Proton reconstruction with the CMS Precision Proton Spectrometer and outlook for a near-beam spectrometer at HL-LHC

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On behalf of the CMS collaboration

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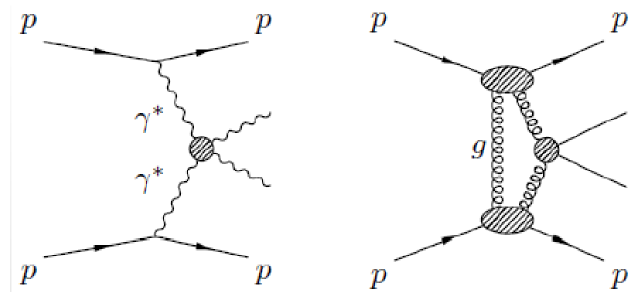
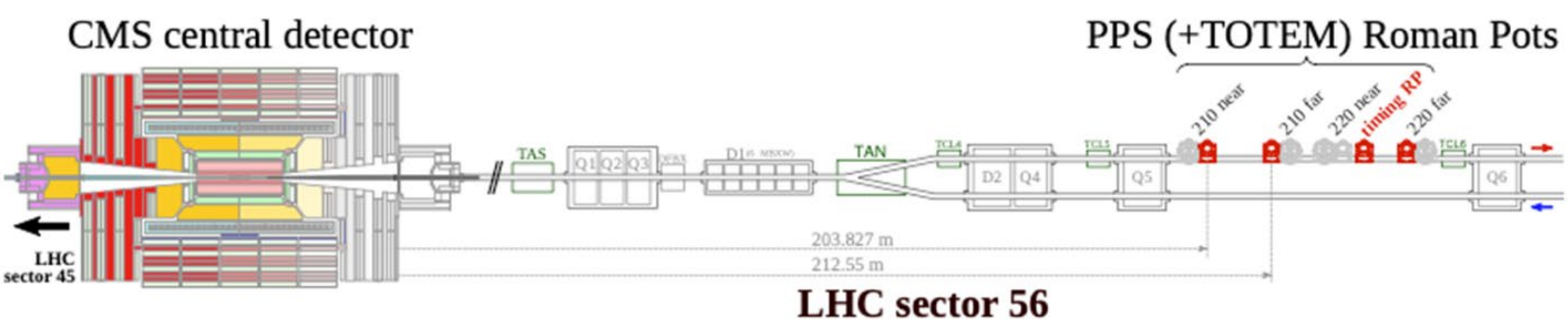
CMS Precision Proton Spectrometer

- ✓ Precise **kinematics measurement** of the scattered **protons** from IP5 (CMS) in a very forward region in **LHC high luminosity conditions**

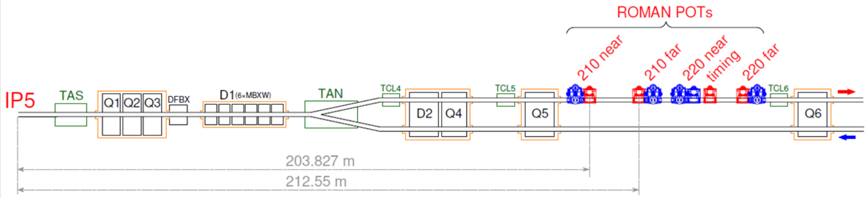
- ✓ Study of physics events where at least one proton survives the interaction

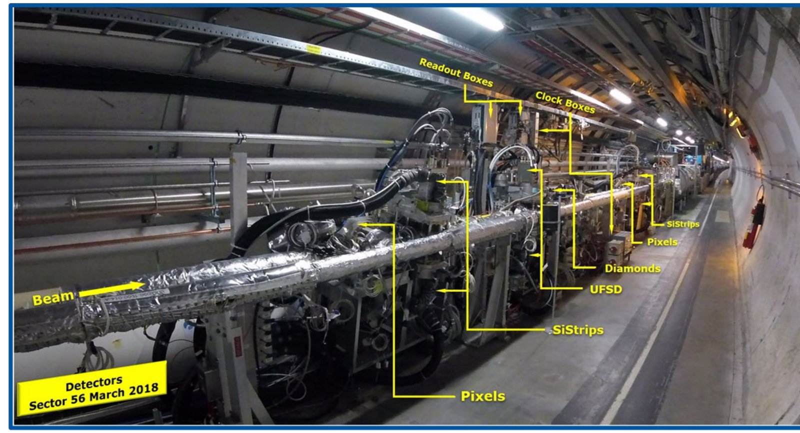


- ✓ Protons with small momentum loss are bent and propagate through the LHC magnetic fields. Near-beam detectors far from IP to maximize low-ξ ($\xi=\Delta p/p$) acceptance (detectors at ~1.5 mm from the beam, without disturbing LHC operations)



PPS experimental setup in Run2

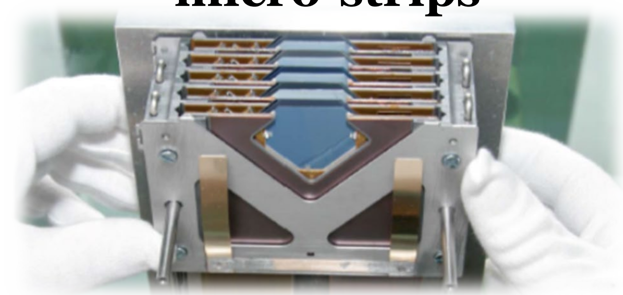




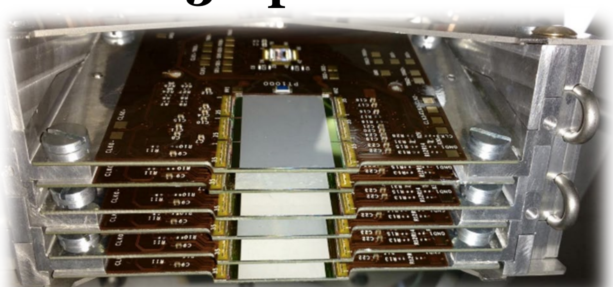
PPS detectors in horizontal pots
TOTEM strip trackers in vertical ones
(used also for PPS alignment)

Tracking detectors: measure (ξ, t)

micro-strips

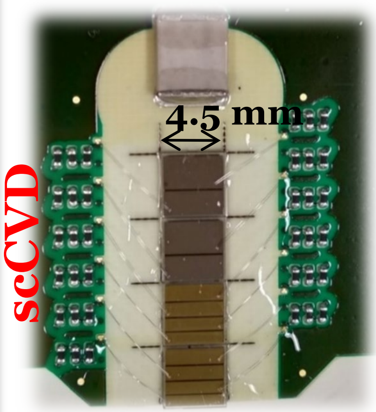


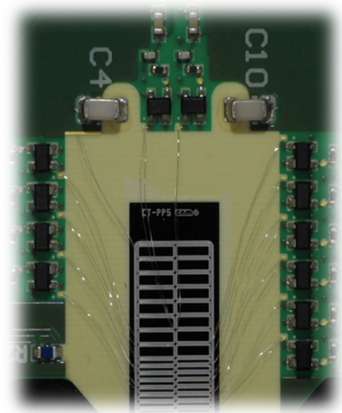
3D pixels



Timing detectors: pile-up rejection

scCVD



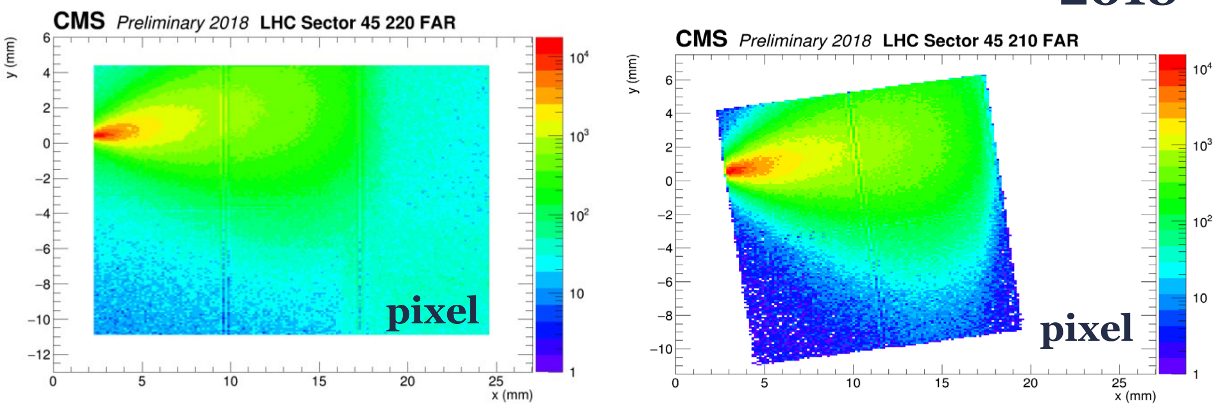


Ultra-Fast (LGAD)

Proton reconstruction at a glance

Hits in tracker in sector 45

2018



- Hit reconstruction

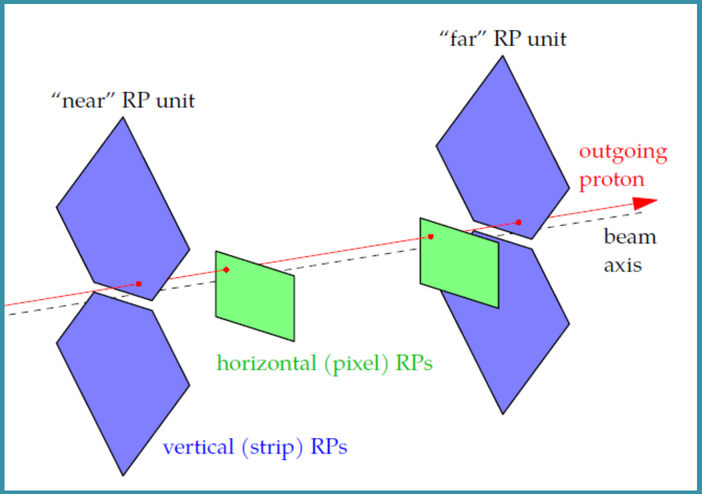
  ⬇ ← Local alignment (among detectors)

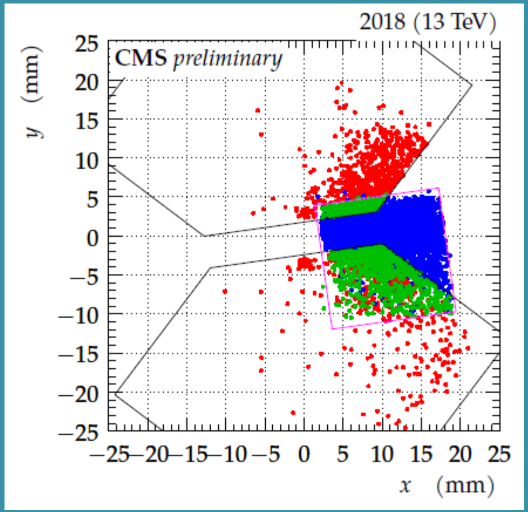
- Track reconstruction

  ⬇ ← Global alignment (with beam)
Optics knowledge

- Proton kinematics ($\xi = \Delta p/p$)

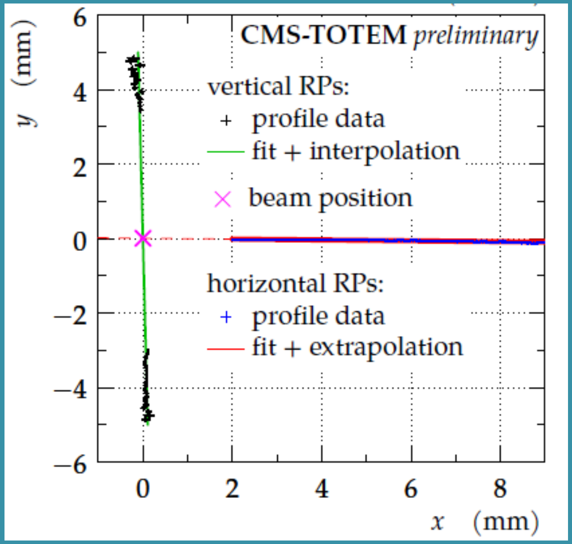
Alignment in special runs





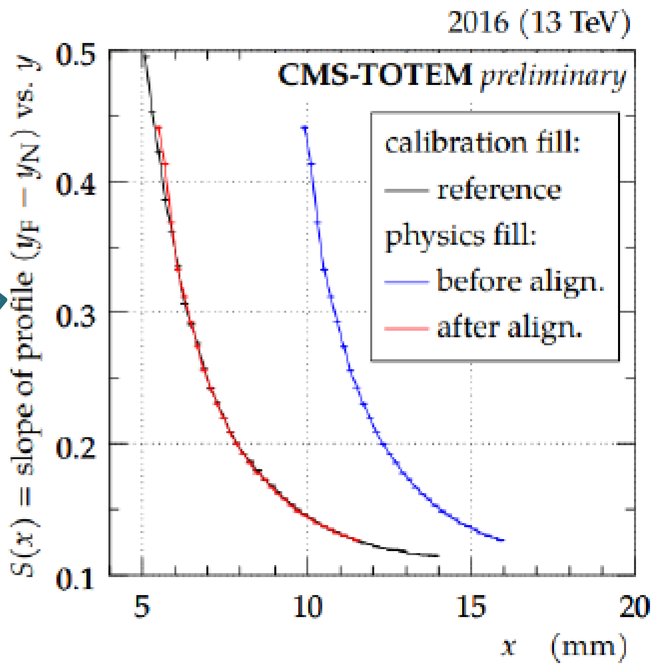
Local Alignment

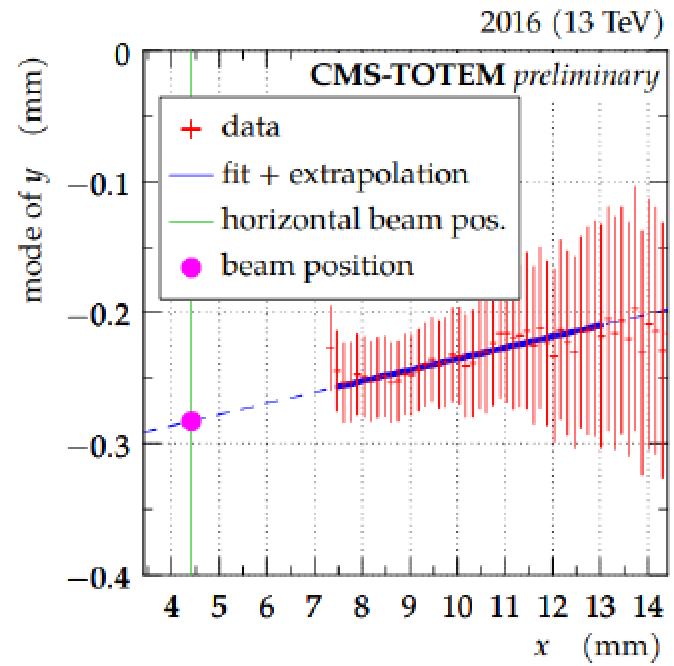
- Both TOTEM vertical and PPS horizontal RPs inserted
- Low luminosity → RPs inserted very close to beam → detector overlap
- TOTEM vertical RPs: elastic events → "absolute" alignment w.r.t. LHC beam
- Overlap area for relative alignment of horizontal RPs to verticals
- Method: minimise common track hit residuals in overlap area
- Beam position using extrapolation of vertical and horizontal track profiles



Alignment wrt beam

Alignment in physics fills





- Alignment of high luminosity fills to special alignment fills
- Horizontal alignment: uses specific common RP observables (patterns) in physics and alignment fills
- Alignment and physics fills: same optics required
- Relies on reproducibility of LHC optics
- Vertical alignment: extrapolation and correction at beam position

LHC optics: proton transport from IP to PPS

$$\vec{d}(s) = T(s,\xi)\cdot\vec{d}^*$$

Transport matrix

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

Proton transverse position

Proton Δp/p

Proton angle

$$T = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ \frac{dv_x}{ds} & \frac{dL_x}{ds} & m_{23} & m_{24} & \frac{dD_x}{ds} \\ m_{31} & m_{32} & v_y & L_y & D_y \\ m_{41} & m_{42} & \frac{dv_y}{ds} & \frac{dL_y}{ds} & \frac{dD_y}{ds} \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

- The reconstruction of the proton kinematics requires the inversion of the transport matrix
- The transport matrix is built with the knowledge of the actual LHC optics

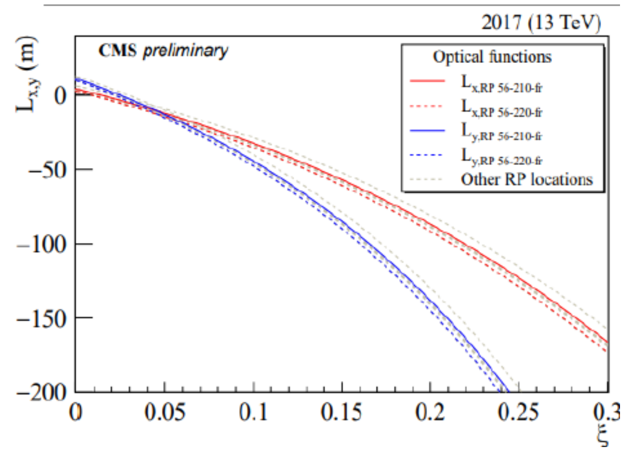
A simplified version of the inversion equations (using most relevant terms)

$$x = v_x(\xi)\cdot x^* + L_x(\xi)\cdot\theta_x^* + D_x(\xi)\cdot\xi$$
$$y = v_y(\xi)\cdot y^* + L_y(\xi)\cdot\theta_y^* + D_y(\xi)\cdot\xi$$

Dispersions

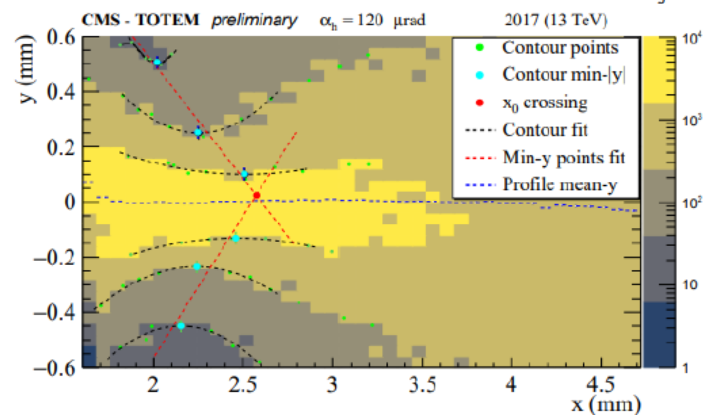
Data driven optics calibration

Effective lengths L_x, L_y calibrated using constraints from data and calculated at each detector station. L_y calibrated with elastic events (ξ=0) in alignment fills.



MAD-X model predicts ξ_0 where $L_y = 0$
Corresponding focal point x_0 measured in RPs

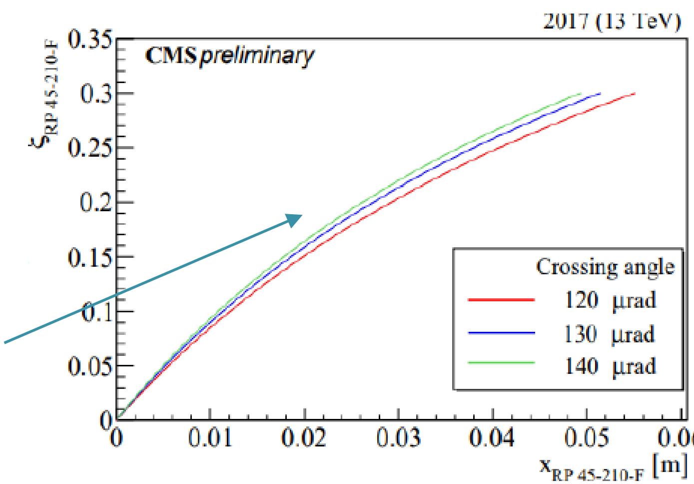
$D_x = x_0 / \xi_0$



Interpolation among different crossing angles used by LHC

$$\xi(\alpha, x) = \xi_{120}(x) + \frac{120-\alpha}{120-140}\cdot(\xi_{140}(x) - \xi_{120}(x))$$

x-to-ξ curves



Proton kinematics reconstruction

Single-RP method

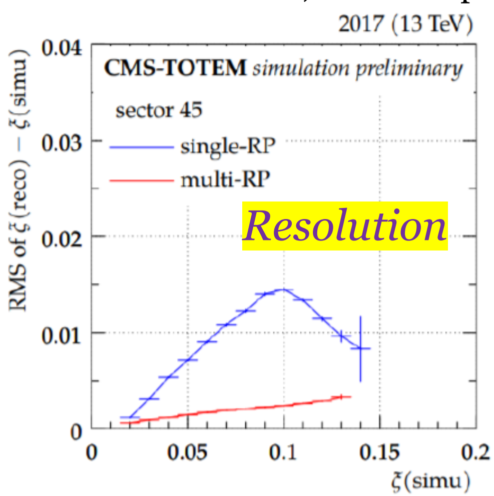
$$x = v_x(\xi) \cdot x^* + L_x(\xi) \cdot \theta_x^* + D_x(\xi) \cdot \xi$$
$$y = v_y(\xi) \cdot y^* + L_y(\xi) \cdot \theta_y^* + D_y(\xi) \cdot \xi$$

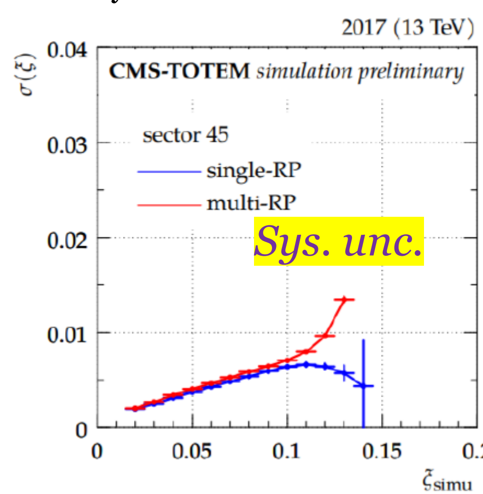
- $\xi \approx x/D_x$
- Utilize the information from a single pot
- Non linearities with x-to-ξ curves
- Smearing from proton scattering angles → limited resolution $\sigma(\xi)$
- Robust and "simple" systematic uncertainty model

Multi-RP method

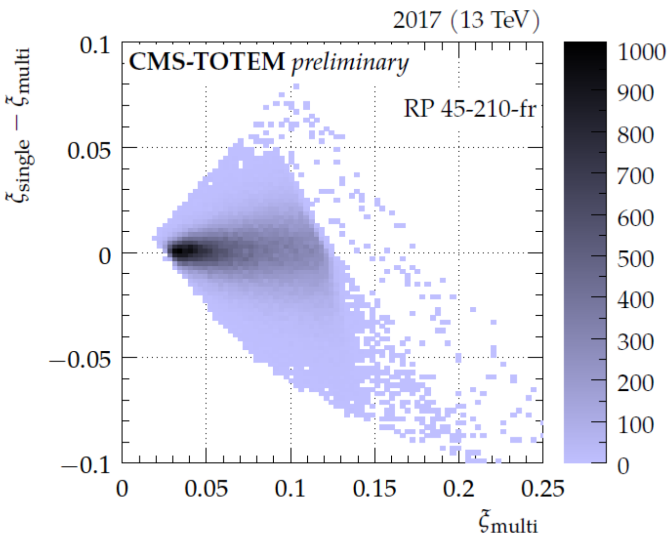
Minimization of $$\chi^2 = \sum_{q=x_N, y_N, x_F, y_F} \left(\frac{q - O_q(x^*, \theta_x^*, y^*, \theta_y^*, \xi)}{\sigma(q)} \right)^2$$

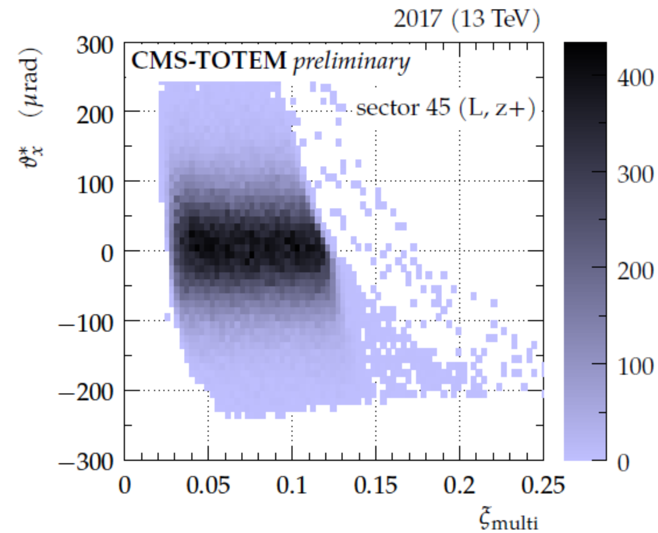
- O_q is the optics prediction for the coordinate, given the proton kinematics
- Combine measurements of 2 RPs to disentangle ξ and θ_x
- Non linearities considered in functions O_q : $L_{x,y}(\xi)$ and $v_{x,y}(\xi)$
- Significantly improves resolution $\sigma(\xi)$
- Assumes careful calibration, more complex systematic uncertainty model

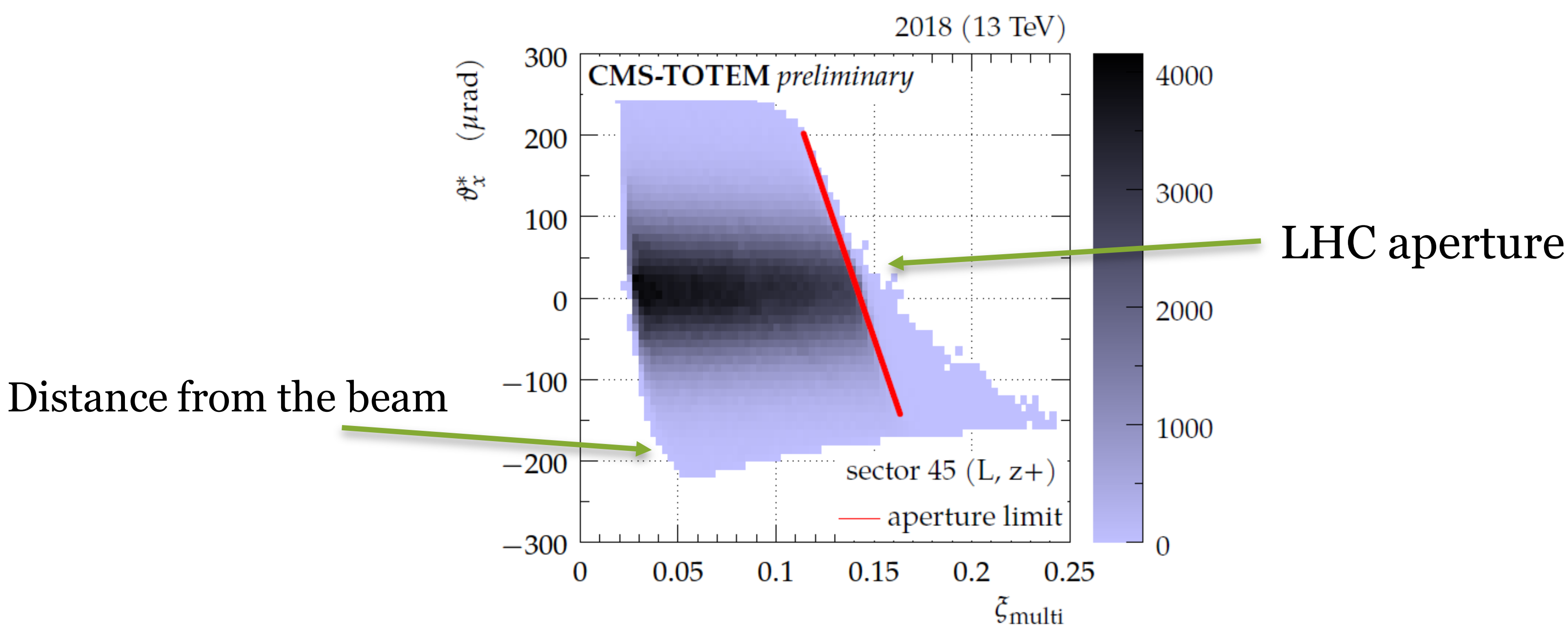




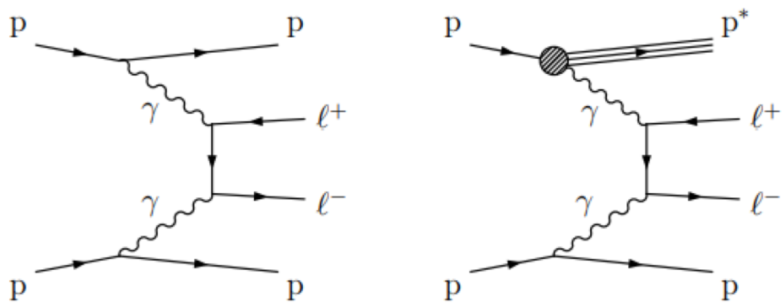
Control plots and acceptance

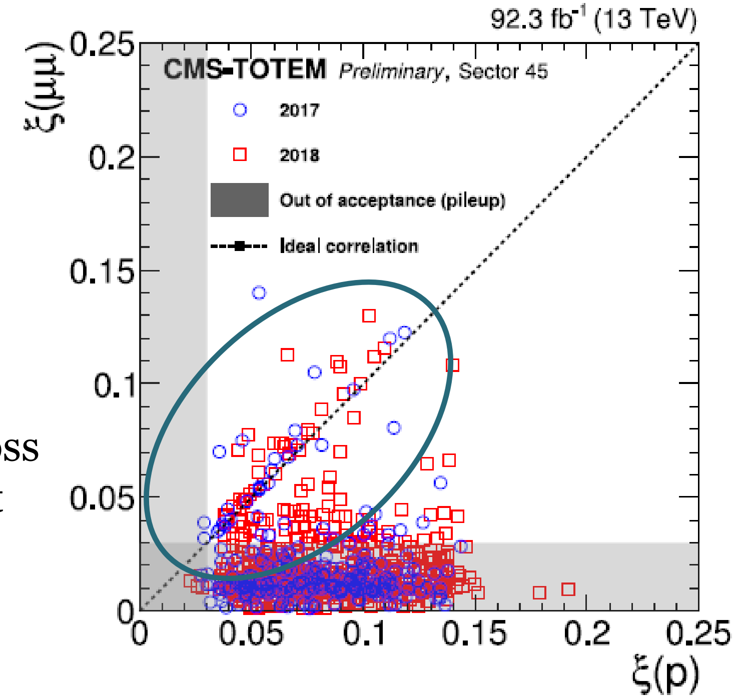




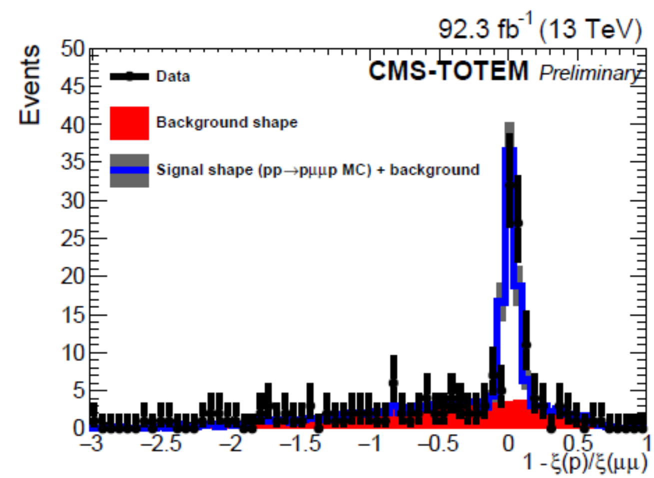


Validation with di-muon control sample





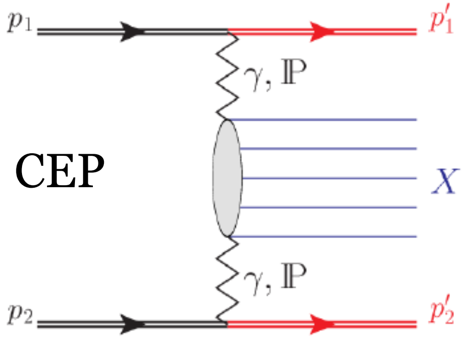
Correlations between fractional momentum loss reconstructed from di-muon pair ξ(μμ) vs that measured with proton(s) ξ(p) in data.
Signal on the diagonal as expected.



Correlation peak width consistent between data and simulation: **well described resolution**.
Peak position at 0 as expected.

PPS in Run3 and HL-LHC

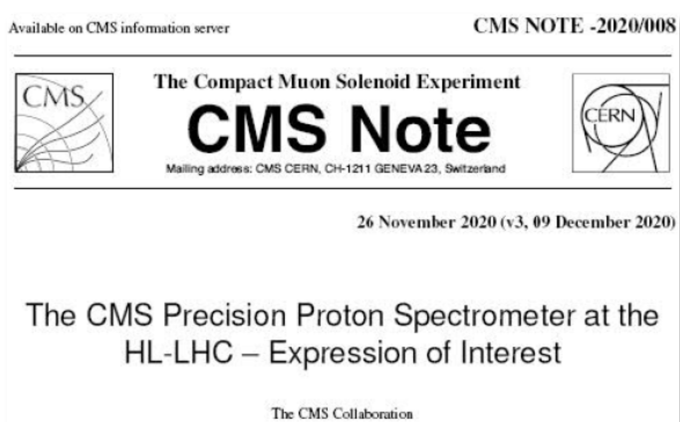
Central Exclusive Production



PPS will take data in **Run3** with an upgraded setup

- 2 tracking pots per side with movable pixel detectors
- 2 timing pots per side with diamond detectors
- Detector installation scheduled for October 2021
- Physics goal: improve statistics of CEP in the same mass range of Run2 350 GeV < M_X < 2 TeV

CMS has presented an **Expression of Interest for a PPS at HL-LHC.** Well recieved by LHC-Committee.
TDR(s) phase starting, more collaborators are welcome.



Available on CMS information server CMS NOTE -2020/008

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 November 2020 (v3, 09 December 2020)

The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest

The CMS Collaboration

https://cds.cern.ch/record/2750358

A major upgrade needed:

- New tracking and timing detectors
  - High radiation levels and μ~200
- New insertion positions in LHC (at ~200m and ~400m)

Physics goals:

- dramatically improve statistics of CEP
- extend the mass range to
  - 130 GeV < M_X < 2.7 TeV
  - 40 GeV < M_X < 2.7 TeV

Depending on setup

PPS@HL-LHC: physics motivations, SM

Cross sections in two main scenarios

Process	fiducial cross section [fb] all stations $\mathbb{P}-\mathbb{P}$	all stations $\gamma-\gamma$	w/o 420 $\mathbb{P}-\mathbb{P}$	w/o 420 $\gamma-\gamma$
jj	$\mathcal{O}(10^6)$	60	$\mathcal{O}(10^4)$	2
W^+W^-	—	37	—	15
$\mu\mu$	—	46	—	1.3
$t\bar{t}$	—	0.15	—	0.1
H	0.6	0.07	0	0
$\gamma\gamma$	—	0.02	—	0.003

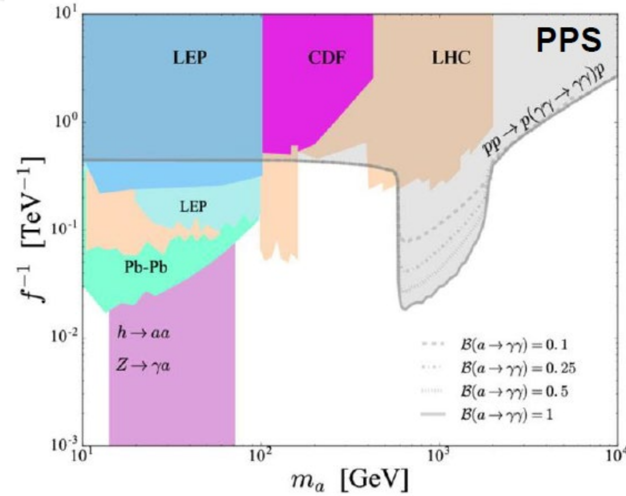
QCD
- Systematic study of screening effects in central exclusive di-jet production
- Exclusive $b\bar{b}$ production: dominant background for exclusive Higgs

Electroweak
- Complete the study of pllp and pVVp exclusive production with a sizable number of events with 2 protons in acceptance

Top
- Di-top mass resolution of ~few GeV, probe near threshold production of exclusive ttbar

Higgs
- Cross section estimates vary by an order of magnitude due to the lack of knowledge of screening effects
- Measurement of the central exclusive production of the Higgs boson is possible only with all stations (no acceptance w/o 420 m)

PPS@HL-LHC: physics motivations. BSM



Axion like particles

- High mass reach
- CEP via γ fusion (γγ collider)

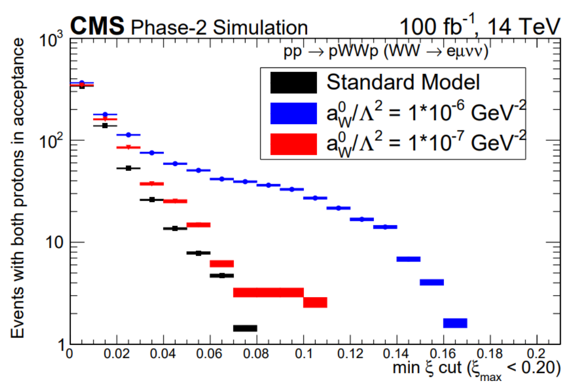
SUSY searches

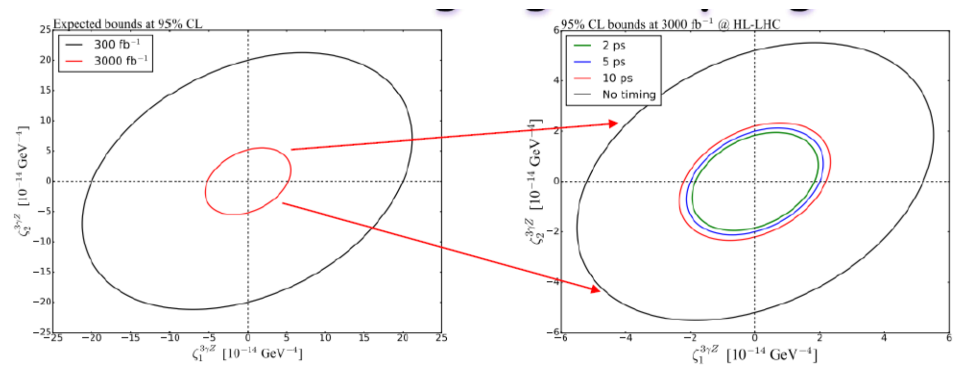
- High mass reach
- Di-slepton production in CEP: direct measurement of di-slepton mass

$$pp \to \tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$$

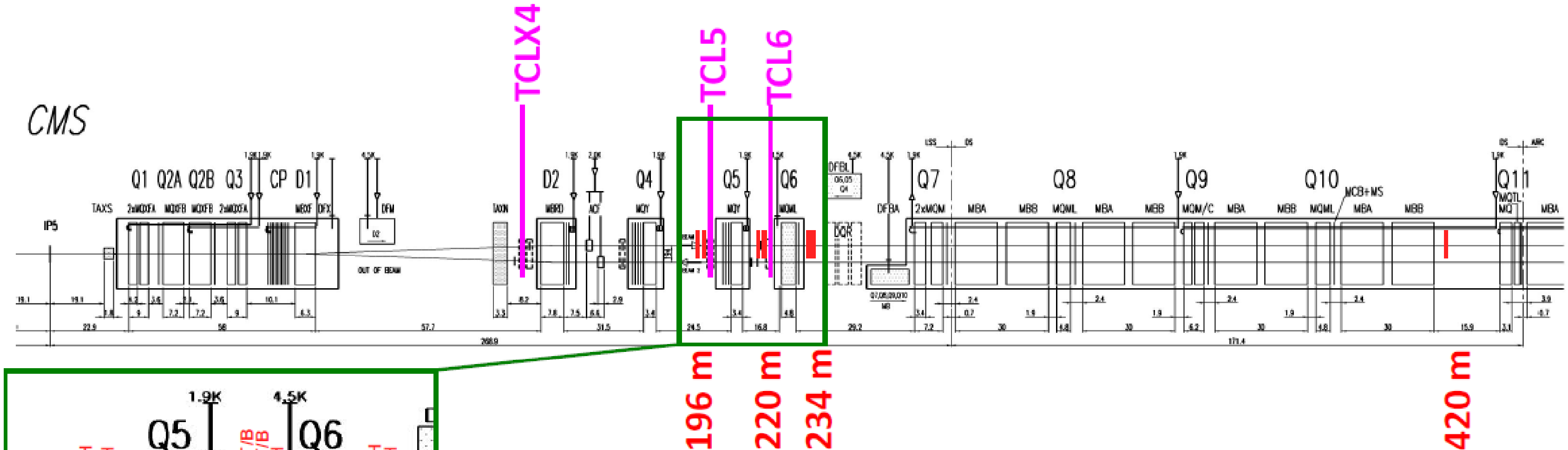
Anomalous gauge couplings

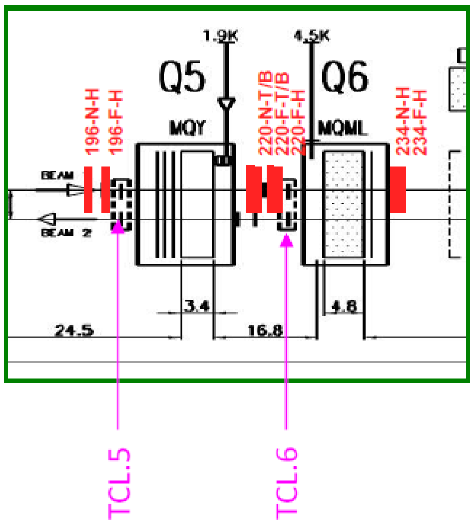
- Exclusive WW production sets stringent upper limit on the anomalous quartic gauge coupling operators
- γγγ Z coupling can be probed in γγ → Z γ channel search.





PPS@HL-LHC: proposed layout





suitable for Roman Pot technology,

in each location 2 units

with a few metres lever arm

(→ track angles)

- needs cryogenic bypass
- signal protons between beam pipes
  → limited space

→ new developments needed

→ second stage

Next step: TDR(s):

First priority: detector vessel (warm stations), machine integration, services

Staged approach: 420 m station in a second step

Detector technologies to be chosen.
Possibly use synergy with existing CMS subdetectors

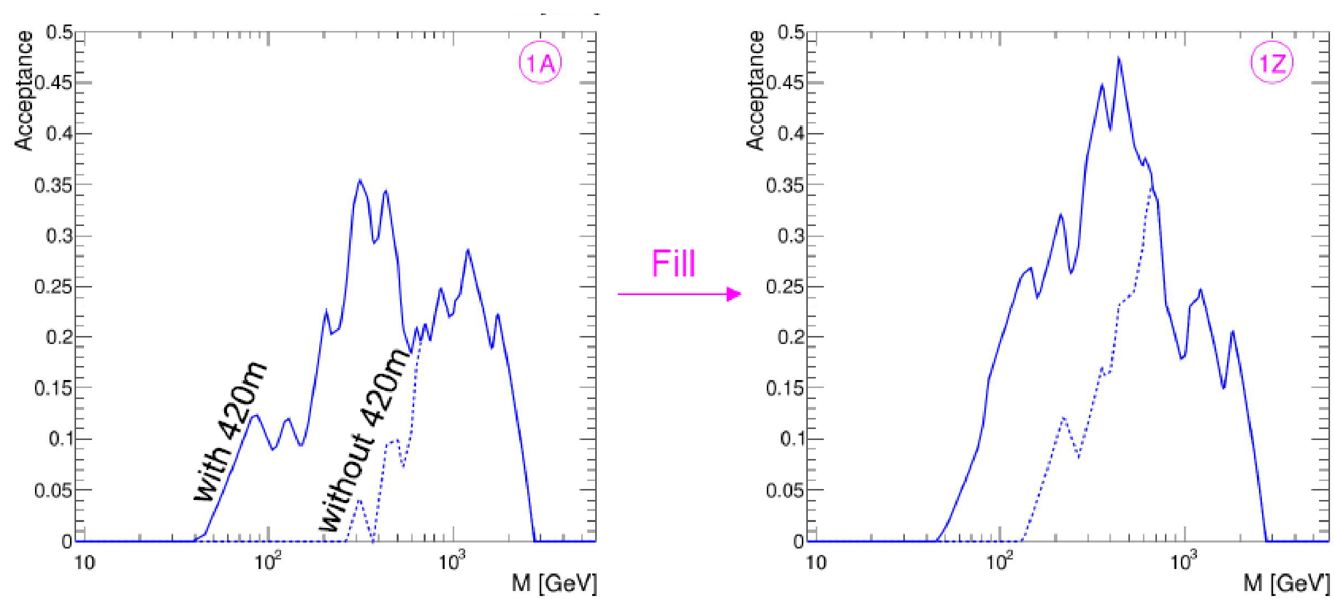
PPS@HL-LHC: mass acceptance

Mass acceptance depending on LHC optics and detector locations

Vertical Crossing-Angle				
Station	$\|\xi_{\min}\|$	$\|\xi_{\max}\|$	$M_{\min}$ [GeV] @ y = 0	$M_{\max}$ [GeV] @ y = 0
196 m	0.0786–0.0856	0.1967	1100.87–1197.80	2754.27
220 m	0.0371–0.0381	0.0688	519.89–533.18	962.70
234 m	0.0189–0.0095	0.0263	264.96–132.80	368.11
420 m	0.0031–0.0034	0.0116	43.38–47.04	162.66

$$\ln\frac{M}{\sqrt{s}} = \frac{1}{2}(\ln\xi_1 + \ln\xi_2)$$

$$y = \frac{1}{2}(\ln\xi_1 - \ln\xi_2)$$



Summary

- The proton reconstruction performed by the Precision Proton Spectrometer detector in CMS has been described in detail
- PPS has successfully taken data during LHC Run2 and will take data in Run3
- The perspective for a PPS also in the High Luminosity phase of LHC has been discussed

See also K.Shchelina's talk on PPS physics performance.

References

- Proton reconstruction with the Precision Proton Spectrometer in Run 2. - CMS DP 2020-047
- CMS and TOTEM Collaborations, "CMS TOTEM Precision ProtonSpectrometer ," CERN LHCC 2014 021
- The CMS Precision Proton Spectrometer at the HL-LHC -- Expression of Interest, CERN-CMS-NOTE-2020-008