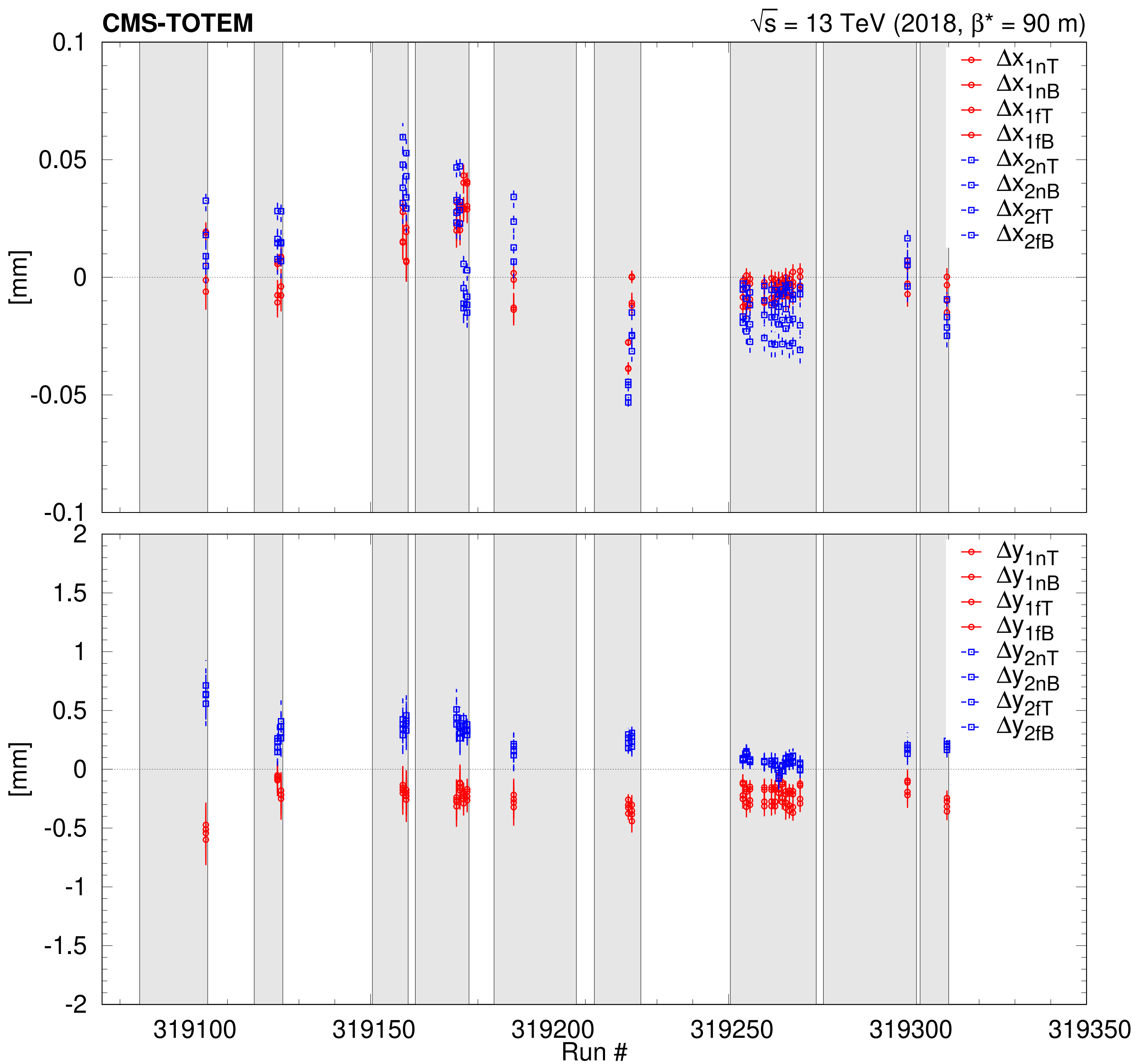


Use symmetries for interaction point (x^*, y^*), momentum sums $(\sum p_x, \sum p_y)$, local hits (x, y)

Scattered protons – absolute alignment, residuals – aligned



Scattered protons – deduced displacements vs run

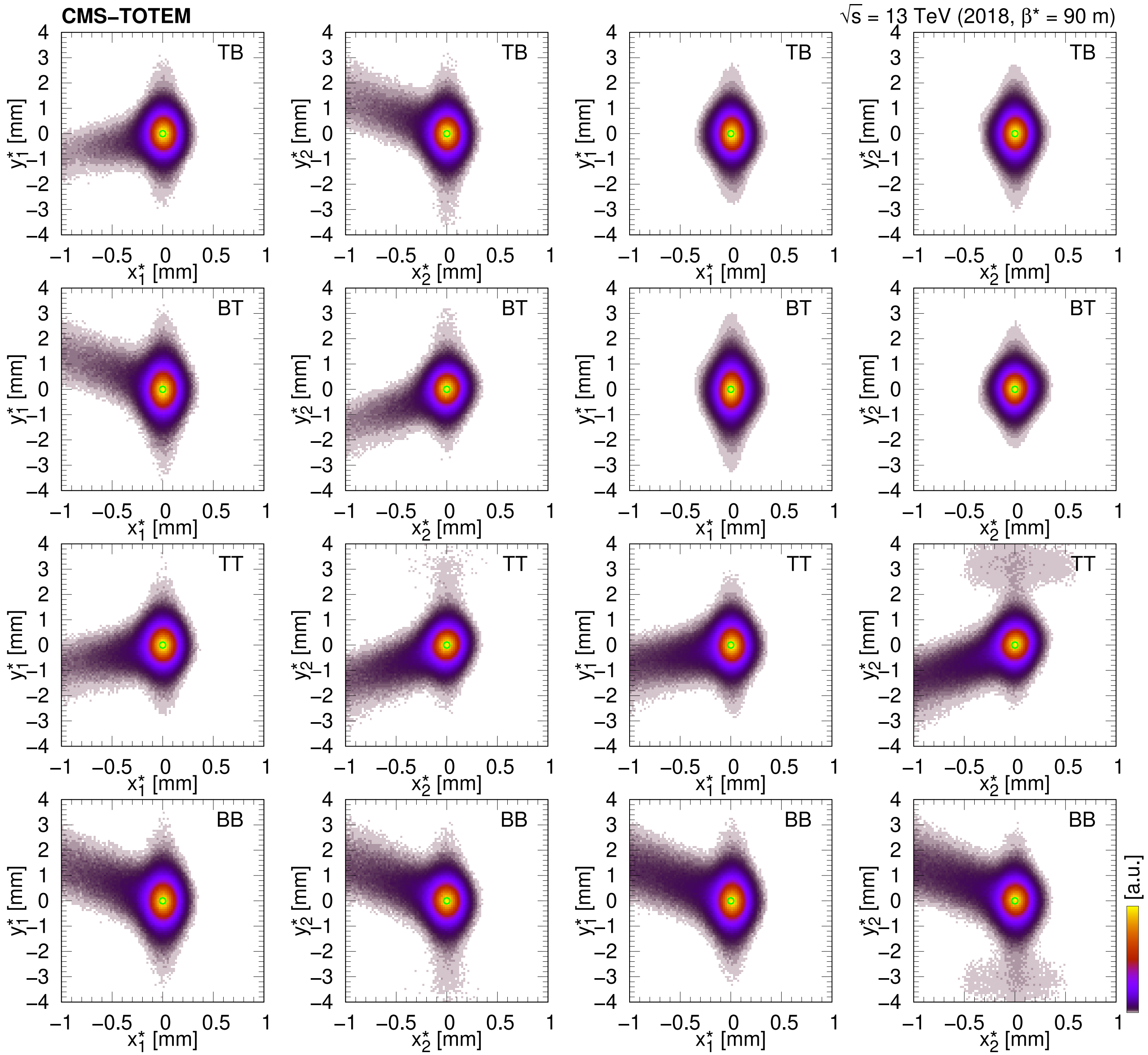


- Deduced displacements
  - in x direction (lateral):
    an arm moves together
    similar changes in both arms
  - in y direction (up-down):
    an arm moves together
    changes are opposite in arm 1/2

Points to common source:
drifting LHC proton orbits

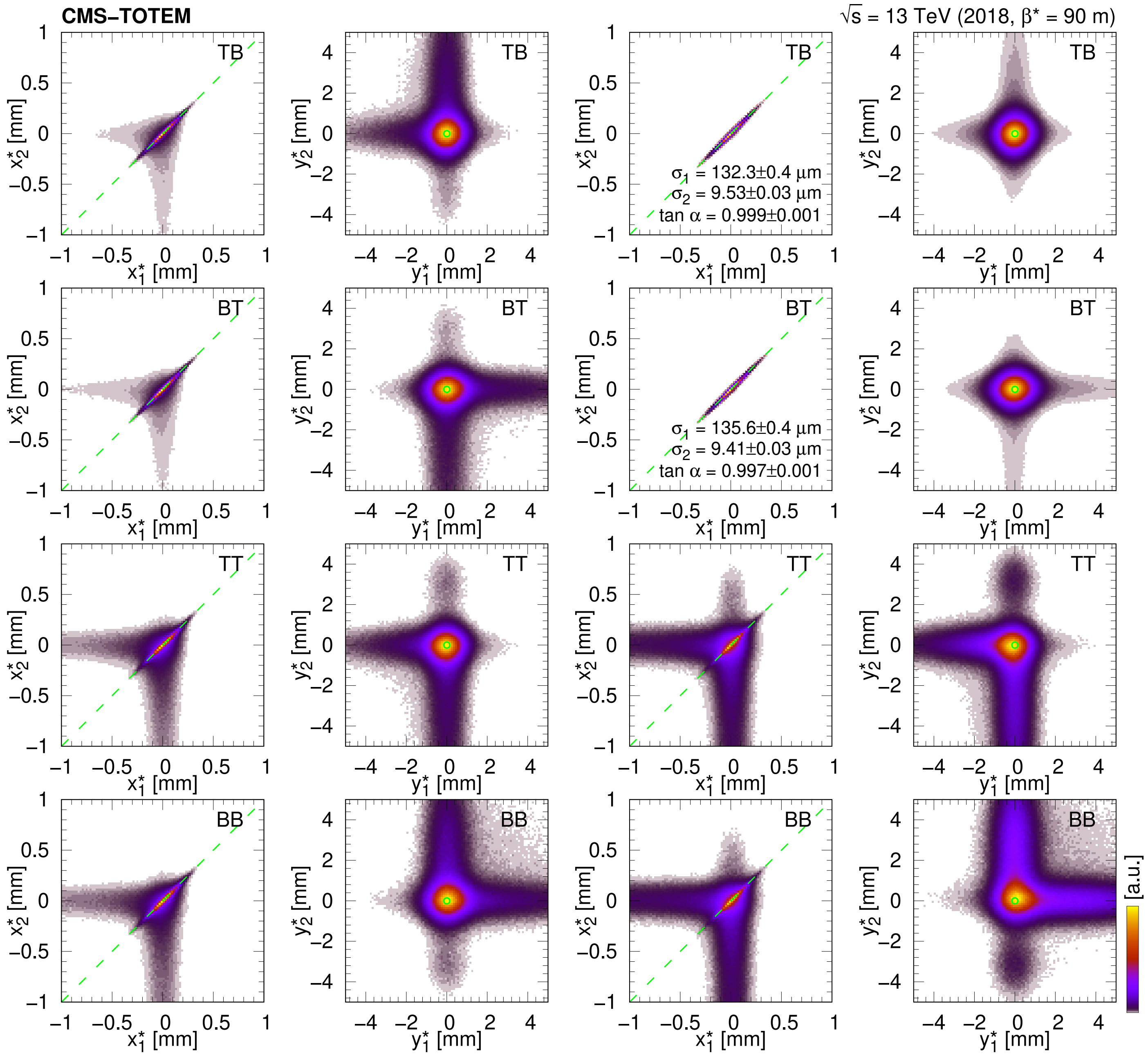
(RP movement system ensures reproducibility of about 20 μm)

Results – collision vertex



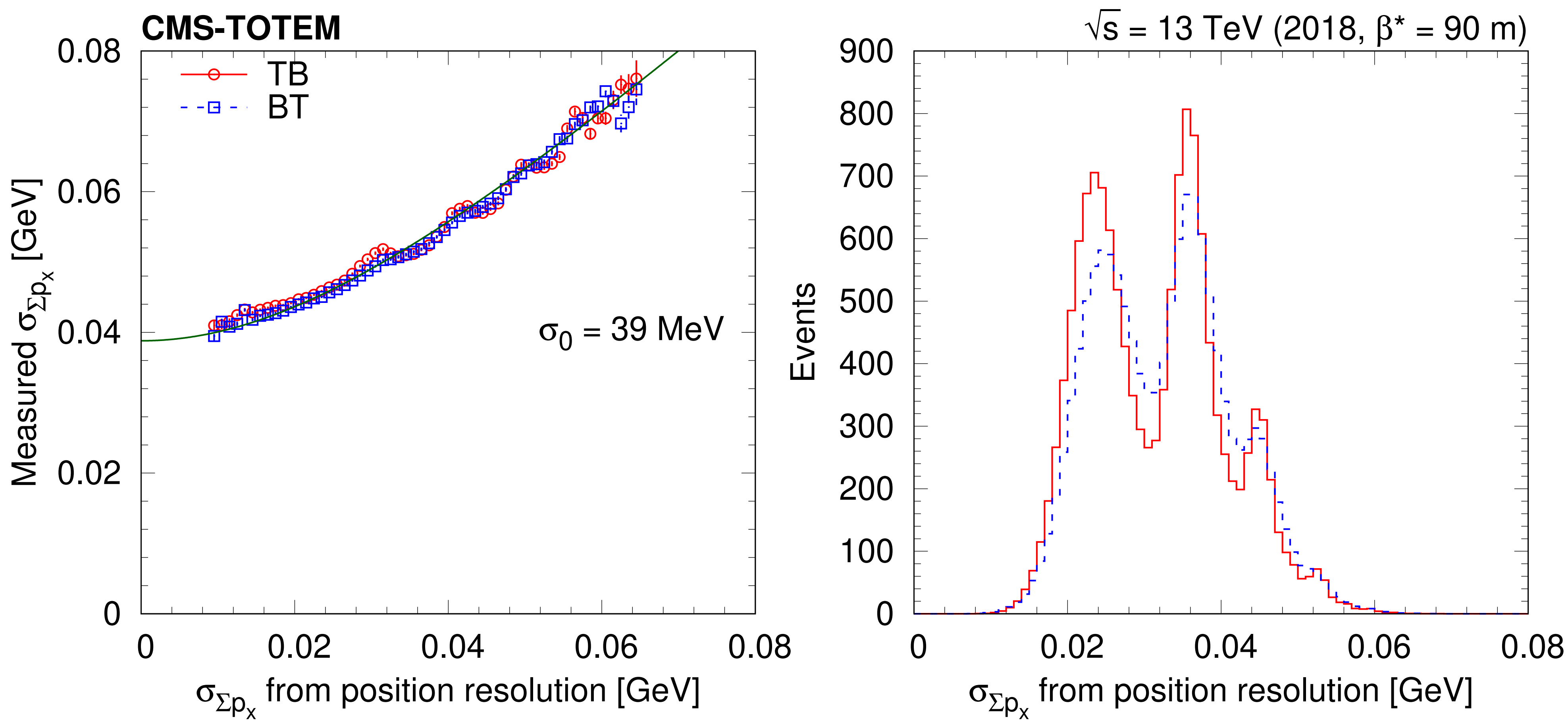
- Reconstructed vertices
  - from one arm only
  - location of the primary pp interaction in the $x - y$ plane at the IP
  - all distributions are well centred on $(0, 0)$

Results – collision vertex



- Reconstructed vertices
  - from using both arms
  - joint distribution of x^* or y^* coordinates of the primary pp interaction
  - beam spot normally distributed with size $\sigma \approx 95\,\mu$m with precision $6 - 7\,\mu$m

Results – momentum resolution – x direction



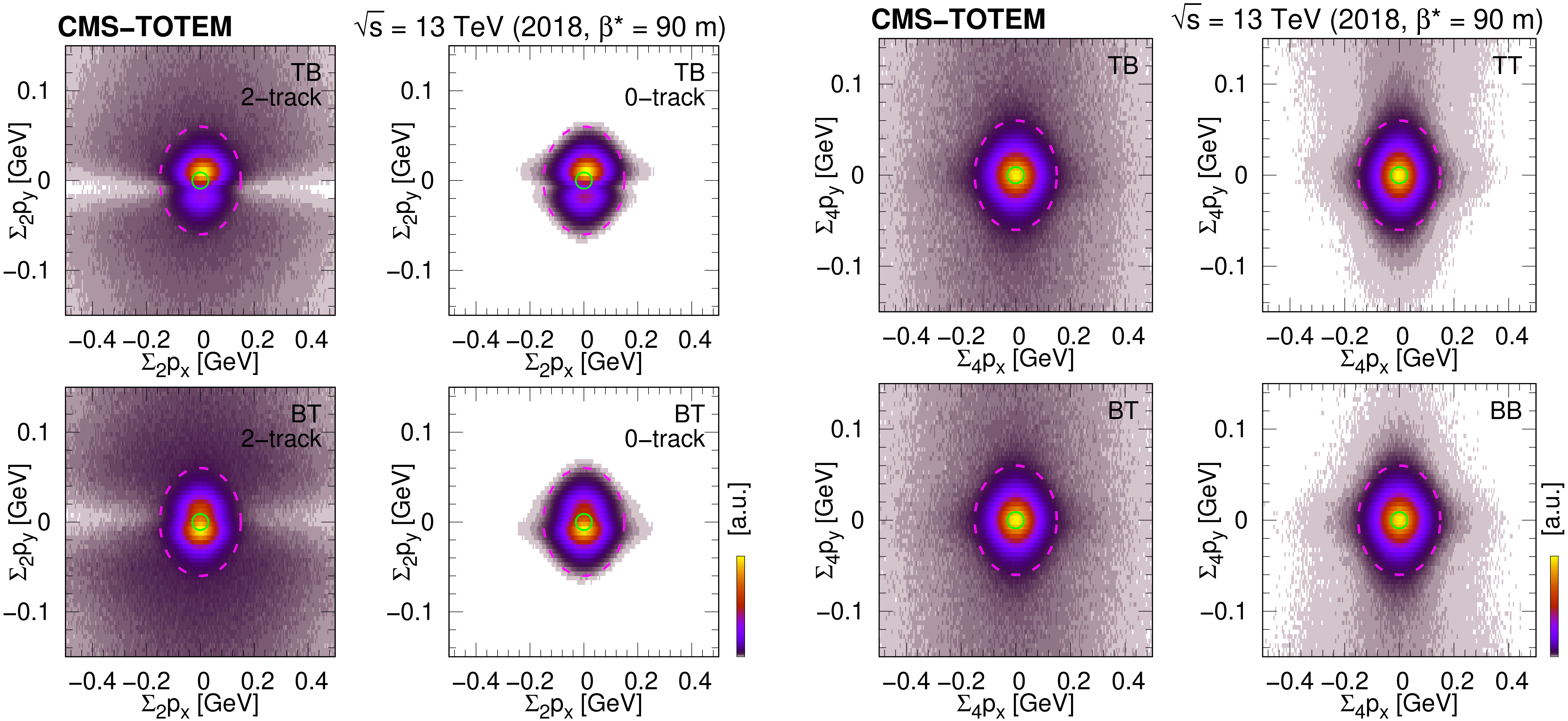
Looking at $\sigma_{\sum p_x}$ of scattered protons

Correctly follows $\sqrt{\sigma_0^2 + \sigma^2}$ with $\sigma_0 \approx 40\,\mathrm{MeV}$

Beam divergence, multiple scattering, physics process, apparent momentum imbalance

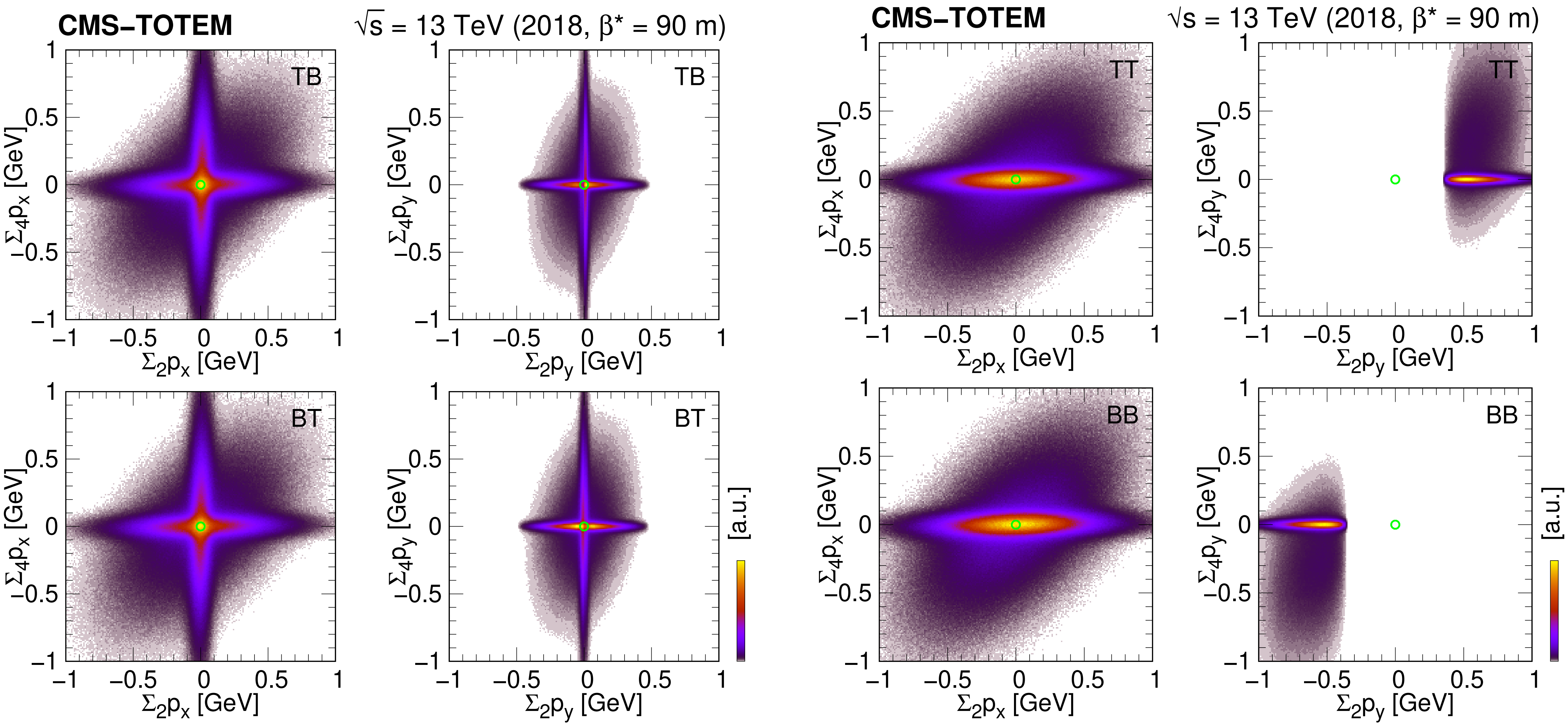
Results – momentum sums

central exclusive (2h) | elastic (0h)



Ellipses with semi-minor axes of 150 MeV (x) and 60 MeV (y) are overlaid

Results – momentum sums – true exclusive vs pile-up



Based on $(\sum_4 p_x$ vs $\sum_2 p_x$, $\sum_4 p_y$ vs $\sum_2 p_y)$

Summary

- Details
  - Roman pot detectors of the TOTEM experiment
  - to reconstruct the transverse momentum of scattered protons
  - to estimate the transverse location of the primary interaction

- Results
  - novel method, by finding a common polygonal area in the intercept-slope plane
  - relative alignment of detector layers with μm precision
  - tag-and-probe methods to extract strip-level detection efficiencies
  - absolute alignment of the roman pot system system
  - used in the physics analysis of central exclusive production events