CMS-PPS at HL-LHC

A Precision Proton Spectrometer for High-Luminosity LHC

DIS2026

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On behalf of CMS collaboration

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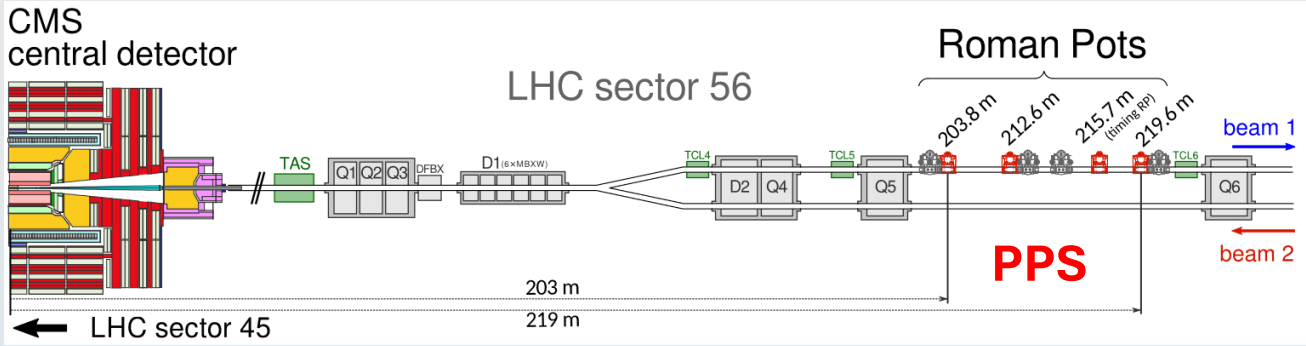
Current setup

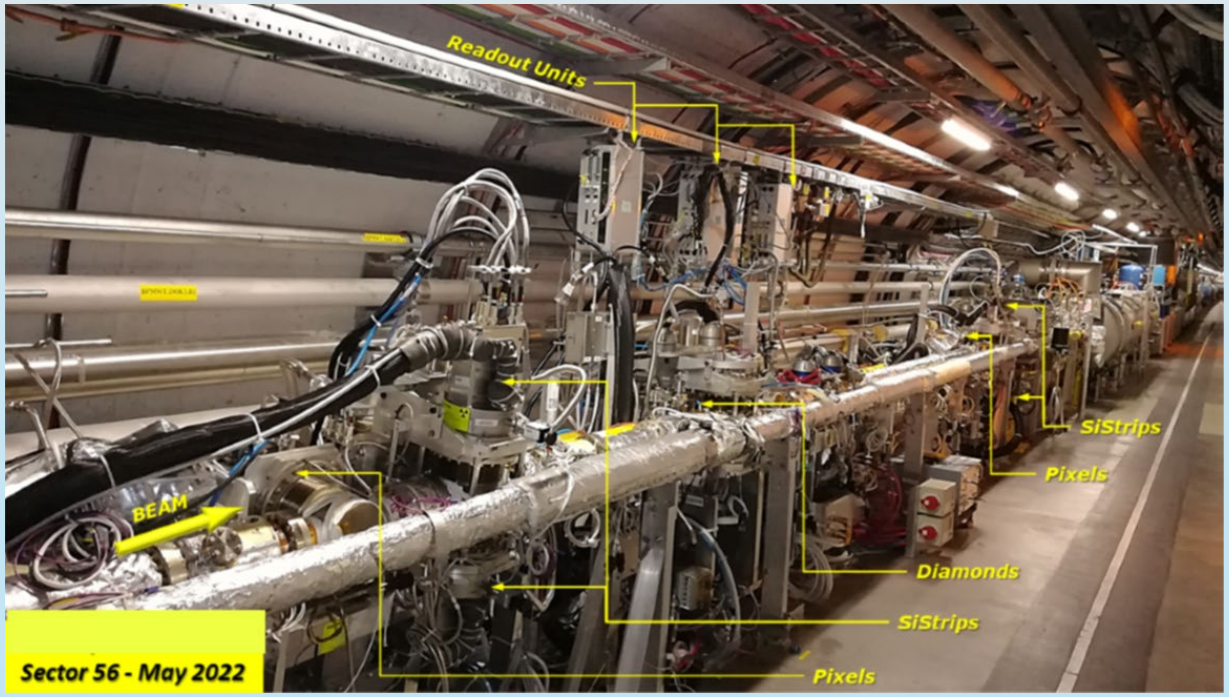
- 4 horizontal Roman Pots per side of CMS
  - 2 for tracking: 3D pixels
  - 2 for timing: scCVD double diamonds
- 4 vertical RP: for alignment only
  - TOTEM Si-strips



Tracking detectors measure the fractional momentum loss ξ of the scattered protons

Timing detectors measure the TOF of the scattered protons to reduce pile-up effects

PPS took data in LHC Run 2 and is taking data in Run 3



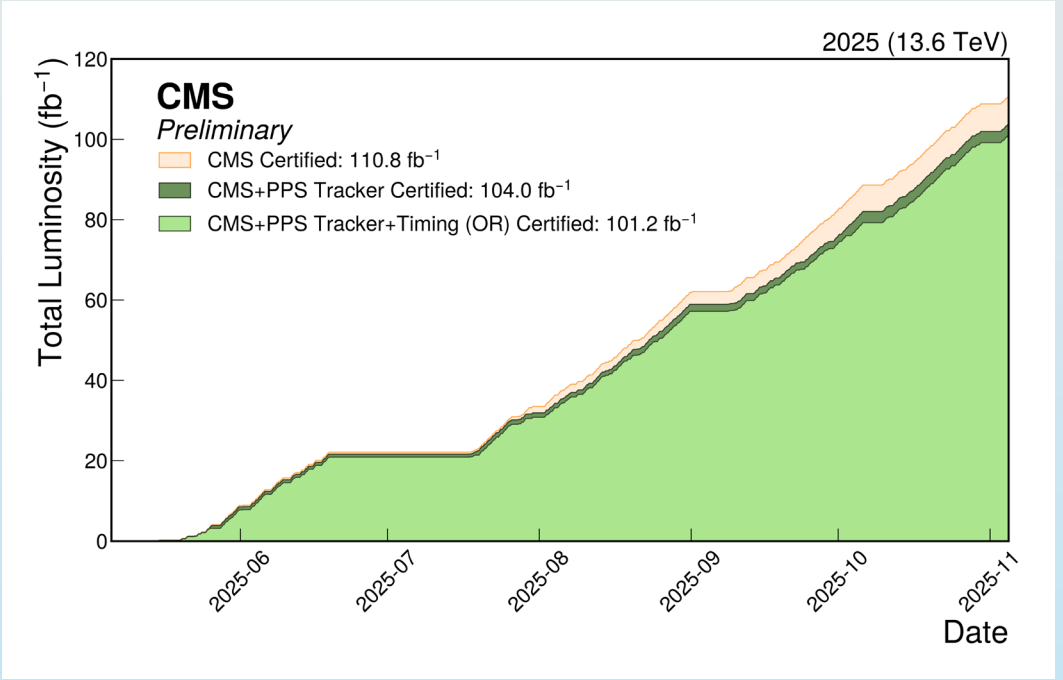
Current status

- PPS has been taking data in all runs since 2016 (typically >95% of central CMS luminosity recorded by PPS too)
- Successful pot rotation in 2025 (to cope with change of crossing angle)
- Very good data taking also last year
- Now taking data (last LHC data before HL-LHC)

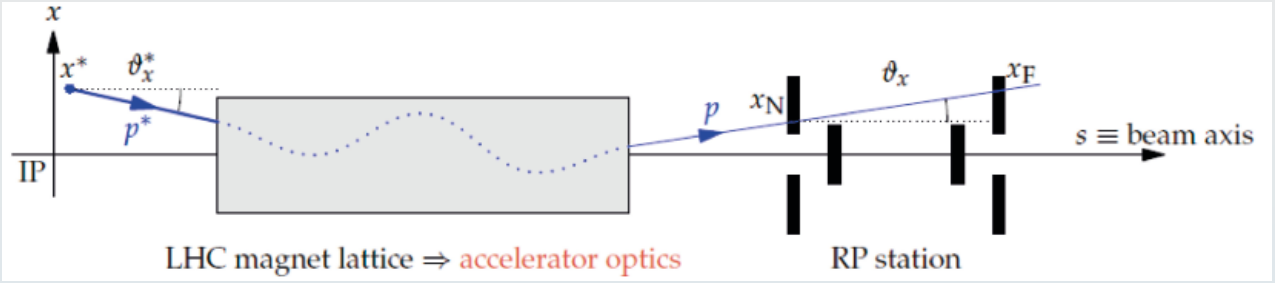
2025 data taking

93.9% of CMS certified luminosity with **pixels good for physics**

91.3% of CMS certified luminosity with **pixels and timing good for physics**



Proton kinematics and optics



- (x*, y*): vertex position
- (θ_x^*, θ_y^*): scattering angle: $t \approx -p^2(\theta_x^{*2} + \theta_y^{*2})$
- **$\xi = \Delta p/p$: momentum loss**

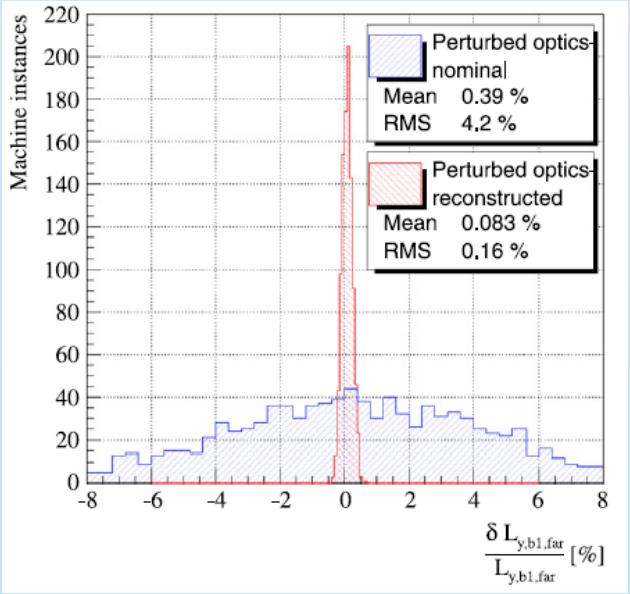
Measured in RP

$$\begin{pmatrix} x \\ \Theta_x \\ y \\ \Theta_y \\ \Delta p/p \end{pmatrix}_{RP} = \underbrace{\begin{pmatrix} v_x & L_x & 0 & 0 & D_x \\ v'_x & L'_x & 0 & 0 & D'_x \\ 0 & 0 & v_y & L_y & 0 \\ 0 & 0 & v'_y & L'_y & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}}_{\text{Product of all lattice element matrices}} \begin{pmatrix} x^* \\ \Theta_x^* \\ y^* \\ \Theta_y^* \\ \Delta p/p \end{pmatrix}_{IP5}$$

Values at IP5 to be reconstructed

$$x_{RP} = L_x \Theta_x^* + v_x x^* + D_x \xi$$
$$y_{RP} = L_y \Theta_y^* + v_y y^*$$

- L_x, L_y: effective length (sensitivity to scattering angle)
- v_x, v_y: magnification (sensitivity to the vertex position)
- **D_x : dispersion (sensitivity to momentum loss)**; $D_y \sim 0$



Reconstruction of the proton kinematics inverting the transport equations

Need precise knowledge of the optics

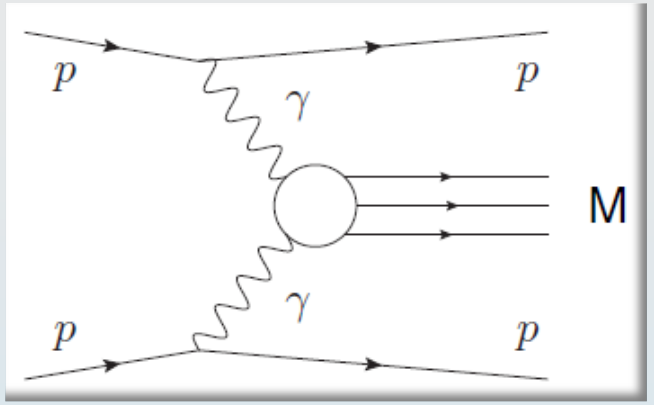
Physics motivation of PPS

PPS mainly studies Central Exclusive Production

- Double colorless exchange via QED or QCD
- Proton(s) remain intact

With proton tagging PPS provides

- Full reconstruction of the final state
- Strong background rejection



Central Exclusive Production

- LHC as a γ-γ collider
- Requiring the momentum balance between the central system and the detected protons creates strong kinematical constraints
- Central system mass is measured by the momentum loss of the two protons
  - makes it possible to study difficult to reconstruct final states
- Gauge boson production by γ-γ fusion and anomalous γγWW, γγZZ and γγγγ couplings
- Search for new BSM resonances

$$\xi_{1,2} = 1 - \frac{|p'_{1,2}|}{|p_{1,2}|}$$

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

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

Physics results from Run 2

γγ→ee and/or γγ→μμ: First single-arm observation at EWK scale with 2016 data [JHEP 07 (2018)] and 2017-2018 data [JINST 18 (2023) 09, P09009]

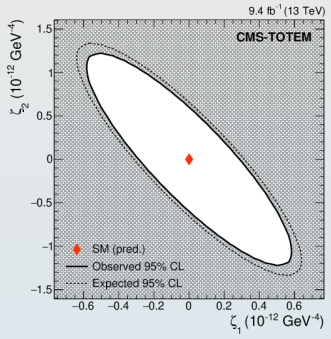
γγ→γγ: First/best collider limits on anomalous γγγγ couplings: [Phys.Rev.Lett. 129 (2022)], and limits on Axion-like particles with full Run 2 data [PAS, PRD 110 (2022)]

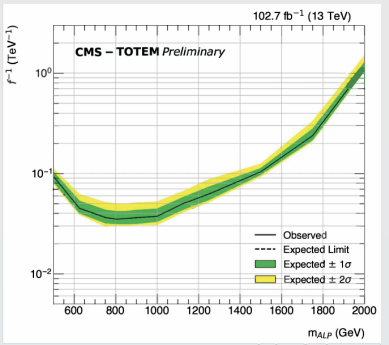
First use of missing-mass search technique at a hadron collider, in Z+X and γ+X: [Eur. Phys. J. C 83, 827 (2023)]

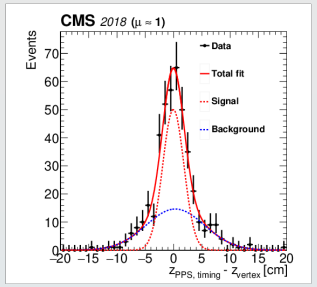
First cross section limits on exclusive t-tbar: [PAS, JHEP 187 (2024)]

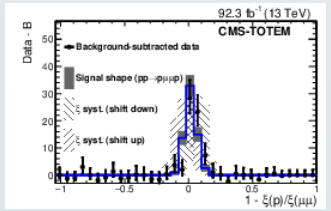
γγ→WW and γγ→ZZ: New limits on anomalous γγZZ and γγWW couplings with full Run 2 [JHEP 07 (2023) 229]

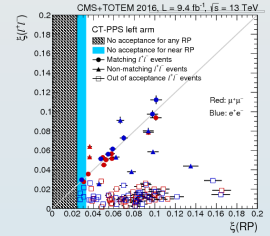
+other ongoing analyses

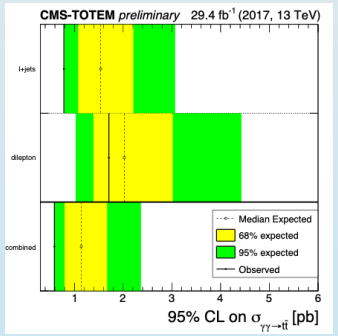


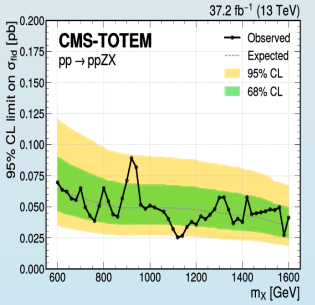


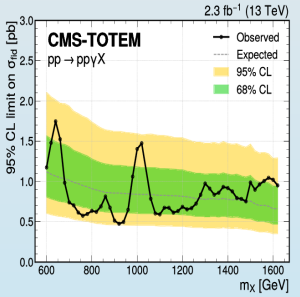


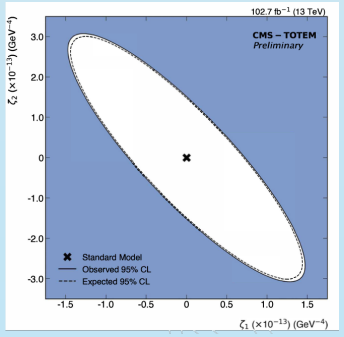


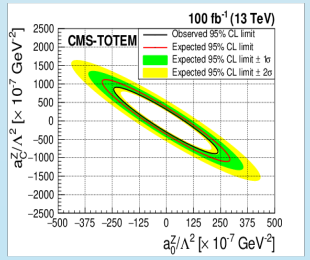


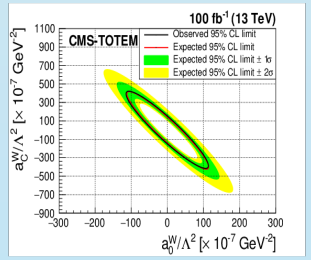












Motivations to have a PPS at HL-LHC

More luminosity

- Current results using PPS are based on ≤ 100 fb^{-1} from Run 2
- With Run 3 data, expect almost all results to be limited by statistical uncertainties

Larger energy range in $\sqrt{s}(\gamma\gamma)$

- Current analyses are limited to the range ~350 GeV - 2 TeV when both protons are detected
- HL-LHC will allow exploration of higher final-state masses (**2.8-4 TeV**): large increase in reach for BSM searches, EFT/anomalous coupling studies
- With vertical crossing angle expected in Run 4, HL-LHC will allow exploration of lower final-state masses as well (**down to ~200 GeV**): large improvement in statistics for SM cross section measurements

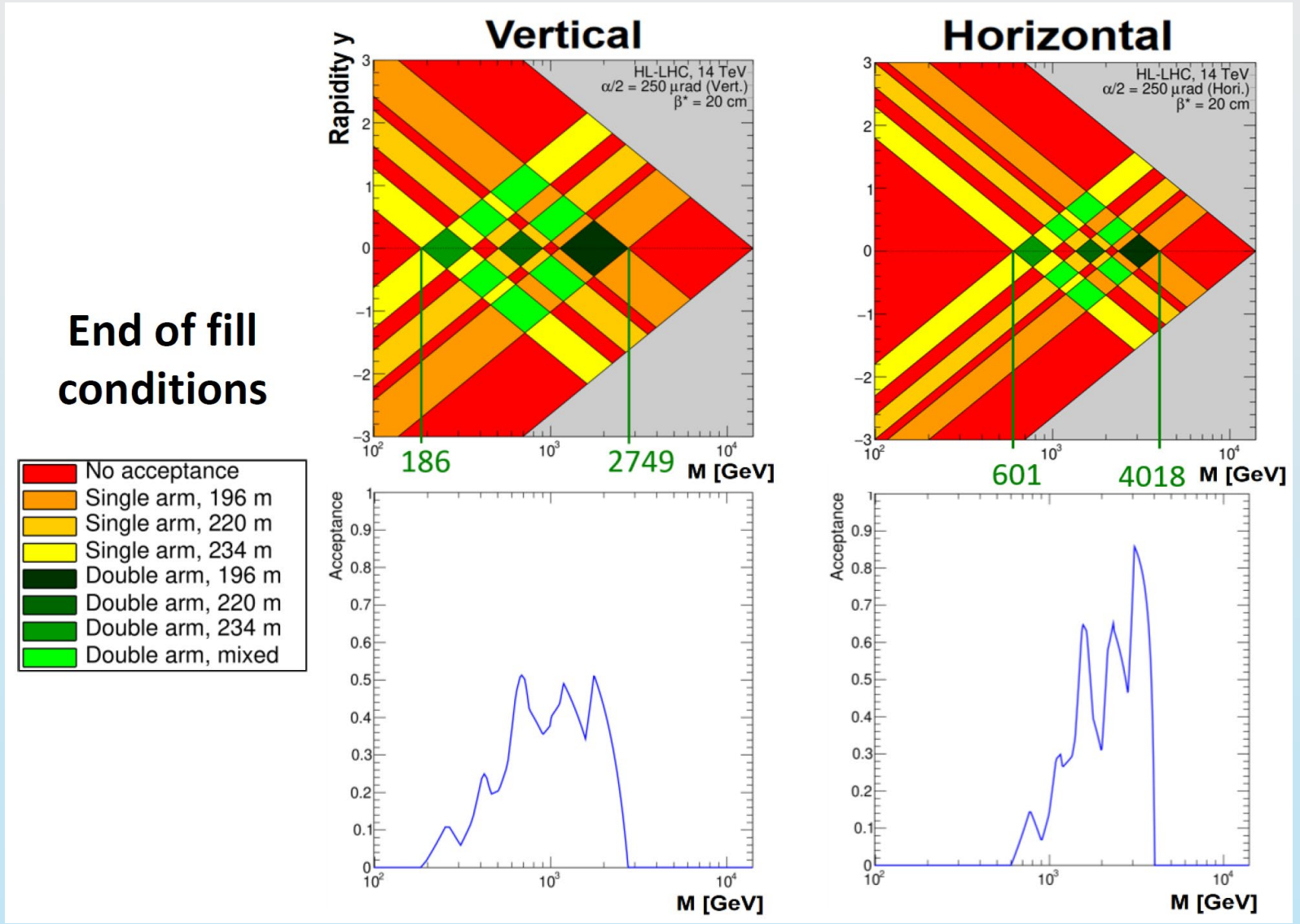
Uniqueness and complementarity

- No other equivalent detector (e.g. in ATLAS) will be present at HL-LHC
- Provides a unique extension to the CMS VBS/VBF physics program

Geometrical acceptance (pp→pXp events)

Using latest HL-LHC optics and lumi leveling scenarios

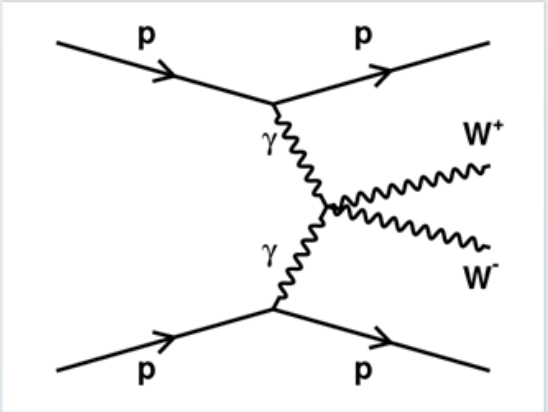
- Precise values will slightly change during the fill and from year-to-year, following the β* leveling scheme
- **Green diamonds**: both protons can be detected
- Yellow/orange bands: at least 1 proton can be detected



Complementarity with VBS and HI

VBS/VBF physics is an important piece of the HL-LHC program for CMS

- New Phase-2 upgrades in the forward region (HGCAL, etc.) help turn CMS into a "W/Z collider", where VBS/VBF events are tagged by forward jets
- PPS adds a "γγ collider" mode, where VBS/VBF events are tagged by forward protons
- Strong complementarity in physics reach, with completely different experimental tagging methods



CMS (+ATLAS, ALICE, LHCb) have an extensive γγ physics program in Heavy Ion collisions

Highly complementary to the PPS physics program

- Pb-Pb collisions benefit from huge photon fluxes (Z^4 enhancement compared to p-p), plus low-pileup conditions
  - Ideal for low-mass SM cross section measurements + BSM searches below ~100 GeV
- p-p collisions with PPS benefit from higher energy γγ interactions (up to ~TeV scale) and use of full integrated p-p luminosity
  - Ideal for studying heavy SM final states and high-mass BSM searches above 100 GeV

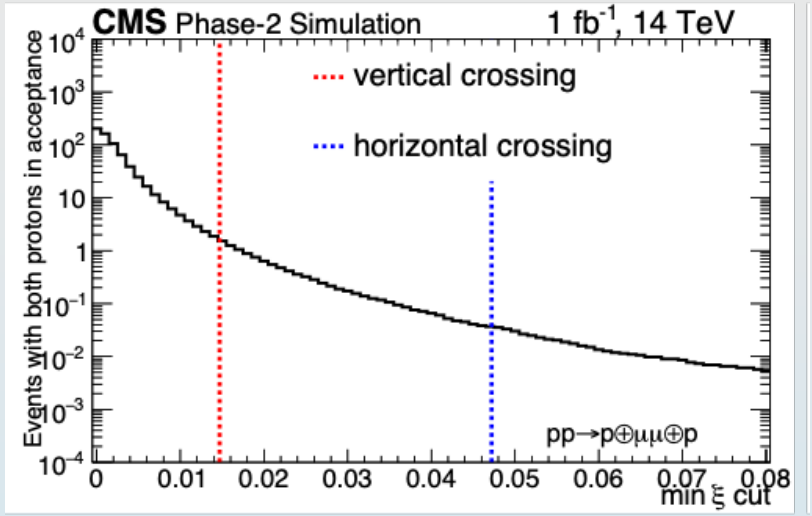
Physics potential at low mass

Acceptance at low masses: essential for SM studies and spectrometer calibration

Many Central Exclusive Production channels to be studied:

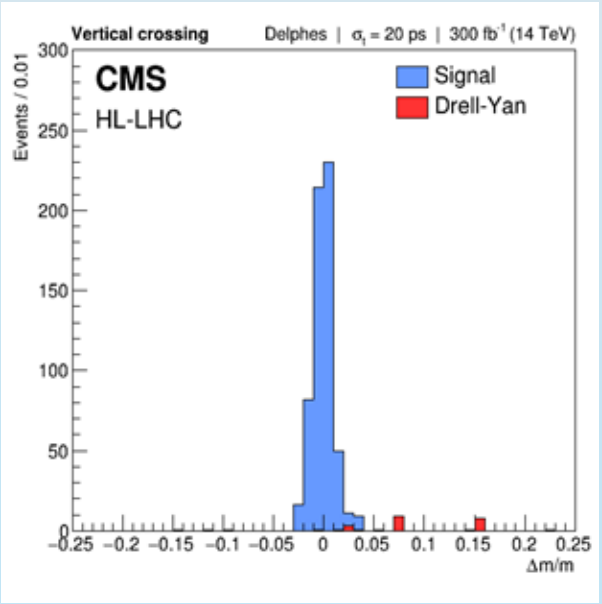
- QCD physics: $pp \to p+jj+p$
- EWK physics: $pp \to p+WW/\ell^+\ell^-+p$
- Top physics: $pp \to p+tt+p$
- Higgs physics: $pp \to p+HWW+p$

Sensitive to the minimum ξ acceptance



Example: $pp \to p+\mu\mu+p$

- In 1 nominal HL-LHC year (300 fb^{-1}), a large number of signal events expected with very low background after timing and rapidity matching cuts
- Much better than the current Run 2/3 PPS



Physics potential at high mass

BSM indirect searches

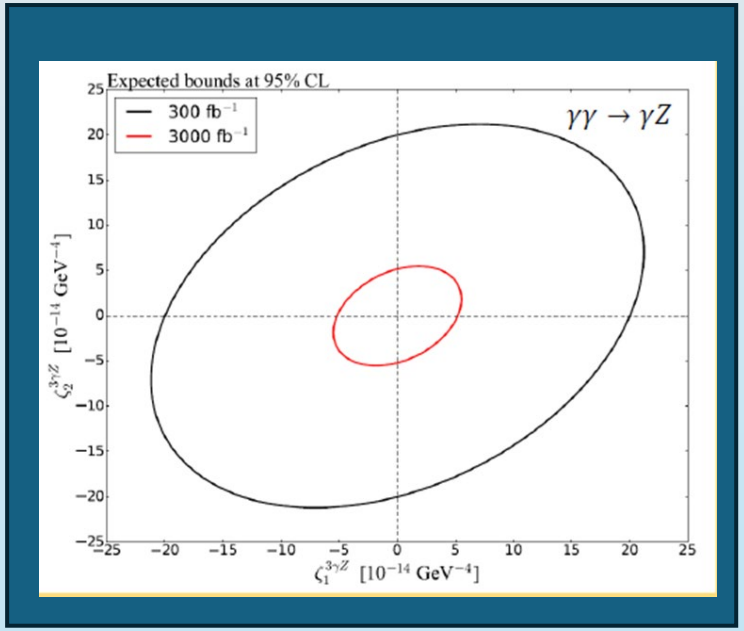
Look for non-resonant excesses above the Standard Model in the high-mass (high-ξ tails)

Di-boson final states

- γγ→γγ (PPS Run 2 results: link, link)
- γγ→WW (PPS Run 2 results: link)
- γγ→ZZ (PPS Run 2 results: link)
- γγ→Zγ

Di-fermion final states

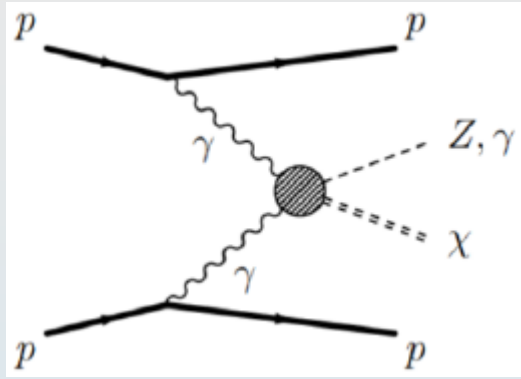
- γγ→tt (PPS Run 2 results: link)
- γγ→ττ (sensitive to τ g-2)



Physics potential at high mass

BSM direct searches

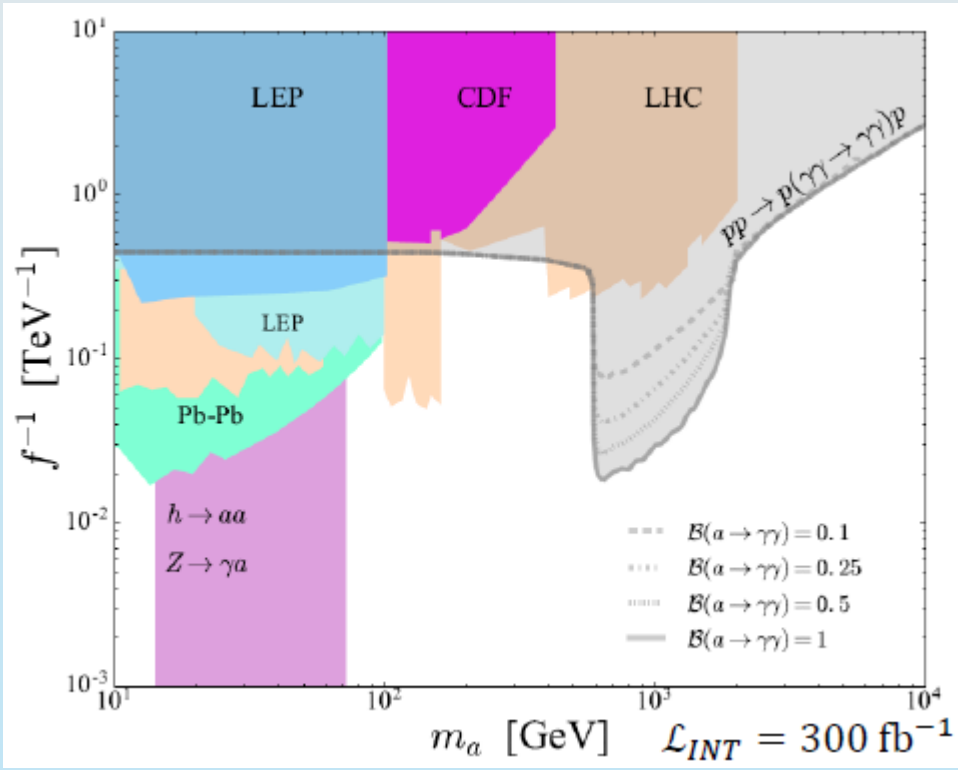
If BSM physics is below a few TeV, new particles could be directly produced with protons in PPS2



s-channel resonances
- Axion-like particles in γγ→a→γγ (PPS Run 2 results: link)

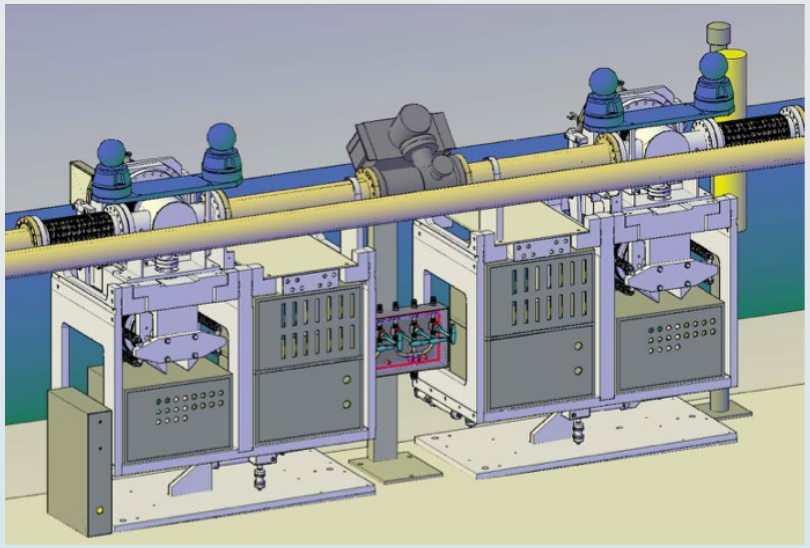
"Missing mass" searches
- γγ→γX (PPS Run 2 results: link)
- γγ→ZX (PPS Run 2 results: link)
- γγ→XX

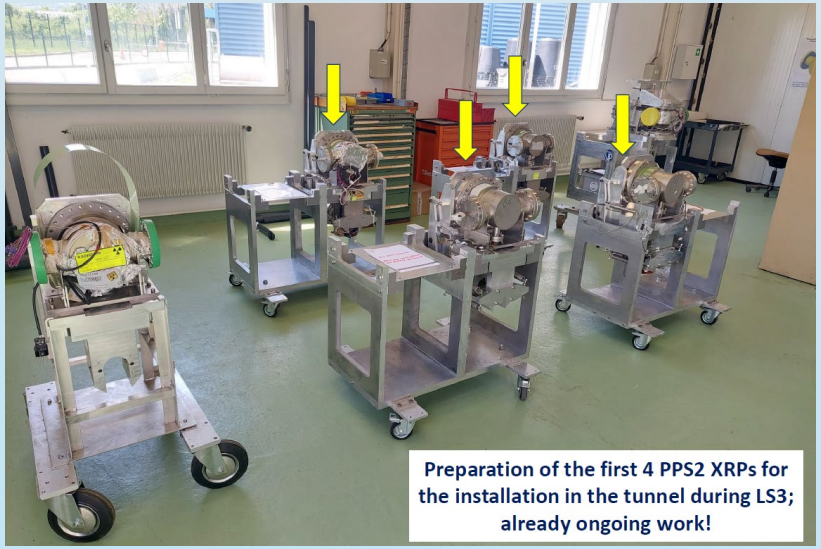
Pair production
- Slepton/chargino pairs
- Doubly charged particles
- Magnetic monopoles



ECR: machine integration and RP locations

- Space for 2 Roman Pots at each of the 196m, 220m, 234m locations - total of 12 horizontal RPs
  - Just before TCL5 (~196m): high masses **~1 - 2.72 TeV**
  - Just before TCL6 (~220m): interm. masses **~520–960 GeV**
  - Just after Q6 (~234m): lower masses **~130–370 GeV**
- In addition, 4 pairs of vertical RPs at 220m for alignment with elastic scattering events
- Positions defined down to ~mm after iterations with HL-LHC integration/layout team
- Including most “ancillaries”: electronics patch panels, cooling patch panels, BLMs, bellows, services

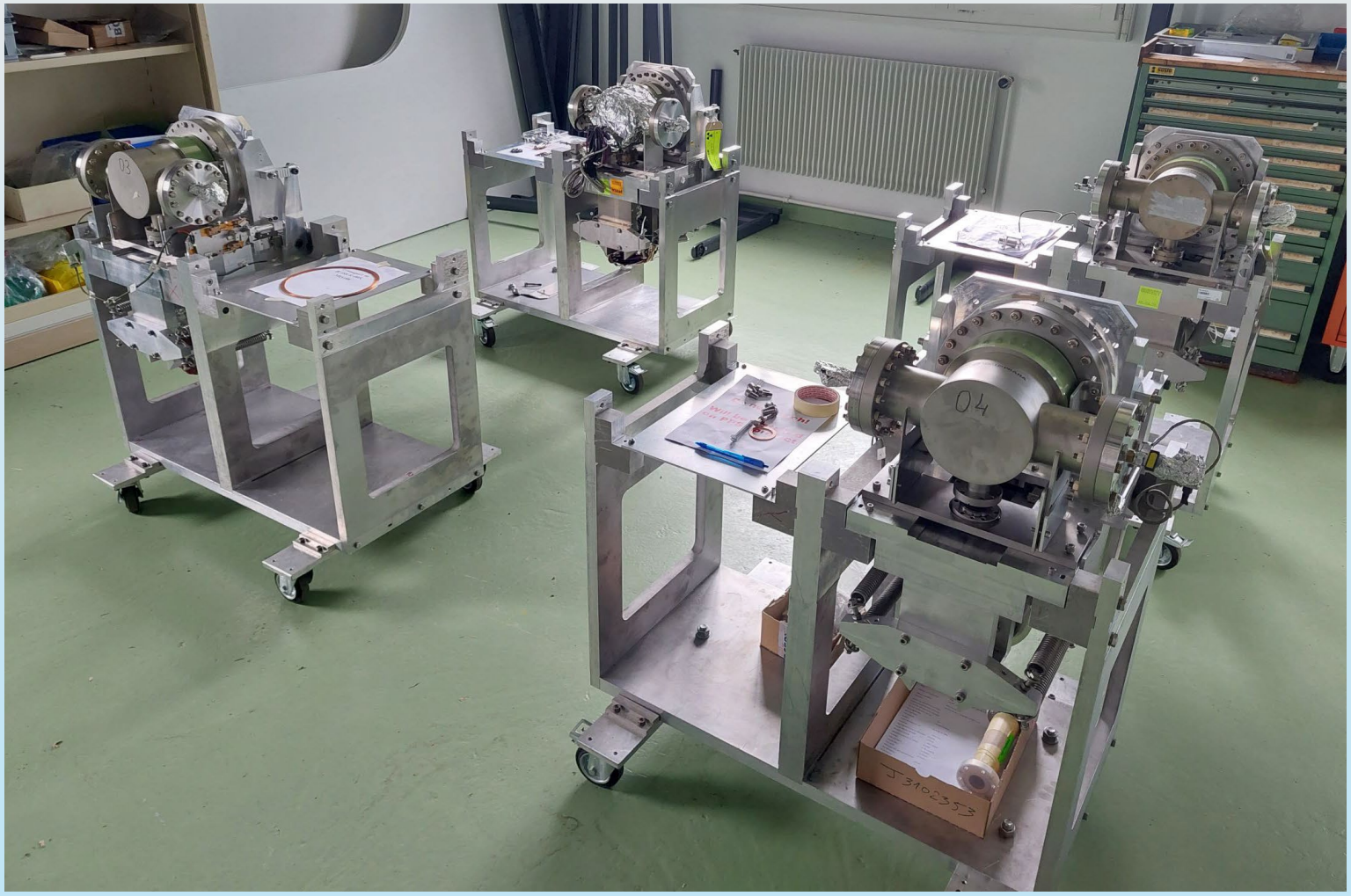




Preparation of the first 4 PPS2 XRPs for the installation in the tunnel during LS3; already ongoing work!

RP stations assembly

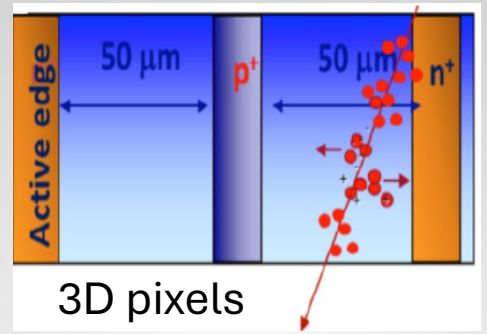
Four XRP station are being completed. The other 8 horizontal and 8 vertical RPs are currently used in the tunnel up to LS3.



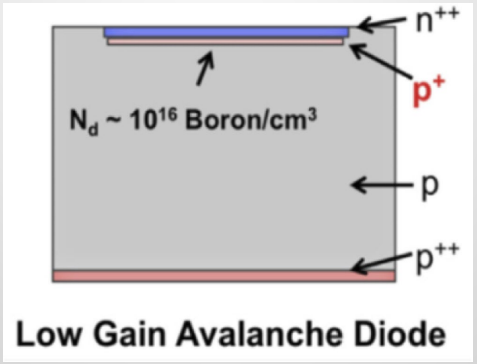
Detector technologies

Baseline technologies

- Tracking
  - 3D (and planar) pixels as for CMS Phase-2 Inner Tracker
- Timing
  - LGAD as for CMS ETL (very fruitful collaboration with Torino, Zurich, Fermilab)



3D pixels



Low Gain Avalanche Diode

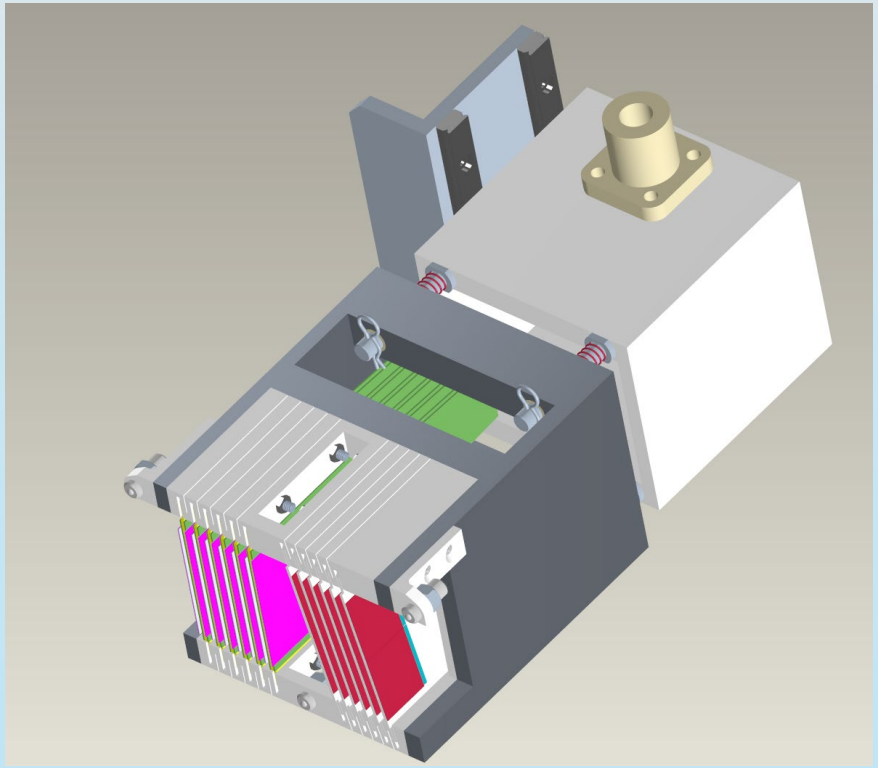
PPS on its own can't afford a full development of dedicated technologies

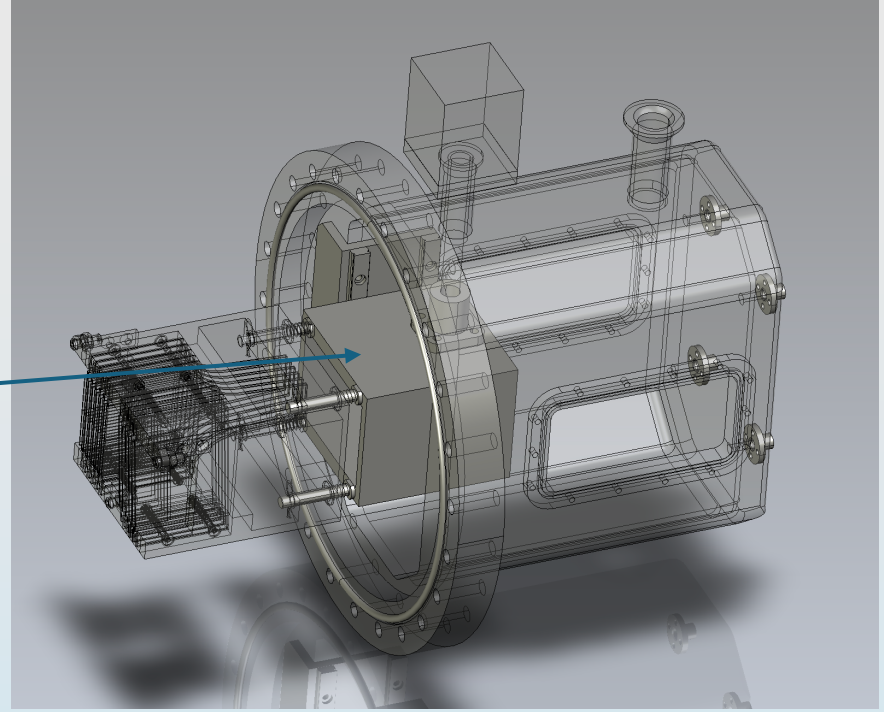
- Synergies with other CMS detectors already existing or being set up
  - ETL for the timing
  - Phase-2 Inner Tracker for the tracking

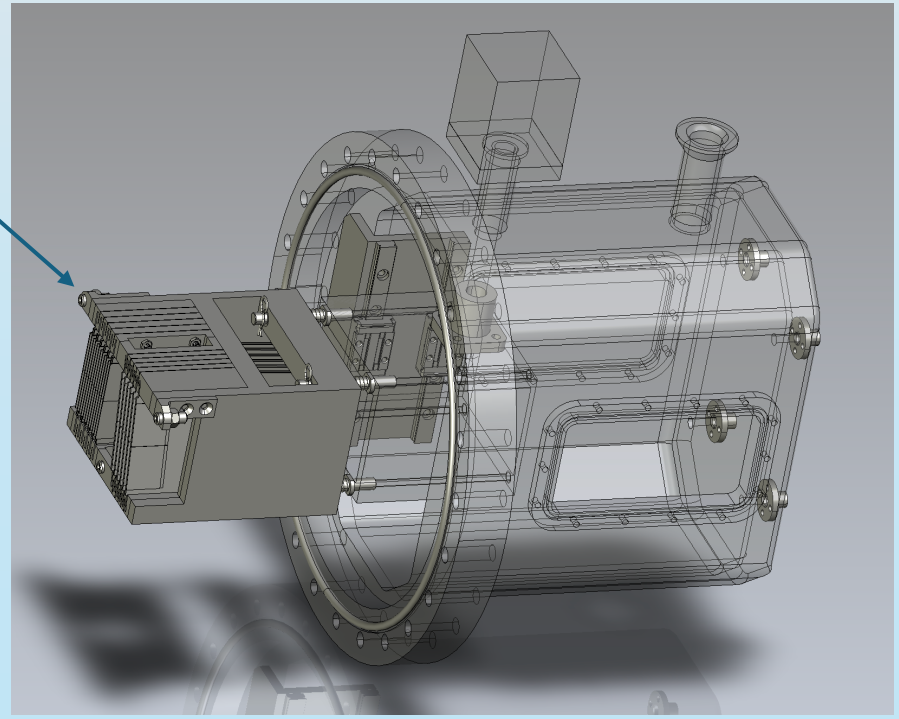
Detector mechanics

Design by CERN, INFN-Genova, INFN-Pisa

- Inside the pots
  - Suspended body: to allow vertical movement
  - Detector package



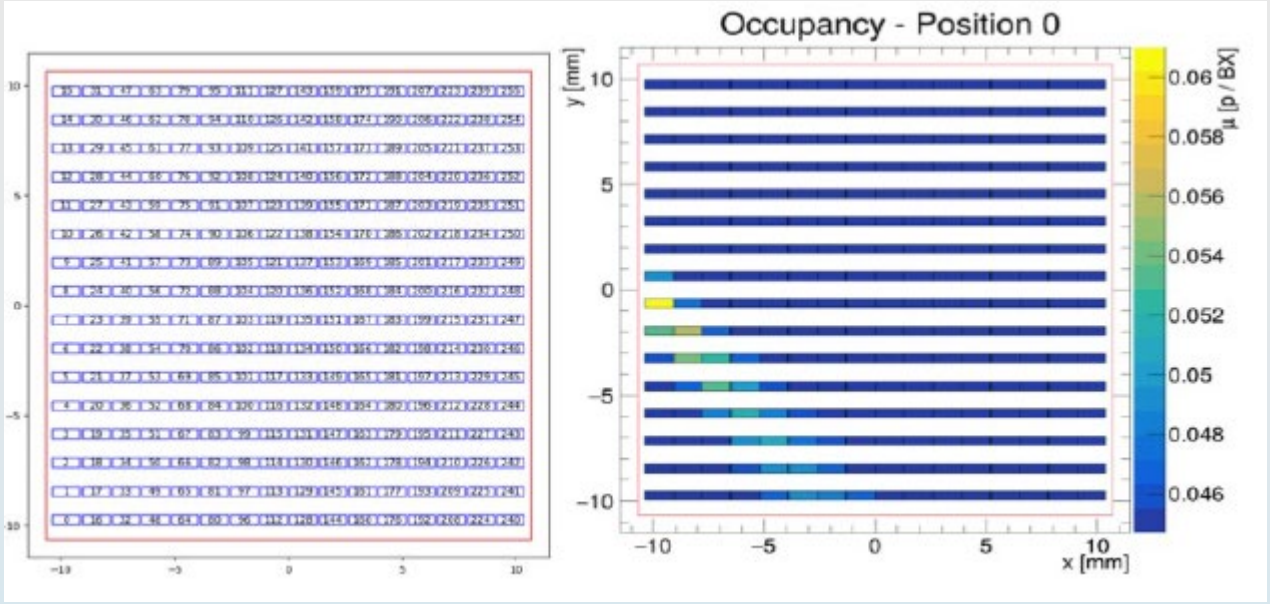


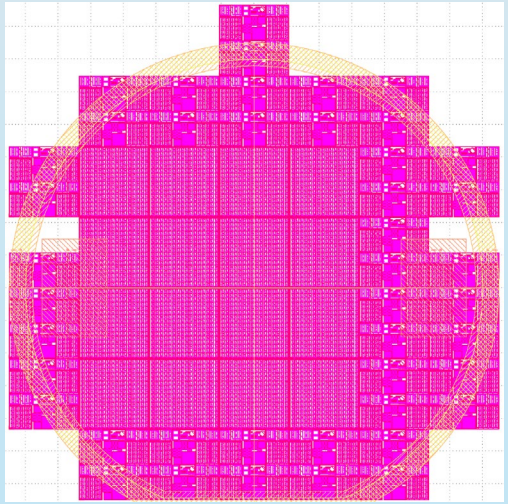


Timing detector

- 5 planes of LGAD sensors read by ETROC chips
- Planes tilted by 8º along x axis
- Each plane made of 2 layers of LGADs+ETROCs, attached to opposite sides of a flex PCB
- Sensor pre-production ongoing at FBK (delivery expected soon)
- Full sensor characterization to be started soon (testing infrastructure ready)
- 2025 irradiation test of LGAD+ETROC show good results at moderate irradiation (<50ps res.)

16x16 LGAD segmentation



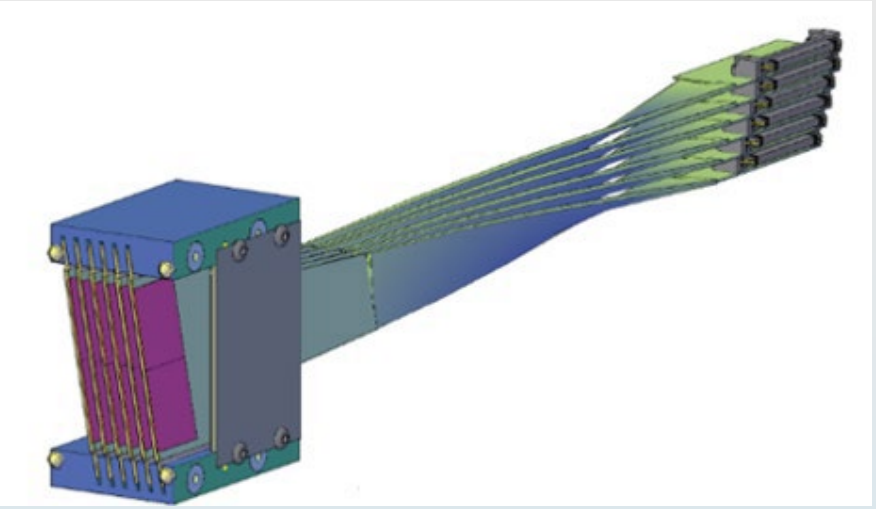


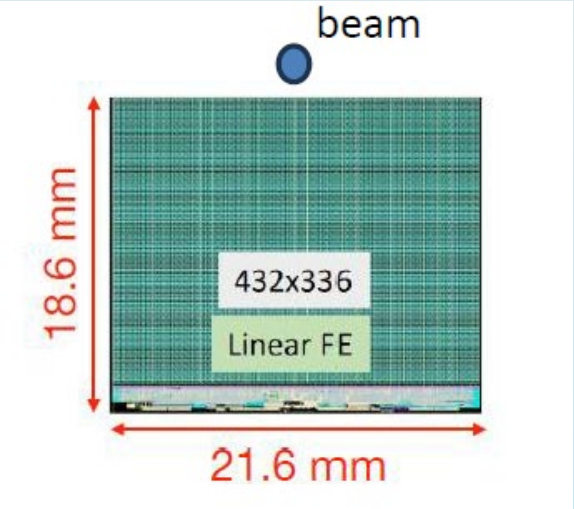
PPS2 pre-production devices consist of:
- 4 2x2 LGADs, with different edge widths
- 2 5x5 LGADs, with different edge widths
- 16x16 pixel LGAD for testing with ETROC
- All PPS2 LGADs use a pixel size with a DRD3 width ~1/3 of ETL nominal

Tracking detector

Tracking with 3D pixels in horizontal and planar pixels in vertical

- 6 planes per horizontal pot with 2 3D sensors each (2 CROCs per plane) – 25x100 um pitch
- 6 planes per vertical pot with 1 planar sensor each (2 CROCs per plane)
- Same bare modules as for Inner Tracker: synergy for the procurement
- FE electronics with new parallel power distribution and adapted to the RP geometry
- Planar/3D usage is transparent from the readout/mechanics/cooling point of view:
  - Front-end: CROC 50×50 μm2 pixels
  - 2 chips/plane
  - Same flex
- Higher bias voltage for planar w.r.t. 3D





Summary

- PPS will be the only forward proton detector for the HL-LHC
- The identified locations for Roman Pots will significantly expand the physics reach, both at low masses (SM cross section measurements) and high masses (BSM/EFT studies)
- We are going to re-install the existing PPS Roman Pots for Run 4, to operate PPS at the HL-LHC
- The machine integration details have been worked out over the past 1-2 years
- CERN management has made a strategic decision to support PPS for many machine-related costs
- It's now time to start building the detectors