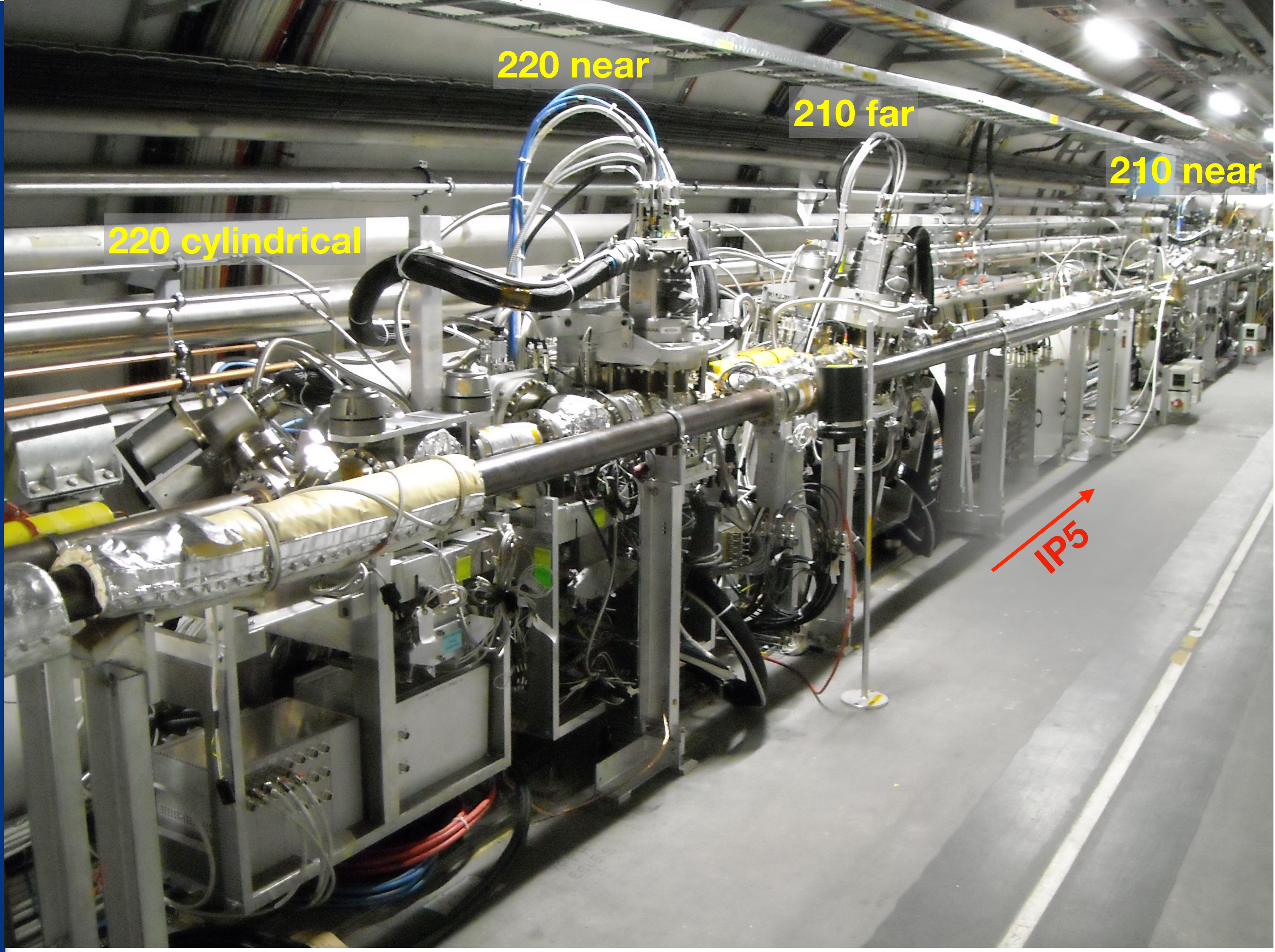


# PPS Experimental Program

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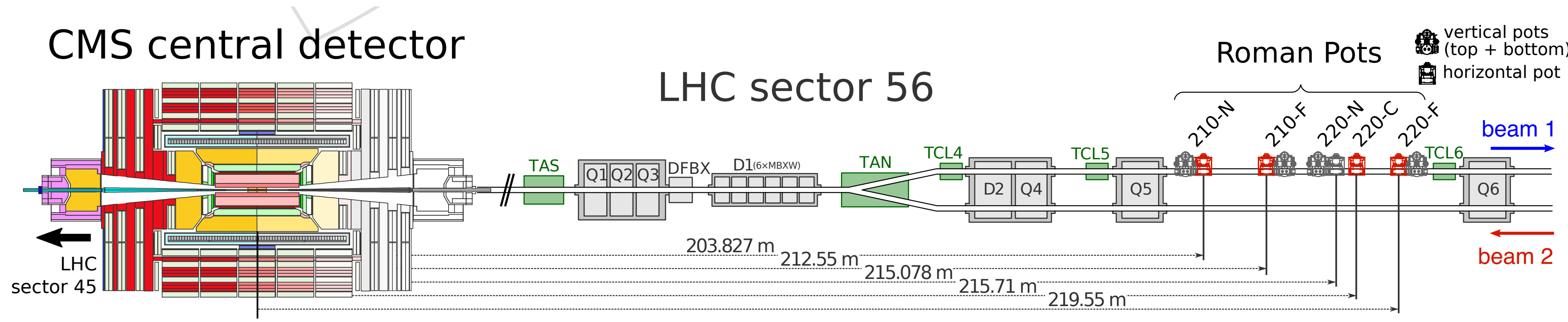
ITDM Workshop
September 13, 2023

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

# Overview of PPS

**symmetric on the other side**




**Near-beam tracking and timing detectors, installed in the LHC tunnel ~200m from the central CMS detector**

**Detects intact protons from high-energy γγ interactions, to study a variety of Standard Model and BSM processes**

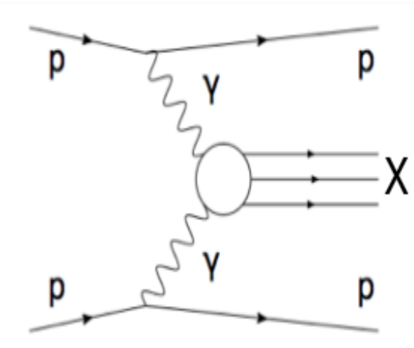
**The LHC magnets are used to bend the protons between the CMS IP and PPS**

**In signal events the full collision energy can be reconstructed: closure of event kinematics, missing mass searches, etc.**

Proton kinematics:

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} \quad M_X = \sqrt{s\xi_1\xi_2}$$

$$t = (p_f - p_i)^2 \quad y_X = \frac{1}{2}\log\left(\frac{\xi_1}{\xi_2}\right)$$



# Physics results from LHC Run 2

**First observation of EWK-scale proton tagged dilepton production with 2016 data [JHEP 07 (2018) 153], and update with 2017-2018 data [JINST 18 (2023) 09, P09009]**

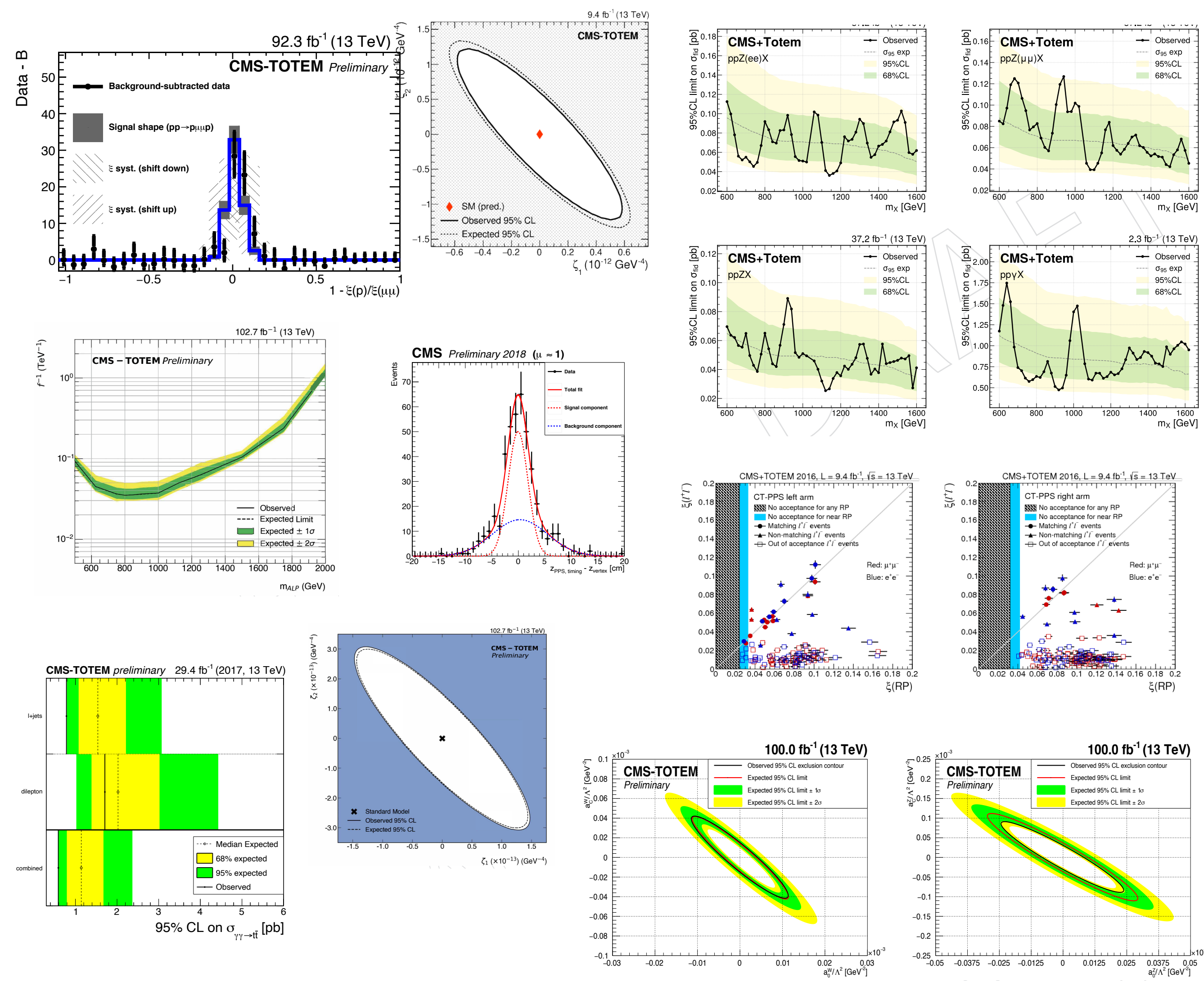
**First use of missing-mass search technique at a hadron collider, in Z+X and γ+X: [Accepted by EPJ-C]**

**First and best collider limits on anomalous γγγγ couplings: [Phys.Rev.Lett. 129 (2022) 1, 011801], and limits on TeV scale axion-like particles [CMS-PAS-EXO-21-007]**

**New limits on anomalous γγZZ and γγWW couplings from fully hadronic decays:[JHEP 07 (2023) 229]**

**First limits on exclusive t-tbar production: [CMS-PAS-TOP-21-007]**

**Calibration of timing detectors with inclusive CD/DPE events [JINST 18 (2023) 09, P09009]**

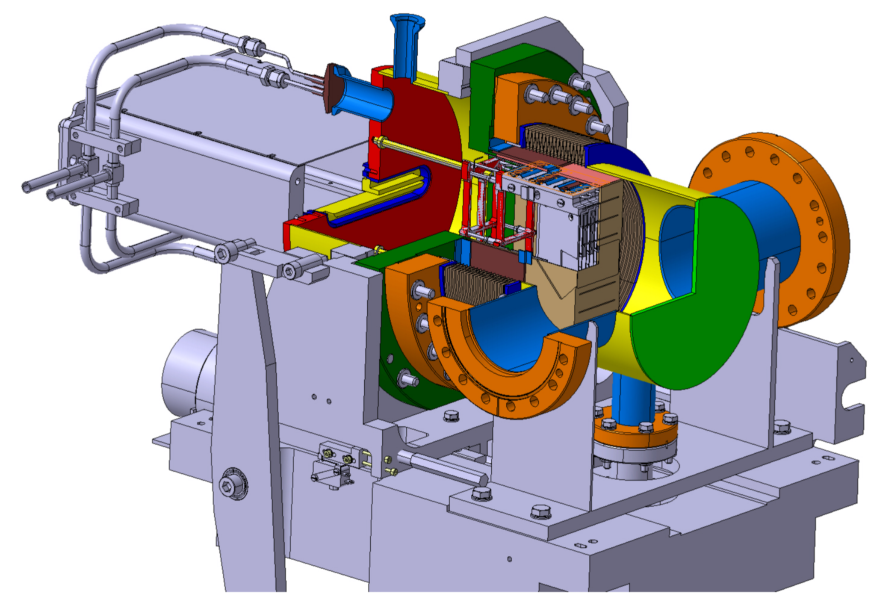


# Roman Pots

**To detect protons scattered at very small angles, the detectors must be brought very close to the beam**

**PPS began as a joint project of the CMS+TOTEM collaborations in Run 2, using the Roman Pots developed for TOTEM**

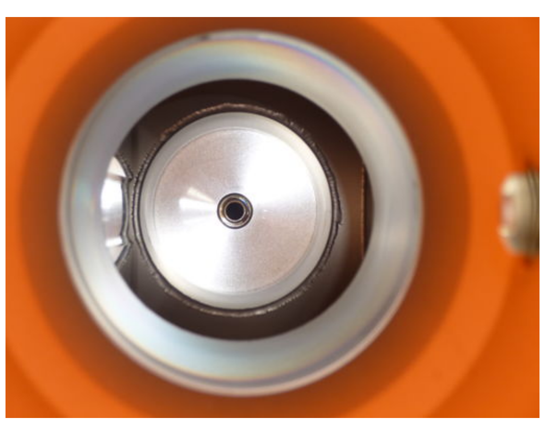
**Detectors are kept in movable vessels under secondary vacuum, separated from the beam-pipe by a "thin window" of 200-300μm**



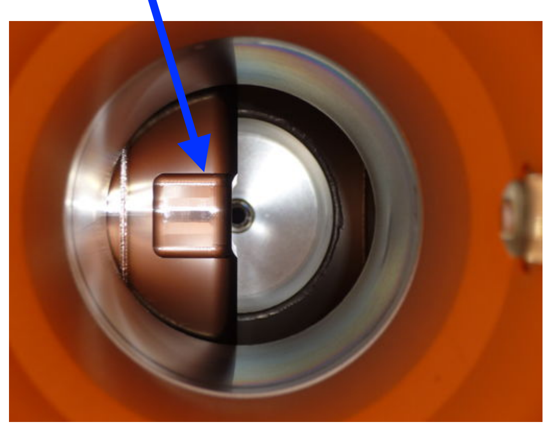
**Detectors are moved to within ~2mm of the beam at full intensity**

**Operated successfully in almost all LHC fills since 2016**

**View from inside beampipe**



**Roman Pots retracted**



**Roman Pots inserted**

# PPS Detectors

**Very small detectors, at most a few cm$^2$ active area per plane**

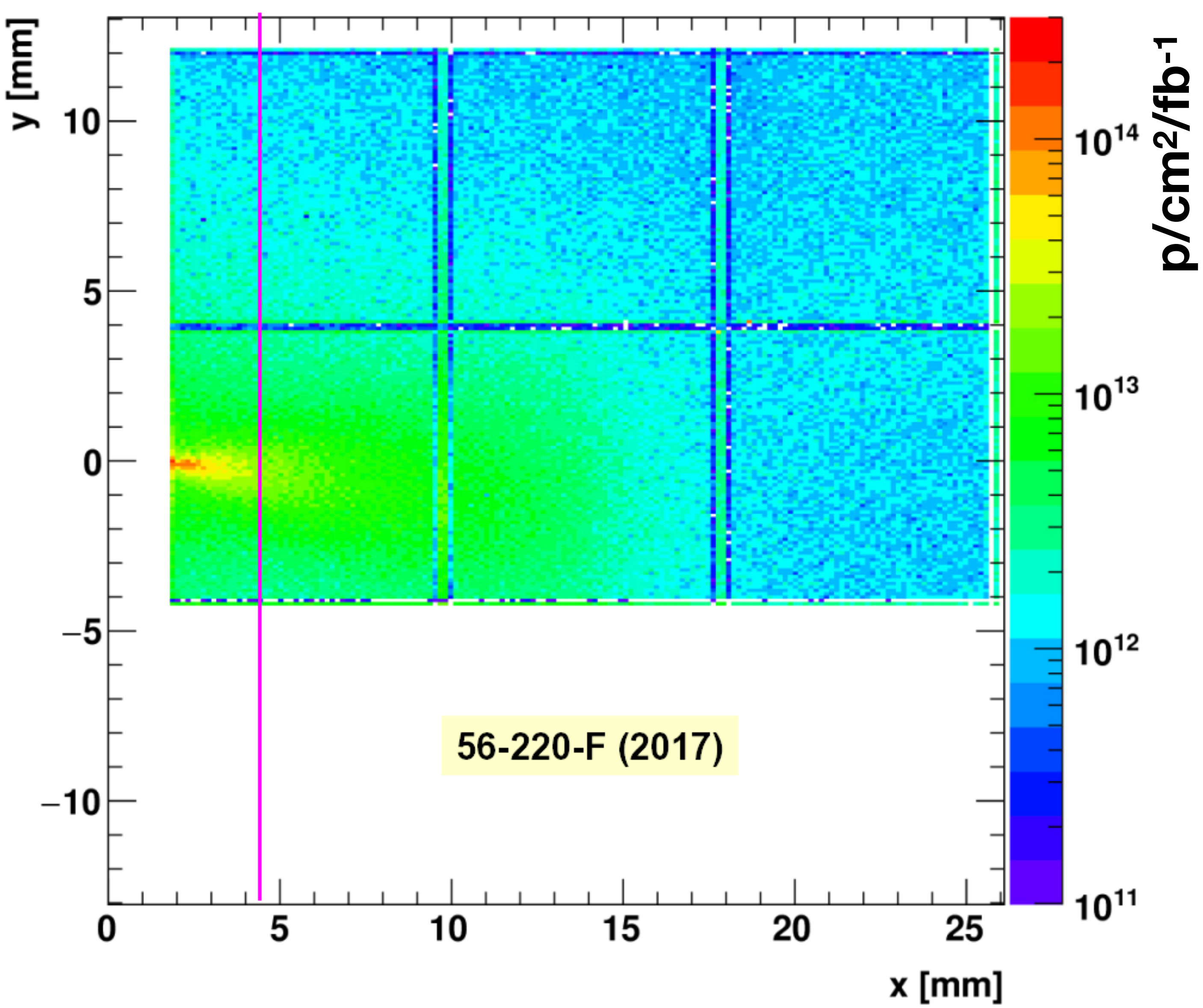
**Opportunity to use new/ innovative detectors, at small scales under extreme conditions**

- **First dedicated precision timing detector at the LHC**
- **First use of 3D pixels for tracking in CMS**

One complete PPS pixel detector plane (Run 2 version)


Active area

# PPS Radiation Environment




**Due to close proximity to the LHC beam, PPS detectors experience a very difficult radiation environment**

**Both in terms of maximum dose, and non-uniformity**

**Peak of O(1E14) p/cm$^2$ per fb$^{-1}$**

**⇒O(5E15) p/cm$^2$ per year**

**Factor of >10 gradient over a distance of ~10mm (~1 pixel ROC)**

# PPS Detector technologies

| Year | Tracking | Timing |
|---|---|---|
| **2016** | Si-strips | |
| **2017** | Si-strips + 3D pixels | Single diamonds (3 planes/arm) + UFSD/LGADs (1 plane/arm) |
| **2018** | 3D pixels | Single diamonds (2 planes/arm) + Double diamonds (2 planes/arm) |
| **2022** | 3D pixels | Double diamonds (4 planes/arm) |
| **2023** | 3D pixels | Double diamonds (7 planes/arm in 2 stations) |

**Improvements to keep pace with evolving LHC luminosity & pileup conditions**

**Since 2018 primarily 3D pixels (tracking) & double diamonds (timing)**

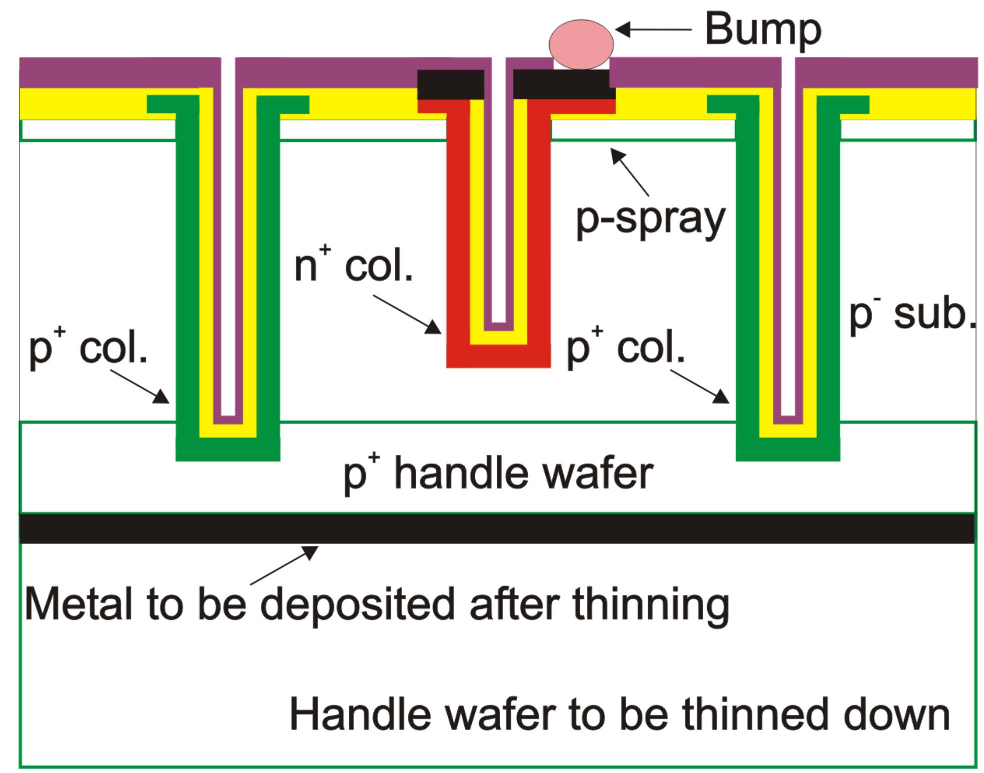
# Tracking

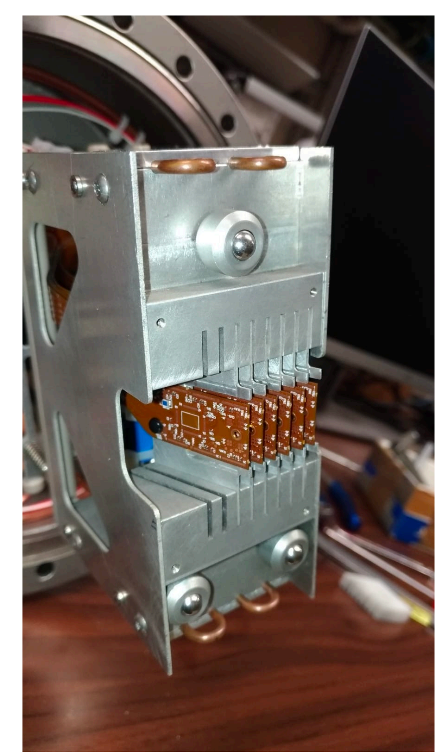
**3D pixels chosen for radiation hardness, resolution, and ability to reconstruct multiple protons in the same LHC bunch crossing**

- **Now also chosen for innermost layer of the central CMS pixel detector at HL-LHC**

**Run 3: "single side" sensors from FBK, with junction and ohmic columns on the same side of the wafer**

- **Total of 12 planes, in 4 Roman Pots (2 on each side of CMS)**

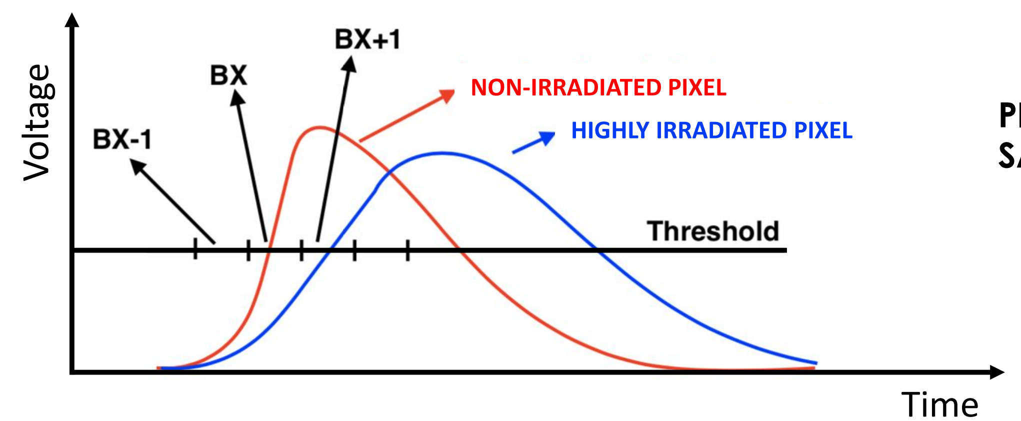


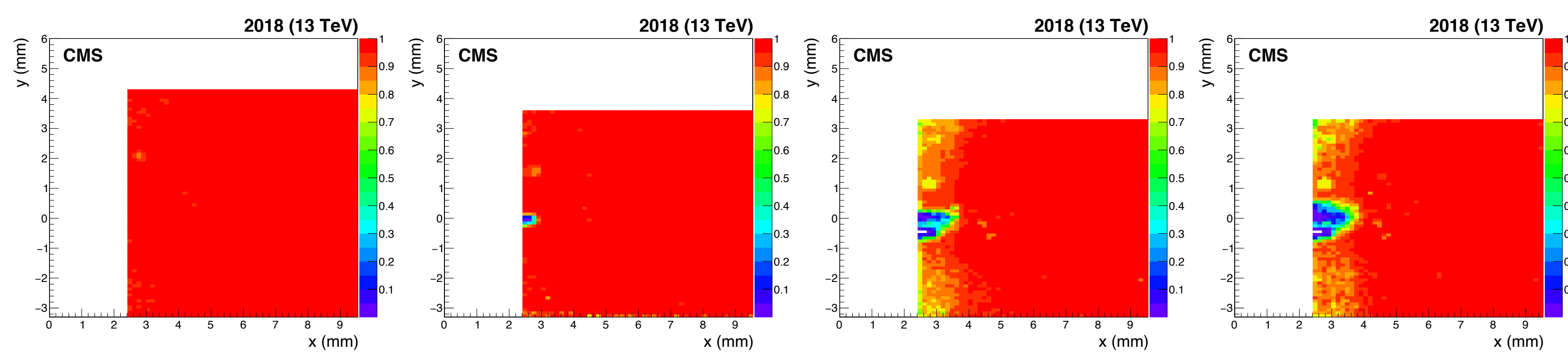
# Tracking: evolution of 3D pixel efficiencies

Sensitivity mainly from the readout chips (PSI46 in Run 2, PROC600 in Run 3) the 3D pixels are bonded to

- Inefficiencies due to signal slewing into the next bunch crossing are visible
- In good agreement with non-uniform X-ray irradiation tests of the ROC
- Not a large effect, but leads to ~1mm inefficient area after 1 year of LHC running



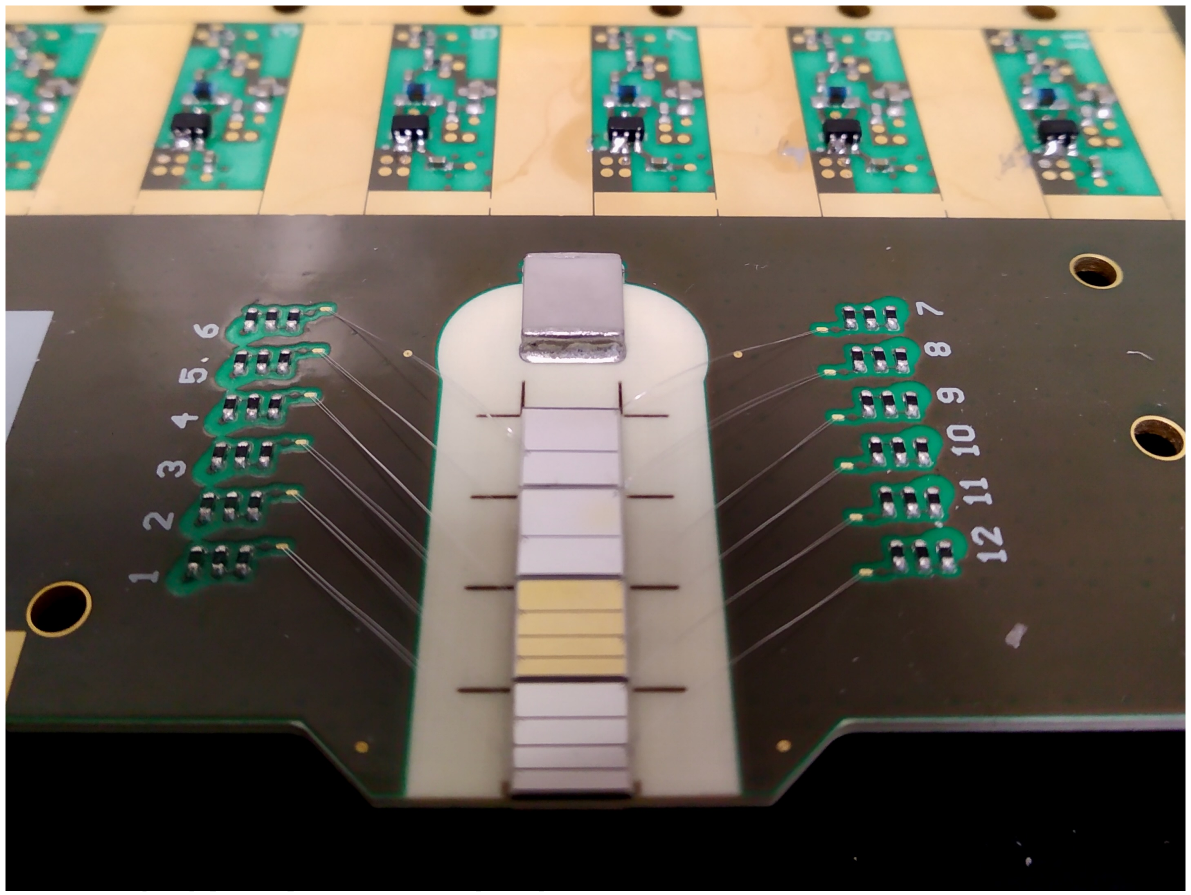

PIXELS NOT RESPONDING IN THE SAME 25 ns CLOCK WINDOW (BX)




L=0fb$^{-1}$ L=21.3fb$^{-1}$ L=50.3fb$^{-1}$ L=57.8fb$^{-1}$

For LHC Run 3, a new vertical movement system has been deployed, to distribute the irradiation over a larger vertical area

# Timing

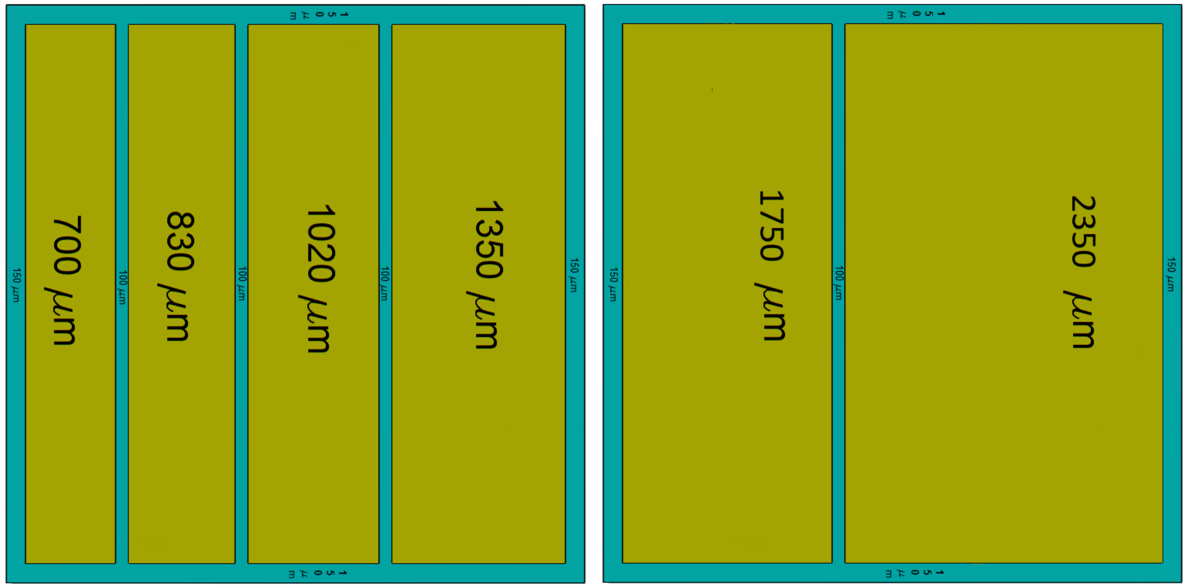



**Synthetic single-crystal CVD diamonds chosen for radiation hardness, segmentation, low material budget**

**3-4 diamonds per plane, with further 1-d segmentation achieved by metallization**

**Readout via NINO+HPTDC**

**Variable segmentation to deal with non-uniform fluxes: from 700 µm close to the beam to 2350 µm farther from the beam**



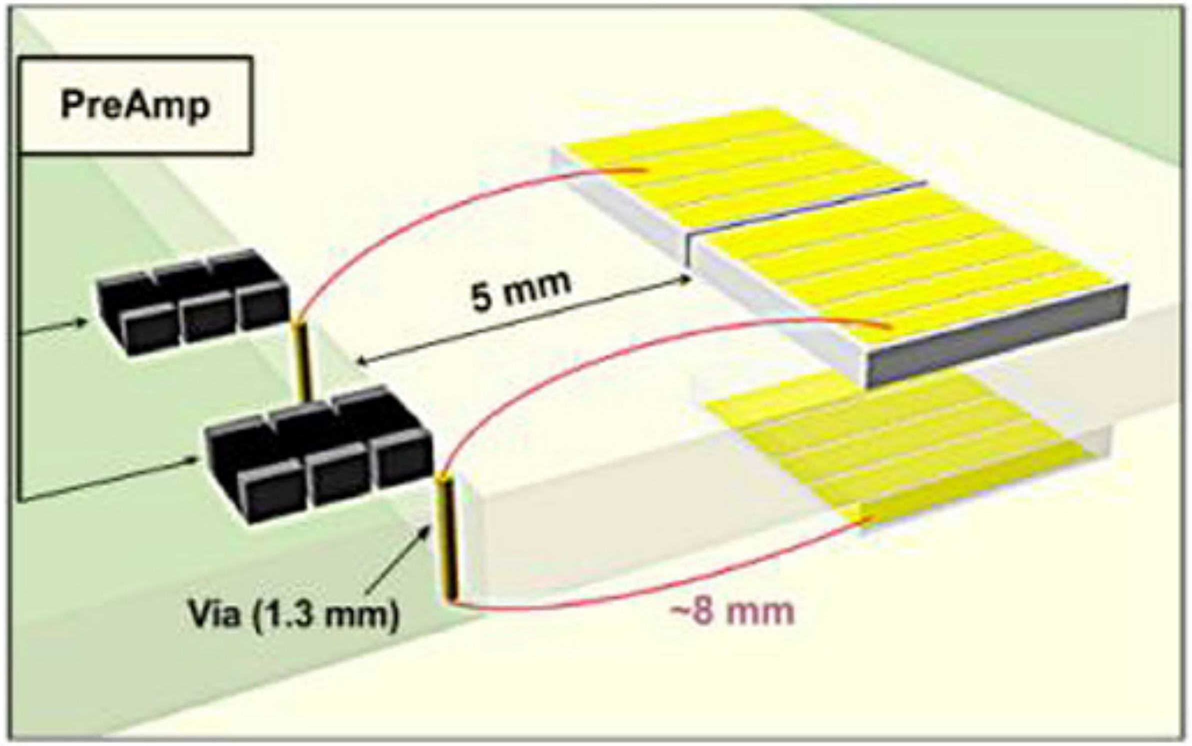

4-pad diamond 2-pad diamond

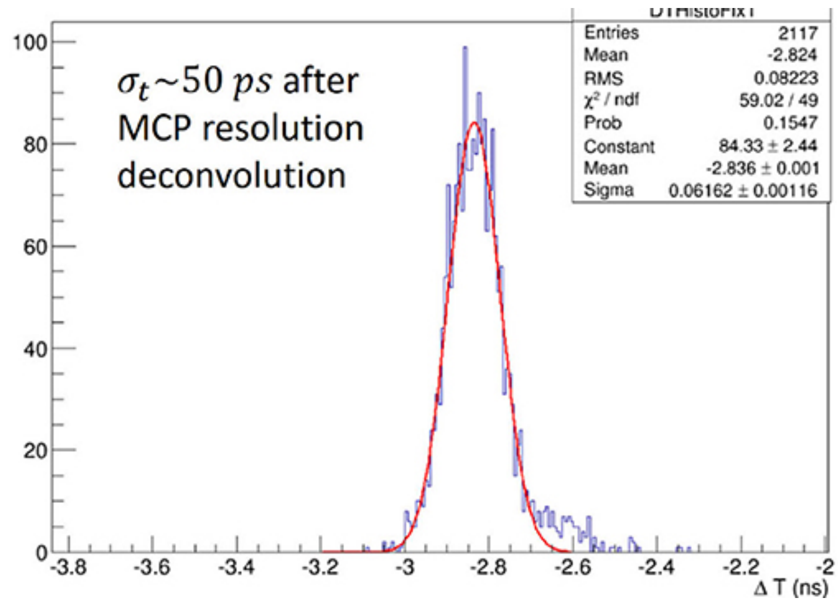
# Timing: double diamonds

**Since 2018 "double diamonds" have been used, with pads of 2 diamond crystals connected to the same pre-amplification channel**

- **Nearly doubles collected charge, with similar noise level (dominated by pre-amp)**

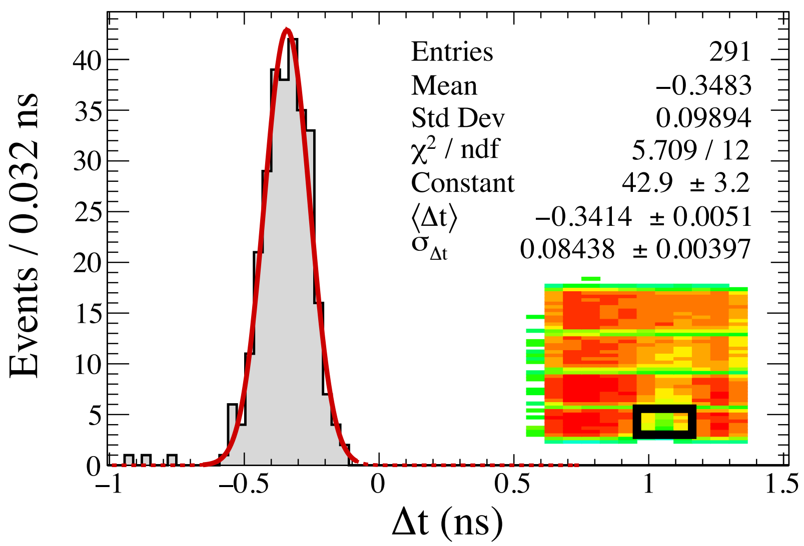
- **Sensor resolution of 50-60 ps/plane in testbeams**

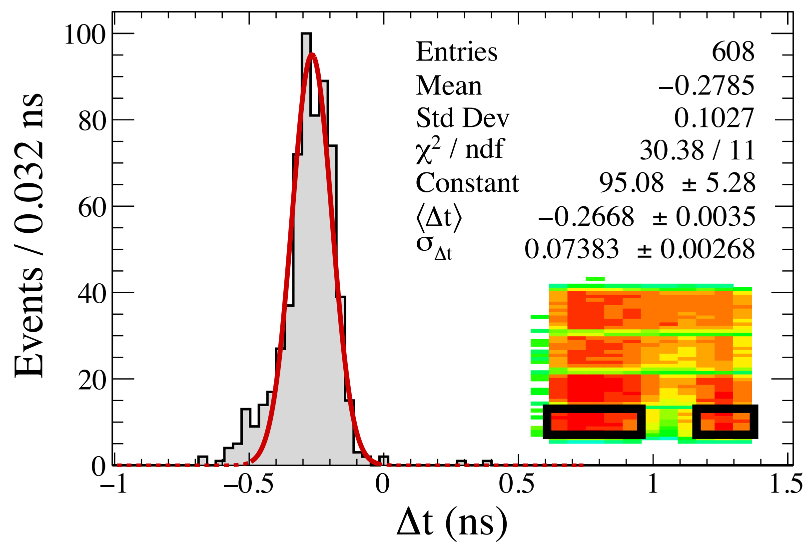


# Timing

## After Run 2, Diamonds exposed to 50-100fb$^{-1}$ of LHC data were retested




**Observed 30-40% overall resolution degradation, not correlated with distance to beam, due to irradiation of pre-amplifiers**

**10% localized resolution loss in most irradiated regions**

### For LHC Run 3:

**Hybrid board modifications to place pre-amplifiers farther from the beam, i2c control of amplifier LV settings to compensate performance losses**

**Parallel full waveform sampling readout (SAMPIC) of selected channels at lower rates**

**2nd timing station instrumented: increase from 4 to 7 double diamond planes/arm**

# Summary

**PPS has successfully operated a near-beam forward proton spectrometer since 2016, with tracking+timing detectors**

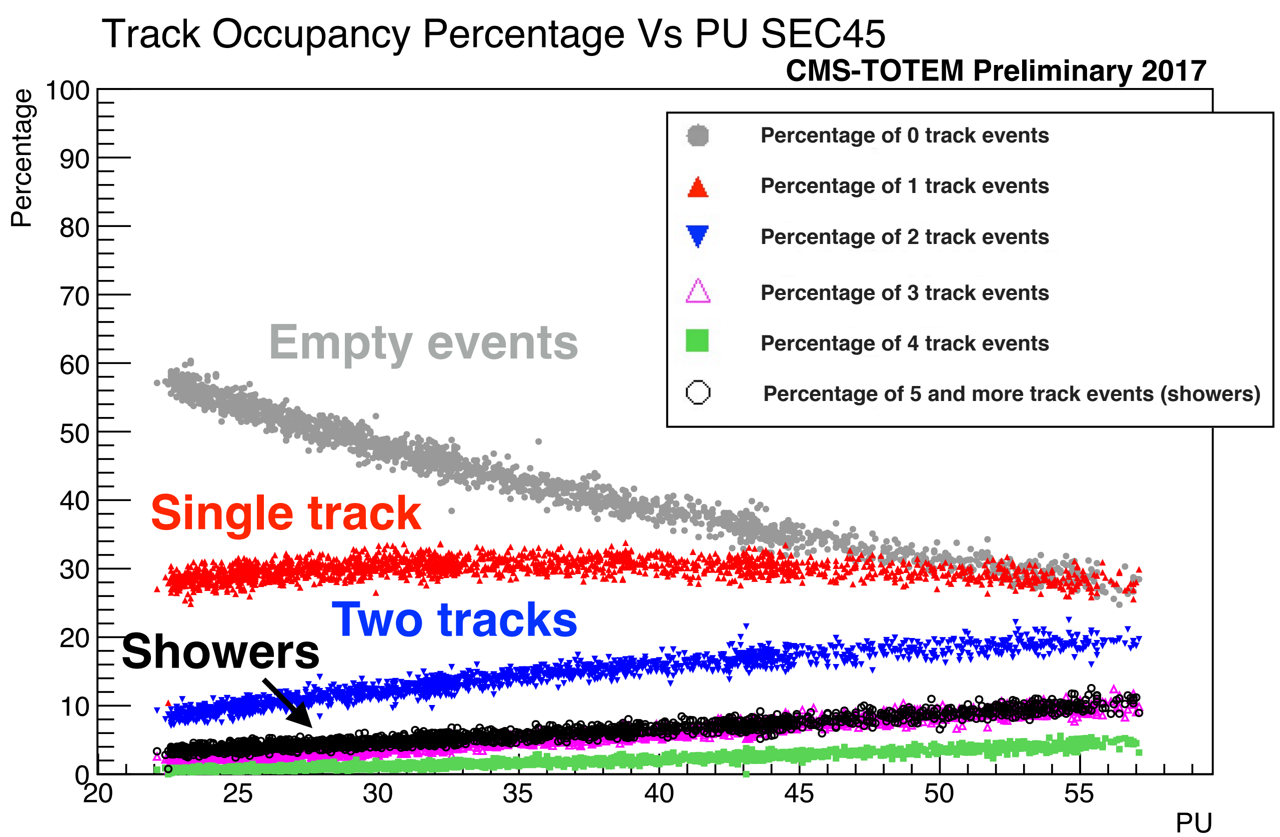
- **First of it's kind at a high-energy hadron collider, with several unique physics results published**

**Proximity to the beam and highly non-uniform irradiation is a major challenge**

- **Also an opportunity to adapt new developments on a relatively small scale**
- **Run 3 underway with 12 planes of 3D pixels for tracking + 7 planes of double-diamonds for timing on each arm, plus studies underway for HL-LHC**

# Extra

# Tracking: pixel track multiplicity vs. pileup



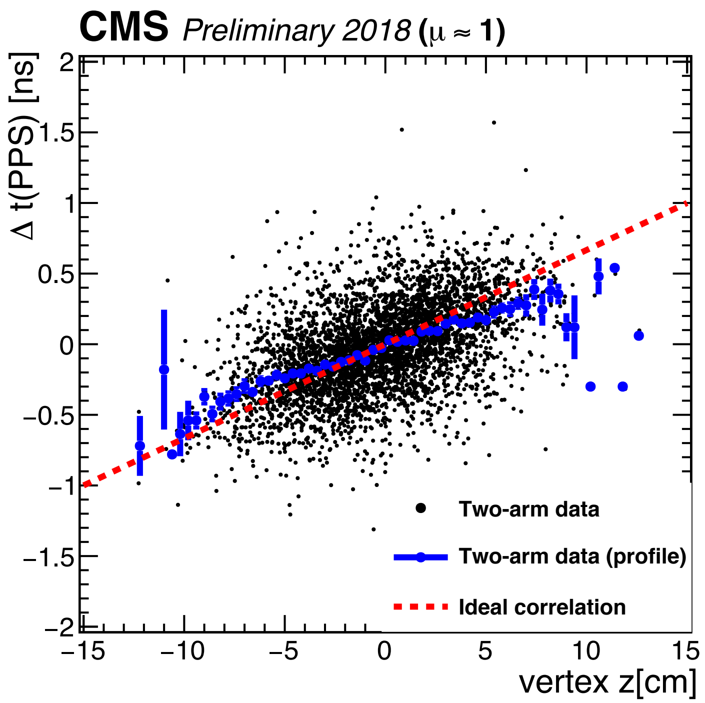
# Use of timing in collision data

**Main background for many analyses is combinatorial: central system combined with unrelated protons from pileup**

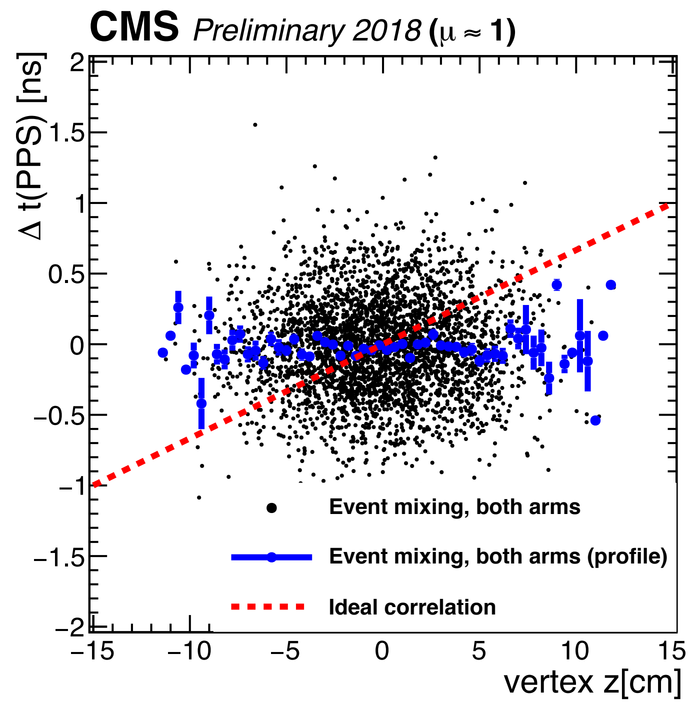
**In signal events the difference of proton times is correlated with the spatial position of the signal vertex**

$$z_{vtx} = (c/2) * \Delta t_{PPS}$$

Signal selection

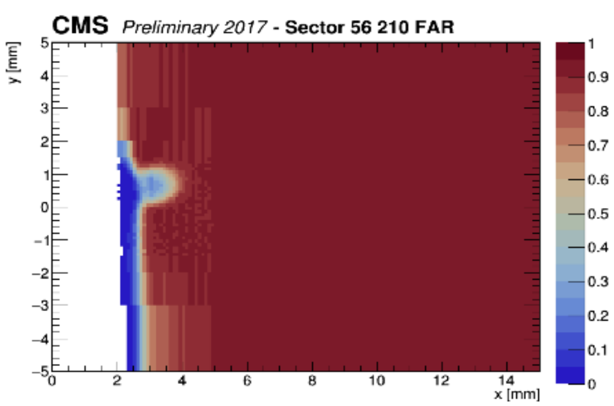



Pileup background (event mixing)

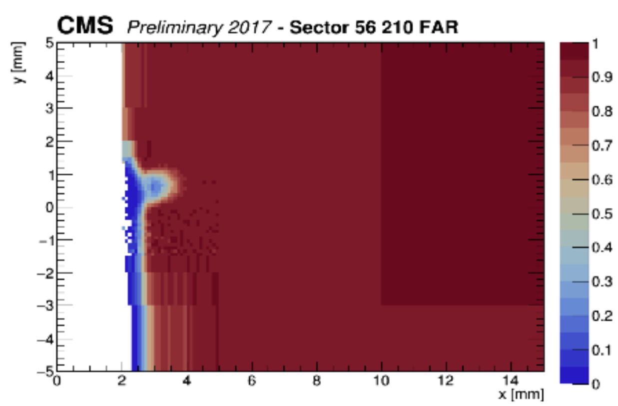



**Correlations verified in p-p collisions in short runs with low pileup**

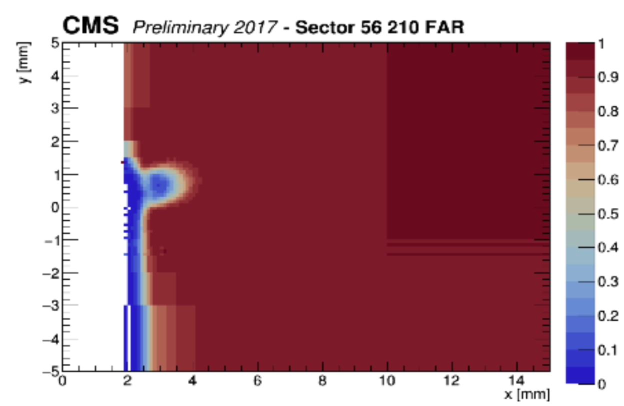
# Tracking: Si strip detector efficiencies



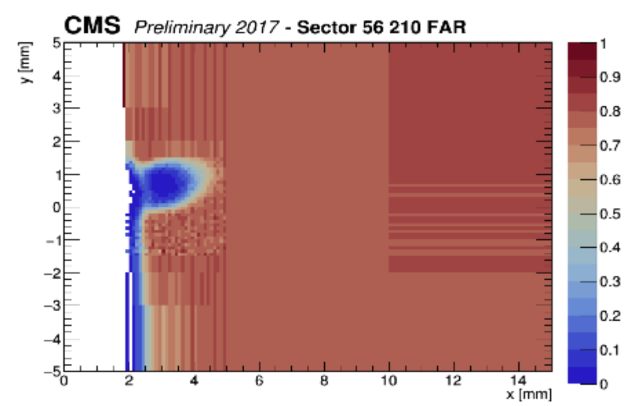

**Accumulated**
**$L_{int}$ = 0 - 9fb$^{-1}$**




**Accumulated**
**$L_{int}$ = 9 - 10.7fb$^{-1}$**




**Accumulated**
**$L_{int}$ = 10.7 - 18.5fb$^{-1}$**




**Accumulated**
**$L_{int}$ = 18.5 - 22.2fb$^{-1}$**