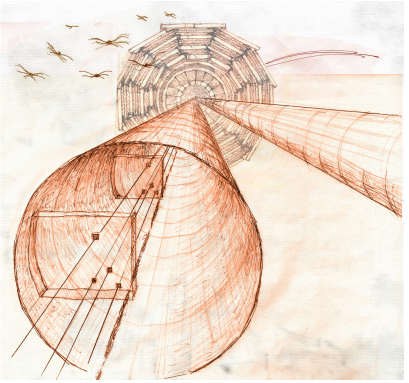
The CT-PPS Project

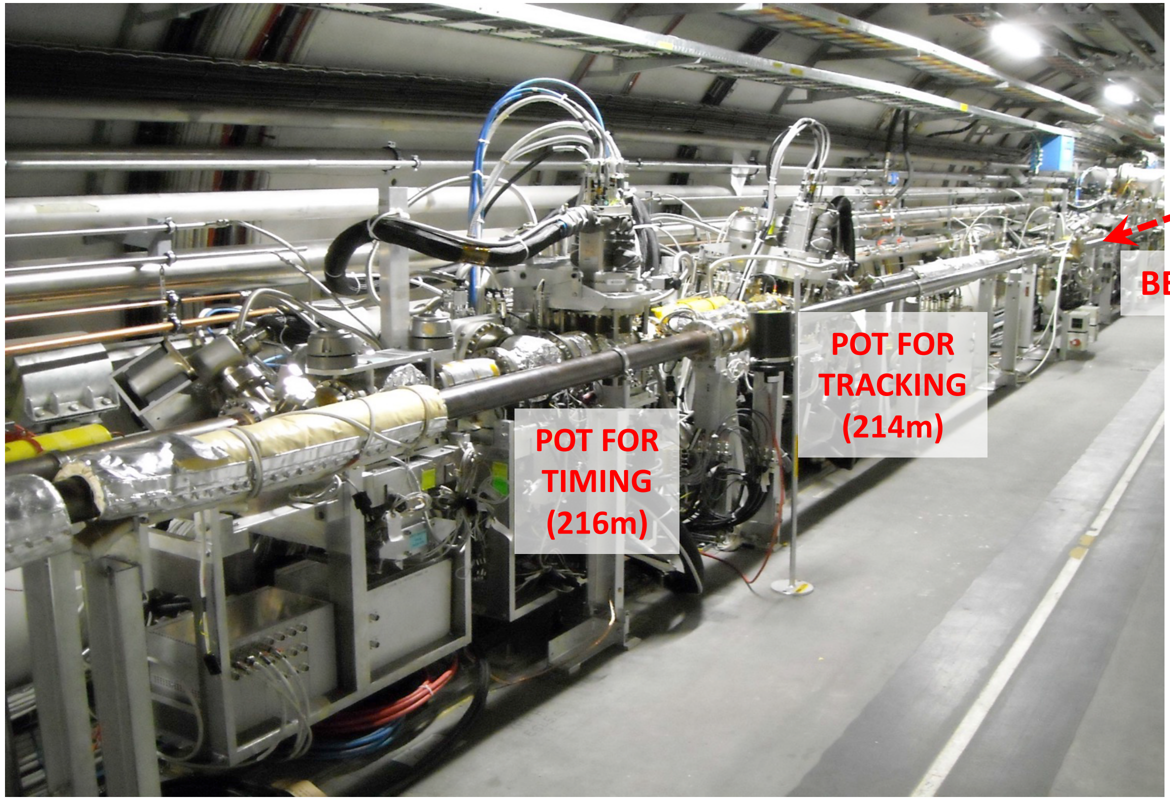
V. Sola on behalf of the CMS and TOTEM Collaborations

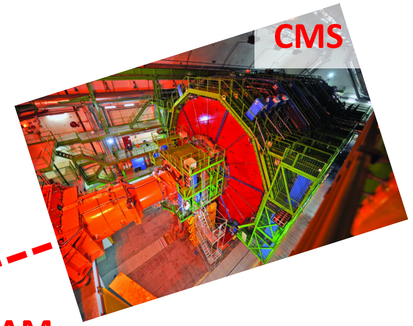
Università di Torino and INFN



OUTLINE

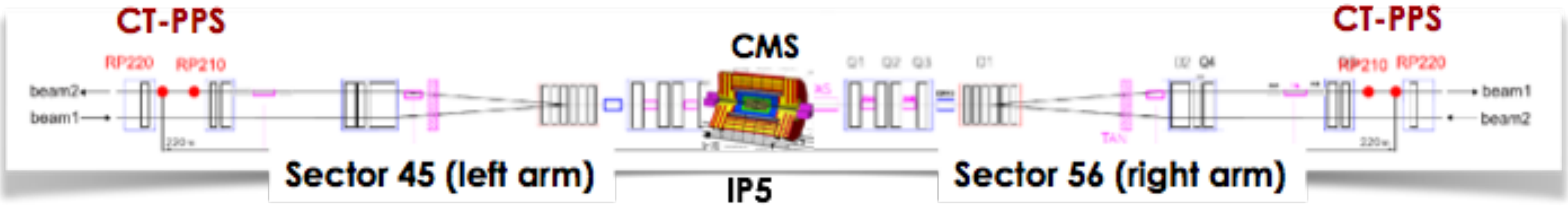
- **Project Overview**
- **Experimental Apparatus**
  - Silicon Strips
  - 3D Silicon Pixels
  - Diamonds
  - UFSD
- **Operation in 2017**
  - Tracking System
  - Timing System
- **Plans for 2018**





CT-PPS Project

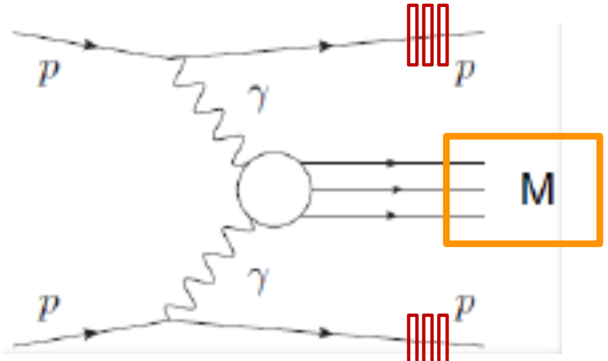
- The CMS TOTEM Precision Proton Spectrometer (CT-PPS) aims at measuring the surviving scattered protons on both sides of CMS in standard LHC running conditions, using LHC magnets to measure the proton momentum
- Tracking and timing detectors at ~ 220 m from CMS inside Roman Pots to be able to move as close as possible to the circulating beams
  - Tracking to measure proton momentum
  - Timing to disentangle pile-up
- CT-PPS took data in 2016 with an 'accelerated program' configuration
  - Si strip & Diamond detectors from TOTEM experiment for Tracking only
- CT-PPS started data taking with the designed detector configuration in May 2017
  - 3D Silicon Pixels & Strips for Tracking
  - Diamonds + UFSD for Timing



CT-PPS Physics Motivation

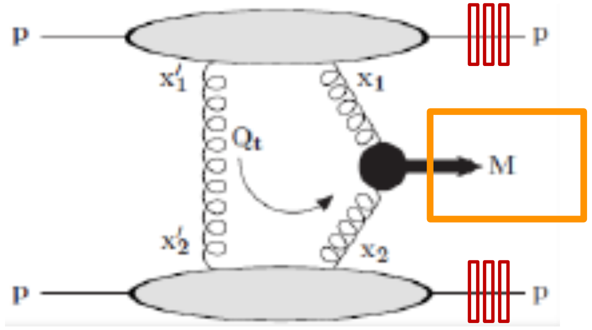
Experimental strategy

- High-p_T system detected by the **CMS central detector** together with very low angle scattered protons detected by **CT-PPS**
- Requiring the momentum balance between the central system and the detected protons creates strong kinematical constraints
- Central system mass is measured via the momentum loss of the two protons



Physics

- **EWK**: LHC as $\gamma\gamma$ collider with tagged protons
  - Measurement of $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
  - Search for aQGC with high sensitivity
  - Search for SM forbidden $ZZ\gamma\gamma$, $\gamma\gamma\gamma\gamma$ couplings
- **QCD**: LHC as gg collider with tagged protons
  - Exclusive two- and three-jets event
  - Tests of pQCD mechanism of exclusive production
  - Gluon jet samples with small component of quark jet
- **BSM**
  - Clean events (no underlying pp events)
  - Independent mass measurement by pp system
  - J^{PC} quantum numbers 0^{++}, 2^{++}



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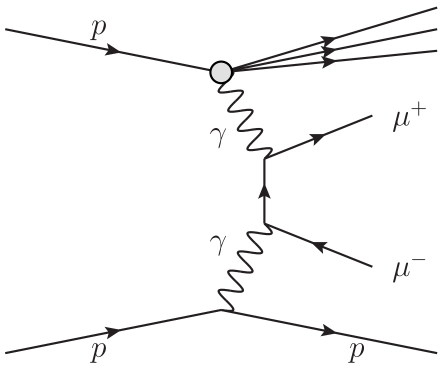
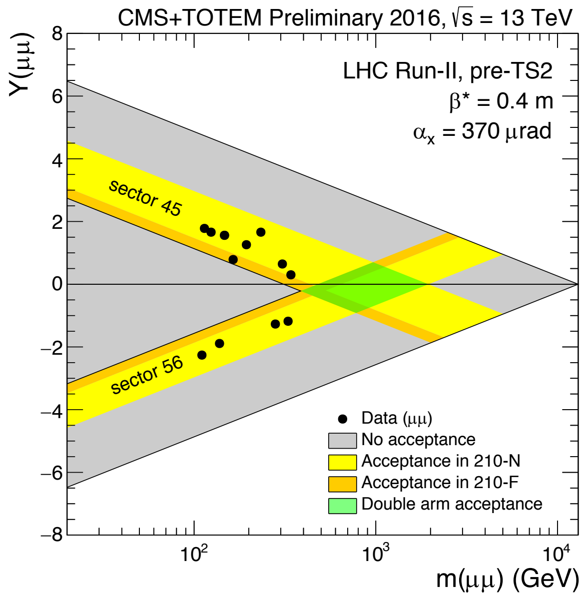
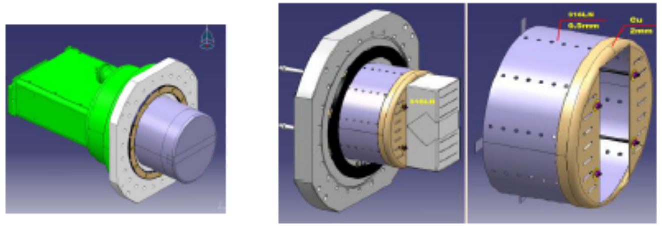




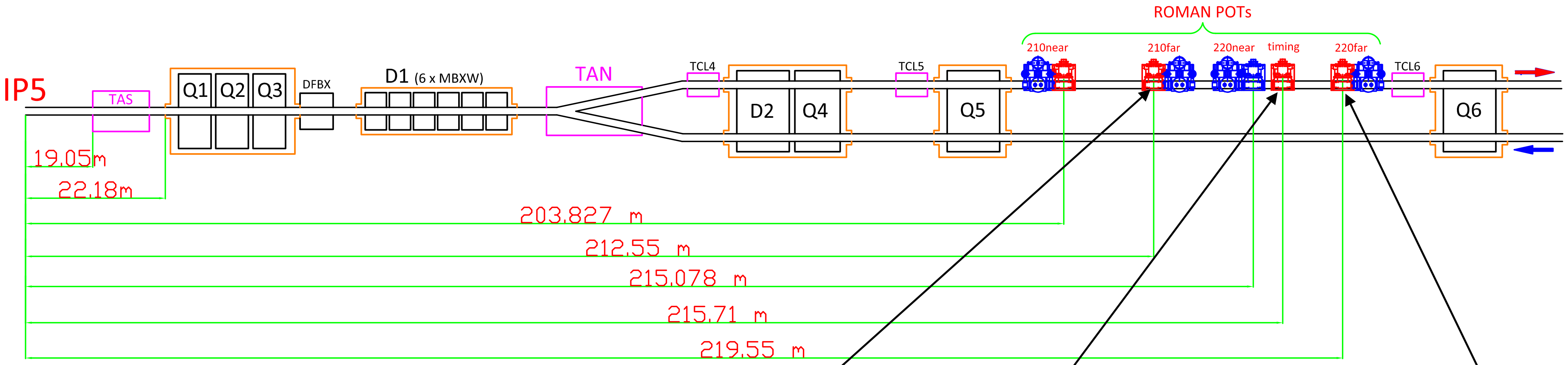
[The CMS and TOTEM Collaborations, CMS PAS-PPS-17-001, TOTEM NOTE-2017-003]

CT-PPS Experimental Apparatus

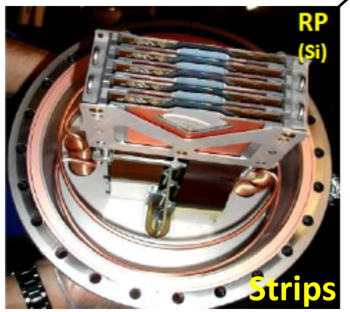
- Roman pot stations
  - 2 horizontal pots at 213 m and 220 m for Tracking
  - 1 horizontal pot at 216 m for Timing

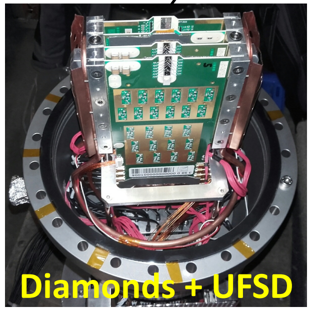


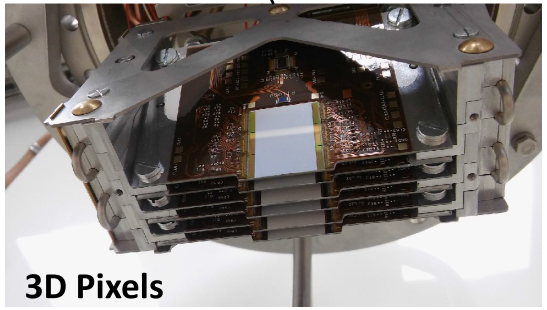
CT-PPS Horizontal Cylindrical RP (low impedance, can approach the beam avoiding instabilities)



In 2017 CT-PPS run at
12 σ_{beam} + 0.3 mm distance from the beam
(minimum allowed distance is 1.5 mm)



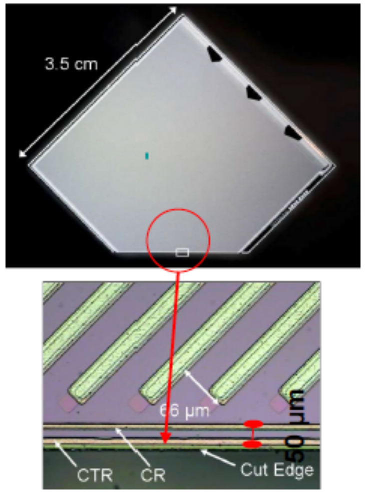


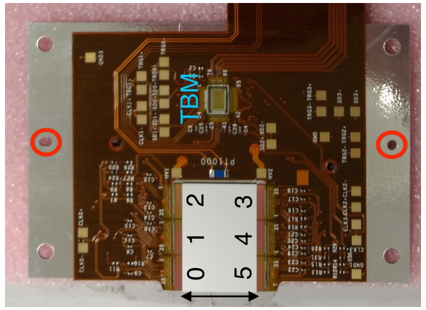


Detectors in 2017

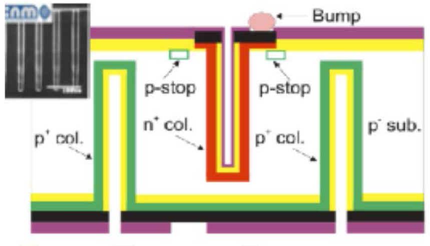
Tracking detectors

- Aim: measure proton momentum
  - Detailed knowledge of the LHC optics required
- Technologies:
  - Silicon Strips
  - 3D Silicon Pixels (radiation hard, high granularity and 'edgeless')





1.6 cm

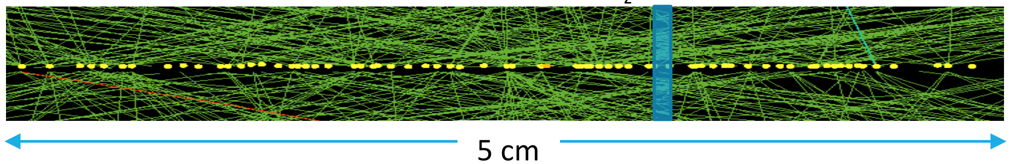


Timing detectors

- Aim: disentangle primary vertex from pileup

$\sigma_{time} \sim 20$ ps $\rightarrow \sigma_Z \sim 4$ mm

$\sigma_z \sim 4$ mm

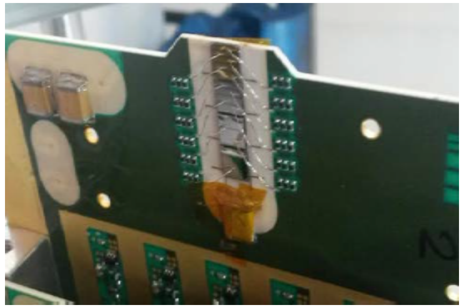


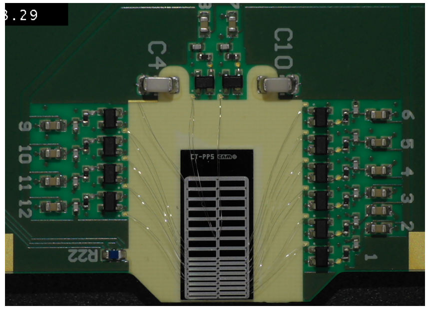
5 cm

$$\sigma_{z_{vtx}} = \frac{c}{2}\sqrt{2\sigma^2_{\Delta t}} \overset{\sigma_{\Delta t}=10\text{ps}}{\approx} 2 \text{ mm}$$

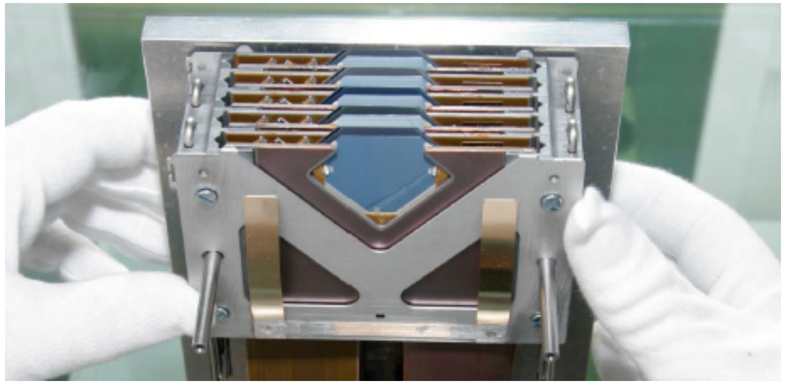
$$\overset{\sigma_{\Delta t}=30\text{ps}}{\approx} 6 \text{ mm}$$

- Technologies:
  - 3 Diamond planes
  - 1 Ultra-Fast Silicon Detector (UFSD) plane





Tracking Detector - Silicon Strips

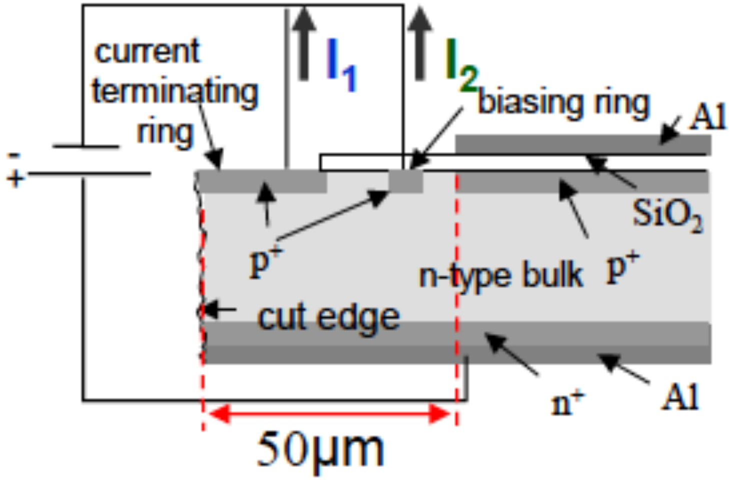


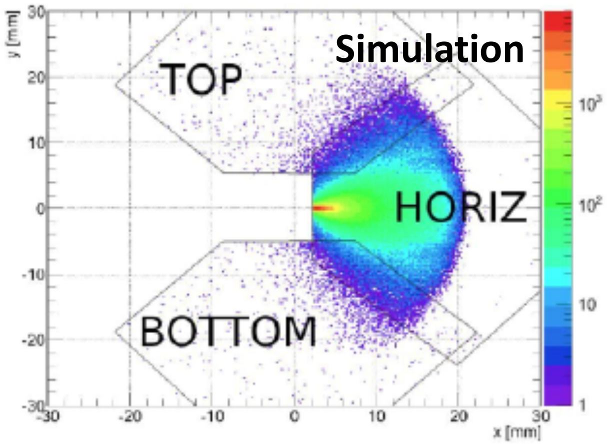
10 planes per pot of silicon strip detectors
- 512 strips at $\pm$ 45°
- Pitch: 66 μm
- Resolution ~ 20 μm
- Lifetime up to an integrated flux of 5×10^{14} p/cm^2
  → too low for CT-PPS requirements, detector pushed to its limits

Micro-strip silicon detectors with edgeless technology (inactive edge ~ 50 μm)

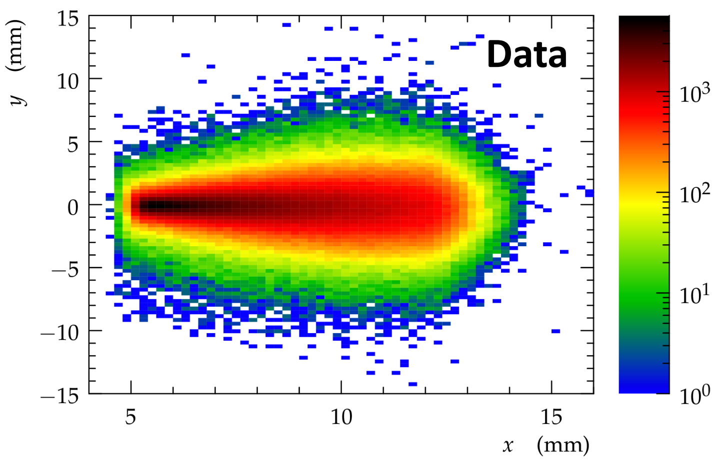
Hit/track reconstruction using consolidated TOTEM algorithms (software fully integrated in CMS official software)

Planar technology + CTS (Current Terminating Structure)





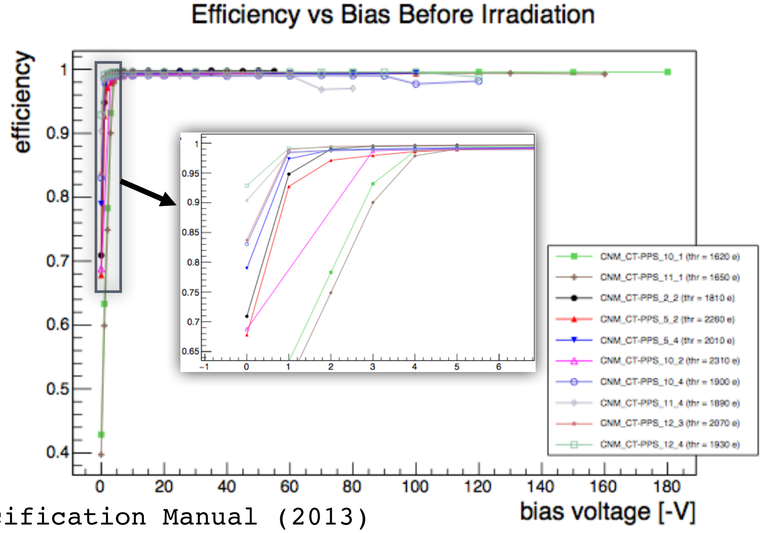
CMS+TOTEM Preliminary 2016, $\sqrt{s}$ = 13 TeV

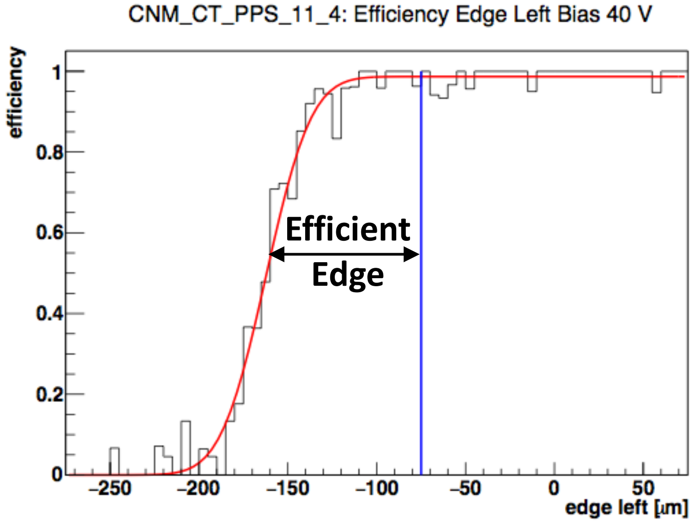


Tracking Detector - Silicon 3D Pixels

6 planes per pot of 3D silicon pixel detectors

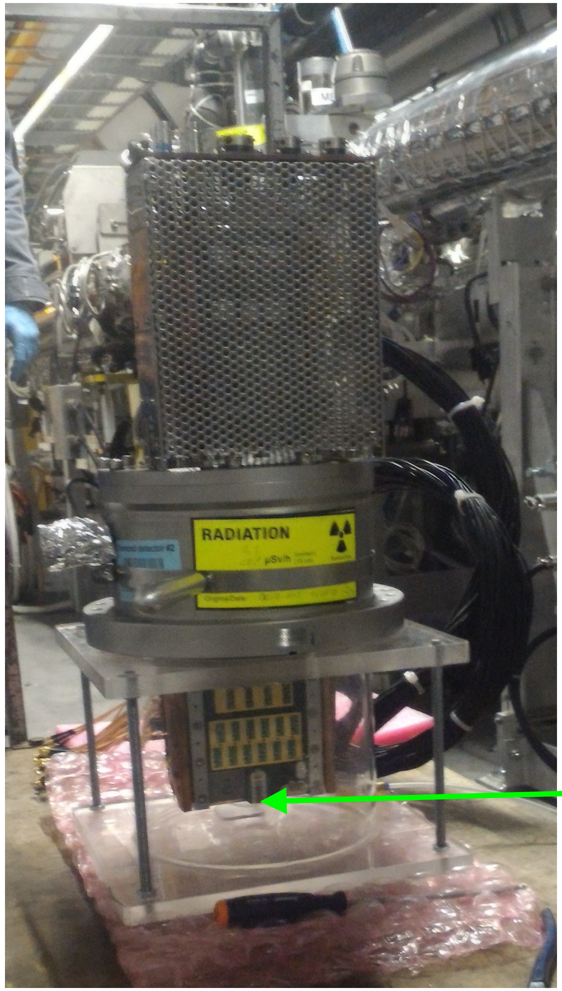
- 3D sensor in double-sided not fully passing-through technology
- Intrinsic radiation hardness → to withstand overall integrated flux of 5×10^{15} p/cm^2
- 200 μm slim edge → to approach the beam as much as possible
- Pixel dimensions: 100x150 μm^2 → very high granularity
- Resolution < 30 μm
- Planes tilted by 18.4° to optimize efficiency and resolution
- Front-end chip: latest version of PSI46dig[1], same as for new CMS Pixel detector
- Very good performances, bad pixels (efficiency < 90%) less than 0.05% of all channels





[1] F. Meier, psi46dig pixel chip External Specification Manual (2013)

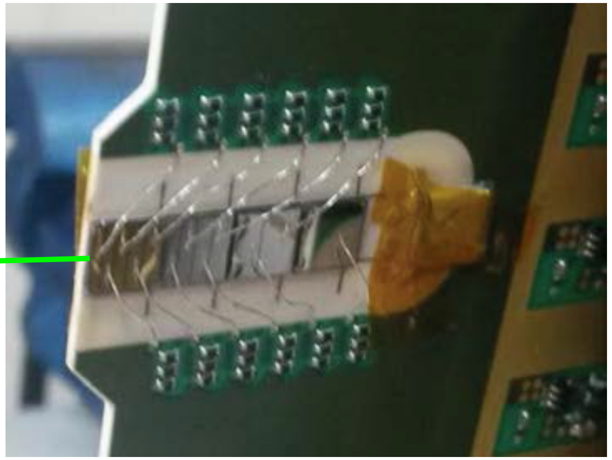
Timing Detector - Diamonds

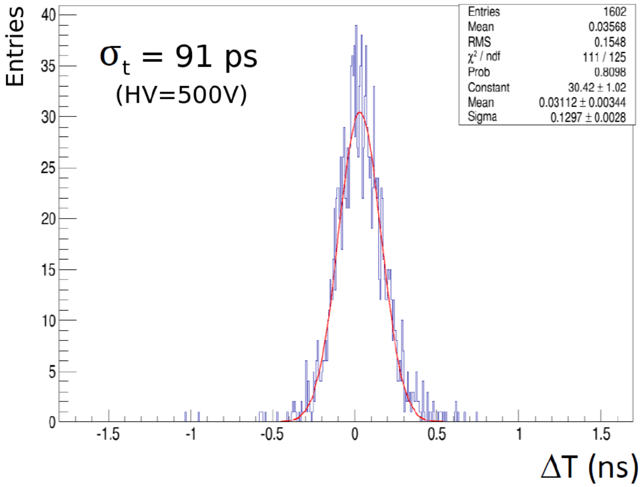


3 planes per pot of scCVD Diamonds

- Four 4x4mm^2 diamond sensors per plane, with different pad patterns
- Intrinsic radiation hardness → to withstand overall integrated flux of 5x10^{15} p/cm^2
- Allow for high granularity (wrt to, e.g., quartz)
- Time resolution ~ 80 ps per plane
- Amplification with TOTEM hybrid[2]
- Readout with NINO chip[3] + HPTDC[4]

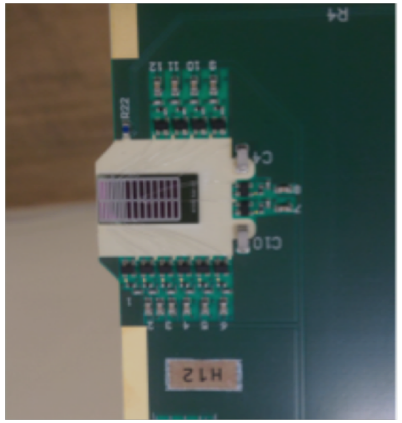
[2] TOTEM Coll., JINST 12 (2017) P03007
[3] F. Anghinolfi et al., NIM A 533 (204) 183
[4] M. Mota and J. Christiansen, IEEE JSSC 34 (1999) 1360





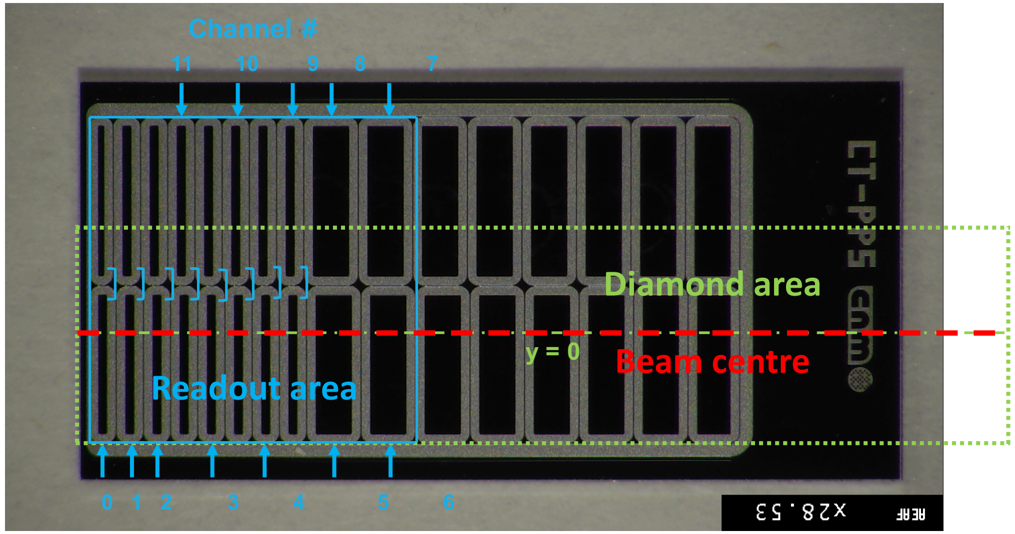
Time resolution for the detector prototype as measured in the LHC test run in 2015

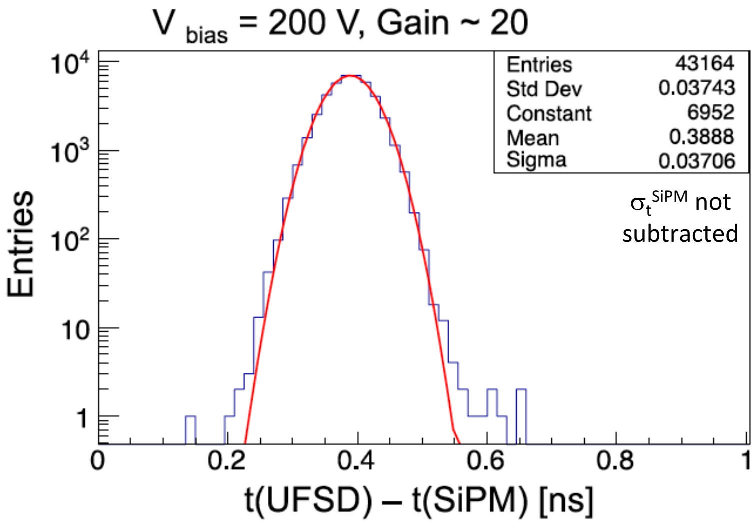
Timing Detector - UFSD



1 plane per pot of UFSD - **First installation in HEP**

- ▻ Eight 0.5x6mm^2 pads, four 1x3mm^2 pads
- ▻ Radiation hardness still an issue → in RP environment (T > 30^{o}C) lifetime $\lesssim 10^{15}$ p/cm^2
- ▻ Allow for high granularity (wrt to, e.g., quartz)
- ▻ Time resolution ~ 35 ps per plane
- ▻ Amplification with modified TOTEM hybrid[2]
- ▻ Readout with NINO chip[3] + HPTDC[4]

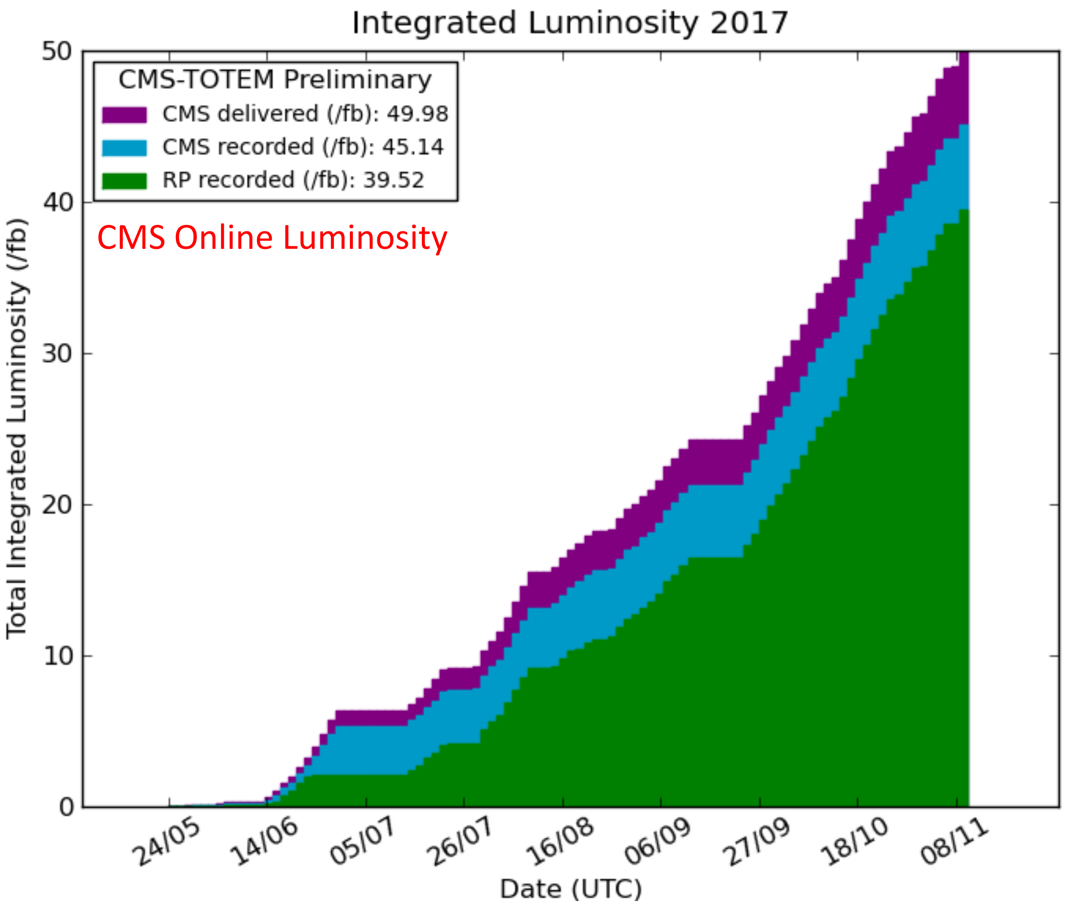




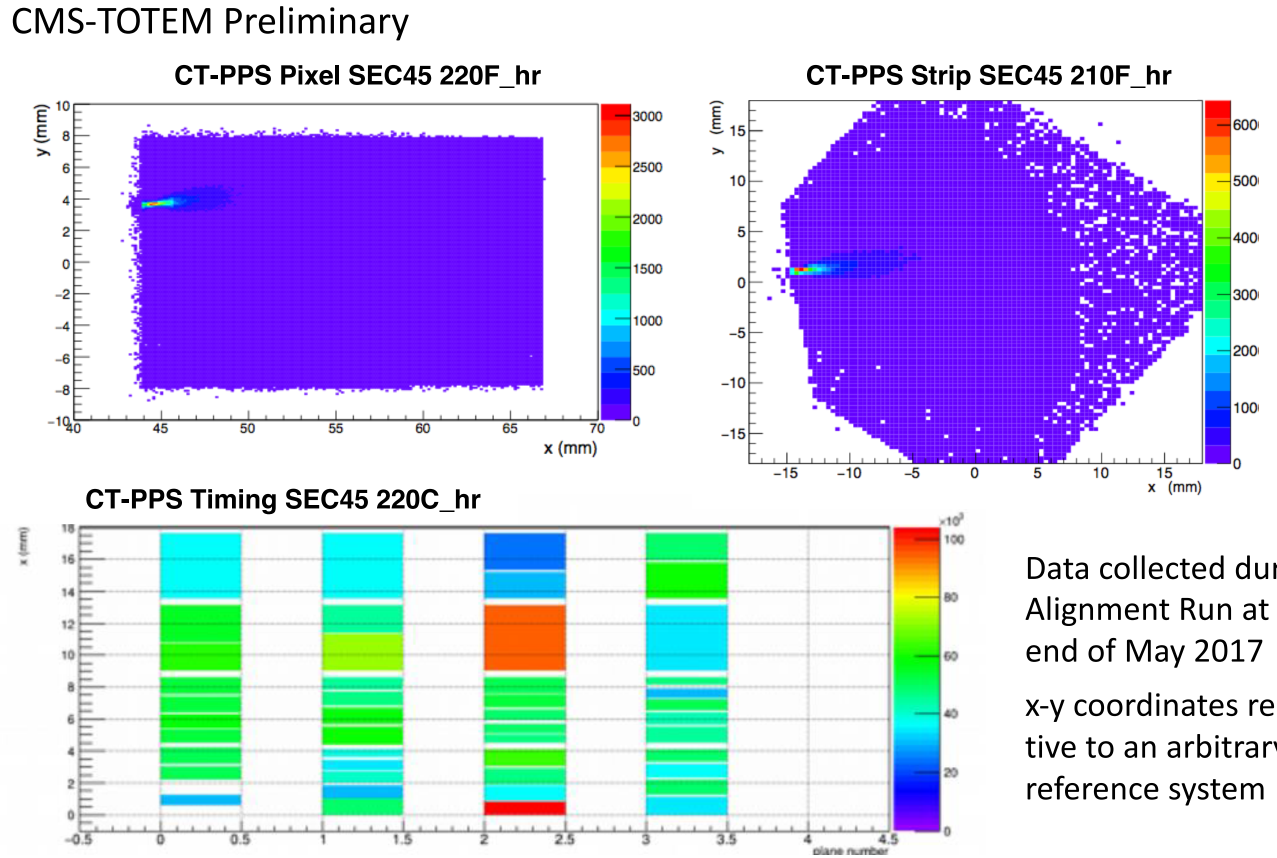
[N. Cartiglia et al., NIM A 850 (2017) 83]

2017 Data Taking

- CT-PPS collected ~ 88% of the full statistics recorded by CMS in 2017
- Very good quality of data collected by CT-PPS



Hit distributions for detectors in Sector 45

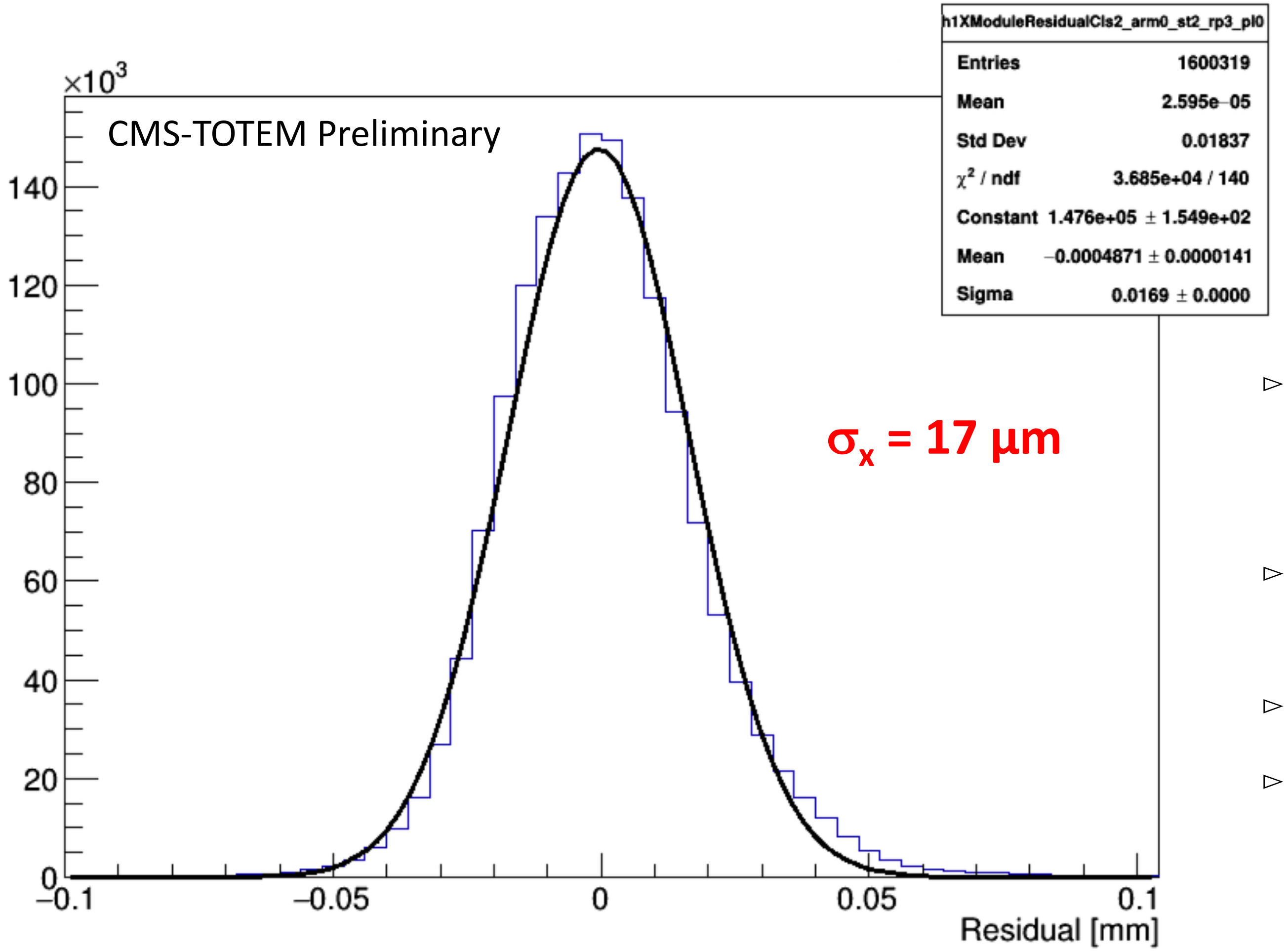


Data collected during Alignment Run at the end of May 2017

x-y coordinates relative to an arbitrary reference system

2017 Data Taking - Tracker Performances

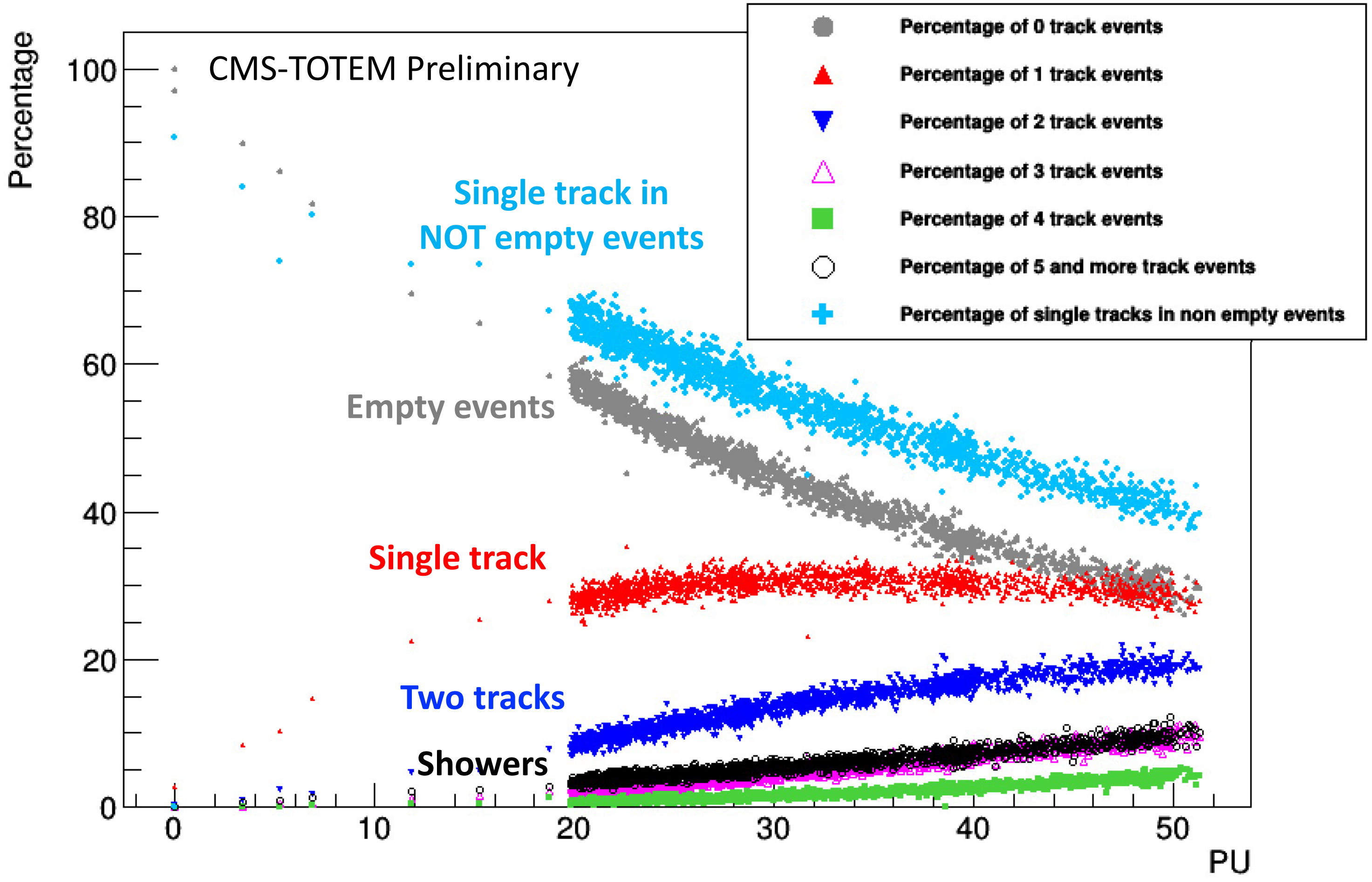
➢ Hit residual for **Pixel plane**



- Hit residuals for single planes are evaluated with respect to the local track reconstructed in the Pixel RP
- Residuals are consistent with those obtained at the beam tests
- **The pixel tracker works as expected**
- Track resolution under final evaluation

2017 Data Taking - Tracker Performances

➢ Reconstructed tracks as a function of Pile-Up (PU) from **Pixel detector** (Sector 45)

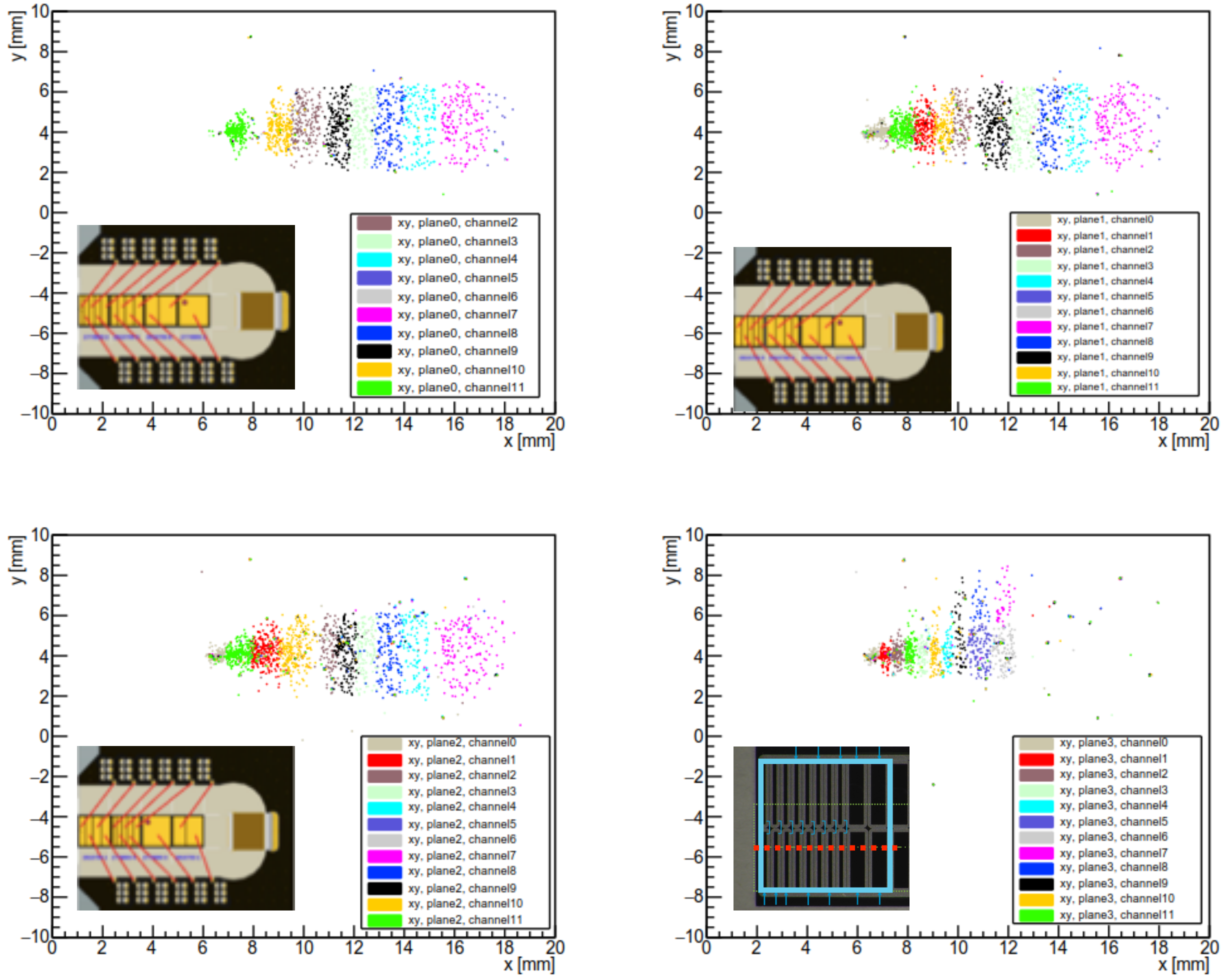


- The number of tracks reconstructed by the pixel detector shows a clear correlation with the number of PU events
- Due to the high pile-up of 2017 run, the percentage of single tracks for events with activity in the pot goes down to 40%, **showing the advantage of a pixel detector with respect to a strip one**
- The percentage of showers (tracks ≥ 5 - empty black points) is directly proportional to PU and at the maximum instantaneous luminosity reaches 10%

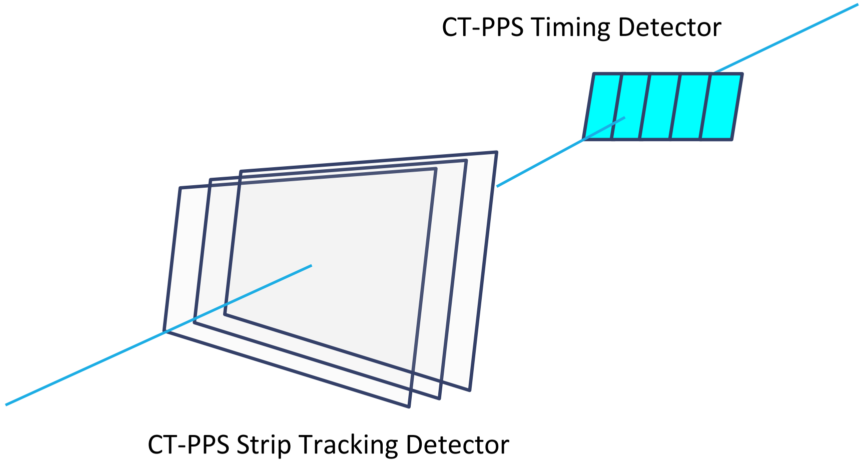
2017 Data Taking - Timing Performances

- Tomography of the **Timing Detectors**

CMS-TOTEM Preliminary



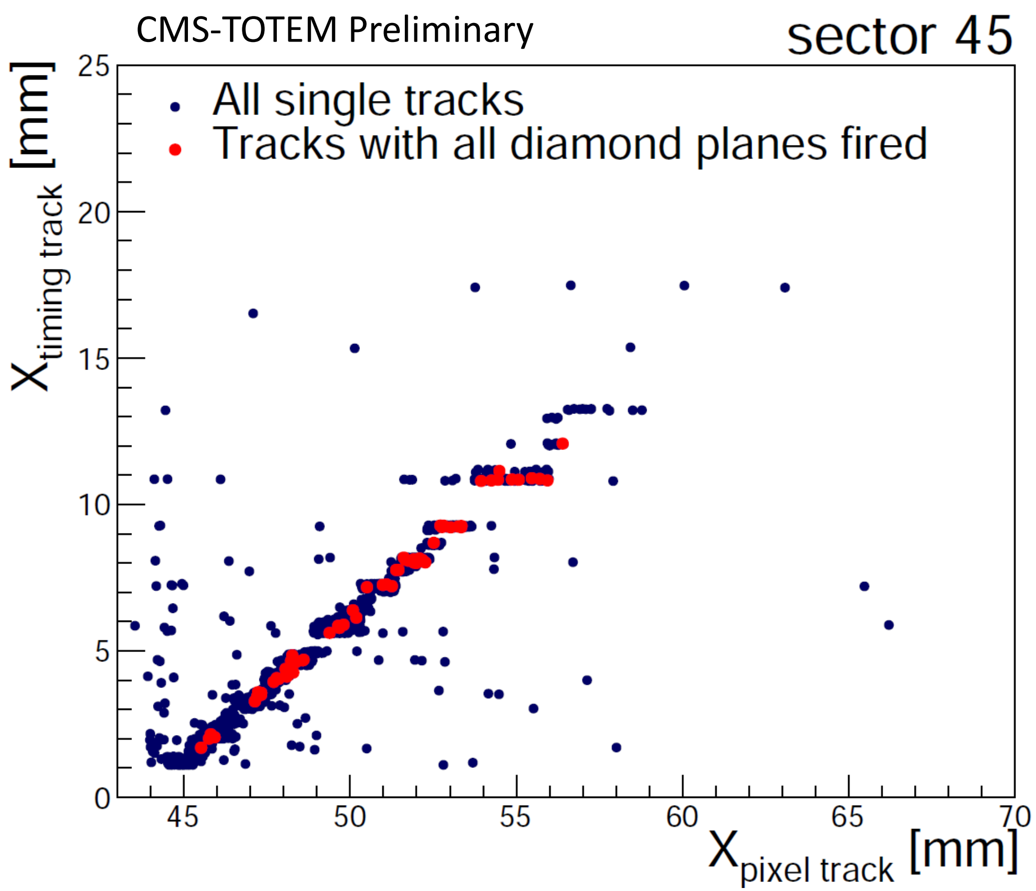
- Track distribution in the Strip detector when there is a hit in one channel of the Timing detector



- **Good correlation between Timing and Tracking detectors**

2017 Data Taking - Timing Performances

➢ Correlation between tracks measured in the **Pixel** and the **Timing detectors**

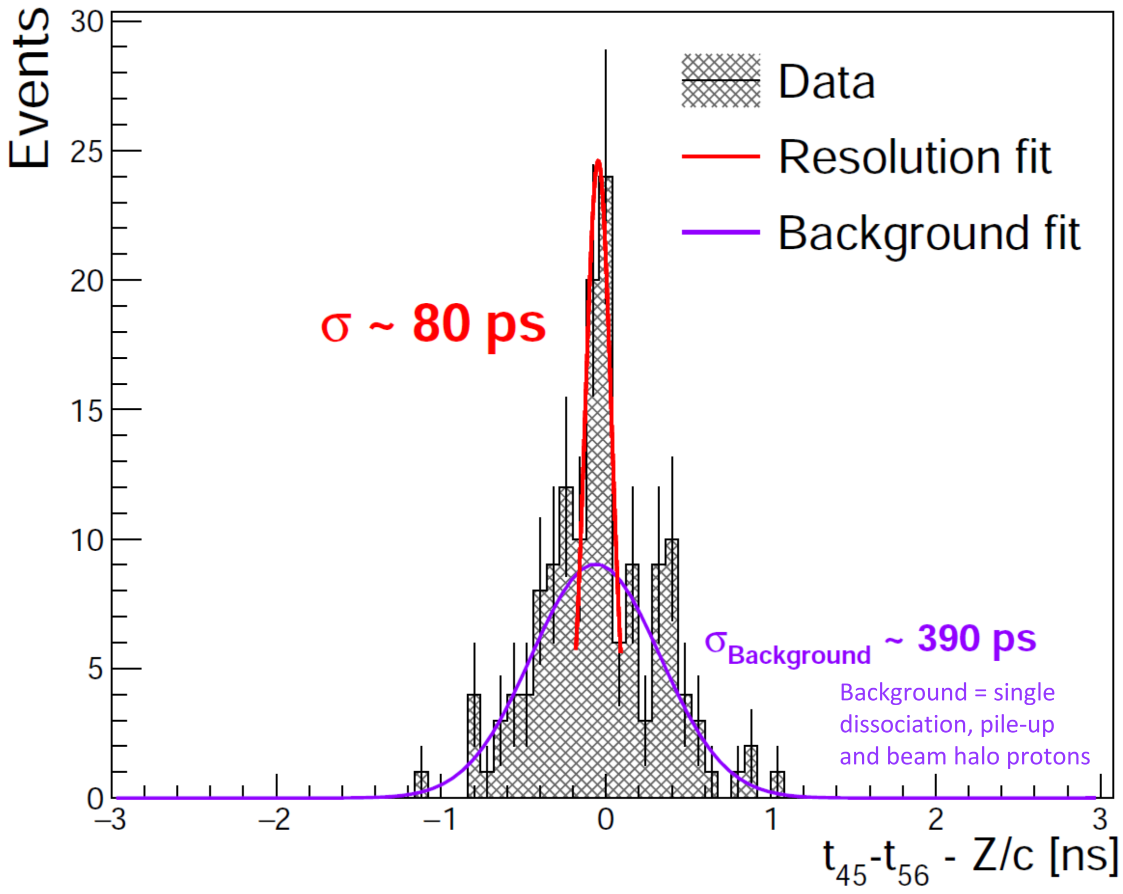


- The horizontal position of the reconstructed track in the CT-PPS Pixel detector versus the horizontal position of the tracks reconstructed using CT-PPS Timing detector information in low Pile-Up data (<PU> ~ 0.8)
- The data sample is selected by requiring a single vertex reconstructed in CMS, a single track reconstructed in CT-PPS pixel detector in each of the arms and a single track reconstructed in CT-PPS timing detector in each of the arms
- The **blue points** show all events passing the double arm selection
- The **red points** represent a subsample of the previous selection, in which all Diamond detector planes were fired, with a single hit per plane

2017 Data Taking - Timing Performances

➢ Time resolution of the CT-PPS **Diamond Timing detector** measured using low pileup data (<PU> ~ 0.8)

CMS-TOTEM Preliminary



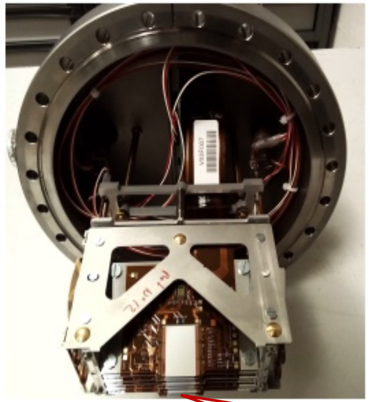
- The data sample is selected by requiring a single vertex reconstructed in CMS, a single track reconstructed in the CT-PPS pixel detector, and a single hit per plane in CT-PPS diamond planes on each arm
- In addition, the total mass of CMS particle flow objects is required to be greater than 320 and less than 1500 GeV (double-arm acceptance region of CT-PPS)
- For the time difference between the two arms, the average between the leading edge times of the planes on each arm is used, corrected for the time of flight difference due to the longitudinal position of the CMS vertex (Z/c, where c is the speed of light).

☞ **σ ~ 80 ps is compatible with a time resolution of 57 ps per arm**

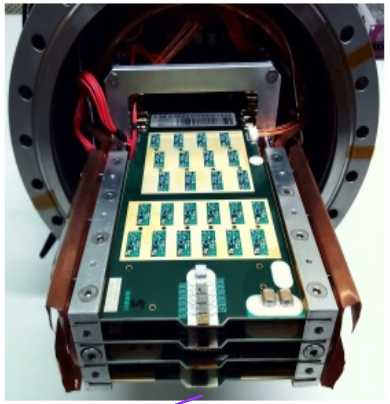
CT-PPS Experimental Apparatus in 2018

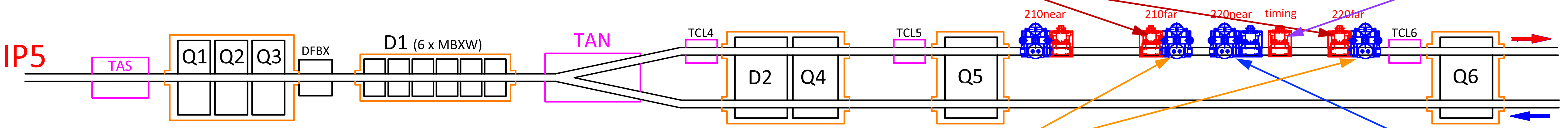
- CT-PPS → High Luminosity Runs
  - 3D Silicon Pixels for Tracking
  - Diamonds + Double Diamonds for Timing
- CMS-TOTEM → Low Luminosity special Runs
  - Silicon Strips for Tracking
  - UFSD for Timing

6 planes of 3D Silicon Pixel Detectors [H]



2 planes of Diamond + 2 planes of Double Diam. Detectors [H]



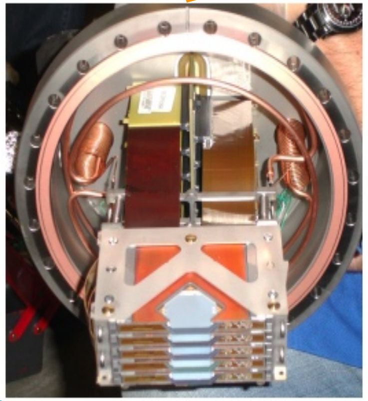


[H] CT-PPS Horizontal Roman Pots for high lumi - low β* runs (high PU)

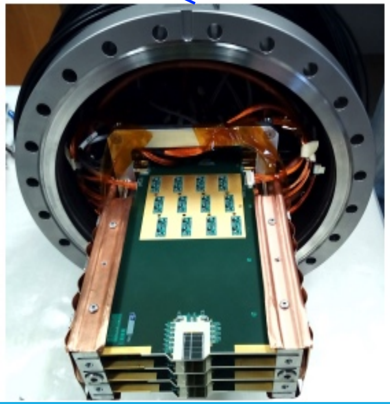
[V] CMS-TOTEM Vertical Roman Pots for low lumi - high β* runs (low PU)

→ to access central exclusive production of low mass systems

10 planes of Silicon Strip Detectors [V]



4 planes of UFSD [V]



SUMMARY

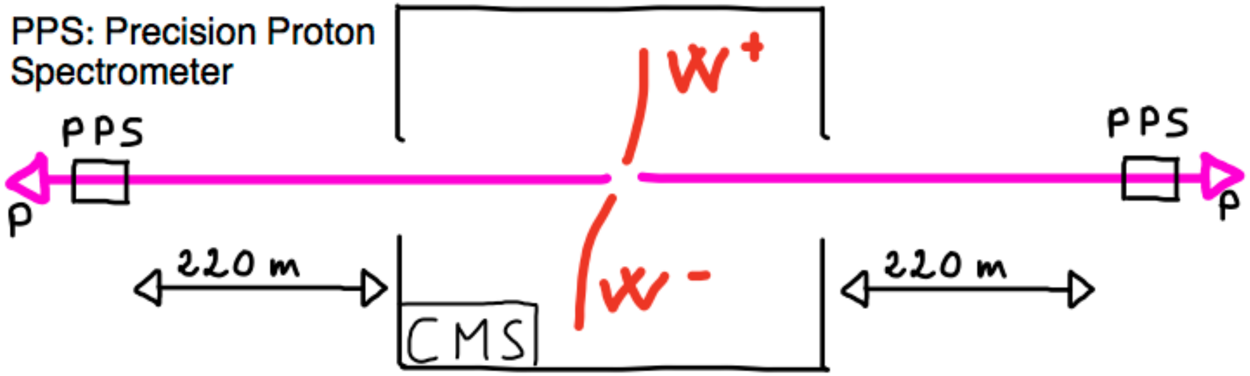
- ➢ 2016 CT-PPS with an ‘Accelerated Program’
  - ▻ Silicon Strips + scCVD Diamond Detectors used
  - ▻ 15 fb^{-1} of high quality Data @ $\sqrt{s}$ = 13 TeV collected
    - ✎ First evidence for proton tagged, central muon pairs production [CMS PAS-PPS-17-001, TOTEM NOTE-2017-003]
- ➢ 2017 CT-PPS Detector Configuration
  - ▻ 4 different detector technologies
  - ▻ 40 fb^{-1} of high quality Data @ $\sqrt{s}$ = 13 TeV collected
  - ▻ All detectors worked as expected
    - ✎ Tracking hit residuals → $\sigma_x \sim 17$ **μm**
    - ✎ Time resolution per plane → $\sigma_t \sim 57$ **ps**
- ➢ 2018 CT-PPS Installation ongoing

☞ **Many more high quality data to come!**

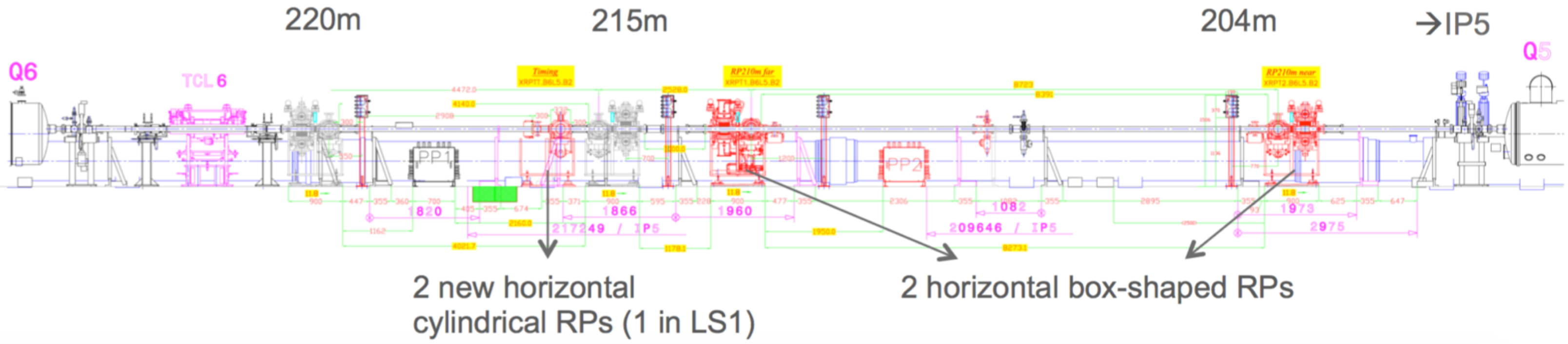
BACKUP

CT-PPS: CMS-TOTEM PRECISION PROTON SPECTROMETER

A proton spectrometer to study central exclusive production at the LHC

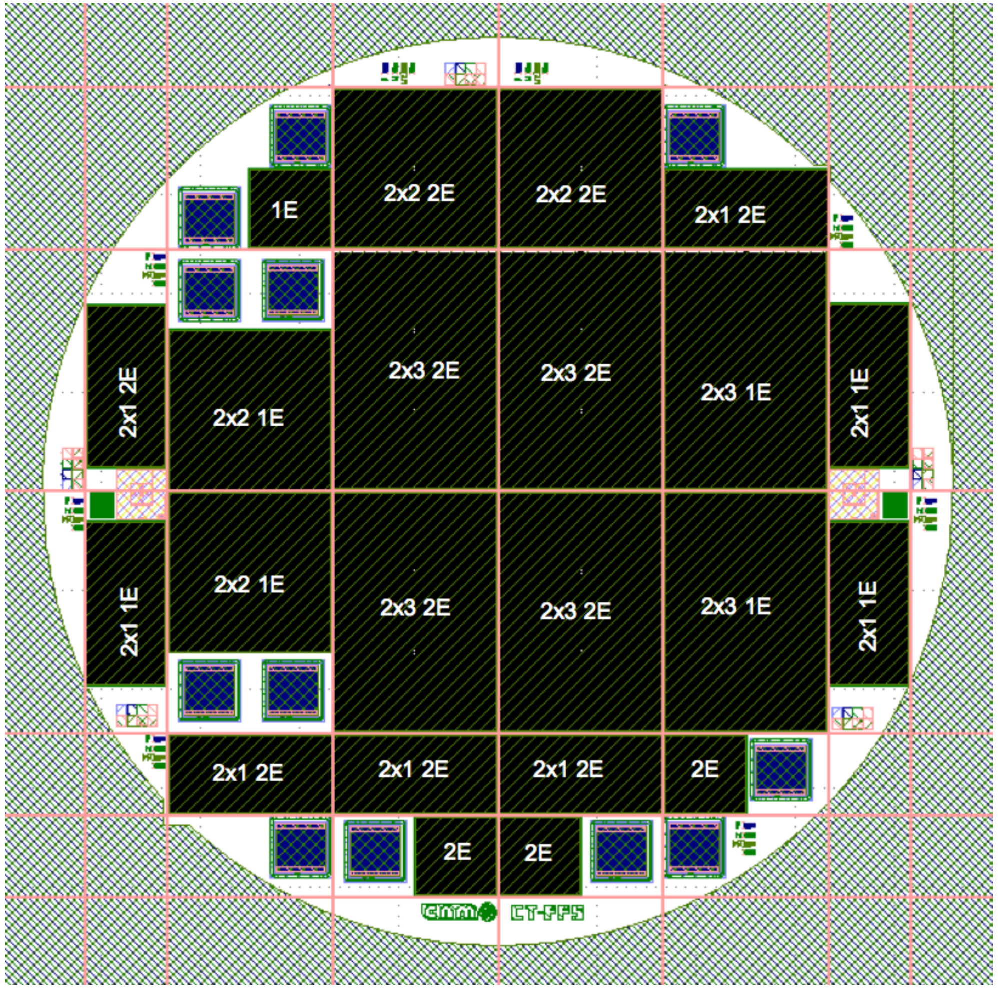


CT-PPS consists a silicon tracking system to measure the position and direction of the protons, and a set of timing counters to measure their arrival time



Tracking Detector - Silicon 3D Pixels

3 batches of 12 wafers each have been produced at CNM



Specifications to qualify the devices:

Define: $V_{op} = V_{depl} + 10$ V where V_{depl} and V_{op} are the full depletion and operation voltages, respectively

The following specifications, taken at room temperature (20-24°C), qualify a device as functioning correctly:

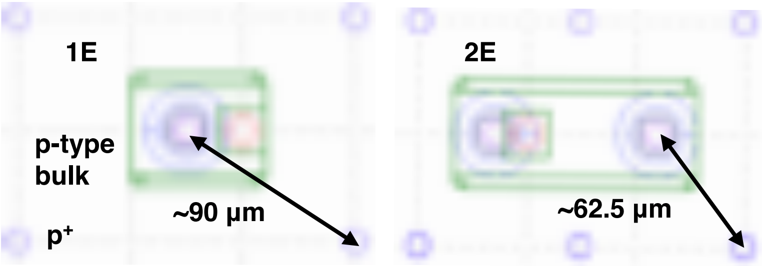
- **V_{depl} < 20 V**
- Breakdown voltage **V_{bd} > 35 V**
- **I(25V) / I(20V) < 2**

Current at operation voltage:

Class A I (V_{op}) < 2 µA per tile

Class B 2 µA < I (V_{op}) < 10µA per tile

Class C I (V_{op}) > 10 µA per tile



Tracking Detector - Silicon 3D Pixels

Sensor IV curves have been measured on wafer before bump-bonding by means of a temporary metal deposition to short all the pixels

First batch of 12 wafers completed in December 2015

In general good quality sensors but low yield, in particular of the class A ones.

Pixel configuration	Class A	Class B	Class A + B	2E + 1E
3x2 2E	3	10	13	22
3x2 1E	7	2	9	
2x2 2E	4	9	13	24
2x2 1E	6	5	11	
			Total	46

Second batch production completed in May 2016

Problematic, probably due to the p-stop implantation → values of breakdown voltage too low to allow using the sensors

To recover the production a low-dose neutron irradiation is under study

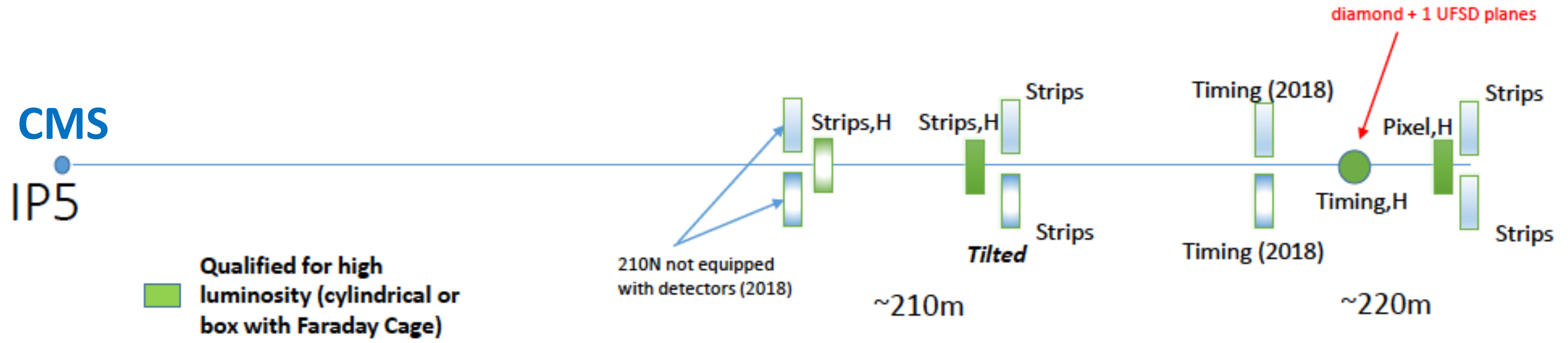
Third batch production completed in June 2017.

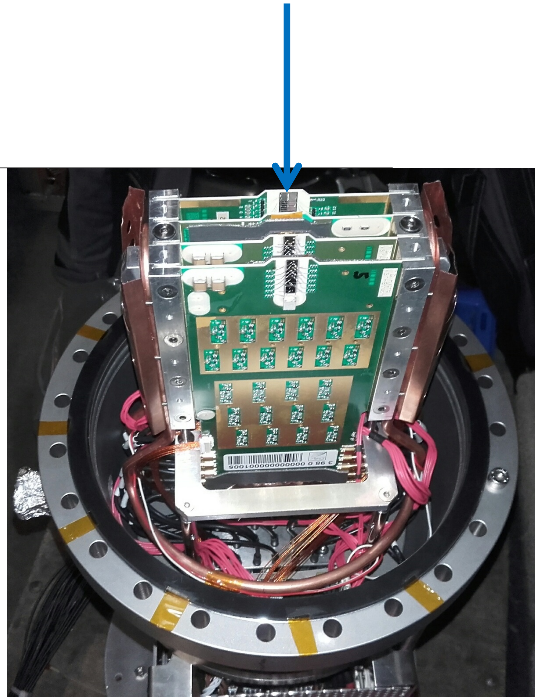
Sensors showed a large leakage current that would classify all the modules as **class C**

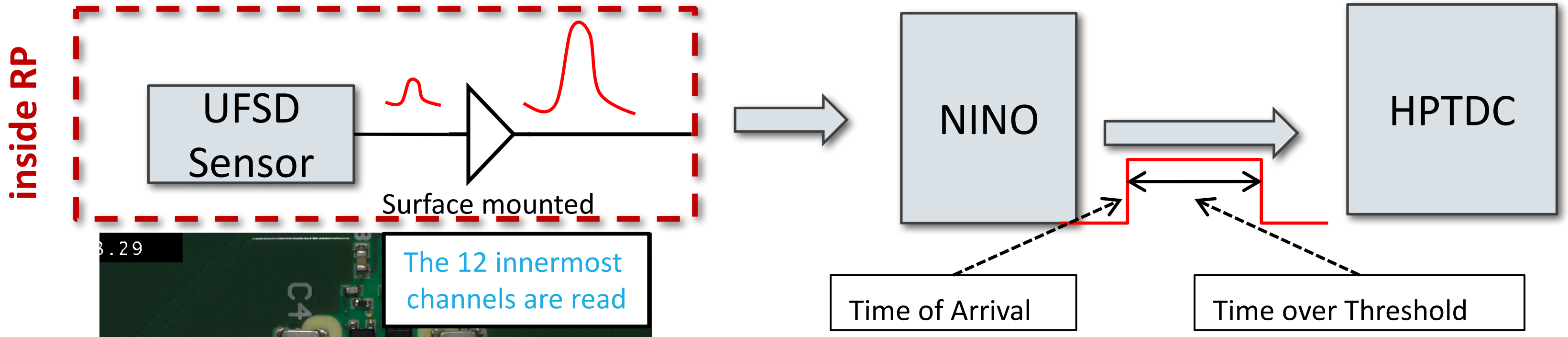
After discussing with the psi46dig chip designers it has been decided to relax the current limit above the ROC specifications and accept sensors with a leakage current up to 400 μA per tile

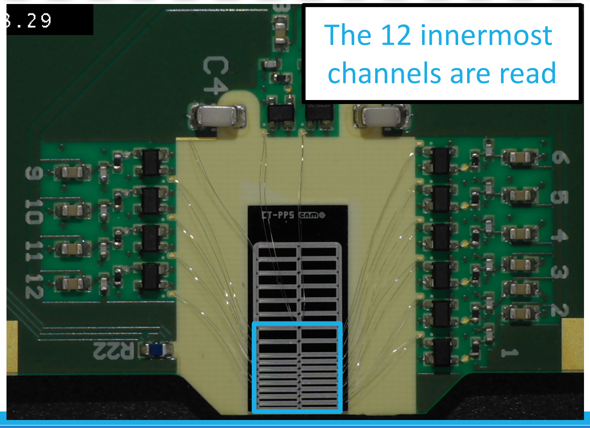
→ Further ~50 modules are available

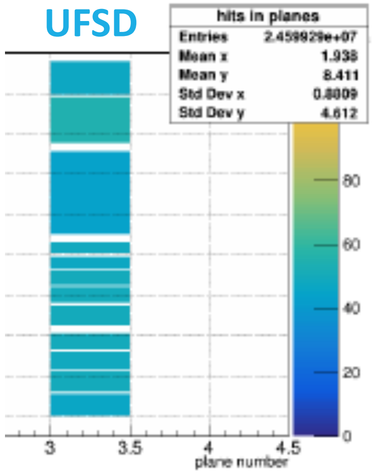
First UFSD Installation at CT-PPS











Run 294737
Sun 21, 21:36

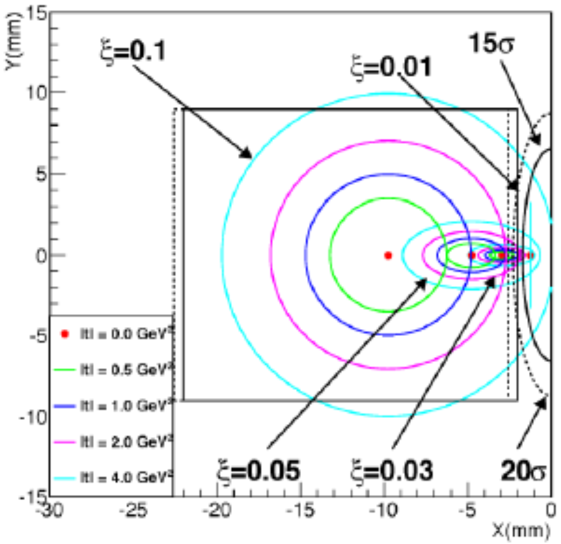
DQM Plot from UFSD plane in RP Sector 56

UFSD working properly

Roman Pot Insertion

- The insertion of Roman Pots inside the LHC beam pipe is a delicate procedure that needs to be tested and approved by the machine
- The minimum distance of approach to the beam dramatically affects the detector acceptance and therefore the physics reach
- In 2016 CT-PPS ran at $15\sigma_{beam}$ from the beam in nominal runs at the maximum available luminosity
- In 2017 CT-PPS runs at $12\sigma_{beam}$ + 0.3mm from the beam to reach ~ same kinematic coverage as in 2016 (minimum allowed distance from the beam is 1.5mm)

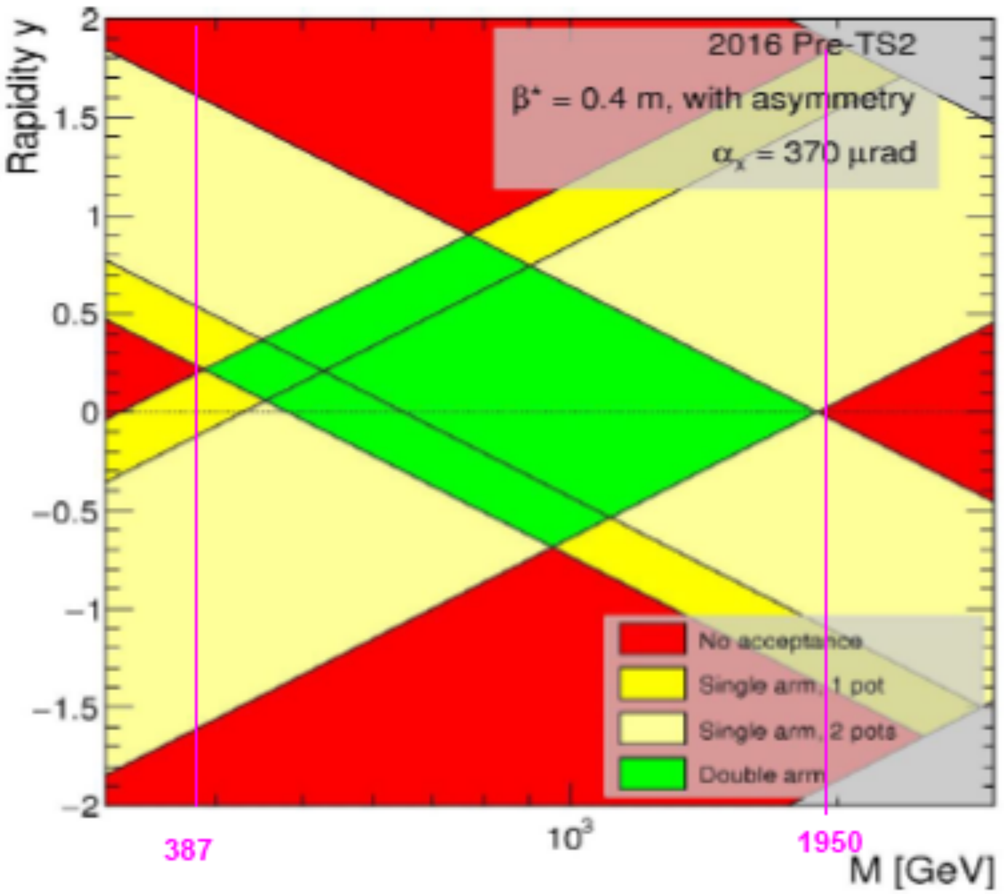
To be monitored during the runs
- beam losses/showers and interplay with collimators
- impact on impedance
  - heating
  - vacuum stability
  - beam orbit stability



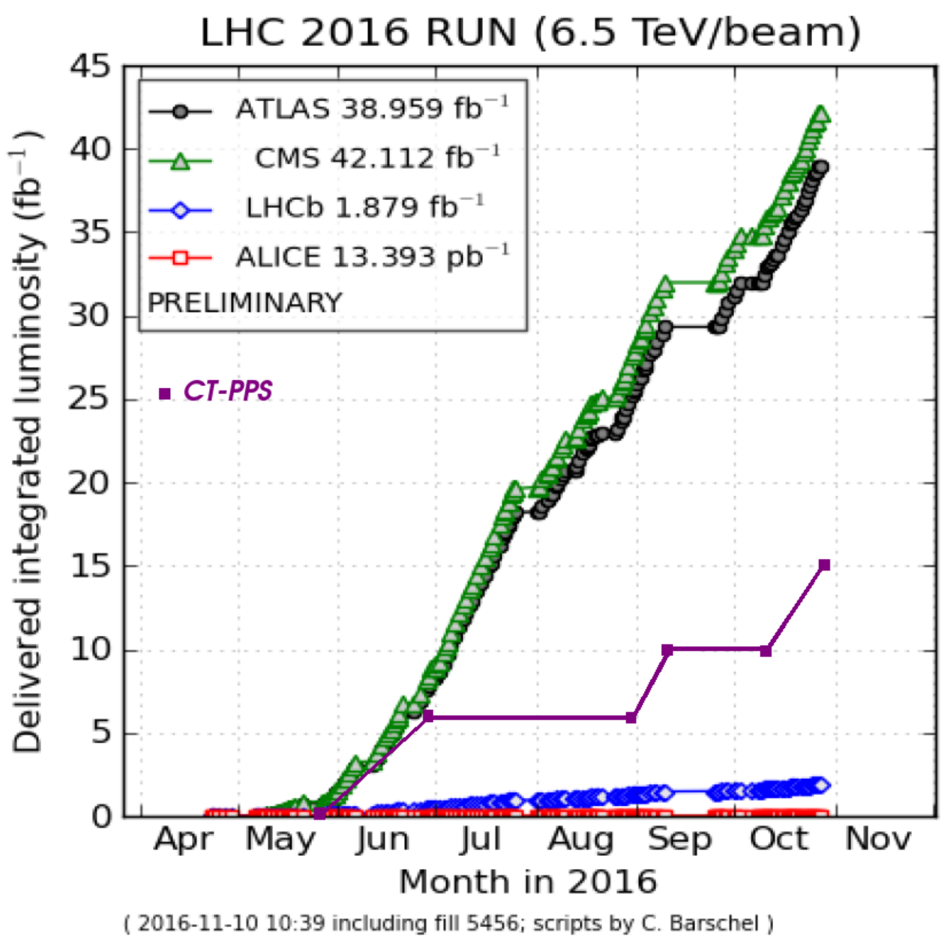
Detector acceptance in 214m RP (X as of CMS) from CT-PPS TDR [TOTEM-TDR-003, CMS-TDR-13]

2016 Data Taking

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

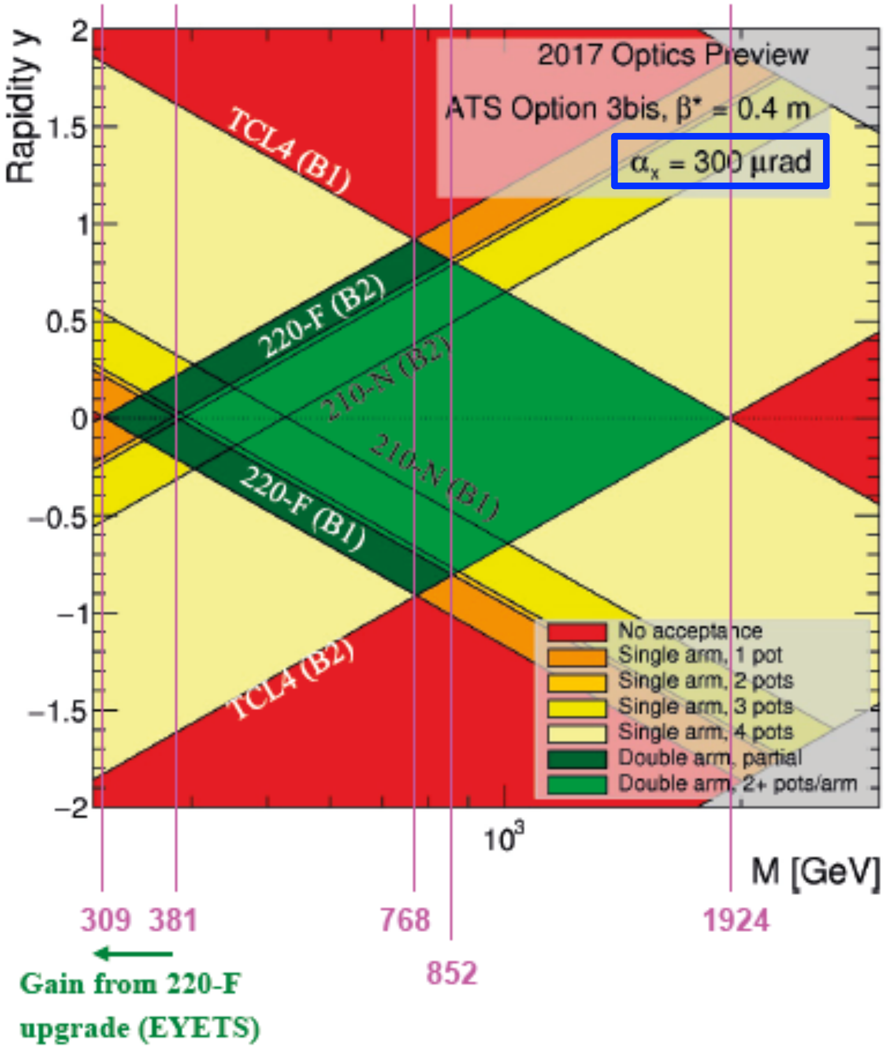


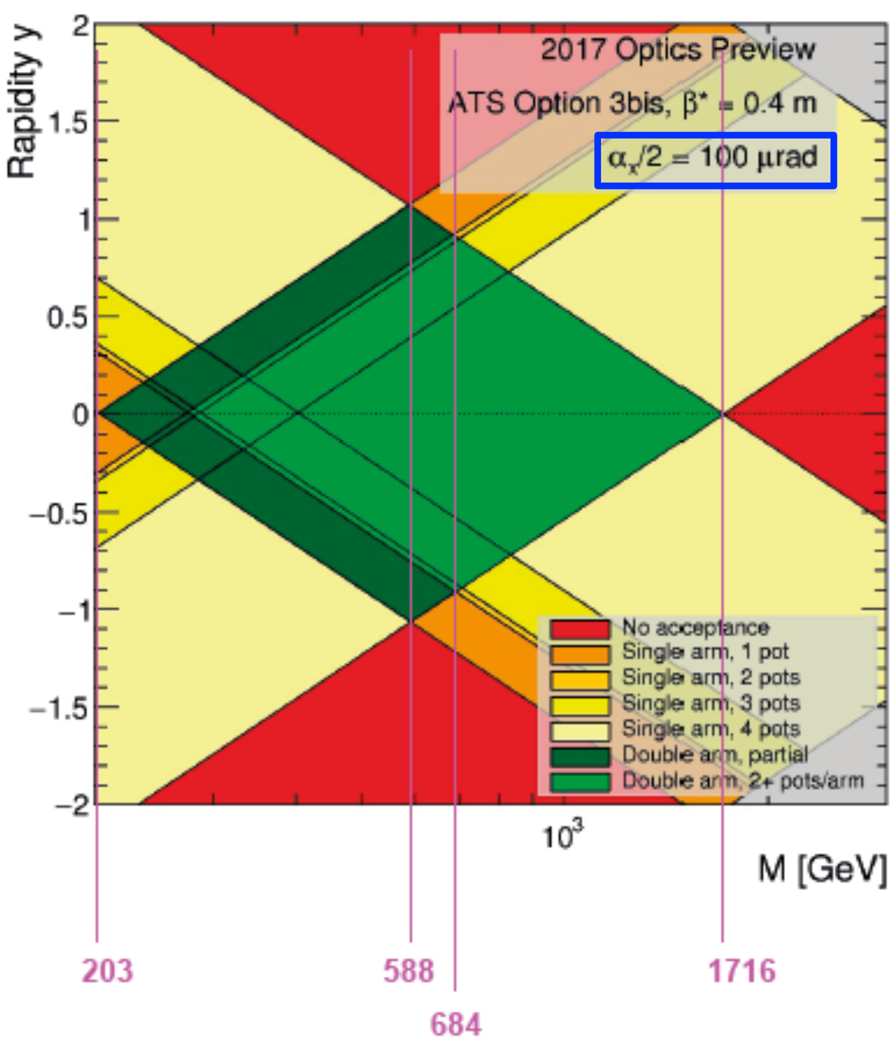
$$M^2 = \xi_1 \xi_2 s$$



Data collected with Silicon Strips & Diamonds only

2017 Data Taking



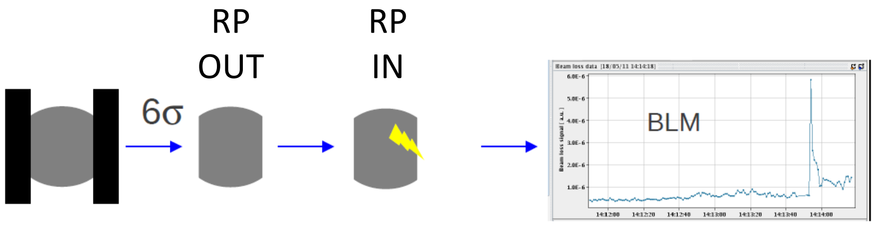


In 2017 LHC used different optics conditions, varying the crossing angle at the CMS IP and β^*

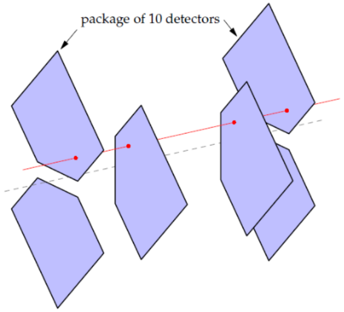
→ **CT-PPS kinematic acceptance strongly affected by the LHC optics**

2017 Data Taking - Alignment & Optics

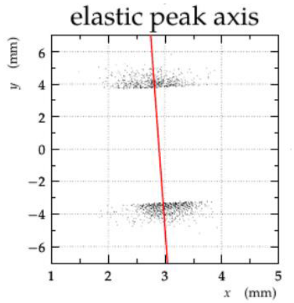
To validate each optics configuration, LHC requires a low intensity run where also the TOTEM vertical RP approach the beam, allowing to align the RPs among themselves (2.) and wrt the beam (3.)



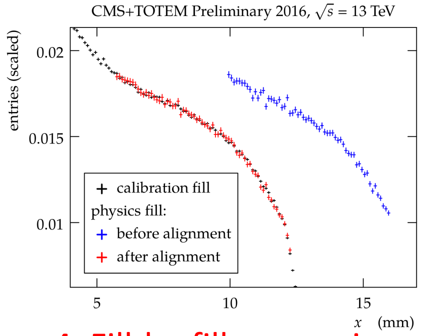
1. Alignment wrt the collimators



2. Relative RP alignment



3. Global alignment wrt the beam using elastic scattering



4. Fill-by-fill comparison of hit X distribution

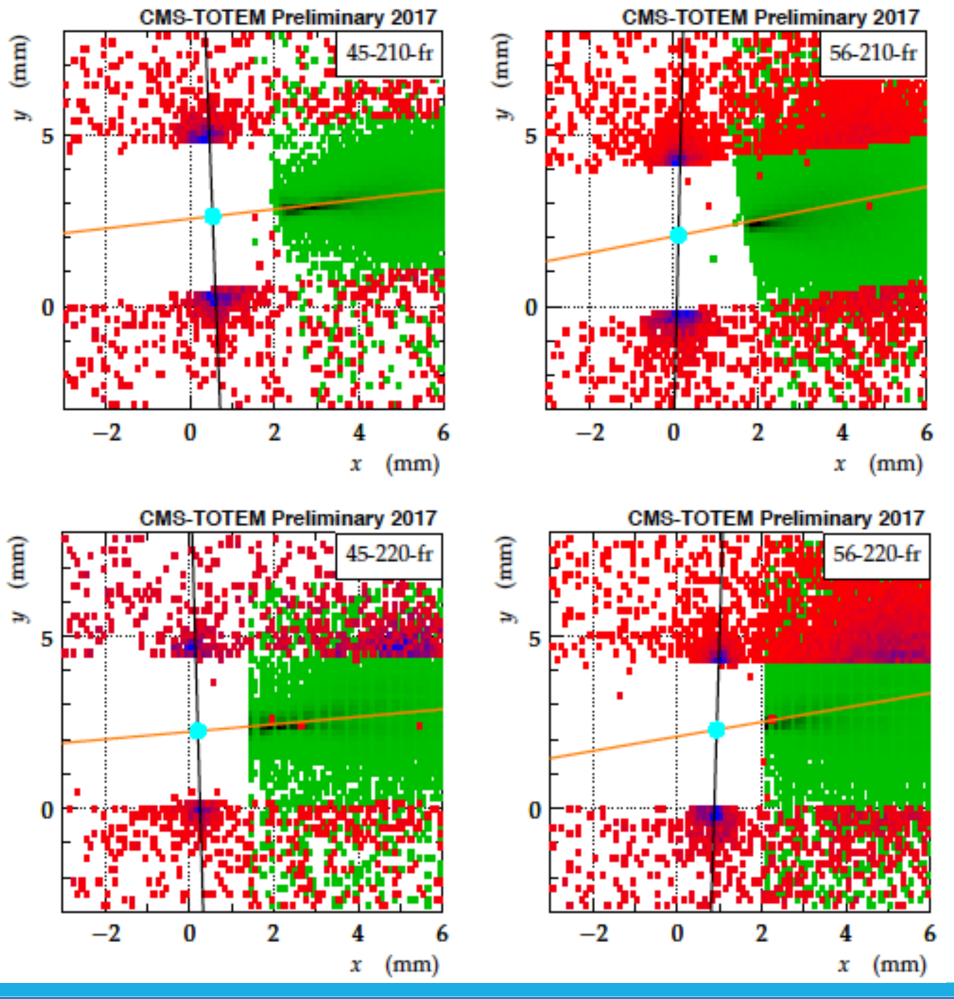
For each physics run the RP position can be determined by comparing the measured shape of the X distribution with the one obtained in the alignment run

A detailed knowledge of the LHC optics is essential to precisely reconstruct the event kinematics

LHC magnetic model is adjusted to match measurements from RP and beam position monitors [CERN-TOTEM-NOTE-2017-002]

2017 Data Taking - Alignment & Optics

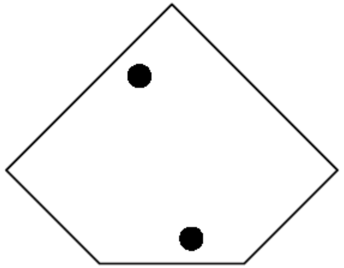
➢ Roman Pot relative and global alignment

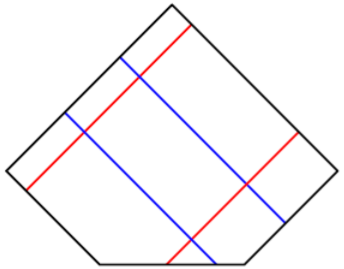


- Black line: axis of elastic hits
- Orange line: fit and extrapolation of hit profile in the horizontal RPs
- Cyan point: intersection of black and orang line, estimate of beam position

2017 Data Taking - Strip Performances

➢ Silicon Strips Track reconstruction efficiency as a function of Pile-Up



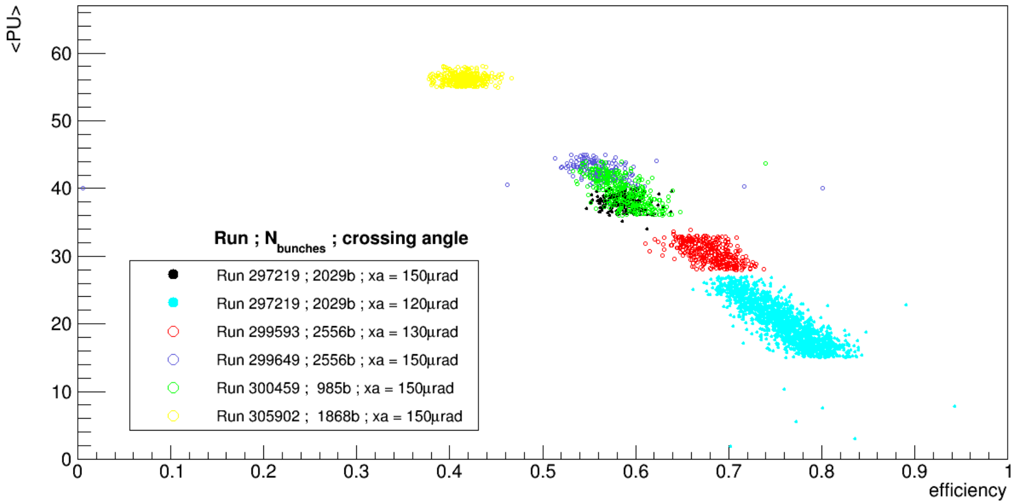


▻ Strips alone cannot reconstruct more than one track per event

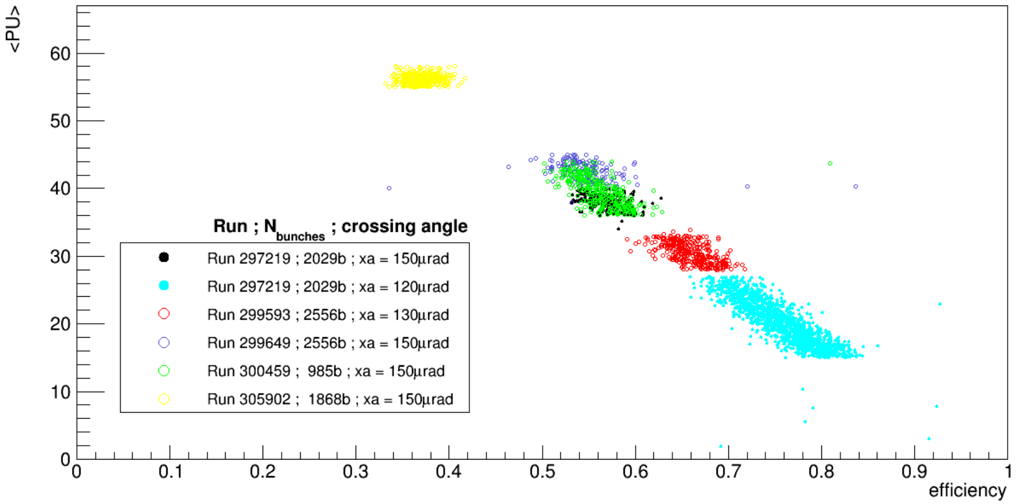
▻ The reconstruction efficiency is evaluated as the ratio

$$\text{eff} = \frac{\text{not empty event \& one track reconstructed}}{\text{not empty even}}$$

CMS-TOTEM Preliminary **Sector 45**

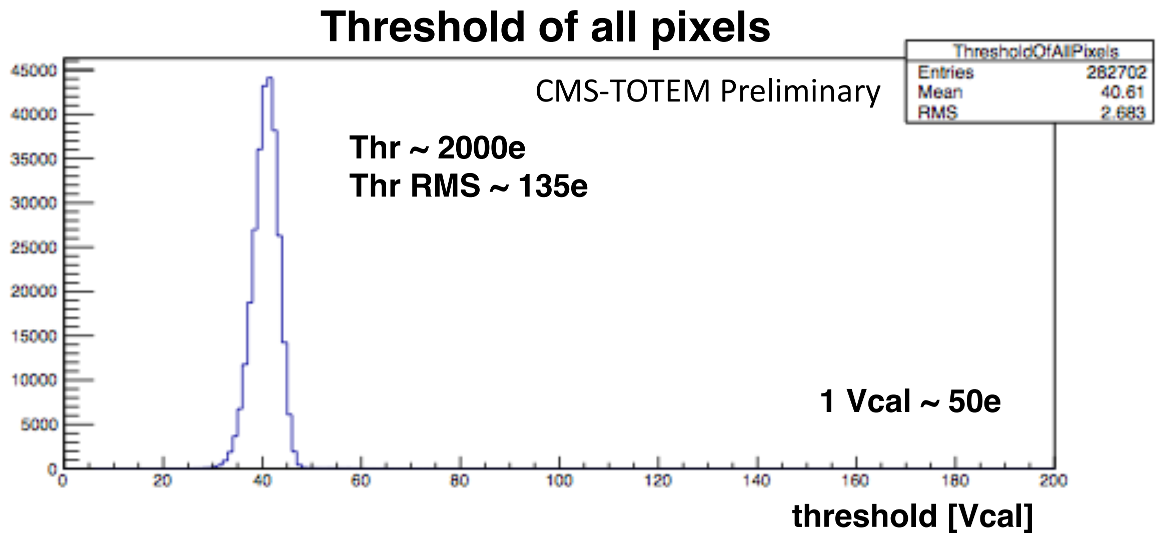


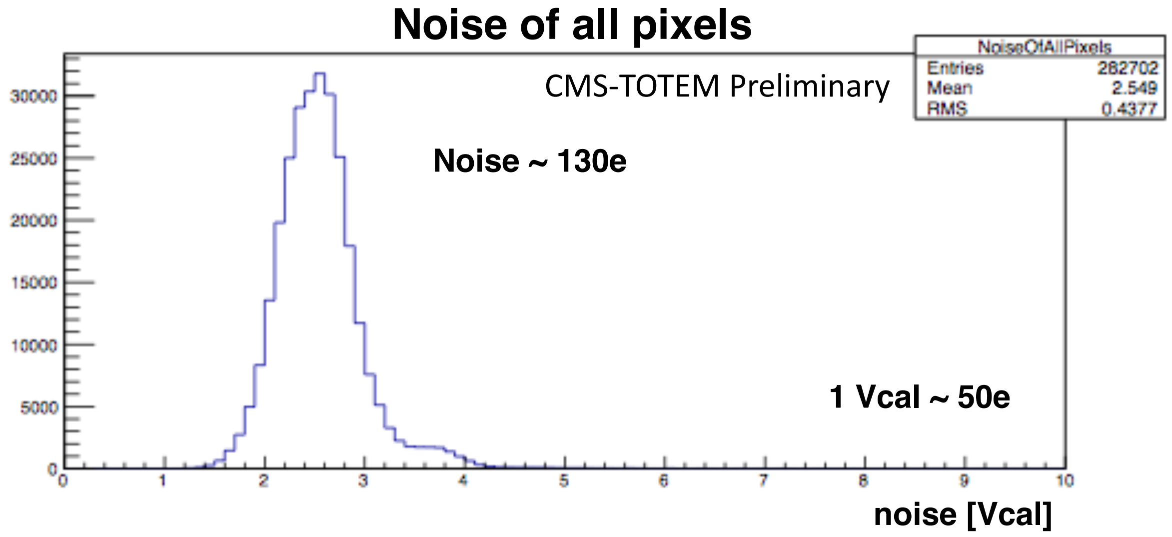
CMS-TOTEM Preliminary **Sector 56**



2017 Data Taking - Pixel Performances

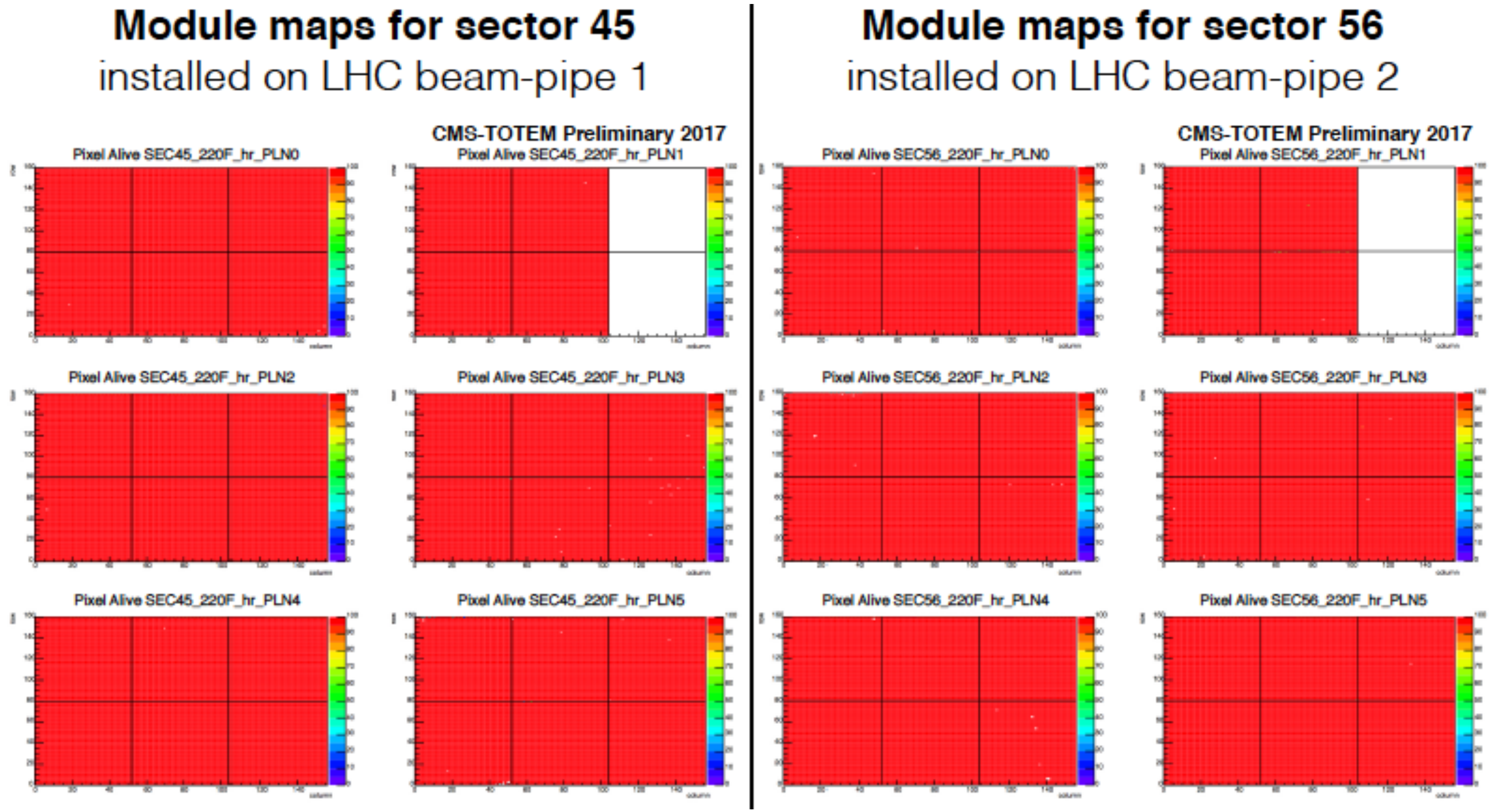
- Pixel noise and threshold





2017 Data Taking - Pixel Performances

- Pixel channels alive



☞ Very low number of bad pixels (eff < 90%) = 129 (< 0.05% of all channels)