Proton reconstruction with the Precision Proton Spectrometer in Run 2 and expectations for Run 3

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Forward proton reconstruction @ CMS

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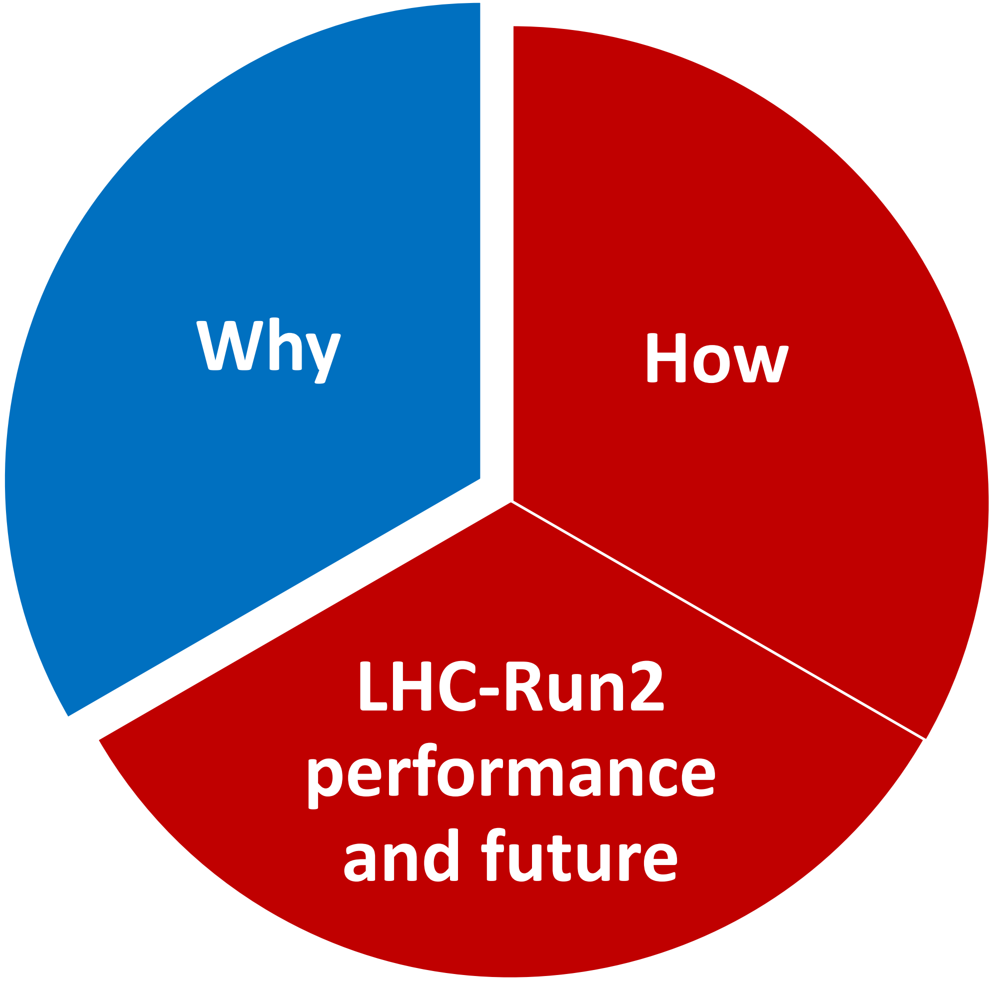


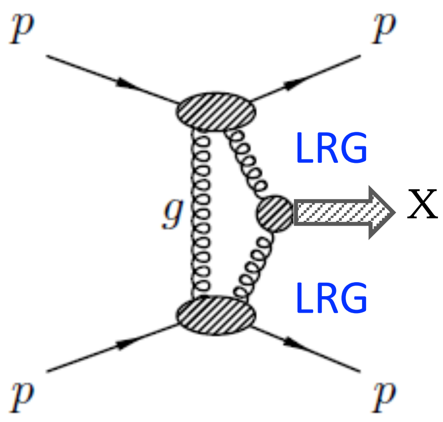
Why reconstructing forward protons at CMS?

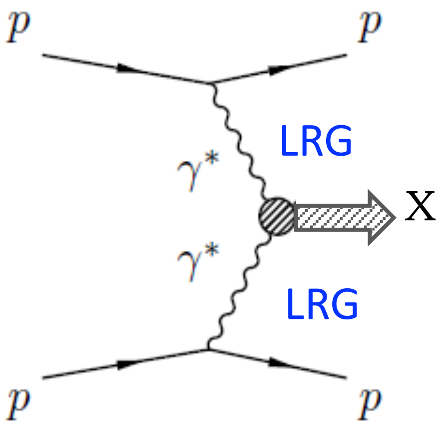
In typical pp collisions at the LHC protons dissociate and large number of energetic particles is produced.

In rare cases (**CEP - Central Exclusive Production**)

- protons remain intact
- low track activity

p p -> p X p





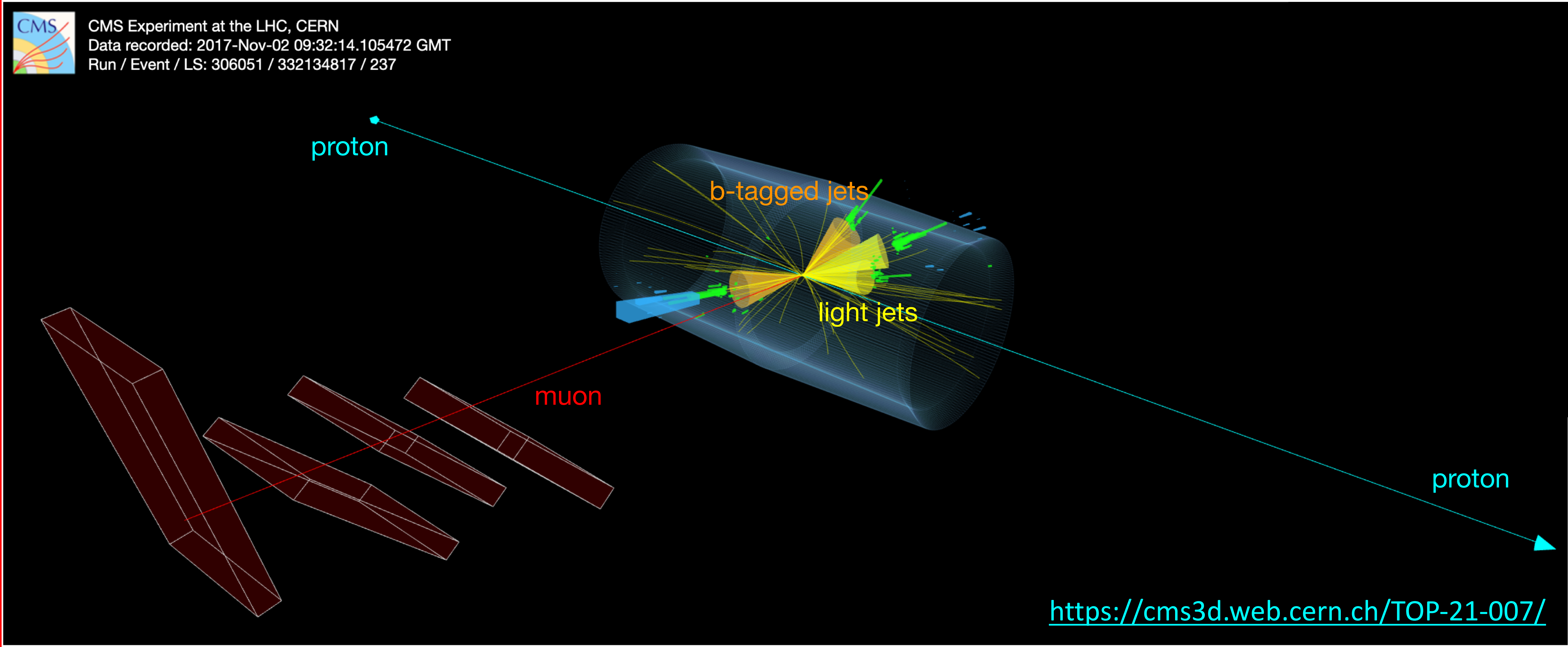
Low track activity due to exchange of color singlets via QCD (Pomeron) or QED (γ) → Large rapidity gap (LRG)

With CEP a wide range of physics measurements become accessible:

- ✓ rare SM processes
- ✓ searches for anomalous quartic gauge couplings
- ✓ direct serch new resonances, including invisible states

More in A. Bellora's talk

Production of $t\bar{t}$ with 2 tagged forward protons



Details in B. Ribeiro Lopes' poster

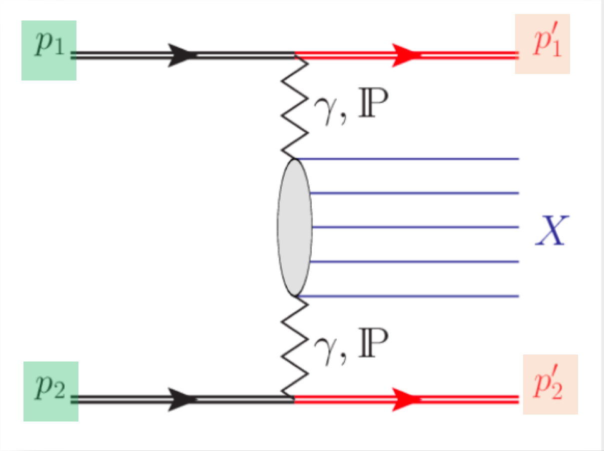
Proton tag: a powerful tool to study CEP

CEP events characterized by a striking signature:

- two final state forward protons on opposite sides of the interaction point (IP)
- large rapidity gaps between central system and leading protons

Difficult to exploit in standard LHC running conditions due to high pile-up

In CEP events the energy lost by the protons in the interaction goes into producing the X system



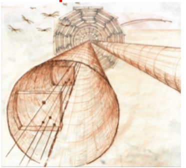
If the fractional momentum loss of the two protons emerging intact from the IP is measured

$$\xi_i = \frac{|p_i| - |p'_i|}{|p_i|}$$

mass and rapidity of the central system X produced in the interaction can be determined as

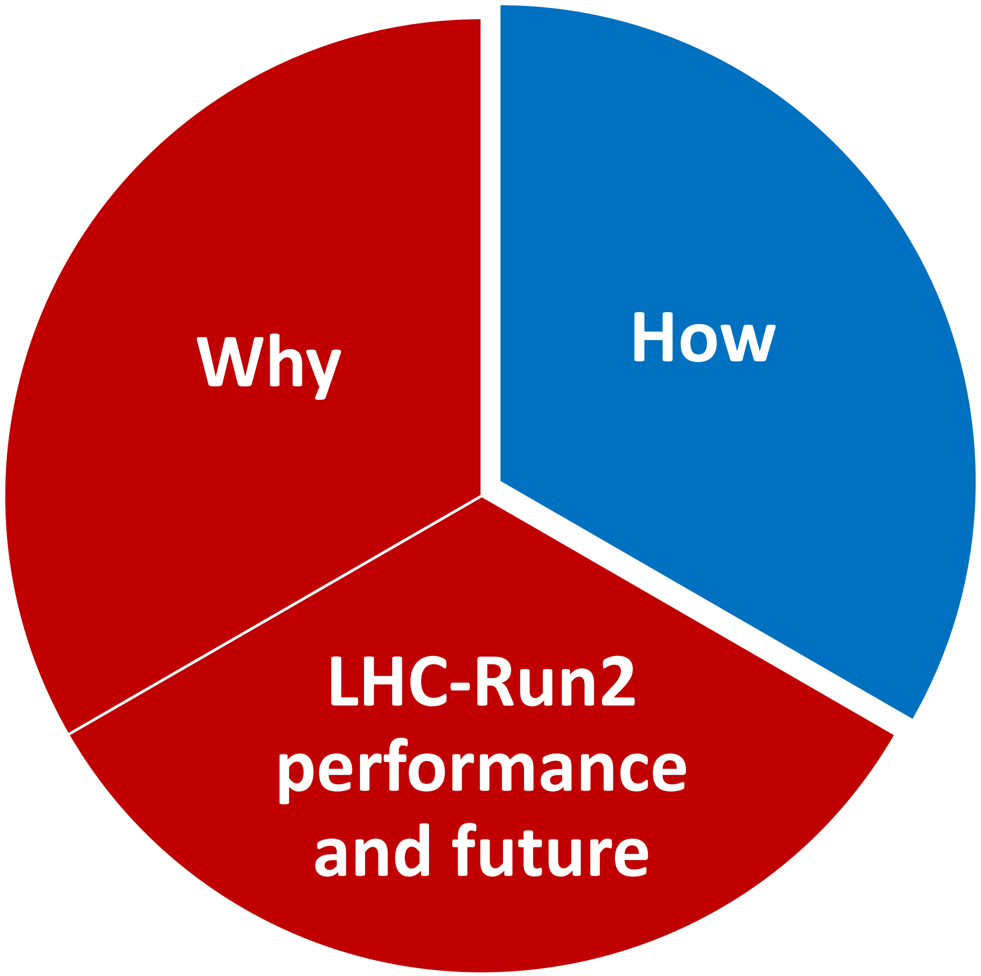
$$M_X = \sqrt{\xi_1 \xi_2 s}$$

$$y_X = \frac{1}{2} \ln\left(\frac{\xi_1}{\xi_2}\right)$$



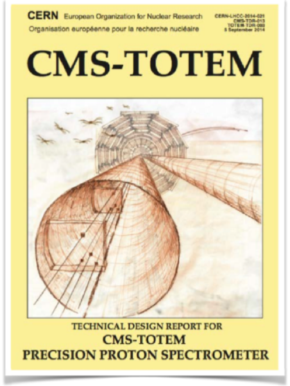
Full event reconstruction by matching central system and leading protons kinematics

Forward proton reconstruction @ CMS



2016: PPS (Precision Proton Spectrometer) was added to CMS

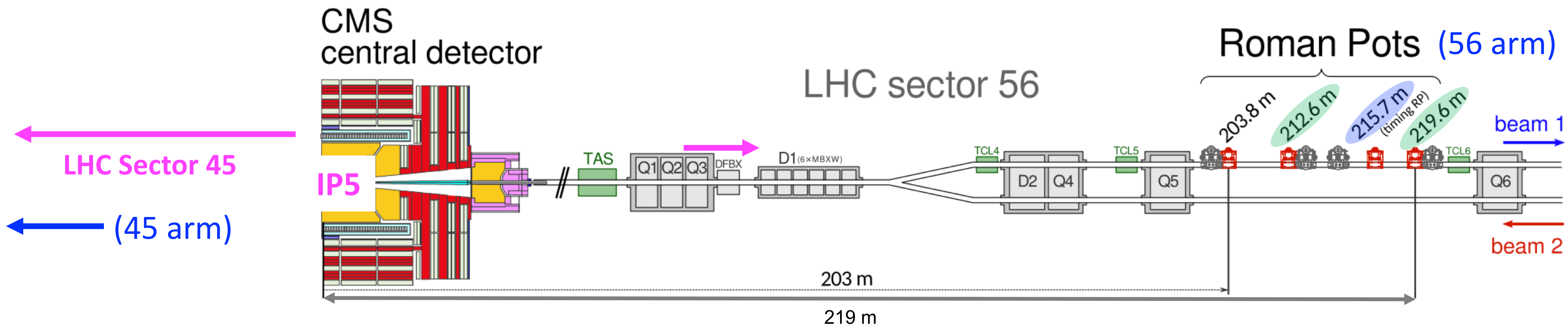
Precision Proton Spectrometer (PPS)



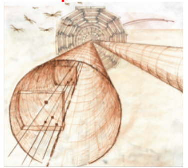
CERN-LHCC-2014-021

PPS detectors located along the LHC beam line (~1.5 mm from the beam axis), at ±~200 m from the CMS interaction point (IP5)

- **Tracking detectors** measure the proton displacement w.r.t. the beam which is translated into longitudinal and transverse momentum of the proton
- **Timing detectors** measure the proton time of flight; used to disentangle pile-up



LHC magnets between IP5 and the detector stations used to **bend out of the beam envelope protons** that have lost a small fraction of their initial momentum in the interaction



PPS designed to operate continuously at **standard LHC running conditions**

PPS tracking detectors

Different detector configurations used in LHC-Run2

SiStrip

10 planes of micro-strip silicon detectors per RP

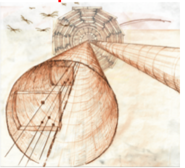
- 512 strips per plane, ±45° orientation
- Thickness: 300 μm - Pitch: 66 μm
- Resolution ~20 μm
- Lifetime: up to 5×10^{14} p/cm^2 integrated flux
- No multi-track reconstruction capability

3D pixel

6 planes of 3D silicon pixel sensors per RP

- Pixel area: 100x150 μm^2 Sensor thickness: 230 μm
- Resolution ~20 μm
- Lifetime: ~5×10^{15} p/cm^2 integrated flux
- Multi-track reconstruction capability

	210 m	220 m
2016	SiStrip 	SiStrip 
2017	SiStrip 	3D Pixel 
2018	3D Pixel 	3D Pixel 



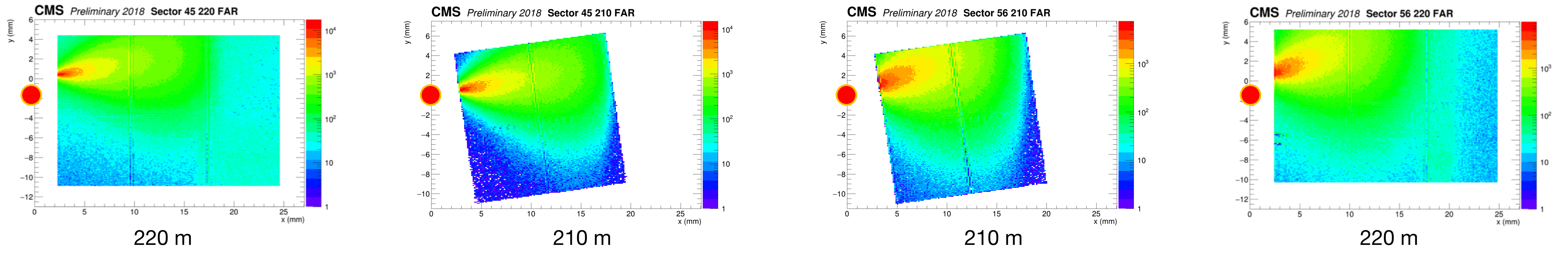
Forward proton reconstruction at a glance

Input: reconstructed hits in the tracking detectors → Track reconstruction → Proton kinematics (px, py, pz)

Local alignment among detector planes and between RPs in the same arm

Global alignment wrt the beam
Beam optics knowledge

BEAM **2D (x,y) TRACK IMPACT POINT DISTRIBUTION - 2018 DETECTOR CONFIGURATION**



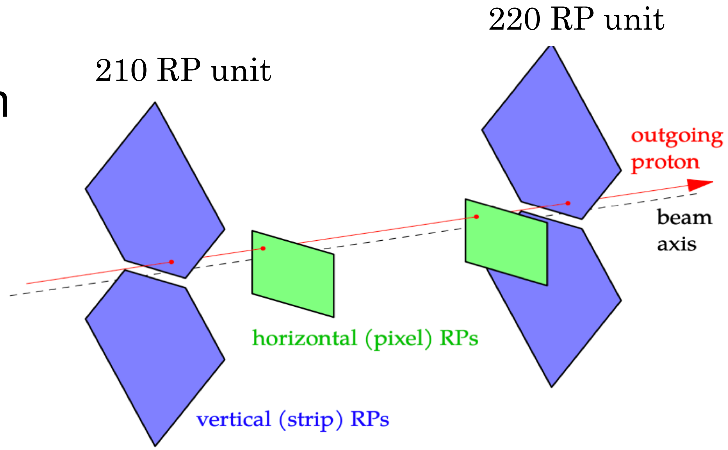
LHC SECTOR 45 ← **IP5** → **LHC SECTOR 56**

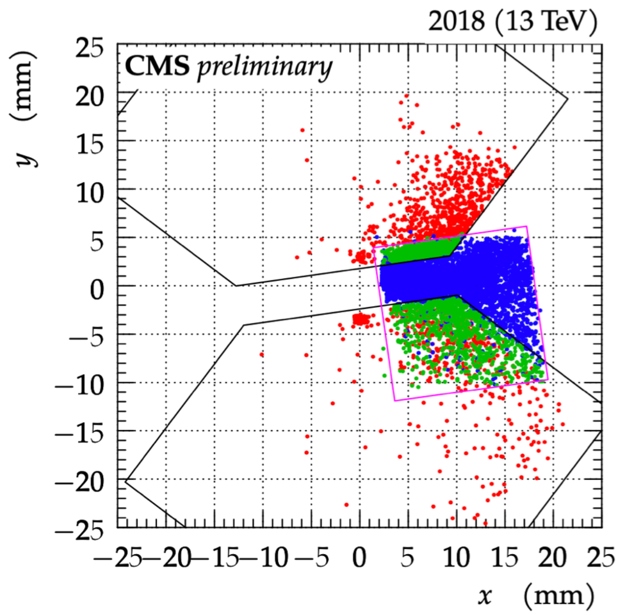
CMS-PAS-PRO-21-001, CERN-TOTEM-NOTE-2022-00

RP alignment: a multi-step procedure

DEDICATED ALIGNMENT RUNS

- Low luminosity (2 or 3 bunches/fill) → RPs inserted very close to the beam
- LHC settings (crossing angle, β*) identical to those used in standard data taking
- Both vertical and horizontal RPs inserted





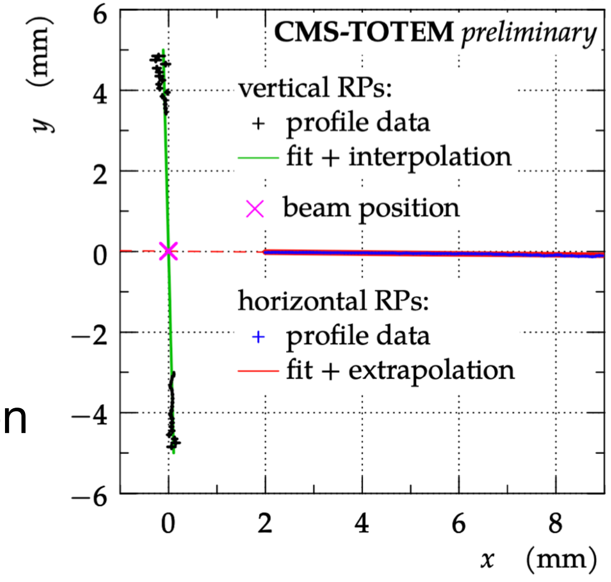
Horizontal/vertical detectors overlap allows to **align vertical and horizontal RPs** among themselves (uncertainty: few μm)

Alignment of RPs wtih respect to the beam:

- elastic scattering events (vertical RPs)
- minimum bias events (horizontal RPs)

Beam position determined using extrapolation of vertical and horizontal track profile

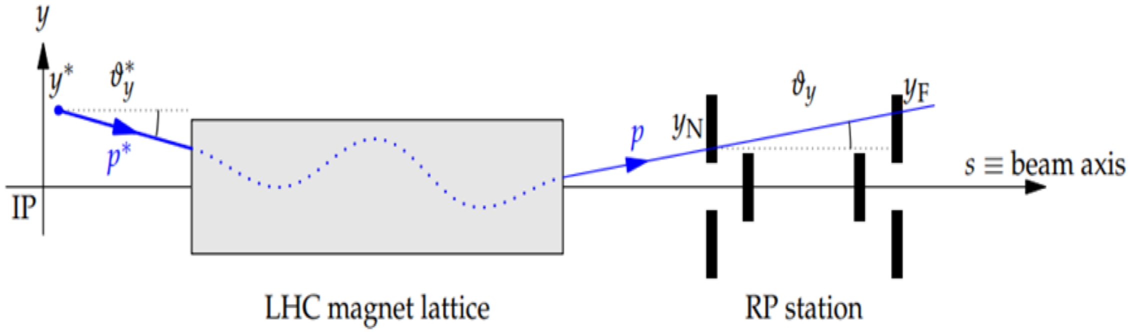
Typical uncertainty: 10 μm



ALIGNMENT ON FILL-BY-FILL BASIS (RP are movable objects, limited accuracy in fill-to-fill beam position reproducibility) maching observables from the fill to those from the dedicated allignment run

LHC optics: proton transport from IP to PPS

The proton kinematics at the IP



PROTON TRANSVERSE POSITION

$$\vec{d}^* = (x^*, \theta_x{}^*, y^*, \theta_y{}^*, \xi)^T$$

PROTON SCATTERING ANGLES

determined from the proton kinematics measured at the tracking detector through knowledge of the LHC optics parameters:

RP **TRANSPORT MATRIX** IP

$$\begin{pmatrix} x \\ \theta_x \\ y \\ \theta_y \\ \xi \end{pmatrix} = \begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & D_y \\ 0 & 0 & v'_y & L'_y & D'_y \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x^* \\ \theta_x^* \\ y^* \\ \theta_y^* \\ \xi \end{pmatrix}$$

A semplified version of the transport equations, keeping only significant terms:

RP

$$x = v_x(\xi) \cdot x^* + L_x(\xi) \cdot \theta_x^* + D_x(\xi) \cdot \xi$$

$$y = v_y(\xi) \cdot y^* + L_y(\xi) \cdot \theta_y^* + D_y(\xi) \cdot \xi$$

Dominant terms

Magnification functions Effective lengths Dispersions

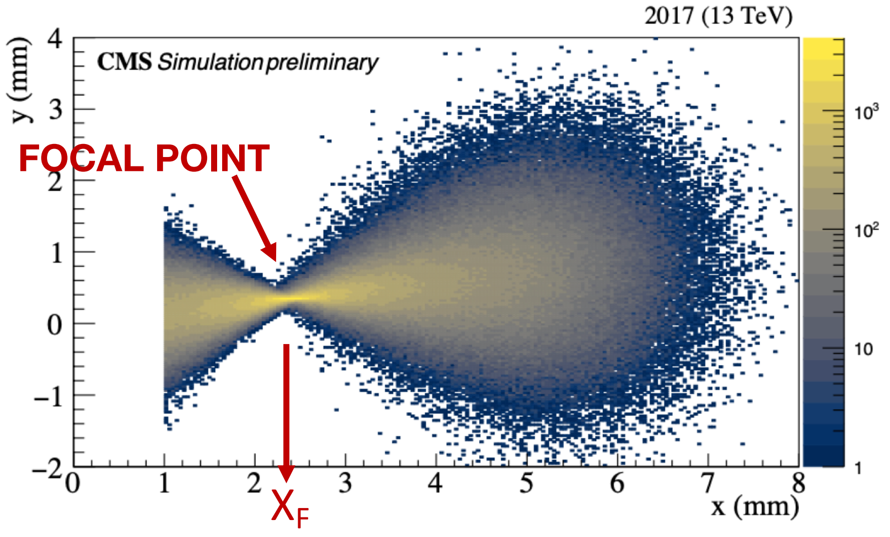
Optics calibration

A **precise knowledge and calibration of the LHC beam optics is needed** in order to correctly reconstruct the proton kinematics at the IP

- ✓ Nominal optics calculated with MAD-X (accelerator simulation software)
- ✓ Data driven calibrations
  - L_y determined using elastic events (ξ=0) in dedicated alignment run
  - D_x derived with 2 independent methods :
    - focal point (L_y=0) in min bias events:

$$D_X = \frac{x_F}{\xi_F} \qquad \text{with } \xi_F \sim 4\%$$

    - ξ_{CMS} vs ξ_{PPS} in semi-exclusive $\mu\mu$ events



2D (x,y) DISTRIBUTION OF THE PROTON IMPACT POINTS IN THE NEAR (210m) RP

Forward proton kinematics reconstruction

Two reconstruction algorithms

Single-RP method

- Treat each RP as a separate detector
- Only 2 reconstructed variables (dominant term in transport equation)

$$\xi = \frac{x}{D_x} \quad \text{and} \quad \theta_y^* = \frac{y}{L_y(\xi)}$$

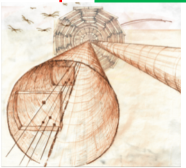
- Limited ξ resolution
- Less sensitivity to systematic uncertainties

Multi-RP method

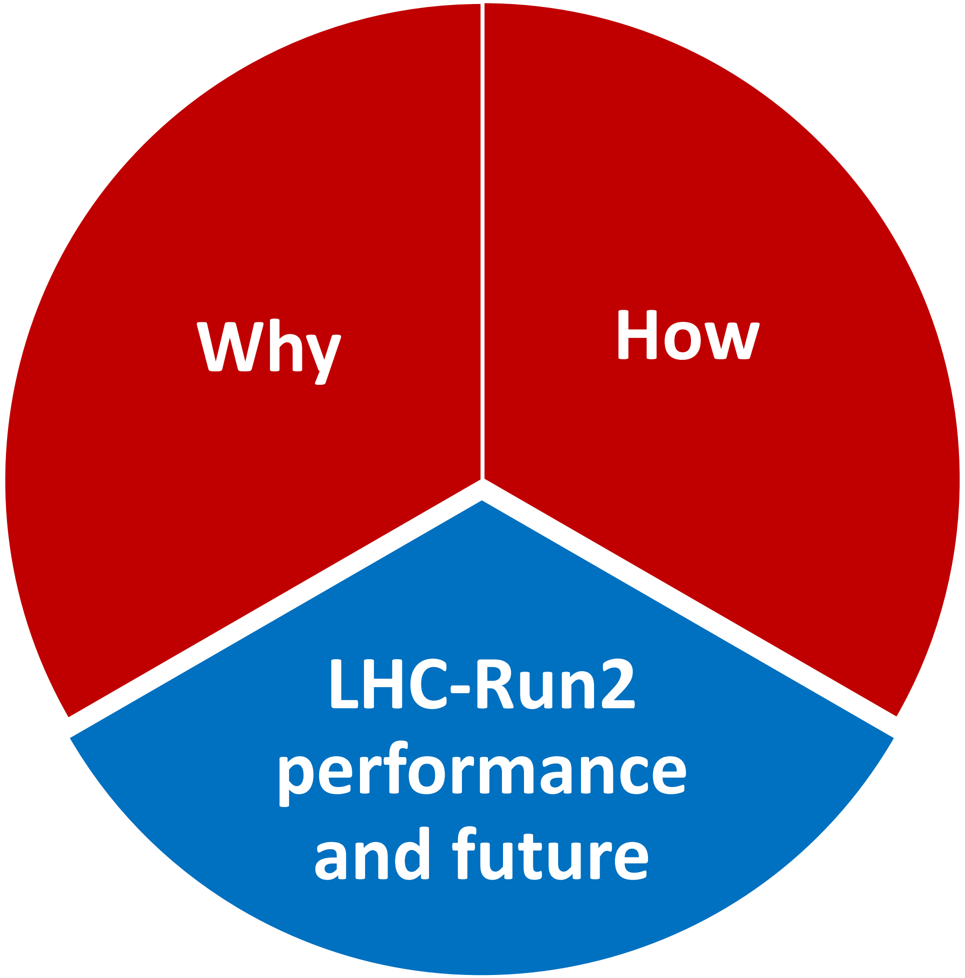
- Combines measurements of 2 RPs
- Minimization of

$$\chi^2 = \sum_{i:\ \mathrm{RPs}} \sum_{q:\ x,y} \left[\frac{d_q^i - (T^i d^*)_q}{\sigma_q^i} \right]^2$$

- Significantly improved resolution on ξ
- Optics calibration more critical → complex systematic uncertainty model



Forward proton reconstruction @ CMS



PPS in LHC-Run2

During Run 2, PPS was operated with 2 tracking RPs and 1 timing RP per arm

Exploratory phase

2015

Data taking with CMS

2016

2017

2018

Data recorded with tracking RPs inserted

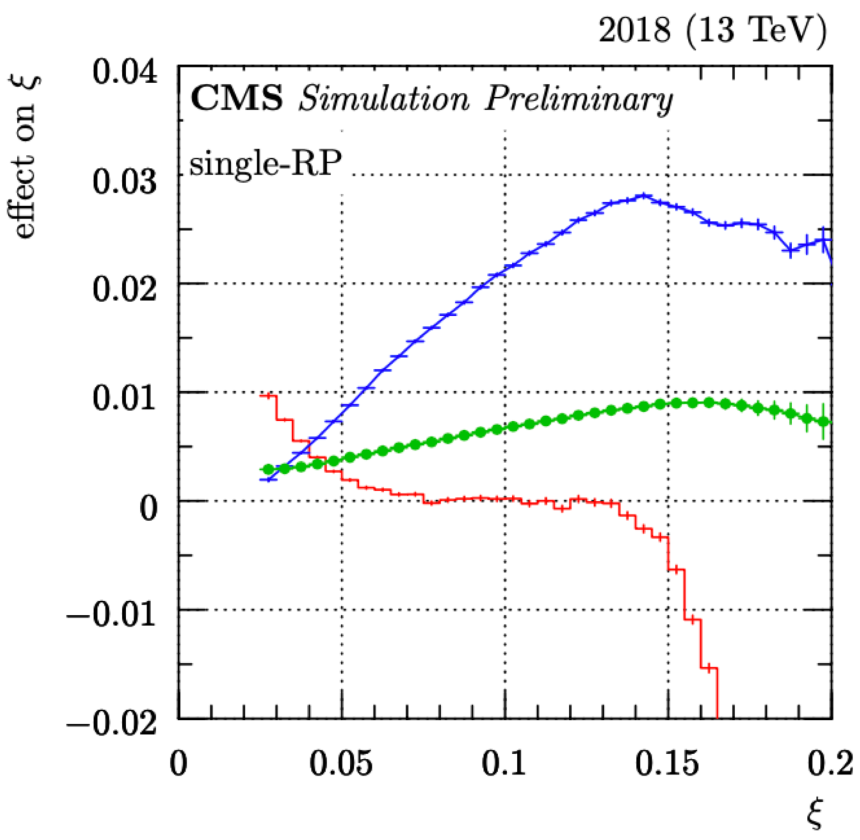
	2016	2017	2018
	L_{INT}~15 fb^{-1}	L_{INT}~40 fb^{-1}	L_{INT}~58 fb^{-1}
	39% OF DATA RECORDED BY CMS	88% OF DATA RECORDED BY CMS	93% OF DATA RECORDED BY CMS

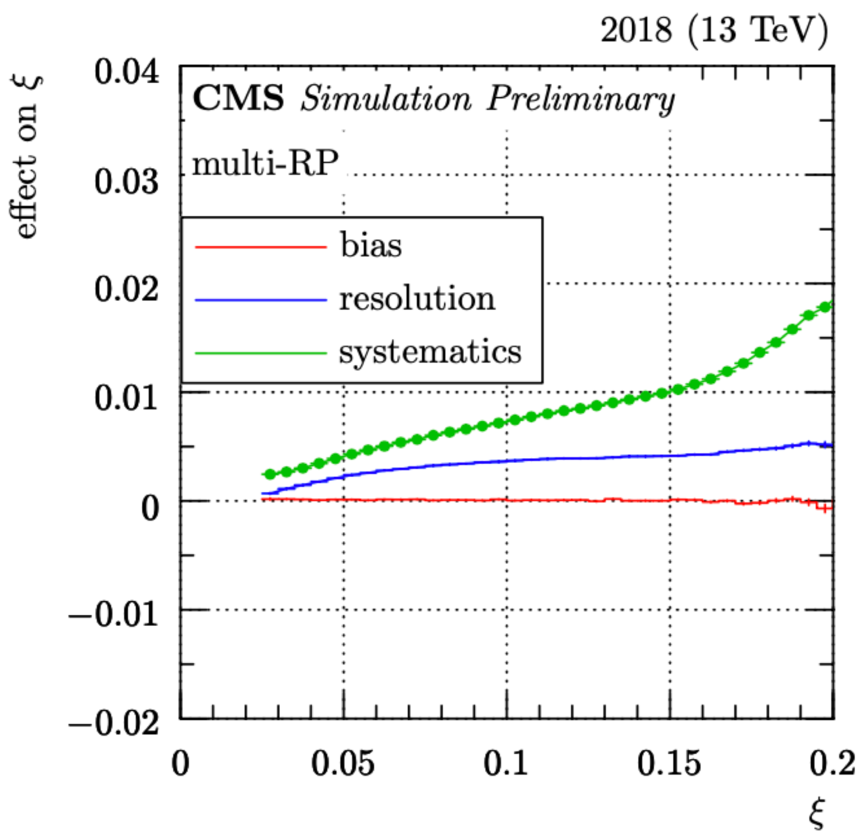
Very high stability in both 2017 and 2018. PPS integrated luminosity in LHC-Run 2 > 110 fb^{-1}

Multiple combinations of β^* and crossing angle were used by the accelerator during Run2, mainly for instantaneous luminosity levelling.

→ Careful optics calibration (especially D_x) required for all data taking conditions

Resolution and systematics studies





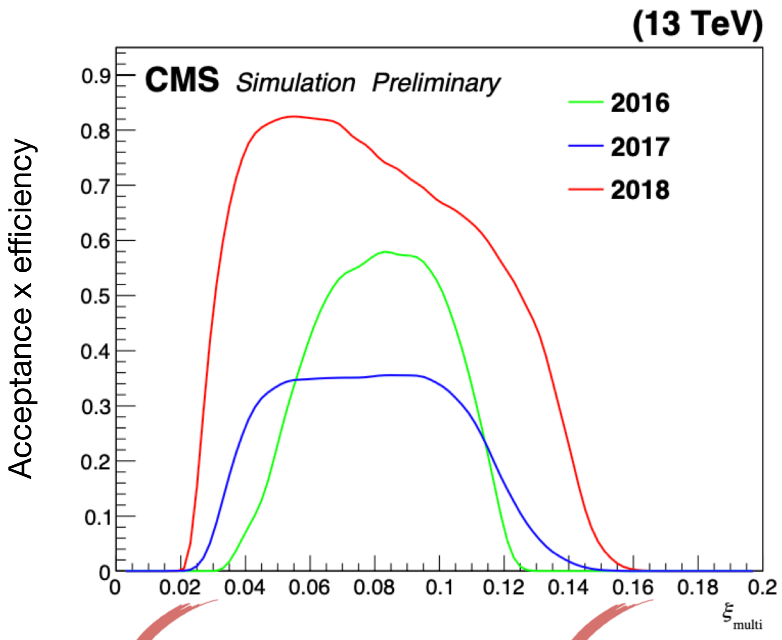
- Single-RP reconstruction resolution dominated by neglecting θ_x^* (at high ξ , width of θ_x^* reduced by LHC collimators)
- Multi-RP reconstruction resolution dominated by detector spatial resolution

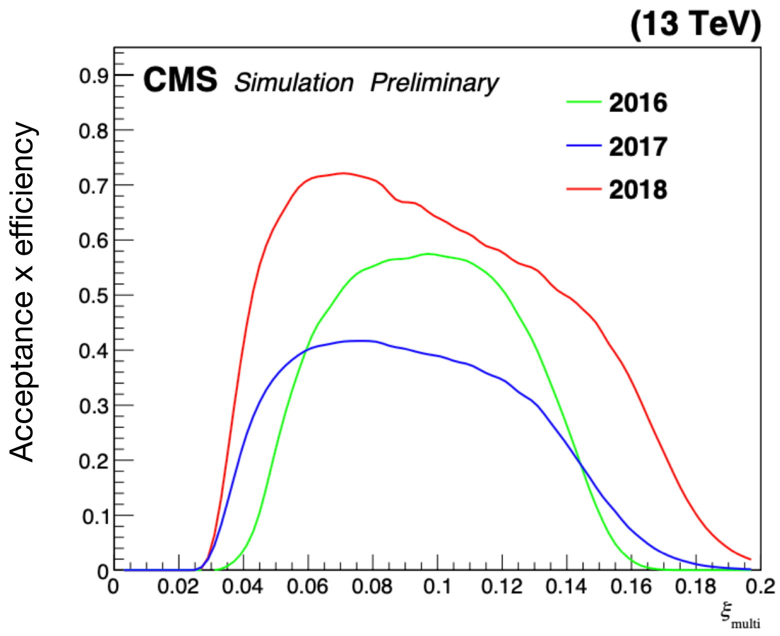
Multi-RP reconstruction shows better resolution and comparable systematics at low ξ

Multi-RP reconstruction efficiency

Multi-RP efficiency from tag-and-probe method on minimum bias data. Efficiency contributions:

- detector efficiency (degrades with radiation damage)
- inefficiency from multiple tracks (strip detectors in 2016 and 2017)
- proton hard interaction probability between 210 m and 220 m RPs
- algorithm efficiency





FRACTION OF RECONSTRUCTED MULTI-RP PROTONS, AS A FUNCTION OF ξ_{MULTI} FOR A SIMULATED PROTON SAMPLE

DISTANCE FROM THE BEAM

LHC COLLIMATOR APERTURE

ξ reconstruction validation

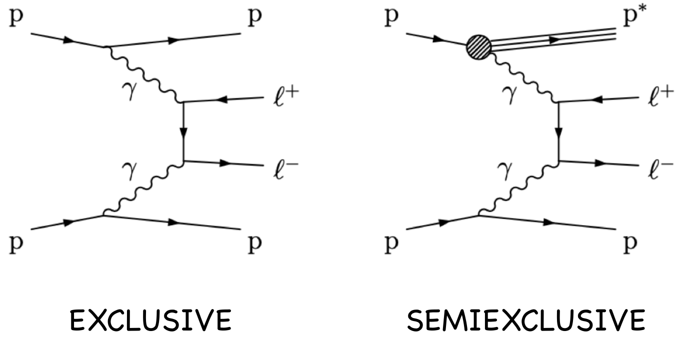
(Semi-)exclusive dimuon events: ξ reconstructed by PPS (ξ_{RP}) compared to ξ(μμ) from di-muon reconstructed in CMS

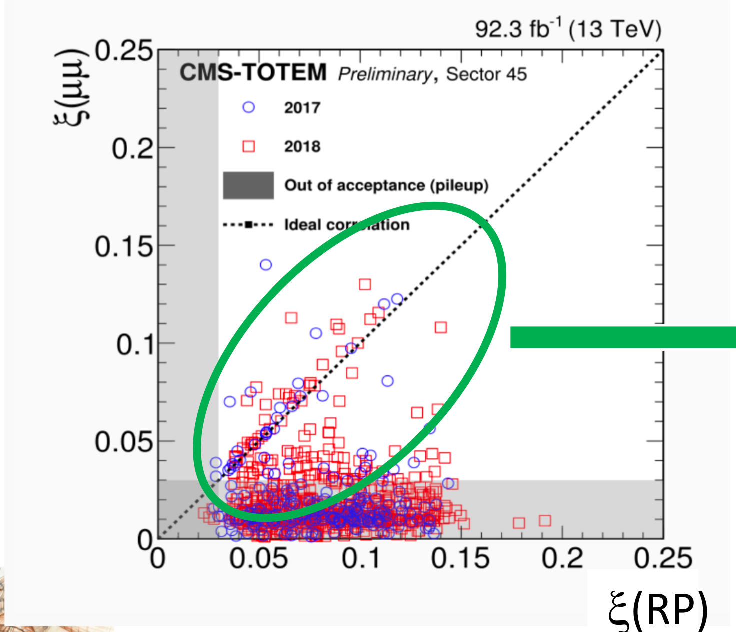
$$\xi^{\pm}(\ell^+\ell^-) = \frac{1}{\sqrt{s}}\left[p_T(\ell^+)e^{\pm\eta(\ell^+)} + p_T(\ell^-)e^{\pm\eta(\ell^-)}\right]$$

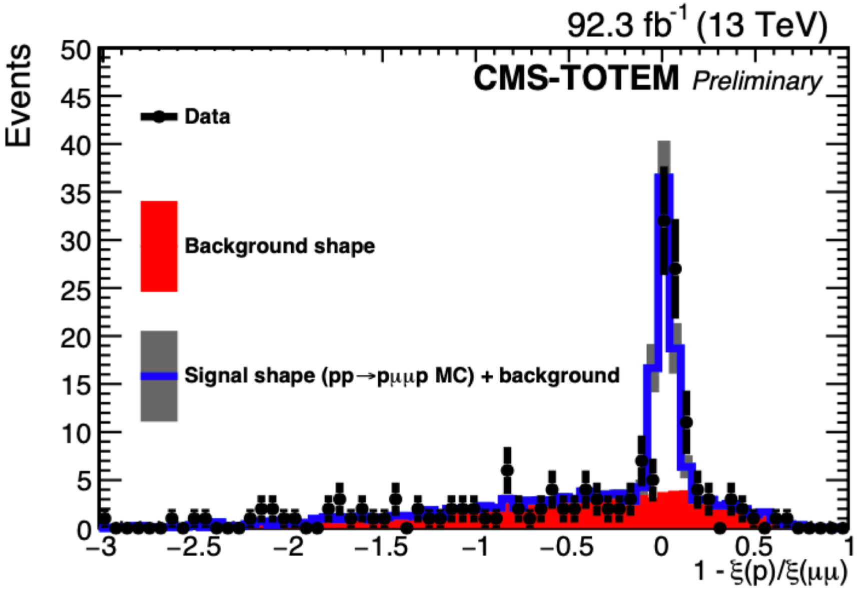
EXACT FOR EXCLUSIVE EVENTS, MOSTLY WITHIN RESOLUTION FOR SEMIEXCLUSIVE EVENTS

2 solutions→protons moving in the ±z direction

Lepton p_T and η from CMS central detector







- ✓ Good correlation between $\xi(\mu\,\mu)$ and the ξ_{RP} up to $\xi \sim 0.12$
- ✓ Mean and width of the signal distribution well reproduced by the simulation, within the known systematic uncertainty.

Optics, alignment, and related systematics of the proton ξ reconstruction are well understood

LHC-Run 3 and beyond

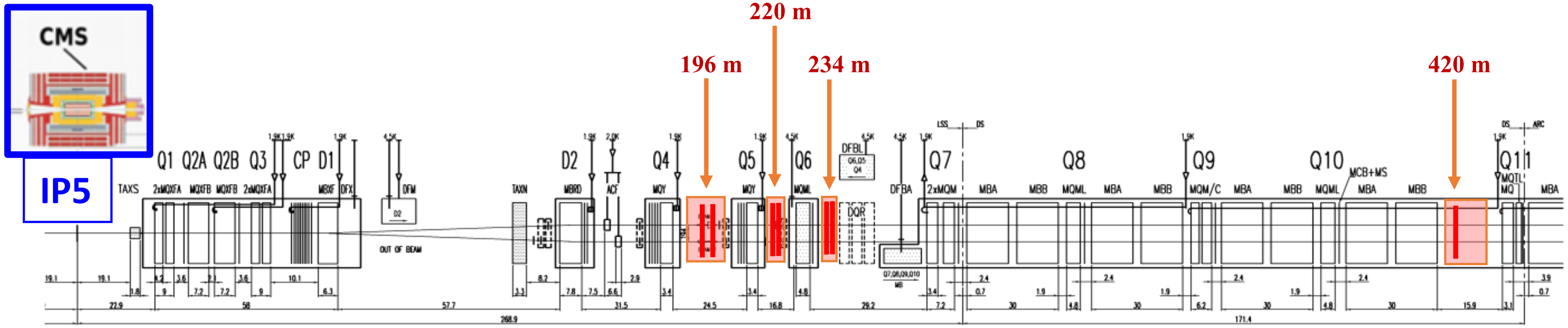
PPS will operate in **Run 3** with an upgraded apparatus:

- ✓ new silicon pixel tracker (with internal motion to mitigate radiation damage)
- ✓ two new timing stations, double-diamond detectors in all planes (expected factor ~2 improvement in *pp* vertex determination)
- ✓ dedicated dijet Level-2 trigger (HLT) line with proton tag, to afford lower p_T threshold

While $\mathcal{L}$→x2, sensitivity expected to increase by ~4-5, due to improved acceptance (tracking) and backgroud rejection (timing)

Expression of interest for a new setup for **HL-LHC** [arXiV:2103.02752]

More in G. Gil Da Silveira's poster



Summary

- ✓ Precision Proton Spectrometer (PPS) empowers CMS with new capabilities, allowing to tag scattered protons in the 'crowded' LHC environment (pile-up up to ~50).

- ✓ PPS has successfully taken data during LHC-Run2.
  - Proton kinematics reconstruction algorithms and calibration procedures have been developed and validated.
  - Good understanding of the LHC optics in the region at ~200 m from interaction point has been demonstrated.

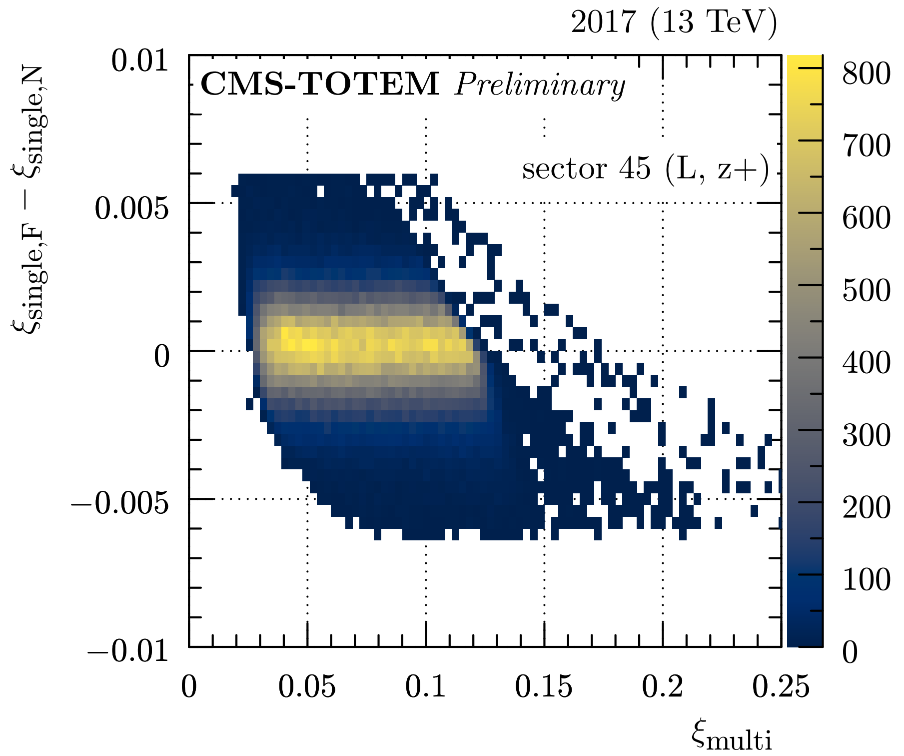
- ✓ First physics results based on LHC-Run2 data presented at this conference.

- ✓ PPS will continue to operate in LHC-Run 3 with an upgraded apparatus. Increase in sensitivity by factor 4-5 expected.

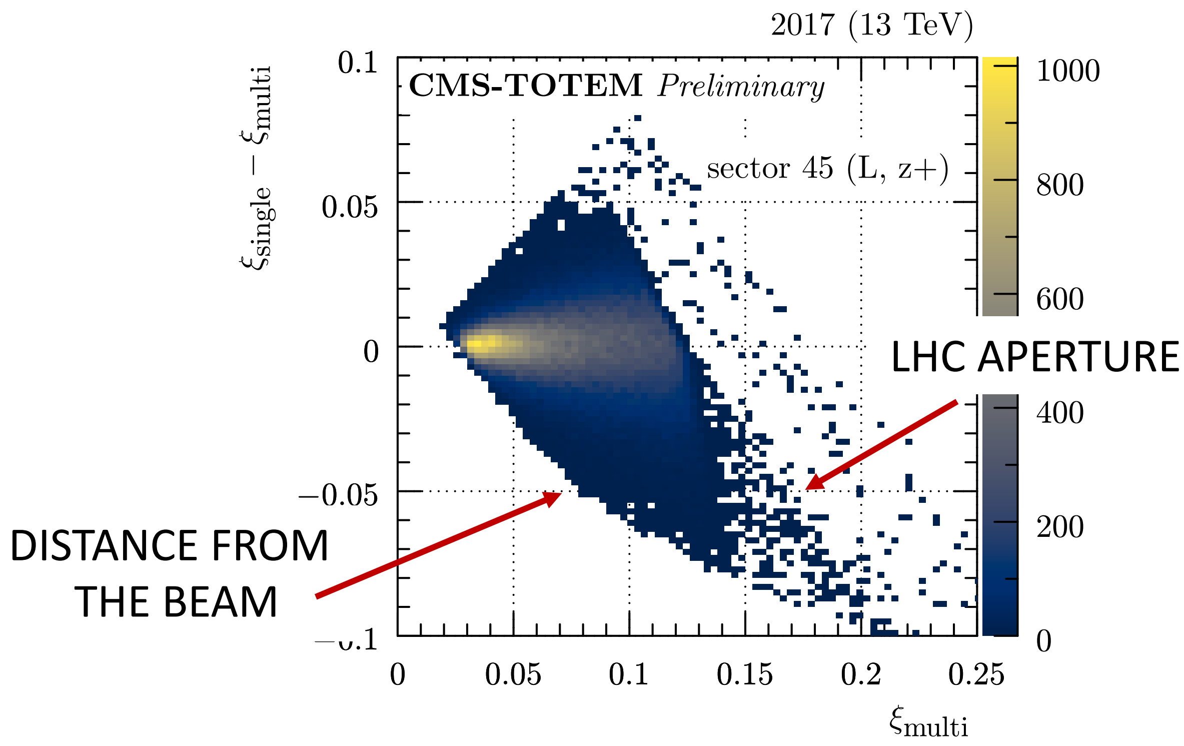
BACKUP

CONTROL PLOTS AND ACCEPTANCE

DIFFERENCE BETWEEN THE SINGLE-RP ξ RECONSTRUCTION FROM THE NEAR AND FAR RPs.



DIFFERENCE BETWEEN THE SINGLE-RP AND MULTI_RP ξ RECONSTRUCTION

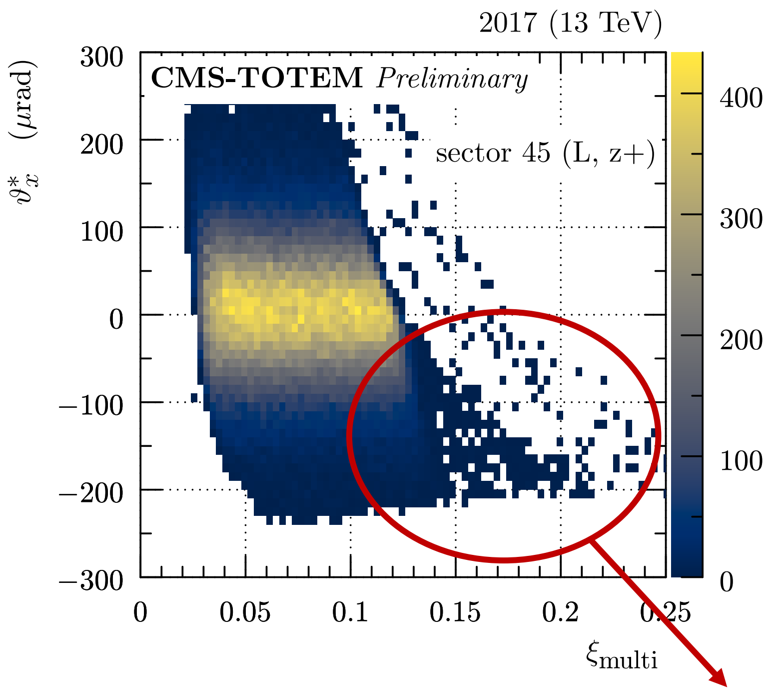


Phase space covered by distributions limited by the distances of the RPs from the beam (low ξ) and the LHC aperture (high ξ).

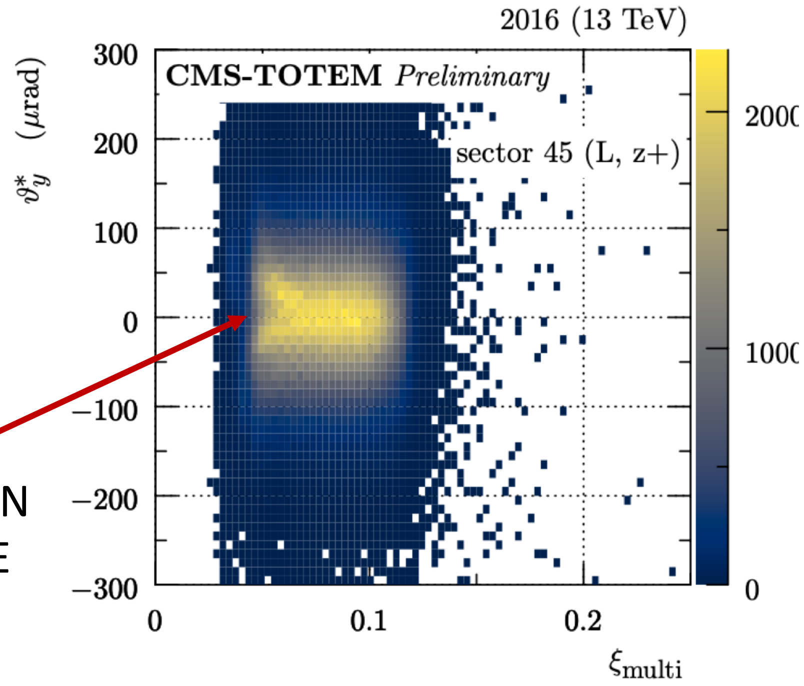
Difference centred at 0 and independent of the reconstructed ξ_{multi} as expected if the alignment and the optics calibration are correct.

PROTON SCATTERING ANGLES

HORIZONTAL SCATTERING ANGLE



VERTICAL SCATTERING ANGLE



RADIATION DAMAGE EFFECT

DATA USED TO MODEL THE LIMITATION CREATED BY THE LHC APERTURE

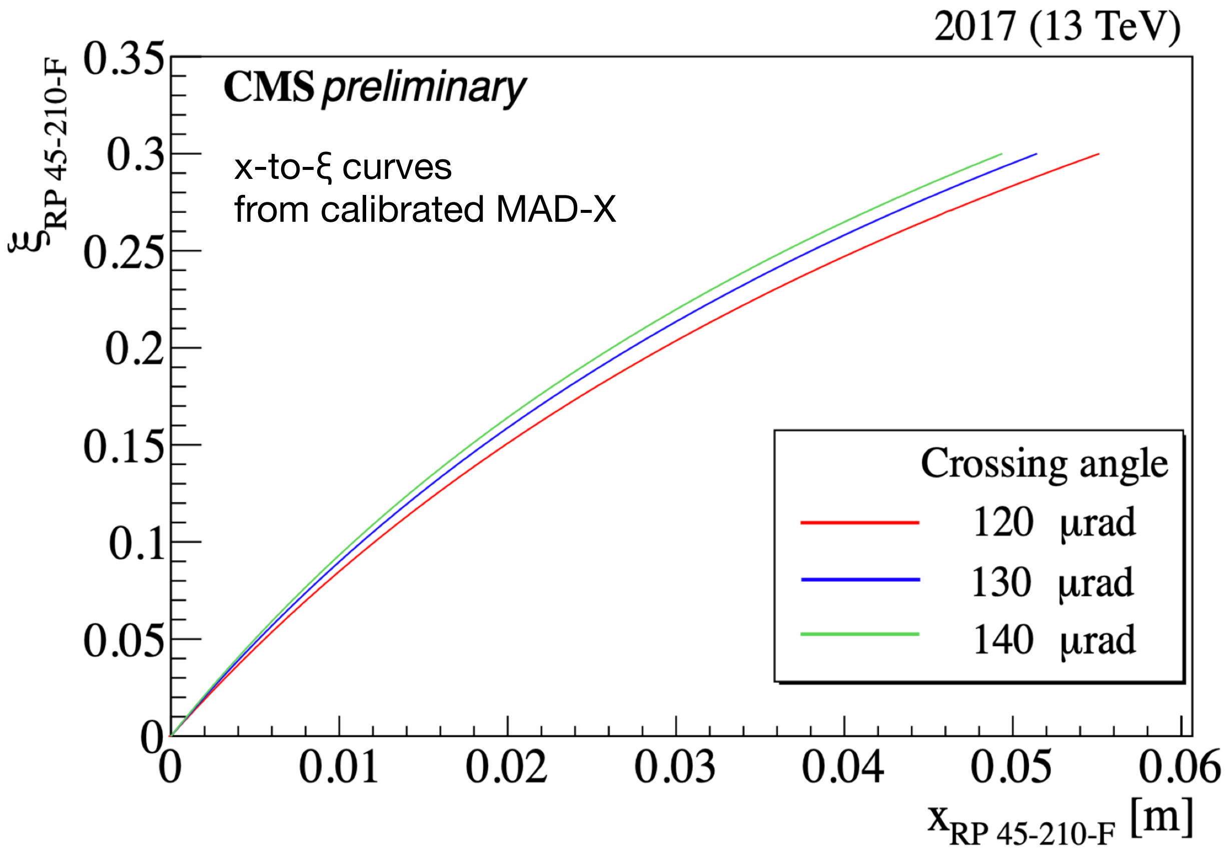
A part from acceptance limitation, distributions symmetric about zero, with no dependence on ξ, as expected

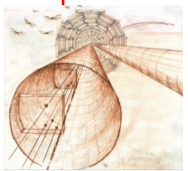
Mean stable over time and close to 0 (within ± 10 μrad) for all data taking period

Proton kinematics reconstruction

Single-RP method

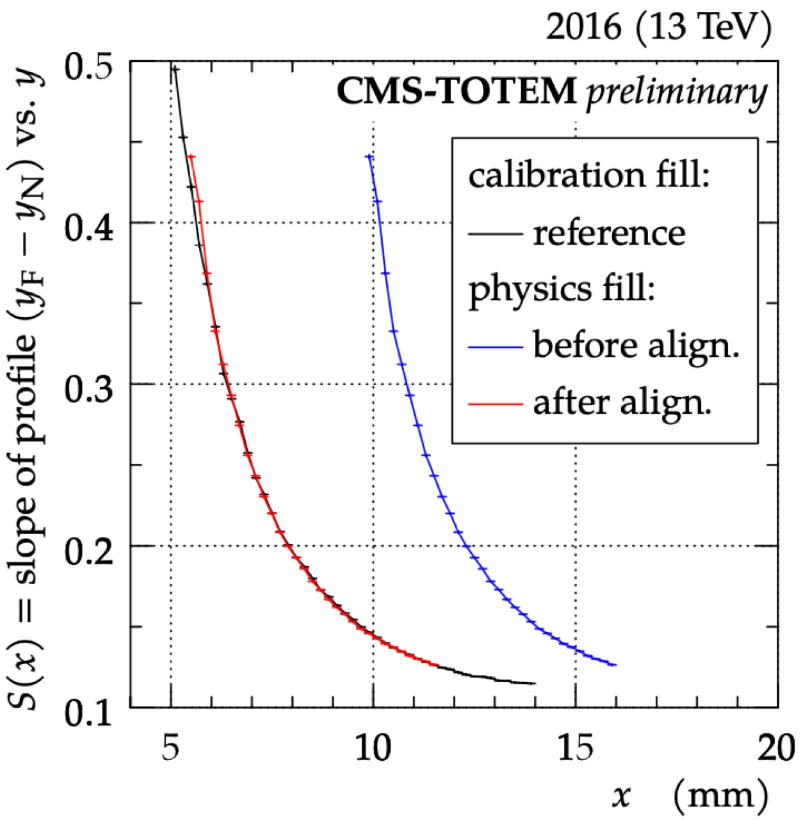
- Treat each RP as a separate detector
- ξ reconstructed from x measured in the RM, using the x-to-ξ curve

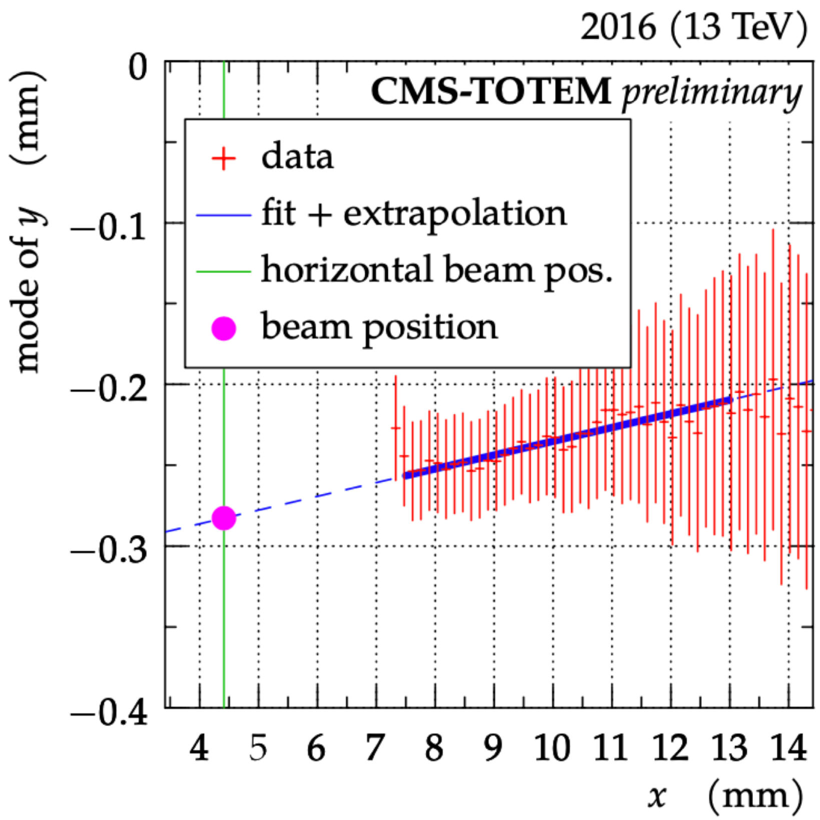




Interpolation among different crossing angle performed, if needed

Fill-to-fill alignment

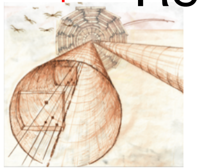




Horizontal alignment obtained by matching observables from the fill to those from the dedicated alignment run

Relies on reproducibility of the beam optics

Vertical alignment obtained by extrapolating the observed vertical profile to the horizontal beam position



Timing RPs are eventually aligned wrt tracking RPs

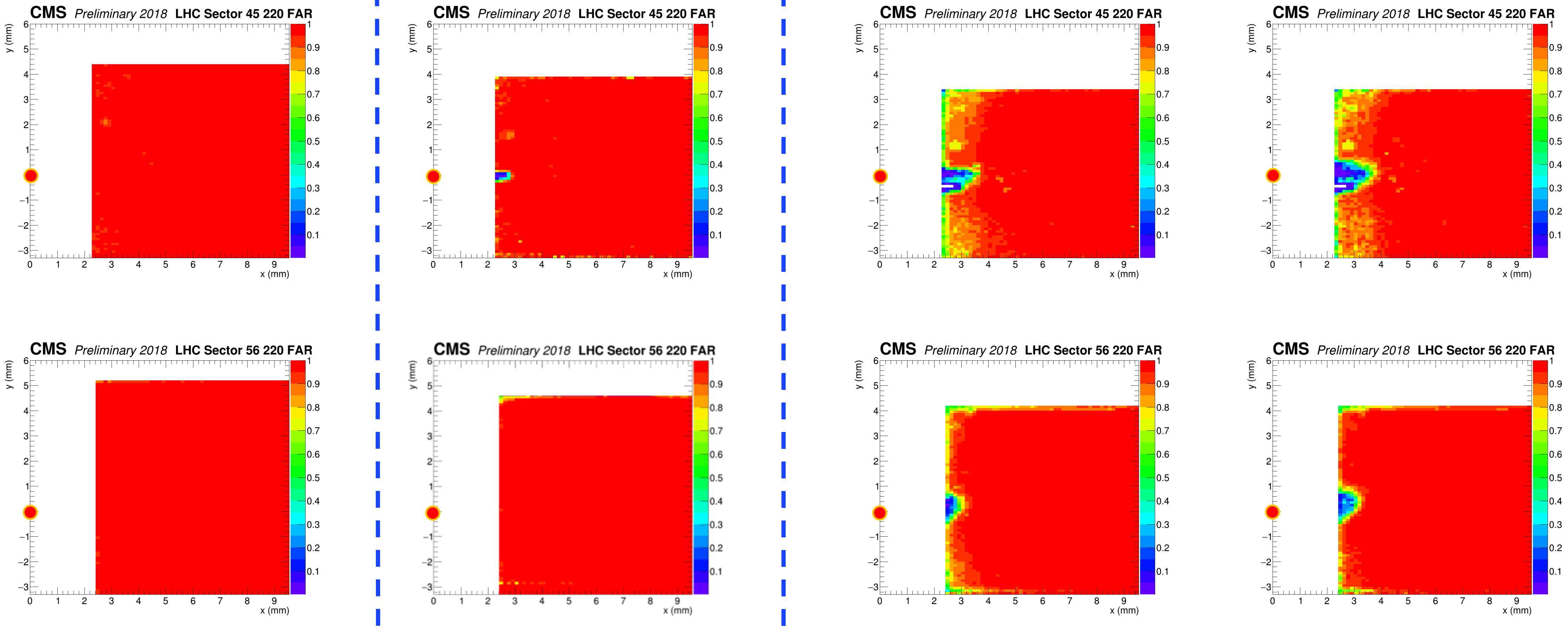
Effect of radiation on RP efficiency (2018)

EVOLUTION OF THE RP EFFICIENCY MAP IN THE DETECTOR REGION CLOSEST TO THE BEAM FOR RP 220 FAR (worst case)

BEGINNING OF DATA TAKING | TS | 21.0 fb^{-1} | TS | 50.fb^{-1} | 58 fb^{-1}

SECTOR 45

SECTOR 56



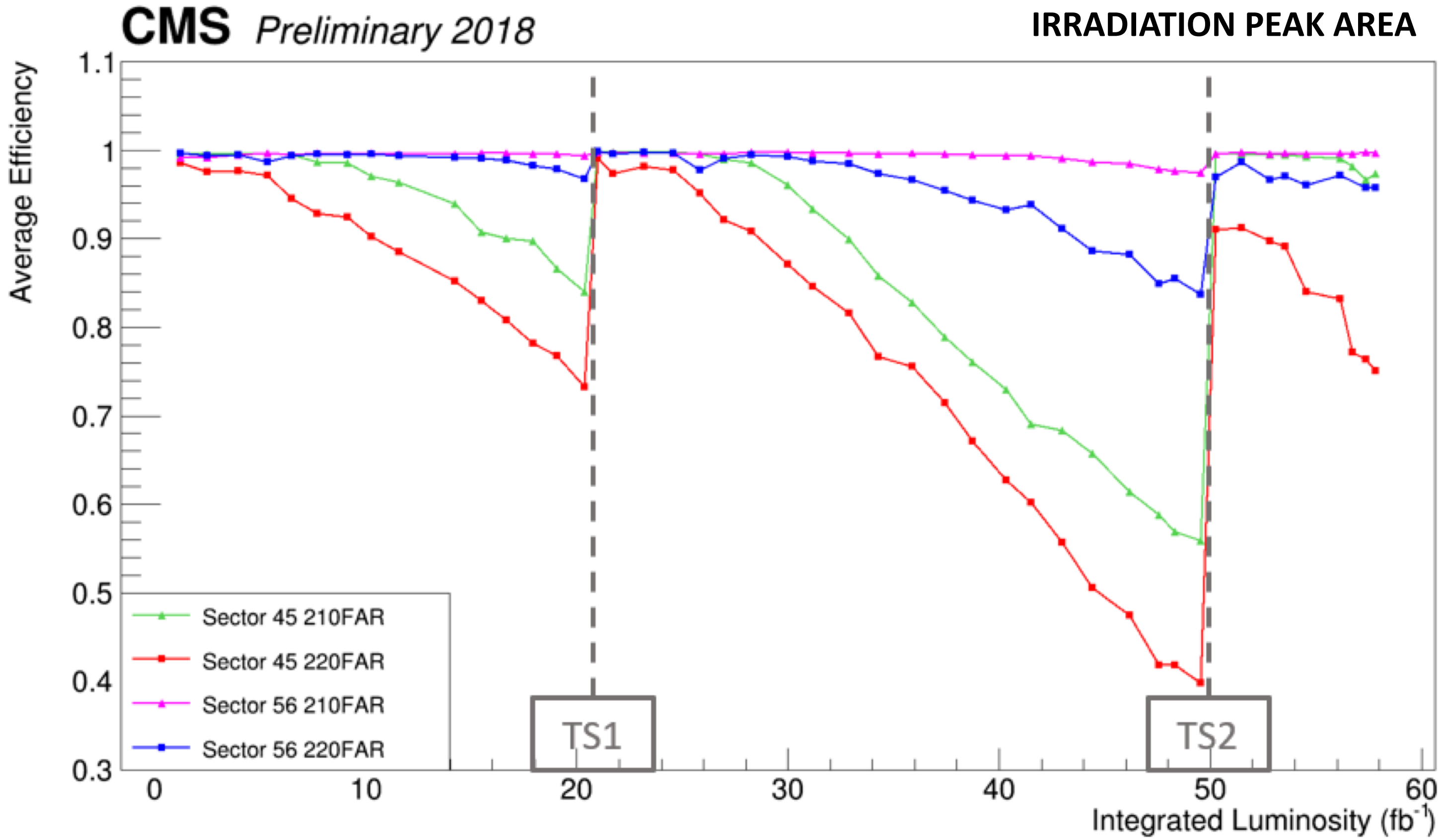
BEAM
[always in x=0, y=0]

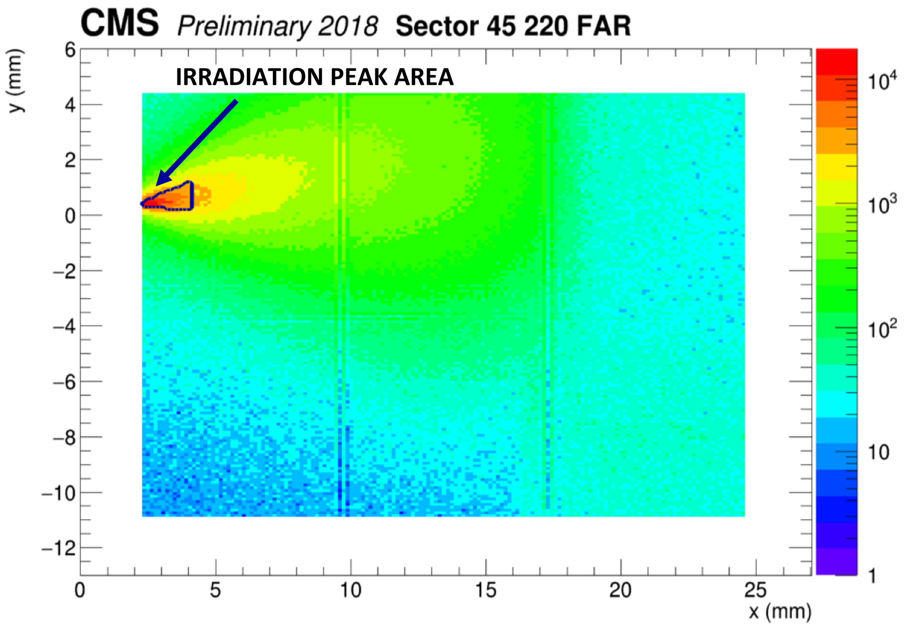
RP SHIFTED BY
0.5 mm DOWNWARDS

RP SHIFTED BY
0.5 mm DOWNWARDS

Deterioration of the RP efficiency caused by the radiation damage

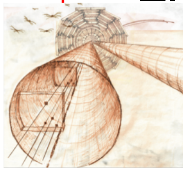
Effect of radiation on RP efficiency (2018)





Average efficiency calculated every ~ 1 fb^{-1} in the critical region around the irradiation peak

Drop in the efficiency due to irradiation clearly visible in the critical region; recovery after each LHC technical stop (TS) due to vertical movement of the RPs.



→ **This plot will be used as monitoring tool in LHC-Run3**