CMS Precision Proton Spectrometer results and prospects

12 December 2024

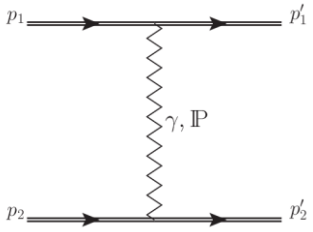
Michael Pitt (CERN)

On behalf of the CMS Collaboration

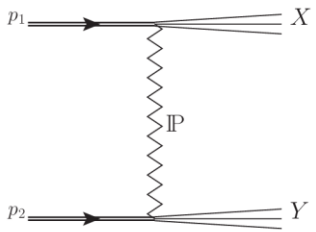
Introduction

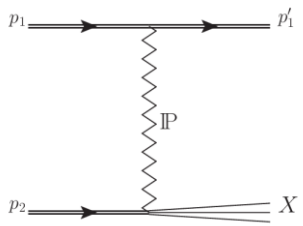
Diffractive/exclusive processes at the LHC

- t-channel exchange of color neutral particles (QED, QCD)

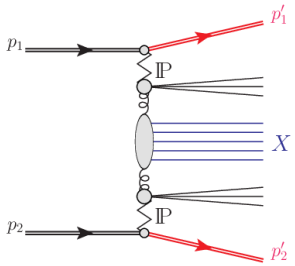


Elastic scattering

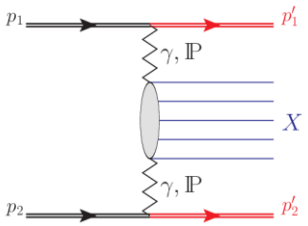




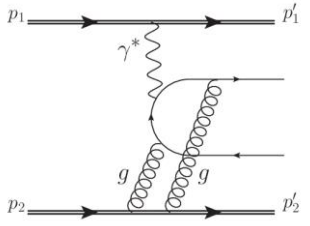
Single/double diffractive dissociation



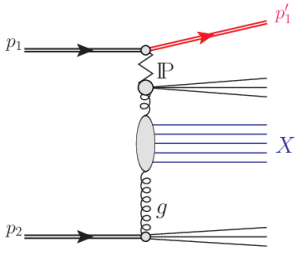
Double pomeron exchange



Central exclusive production



Exclusive photoproduction



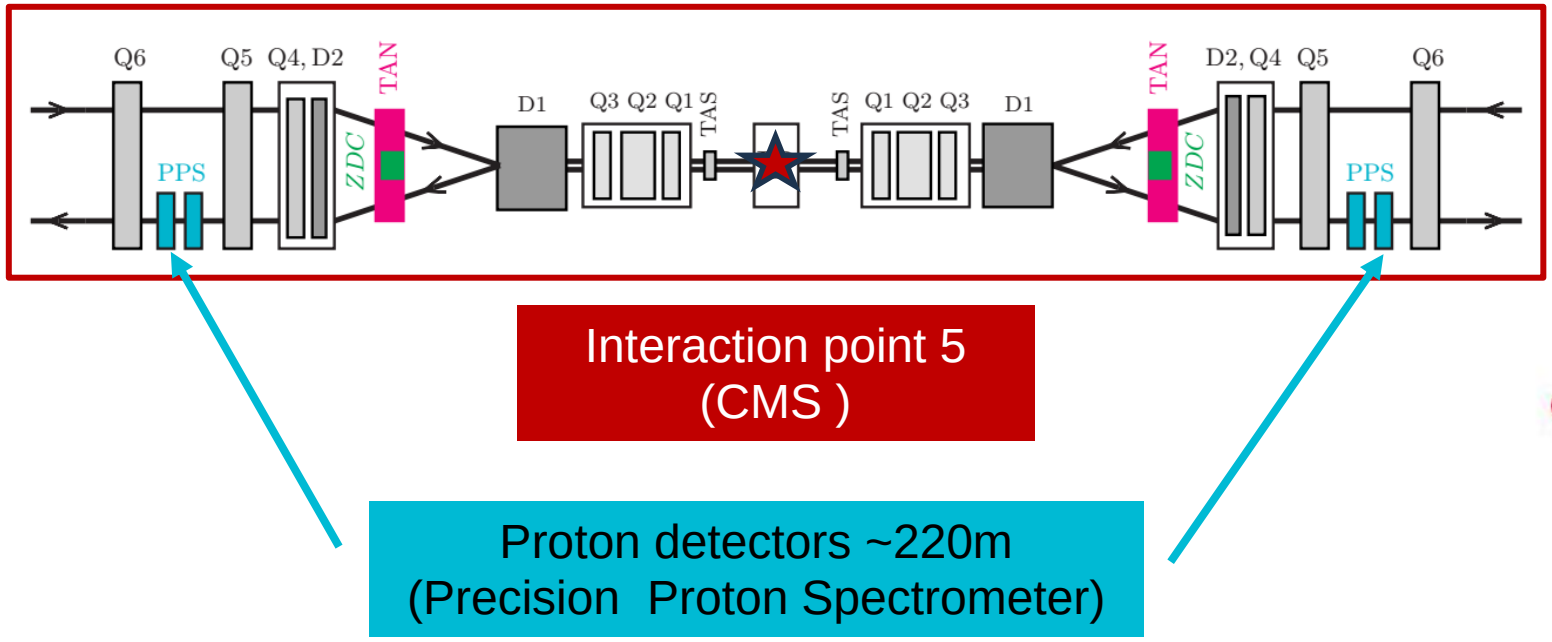
Single-diffraction with central system

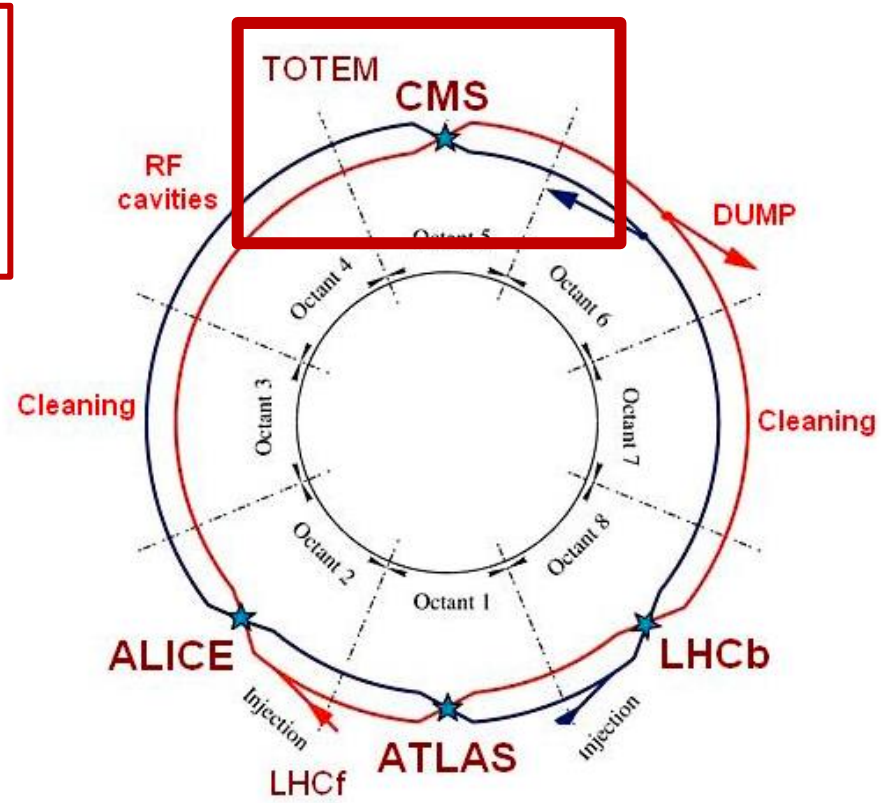
Proton tagging → diffractive/exclusive physics

- Provide a rich scientific program for LHC experiments
- Spans over large kinematic region (MeV – TeV), and large cross-section range

CMS Proton spectrometers

- CMS is equipped with forward proton detectors at about 220 m from the IP, respectively on both sides.





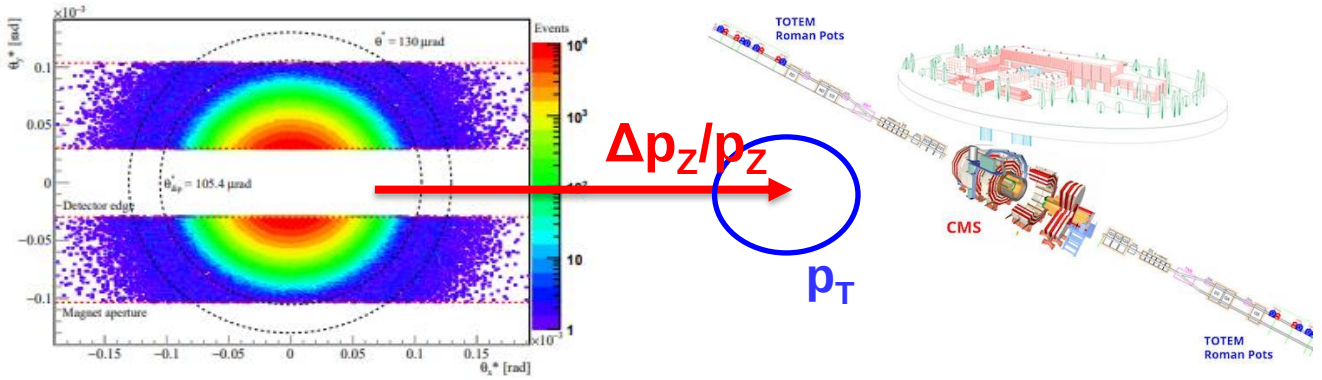
CMS Proton spectrometers

Two type of forward detectors are installed: vertical and horizontal

Vertical detectors (TOTEM in the past)

- Very low pileup (μ~0.02), special LHC optics
- Proton kinematics:

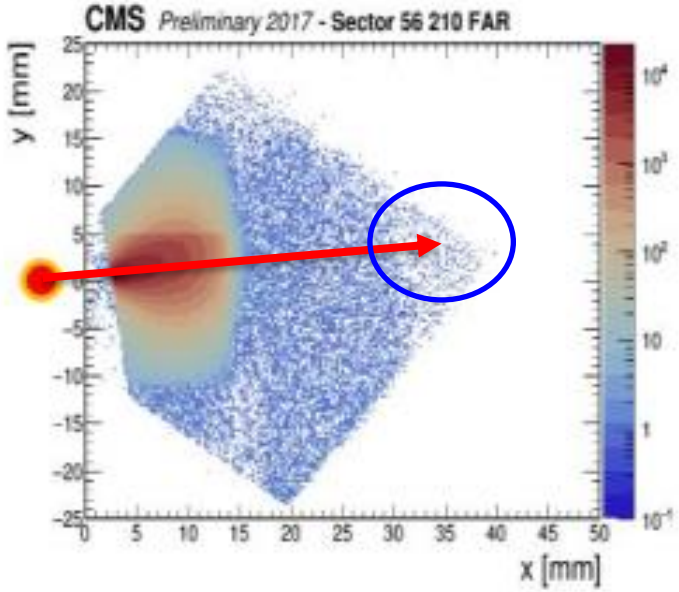
$\Delta p_Z/p_Z$ < 20% and **p_T ~ 0.1 – 2 GeV**



Horizontal detectors

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

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



Forward proton detectors

- CMS Precision Proton Spectrometer (PPS):

- 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

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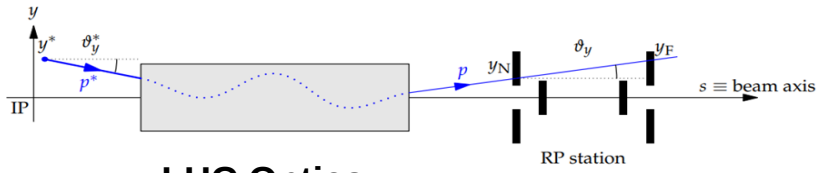
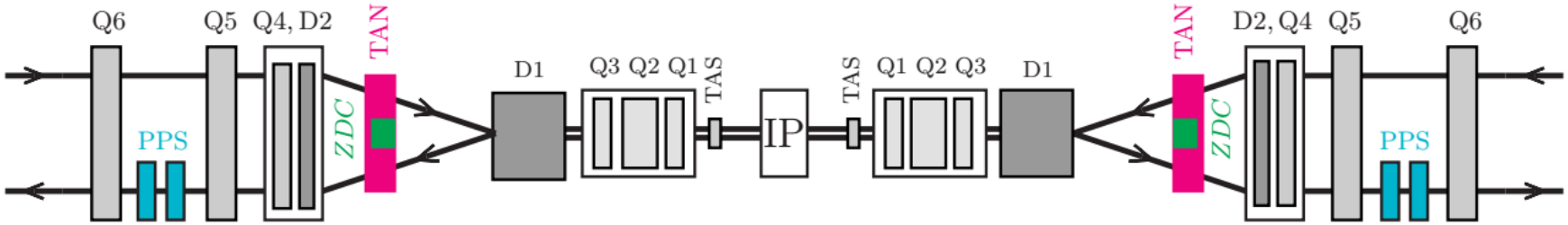


LHC Optics



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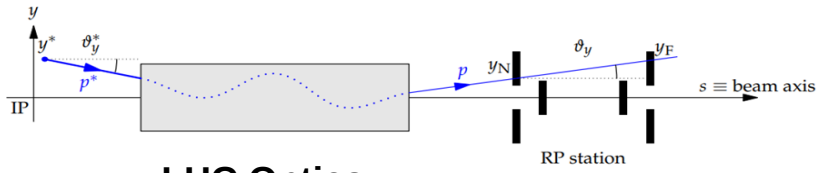

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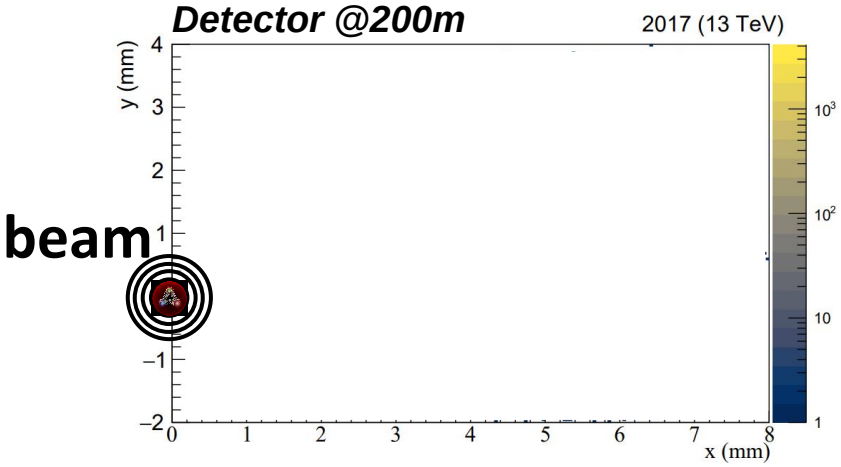

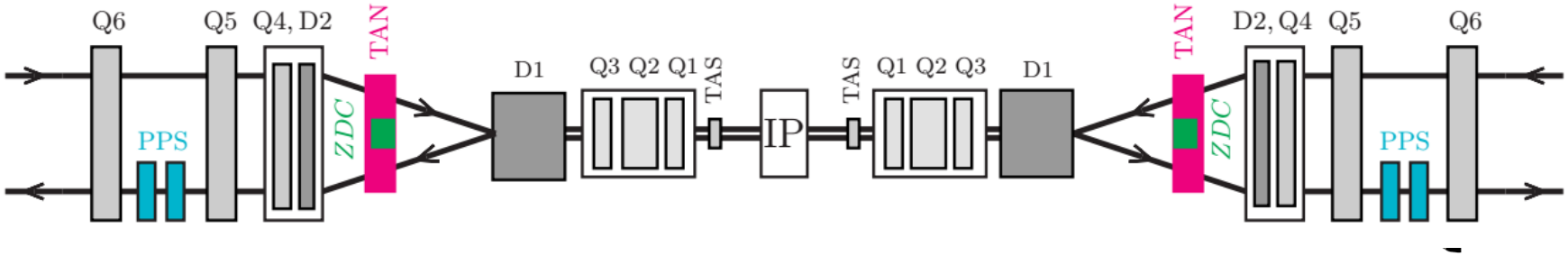

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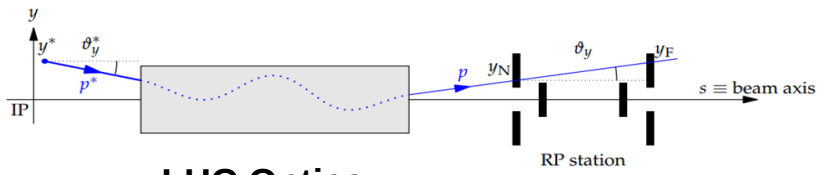

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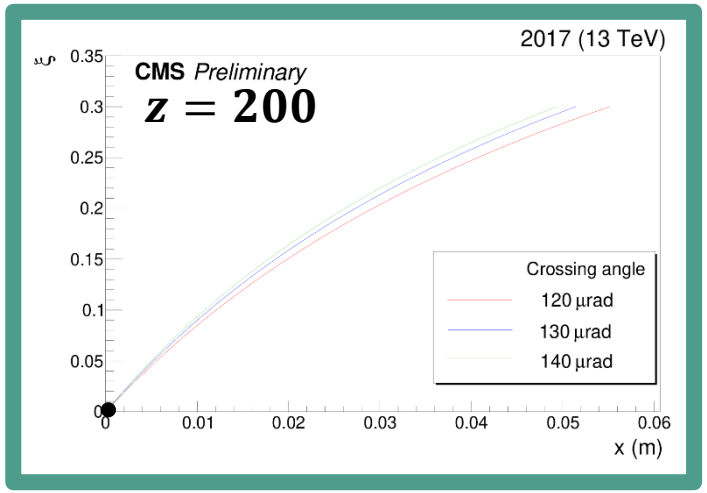

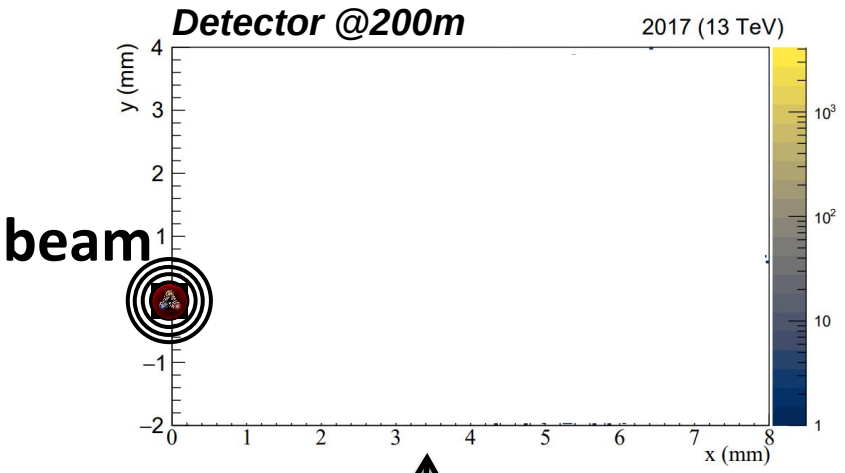

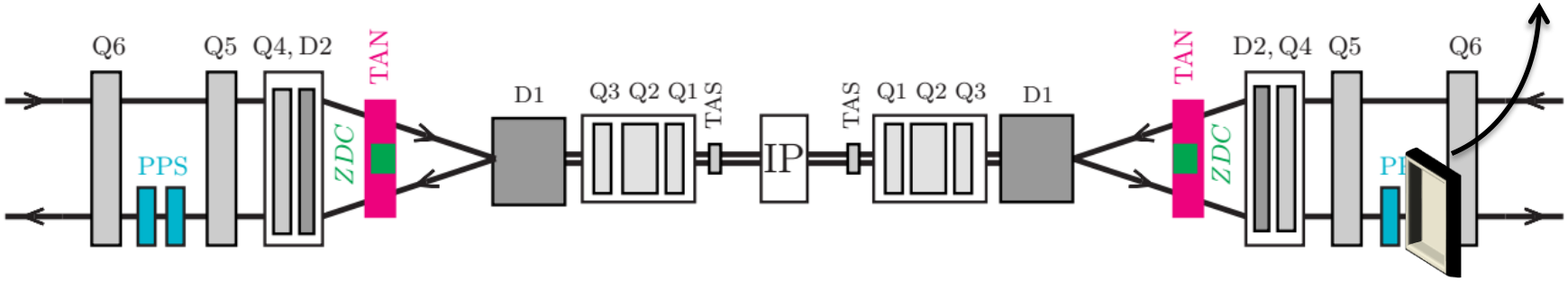

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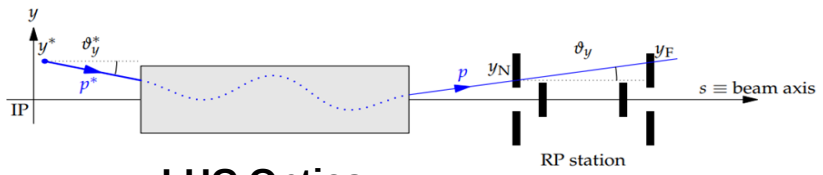

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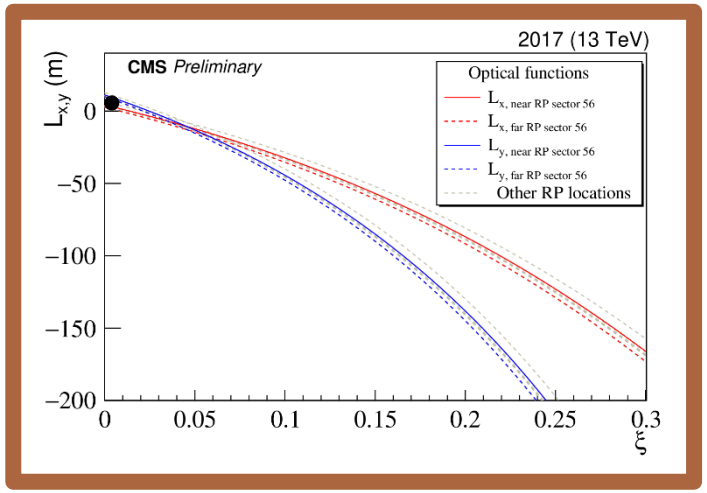

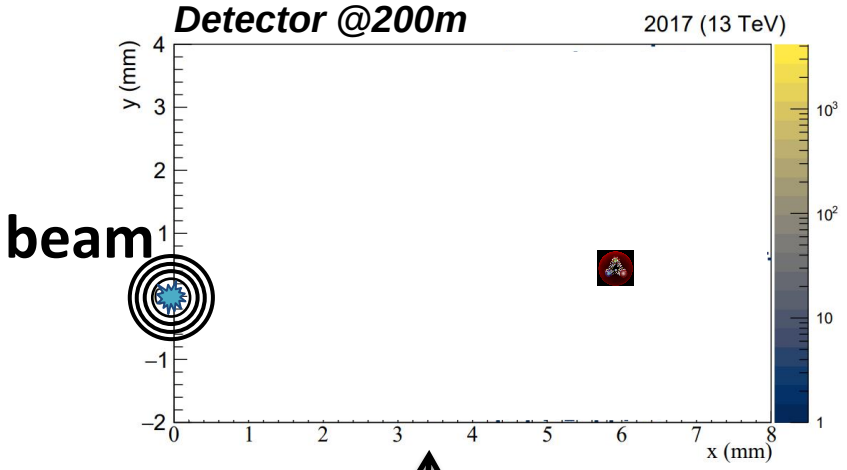

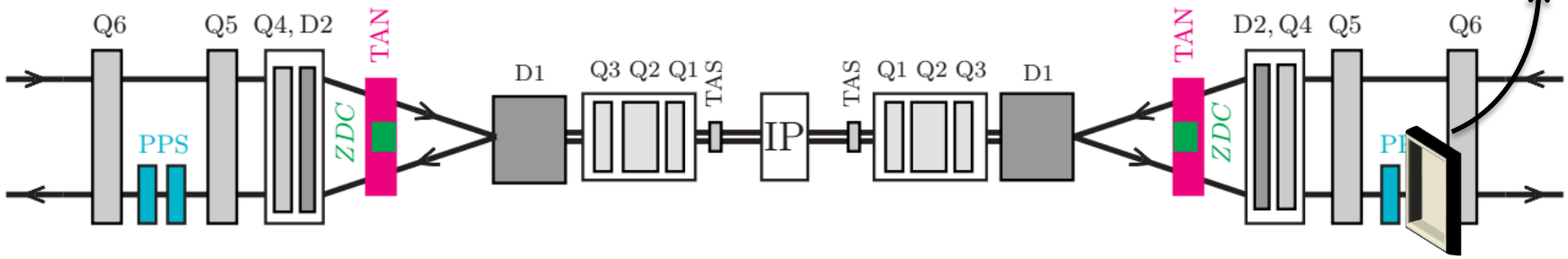

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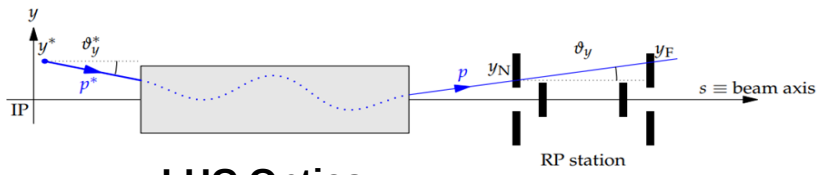
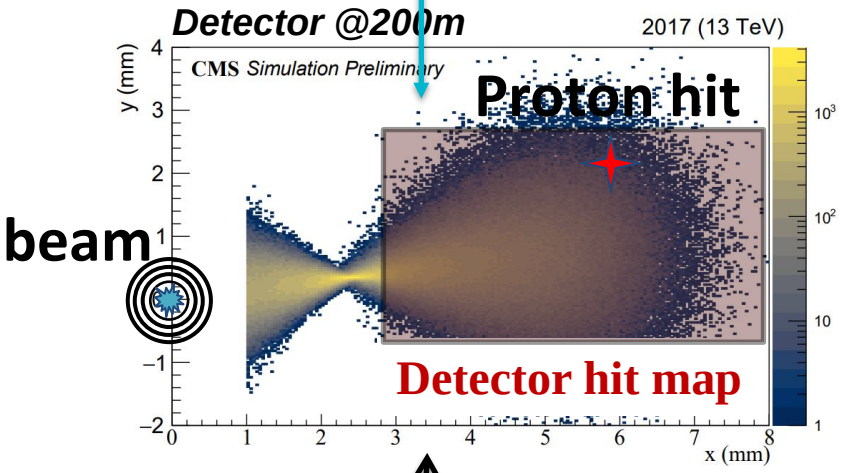


LHC Optics

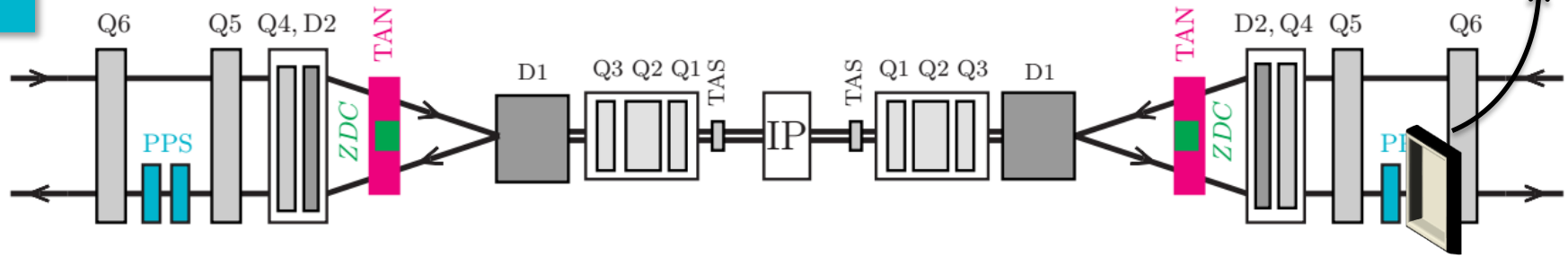
acceptance
2.5% < ξ < 15%

min distance from the beam

Collimators



2 stations



CMS | Detector technology

- Rapid detector evolution since commissioning in 2016!

2016:

2017:

2018:

2022:

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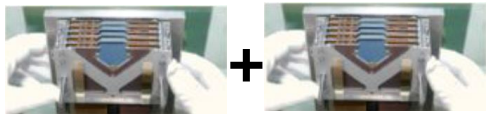
SiStrip SiStrip



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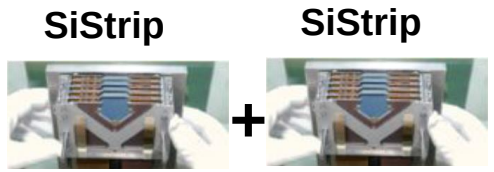

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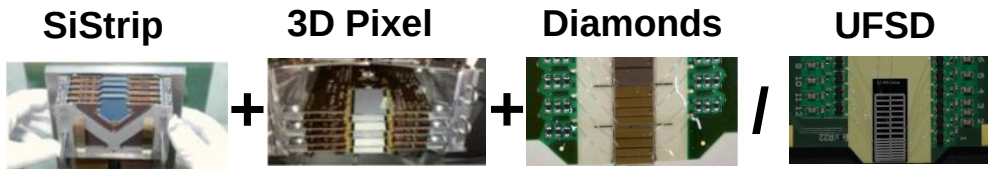

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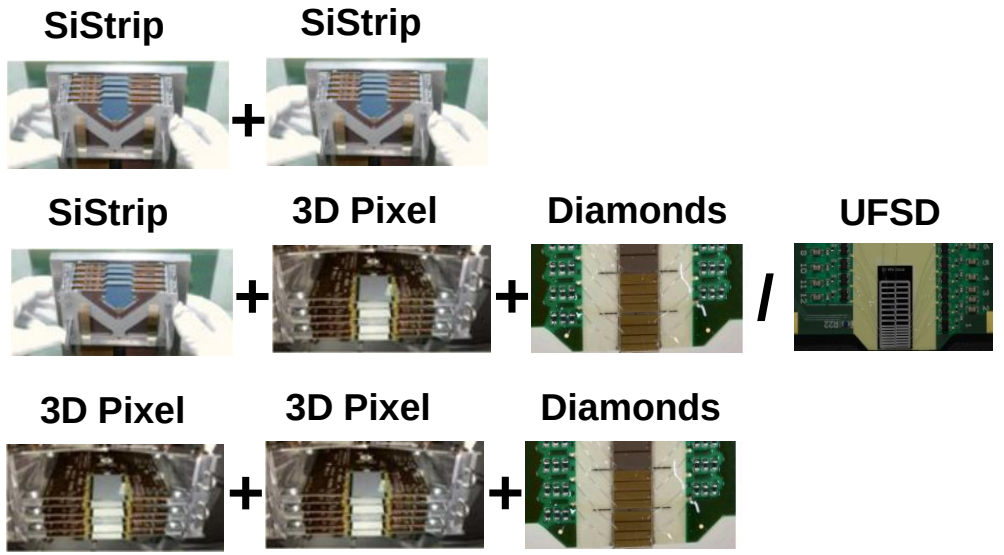

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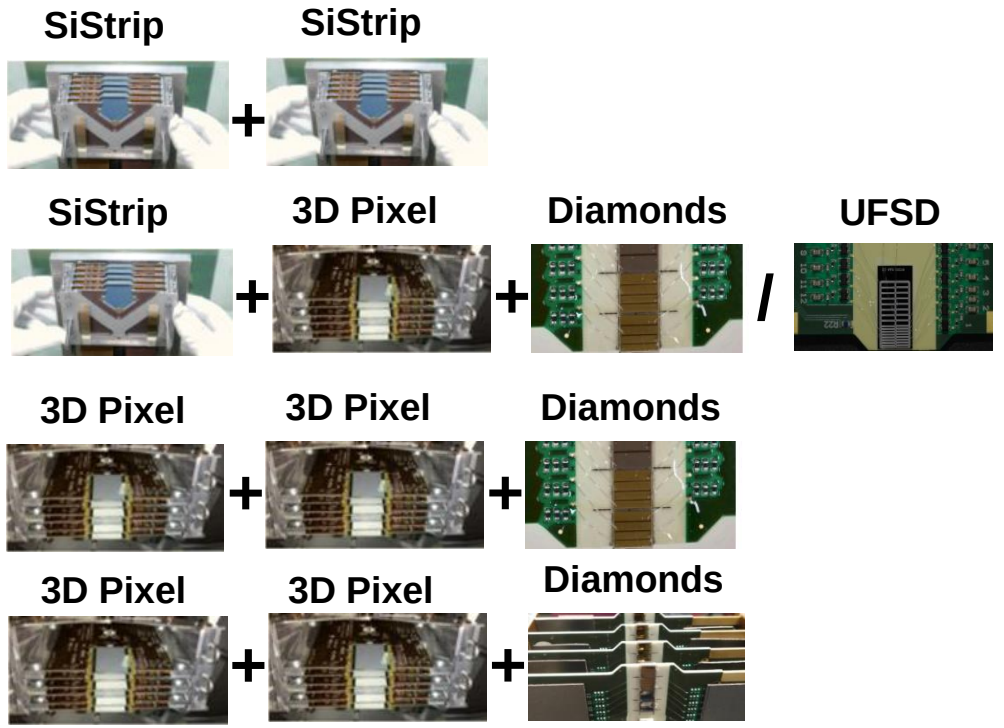

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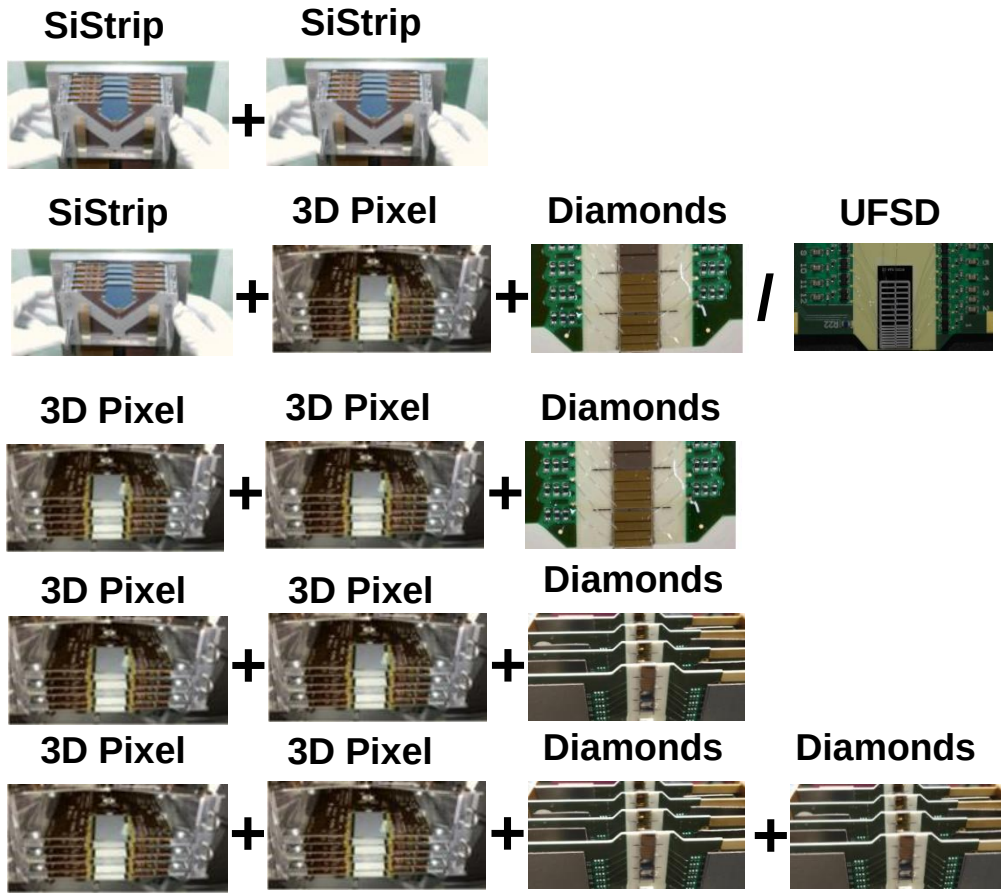

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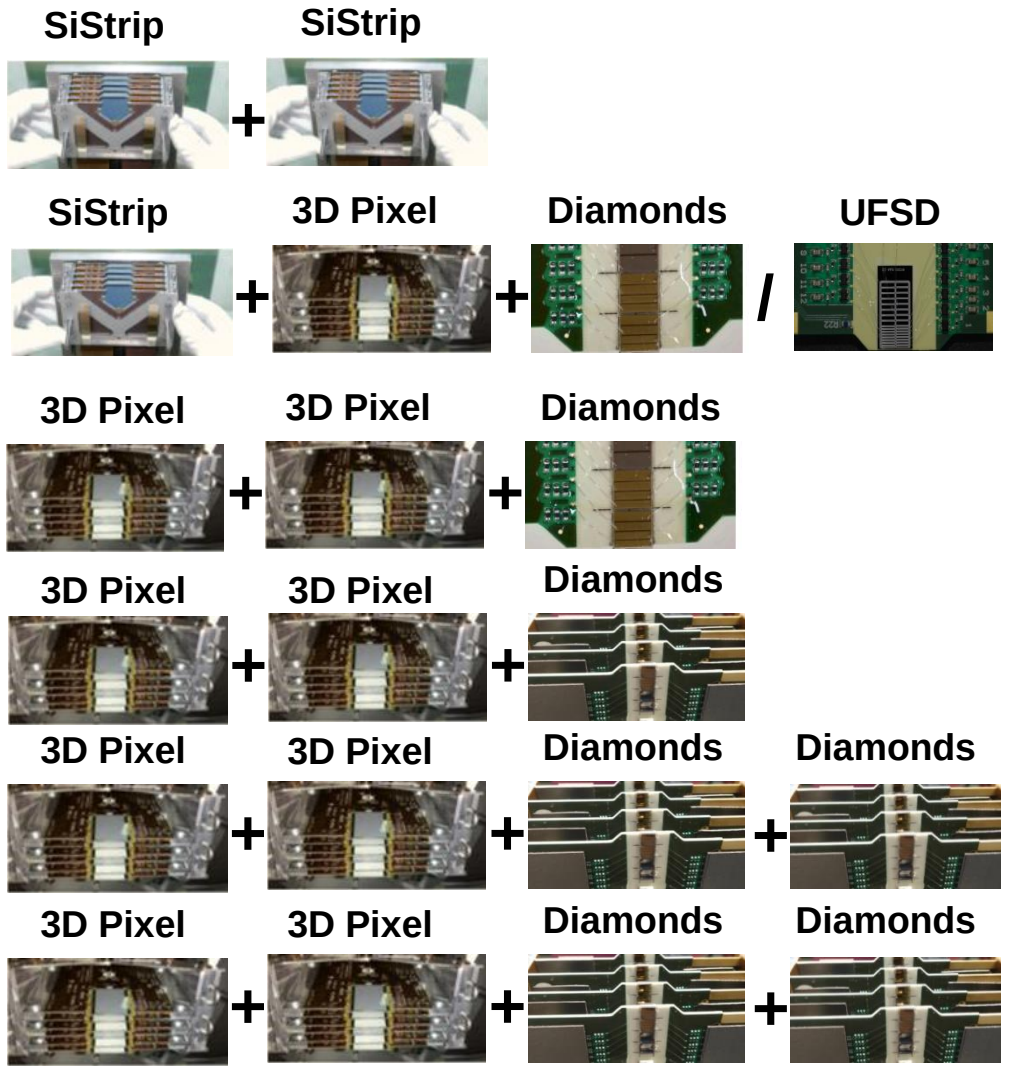
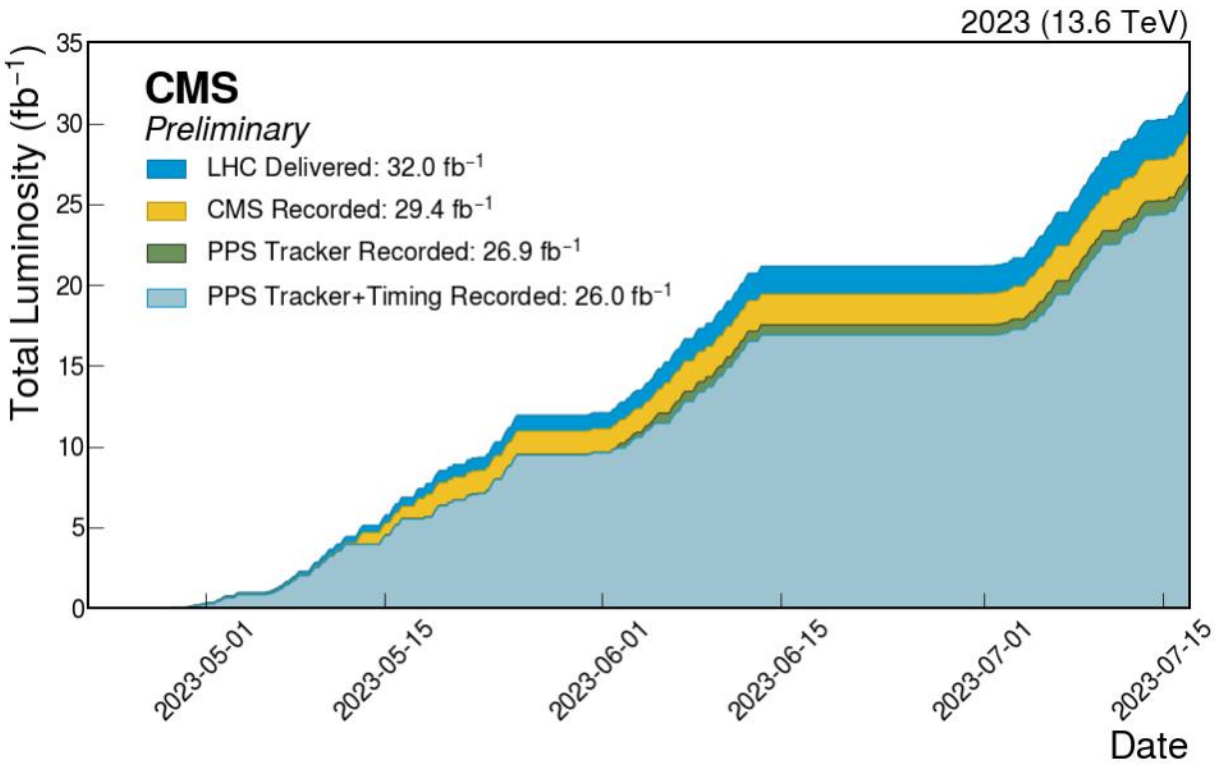
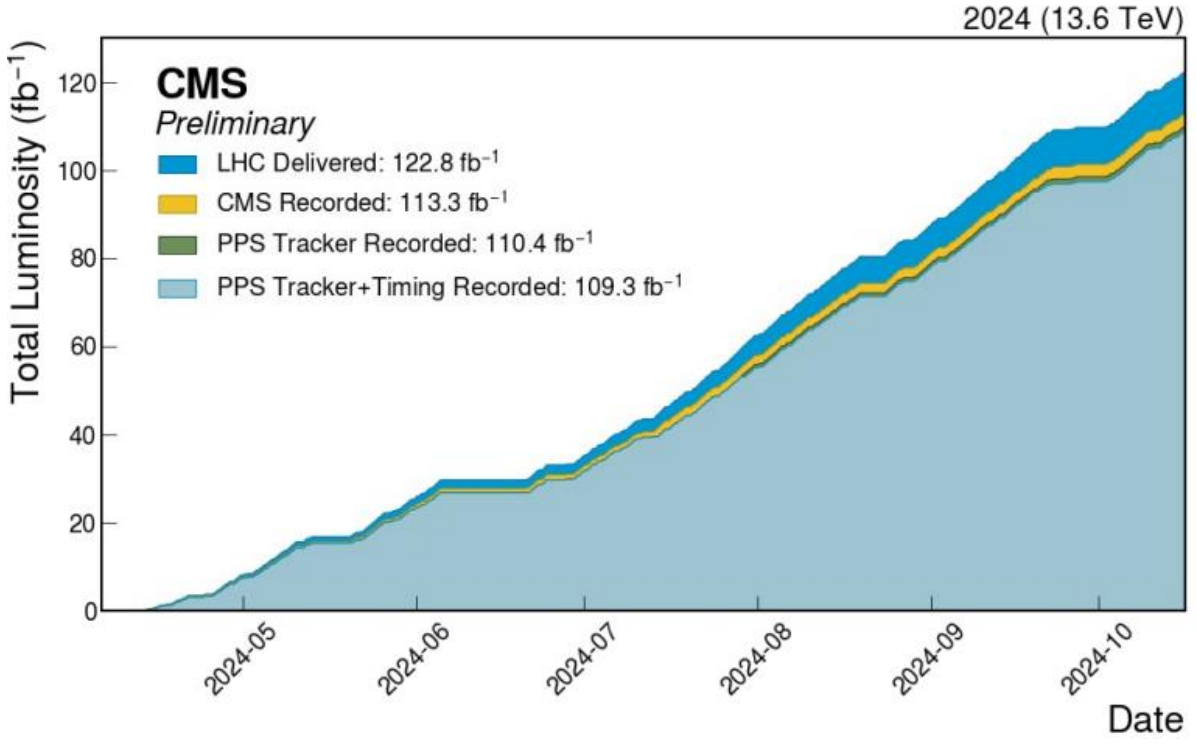


PPS | performance in Run 3

CMS DP-2024/008

- Very stable operation:

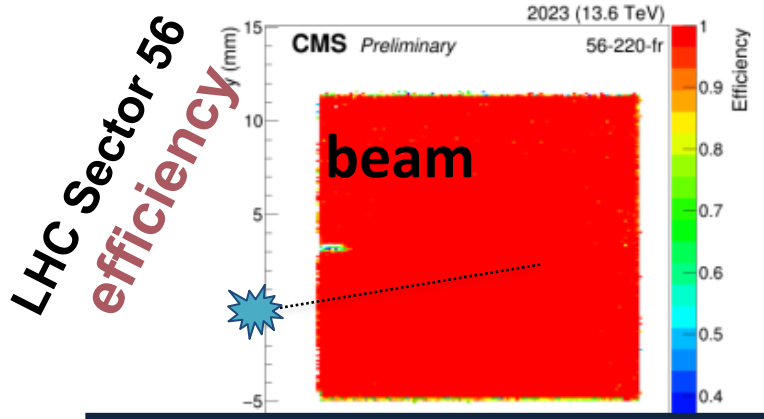




PPS | Tracking efficiency in Run 3

CMS DP-2024/008

- 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



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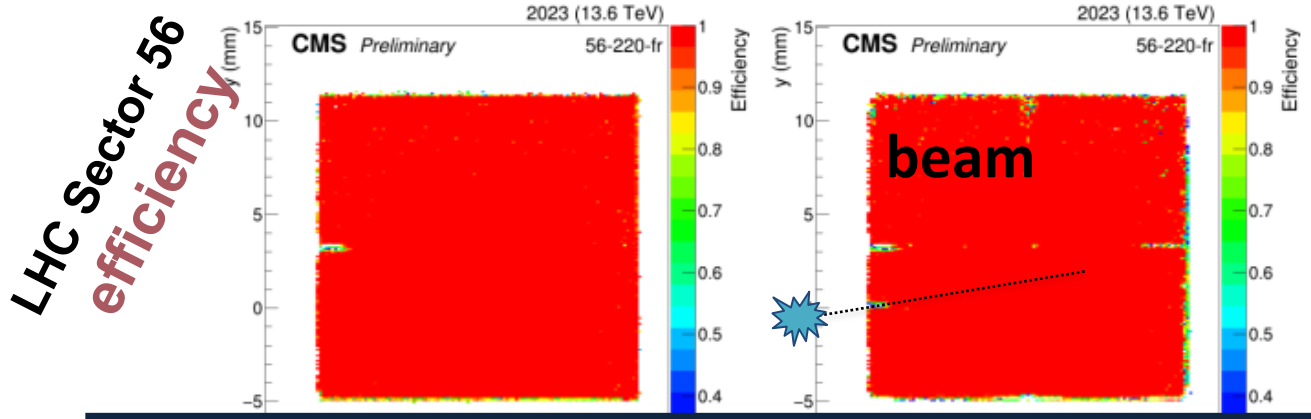

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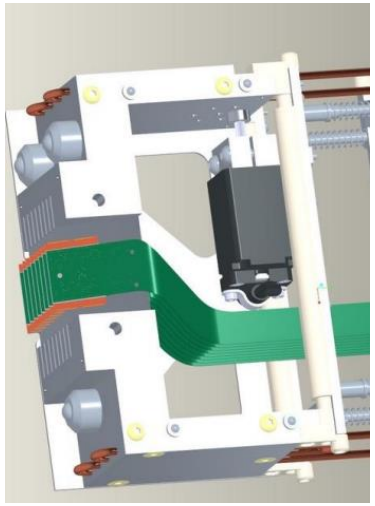

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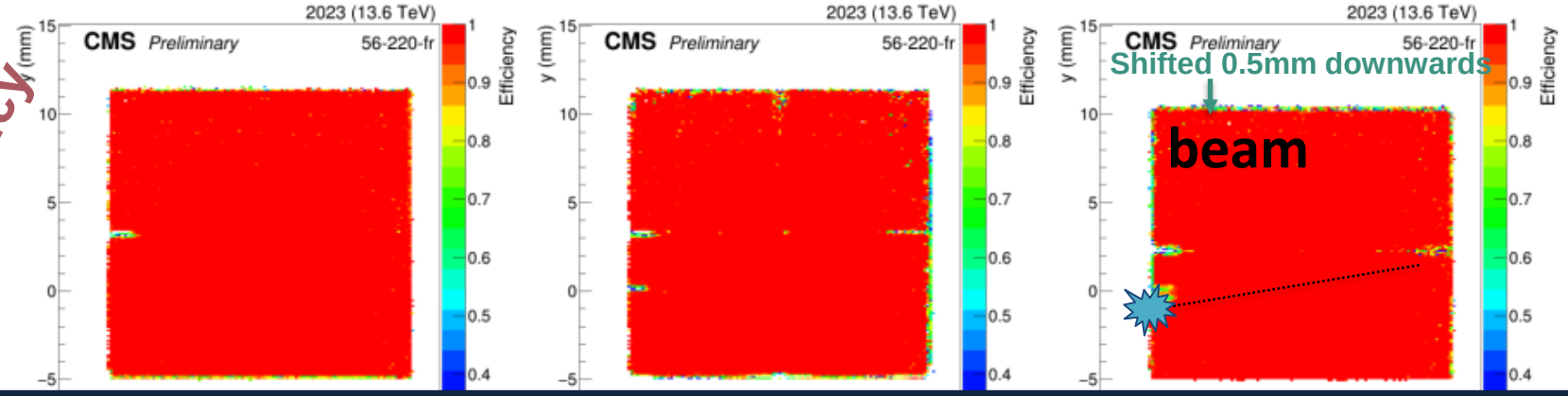
LHC Sector 56 efficiency



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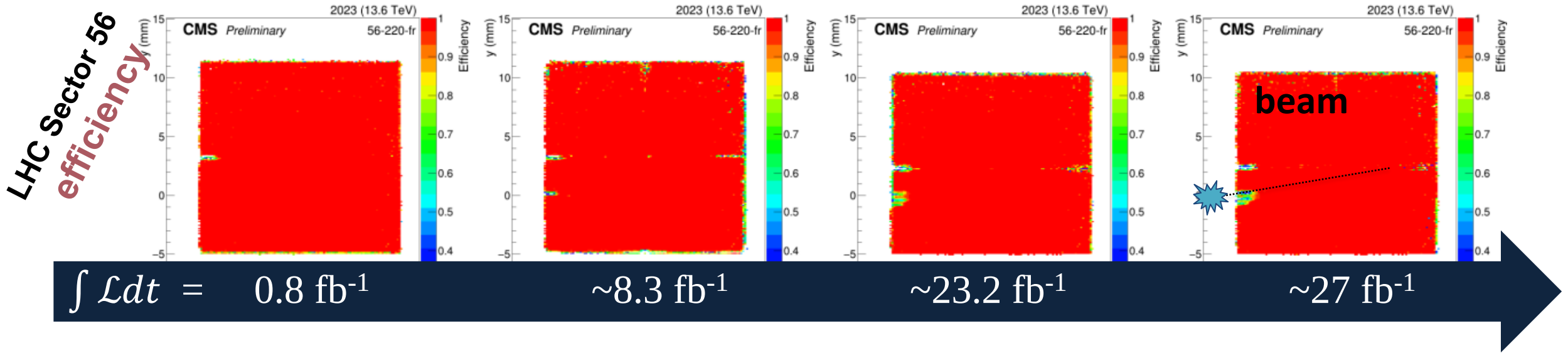
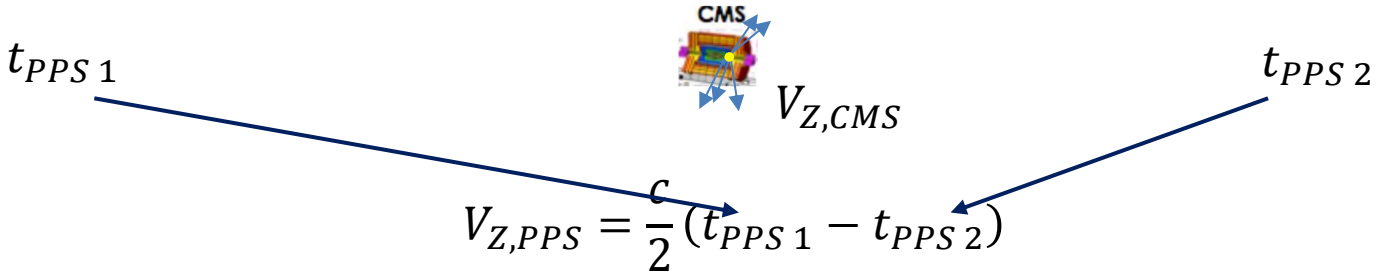


PPS | Timing resolution in Run 3

- Vertex z-coordinate is reconstructed using central tracks or PPS ToF

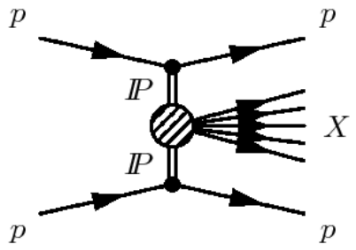


PPS | Timing resolution in Run 3

CMS DP-2024/009

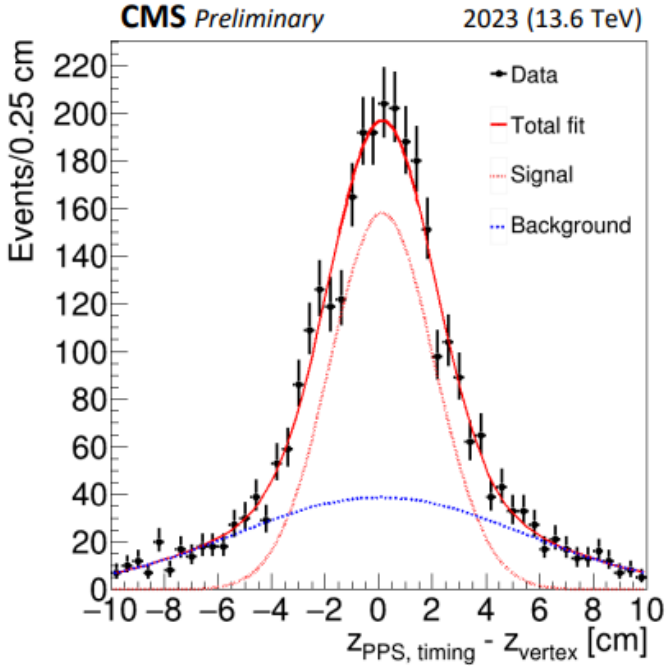
- Vertex z-coordinate is reconstructed using central tracks or PPS ToF
- Timing resolution is measured in low-PU run (μ=1) from inclusive Central Diffractive events

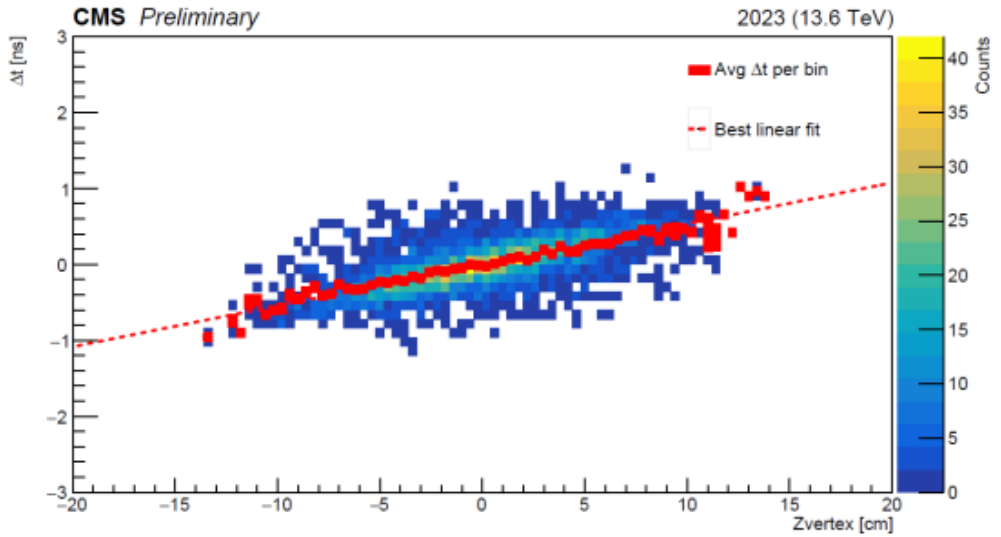
2023 data



Event selection:
- Zero-Bias triggers
- N_{VTX}=1 with
- 1 proton per arm (N_P=2)
- At least 2 active planes / RP

(Same as in Run 2)





Slope = 0.048 ± 0.003 ns / cm
2/c ~ 0.066 ns / cm

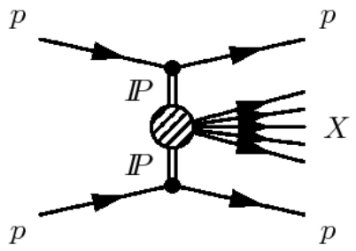
2 station resolution: $\sigma_z = 1.9\,cm$ ($88\,ps$ per arm)

PPS | Timing resolution in Run 3

CMS DP-2024/118

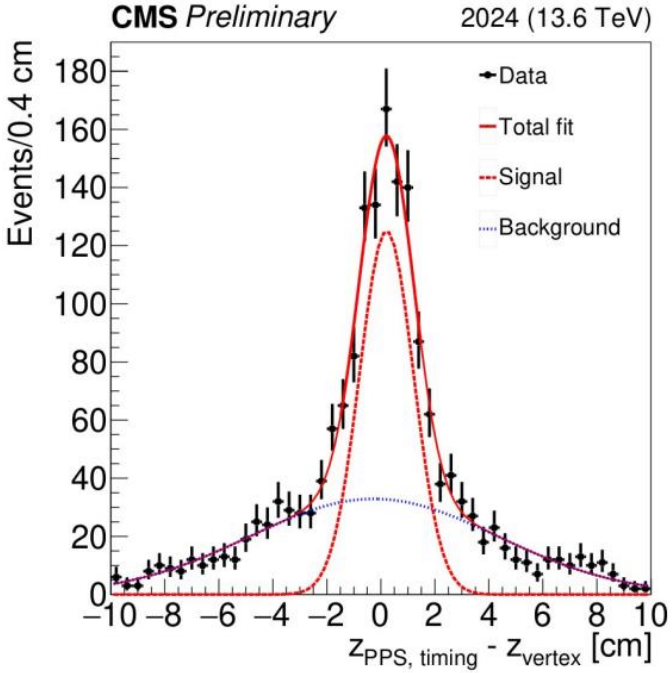
- Vertex z-coordinate is reconstructed using central tracks or PPS ToF
- Timing resolution is measured in low-PU run (μ=1) from inclusive Central Diffractive events

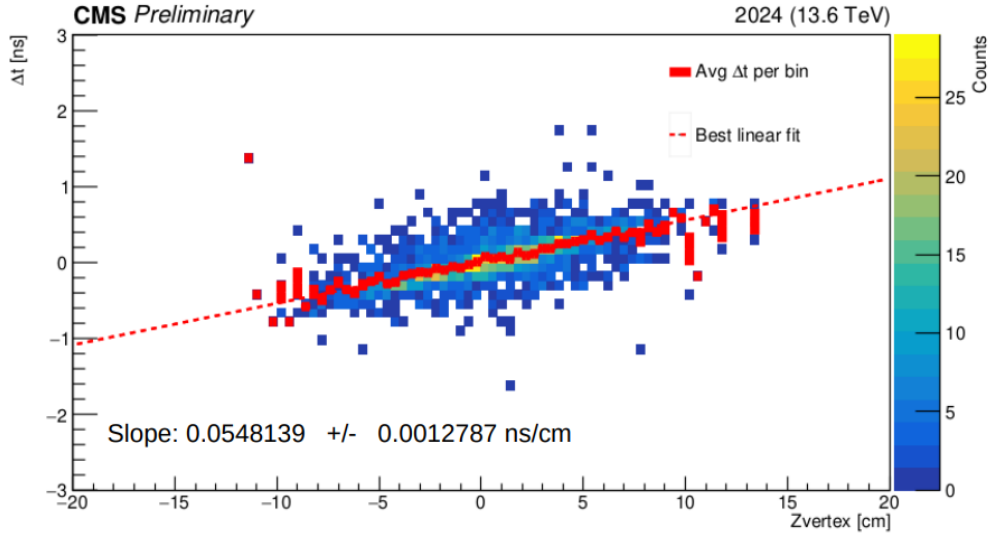
2024 data



Event selection:
- Zero-Bias triggers
- N_{VTX}=1 with
- 1 proton per arm (N_P=2)
- At least 2 active planes / RP

(Same as in Run 2)





Slope = 0.055 ± 0.001 ns / cm
2/c ~ 0.066 ns / cm

2 station resolution: $\sigma_z = 1.0\ cm$ ($47\ ps$ per arm)

PPS | Timing efficiency in 2024

CMS DP-2024/118

- Efficiency degradation in Run 3 more visible than in Run 2
- Radiation → E field distortion due to polarization (traps)
- Can be recovered with red LED light (deactivate trapping levels)

Year	2023	2024
Integrated luminosity on sensors (fb^{-1})	20/fb	30/fb
Instantaneous luminosity (Hz/cm^2)	1.2e32	5.5e32
Pileup	1	62
Number of bunches	900	62
	w/o LED	with LED

PPS | Timing efficiency in 2024

CMS DP-2024/118

- Efficiency degradation in Run 3 more visible than in Run 2
- Radiation → E field distortion due to polarization (traps)
- Can be recovered with red LED light (deactivate trapping levels)
- History / rates also found to have a large effect

Year	2023	2024
Integrated luminosity on sensors (fb^{-1})	20/fb	30/fb
Instantaneous luminosity (Hz/cm^2)	1.2e32	5.5e32
Pileup	1	62
Number of bunches	900	62
	w/o LED	with LED

Same fill in 2024

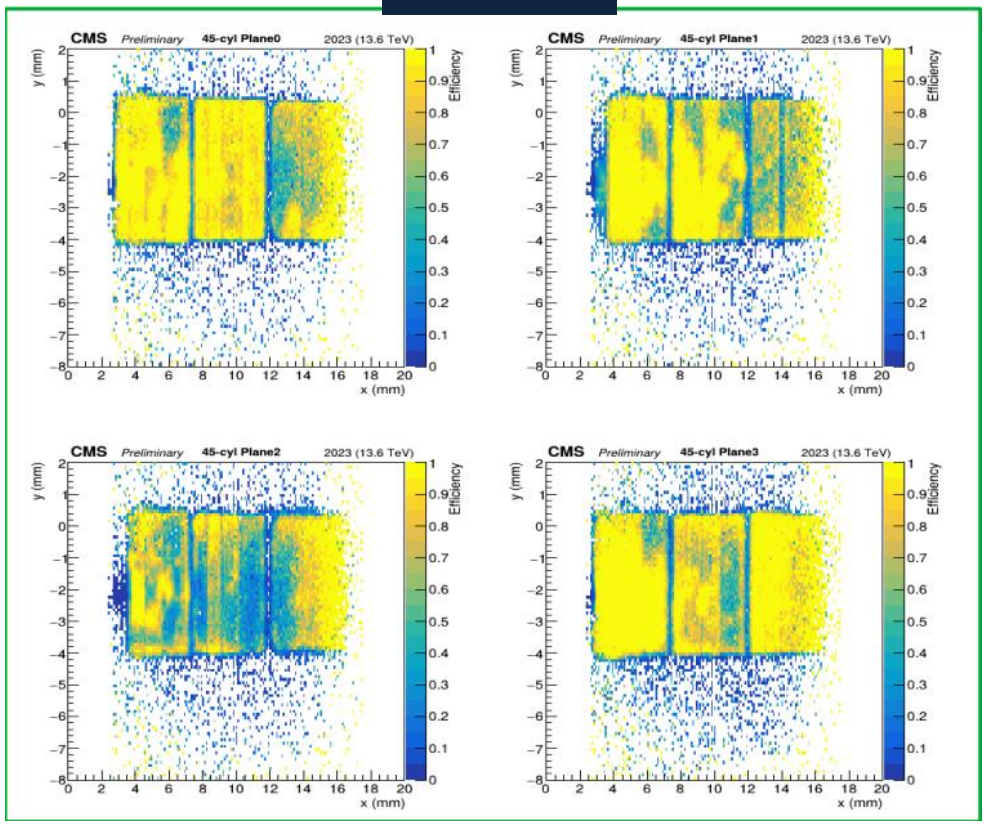
30/fb	30/fb
5.5e32	8e30
62	1
62	62

PPS | Timing efficiency in 2024

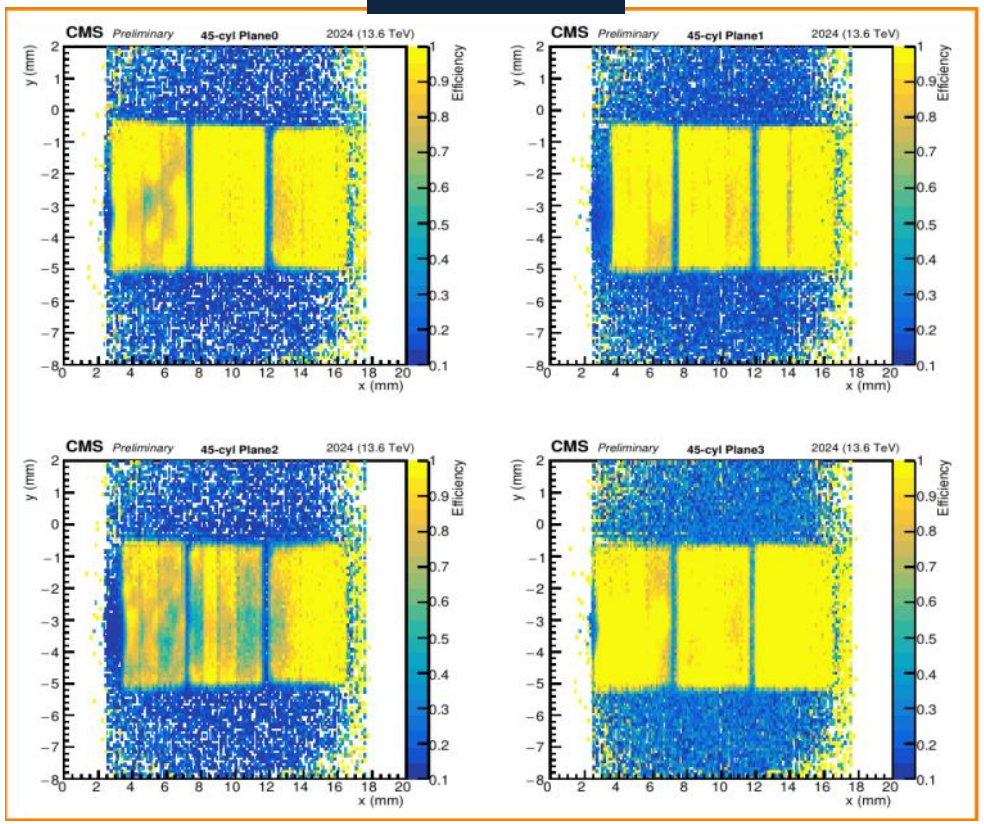
CMS DP-2024/118

- Efficiency with and w/o LEDs
- Despite in 2024 sensors have integrated more lumi, the eff. is better

2023 w/o LED



2024 with LED

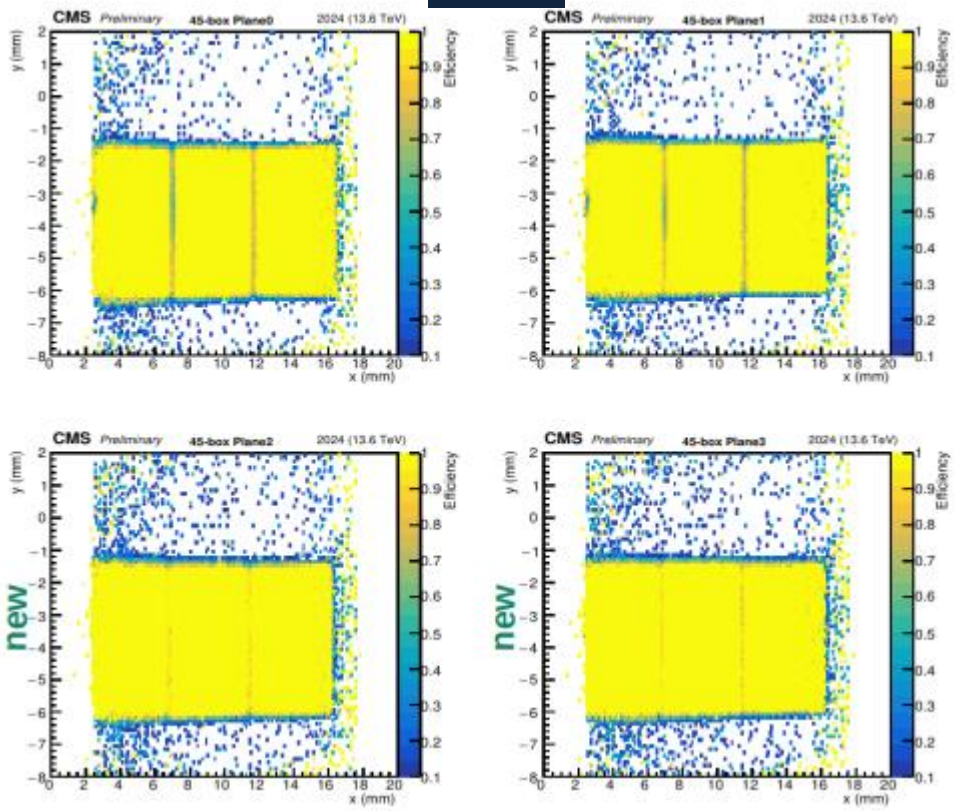


PPS | Timing efficiency in 2024

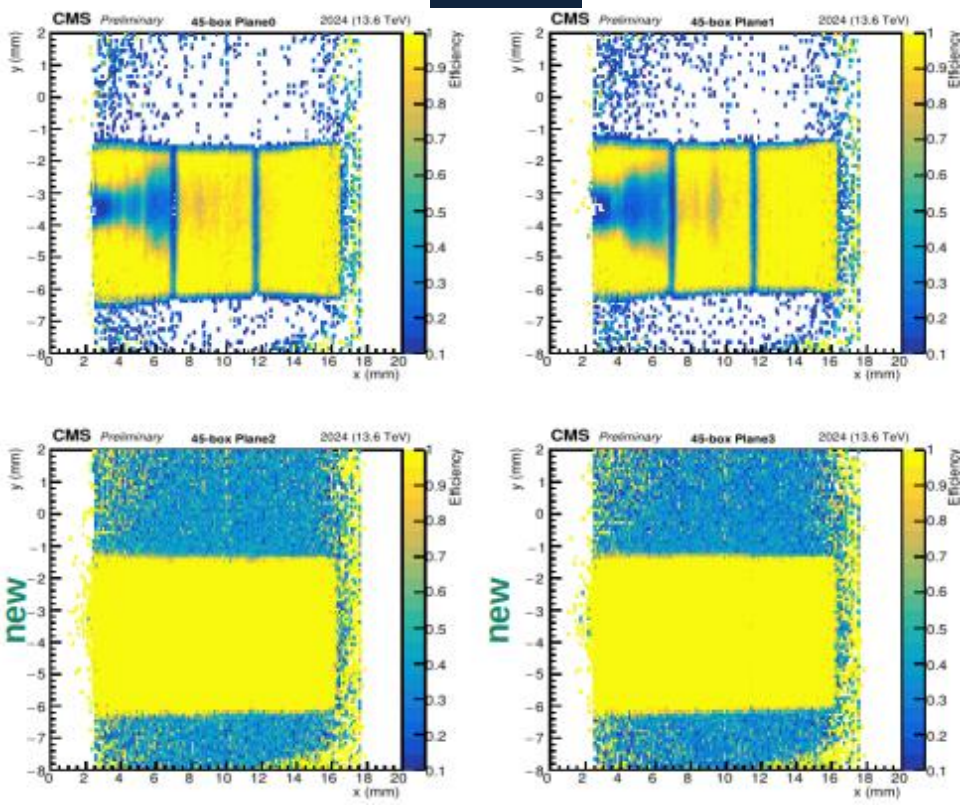
CMS DP-2024/118

- Efficiency at different irradiation rates (per plane)
- New planes are not sensitive changes in the rates

PU = 1



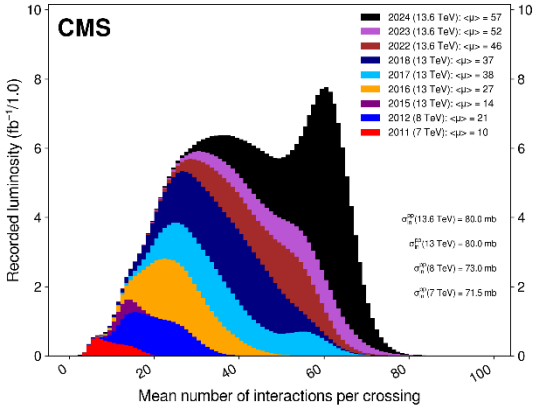
PU = 62

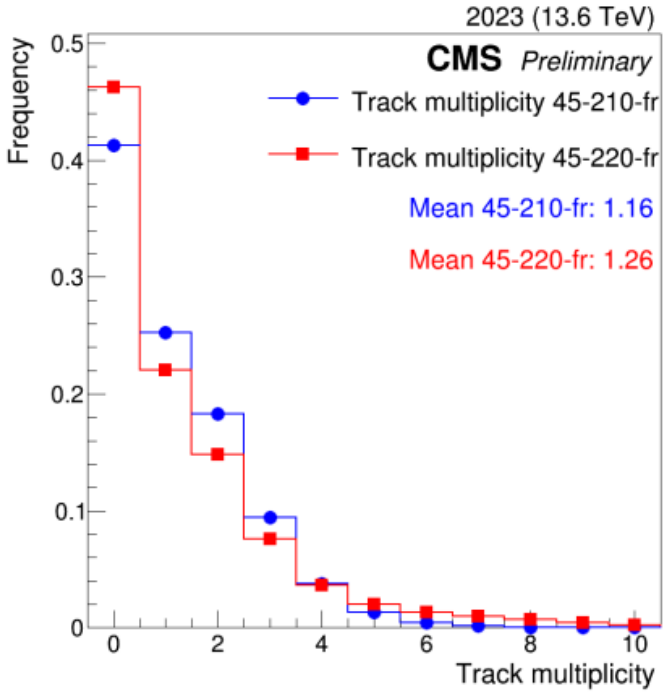


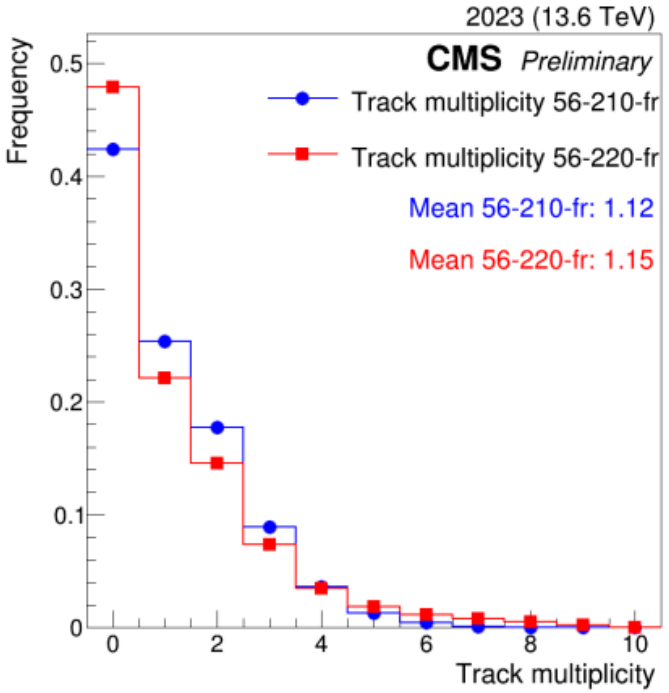
https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

Diffraction and Pileup

- Diffractive protons produced ~20% of non-elastic pp collisions (typically with very low momentum loss ξ<1.5%)
- In high PU environment the average number of PU protons > 1



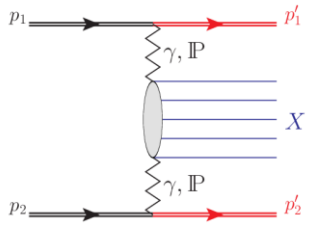




CMS-DP-2024-008

PPS | Physics results from Run 2

- CEP selection successfully reduces PU-related backgrounds
- Exclusive processes suggests a rich playground - analyses covers many physic groups (TOP/EXO/SMP/…)



PPS | Physics results from Run 2

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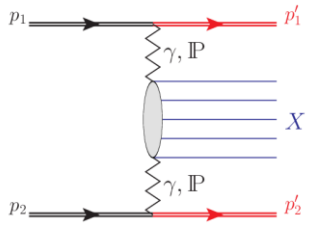
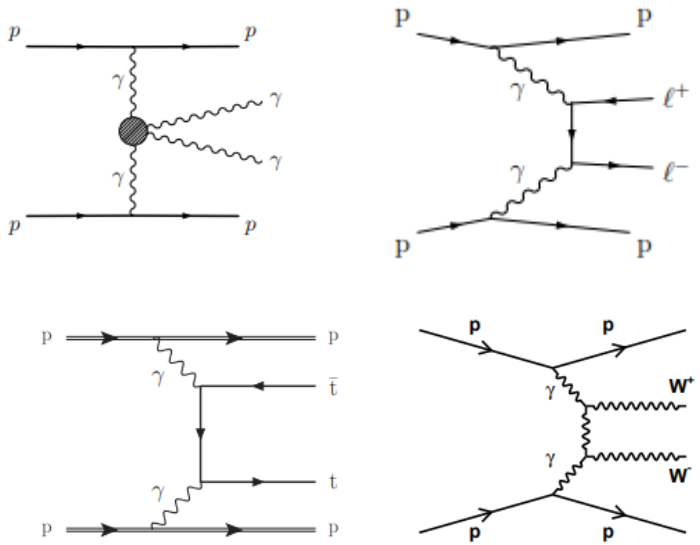
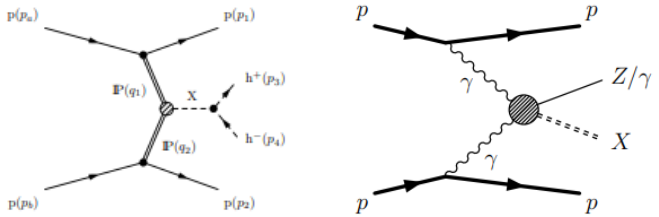


- **SMP**, $\gamma\gamma \to \ell\ell$, JHEP **07** (2018) 153
- **EXO**, $\gamma\gamma \to \gamma\gamma$, PRL **129** (2022) 1, 011801
- **PRO**, PPS Performance, JINST **18** (2023) 09, P09009
- **EXO**, $\gamma\gamma \to$ ALPs, PRD **110** (2024) 1, 012010
- **SMP**. $\gamma\gamma \to WW/ZZ$, JHEP **07** (2023) 229
- **TOP**, $\gamma\gamma \to \bar{t}t$, JHEP **06** (2024) 187
- **EXO**, $\gamma\gamma \to BSM$, EPJC **83** (2023) 827
- **SMP**, $IPIP \to \pi\pi$ (2018 high-β*) PRD **109** (2024) 11, 112013



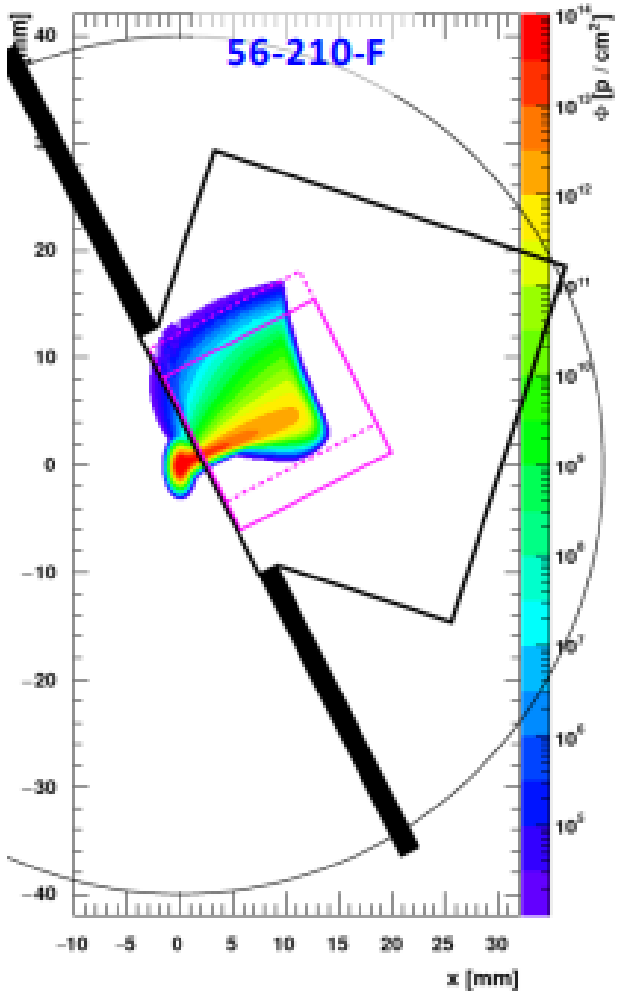


* Since 2024 vertical detectors are part of PPS

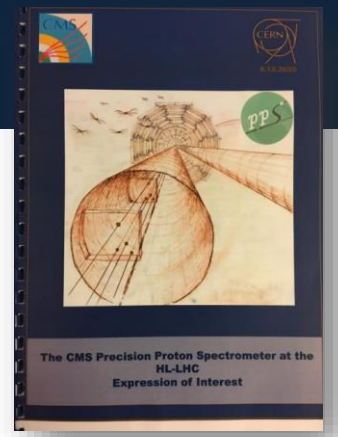
Expected changes in 2025-2026

Beam crossing angle in 2025

- The baseline for 2025 is to have a vertical crossing angle at IP5 (which will change the direction of the diffractive protons)
  - ➢ CMS – decided to rotate the RP
  - ➢ The final acceptances are still to be determined.
  - ➢ Combining all run 3 data should be straight forward



PPS2 @ HL-LHC



- Since after LS3 the whole beamline will be rearranged, a new spectrometer design is proposed in the Expression of Interest

Run 2+3 design: ξ acceptance translated to mass range between 350 GeV and 2 TeV

CMS-NOTE-2020-008, arxiv:2103.02752

- New proposal with extended mass range:

133 GeV – 2.7 TeV for the first 3 stations (0.0142 < ξ < 0.1967)

43 GeV – 2.7 TeV for 4 stations (0.00325 < ξ < 0.1967)

Staged installation

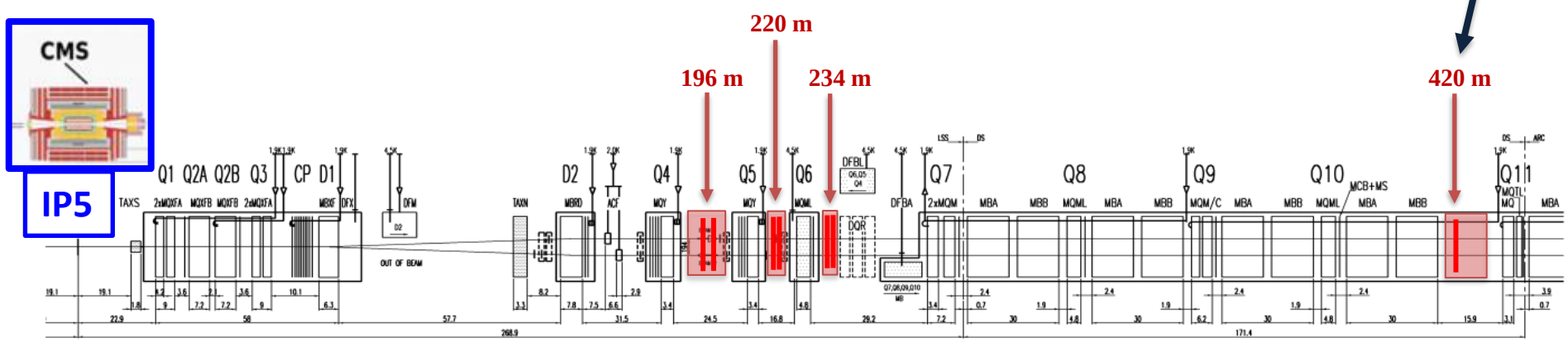


Figure 13: Layout of Long Straight Section LSS5 (Sector 5-6) at HL-LHC [63].

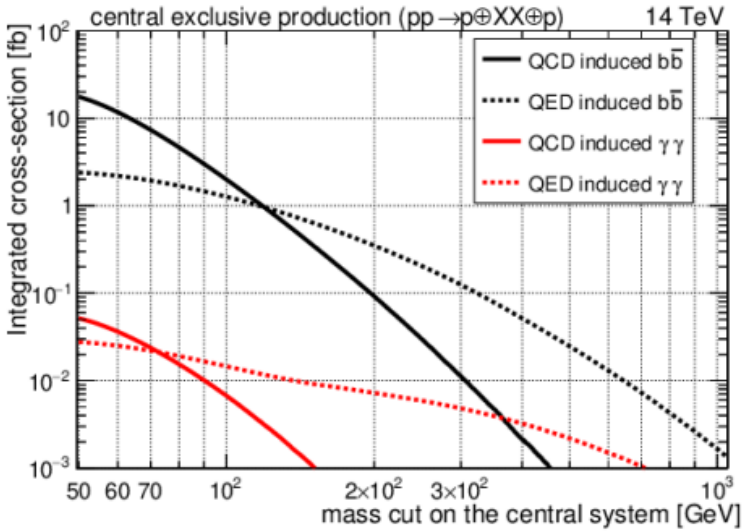
PPS2 @ HL-LHC

- SM CEP via **photon fusion** in pp collisions at $\sqrt{s} = 14$ TeV
- Computed fiducial cross sections for 2-tag and 1-tag categories:

Process	Fiducial cross section [fb] 2 tags	1 tag
jj	2	219
bb	0.04	6.3
W^+W^-	15	152
$\mu\mu$	1.3	172
tt	0.1	0.65
H	0	0.23
HW^+W^-	0.01	0.06
ZZ	0.03	0.23
$Z\gamma$	0.02	0.15
$\gamma\gamma$	0.003	0.19

First year of HL-LHC (~300 fb^{-1})

End of HL-LHC (~3000 fb^{-1})



$pp \to p\, b\bar{b}\, p$, $pp \to p\, \gamma\gamma\, p$,
QCD and QED contributions

[POS(LHCP2023)012]

Summary

- Proton Spectrometers are used to tag CEP events in Run 2 and Run 3
- Beside CEP, also diffractive measurements with PPS detectors are currently ongoing
- PPS2 (PPS@HL-LHC) will be contracted at 200m in LHC Run 4, while the 420m station is planned for Run5+
- Synergy with the Heavy Ion program is under investigation

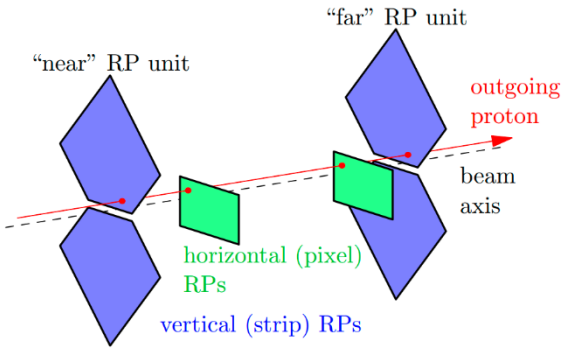
Thank you for your attention

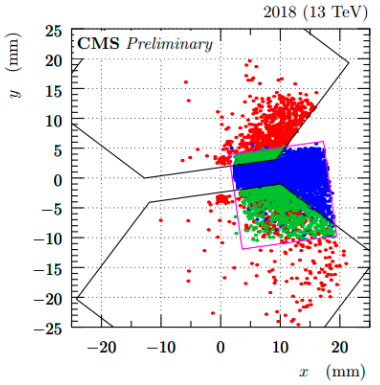
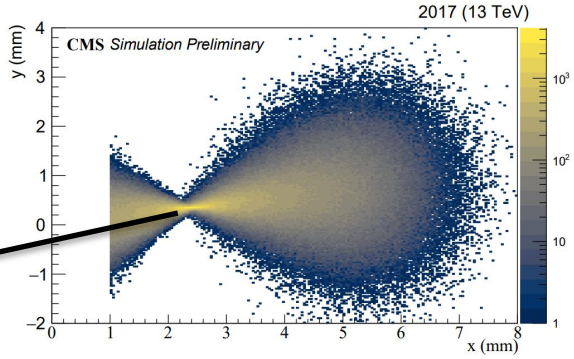
Backup

PPS | Calibration

JINST **18** (2023) 09, P09009

- Alignment (2 steps):
  - Calibration run alignment – performed in special runs (2-3 bunches / beam), vertical detectors are used to determine position of all PPS sensors w.r.t. the beam
  - Physics run alignment – match distribution of proton tracks from physics run to that of the alignment run (fill-by-fill, using horizontal station only)
- Optics:
  - Optical functions validated in data





$L_y(\xi_0) = 0$