Status of the PPS detector

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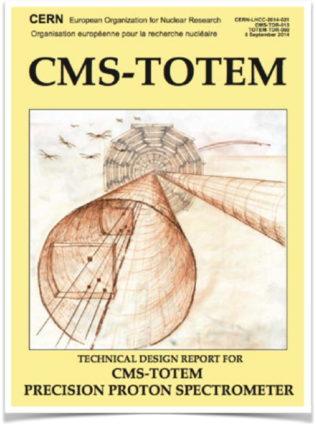
on behalf of the CMS and TOTEM collaborations

Outline

- **Project Overview**
- **Experimental Apparatus**
- **Detector performance in 2017**
- **Detector operation in 2018**
- **Prospects for LHC-RUN3**

The CT-PPS - now PPS - project



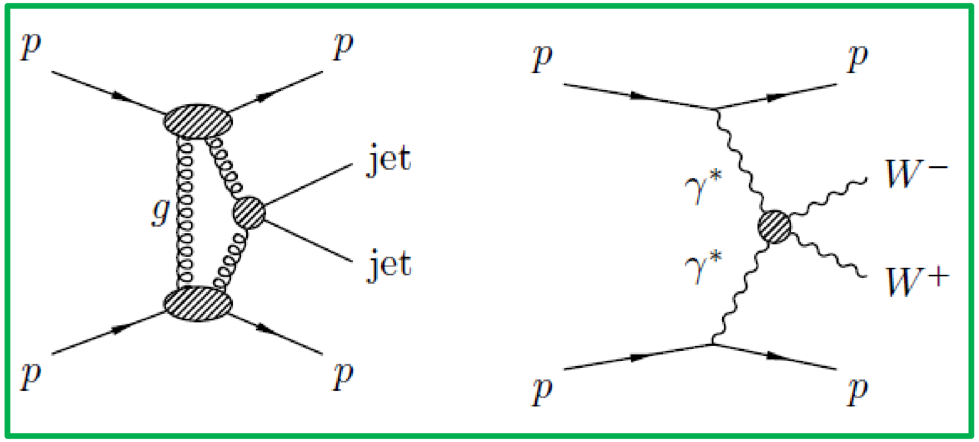
Approved in Dec. 2014 by LHCC and CERN Research Board as common CMS-TOTEM project
(CT-PPS → CMS-TOTEM Precision Proton Spectrometer)

Since April 2018, CT-PPS is a **standard component of CMS**, with name PPS

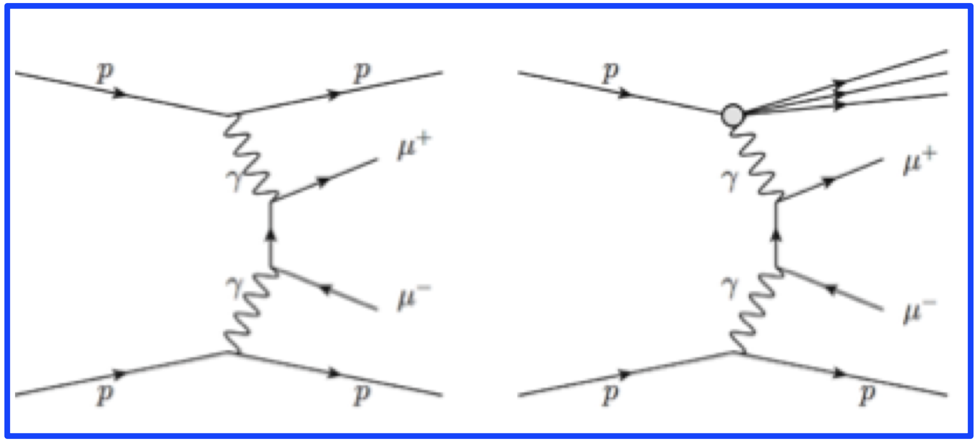
The main goal is to study **central exclusive production (CEP)** processes:

pp → p X p

X = high-E_T jets, WW, ZZ, $\gamma\gamma$ …



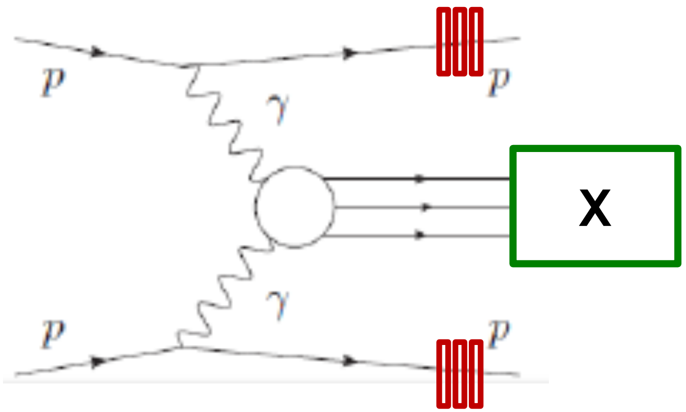
PROCESSES STUDIED IN DETAIL FOR THE CT_PPS TDR

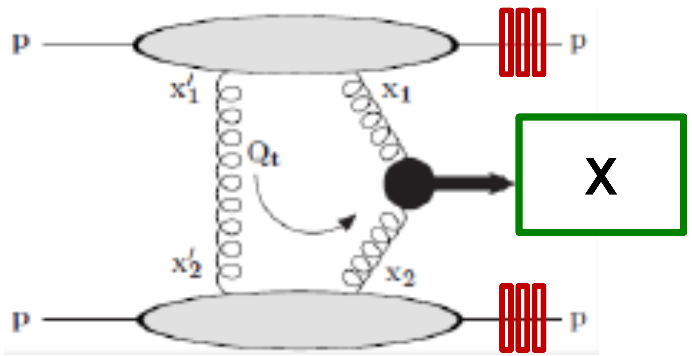


FIRST PHYSICS RESULT, JHEP07 (2018) 153

CERN-LHCC-2014-021

The experimental strategy





- High mass system (X) detected by the **CMS** central detector, scattered protons detected by **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**

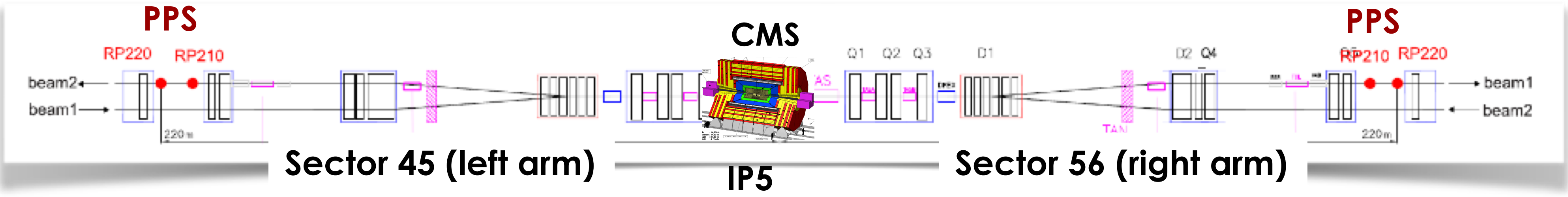
$$M_X = \sqrt{s \cdot \xi_1 \cdot \xi_2}$$

ξ: fractional momentum lost by the proton

Measurements to be performed in **standard LHC high luminosity** conditions

The Precision Proton Spectrometer

The Precision Proton Spectrometer has been designed for **measuring the scattered protons on both sides of CMS.**



✓ **LHC magnets** used **to bend protons**.

✓ **Tracking detectors,** to measure the proton momentum, **and timing detectors,** to disentangle pile-up, **located at ~ 220 m from CMS**

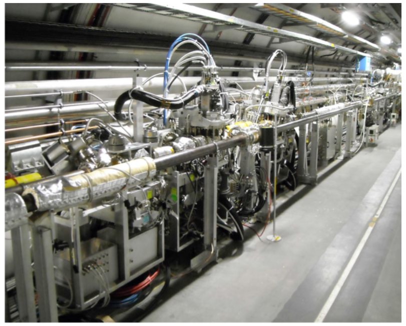
✓ Detectors as close as possible to the beam axis, to maximize acceptance for low momentum-loss protons → located in **Roman Pots (RP)**

Main challenges

- Operate **as close as possible to the beam** line (**~1.3 mm** from the beam axis) without preventing LHC stable operation
- Run detectors in **high radiation environment** (**proton flux up to 5 10^{15}/cm^2**)
- Cope with **high pile-up** of standard LHC running (**~38 average PU events**)

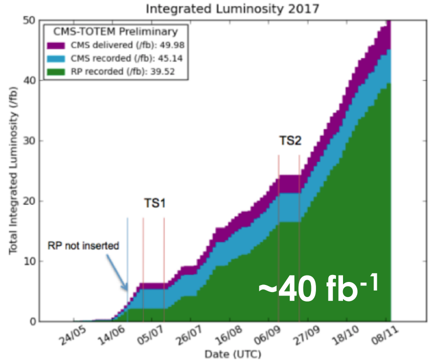
PPS timeline

Data taking in 2016, 2017 and 2018 with different detector configurations

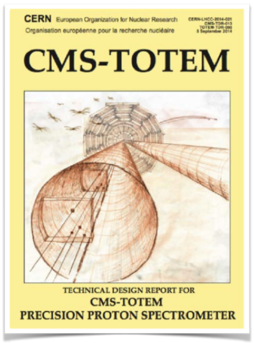


Exploratory phase
2015

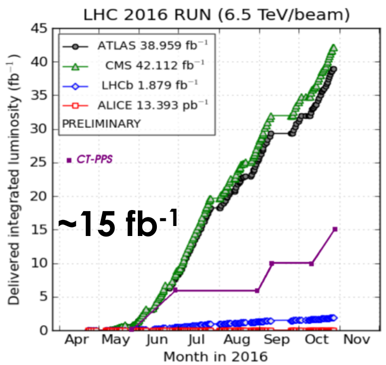
Data taking within CMS
Strip+Pixel+Diamonds+UFSD
2017



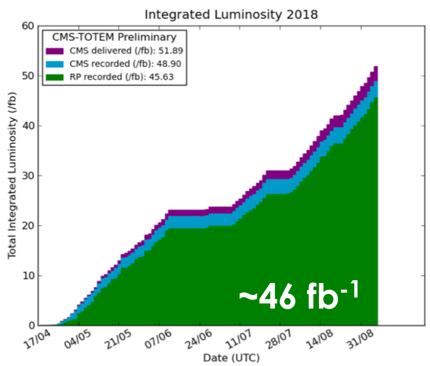
2014
Project approval



2016
Data taking within CMS
Strip (+Diamond)



2018
Data taking within CMS
Pixel+Diamonds



~100 fb^{-1} collected in the entire LHC Run2

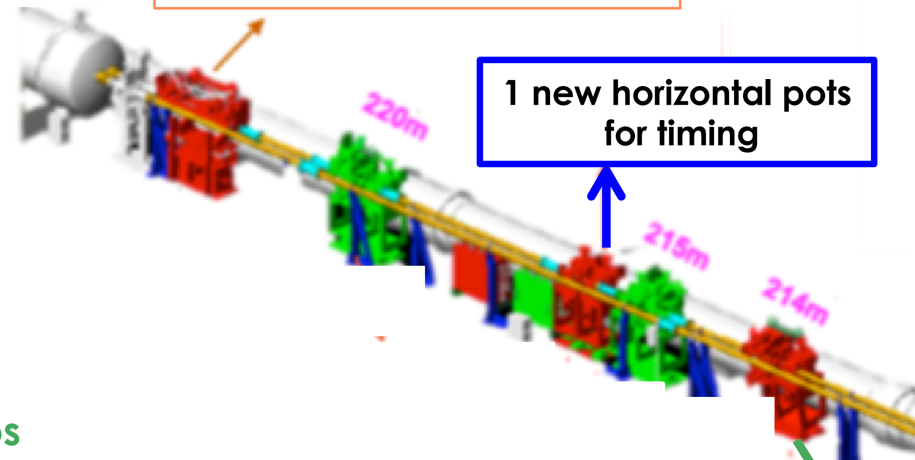
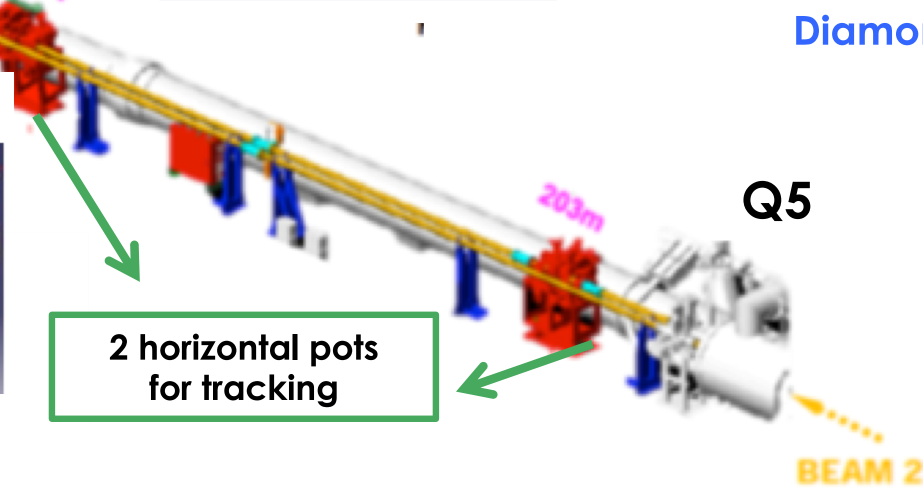
2016: "accelerated program" configuration

TOTEM tracking and timing detectors installed in Roman pots (RP):

- 2 horizontal pots at 203 m and 214 m for tracking
- 1 horizontal pot at 216 m for timing

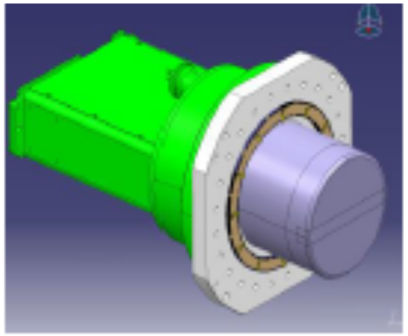
Collimator (TCL6) to suppress debris from RPs

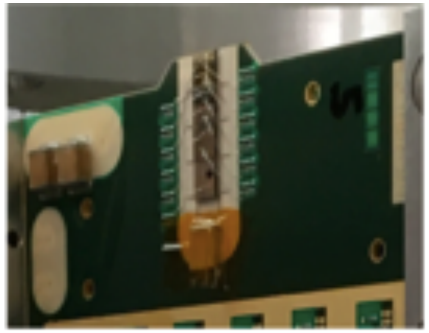
1 new horizontal pots for timing

2 horizontal pots for tracking

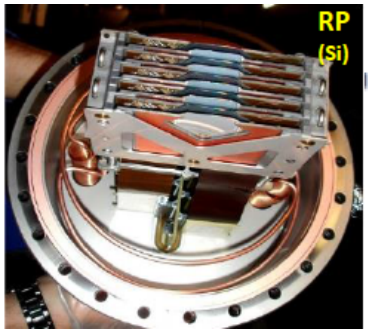
Cylindrical RP for timing detectors to reduce impendance and increase available space

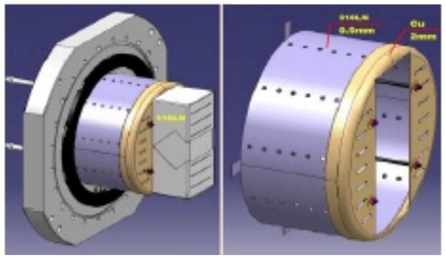




Diamonds

Strips





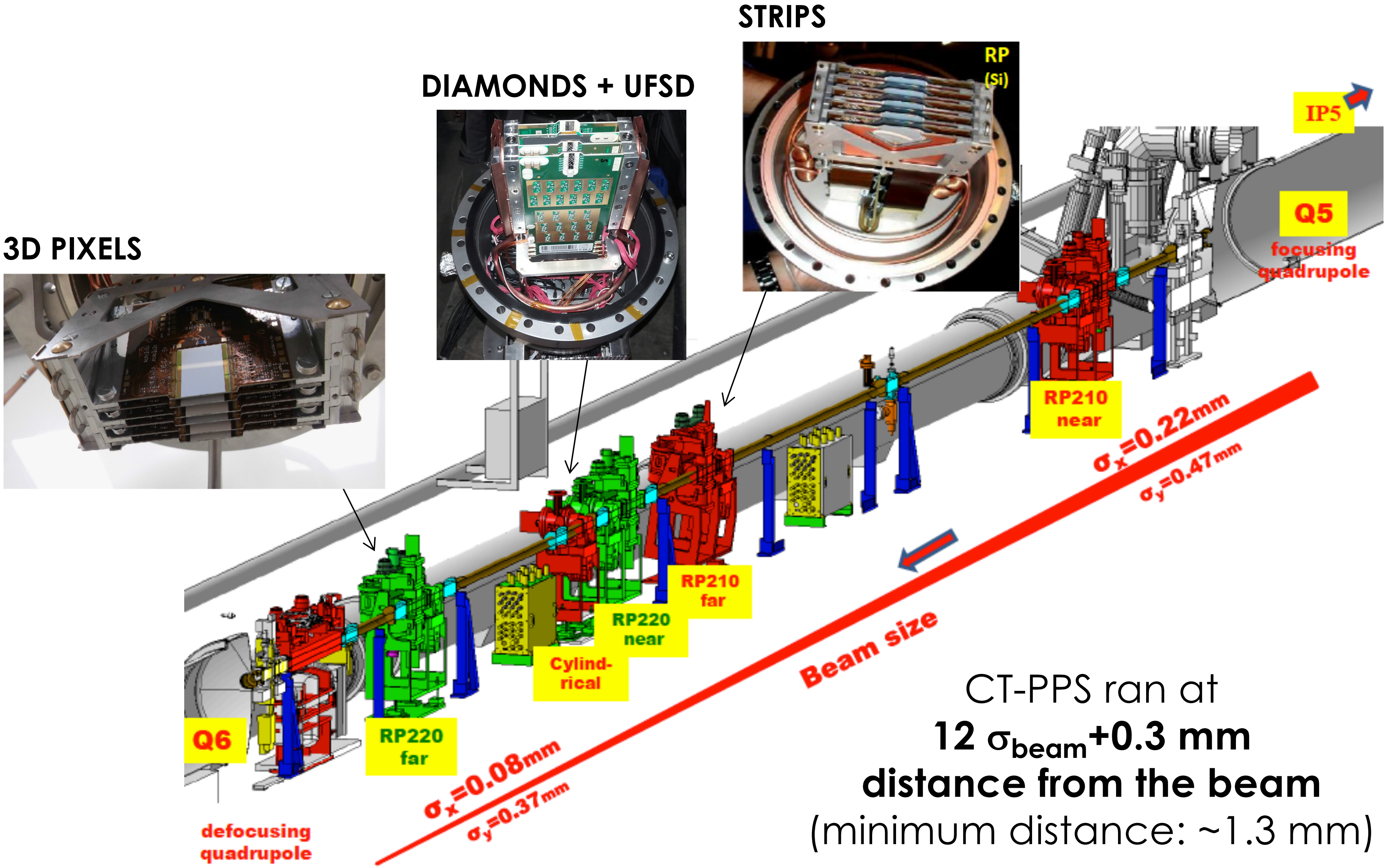
RP equipped with Faraday cages (RF shields)

- ✓ Ability to operate close to the beam-line at high luminosity proved
- ✓ 15 fb^{-1} of data @ $\sqrt{s}$ = 13 TeV collected → JHEP07 (2018) 153

2017: towards “design detector configuration”

Roman pot stations (per arm):

- 2 horizontal at 213 m (**silicon strip**) and 220 m (**3D pixel**) for **Tracking**
- 1 horizontal at 216 m for **Timing** (3 **diamond** planes,1 **UFSD** plane)

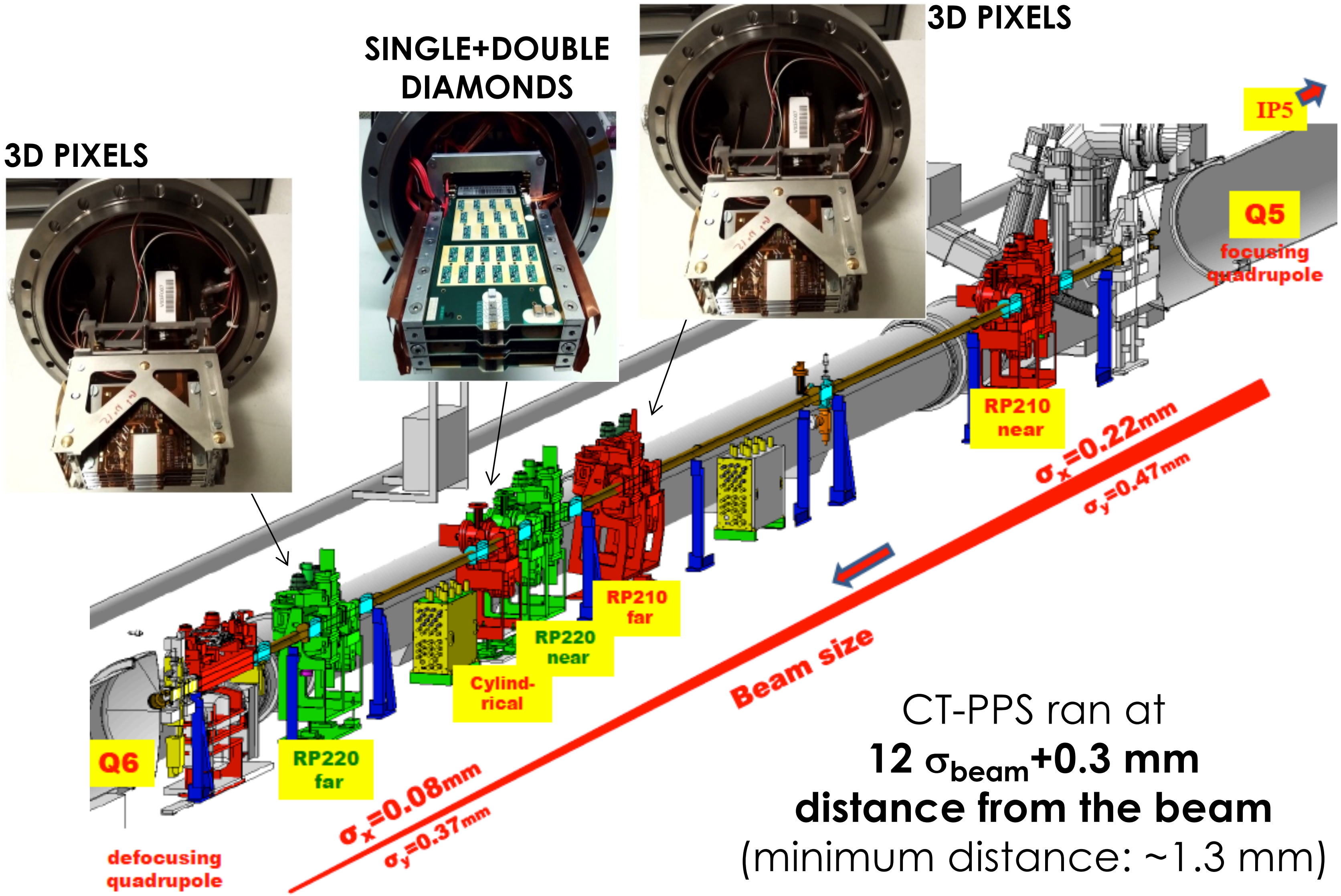


CT-PPS ran at
12 σ_{beam}+0.3 mm
distance from the beam
(minimum distance: ~1.3 mm)

2018: design detector configuration

Roman pot stations (per arm):

- 2 horizontal at 213 m and 220 m (**3D pixels**) for **Tracking**
- 1 horizontal at 216 m (**2 single + 2 double diamond** planes) for **Timing**



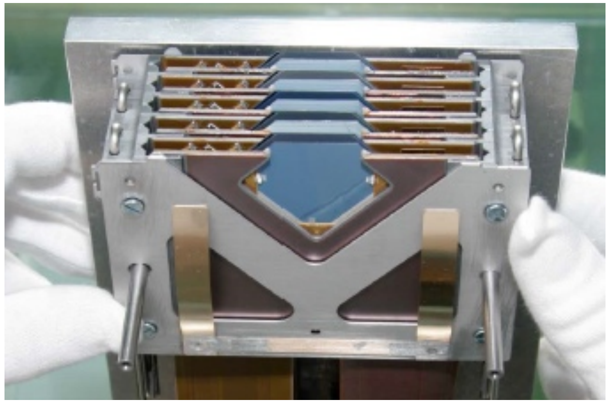
CT-PPS ran at
12 σ_{beam}+0.3 mm distance from the beam
(minimum distance: ~1.3 mm)

DETECTOR TECHNOLOGIES USED IN PPS

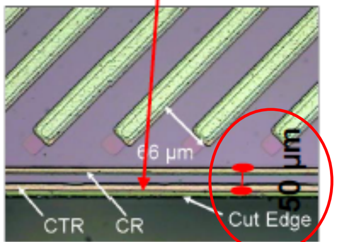
Tracking detector - Silicon strips

10 planes of micro-strip silicon detectors per RP

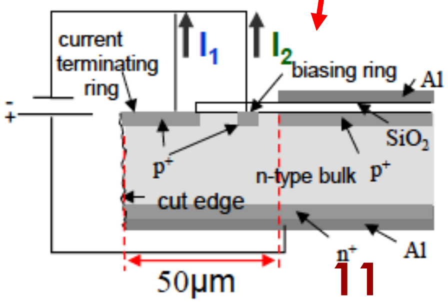
- 512 n-in-p strips per plane, ±45° orientation
- Thickness: 300 μm - Pitch: 66 μm
- Edgeless technology: **50 μm inactive edge**
- **Track resolution ~10 μm**
- **Lifetime: up to 5×10^{14} p/cm^2 integrated flux**



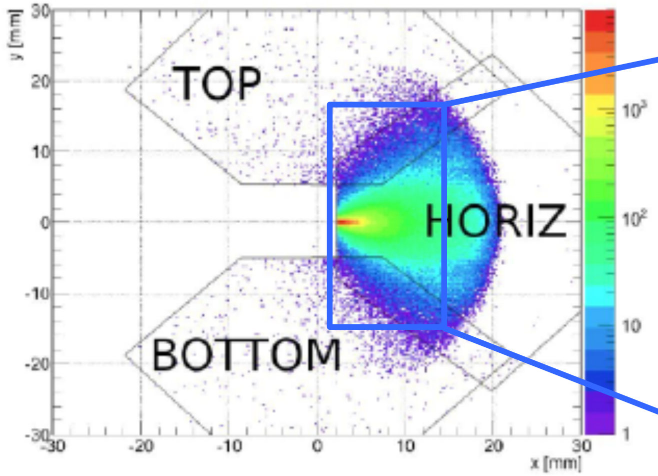
Binary **readout** provided by 4 **VFAT2** (128 channel each) located on a flexible circuit connected to a motherboard



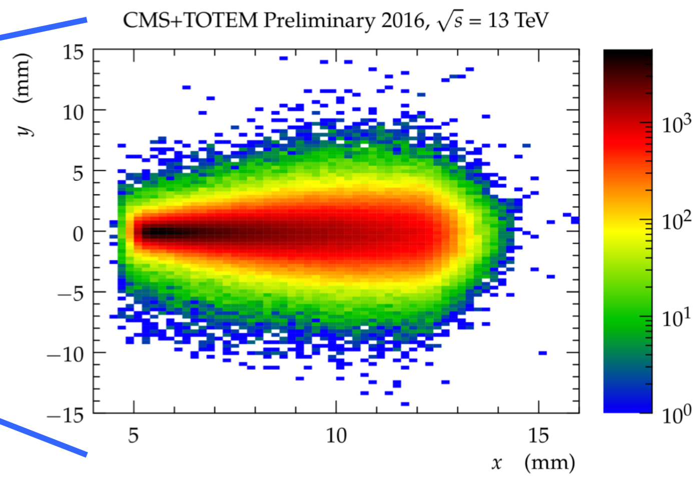
Planar technology + CTS (Current Terminating Structure)



SIMULATION



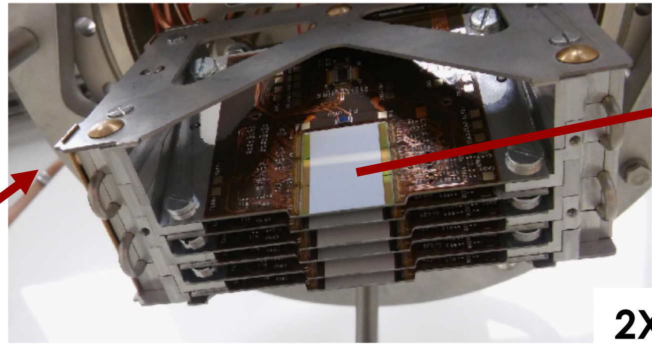
2016 DATA

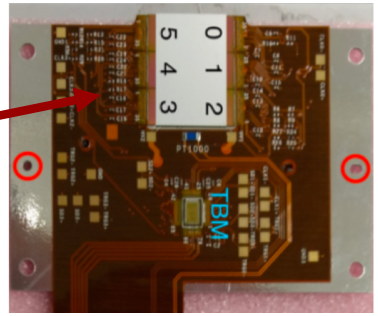


Tracking detector – 3D pixels

3D sensor technology chosen for its intrinsic high **radiation hardness** and the possibility to implement **slim edges**.

- Sensors read out with 4 or 6 **PSI46dig ROCs**, depending on the sensor size





2X3 SENSOR READ OUT BY 6 ROCs

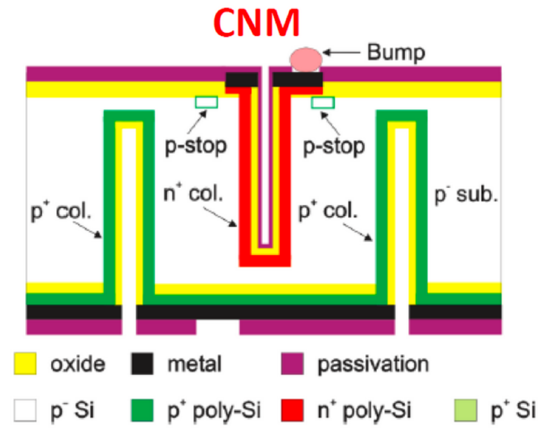
- Same **front-end electronics** of **CMS Phase I pixel upgrade**.
- **Mechanics and cooling** adapted from **TOTEM tracking system.**

6 planes of 3D pixel silicon detectors were installed in each tracking RP

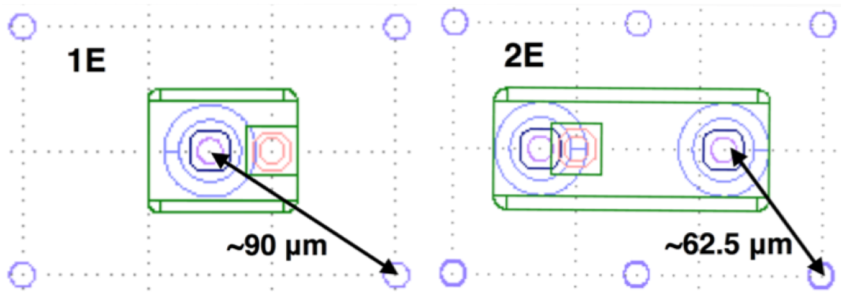
Tracking Detector - Silicon 3D Pixels

✓ 3D sensors produced by CNM: **double side** process with **no passing-through columns**

Pixel area	100x150 μm^2
Sensor thickness	230 μm
Column depth	200 μm
Column diameter	10 μm



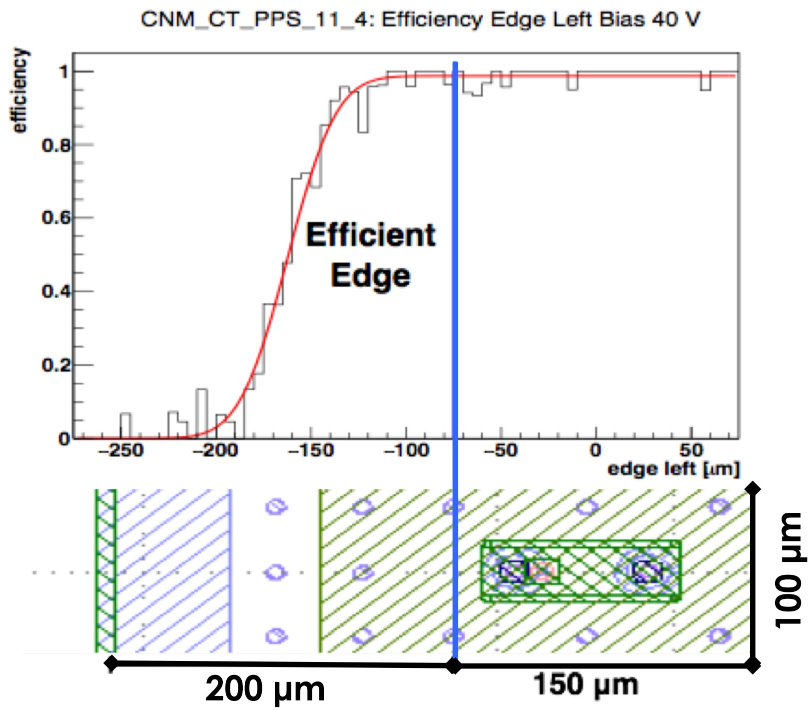
✓ **1E and 2E electrode configuration**



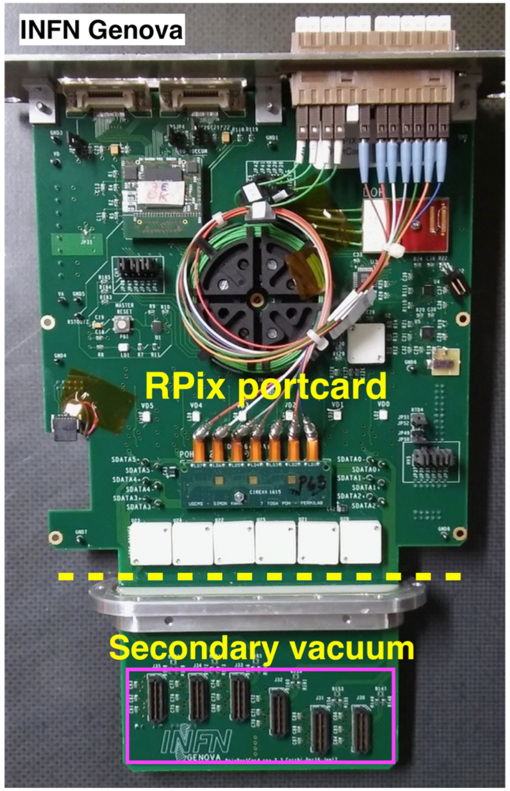
In RP sensors:

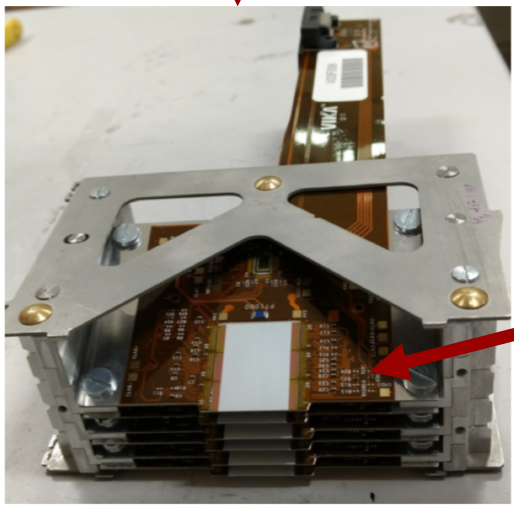
- **are tilted by 18.4°** to increase the charge sharing and **improve resolution**
- **run at -20°C and in a vacuum** (p < 20 mbar)

✓ **200 μm slim edge** made of a triple p-type column fence



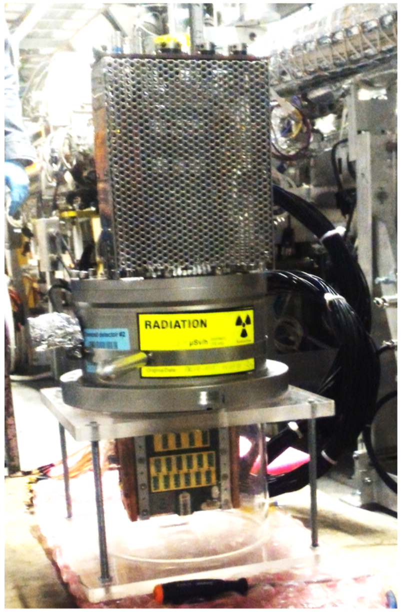
Tracking Detector - Electronics and mechanics



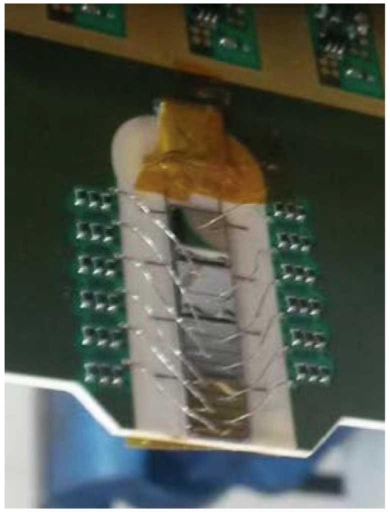


- ✓ Modules wire-bonded to RPIx flex hybrid connected to the RPix portcard.
- ✓ The portcard interfaces the front-end electronics with the detector planes
- ✓ Same front-end boards for data (FED) and control (FEC) as Phase I CMS pixel tracker

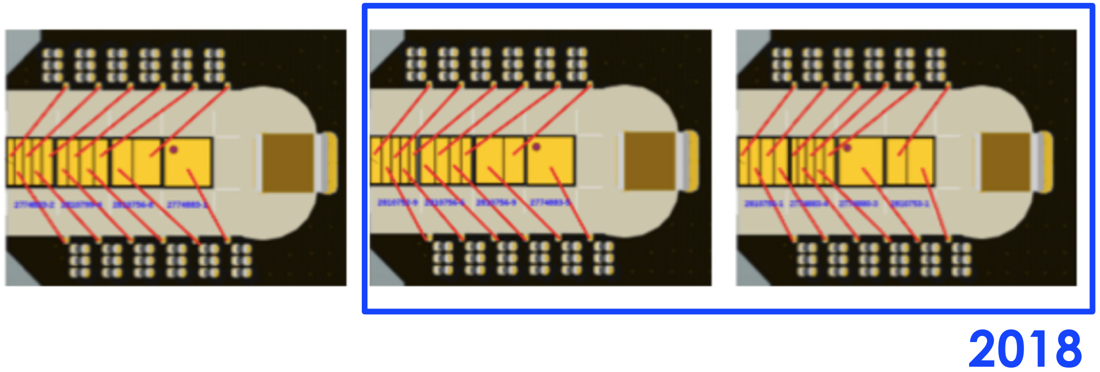
Timing Detector – Single Diamonds



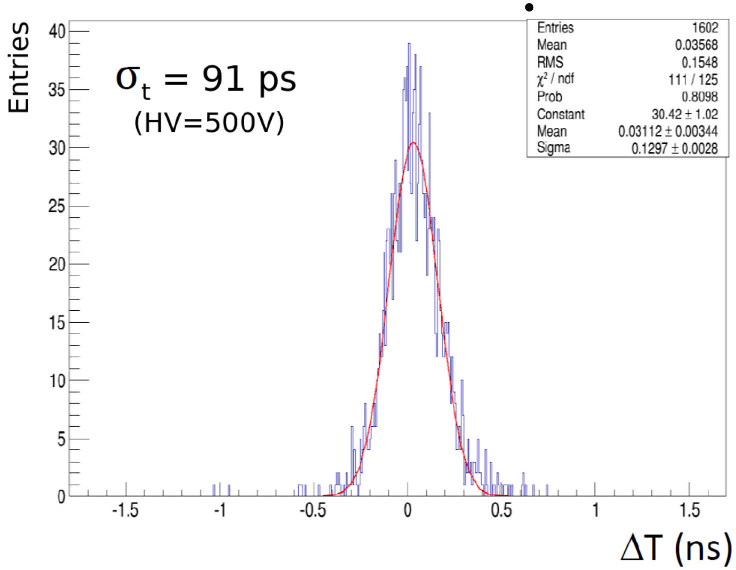
Two planes (3 in 2017) of 500 μm thick scCVD Diamonds



Four 4x4mm^2 diamond sensors per plane with different pad patterns



Intrinsic radiation hardness: up to 5 10^{15} p/cm^2 integrated flux



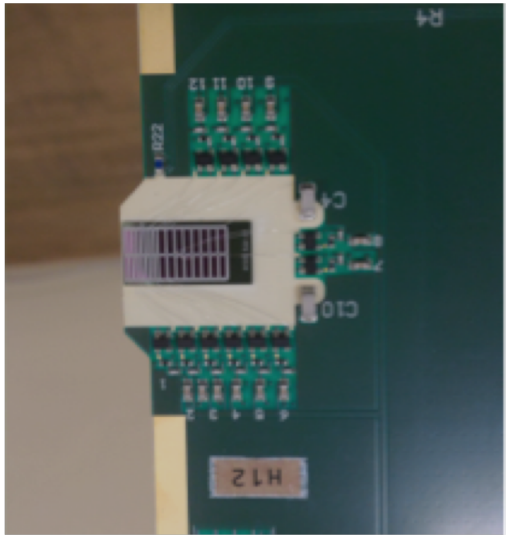
Time resolution: ~ 90 ps [1]
(beam test measurement)

Sensors tested in 2018 in the LHC tunnel after L_{int} ~ 60 fb^{-1} (2017+5 weeks in 2018)
→ Measured time resolution compatible with test beam results

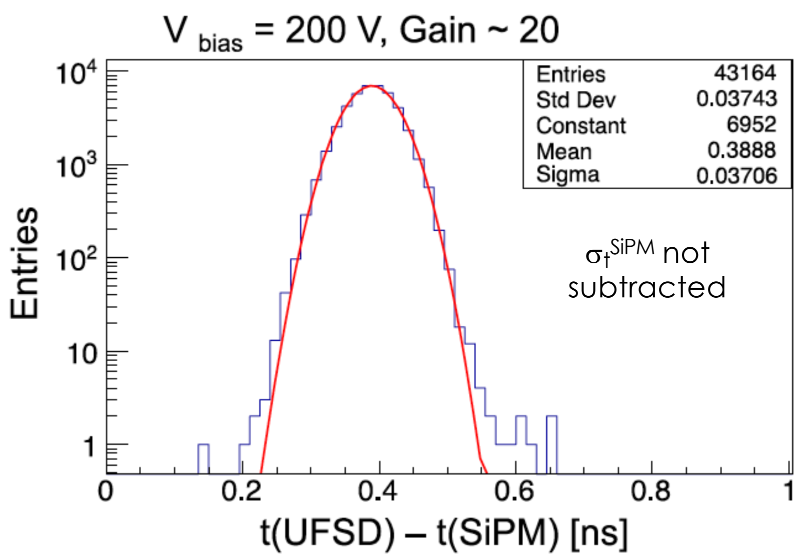
[1] G. Antchev et al.,JINST 12 (2017) P03007

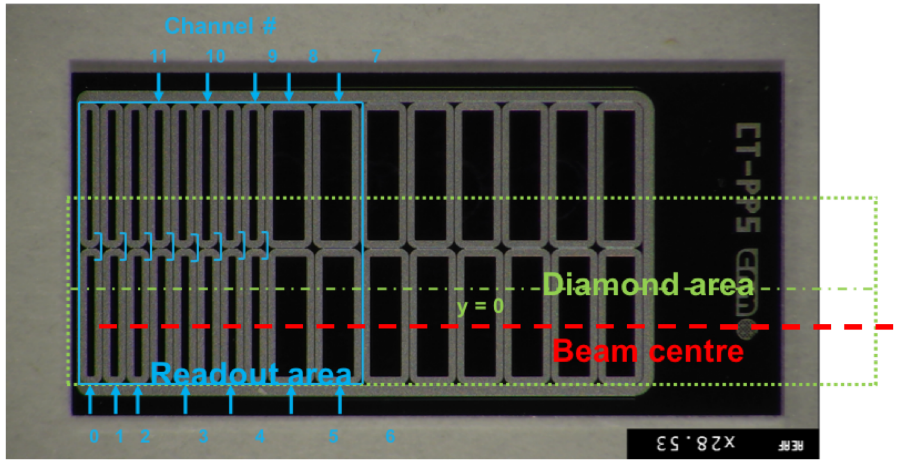
Timing detector - UFSD

1 plane per RP in 2017 - First installation in HEP



- 50 μm thick sensors produced by CNM
- Eight 0.5x6mm² pads, four 1x3mm² pads
- 32 channels (12 read-out)
- Gain ~ 15
- Slim edge of ~200 μm on side A





Time resolution ~ 35 ps [3]

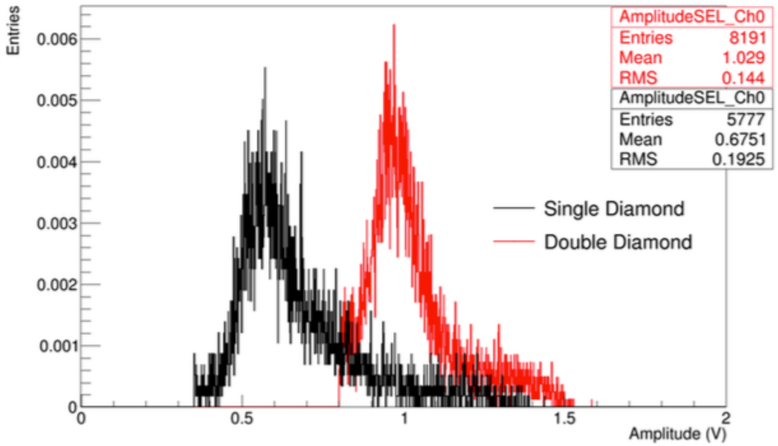
[3] N. Cartiglia et al., NIM A 850 (2017) 83

Radiation hardness: in RP environment (T > 30°C) lifetime ≲ 10^{15} p/cm²

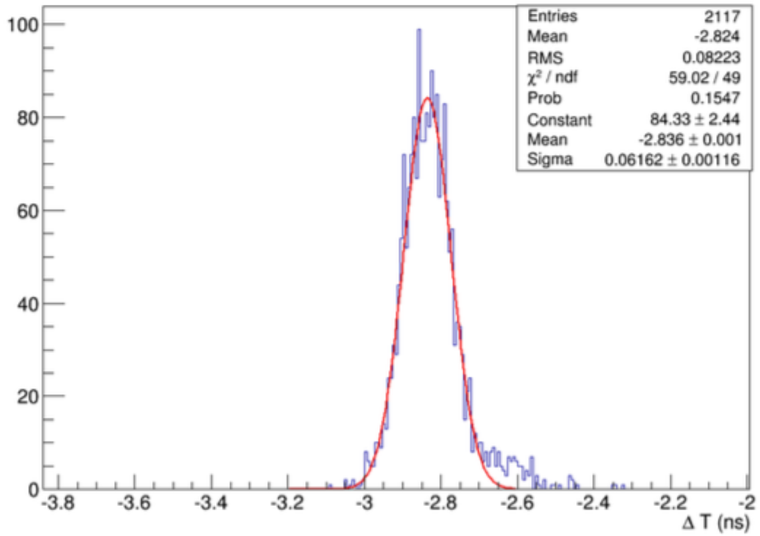
Timing detector – Double diamonds

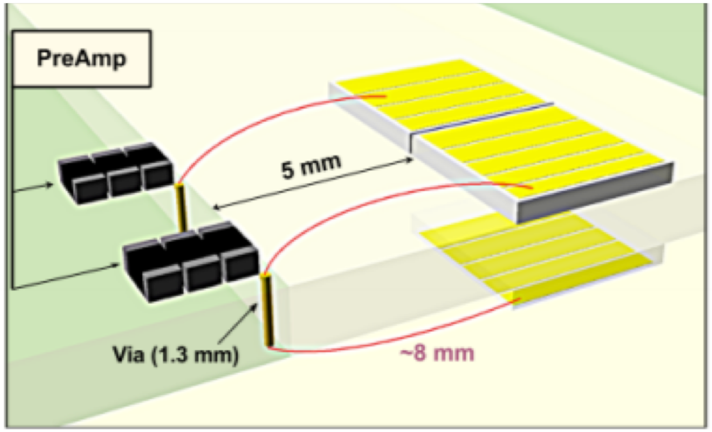
Double-diamond planes (2018 only)

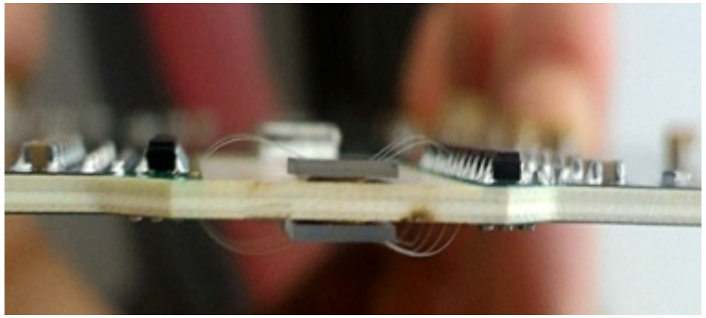
Two scCVD sensors installed back to back and connected in parallel to the same amplifier channel



Time difference distribution between double diamond detector and MCP







Time resolution: ~50 ps [2]
(measured in beam test)

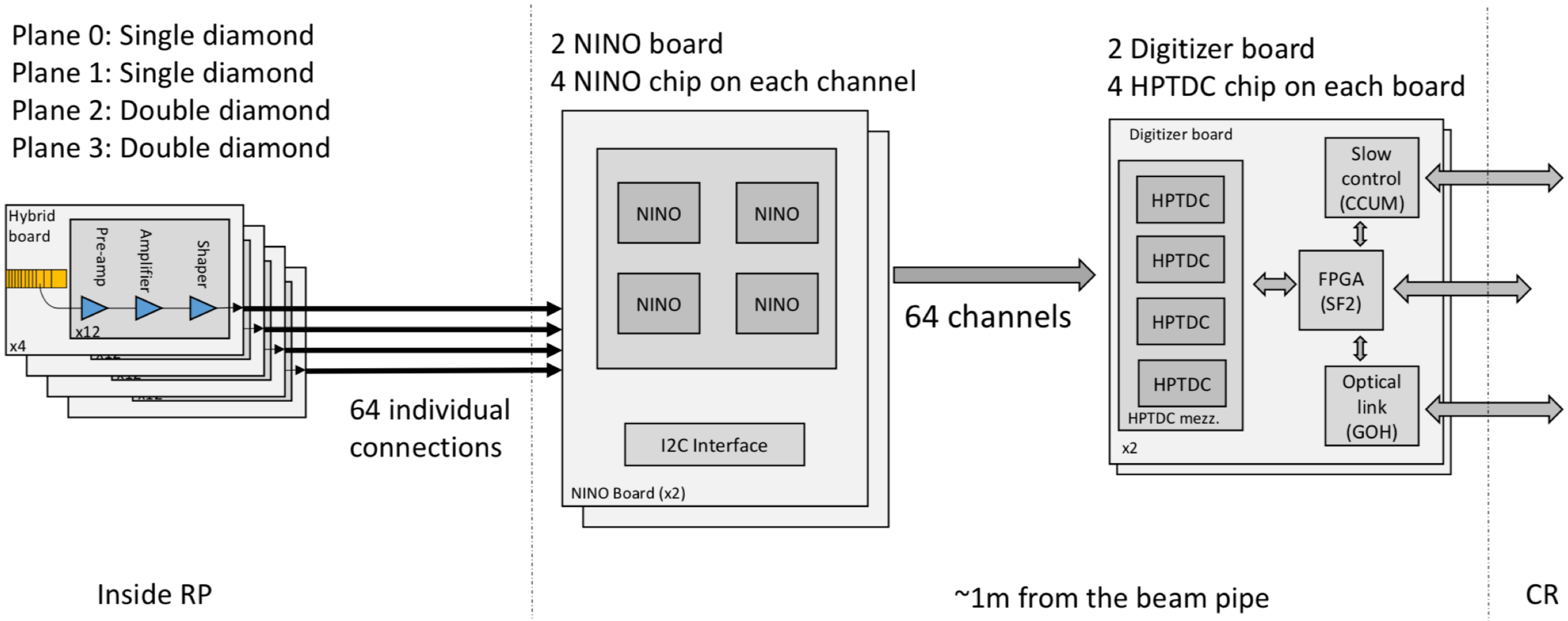
Sensors tested in 2018 in the LHC tunnel after ~5 weeks of data taking (L_{int} ~ 20 fb^{-1})
→ Measured time resolution compatible with test beam results

[2] M. Berretti et al., JINST 12 (2017) P03026

Timing detector read-out

Same read-out chain for single and double diamonds:

- Triple stage amplification with TOTEM hybrid[3]
- Digitization with NINO chip[4] + HPTDC[5]



Detailed study of the time resolution of the entire system with LHC data ongoing

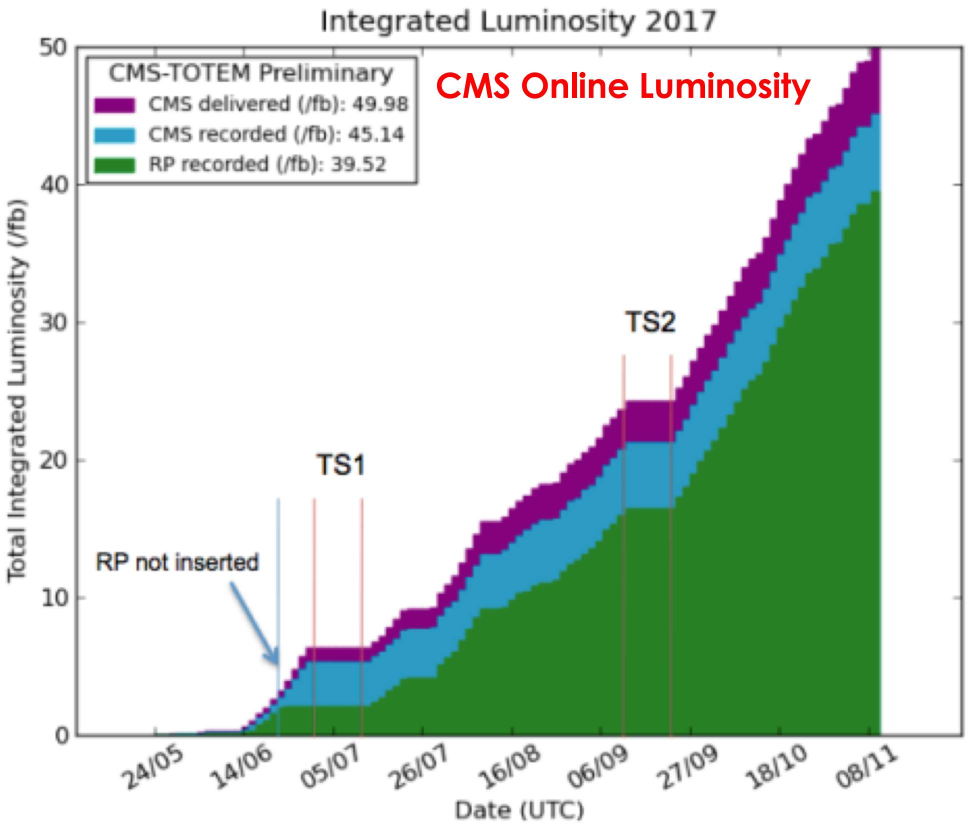
[3] TOTEM Coll., JINST 12 (2017) P03007
[4] F. Anghinolfi et al., NIM A 533 (204) 183
[5] M. Mota and J. Christiansen, IEEE JSSC 34 (1999) 1360

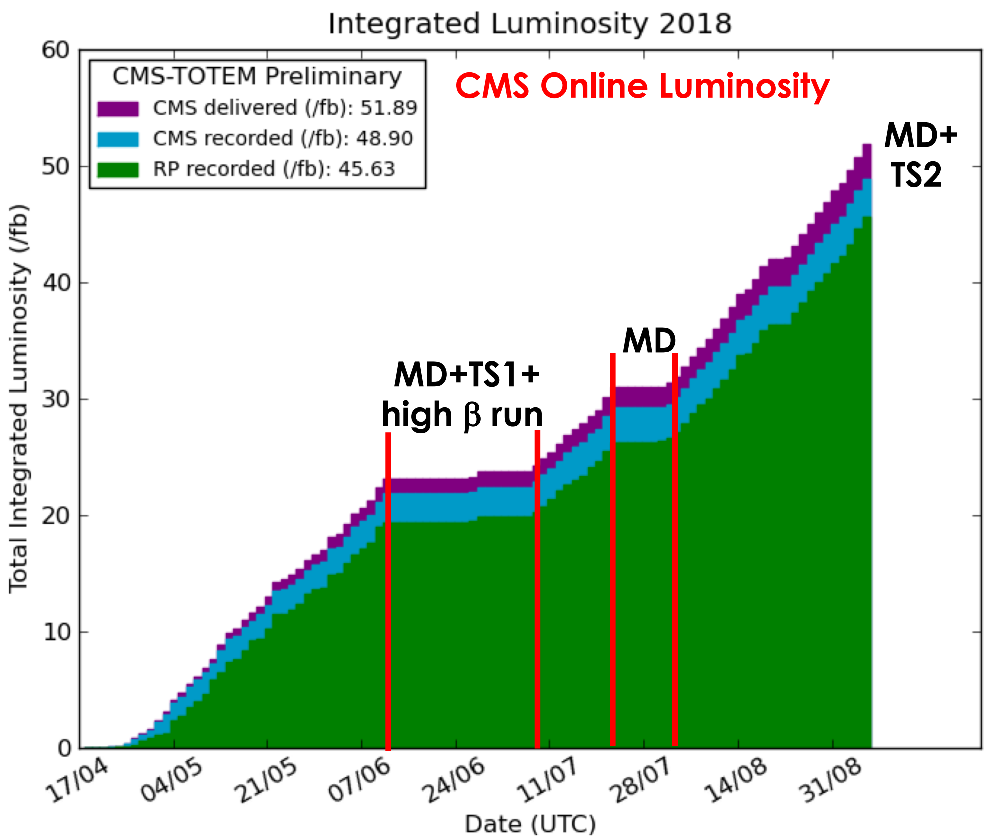
PPS DETECTOR PERFORMANCE

Data taking

CT-PPS collected:

- **~ 88% of the full statistics recorded by CMS in 2017**
  - **→ ~ 40 fb^{-1} with RP data**
- **~ 93 % of the full statistics recorded by CMS in 2018 (till TS2)**
  - **→ ~ 46 fb^{-1} with RP data**

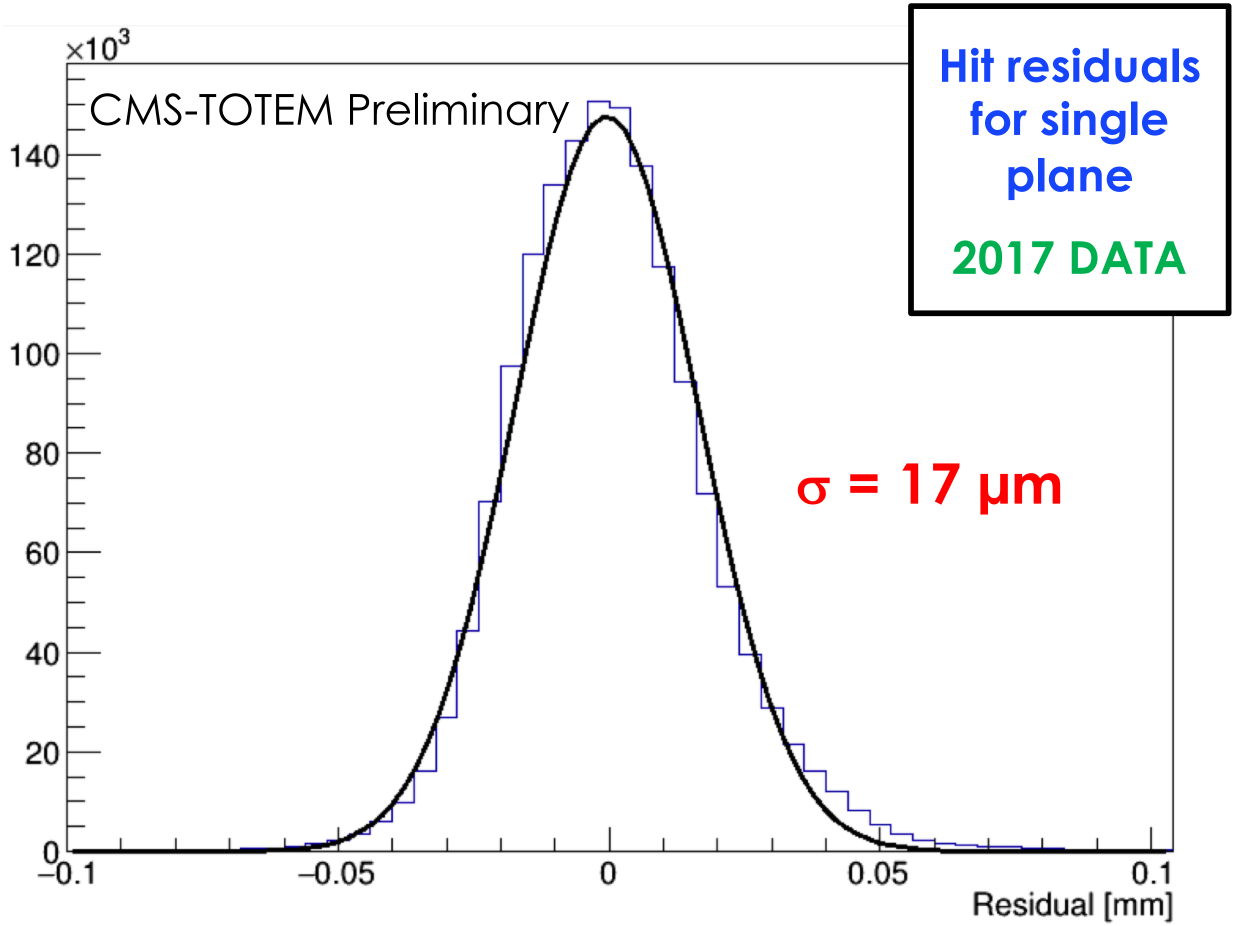




TS = technical stop **MD = machine development**

Tracker performance: hit residuals

Hit residuals for single planes are evaluated with respect to the local track reconstructed in the Pixel RP

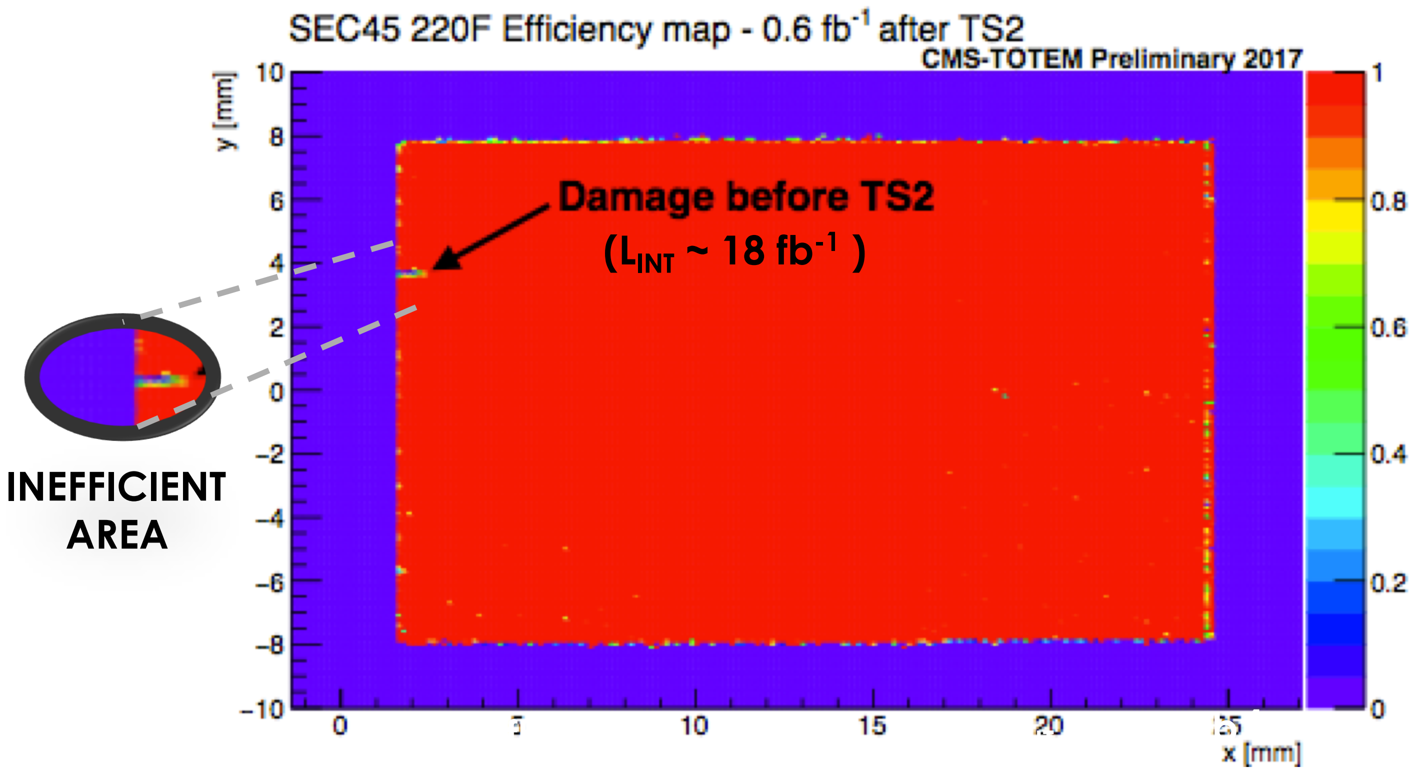


- Residuals are consistent with those obtained at the beam tests
- Similar results in 2018

The pixel tracker works as expected

Tracker performance: efficiency (2017)

Efficiency based on tracks reconstructed within the same tracking station



- 2017 DATA
- SECTOR 45

Similar results for detectors in sector 56 (but lower dose)

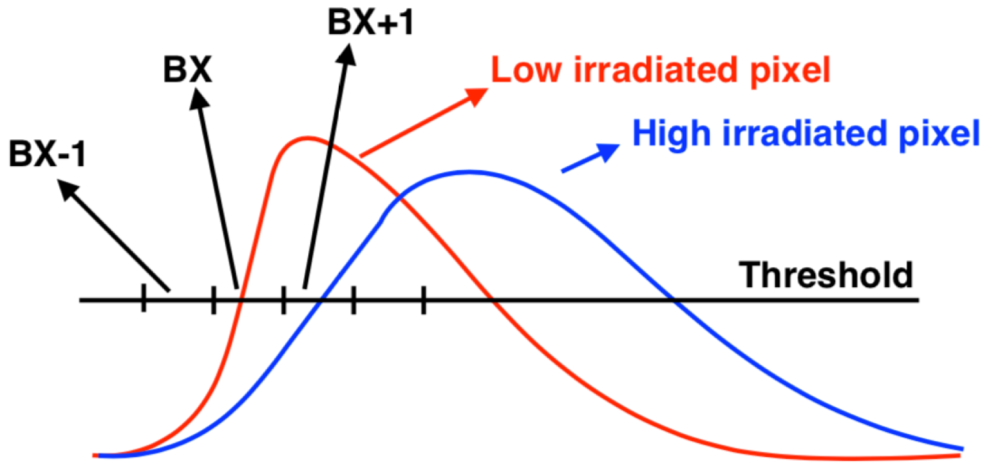
Overall very good performance - **average efficiency: ~98%**

→ Inefficient area (~ 1.5×0.2 mm^2 , ~ 15 pixels) caused by the radiation damage of the read-out chip

Radiation effect on the ROC

The PSI46dig chip **not optimised for non-uniform irradiation**

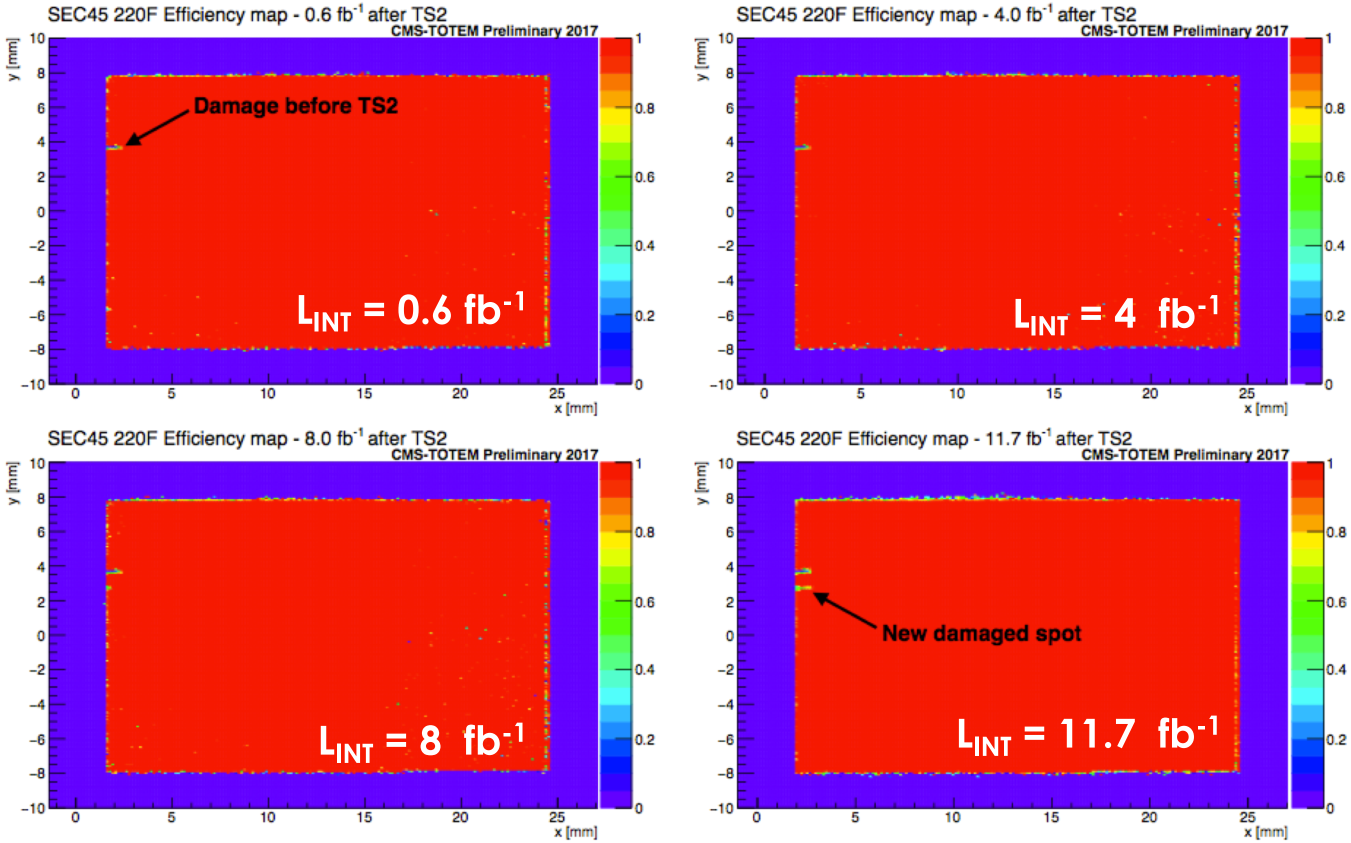
→Non-uniform irradiation causes a difference between the analog current supplied to the most and the least irradiated pixels.



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

- ✓ Irradiation studies performed before installation at LHC showed that the effect **appears after an irradiation corresponding to a collected L_{INT} ~8 fb^{-1}** (expected dose rate in the tunnel ~ 1.61 Mrad/fb^{-1})
- ✓ To mitigate the impact on the data quality, the tracking stations lifted during Technical Stops to shift the occupancy maximum away from the damaged region.

Tracker performance: efficiency



PIXEL DETECTOR EFFICIENCY VS INTEGRATED LUMINOSITY

- **2017 DATA**
- **SECTOR 45**
- **"AFTER TS2" ERA**

→ IN 2017-TS2 TRACKING STATIONS RAISED BY ~ 1mm

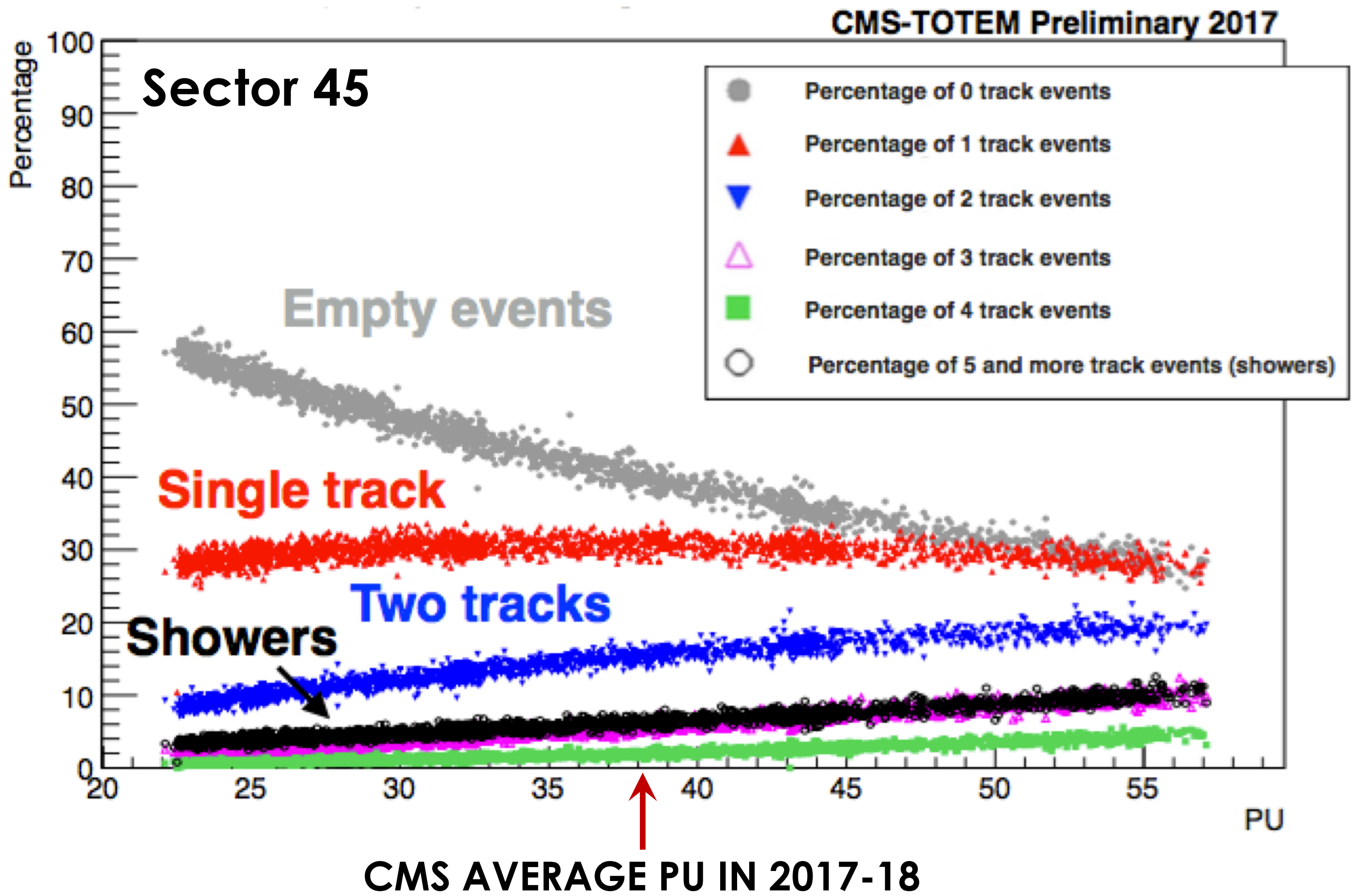
In 2018:

- same strategy to cope with irradiation problems
  → tracking RPs moved twice (during TS1 and TS2) of 0.5 mm
- preliminary efficiency studies performed constantly to have a real-time monitoring of the detector performance
  → overall average tracking efficiency of above 98%

Multi-track capability of the 3D pixel detector

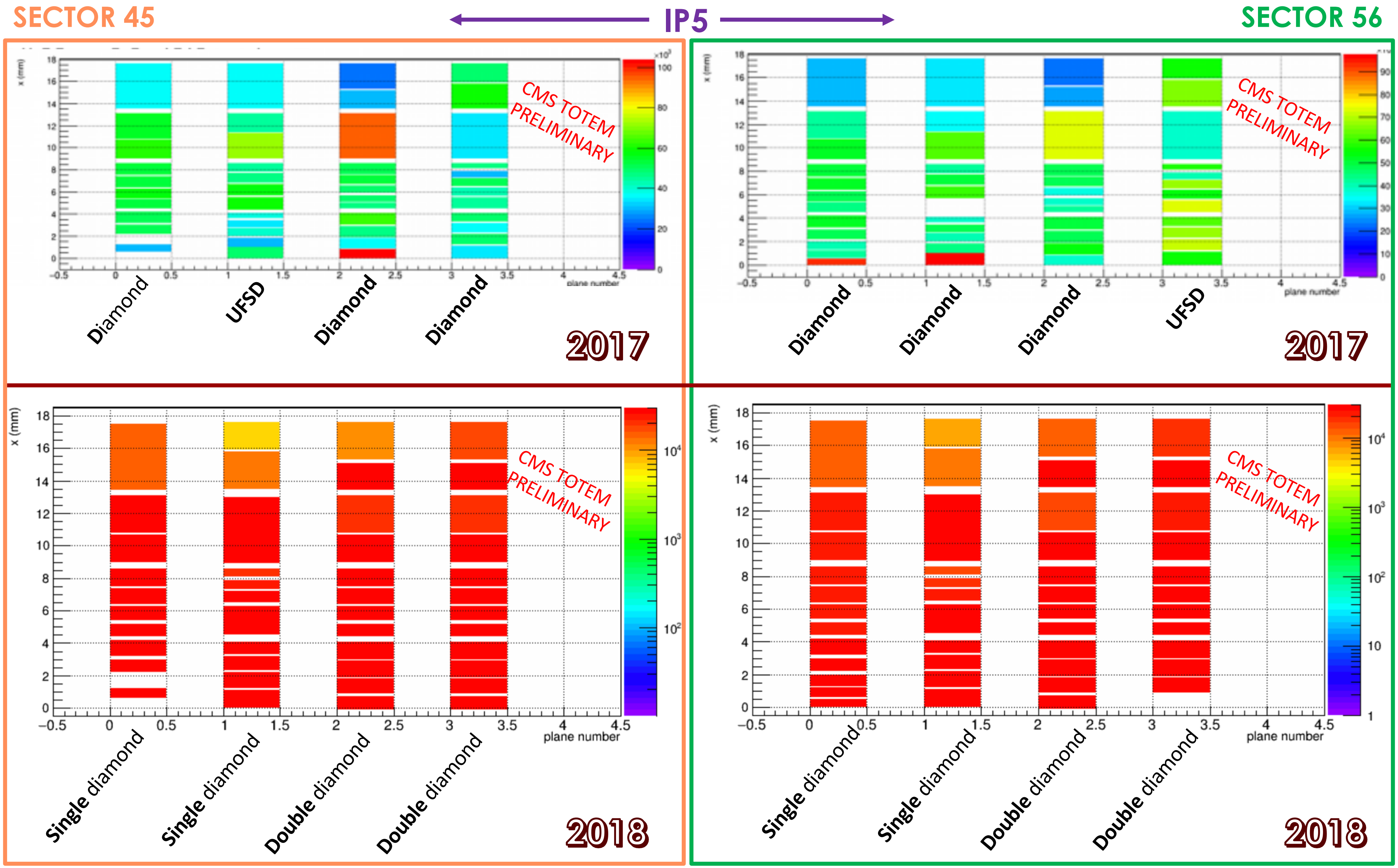
Number of tracks reconstructed by the pixel detector as a function of Pile-Up (PU)

Similar plot for sector 56



- ✓ More then 20% of events with multi-track in standard data taking conditions
- ✓ The increasing number of multi-track events with pile-up clearly shows **the advantage of a pixel detector with respect to a strip one**

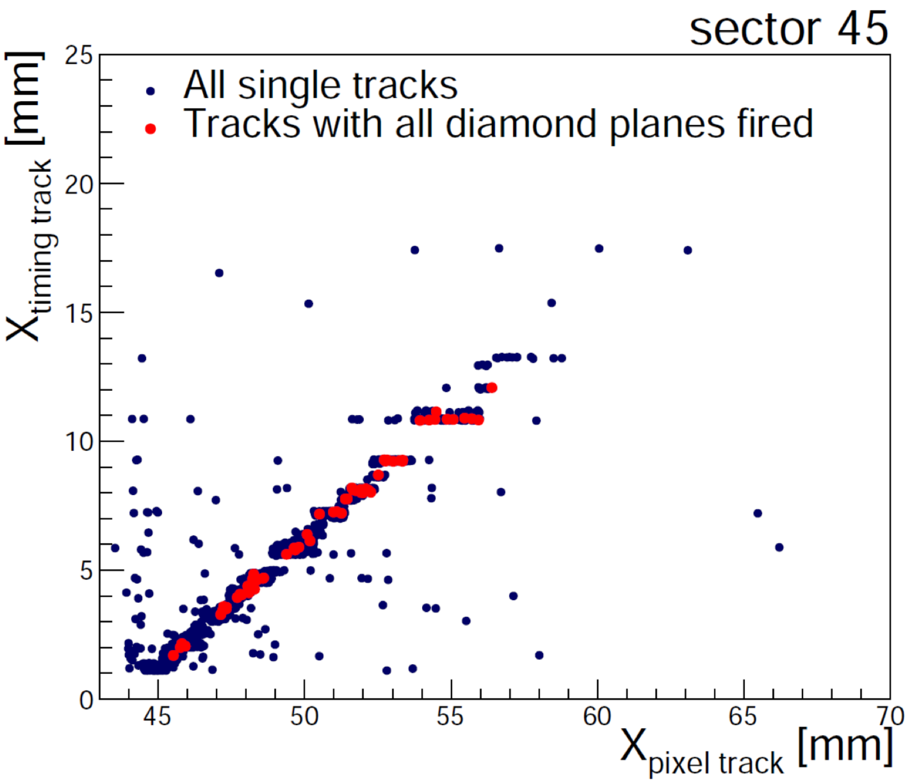
Timing performance: hit distribution



Only few dead channels in both 2017 and 2018

Timing performance

Good correlation between tracks measured in the Pixel and the Timing detectors (both in 2017 and 2018)



Plot produced with 2017 low pile-up data (<PU> ~ 0.8)

Data sample selected by requiring
- a single vertex reconstructed in CMS
- a single track per arm in pixel detector
- a single track per arm in timing detector

Blue points: all events passing the double arm selection

Red points: subsample of the previous selection, in which all diamond detector planes fired, with a single hit per plane

Efficiency of diamonds evaluated with tracks reconstructed by 3D pixels: > 90% in 2018 after TS1

PPS prospects for LHC-Run3

PPS will operate as a full CMS subsystem in LHC-Run3 (2021 - 2023)

→ LHCC endorsement in summer 2018

EXPERIMENTAL APPARATUS:

2 horizontal RPs per arm for tracking

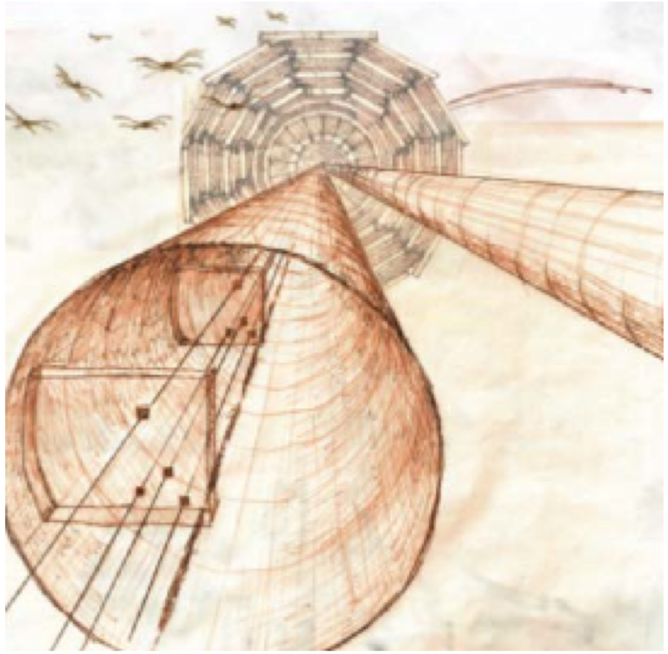
- New 3D Pixels: 2x2 sensors, 150 μm thick, 2E configuration, single side technololy (similar to 3D pixels produced for the Phase-2 R&D)
- PROC600 ROC (same as layer 1 of the CMS pixel detector)
- New detector package with internal movement system, to better distribute the radiation damage

  → Five position spaced by 500 μm, possibility of handling up to ~50 fb^{-1} with minimal efficiency loss

2 horizontal RPs per arm for timing, with separate cooling

- Double diamonds and/or UFSD (under discussion)
- Optimized read-out electronics

Conclusion



- ✓ **PPS** fully integrated **in CMS since 2016**

- ✓ **~100 fb^{-1} recorded at 13 TeV** with Roman Pots inserted and PPS detectors operating on both arms
  - ~39% of CMS total recorded luminosity in 2016
  - ~88% of CMS total recorded luminosity in 2017
  - ~93% of CMS total recorded luminosity so far in 2018

- ✓ PPS **regularly taking data** in high-luminosity fills **with the design detector configuration** since the beginning of 2018:
  - 2 horizontal RP per arm for **tracking with 3D pixel detectors**
  - 1 horizontal RP per arm for **timing with single and double diamond detectors**

  Smooth data taking and overall **very good performance**

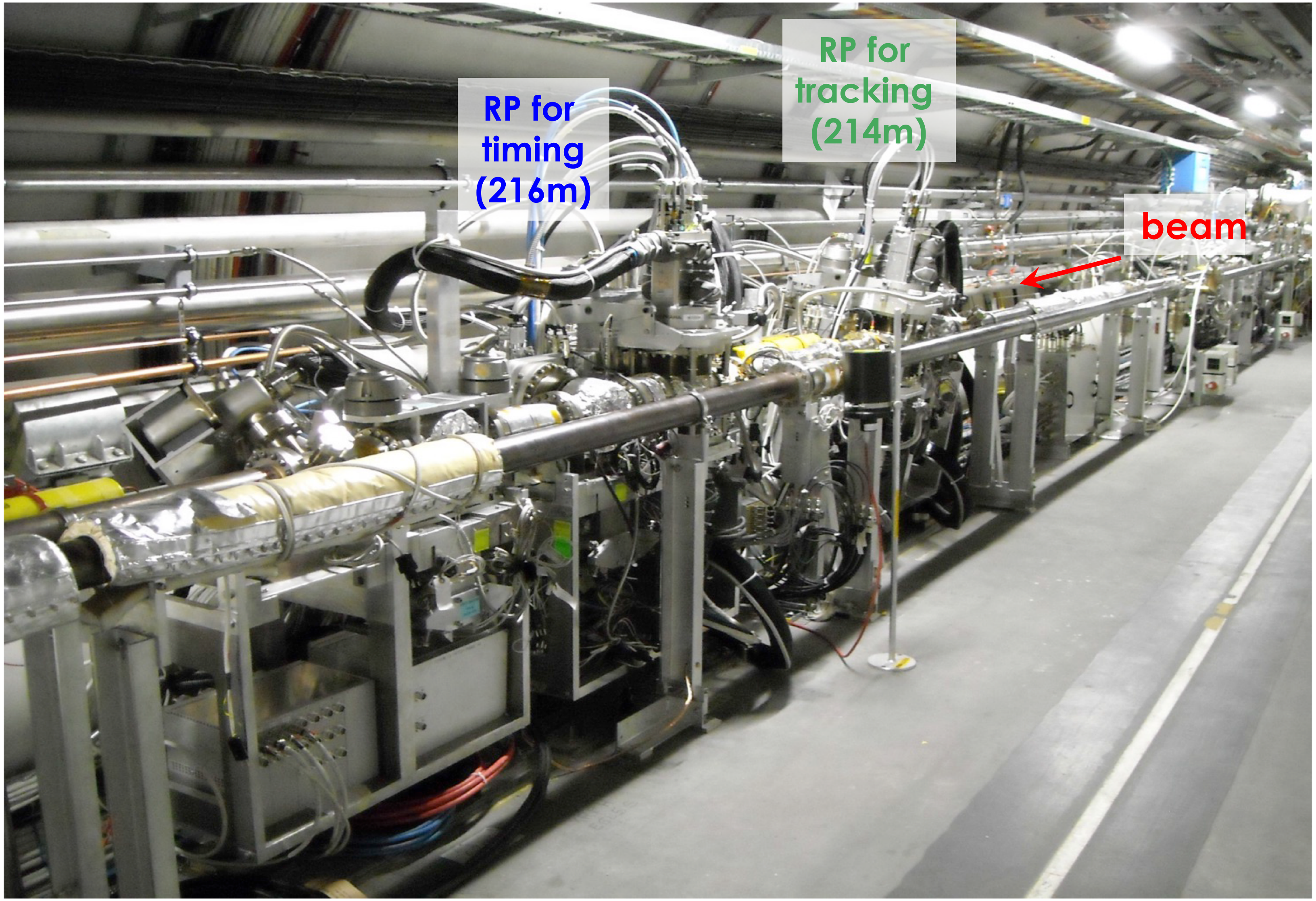
- ✓ 2018 Detector performance studies and Run2 data analysis in progress

- ✓ Preparation for **Run3** started

BACKUP SLIDES

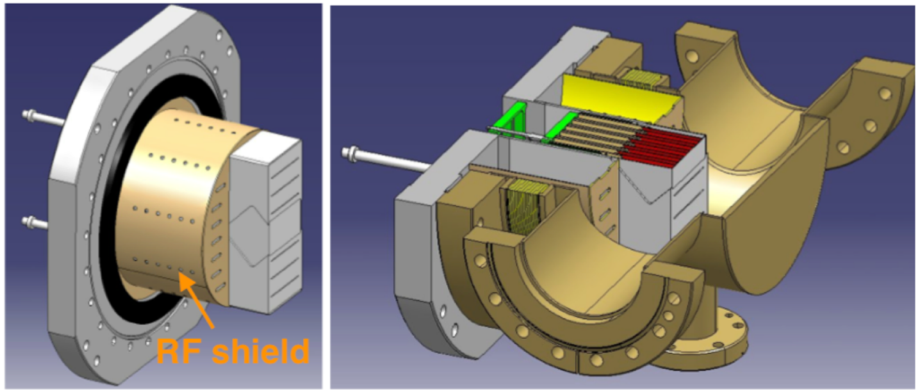
Experimental Apparatus and LHC Tunnel

RP for tracking (220m)

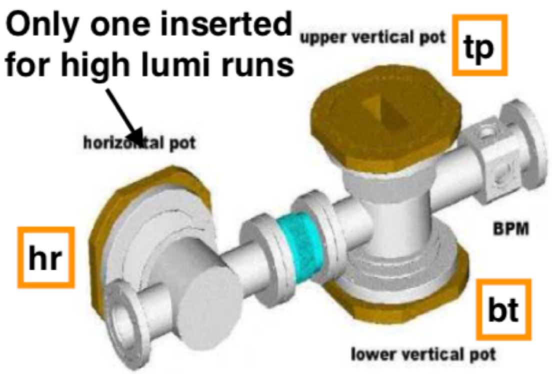


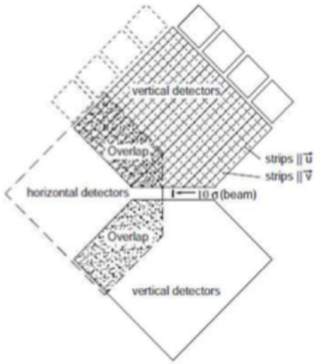
Roman Pots

RP for tracking stations



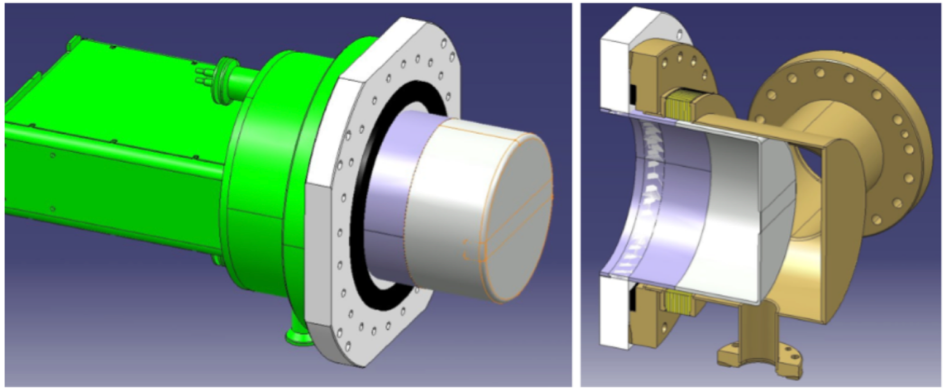
Each station includes 3 RPs





Tracking RPs **equipped with a thin window 150 µm thick toward the beam**

RP for timing stations

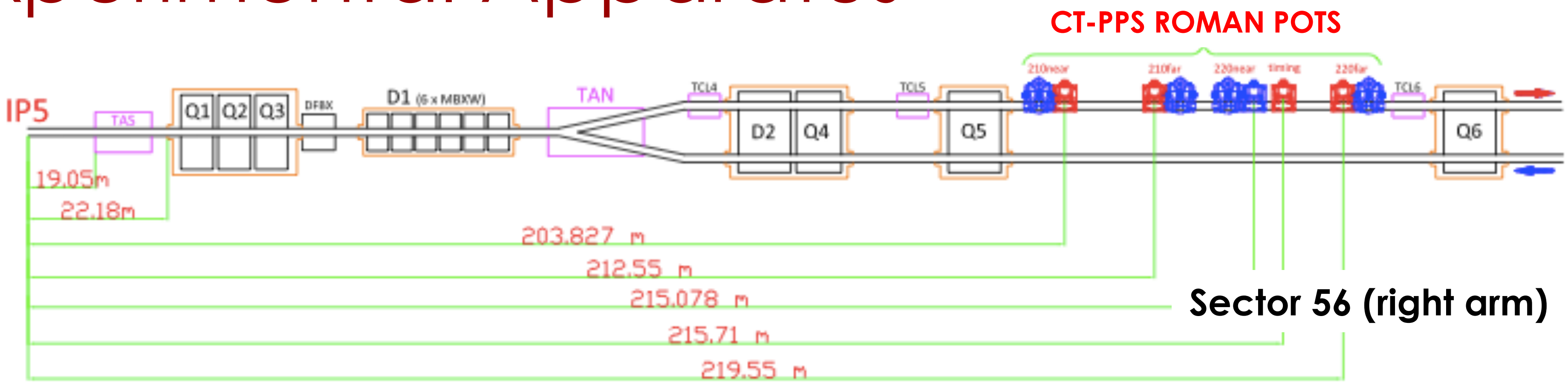


Cylindrical RP specifically designed for PPS to reduce the impedance and host larger detectors.

Equipped with **a 300 µm thick window towards the beam** (thickness required to compensate the pressure gradient on the larger window).

No vertical stations, alignment done by propagating tracks from the tracking stations.

Experimental Apparatus



Proton position and angle measurements, combined with the beam magnets, allow to **determine the momentum of the scattered protons**

- Position resolution of ~10 μm
- Angular resolution of ~1-2 μrad

→ **$\Delta p/p \sim 2 \cdot 10^{-4}$**

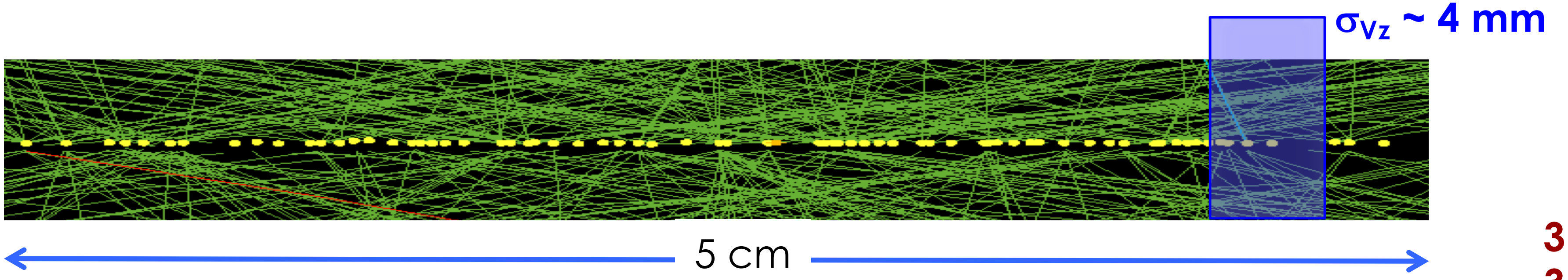
Mass resolution: ~5 GeV/c²

Proton timing measurement from both sides of CMS allows to **determine the primary vertex**, correlate it with that of the central detector and **reject pile-up**

- Time resolution ~20 ps

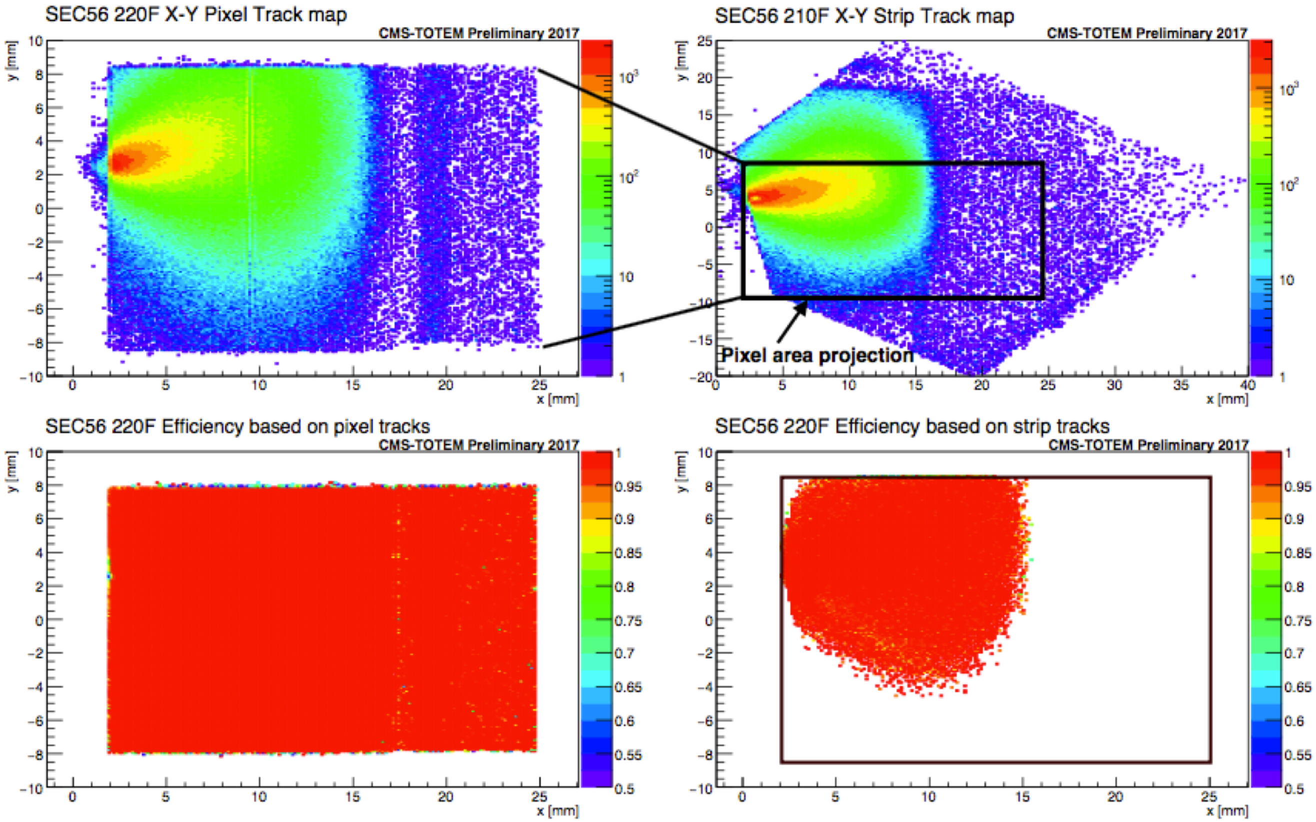
→ **Vertex z-by-timing: ~4 mm**

$$\sigma_{Vz} = \frac{c}{2}\sqrt{2\sigma_{\Delta t}^2}$$



Tracker performance: efficiency (2017)

The **pixel efficiency** calculated with the tracks reconstructed within the same pixel station **validated with tracks reconstructed in the strip detectors.**



TRACK MAPS IN PIXEL AND STRIP DETECTORS

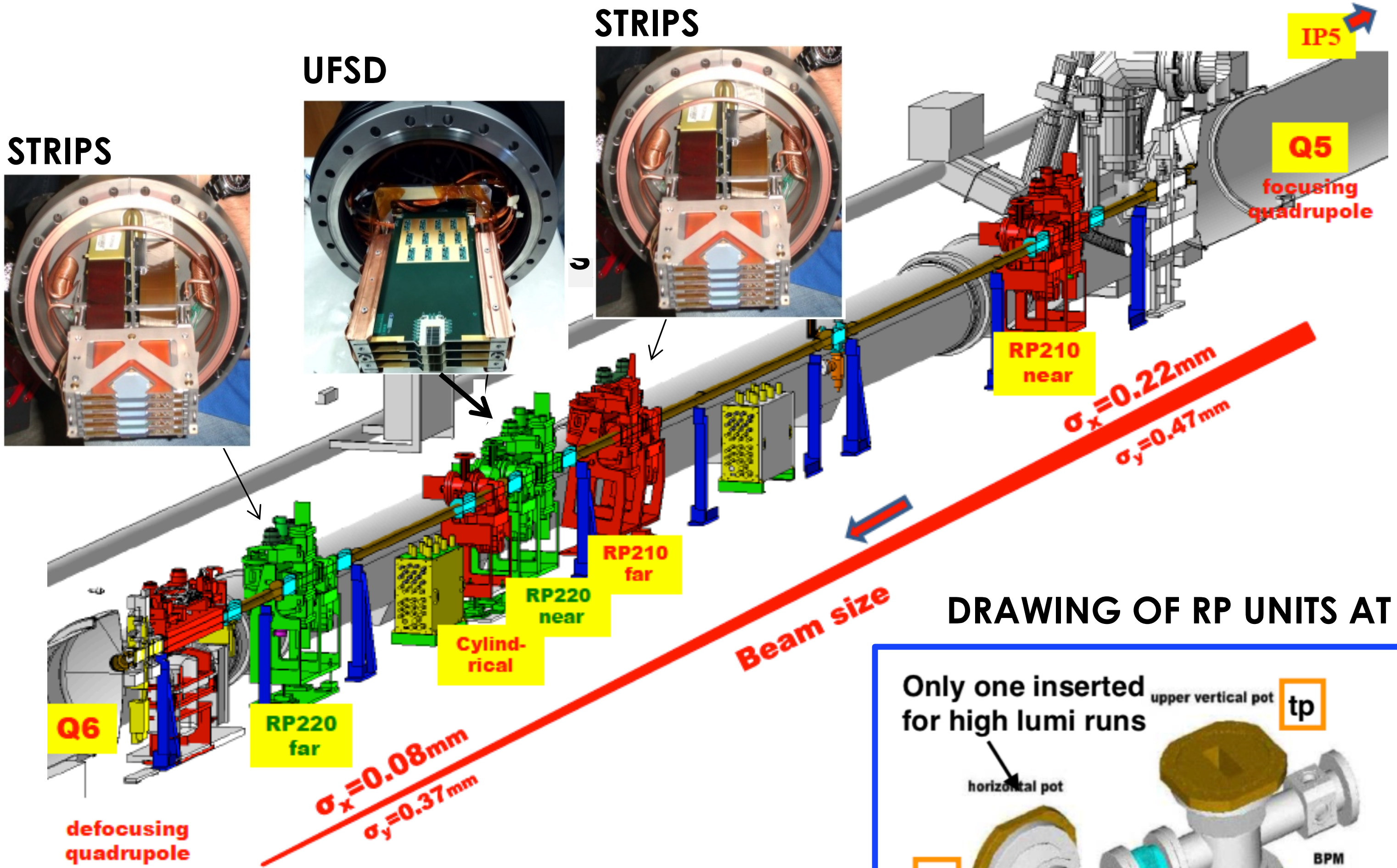
PIXEL DETECTOR EFFICIENCY BASED ON TRACKS RECONSTRUCTED WITH THE STRIP DETECTOR

- Study carried out for a LHC fill with the timing RPs out
- Efficiency calculated with the requirement of at least 15 entries per bin (~ 1 pixel cell) to avoid fluctuations due to low-statistics

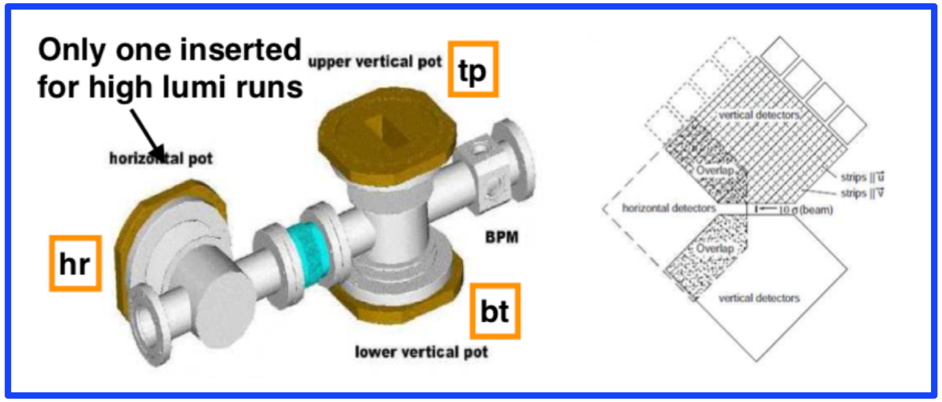
TOTEM experimental apparatus

CMS-TOTEM → Low Luminosity , high β* special Runs (low PU)

- **2 vertical pots** with Silicon Strip planes for **Tracking**
- **1 vertical pot** with UFSD planes for **Timing**



DRAWING OF RP UNITS AT 210 m AND 220 m



TOTEM experimental apparatus

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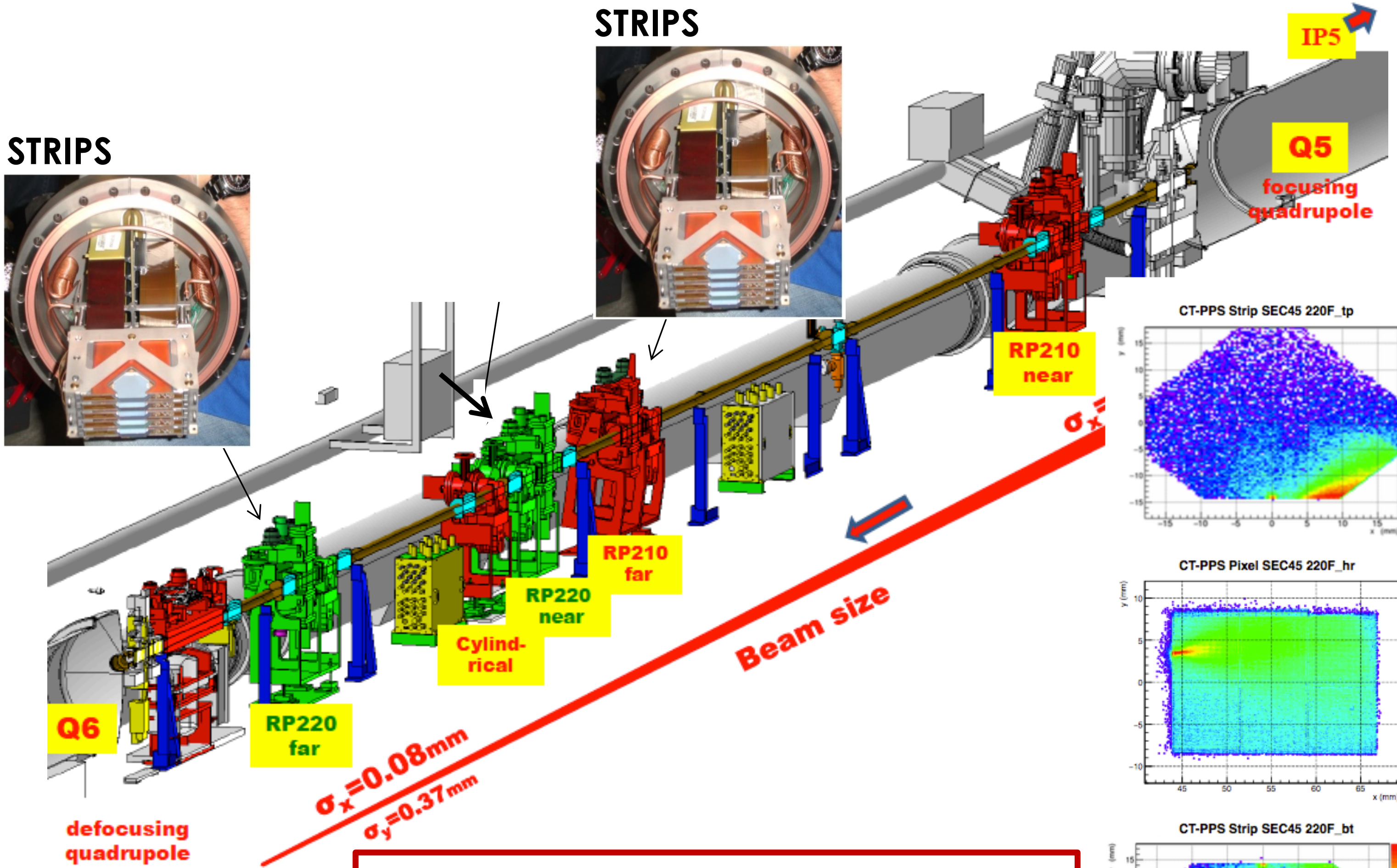
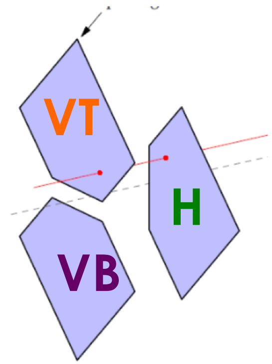
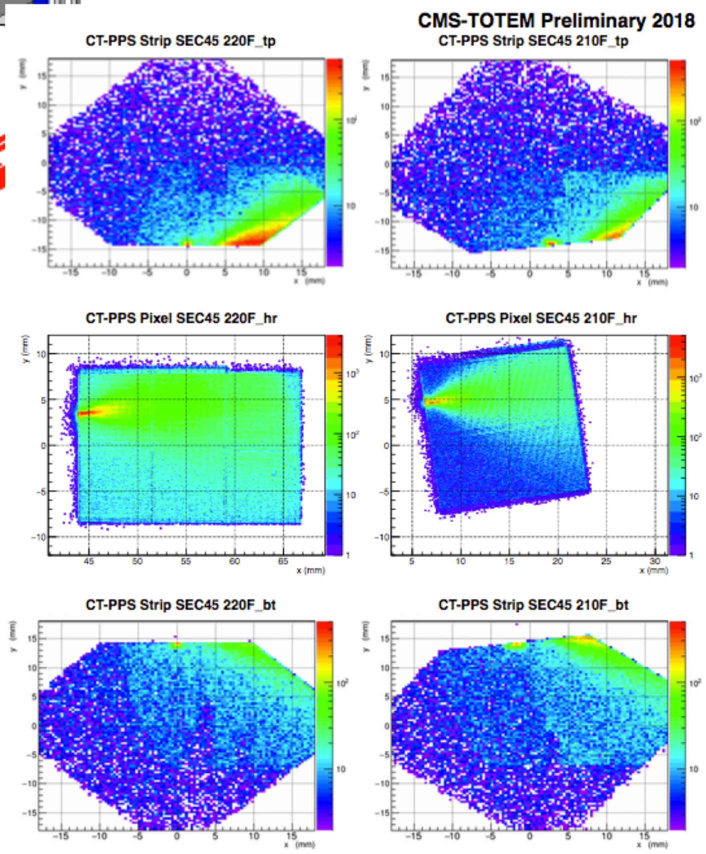




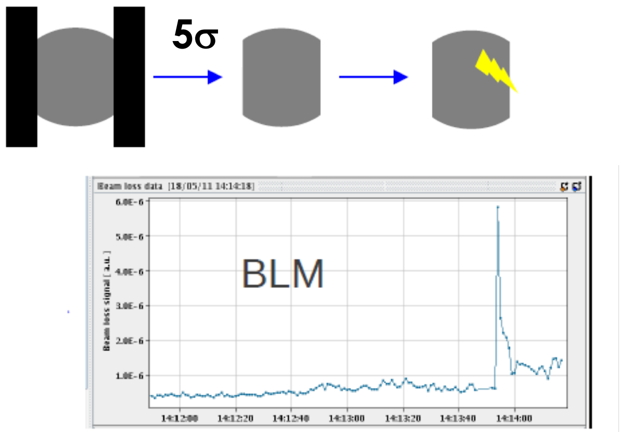


TOTEM strip detectors used in dedicate run to align PPS RPs with respect to the beam

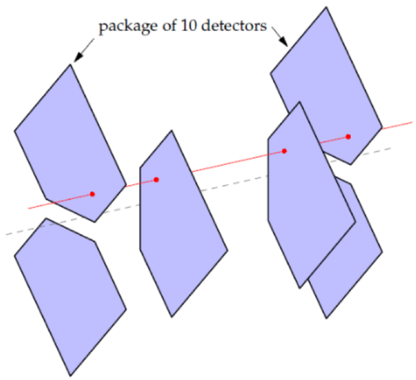
RP Detector Alignment Run

The alignment of RPS among themselves and with respect to the beam done in **dedicated low intensity run** where all (horizontal and vertical) RPs approach the beam.

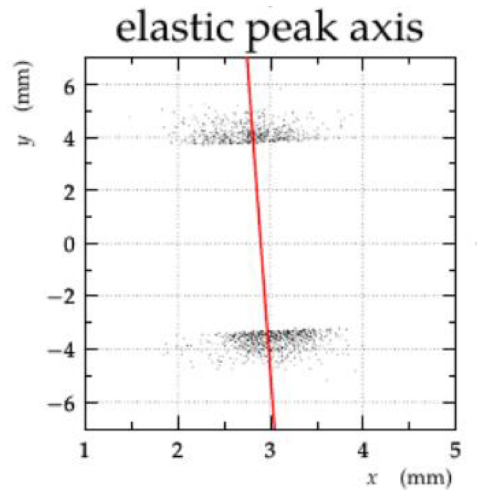
A 3-step procedure[1] developed and extensively used by TOTEM is applied



1. Alignment wrt the collimators



2. Relative RP alignment



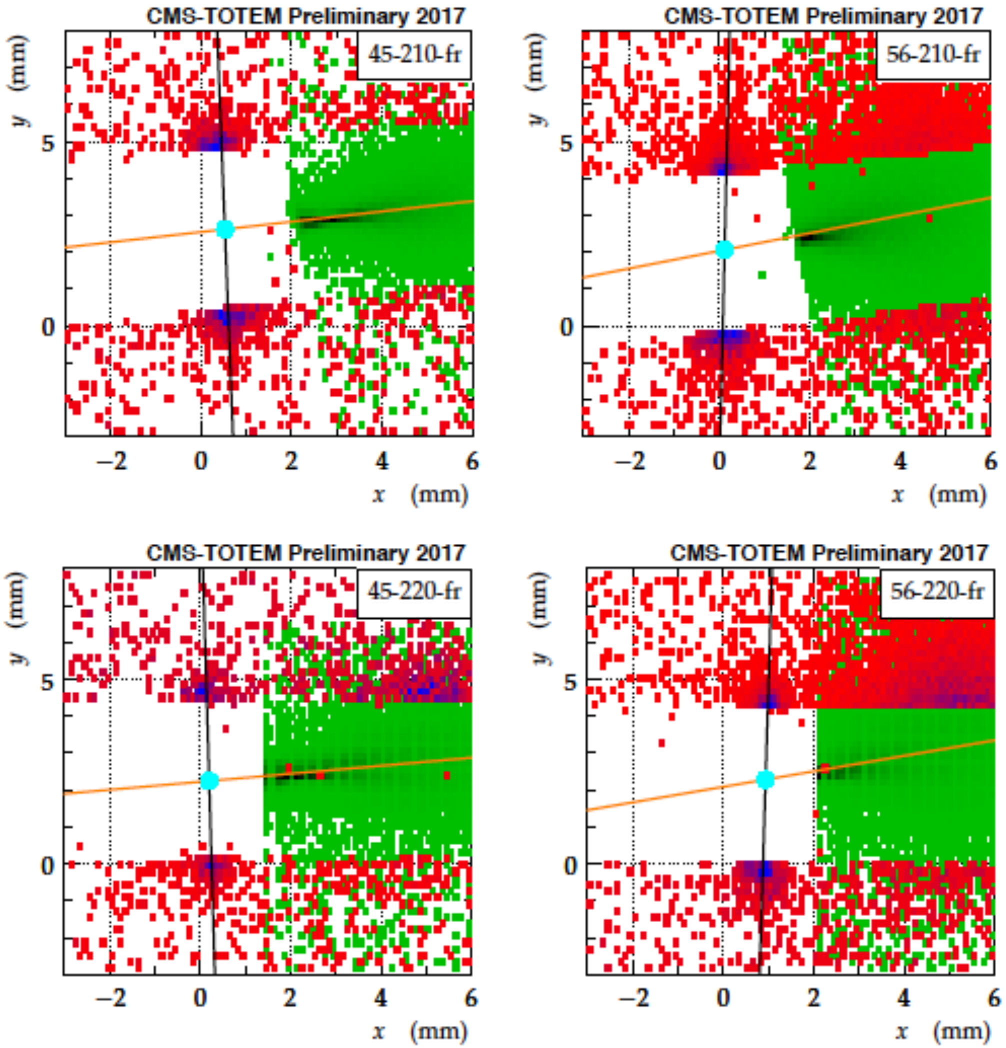
3. Global alignment wrt the beam

For each physics run the RP position is determined by comparing the measured shape of the distribution of the track-impact-point x with the one obtained in the alignment run.

[1] CERN-TOTEM-NOTE-2017-001/002

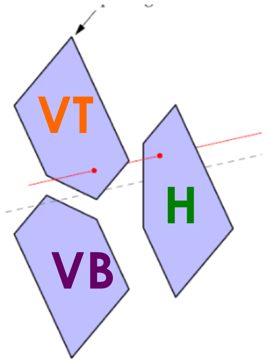
2017 data taking - Alignment

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 orange line, estimate of beam position

2017 Data - Silicon Strips



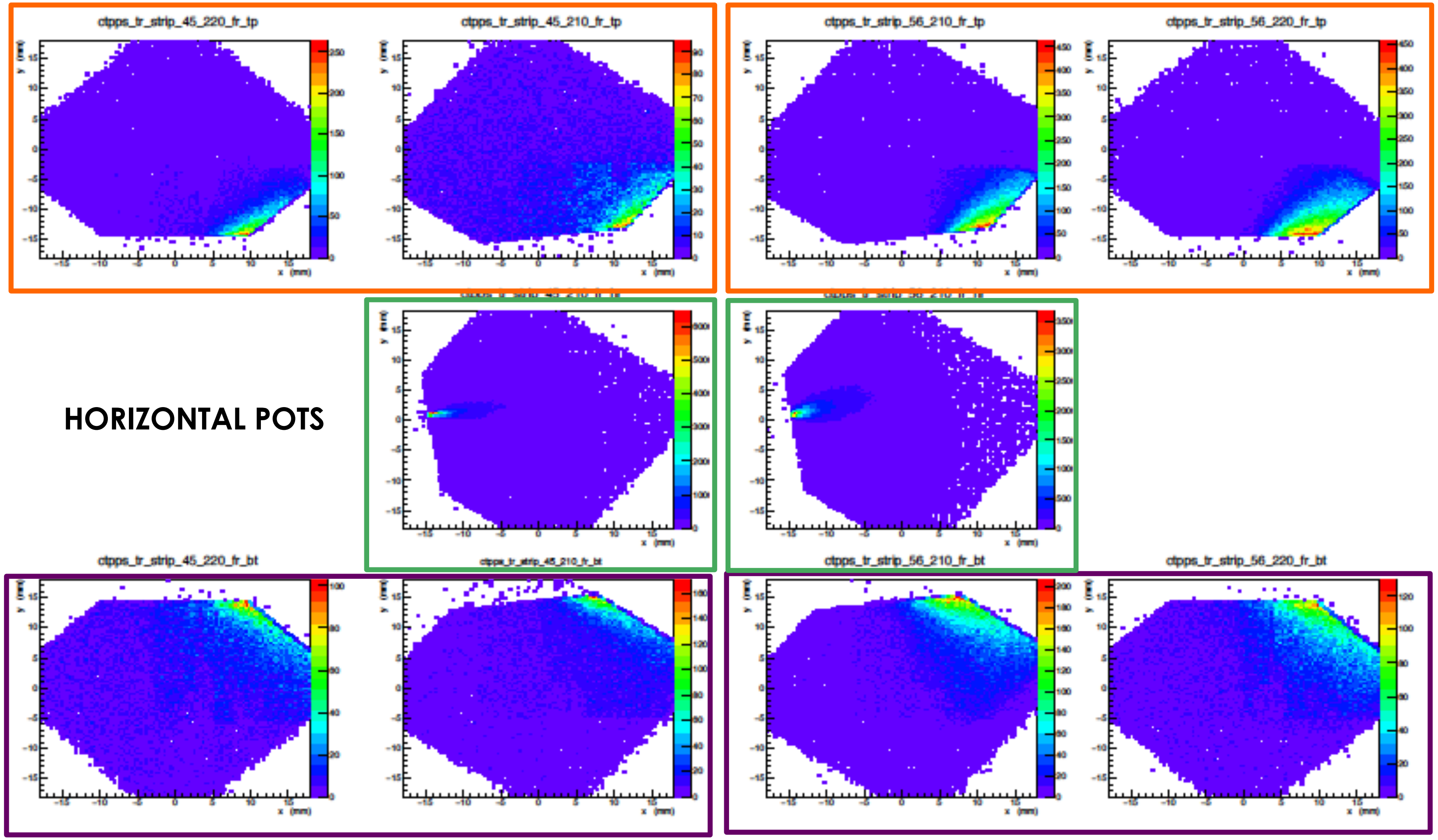
CT-PPS DQM Plots from 20-21 May 2017 Alignment Run

Sector 45 | **Sector 56**

TOP VERTICAL POTS

HORIZONTAL POTS

BOTTOM VERTICAL POTS



Roman Pot insertion

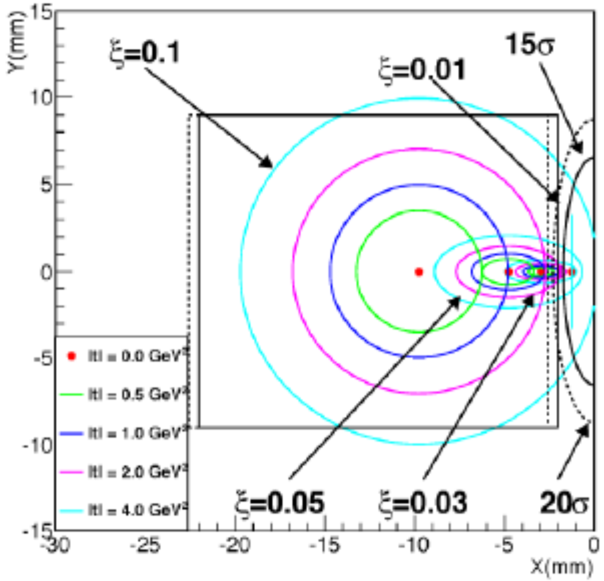
➢ The insertion of Roman Pots inside the LHC beam pipe is a delicate procedure that needs to be tested and approved by the machine

➢ 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 and 2019 CT-PPS ran 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

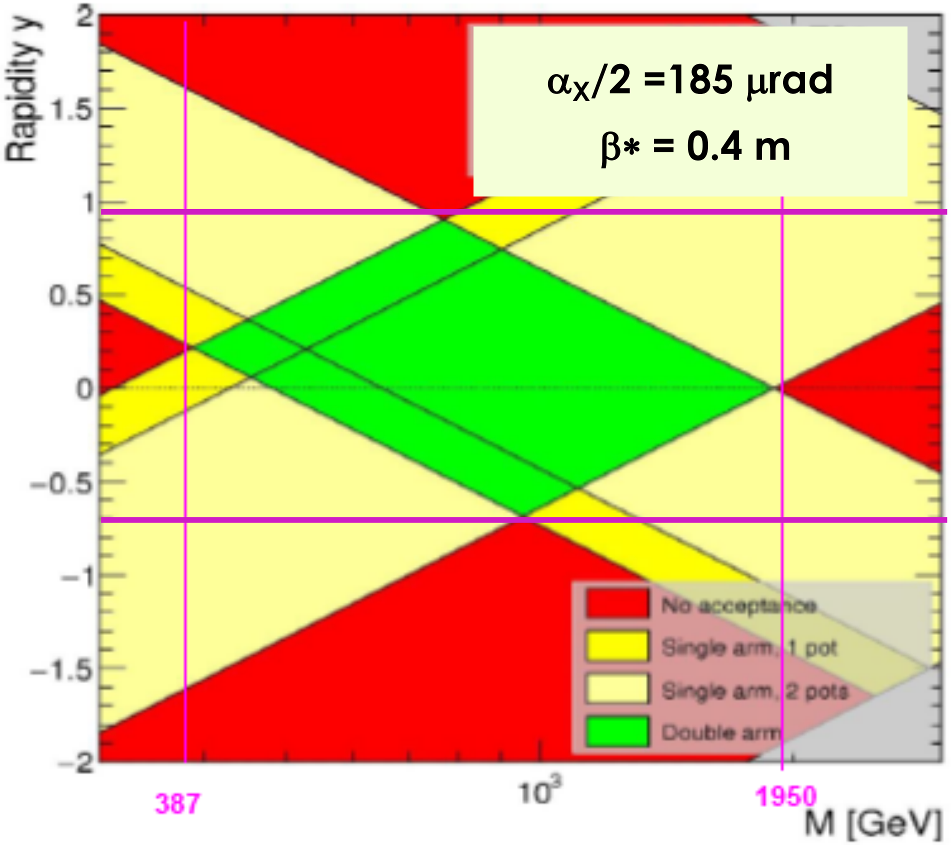


Detector acceptance in 214 m RP (X as of CMS) from CT-PPS TDR [TOTEM-TDR-003, CMS-TDR-13]

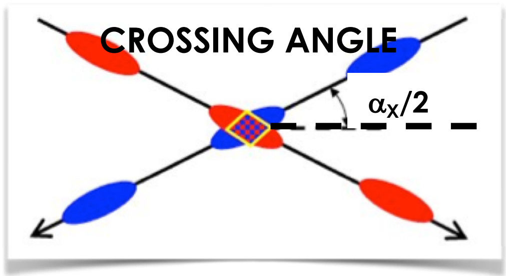
M.M.Obertino – Università e INFN Torino – Vertex workshop 2018

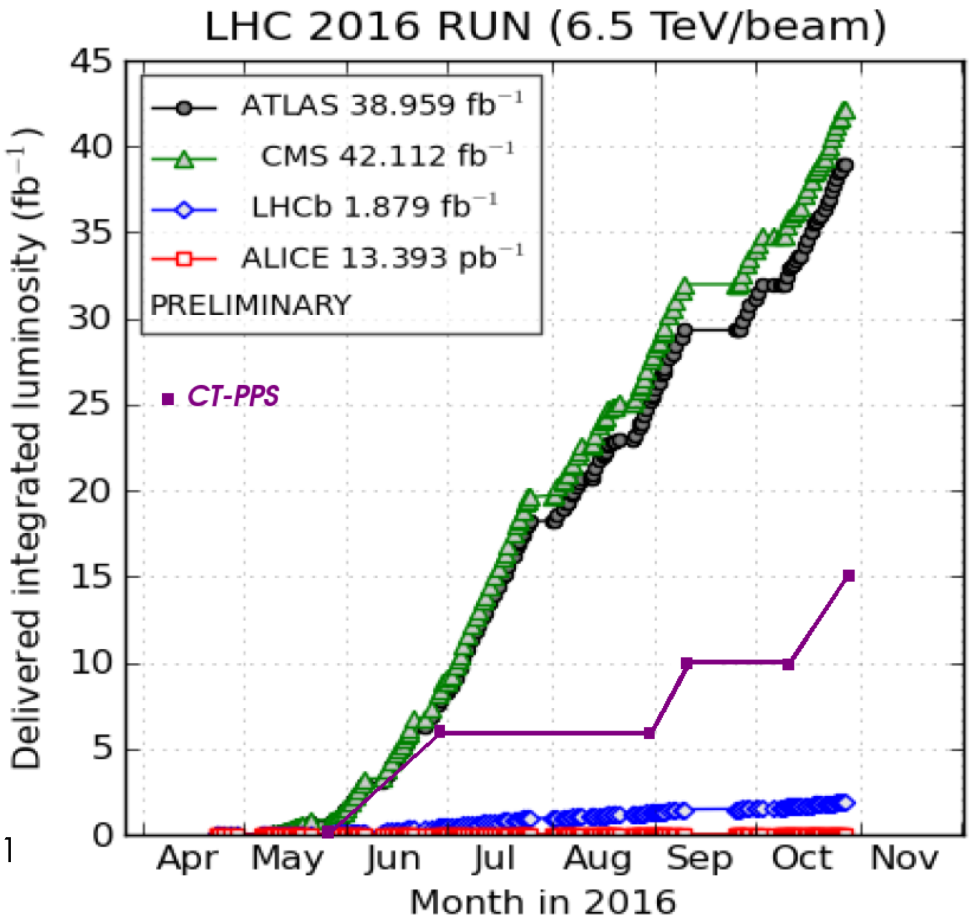
2016 RP acceptance

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



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





Data collected with:

- Silicon Strips only: first 12.5 fb^{-1}
- Silicon Strips & Diamonds: last 2.5 fb^{-1}

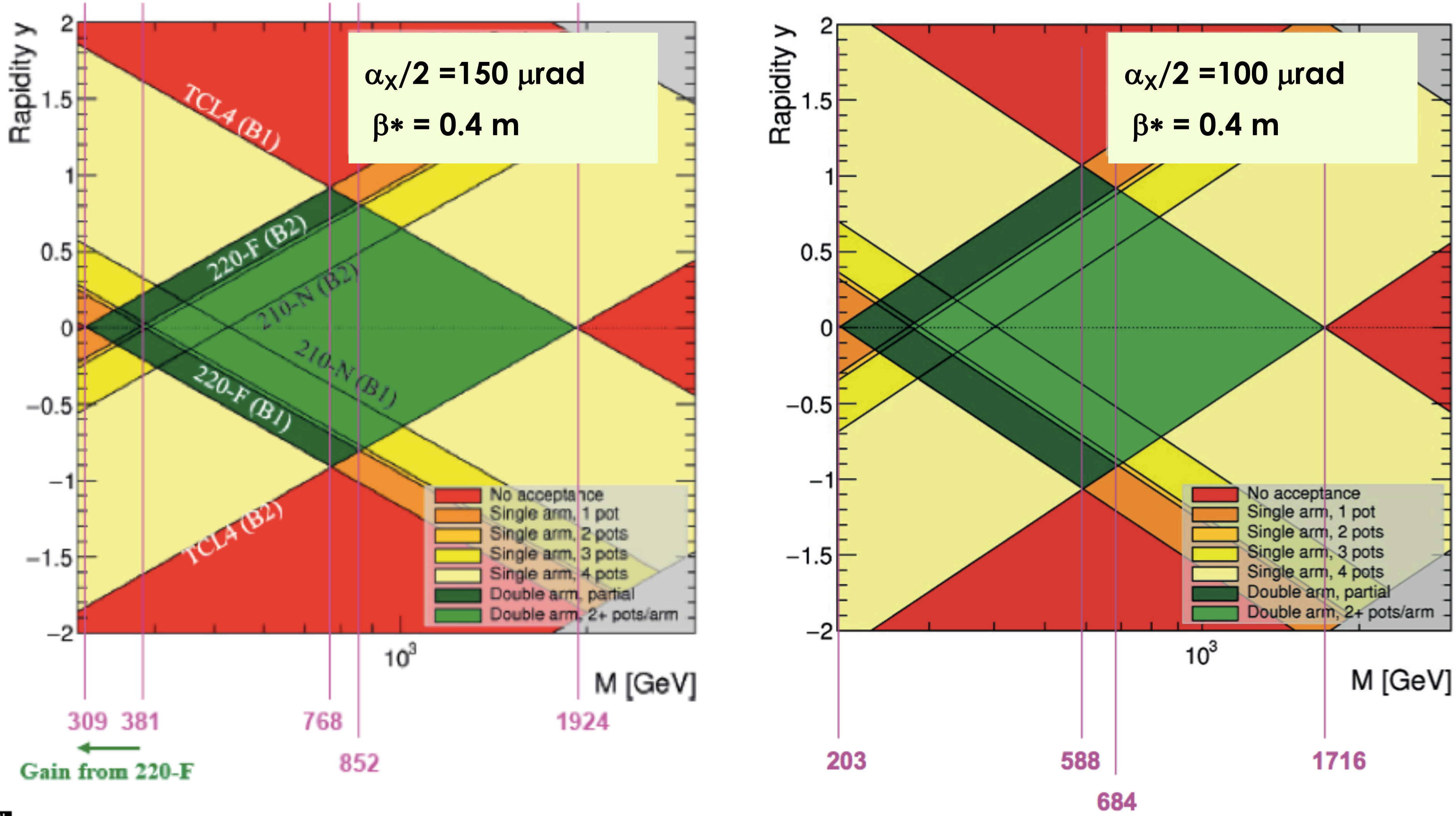
- **Minimum distance** of approach to the beam: **15σ_{beam}**

2017 RP acceptance

In 2017 Roman Pot operation foreseen at 4 crossing-angles

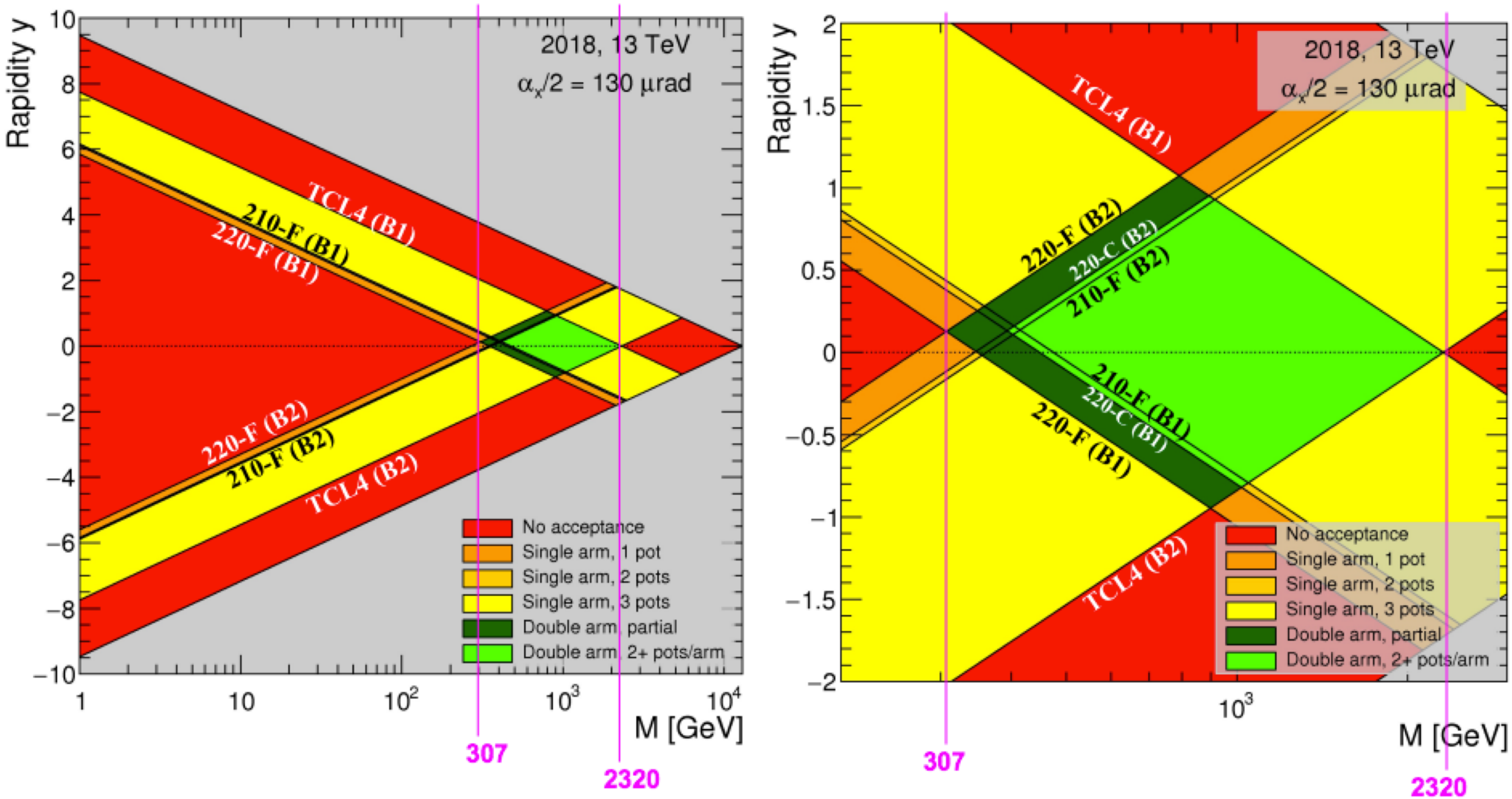
- $\alpha_X/2$: 150, 140, 130, 120 μrad

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

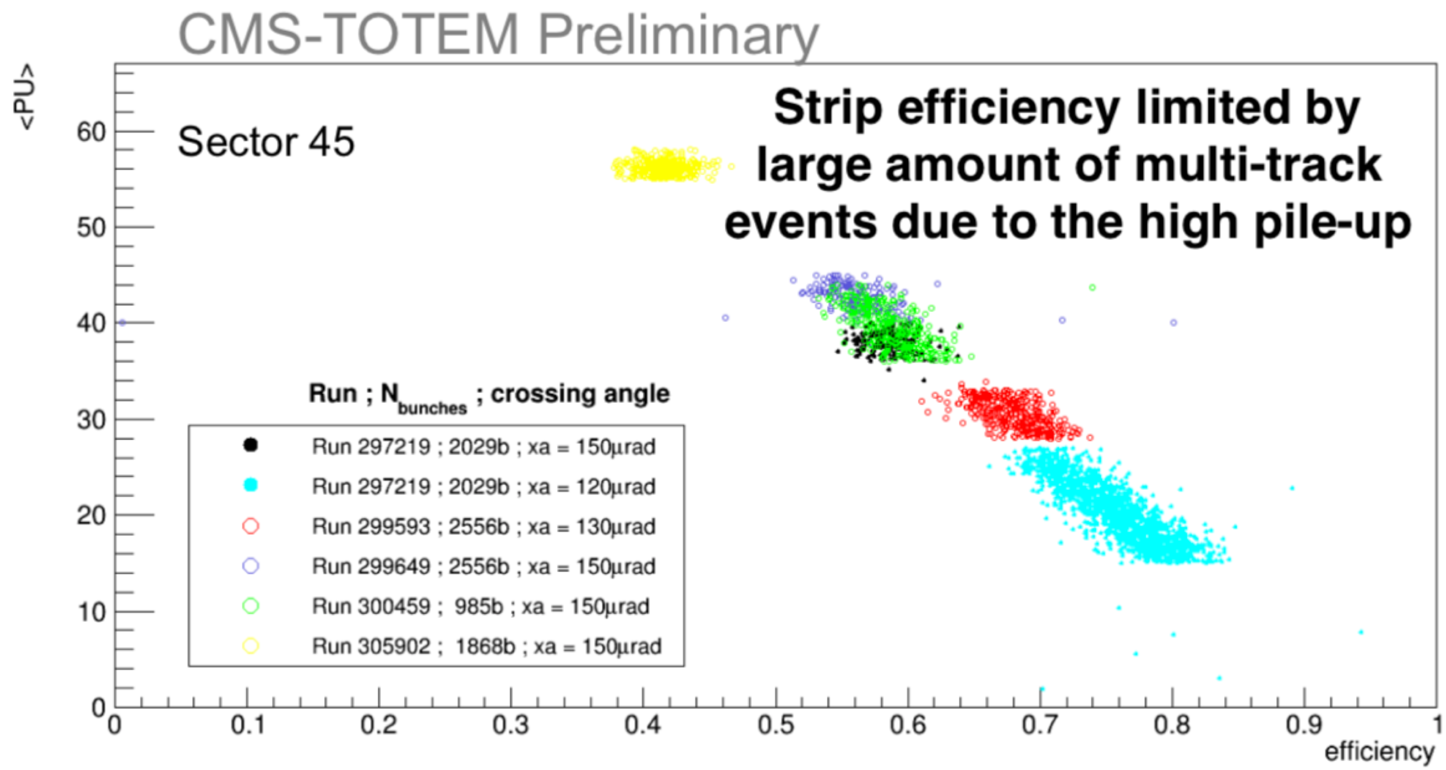


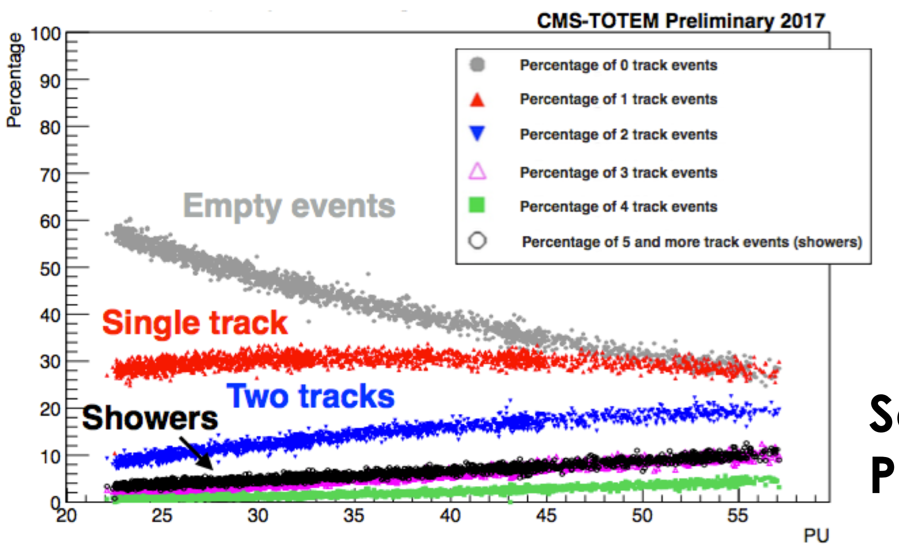
Minimum distance of approach to the beam: **$12\sigma_{beam}$ + 0.3 mm**

2018 RP acceptance



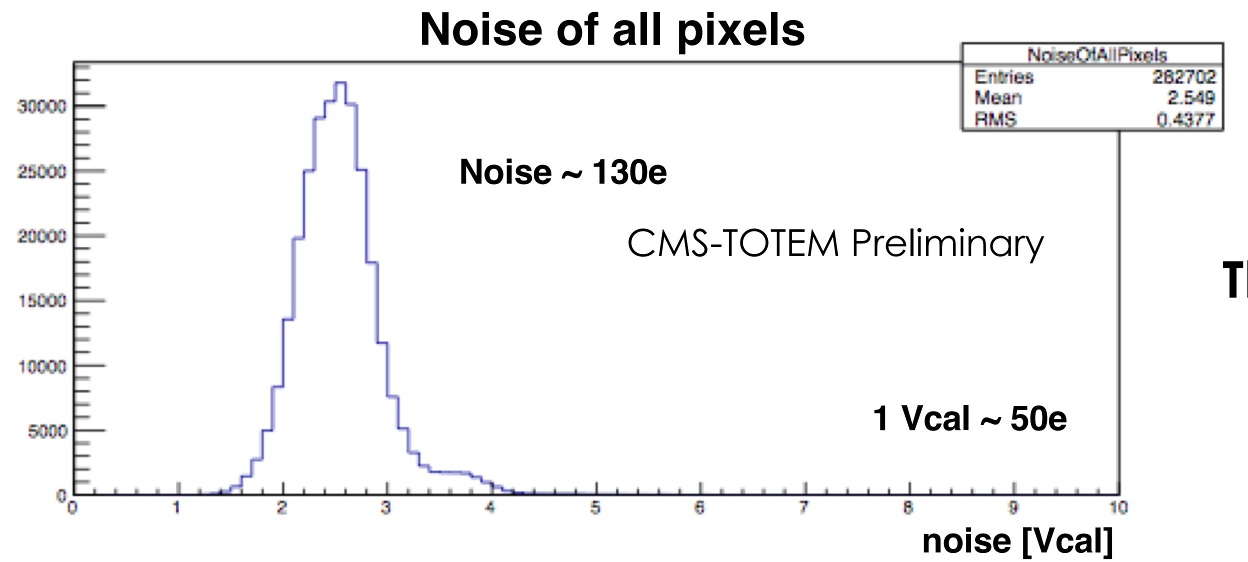
Multi-track capability of strip detector





Sector 45
Pixels

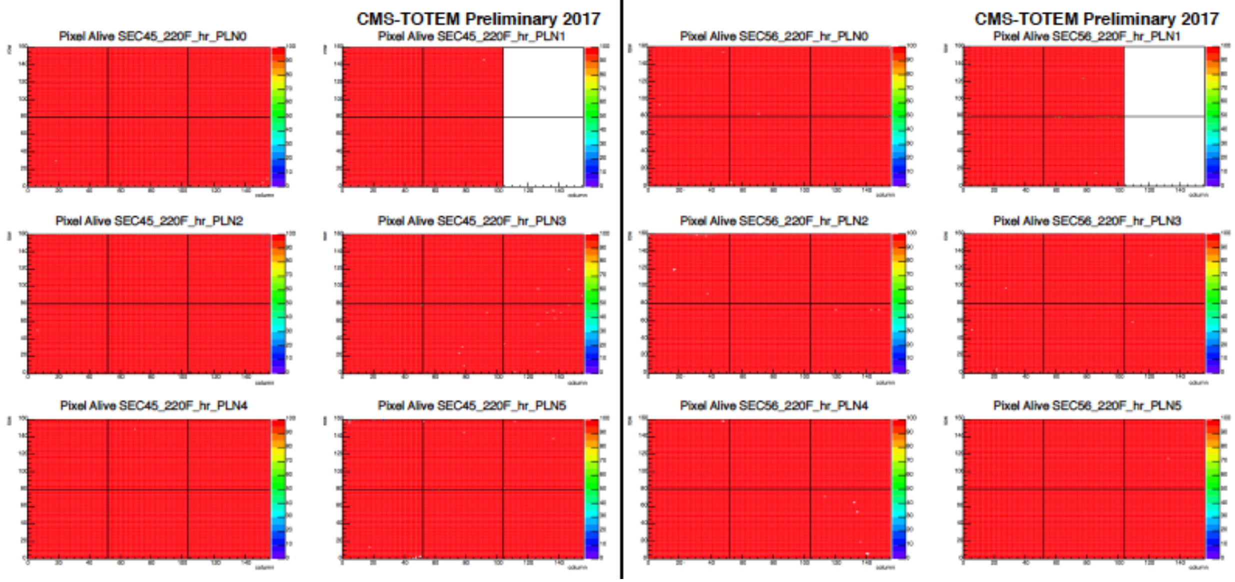
Pixel performances – Noise and bad channels



Threshold ~ 2000e

Module maps for sector 45
installed on LHC beam-pipe 1

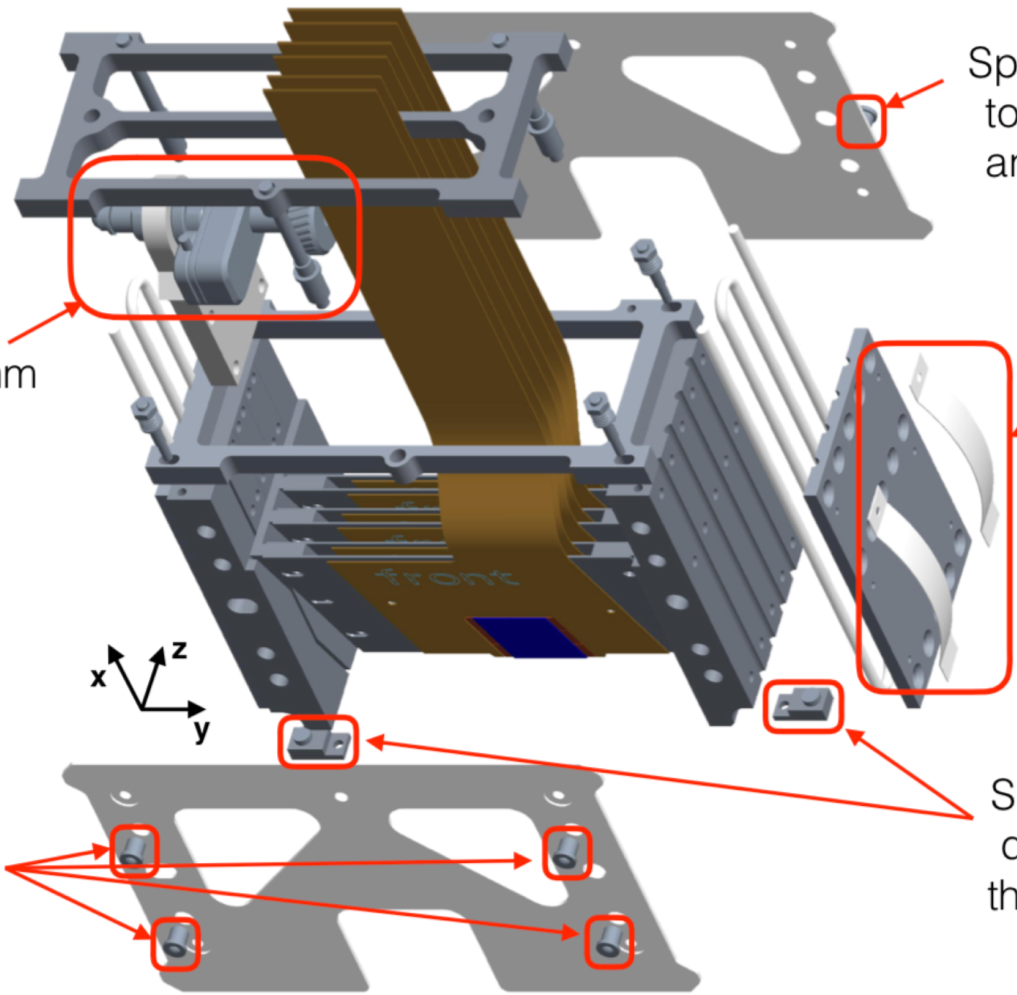
Module maps for sector 56
installed on LHC beam-pipe 2



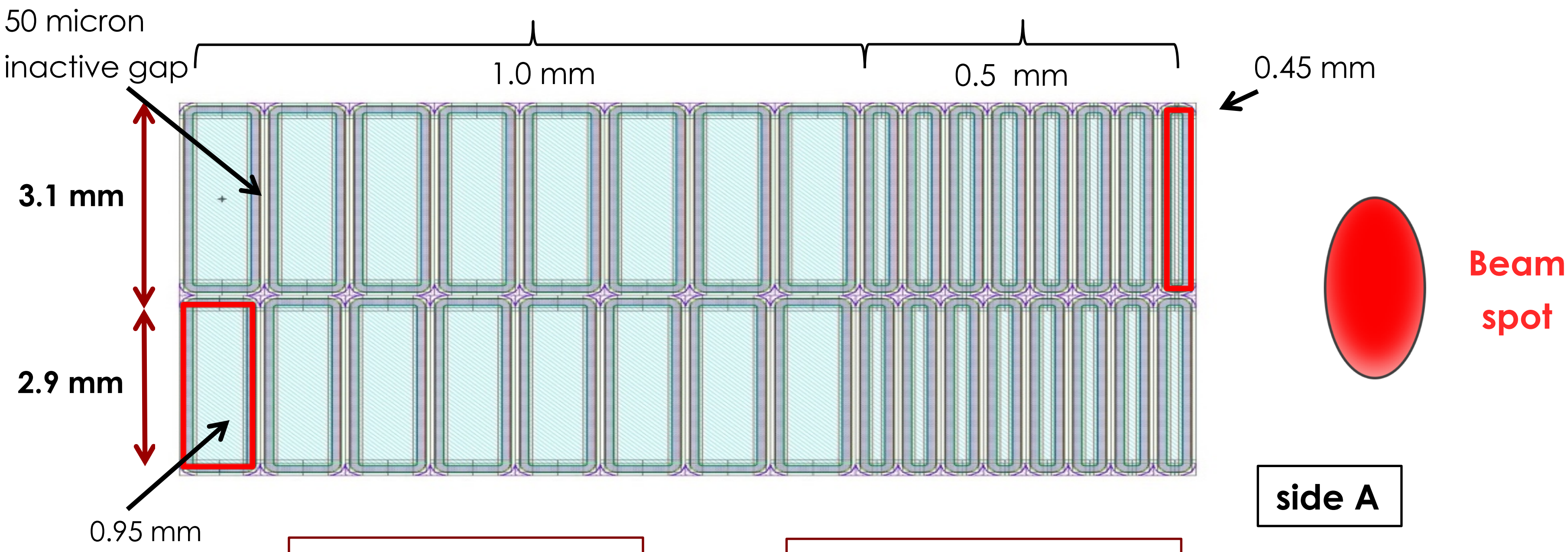
☞ Very low number of bad (eff < 90%) or noisy pixels (< 0.05% of all channels)

Detectors with remote movement

To mitigate the radiation damage of the electronicS, we are developing a new detector package that can be moved inside the RP in a quick tunnel access. Five position spaced by 500 μm will be available, so as to handle up to ~50 fb-1 with minimal efficiency loss. We plan to install the new packages as soon they are ready and validated.



UFSD sensors for ct-pps



16 Pixel ~ 3 mm²
Cap. Pixel ~ 6 pF

16 Pixel ~ 2 mm²
Cap. Pixel ~ 4 pF

Area = 12mm x 6mm
Thickness = 50 μm
# of channels = 32 (12 read-out)
Gain ~ 15
Slim edge of ~200 μm on side A

Time resolution:
~30 ps

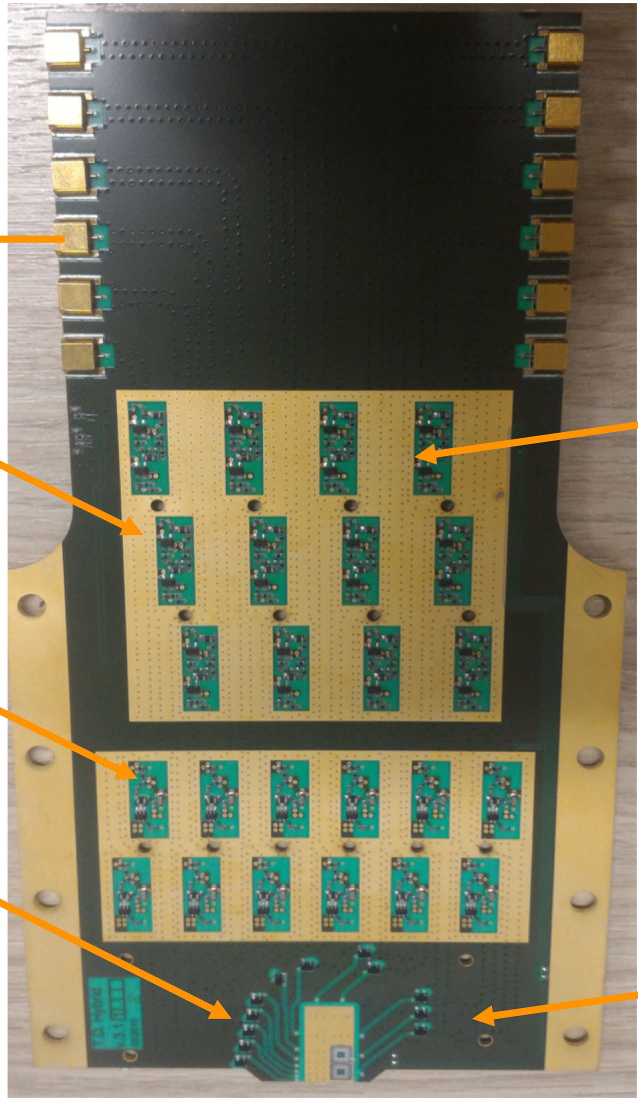
TOTEM hybrid

NINO

3rd amplification stage

2nd amplification stage

1st amplification stage for diamonds



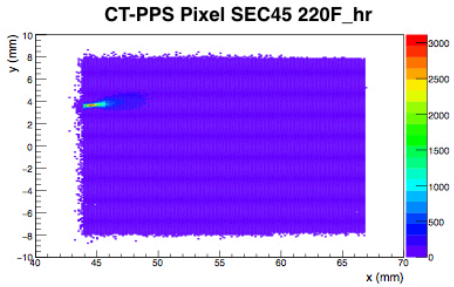
3rd amplification stage detuned to compensate for UFSD internal gain

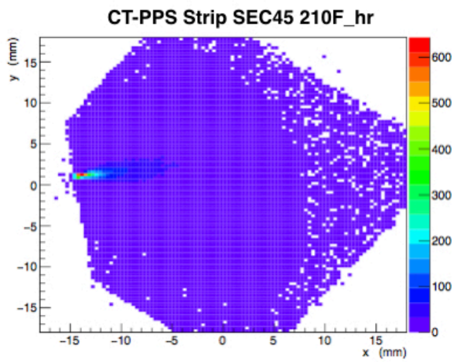
1st amplification stage modified

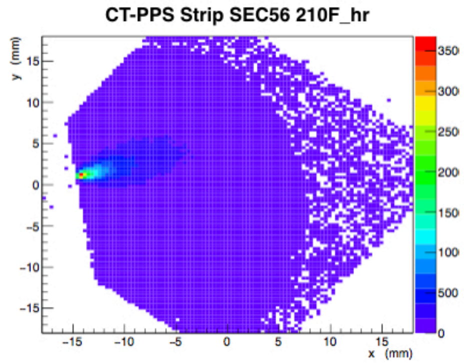
Tracker performance: hit maps

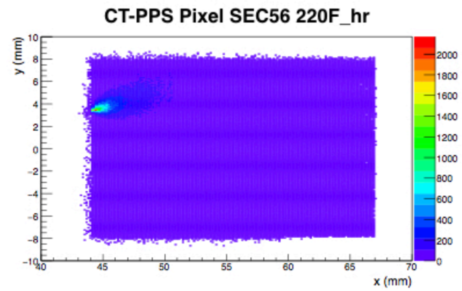
SECTOR 45 ← IP5 → SECTOR 56

2017 DETECTOR CONFIGURATION

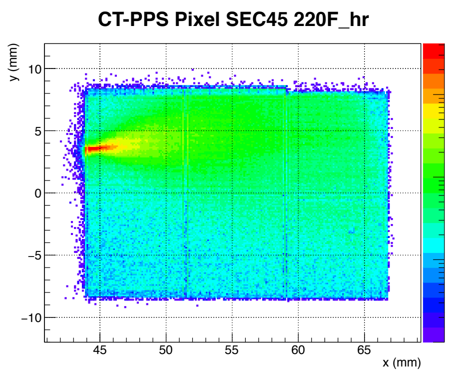


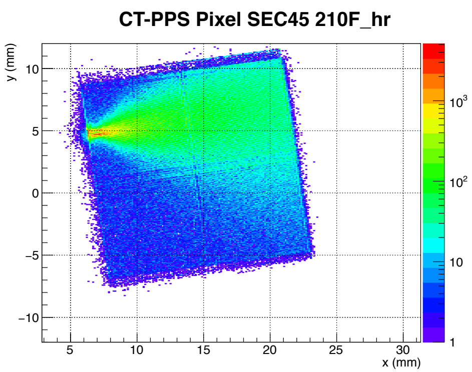


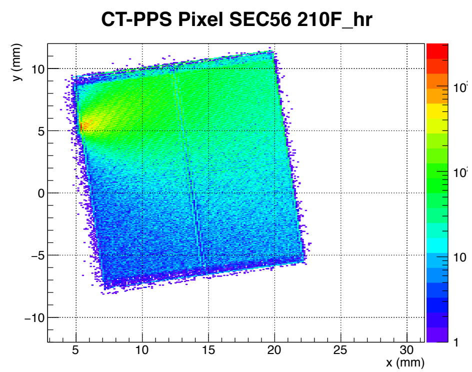


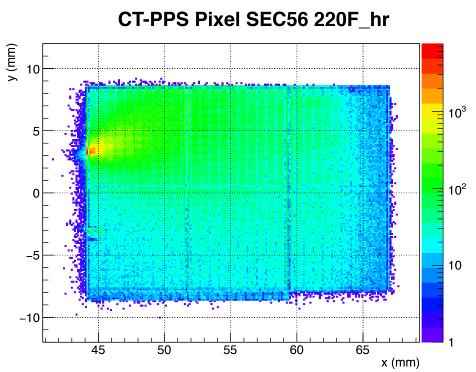


2018 DETECTOR CONFIGURATION







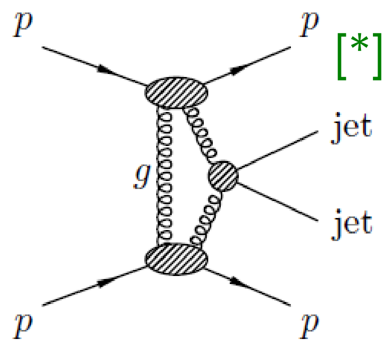


- ✓ Always inserted and taking data in CMS runs
- ✓ Excellent stability in both 2017 and 2018
- ✓ Less than 0.05% bad/noisy pixels

Physics in LHC-Run2 with CT-PPS

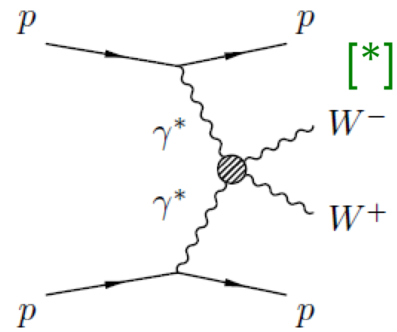
The main goal of CT-PPS is to study central exclusive production (CEP) processes:

pp → ppX



QCD: **LHC as gluon-gluon collider with tagged proton**

- Exclusive two and three jet events
- Test of pQCD mechanism of exclusive production
- Gluon jet samples with small component of quark jets



EWK: LHC used as photon-photon collider

- Measurement of γγ → W+W-, γγ, e+e-, μ+μ-, τ+τ-
- Search for anomalous quartic gauge couplings (AQGCs) with high sensitivity

Beyond Standard Model:

- Clean events (no underlying event)
- Independent mass measurement by pp system
- J^{PC} quantum numbers 0++, 2++

[*] CEP PROCESSES **pp → p X p** STUDIED IN DETAIL FOR THE CT-PPS TDR