Far-Forward Weekly Meeting

Roman Pots alignment at the LHC

17 February 2025

Michael Pitt (CERN)

Some material is "CMS internal", shown here to facilitate technical discussion

Roman Pots (RP) at the LHC

- Two Interaction Points (IP) are equipped with RP at about 200m from the IP1 (ATLAS) and IP5 (CMS)

CMS-Precision Proton Spectrometer (PPS):

- 4 tracking stations at ~215m from the IP (vertical & horizontal)
- 2 stations of timing stations (diamond detectors)

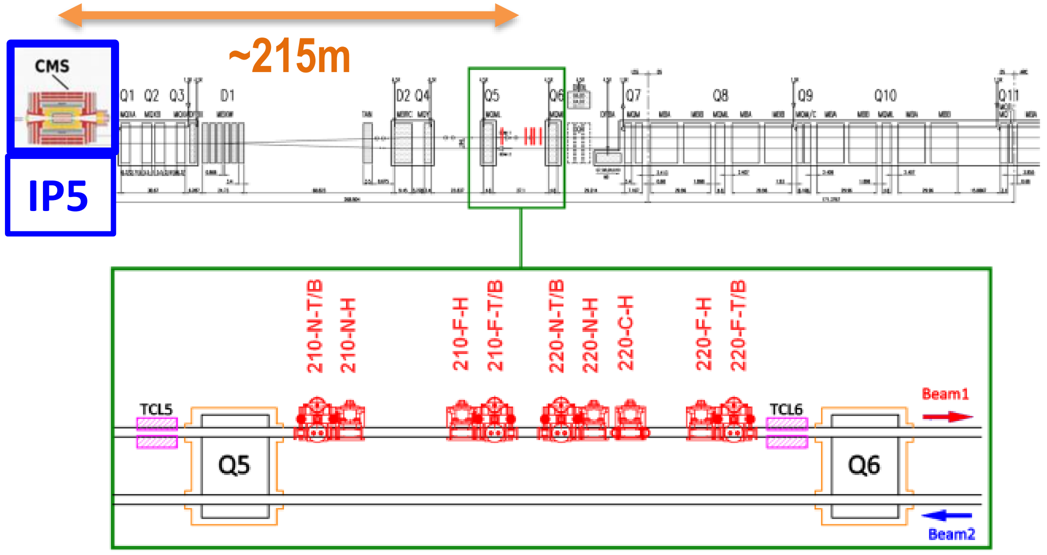
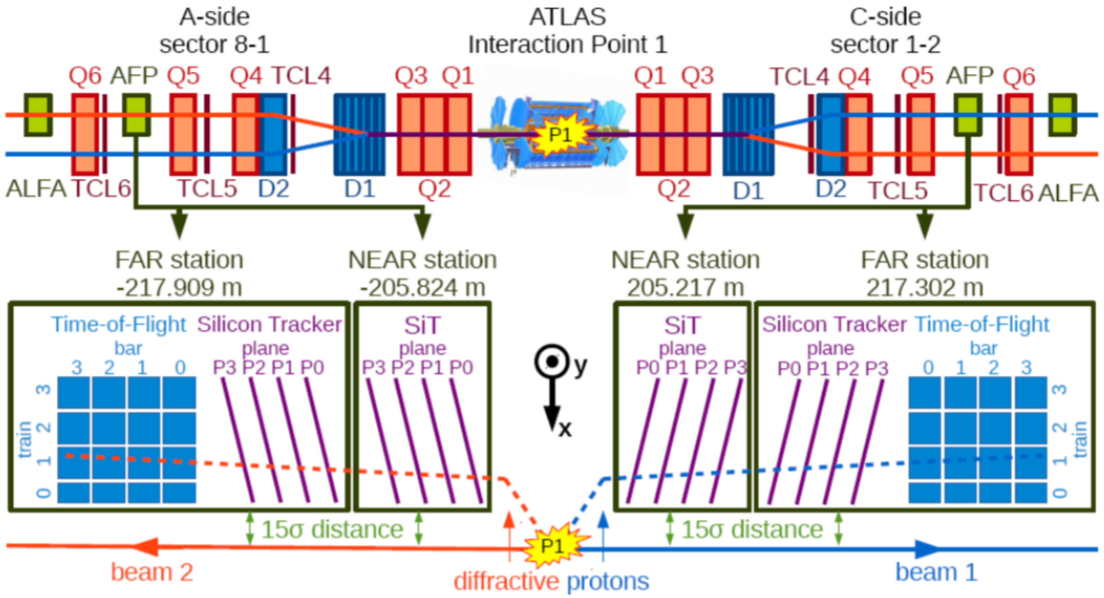


Figure 54: Schematic overview of the PPS units in Sector 5-6 (outgoing Beam 1) in the pre-LS3 configuration (top drawing adapted from [123]). The instrumentation in Sector 4-5 (outgoing Beam 2) is mirror-symmetric.

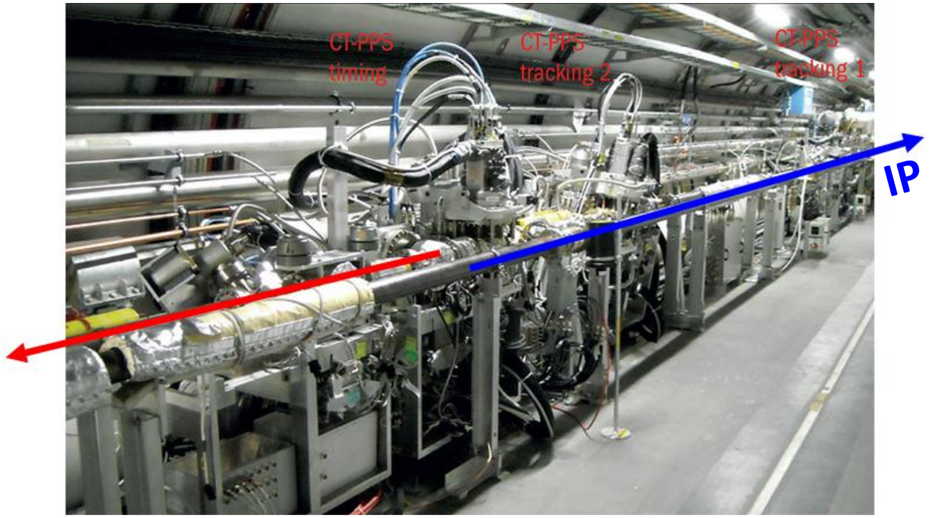
ATLAS Forward Proton (AFP):

- 2 tracking stations at ~210 m from the IP with (horizontal)
- Far stations also have timing stations (quartz bars)



CMS - Precision Proton Spectrometer

- TOTEM expertise (JINST (2008) 3 S08007)
- Operated in CMS since 2016 (TOTEM-TDR-003)
- Located ~ 200m from the interaction point in both arms, equipped with tracking/timing detectors
- A set of near-beam detectors, which approach the beam down to a few mm, hosted in movable vessels (Roman-Pots)



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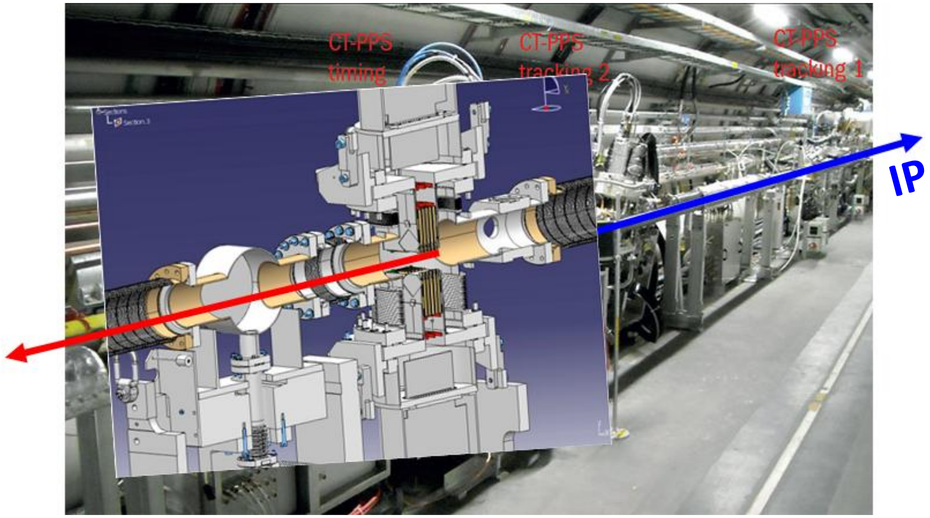
- Located ~ 200m from the interaction point in both arms, equipped with tracking/timing detectors
- A set of near-beam detectors, which approach the beam down to a few mm, hosted in movable vessels (Roman-Pots)
- Off-momentum protons → smaller magnetic rigidity
- Measure protons with ~85-97% momentum w.r.t. beam energy.

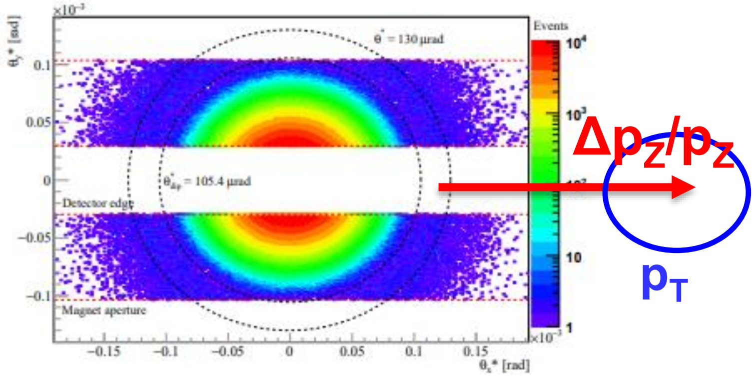


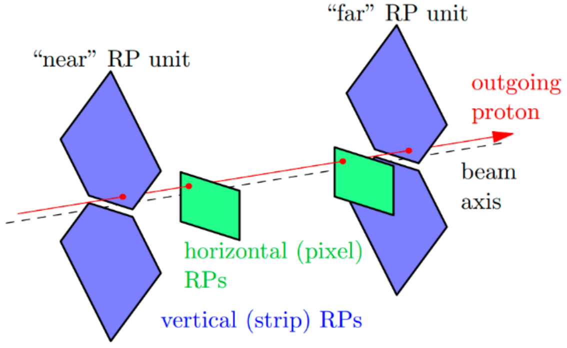
CMS - Precision Proton Spectrometer

Vertical detectors (TOTEM in the past for elastics)

- Operated during calibration runs (alignment)
- Proton kinematics:

$\Delta p_Z/p_Z$ < 20% and **p_T ~ 0.1 – 2 GeV**



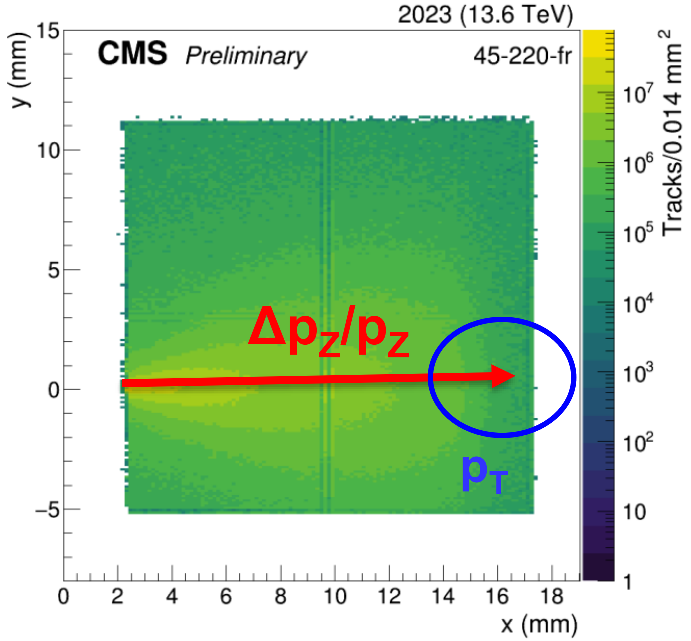


JINST 18 (2023) P09009

Horizontal detectors

- Standard LHC optics (high pileup)
- Proton kinematics:

2.5%<$\Delta p_Z/p_Z$ < 15% and **p_T < 4 GeV**



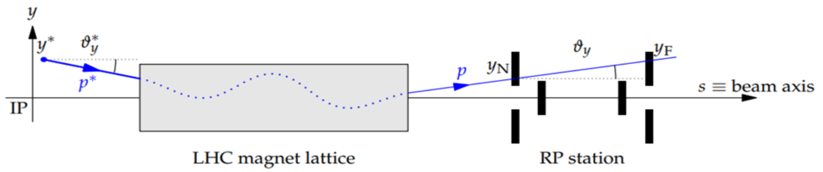
Horizontal crossing

Proton reconstruction

- Intact protons lose a fraction of momentum ($\boldsymbol{\xi = \Delta p_Z/p}$) and are scattered at small angles ($\boldsymbol{\theta_x^*, \theta_y^*}$) → they are deflected away from the beam and measured by the spectrometers

$$\delta x(z) = x_D(\xi) + v_x(\xi)x^* + L_x(\xi)\theta_x^*$$

$$\delta y(z) = y_D(\xi) + v_y(\xi)y^* + L_y(\xi)\theta_y^*$$



IP1 (ATLAS/LHCf)		
β*	1 m	
Half crossing angle	-145 μrad	V (negative) is optimal for LHCf
Leveling value (pile-up)	μ = 0.01-0.03-0.2	2h at 0.2 then 8h at 0.01 then 0.03 for the rest
Peak pile-up	μ ~ 0.44	This is if head-on at the start of the fill.
IP5 (CMS)		
β*	1 m	
Half crossing angle	+60 μrad	H (positive)
Leveling value (pile-up)	No leveling	
Peak pile-up	μ ~ 0.5	This is when head-on at the start of the fill.

https://lpc.web.cern.ch/Run3/SpecialIonRunConfigurations_2025.html

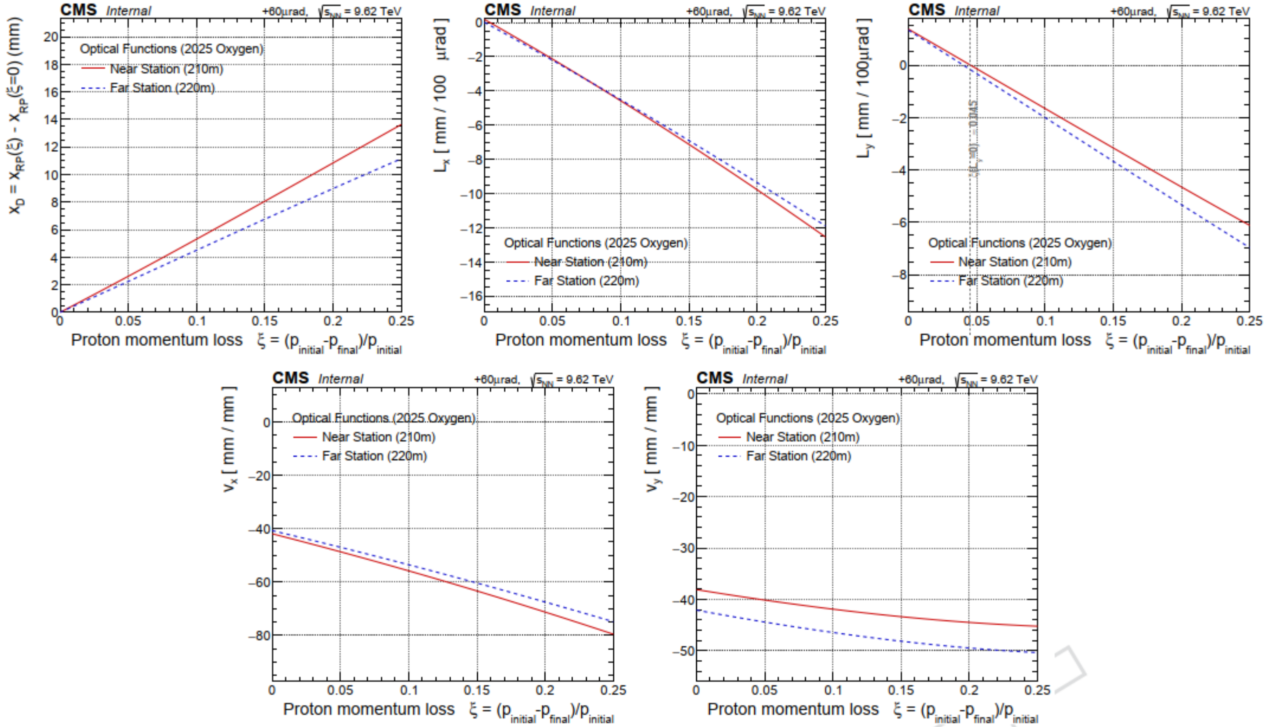


Figure A.1: Parameters of the proton transport matrix (D_x, L_x, L_y, v_x, and v_y) for the pO beam optics, comparing the Near (210 m) and Far (220 m) stations.

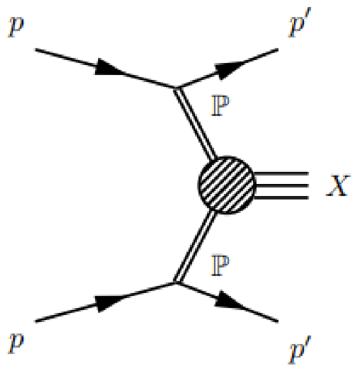
Alignment → Global coordinate system (w.r.t. beam center) → Proton reconstruction

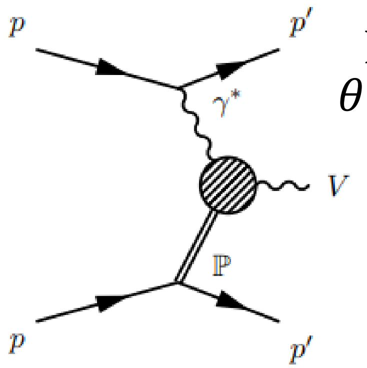
LHC optics

Protons are scattered at small angles (θ^*) and are displaced from the beam center (dx).

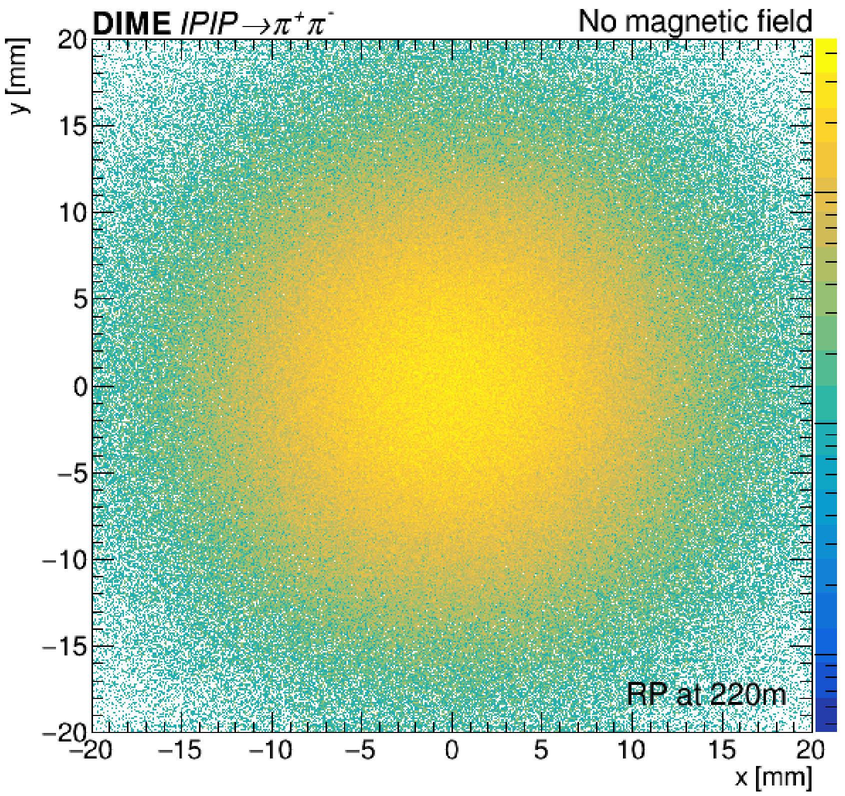
The displacement then is equal to:

The length × the scattering angle
$dx = L \times \theta^*$





$p_T \sim 0.1\text{GeV}$
$\theta^* \sim 0.01\text{mrad}$



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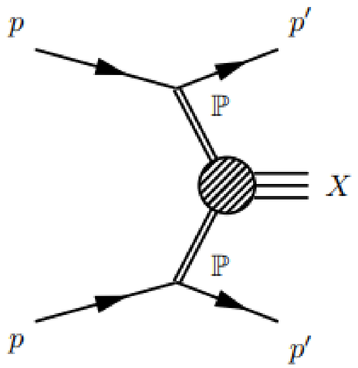

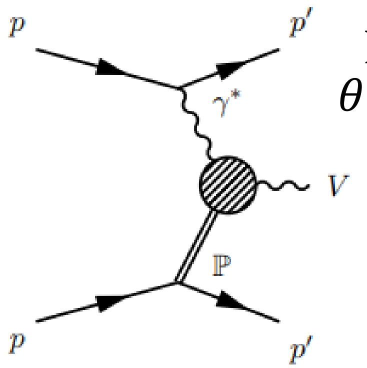

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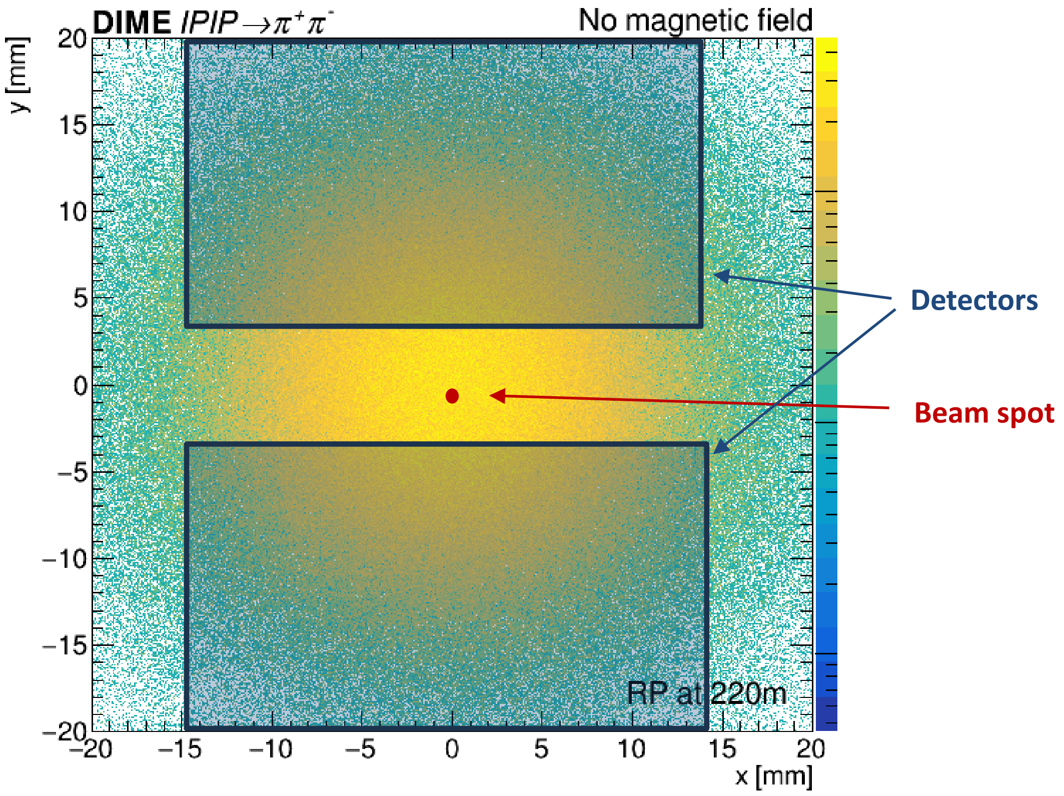


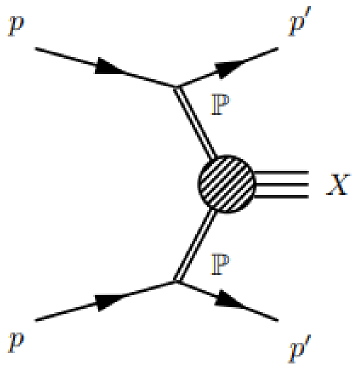
Proton hit map @PPS, no magnetic fields, L=220m

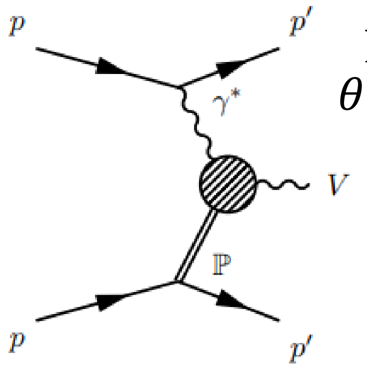
LHC optics

Protons are scattered at small angles (θ^*) and are displaced from the beam center (dx).

The displacement then is equal to:

The effective length × the scattering angle
$dx = L^* \times \theta^*$





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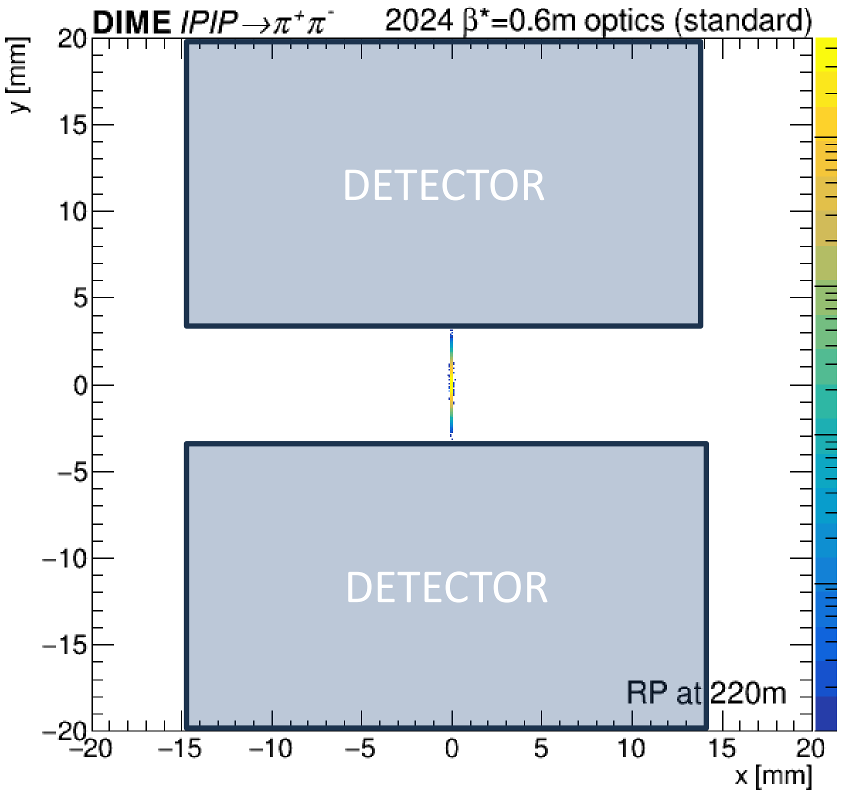


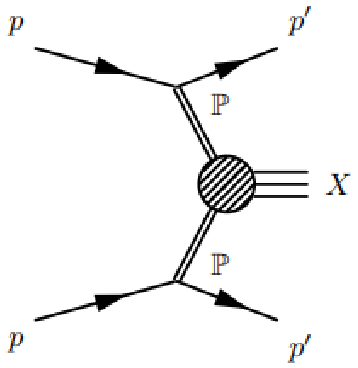
Proton hit map @PPS, Standard LHC optics, L~10m*

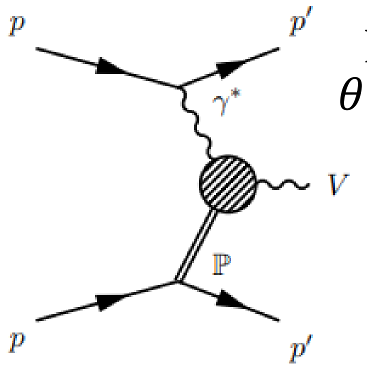
LHC optics

Protons are scattered at small angles (θ^*) and are displaced from the beam center (dx).

The displacement then is equal to:

The effective length × the scattering angle + dispersion
$dx = L^*(\xi) \times \theta^* + \mathrm{D}(\xi)$





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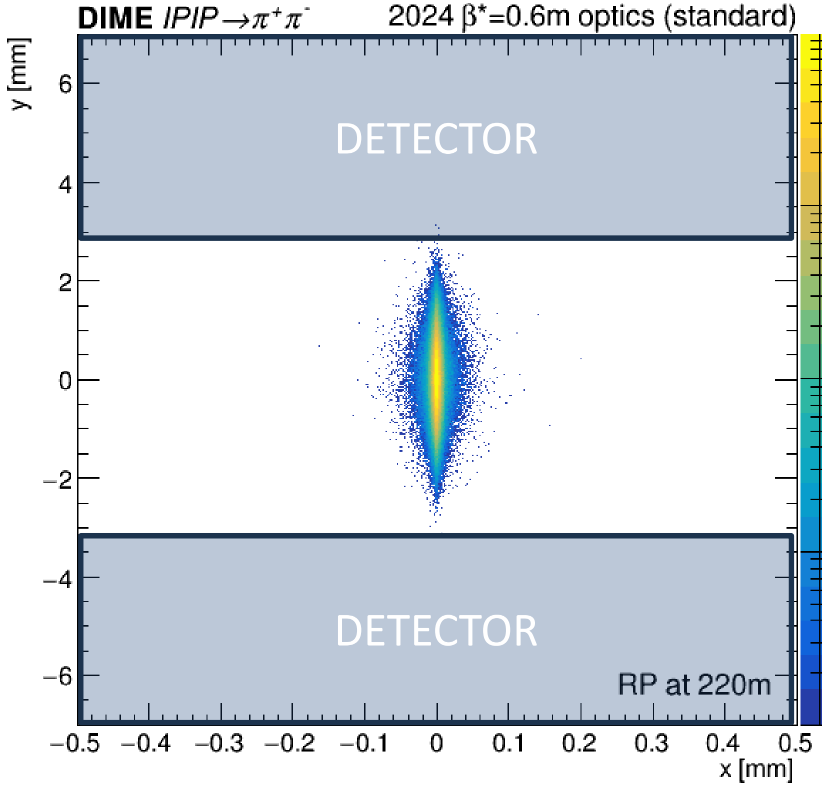


Proton hit map @PPS, Standard LHC optics, L~10m*

LHC optics

Main parameters that impact transport dynamics are:

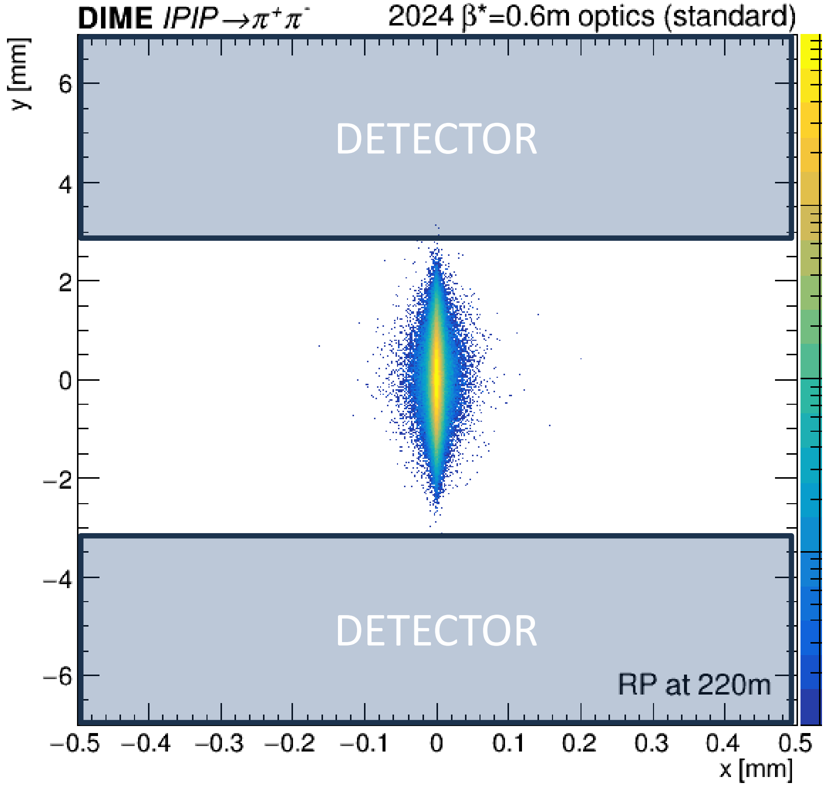
β^* - beam focus (small beam spot → higher luminosity)

$$\mathcal{L}_{inst} \propto \frac{1}{\beta^*}$$

L^* - effective length

$$L^*_{x,y} = \sqrt{\beta_{x,y}\beta^*}\,\sin(\Delta\mu_{x,y})$$

Where $\Delta\mu = \int_{IP}^{RP} \frac{ds}{\beta(s)}$ is betatron phase advance



Proton hit map @PPS, Standard LHC optics, L~10m*

LHC optics

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β^* - beam focus (small beam spot → higher luminosity)

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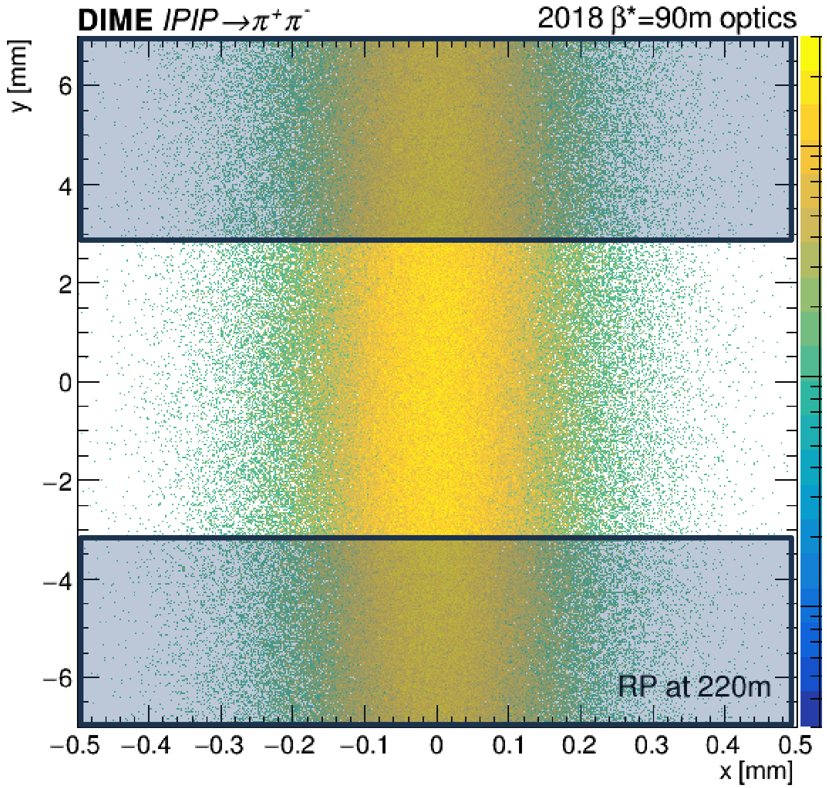
High beta* optics (90m):

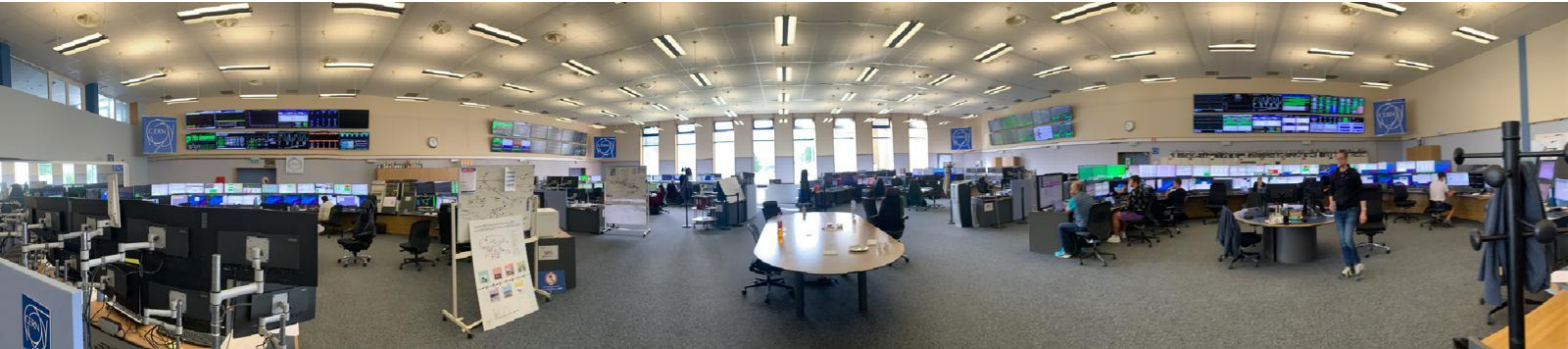
- Low PU
- High acceptance of scattering protons



Proton hit map @PPS, high β optics, L*~250m*

Beam Based Alignment (BBA)

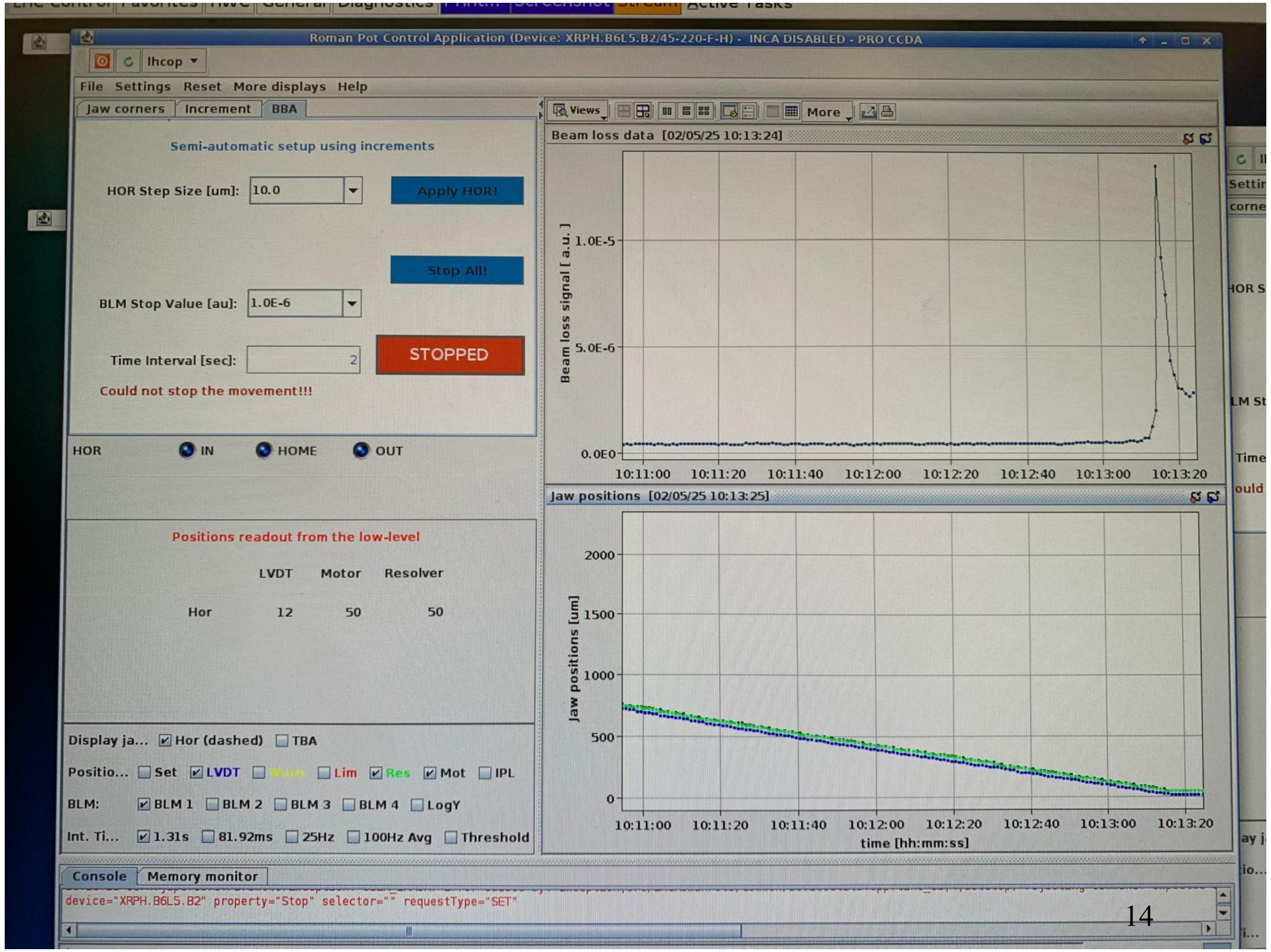
- Performed during special fill – 2 colliding bunches in CERN Control Centre (CCC)
  - Beam optics is the same as in the physics runs (small L*)
  - Alignment of the collimators (by the collimation team) and determination of the collimator distance
  - Move RP toward the beam in small steps, until splashes in beam loss monitors



Beam Based Alignment (BBA)

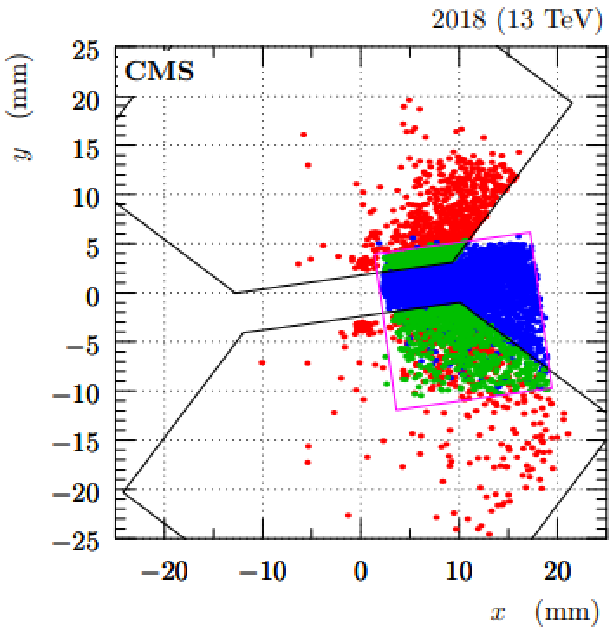
- Move RP toward the beam in small steps, until splashes in beam loss monitors (BLMs)

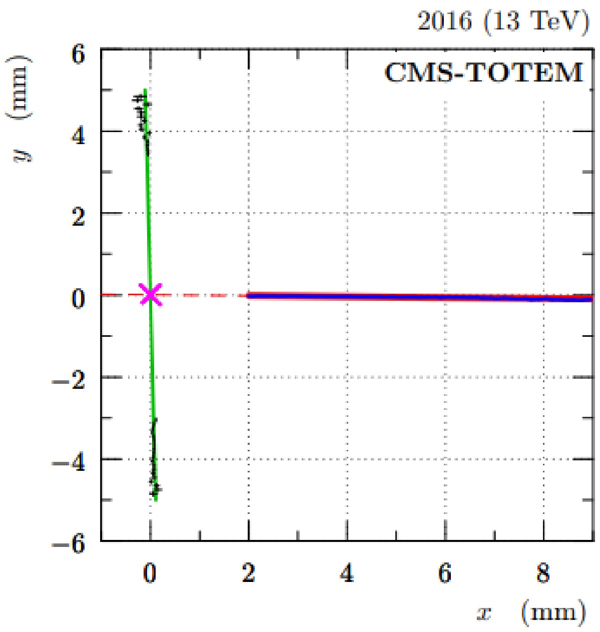
- RP moving panel was developed from the collimator's interface
- Automatic system that moves RP (10μm/2sec) until BLM
- The absolute RP distance from the beam is determined using the calibrated collimator edge position.
- The near detectors are aligned first, the collimators scrape the beam, and then the far detectors start to approach.

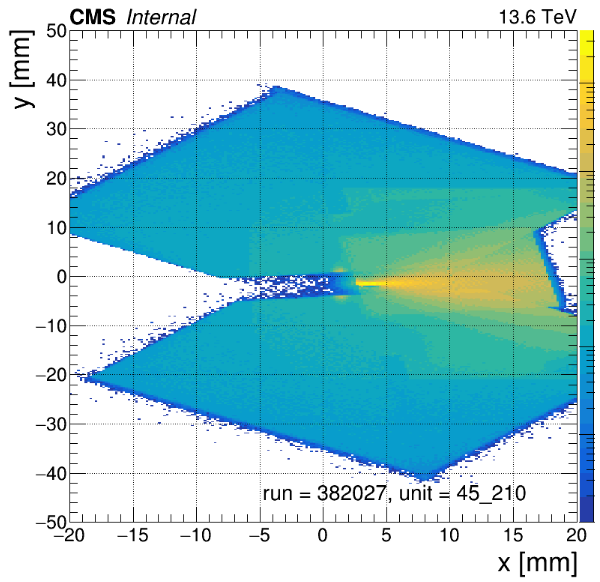


Relative alignment

- Following the BBA, detectors are placed ~1-2mm from the beam centre and a few hours run is performed:
  - Vertical/horizontal detectors are relatively (to horizontal) aligned based on the overlapping tracks
  - Fit to beam halo/elastics and diffractive line







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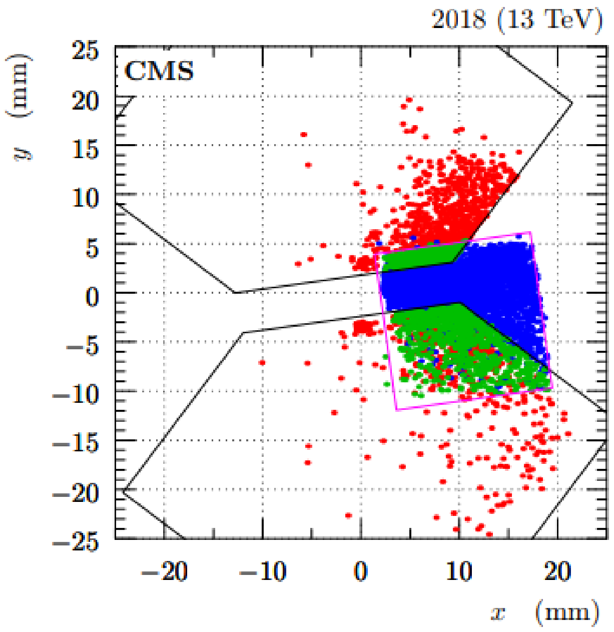

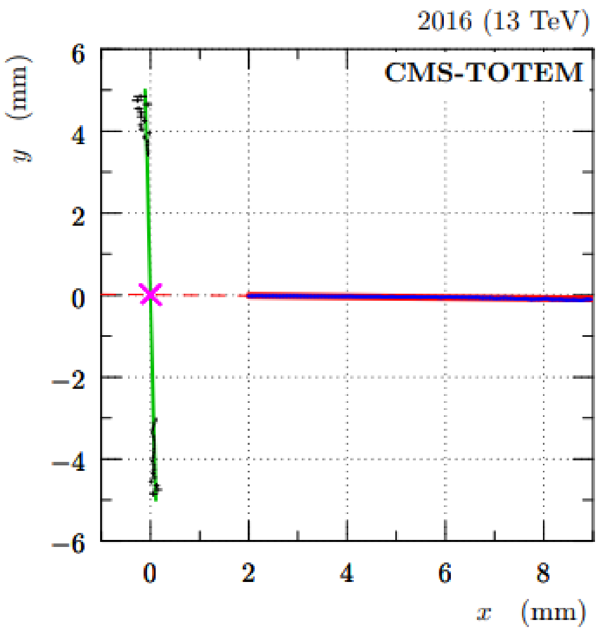

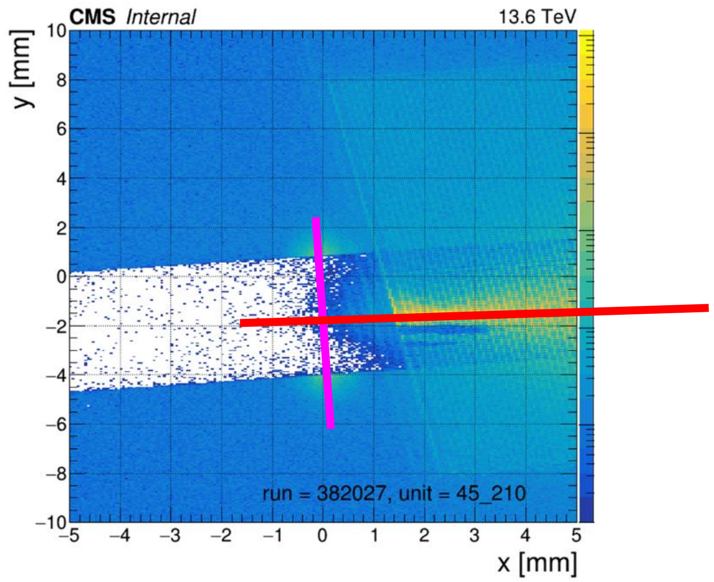

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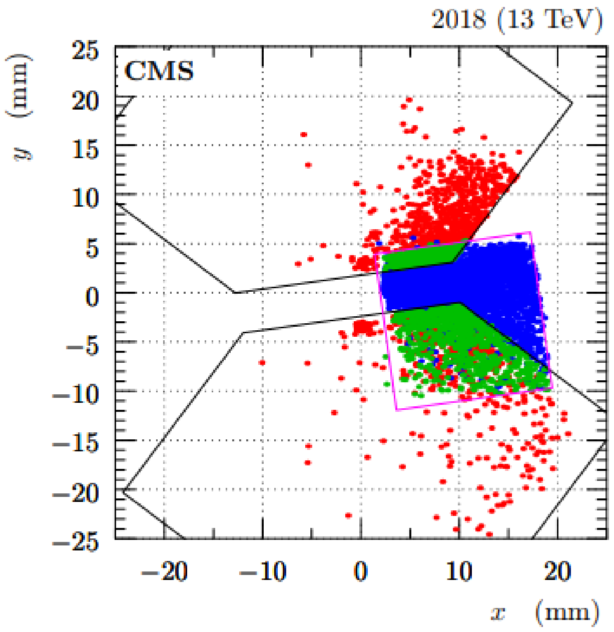
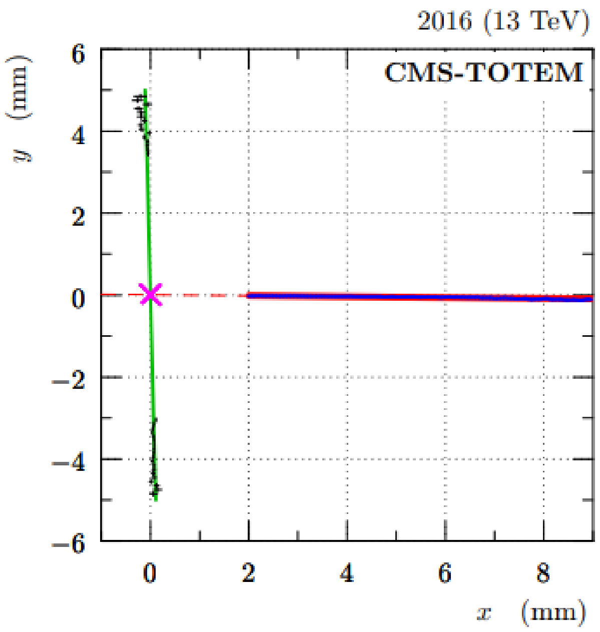
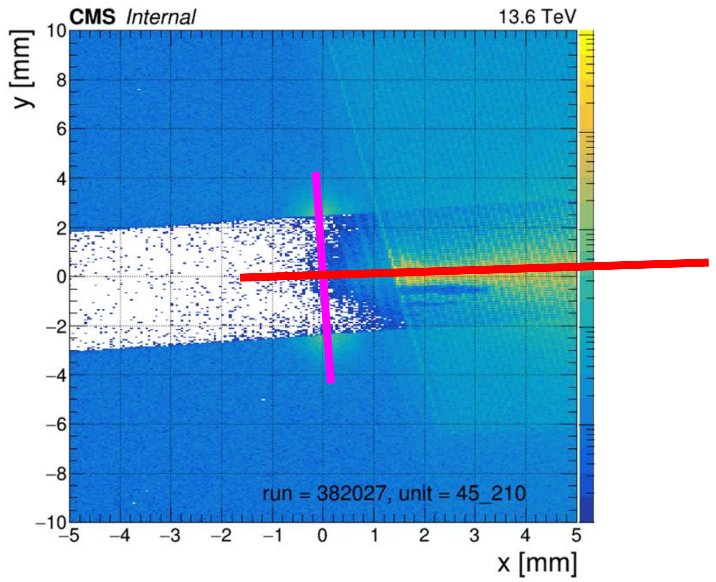


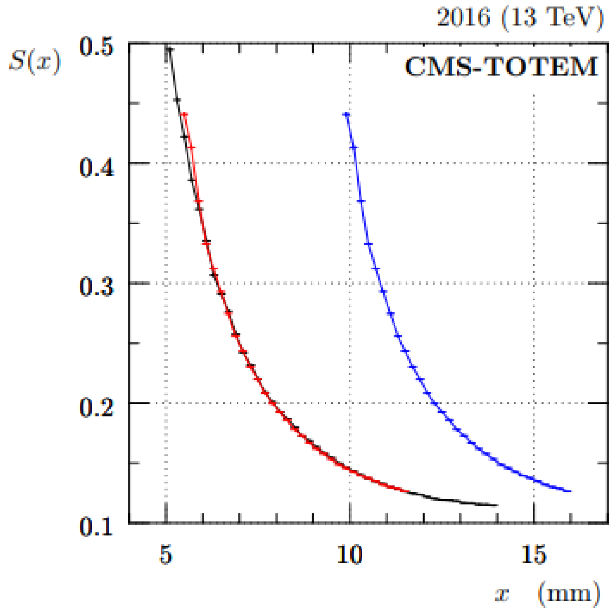


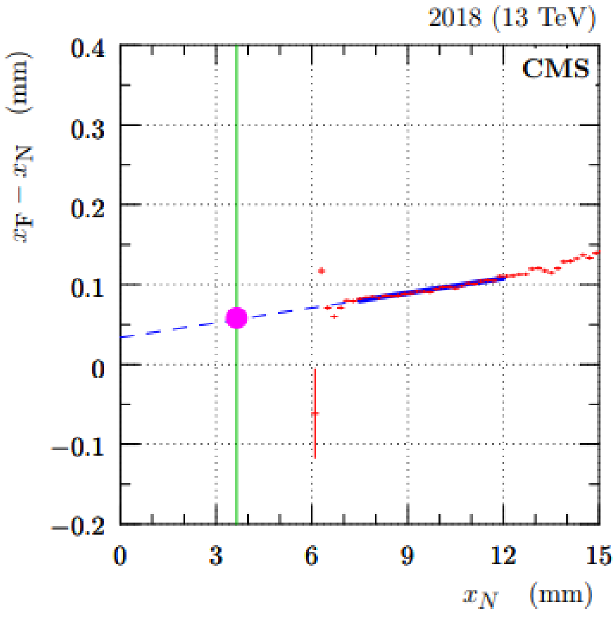


Global alignment – fit functions

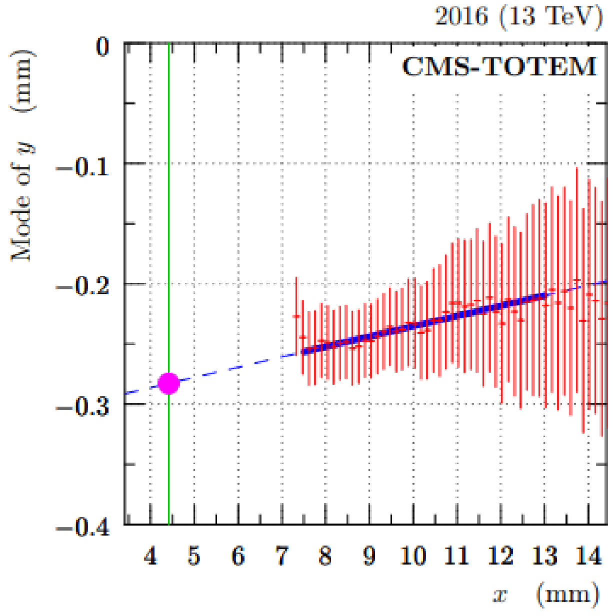
- At high intensity run, the “safe” distance of the detectors is larger
- Every fill (after stable beams are declared), RPs are inserted to a fixed position.
- Due to variation of the beam spot, the beam center might be misaligned. Further alignment is needed – two metrics are used (see next slides)

Horizontal alignment

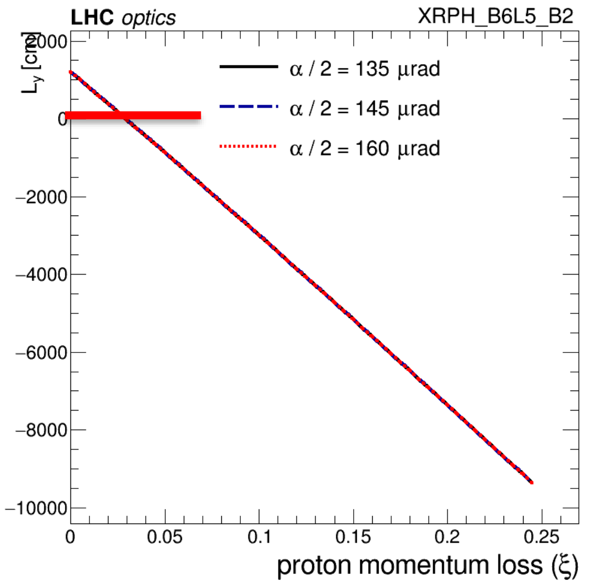




Vertical alignment



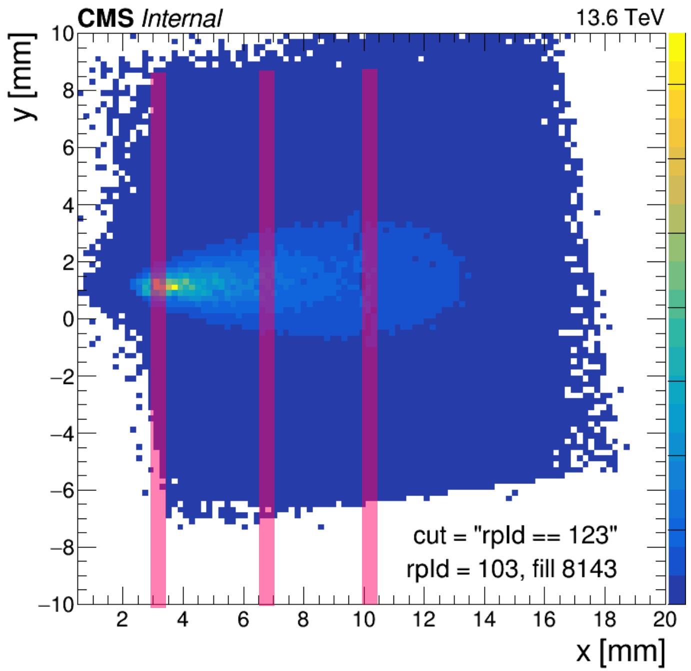
Horizontal alignment

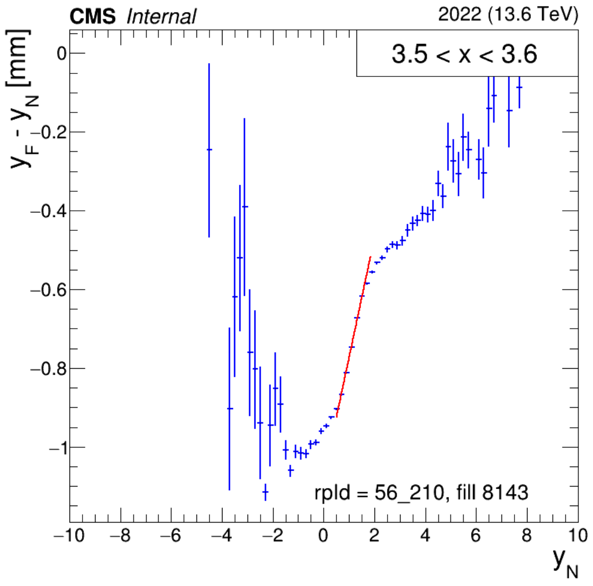


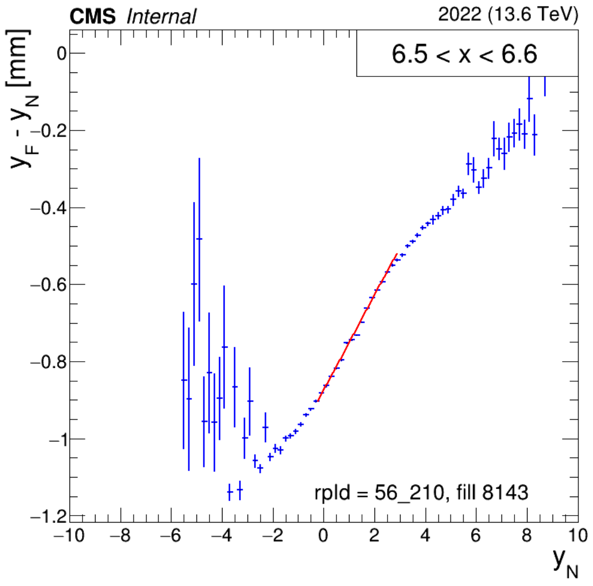
- X alignment is obtained by matching S(x) shape for 1 track events

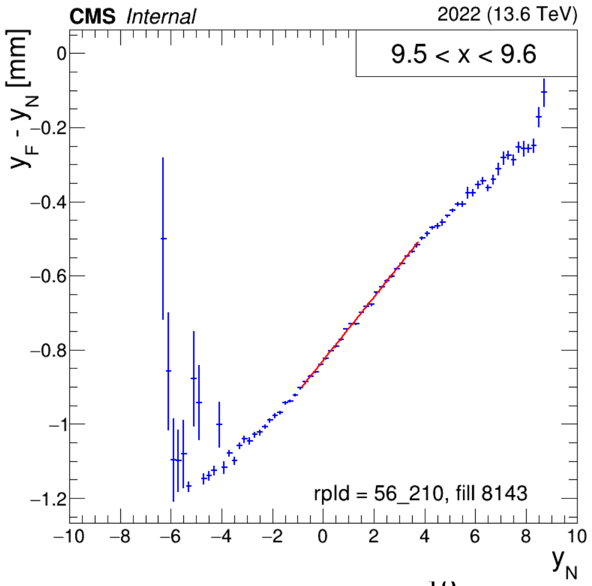
$$S(x) = slope\ of\ profile\ (y_F - y_N)\ vs.\ y_{test} \approx \frac{L_y^F - L_y^N}{L_y} \oplus \cdots$$

- Example of near detector horizontal alignment (physics run):



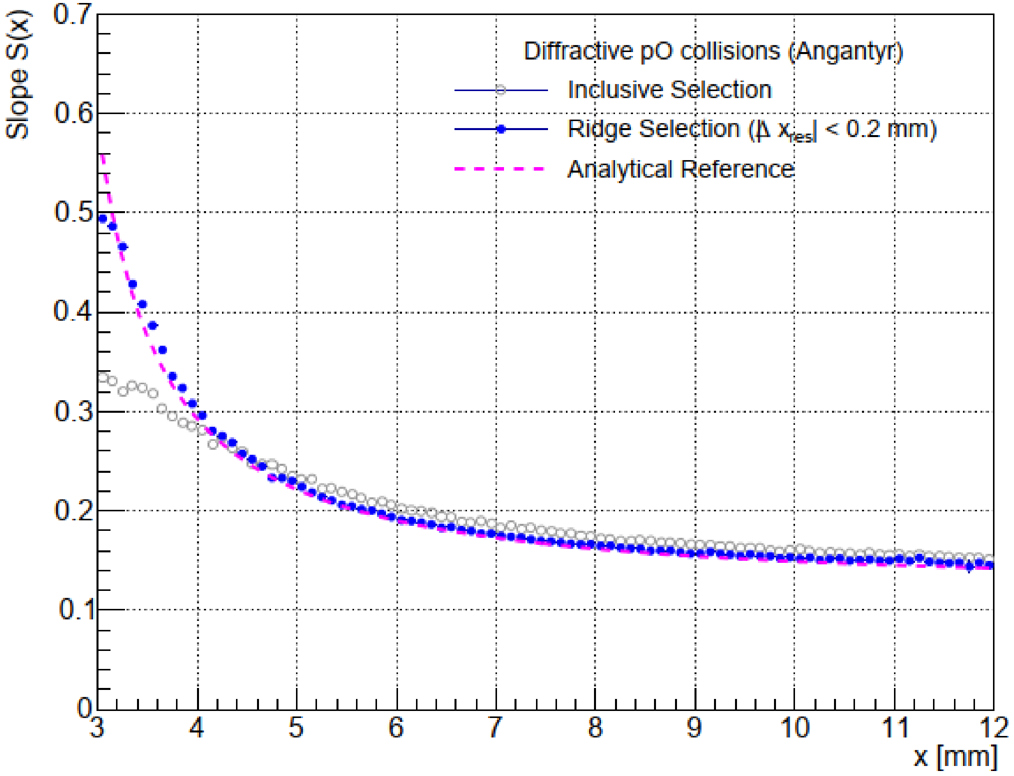


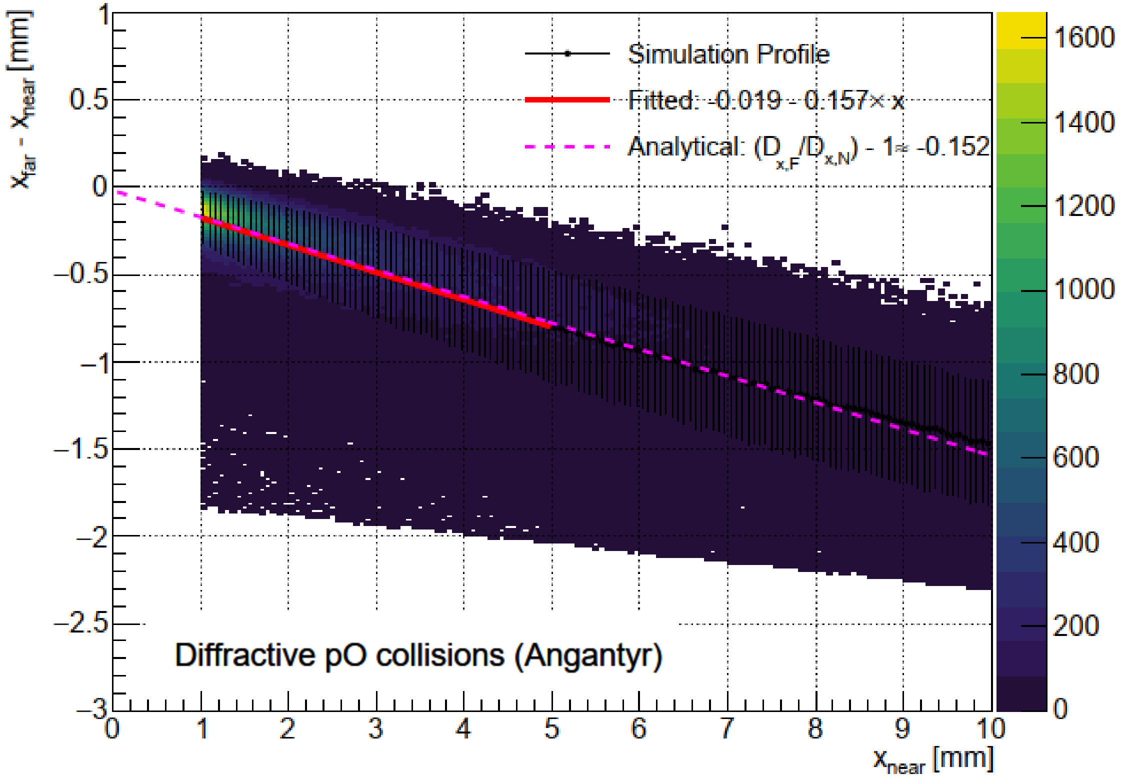




Horizontal alignment

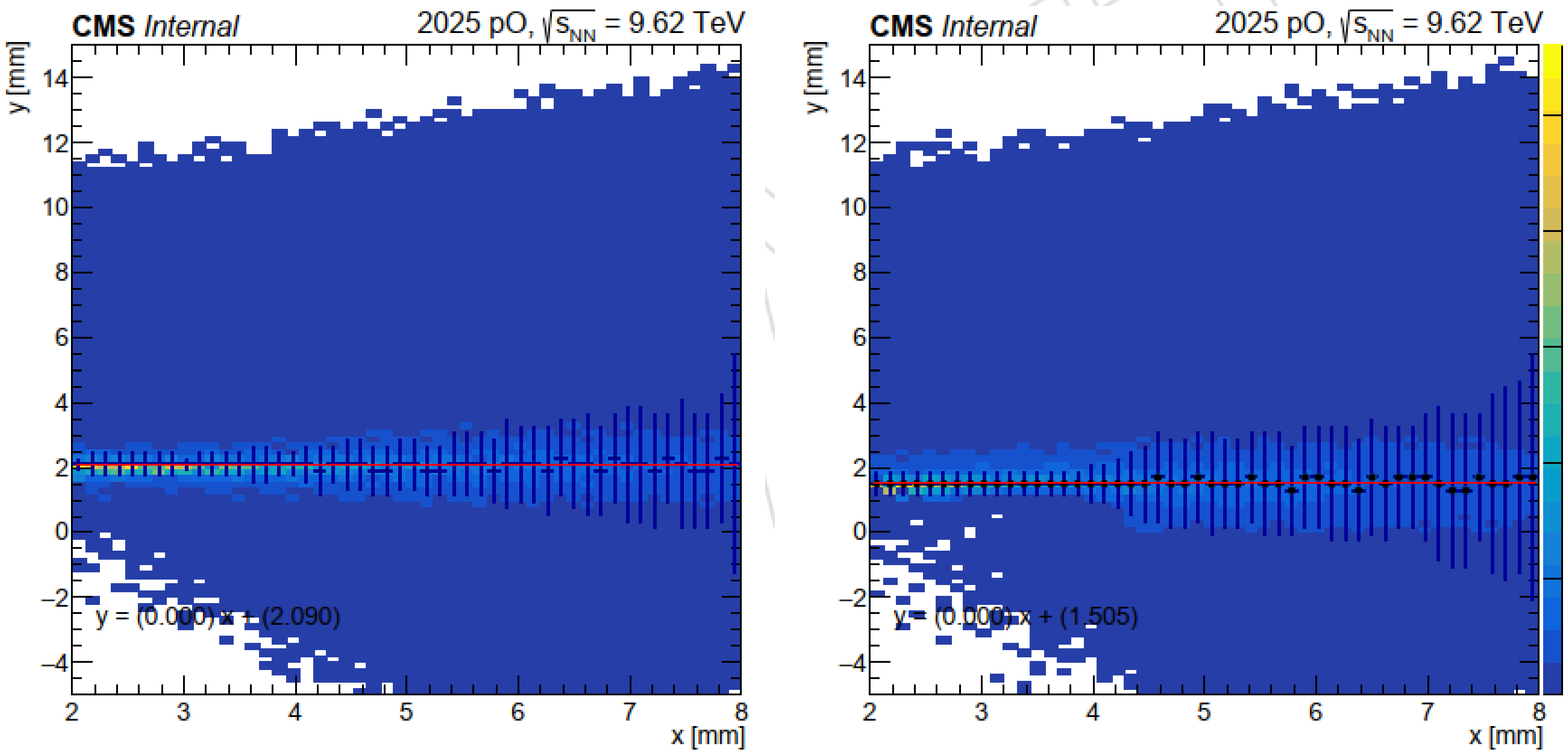
- S(x) is derived as a function of x, while the optics determine proton displacement as a function of ξ. To avoid biases (large θ_X^*) one can filter data, such that x(far) – x(near) is fixed
- Alignment can be validated by plotting the dX vs X to inspect the intersection at the origin





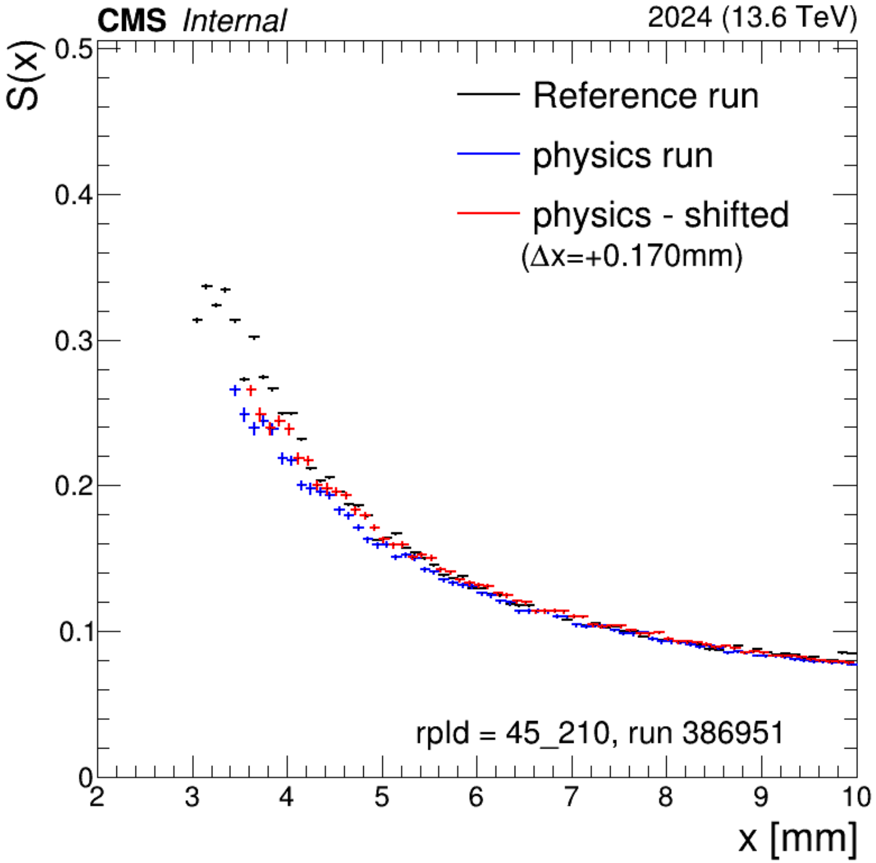
Vertical alignment

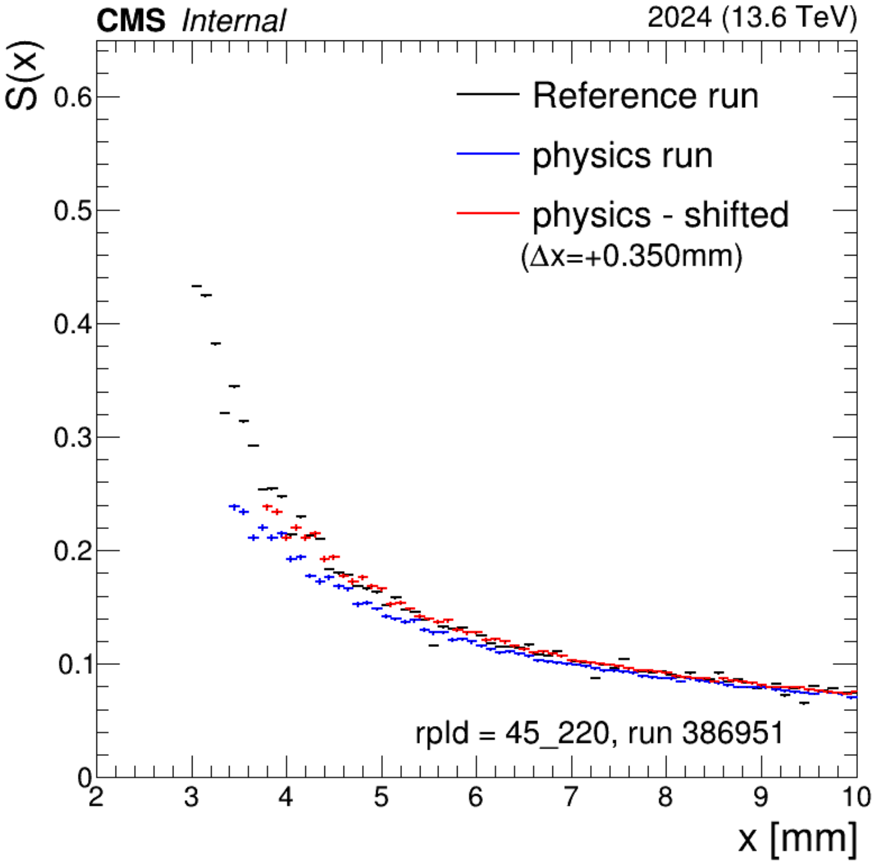
- Vertical alignment can be done after the horizontal is completed (x-coordinate is aligned), to obtain the extrapolation of the diffractive line to the beam center (plots are data)



Physics fills

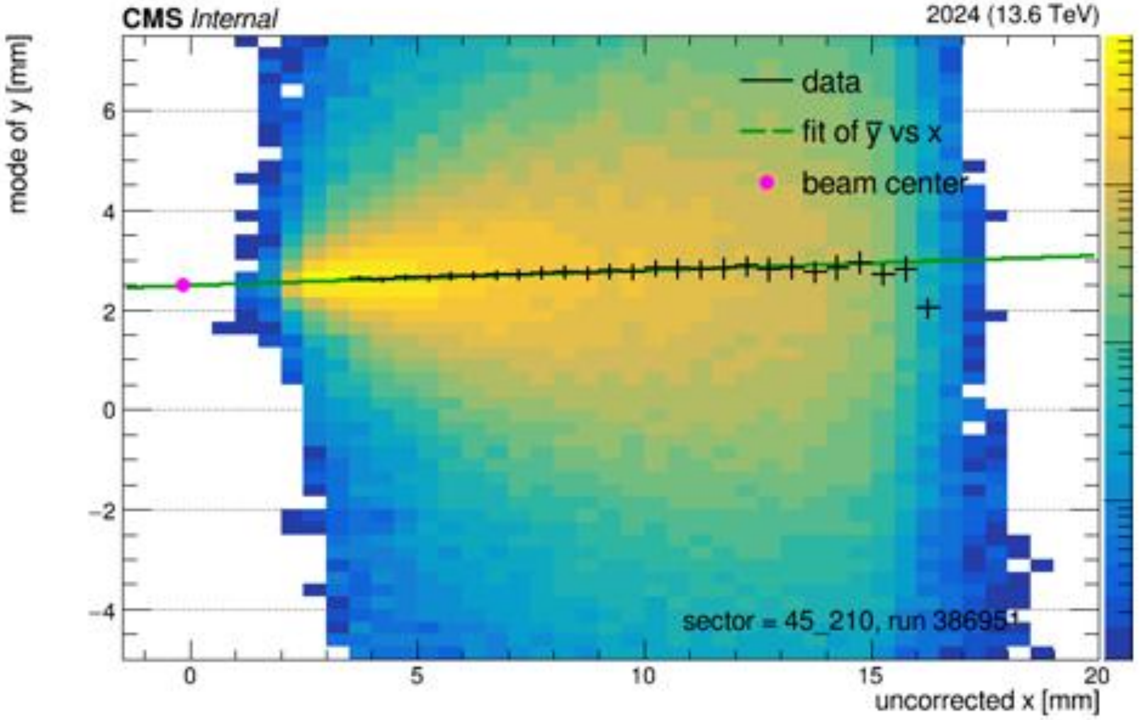
- During the physics fills (as long as the LHC optics is unchanged), the characteristic functions (e.g., S(x)) remain unchanged
- The extracted S(x) function is shifted to match the one obtained during the calibration run

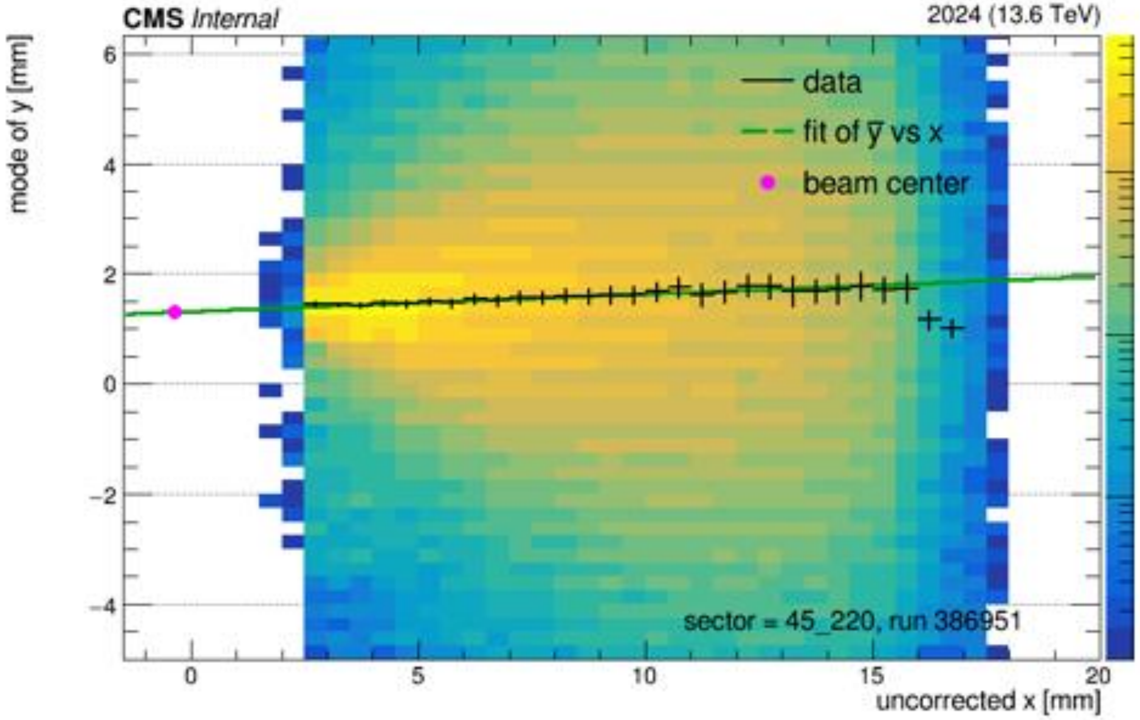




Physics fills

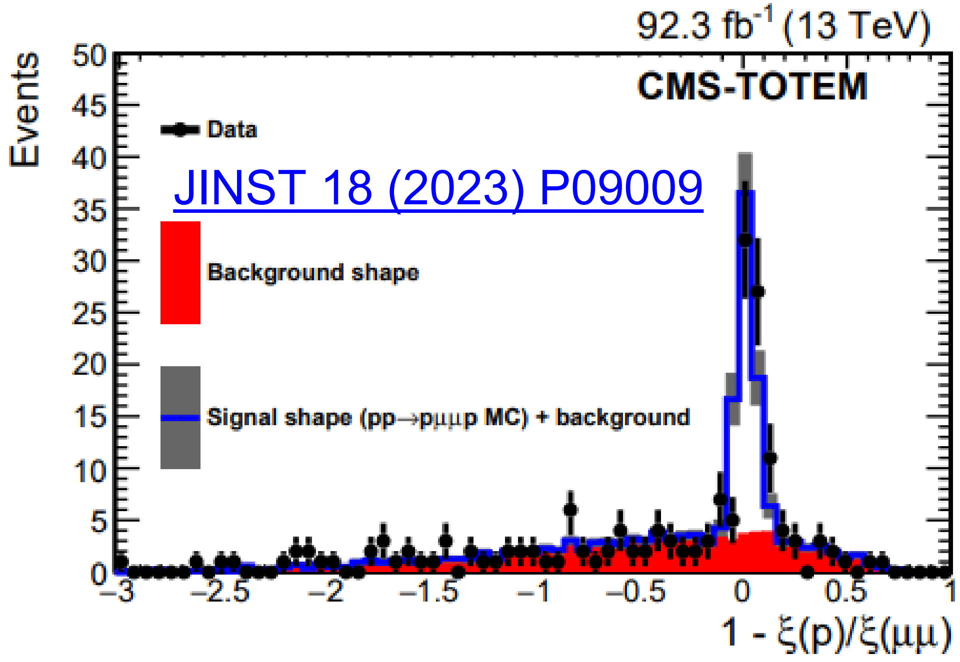
- Then the vertical alignment is performed



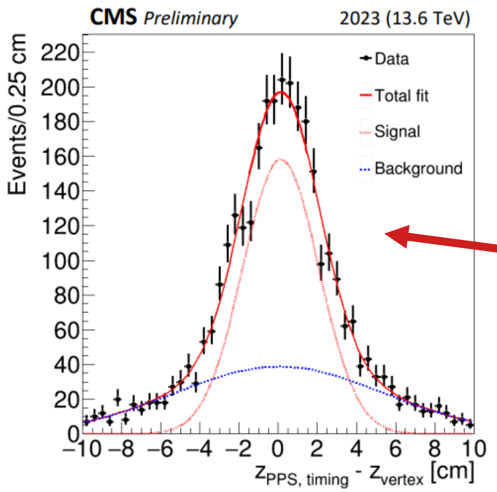


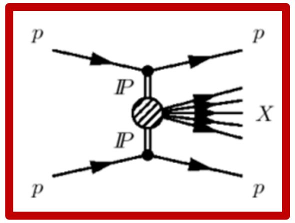
Validation

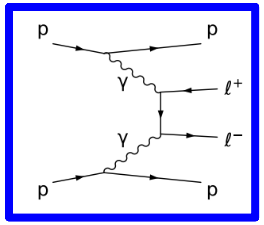
- High PU runs: Tag Central Exclusive events
  - Electroweak physics
  - BSM searches

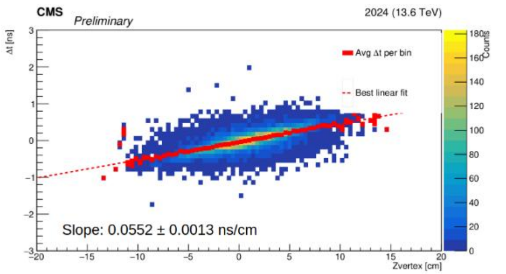


- Low PU runs: Tag Diffractive events
  - Non-perturbative hard interactions
  - Central diffraction
  - Low-mass resonances







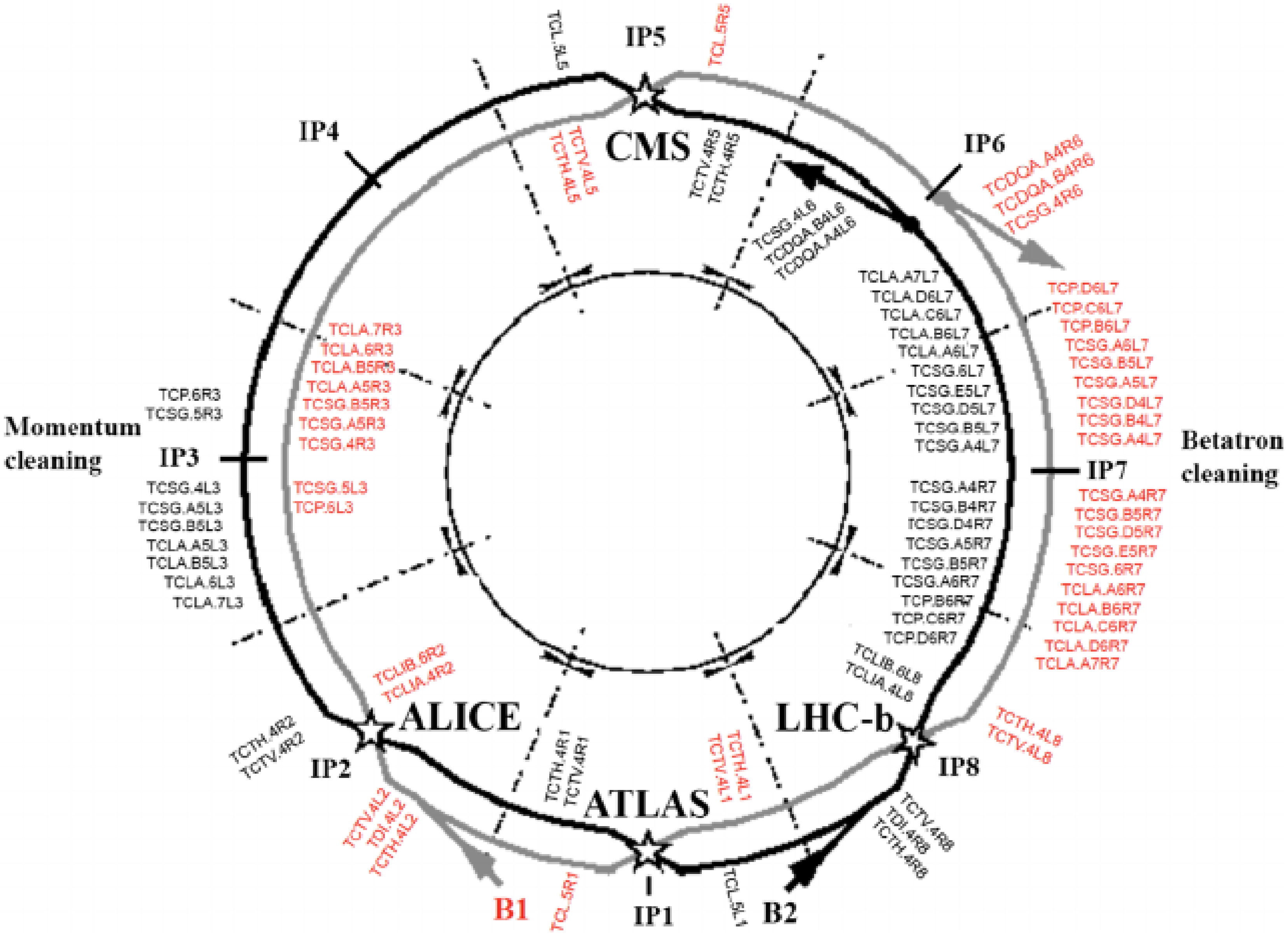


Summary

- Roman Pot alignment is essential for accurate proton kinematics reconstruction.
  - ➢ Absolute alignment is established using Beam-Based Alignment (BBA) during special fills.
  - ➢ Relative alignment is extracted from overlapping tracks and diffractive topology.
  - ➢ Global alignment during physics fills relies on characteristic horizontal and vertical distributions.
- Stability is maintained fill-by-fill as long as the LHC optics remain unchanged.
- Achieved alignment precision that enables diffractive and exclusive measurements with high precision using the forward proton detectors.

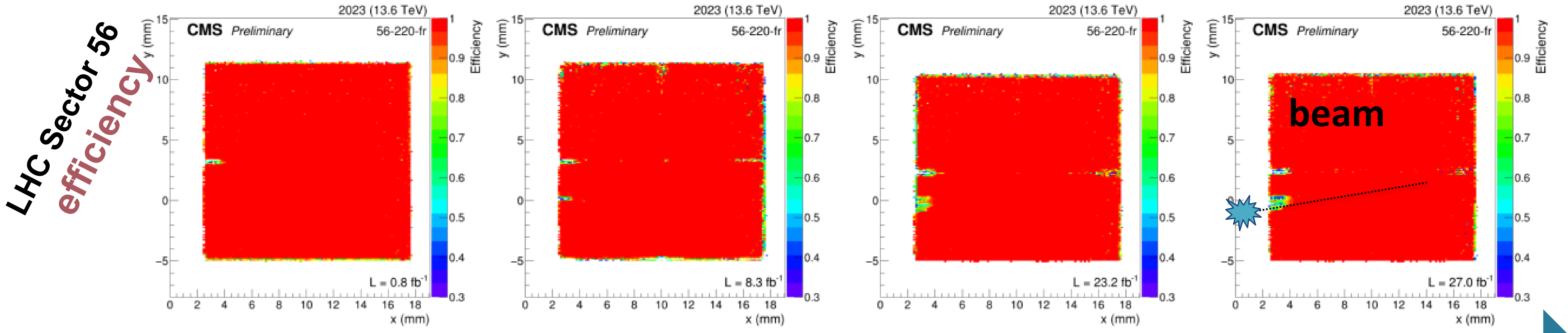
Backup

LHC collimators



PPS efficiency

- Challenges in the standard LHC runs:
  - Efficiency drop due to irradiation
  - Higher x -> Higher ξ -> Higher minimal accepted mass
  - Detectors were shifted by 0.5mm using internal movement system



$\int \mathcal{L}dt =$ 0.8 fb^{-1} ~8.3 fb^{-1} ~23.2 fb^{-1} ~27 fb^{-1}

PPS evolution

- Rapid detector evolution from commissioning in 2016 to 2023!

2016: PPS inherits from TOTEM Silicon strip tracker (used in special runs, cannot resolve multiple tracks)

2017: 3D Silicon pixels - a suitable detector technology was developed, timing technology is tested

2018: 3D pixels + New timing sensors are installed

2022: 3D pixels + Double-Diamond sensor

From 2023: 3D pixels + two stations with DD sensors