The CT-PPS project: detector hardware and operational experience

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Physics motivations

Central Exclusive Production

$$pp \rightarrow p \oplus X \oplus p$$

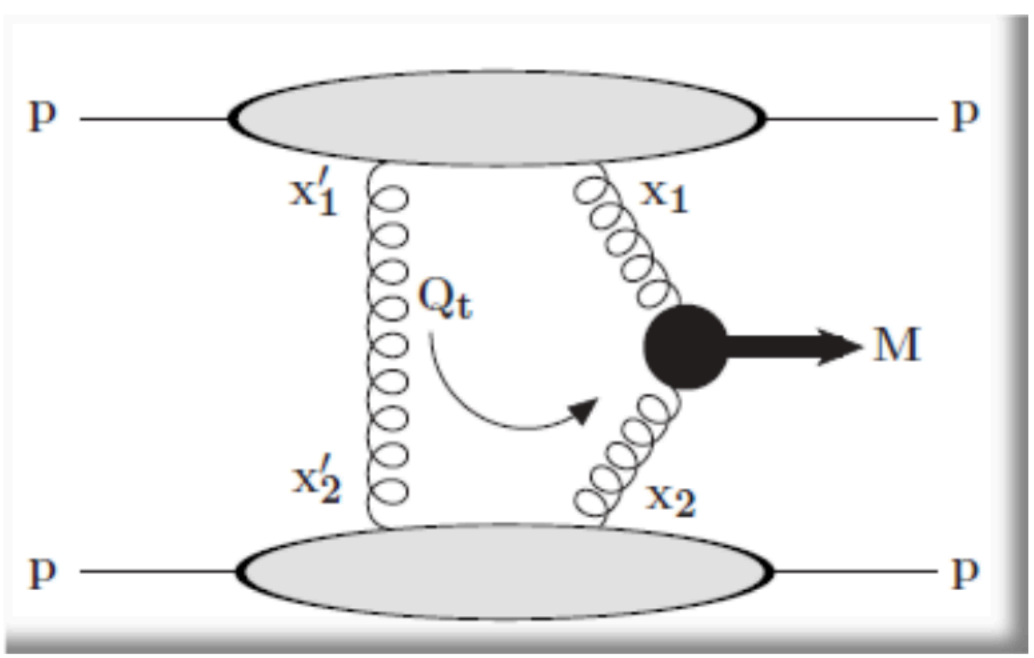
photon or Pomeron exchanges

$\oplus$ rapidity gap

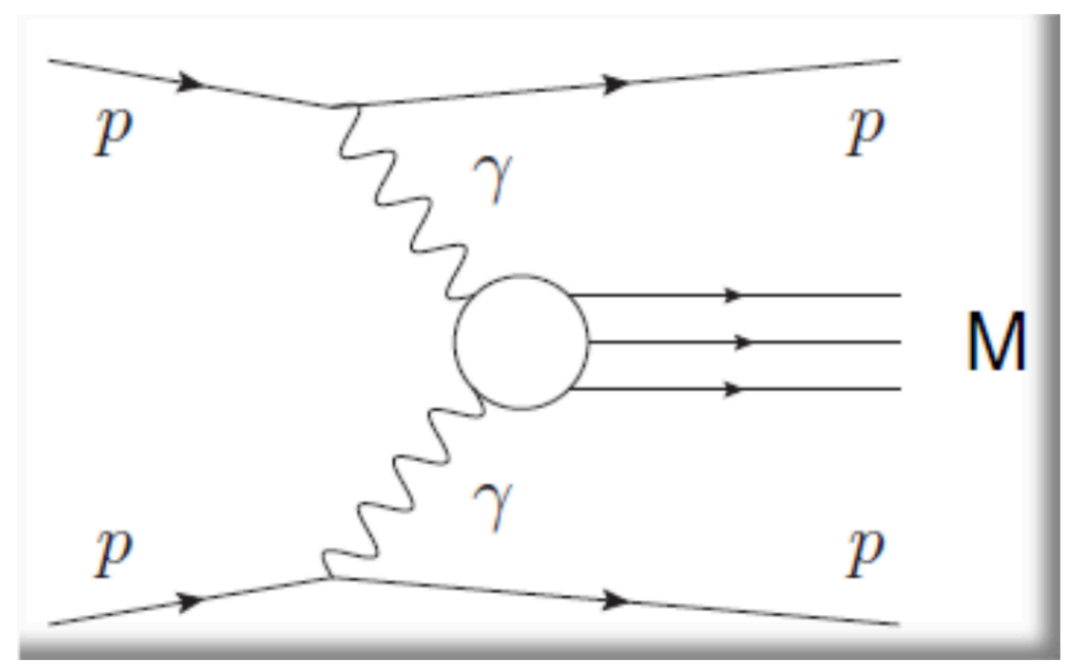
X = high-E_T jets, WW, ZZ, $\gamma\gamma$, … measured in the central detector

Measurement of two scattered protons fully determines the kinematics of the central system X :

- ξ: fractional momentum lost by the proton
- t: 4-momentum transfer squared



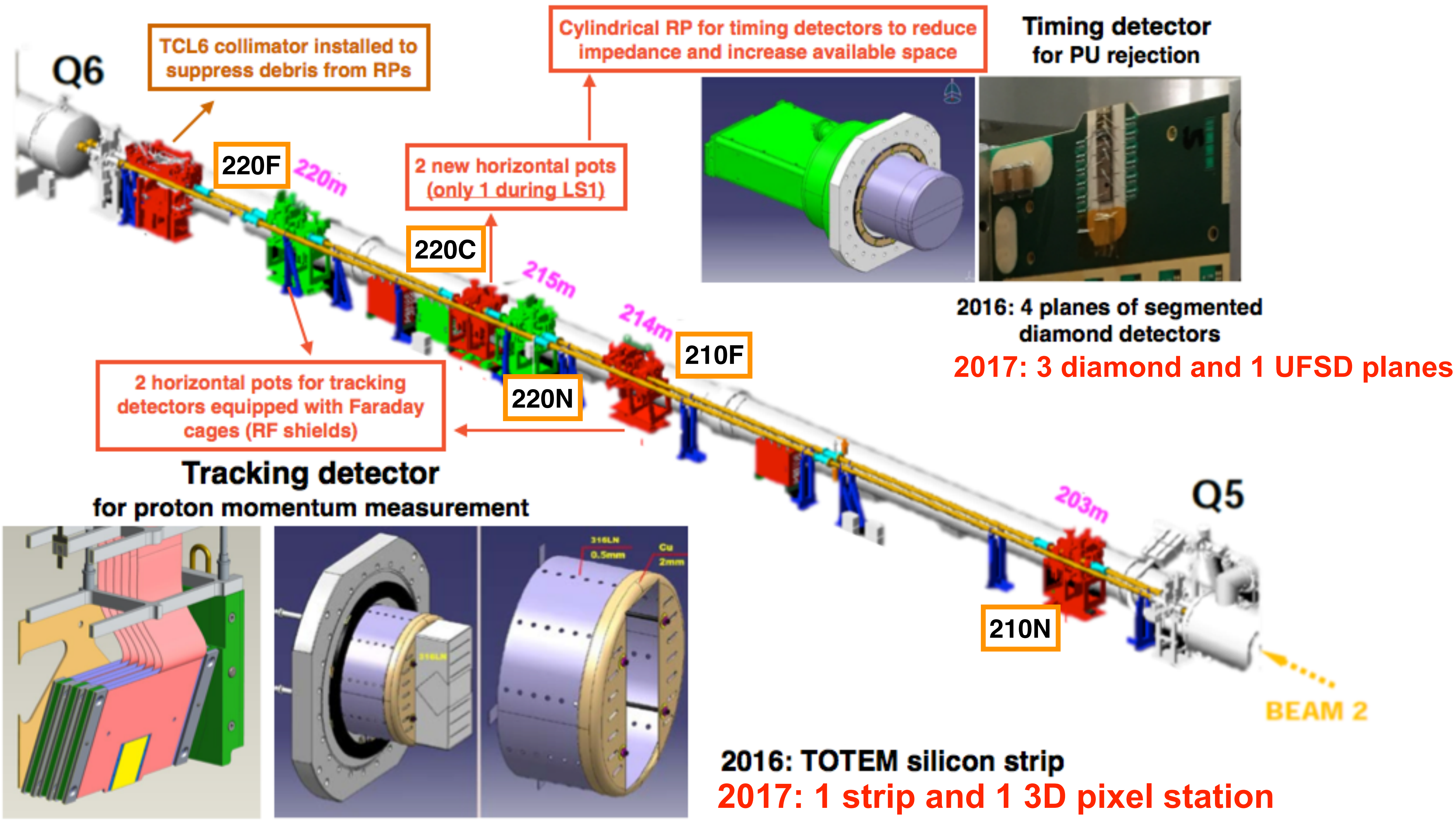
Gluon-gluon interaction. Additional gluon(s) exchange needed to conserve the colour



Photon-photon interaction.

CMS-TOTEM Precision Proton Spectrometer

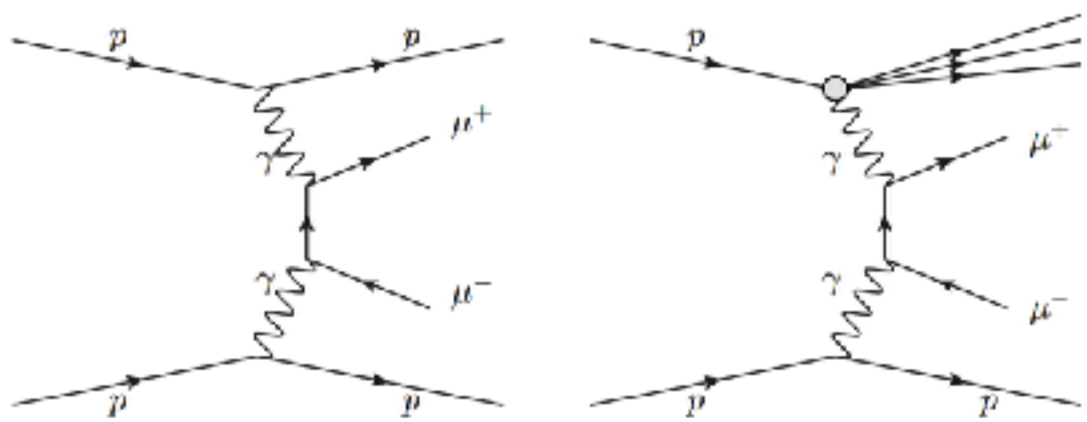
- The **CMS-TOTEM Precision Proton Spectrometer** (CT-PPS) allows the measurement of **proton trajectories in the very forward regions** on both sides of CMS in **standard LHC running conditions**, taking advantage of the machine magnets to bend the protons.
- **Tracking and timing detectors** are installed in Roman pots between 205 and 220 m from the CMS IP.

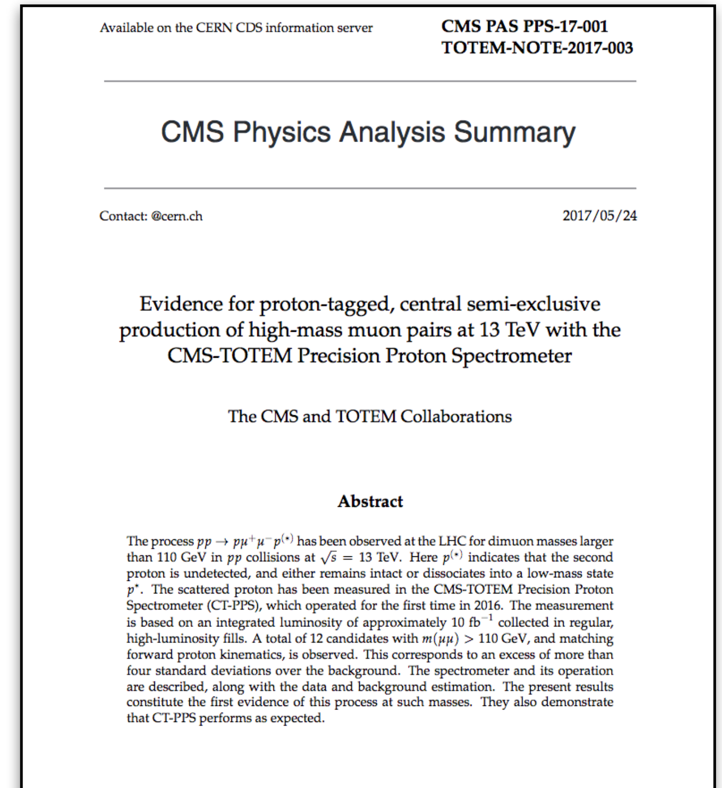


γγ → μ+μ- measurement

CT-PPS already took data in 2016 with an 'accelerated program'
Silicon strip and diamond detectors from the TOTEM experiment were installed in the CT-PPS Roman pots.

A public analysis document has been recently published on the semi-exclusive dimuon production in proton-tagged events.
Dataset: ~10 fb^{-1} of the ~15 fb^{-1} collected during the 2016 runs.




Available on the CERN CDS information server

CMS PAS PPS-17-001
TOTEM-NOTE-2017-003

CMS Physics Analysis Summary

Contact: @cern.ch 2017/05/24

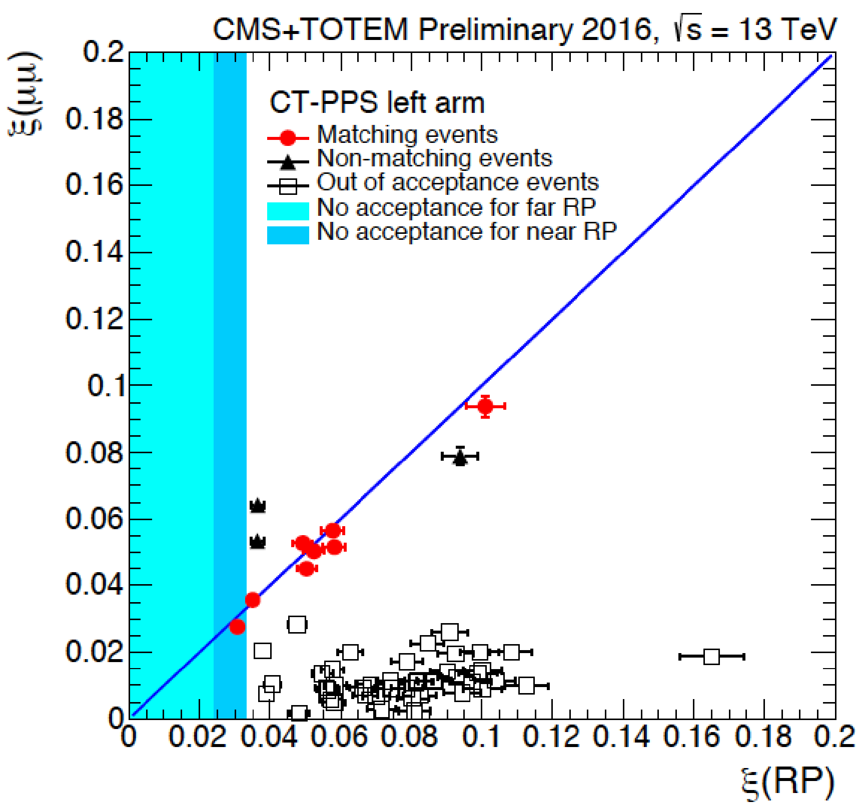
Evidence for proton-tagged, central semi-exclusive production of high-mass muon pairs at 13 TeV with the CMS-TOTEM Precision Proton Spectrometer

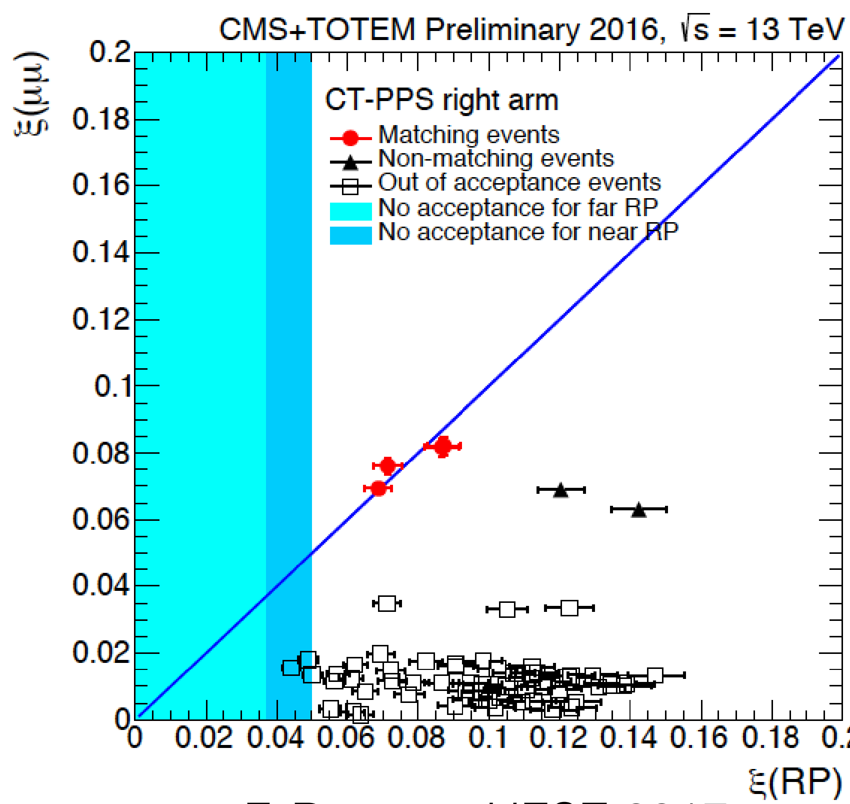
The CMS and TOTEM Collaborations

Abstract

The process $pp \to p\mu^+\mu^- p^{(*)}$ has been observed at the LHC for dimuon masses larger than 110 GeV in pp collisions at $\sqrt{s} = 13$ TeV. Here $p^{(*)}$ indicates that the second proton is undetected, and either remains intact or dissociates into a low-mass state p^*. The scattered proton has been measured in the CMS-TOTEM Precision Proton Spectrometer (CT-PPS), which operated for the first time in 2016. The measurement is based on an integrated luminosity of approximately 10 fb^{-1} collected in regular, high-luminosity fills. A total of 12 candidates with $m(\mu\mu) > 110$ GeV, and matching forward proton kinematics, is observed. This corresponds to an excess of more than four standard deviations over the background. The spectrometer and its operation are described, along with the data and background estimation. The present results constitute the first evidence of this process at such masses. They also demonstrate that CT-PPS performs as expected.

CMS PAS-PPS-17-001
TOTEM-NOTE-2017-003





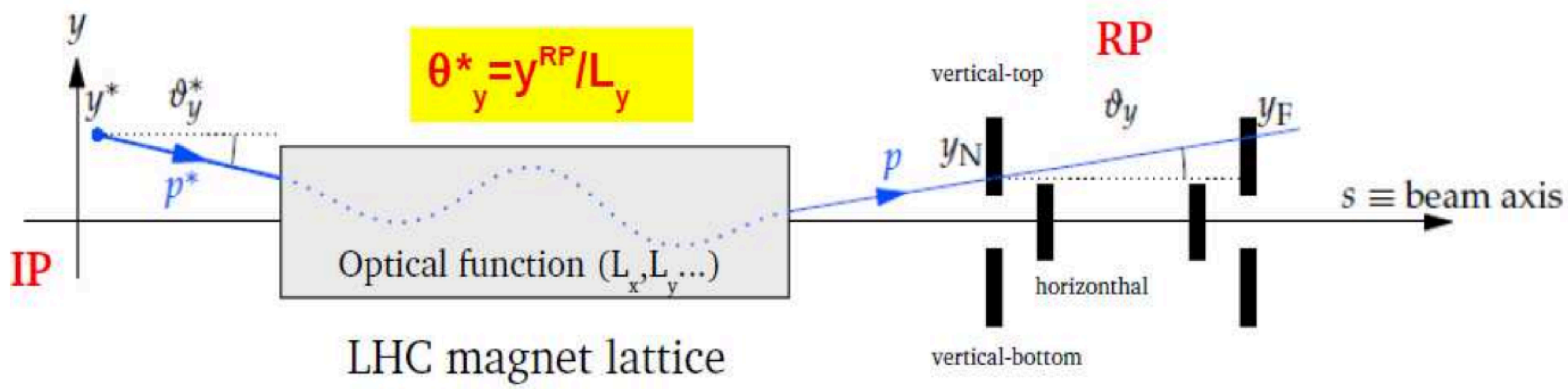
Background: Double proton dissociation or Drell-Yan + protons pile-up events.

By matching the ξ measured by the muons with that of the proton the background is suppressed [1.47 ± 0.06 (stat.) ± 0.52 (syst.) events].

12 events have been observed: Significance of 4.3σ

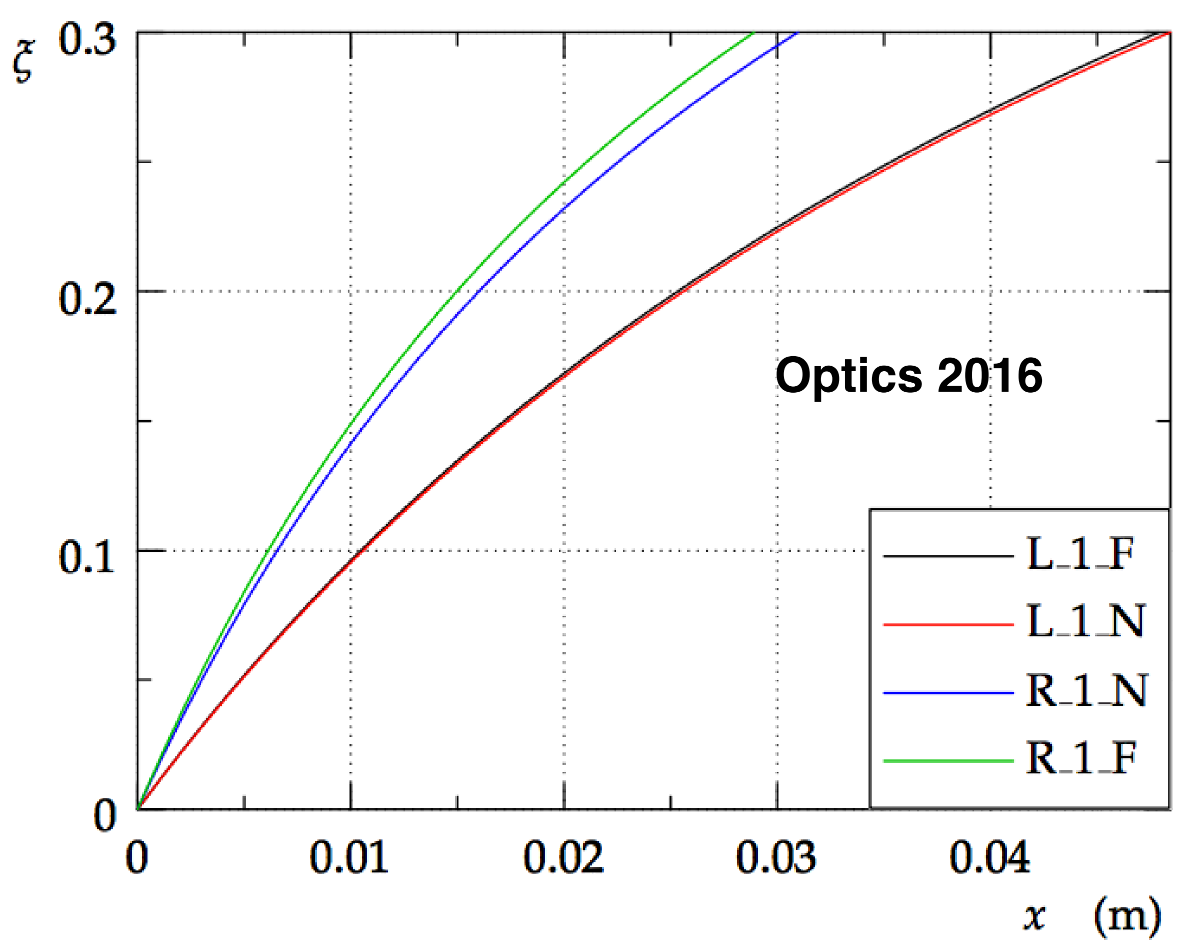
See C. Royon's talk

LHC beam optics



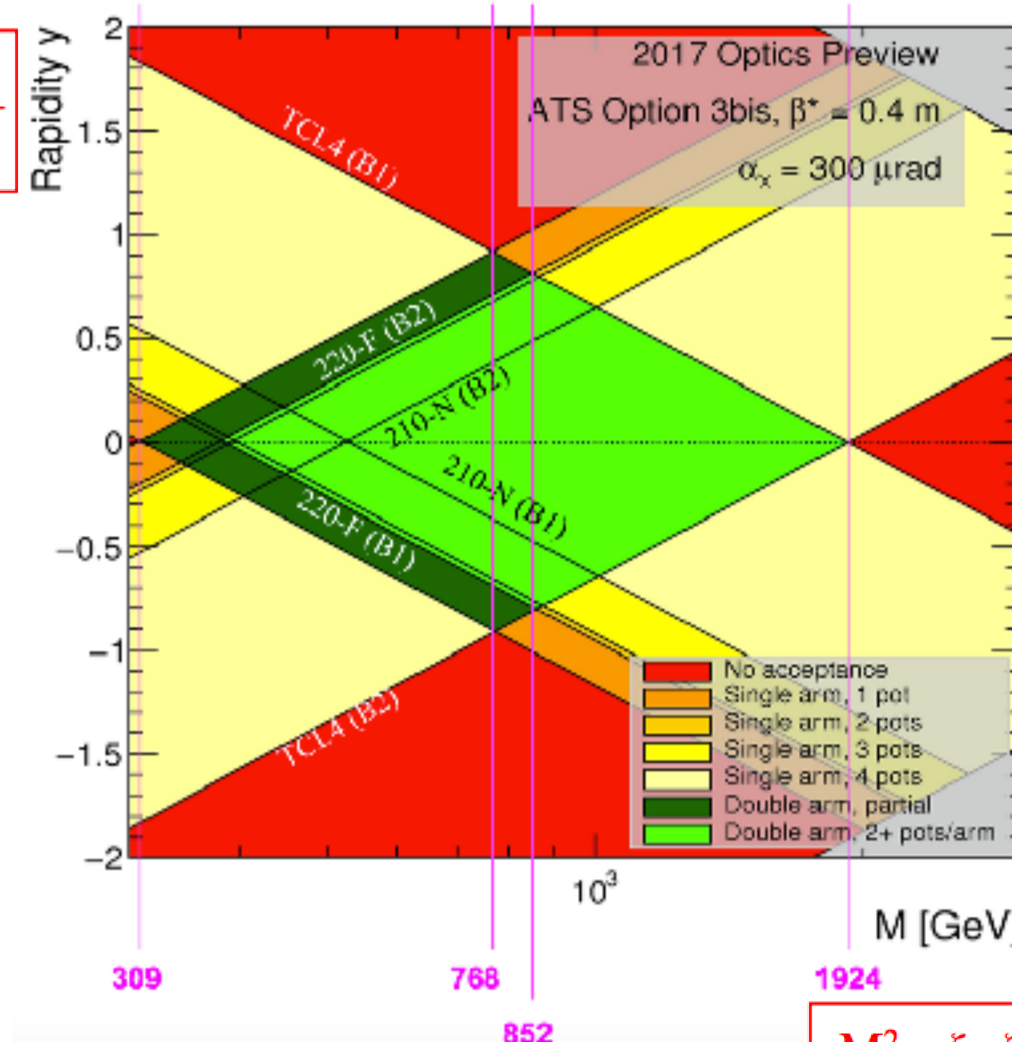
Proton kinematics at the detector is determined by optics and proton kinematics at IP.

ξ vs x at the RP



Mass and rapidity acceptance

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

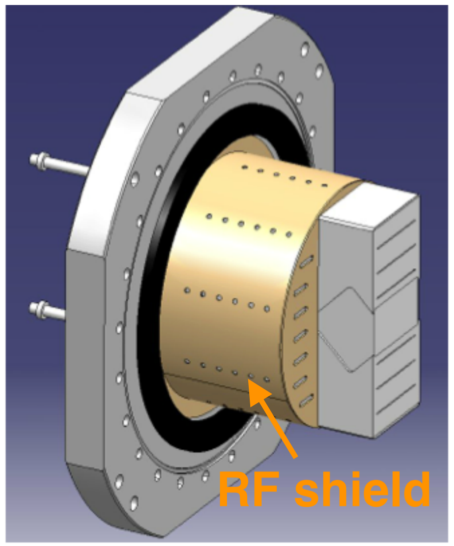


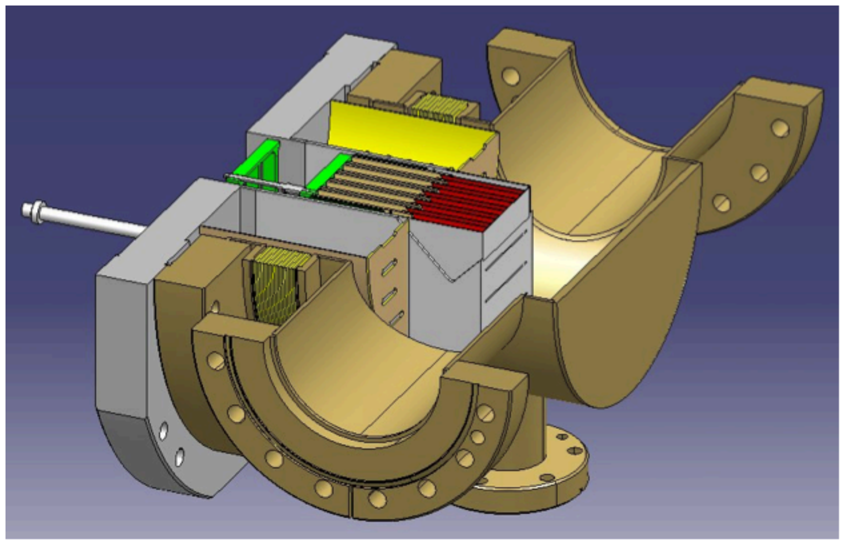
$$M^2 = \xi_1 \xi_2 s$$

The CT-PPS hardware

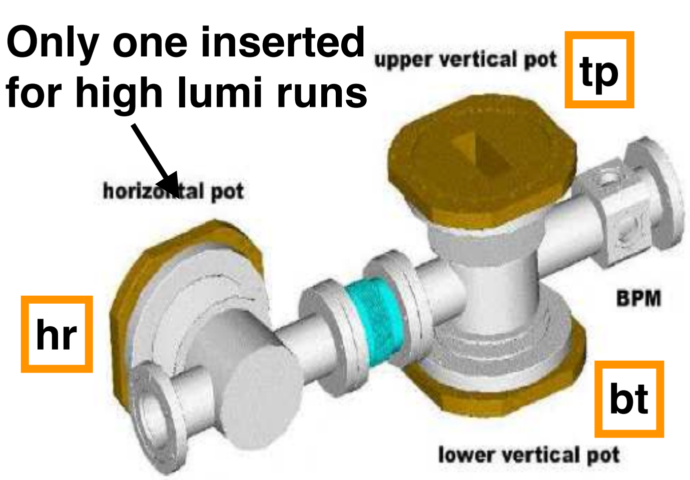
Roman pots (RP)

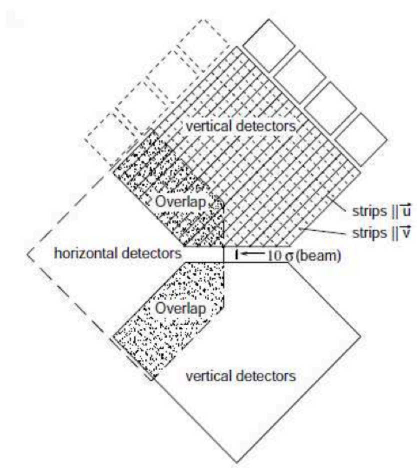
RP for tracking stations





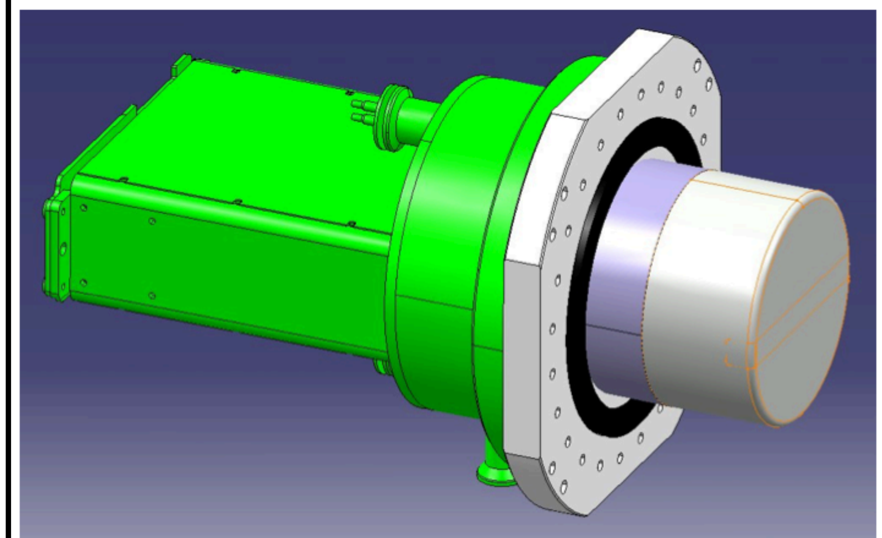
Each station includes 3 RPs (1 horizontal and 2 vertical for alignment runs only).

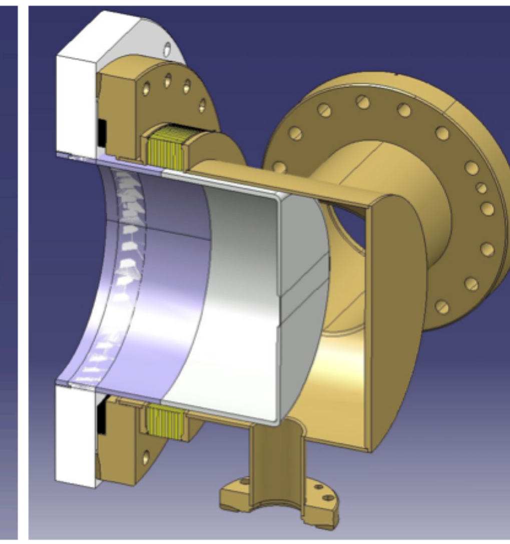




The tracking RPs are **equipped with a thin window 150 μm thick toward the beam**.

RP for timing stations





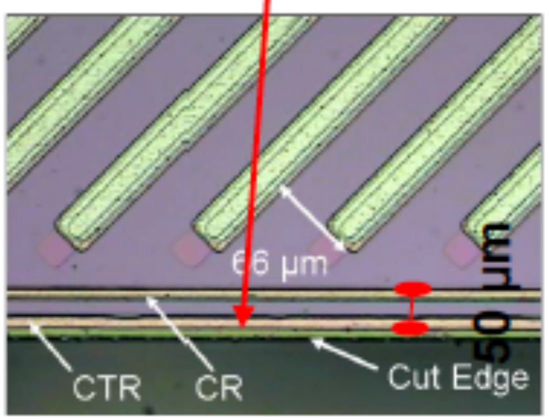
New cylindrical design to host larger detectors and reduce the impedance.

The timing RPs are **equipped with a 300 μm thick window towards the beam.**
The thickness is required to compensate the pressure gradient on the larger window.

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

The CT-PPS RPs are inserted at ~15σ from the LHC beam in standard high lumi fills.

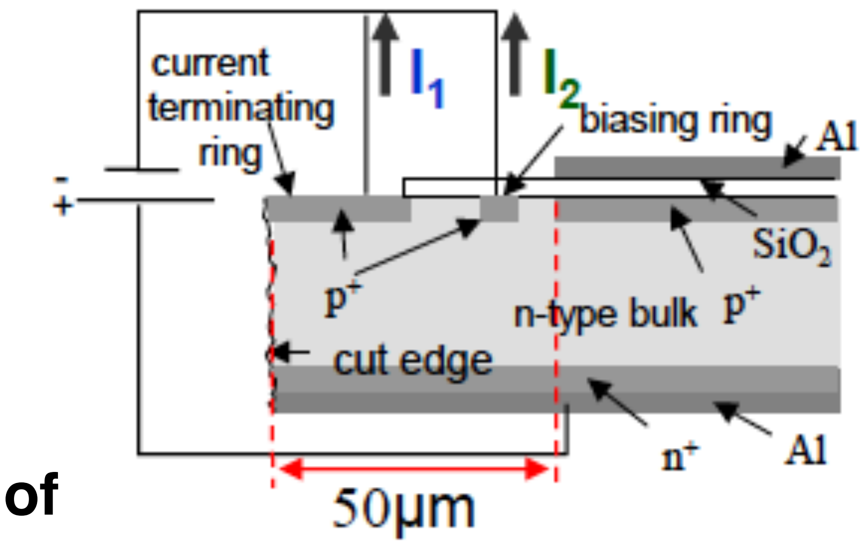
TOTEM strip detectors



Micro-strip silicon detectors with edgeless technology:

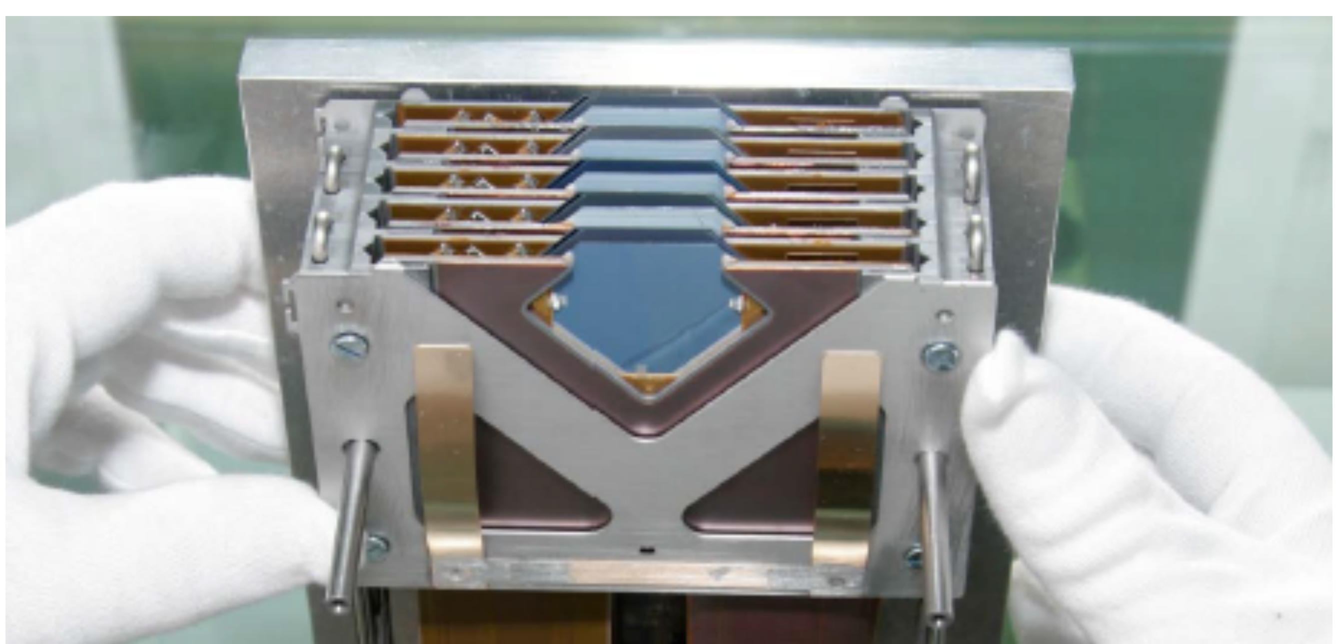
- 512 strips per plane, with ± 45° orientation
- Strip pitch = 66 µm
- Inactive edge = 50 µm
- Resolution ~20 µm
- **Lifetime up to an integrated flux of 5 x 10^{14} p/cm^2**
- Binary readout provided by 4 VFAT2 (128 channel each). VFAT2 has trigger capability, currently not integrated in the CMS L1 trigger system

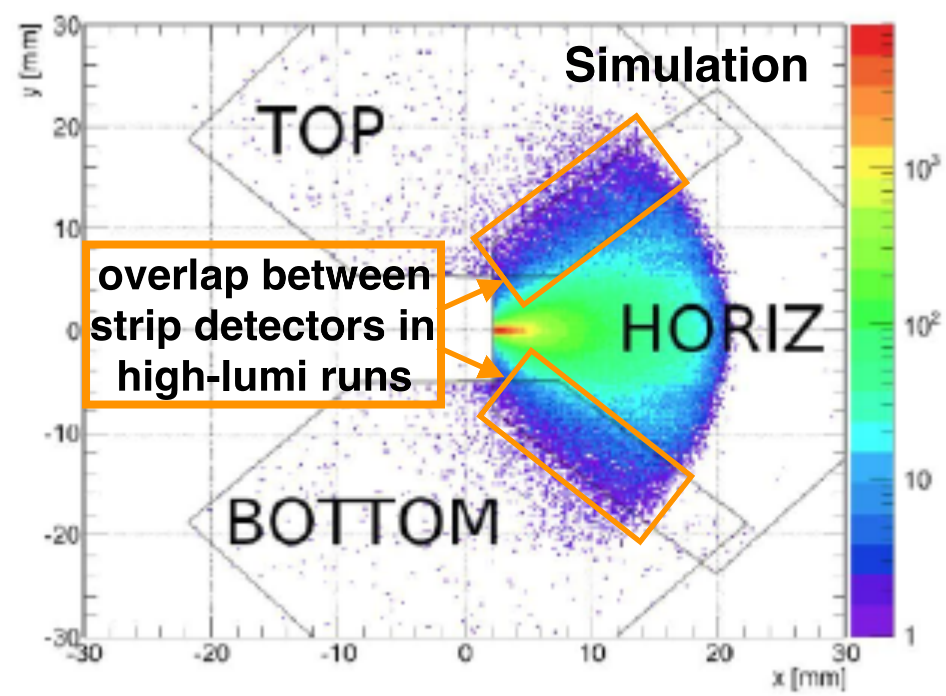
Planar technology + CTS
(Current Terminating Structure)



Each station is composed of 10 planes.

Hit/track reconstruction using consolidated TOTEM algorithms fully integrated in the CMS official software since 2016.



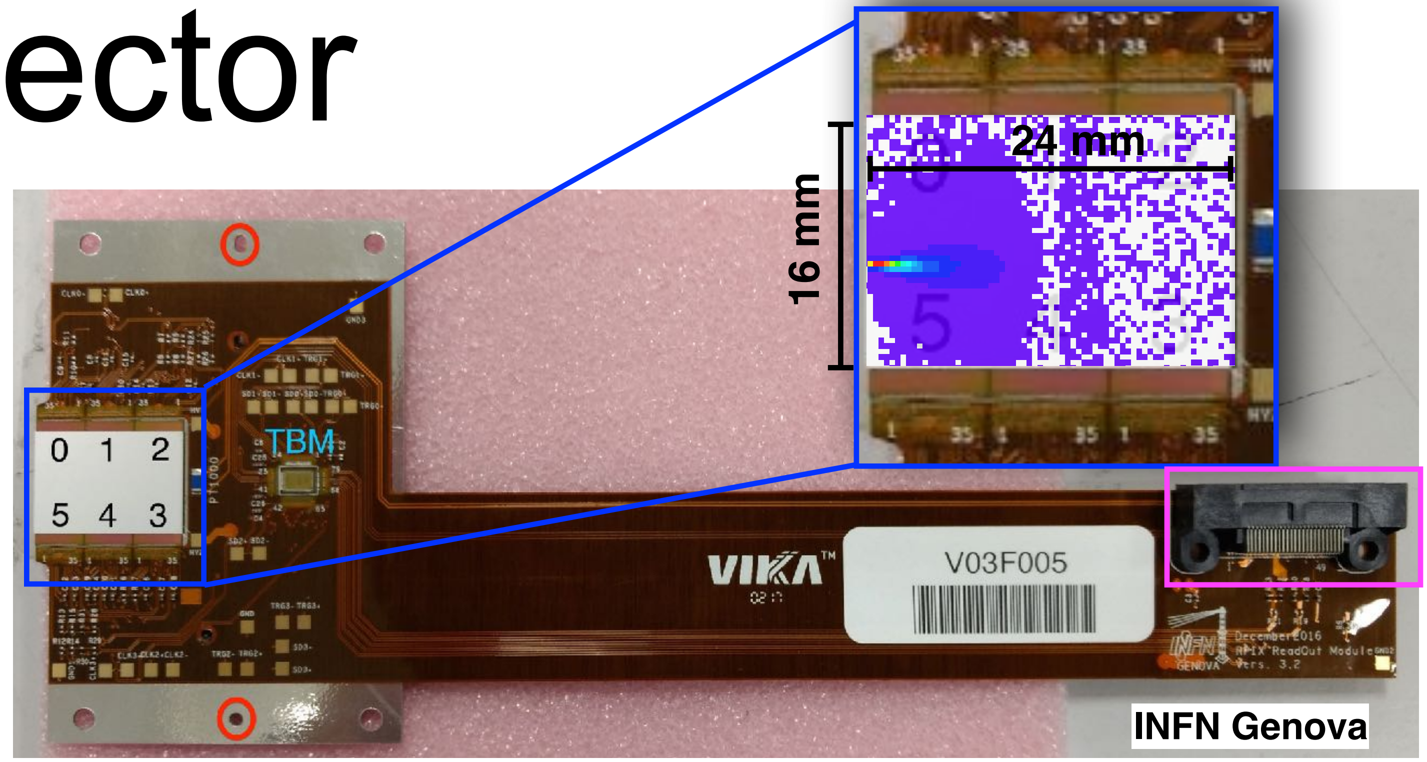


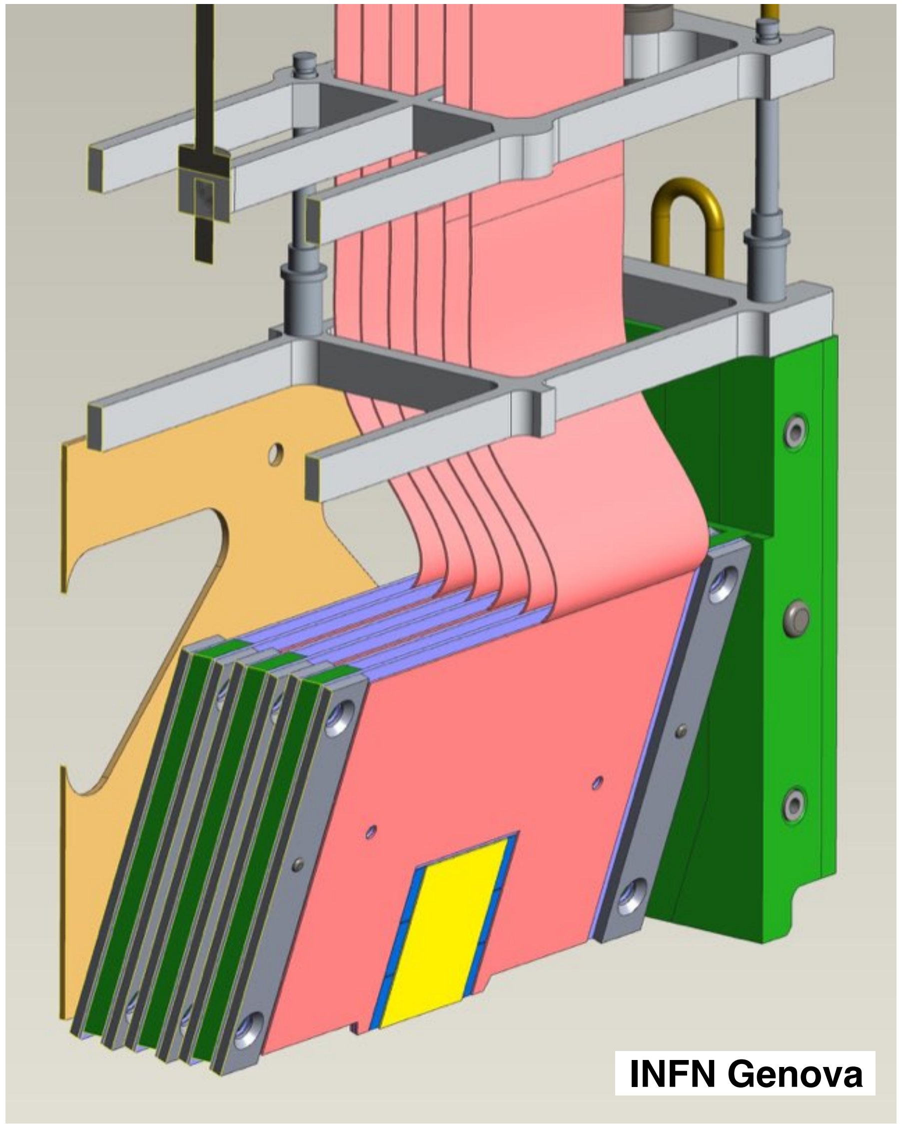
Tracking system with 3D pixels

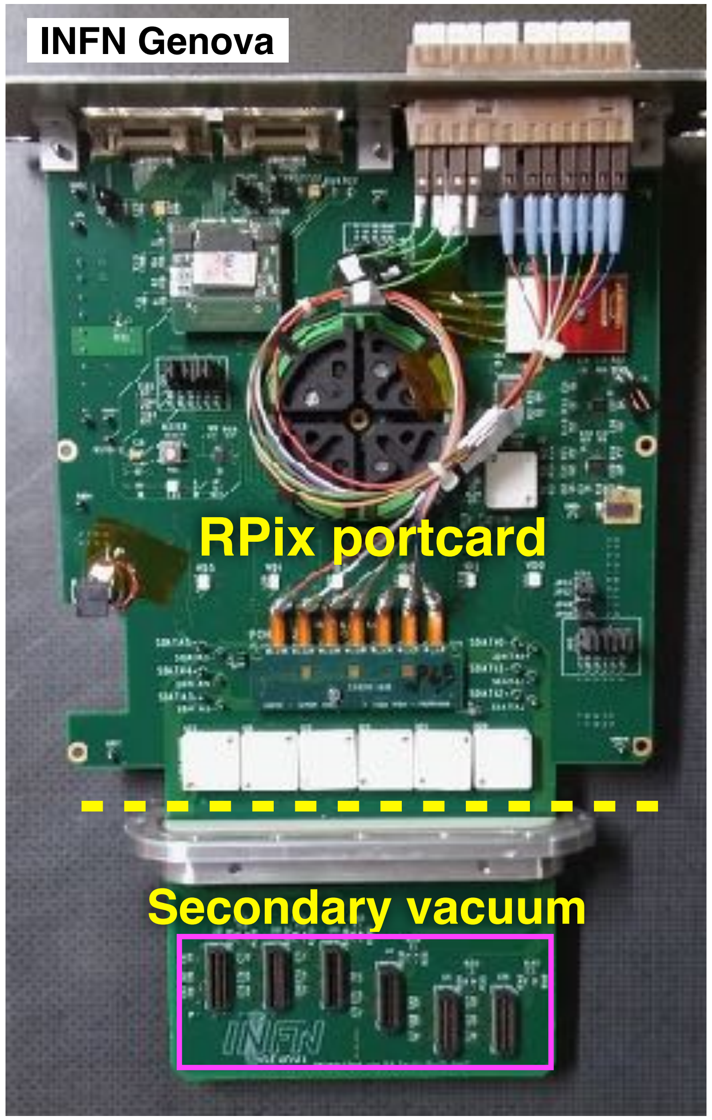
- **Requirements**:
  - **Sustain high radiation levels**: for 100 fb^{-1}, proton flux up to $5x10^{15}/cm^2$ in tracking detectors, corresponding to ~1-3 x 10^{15} n_{eq}/cm^2.
  - **Small inefficient area at the edge of the sensor** towards the beam.
  - **Tracking resolution of ~10 and 30 μm** along x and y directions, respectively.
- **Baseline design**:
  - **3D sensor** technology chosen for its intrinsic high **radiation hardness** and the possibility to implement **slim edges**.
  - **Two stations per side, each with 6 detector planes tilted by 18.4°** to increase the cluster size and **improve resolution**.
  - **Readout chip and front-end electronics as for CMS Phase I pixel upgrade**.
  - Mechanics and cooling adapted from TOTEM tracking system.
  - **Run at -20ºC and in a vacuum** (pressure < 20 mbar) to avoid condensation and stress of the Roman pot thin window.

CT-PPS pixel detector

Each plane is equipped with a sensor bump-bonded to the psi46dig ReadOut Chip (ROC) developed for the CMS Phase I upgrade of the CMS pixel tracker.
The detector is precisely glued on a Thermal Pyrolithic Graphite (TPG) layer that **provides the thermal contact** with the sides of the package connected to the cooling pipes.







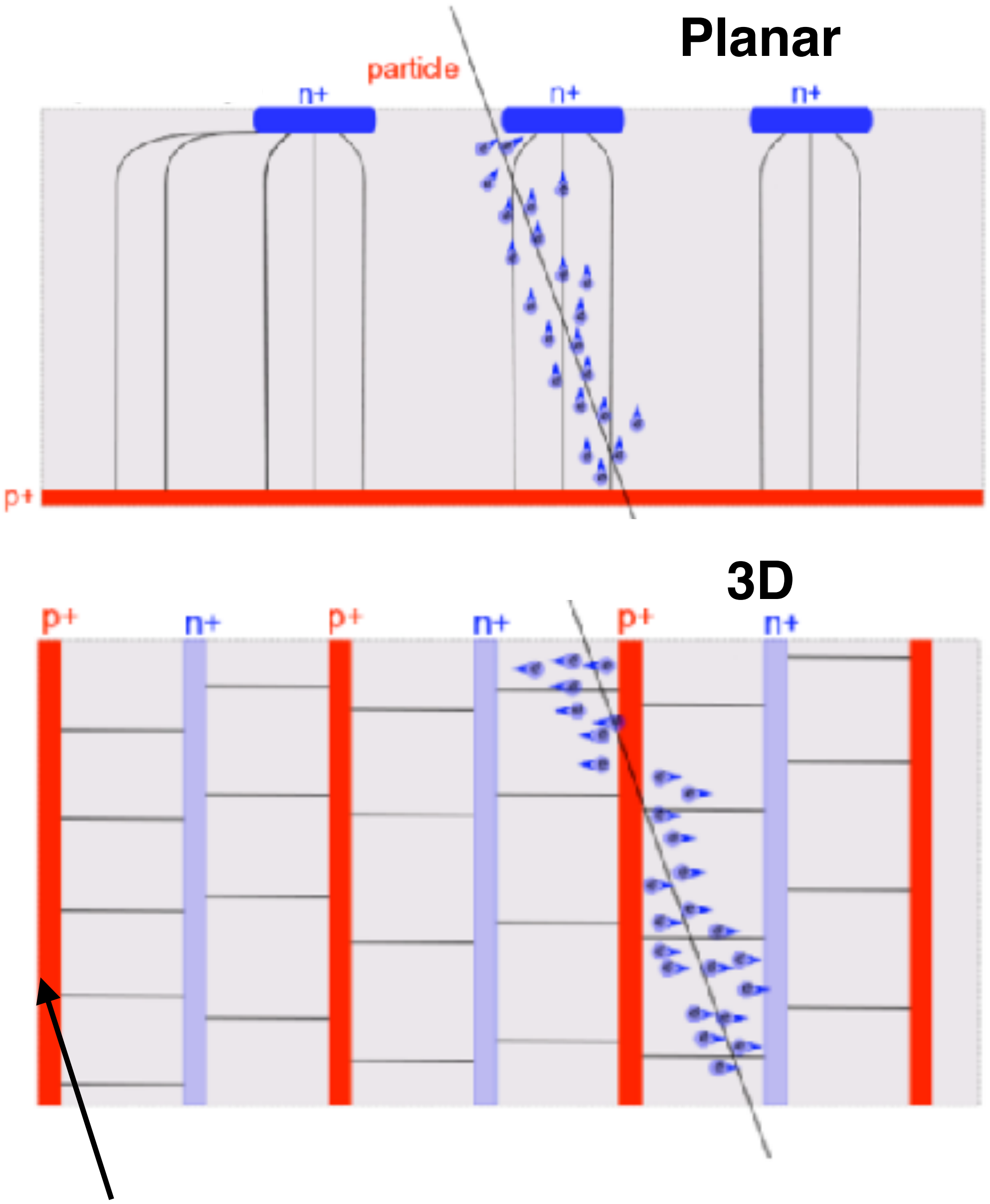
Modules are wire-bonded to the flex circuits which are connected to the RPix portcard.

The RPix portcard interfaces the front-end electronics with the detector planes.
Concept: TOTEM board (to fit the RP space constraints) with components from the CMS Phase I forward pixel readout.

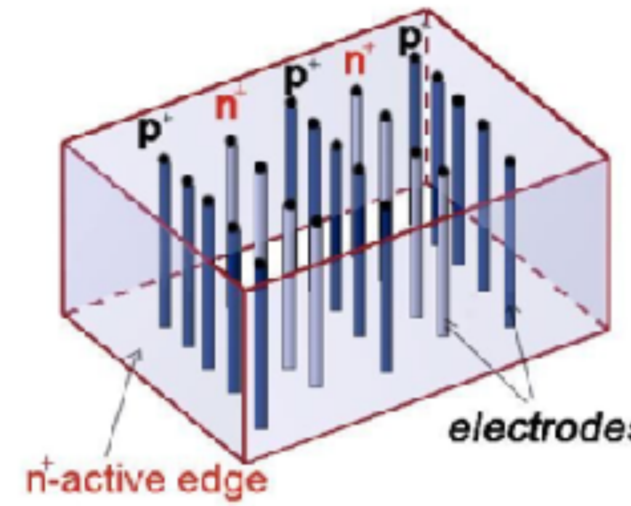
Front-end boards for data (FED) and control (FEC) are the same as those of the Phase I CMS pixel tracker.

3D silicon sensors

3D sensors have electrodes that are etched perpendicular through the silicon bulk with the Deep Reactive Ion Etching.



Possibility to effectively implement active or slim edges.



The architecture decouples substrate thickness and electrode distance.

Columns have radius of ~ 5 µm and the distance between electrodes varies from 100 µm to 50 µm depending on the number of readout electrodes per pixel cell

Advantages of 3D structures in comparison with standard planar sensors:

- Lower depletion voltage.
- Faster charge collection.
- Higher radiation hardness.

Disadvantages:

- Complex technology.
- Higher capacitance.

3D sensors for CT-PPS

3D sensors produced in double-sided not-fully-passing-through technology by CNM
Baseline design:

- **2E pixel** configuration (2 readout columns)
- 200 μm **slim edges** with column fences
- 3x2 sensors (6 ROCs each)

1E and 2x2 sensors as backup solution

Specifications to qualify the devices:

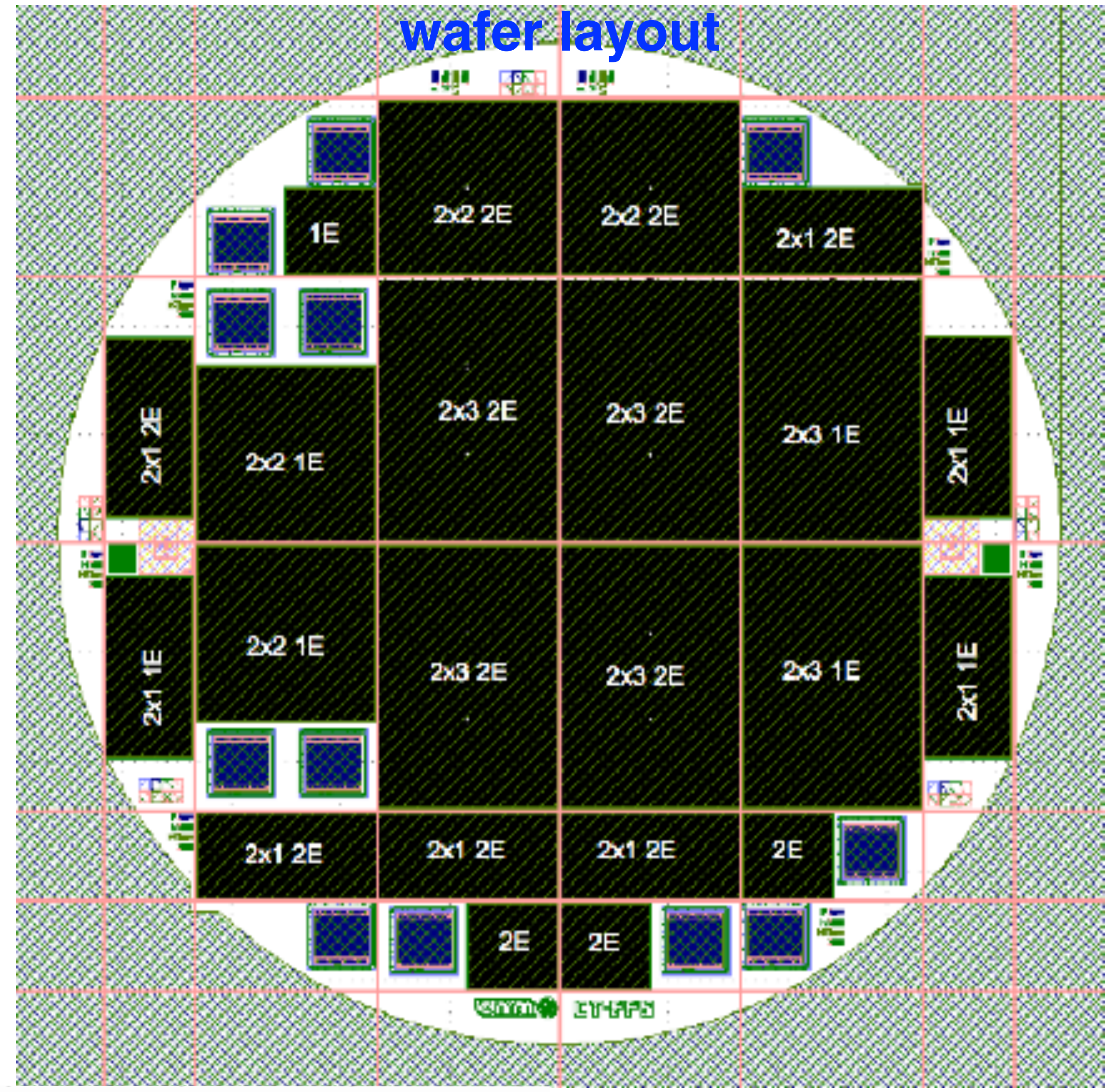
Define: $V_{op} = V_{depl} + 10V$ where V_{depl} and V_{op} are the full depletion and operation voltages, respectively.

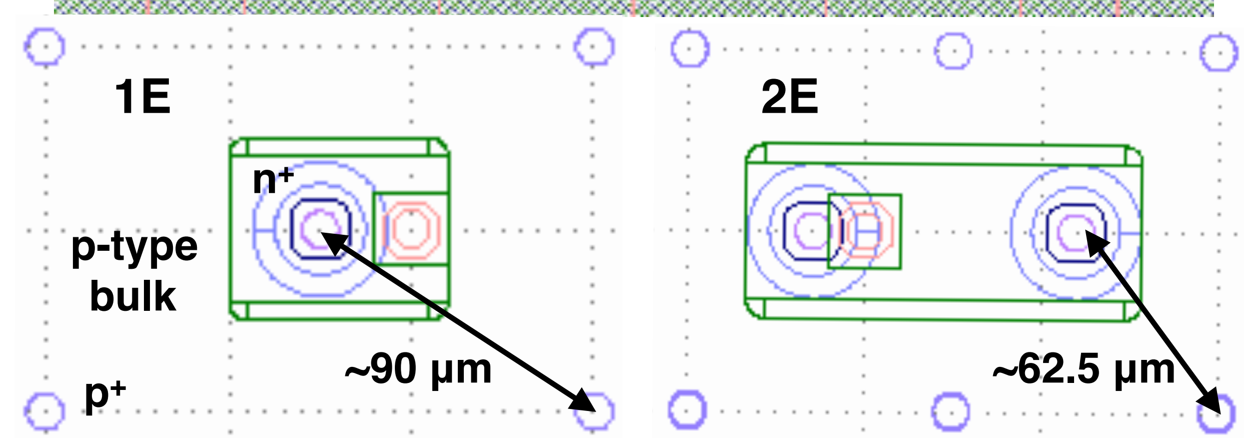
The following specifications, taken at room temperature (20-24 °C), qualify a device as functioning correctly:

- $\mathbf{V_{depl} < 20\ V}$
- Breakdown voltage: $\mathbf{V_{bd} > 35\ V}$
- **[I(25V)/I(20V)] < 2**
- Current at operation voltage:

Class A	I (V_{op}) < 2uA per tile
Class B	2uA < I (V_{op}) < 10uA per tile
Class C	I (V_{op}) > 10uA per tile

3 batches of 12 wafers each have been produced at CNM





CNM production results

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.
A problem, probably with the p-stop implantation, caused values of breakdown voltage too low to allow using the sensors.
In order 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 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 available.

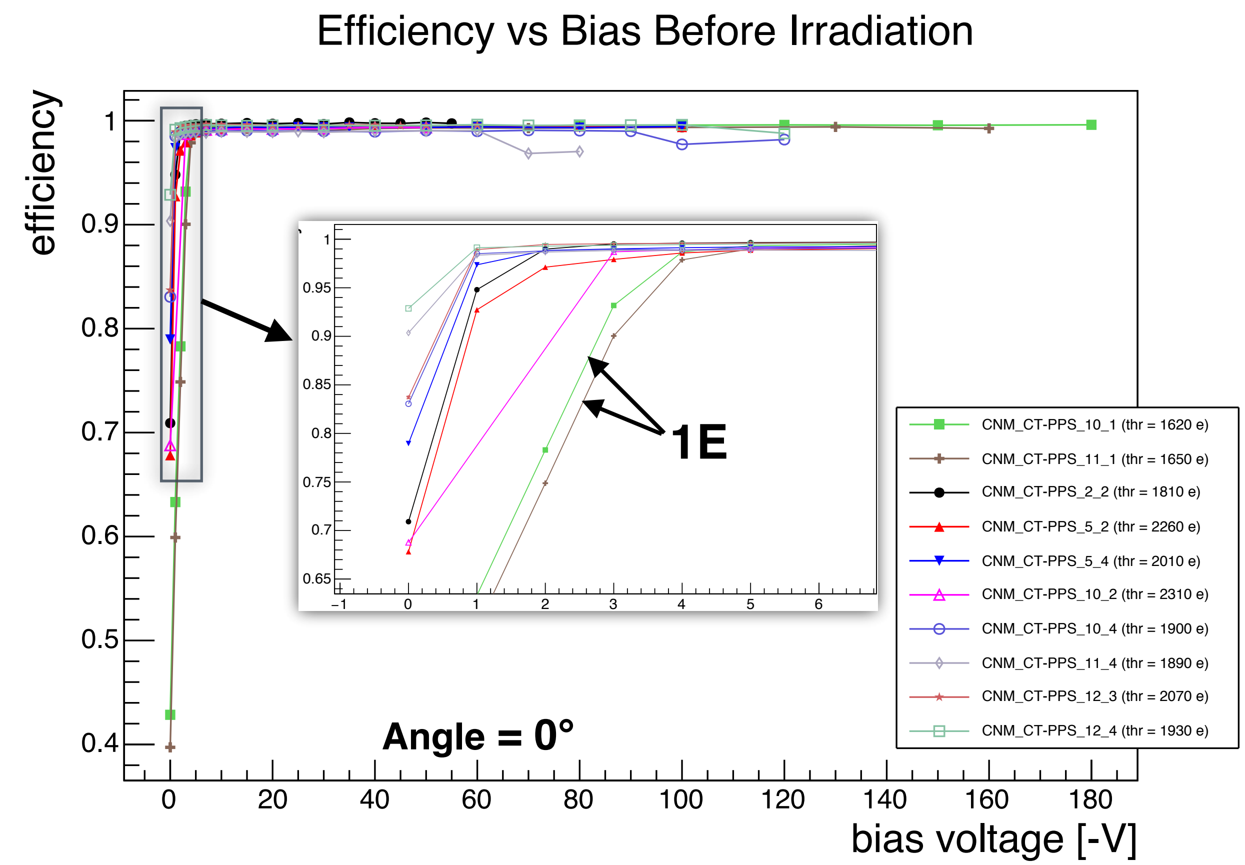
3D detectors - Efficiency

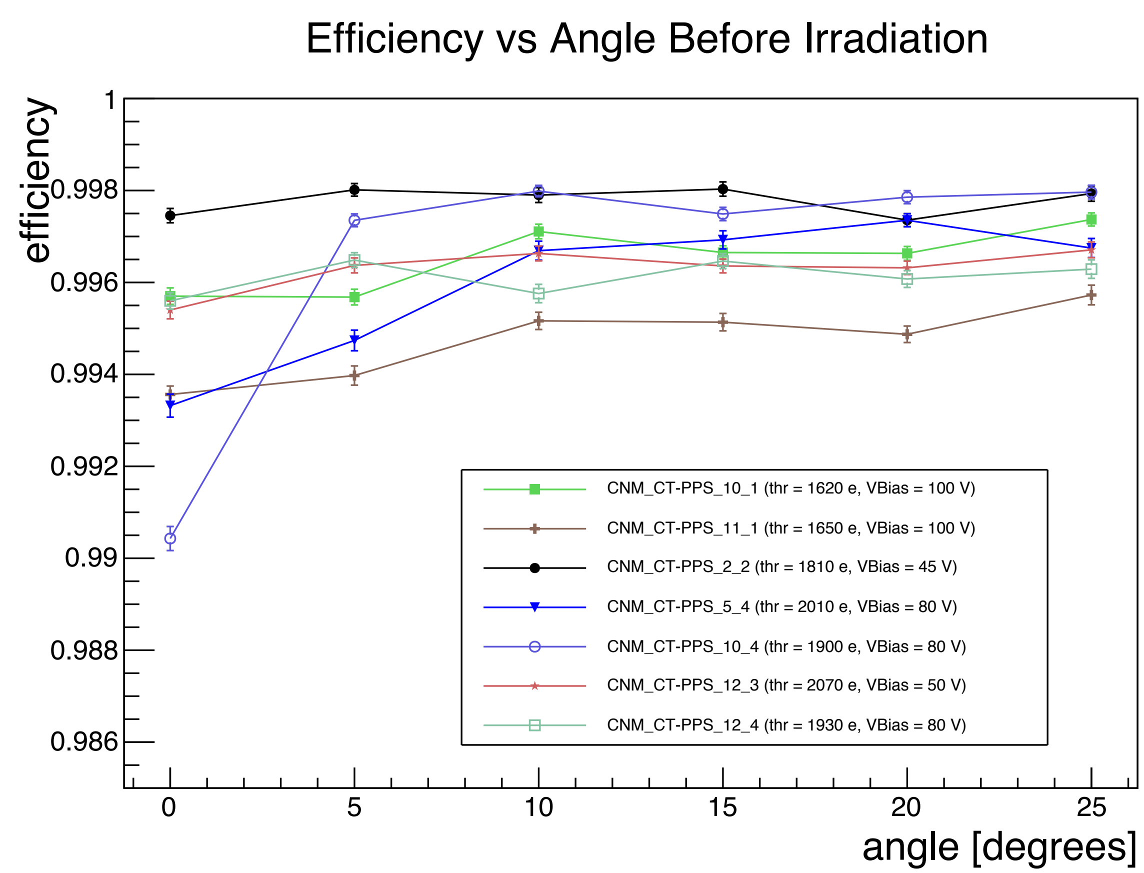
10 single-ROC sensors (**2 1E and 8 2E**) from the first production have been bump-bonded at IZM to the ROC and have been **tested at FNAL on beam.**
Sensors selected of both class A and B.

2E (1E) sensors reach the full efficiency already at bias voltages of ~3 V (5 V).
No difference in efficiency is seen between class A and B sensors.

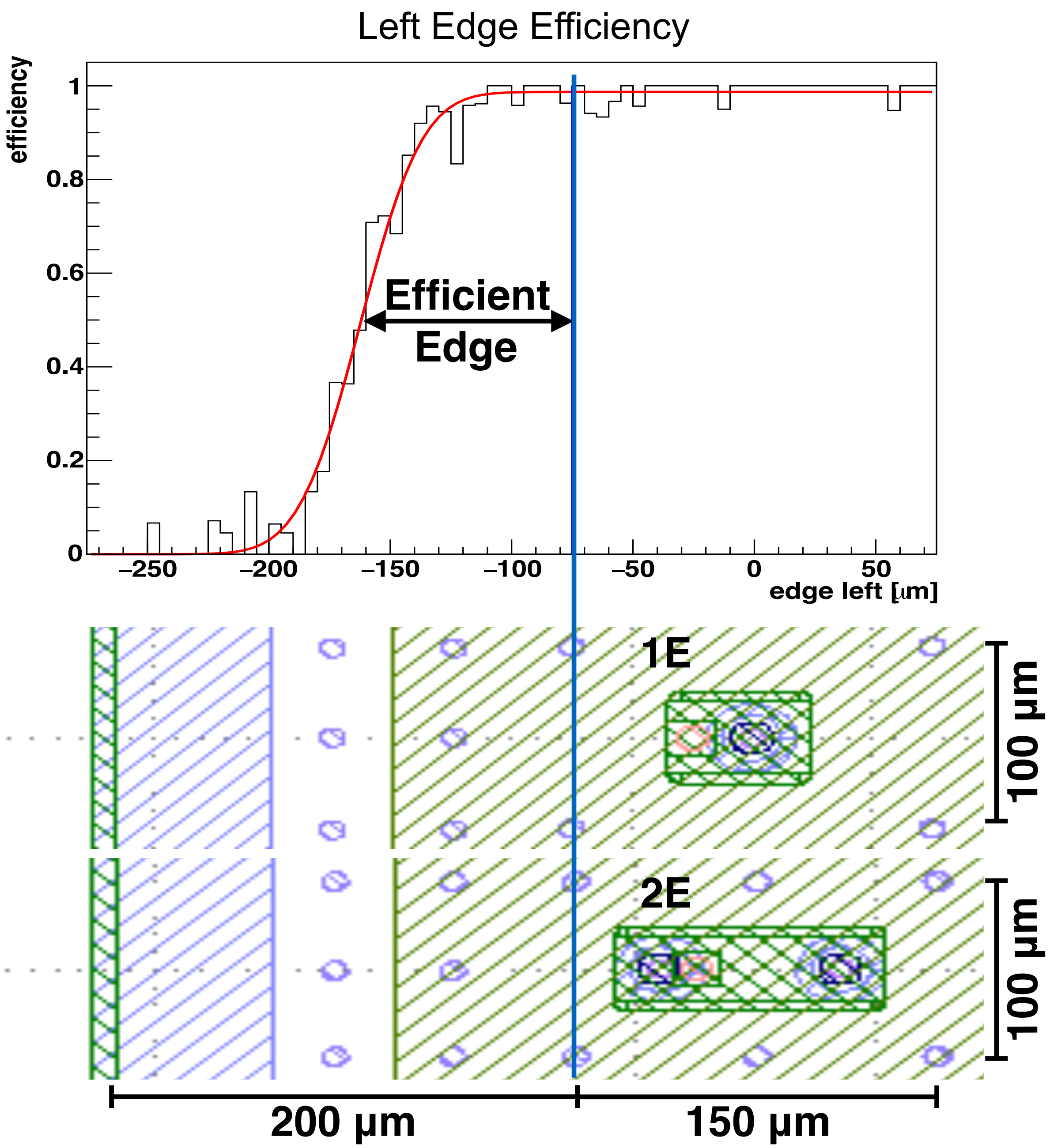
Thanks to the not-fully passing-through columns and the well optimised thresholds, high efficiency is obtained even without rotating the sensors.

Efficiency greater than 99.4% at 20°.
(CT-PPS tracking detector angle = 18.4°)

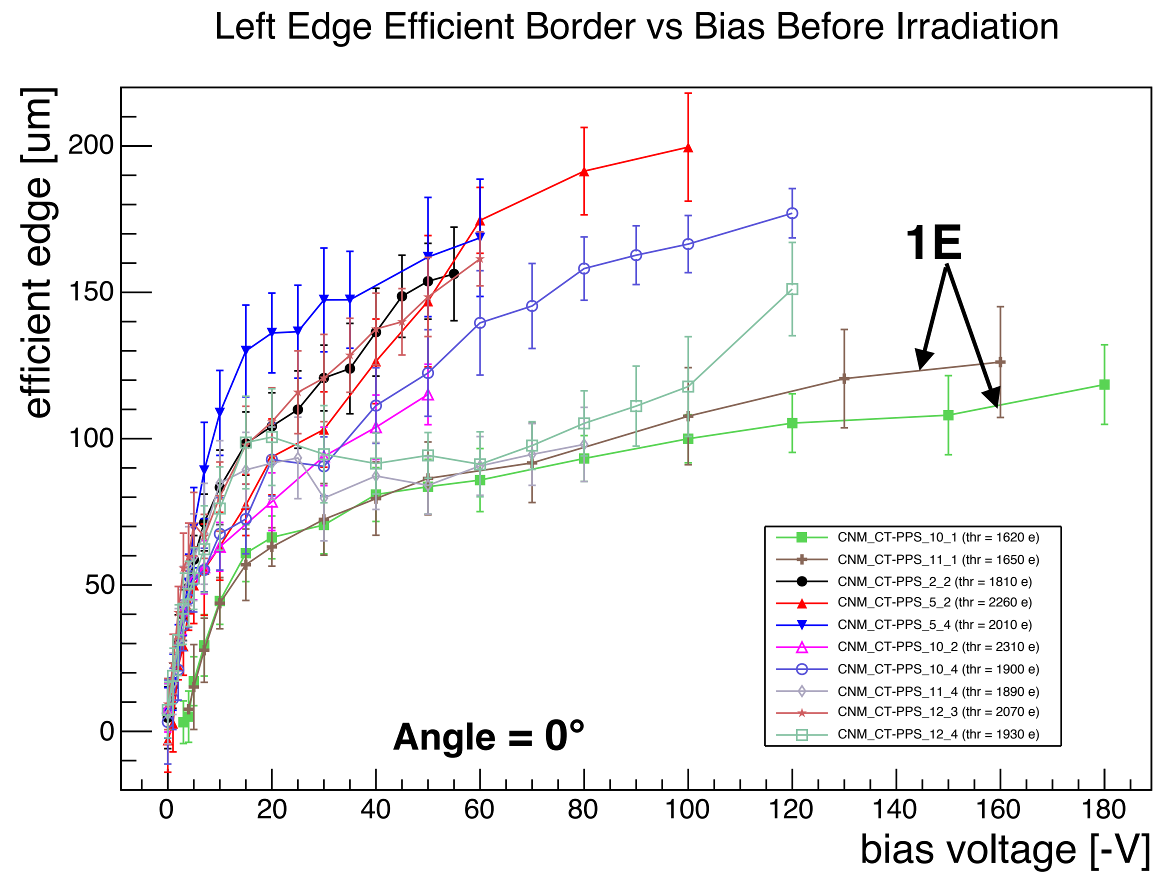




3D detectors - Edge efficiency vs bias



Efficiency at the edge of the sensor fitted with a S-curve. Error bars represent the width of the S-curve.



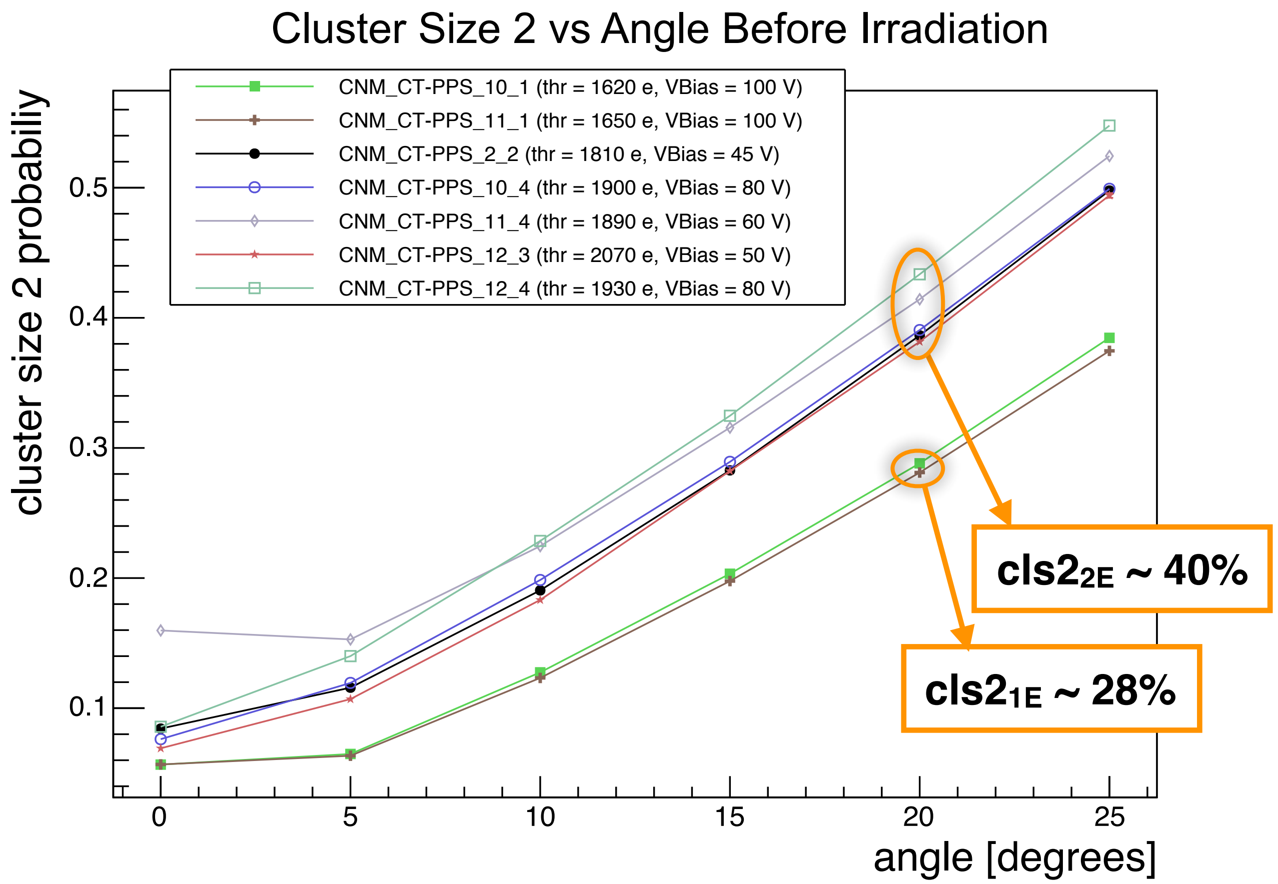
At a bias voltage of 40 V up to 150 μm can be gained at the edge of the sensor with the 2E layout.

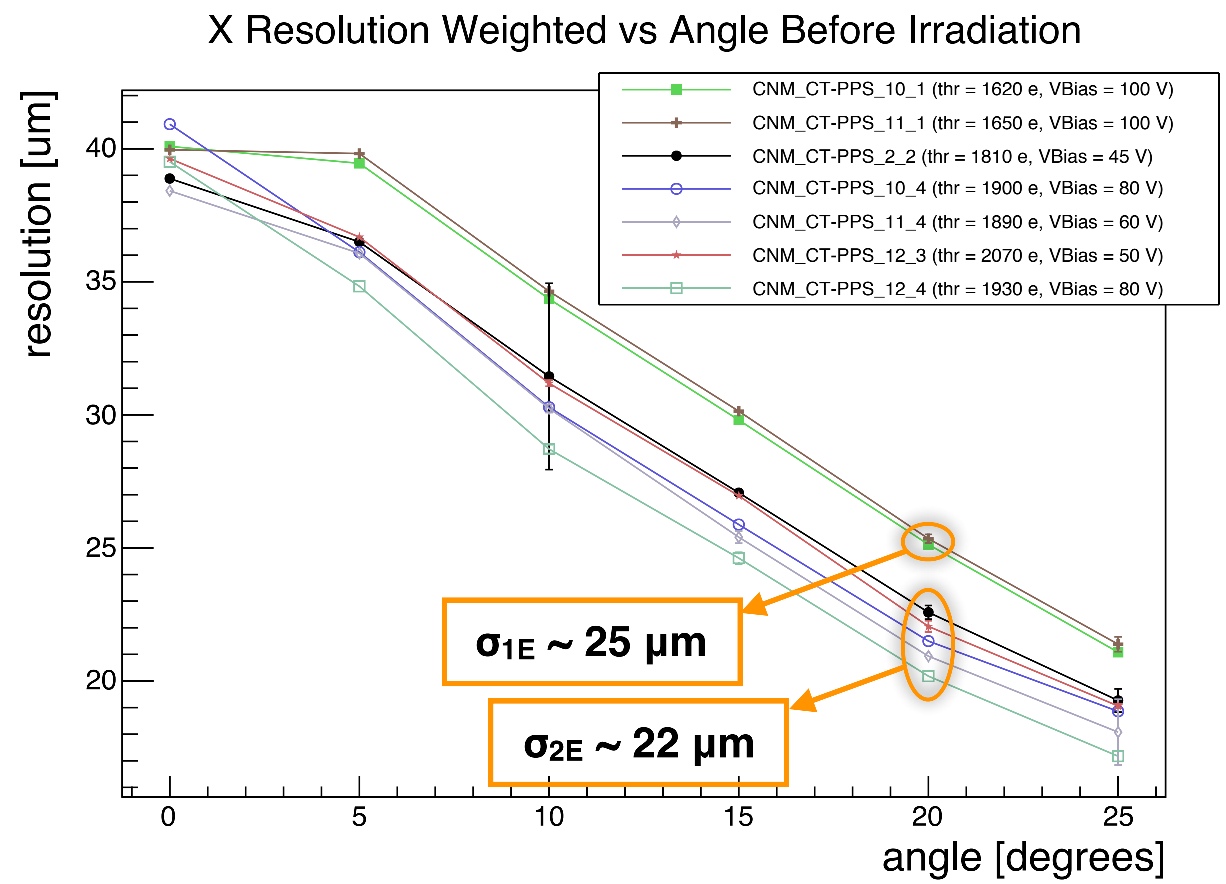
2E detectors allow to gain ~60 μm more than 1E ones at a bias of 40 V thanks to the n^+-electrode closer to the sensor edge.

3D detectors - Resolution vs angle

Detector resolution is evaluated by fitting residuals separately for clusters of size 1 and 2. After subtracting the telescope resolution, the **global resolution is obtained as average of the two values weighted by the cluster size probability**.

Since electrodes are closer to the pixel geometrical edge, **2E sensors have more clusters of size 2 and therefore a better resolution with respect to 1E ones**.

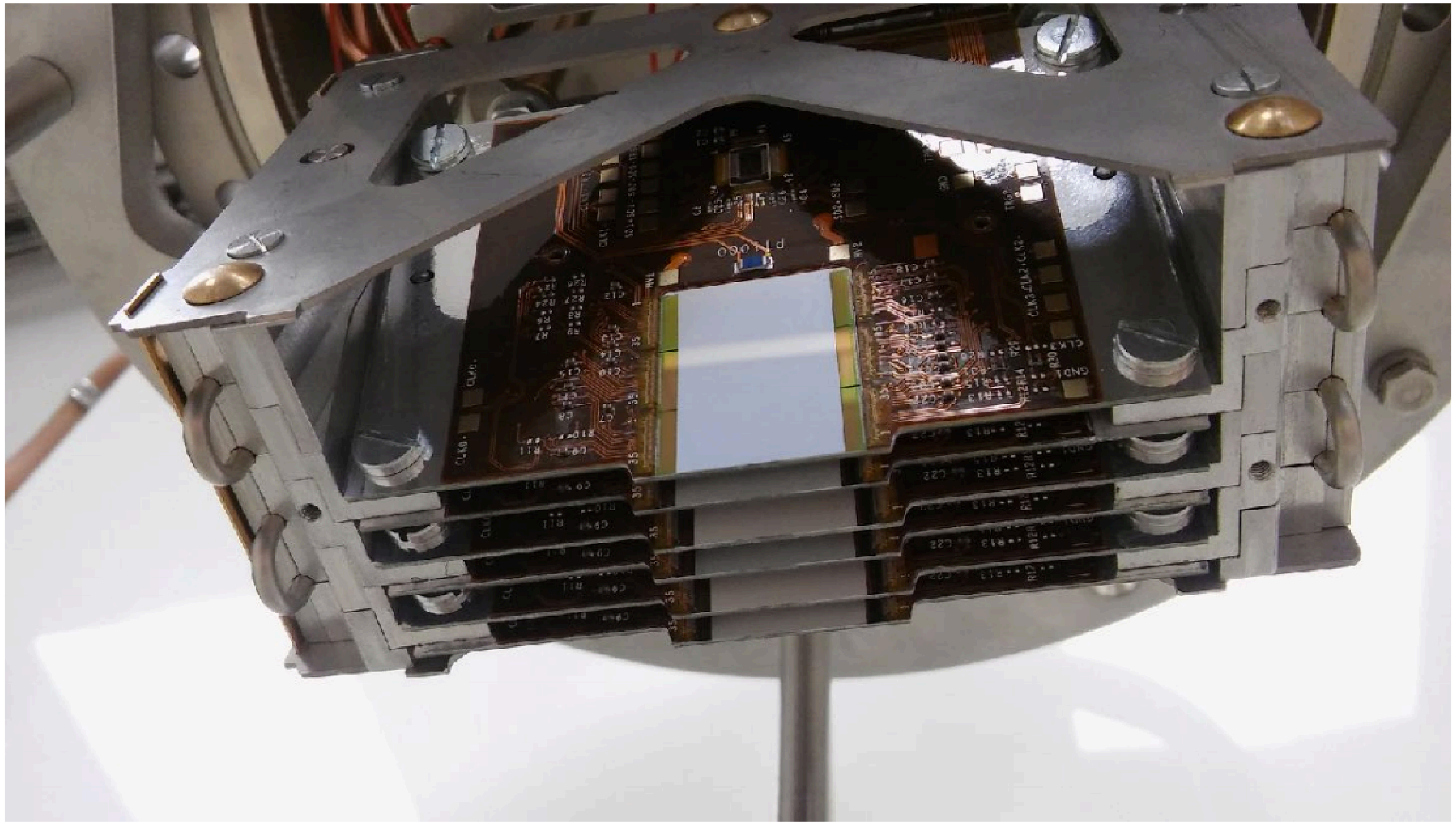




Considering a resolution per single plane between 22 and 25 μm, **the target resolution of ~10 μm can be achieved** considering the 6 planes per station.

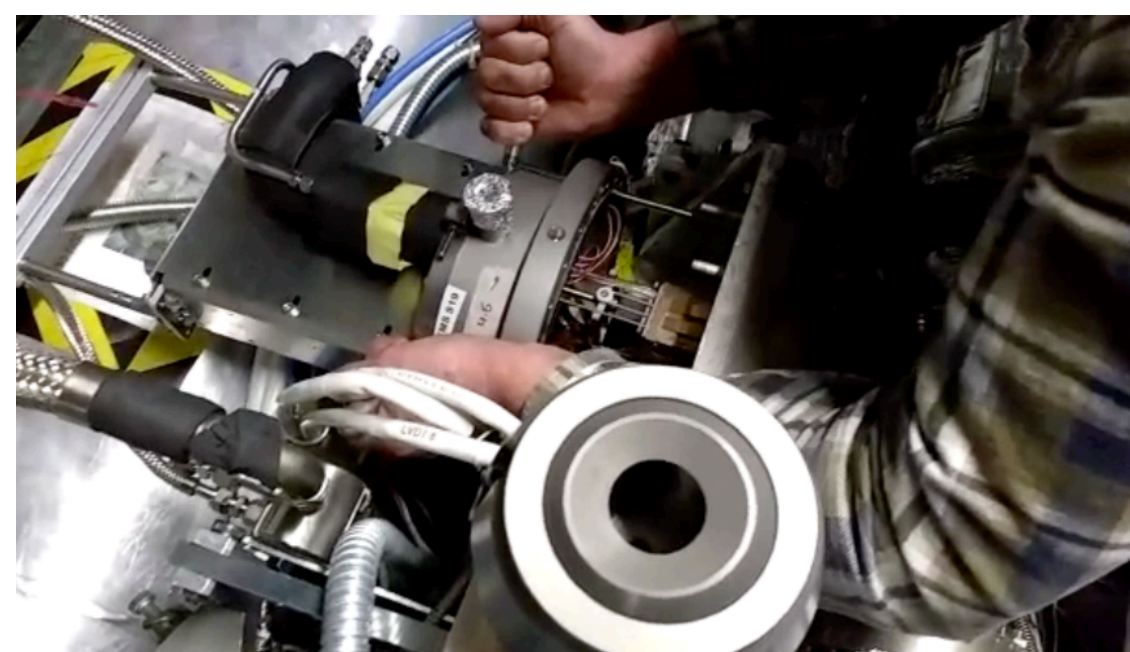
CNM single-ROC sensors demonstrated to fulfill the CT-PPS requirements.

Module assembly and installation



Two tracking stations have been assembled and fully tested in lab and in the expected conditions of secondary vacuum and cooling. Each station has 5 3x2 + 1 2x2 modules.

The detectors were installed in the Roman pots along the LHC at the end of March and connected to services and power.



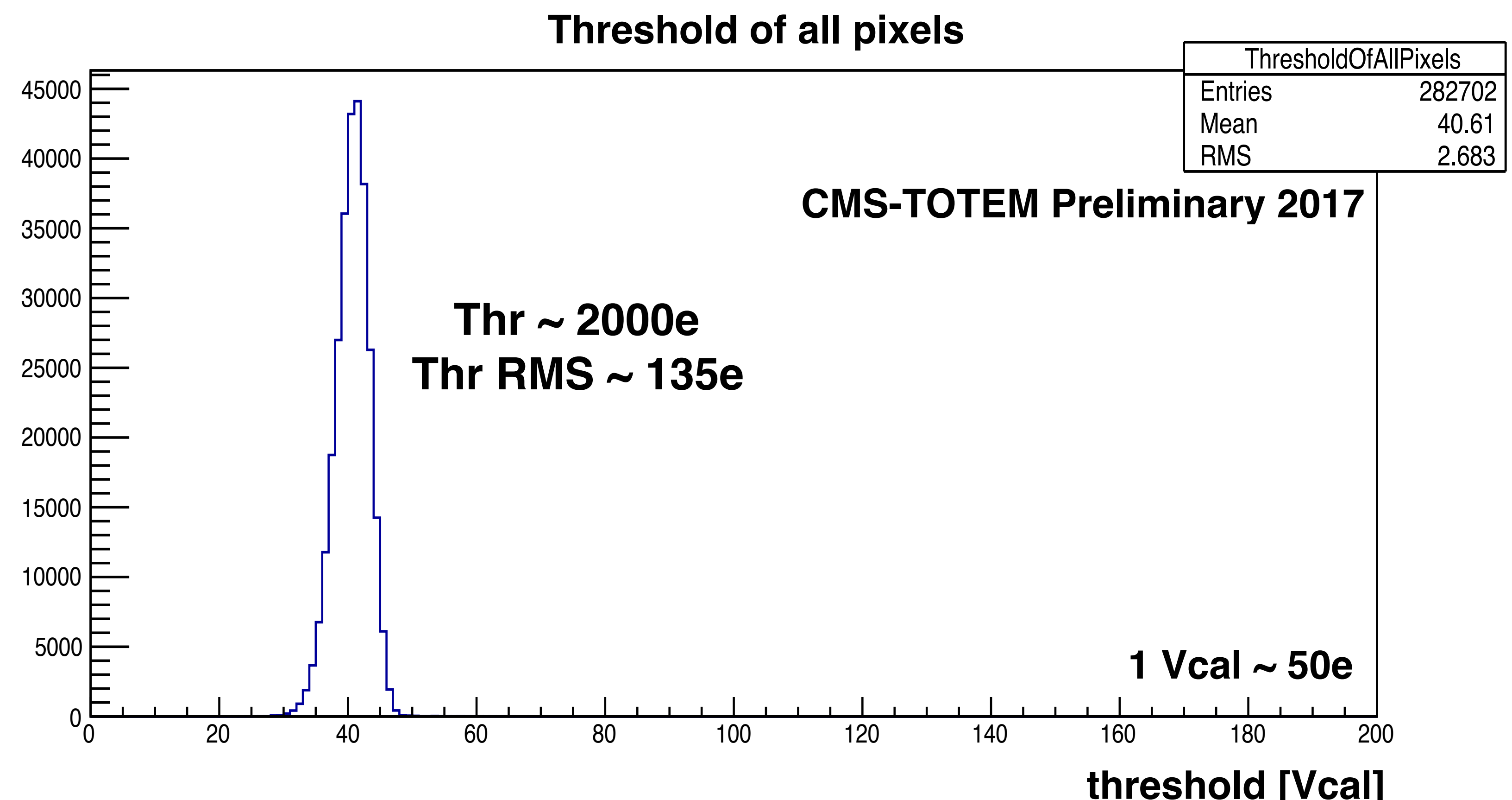
Pixel calibration - I

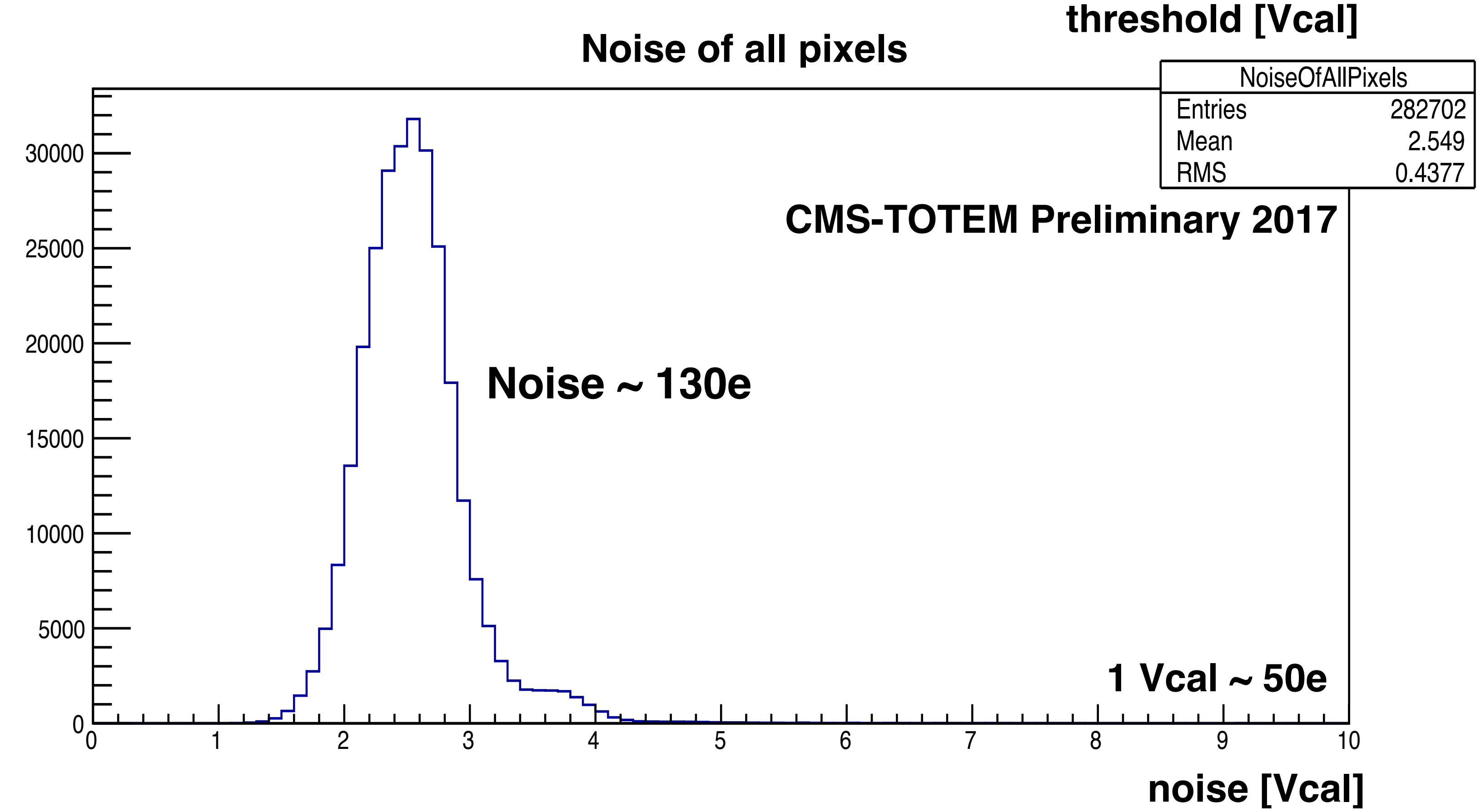
The pixel modules have been tested and optimised in the Torino and Genova laboratories during the module selection phase, with the same procedure used for the CMS Phase I ones.

The calibrations and tests are made by means of the internal calibration circuit present in the psi46dig ROC.

The obtained register values have been used as a starting point for the detector optimisation in the LHC tunnel.

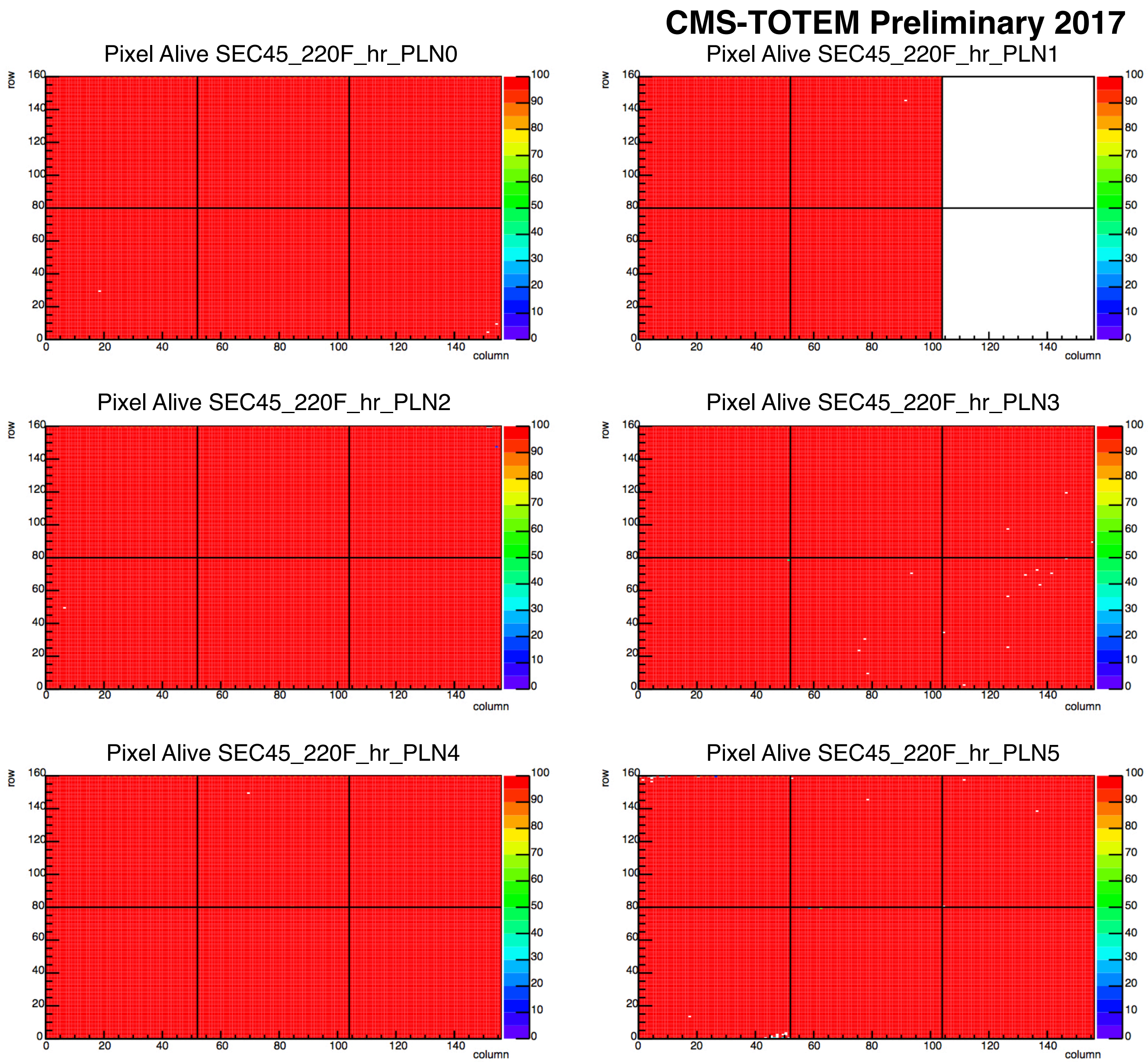
A calibration campaign has been carried out.



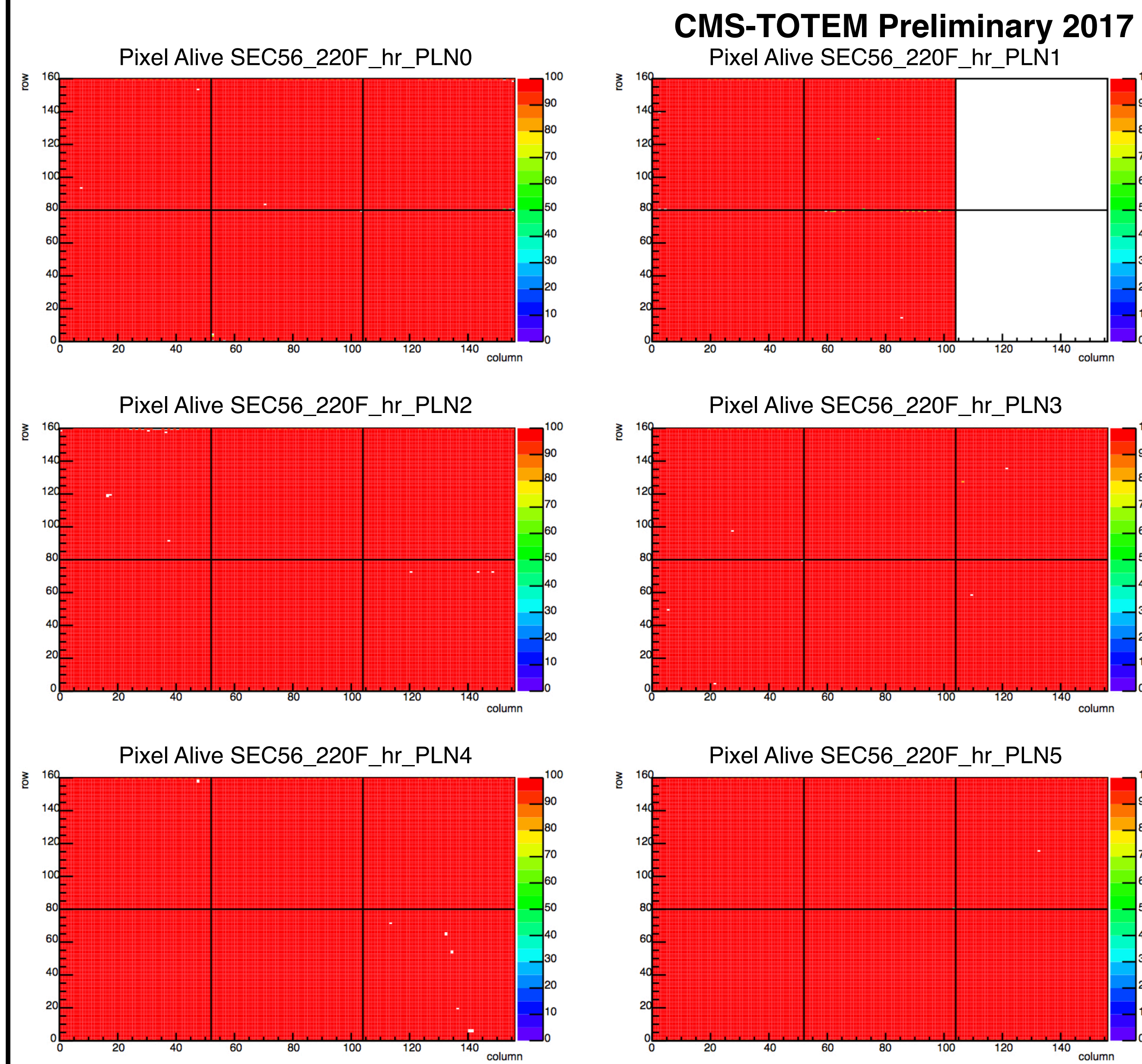


Pixel calibration - II

Module maps for sector 45
installed on LHC beam-pipe 2



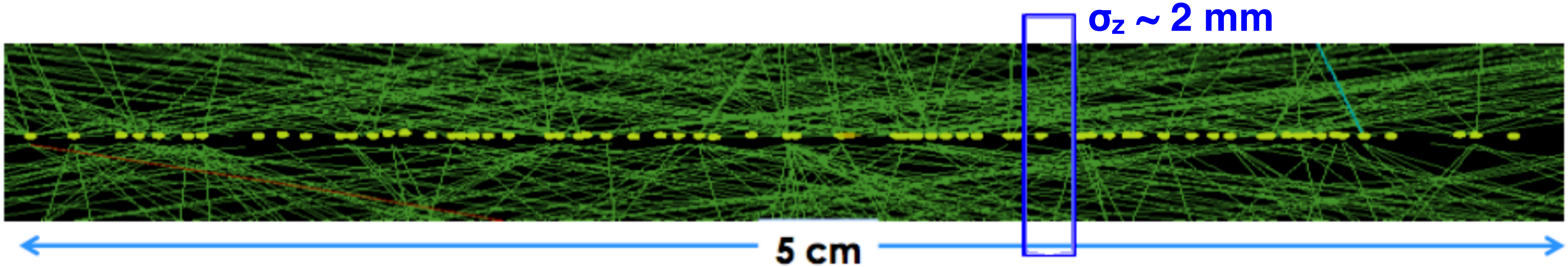
Module maps for sector 56
installed on LHC beam-pipe 1

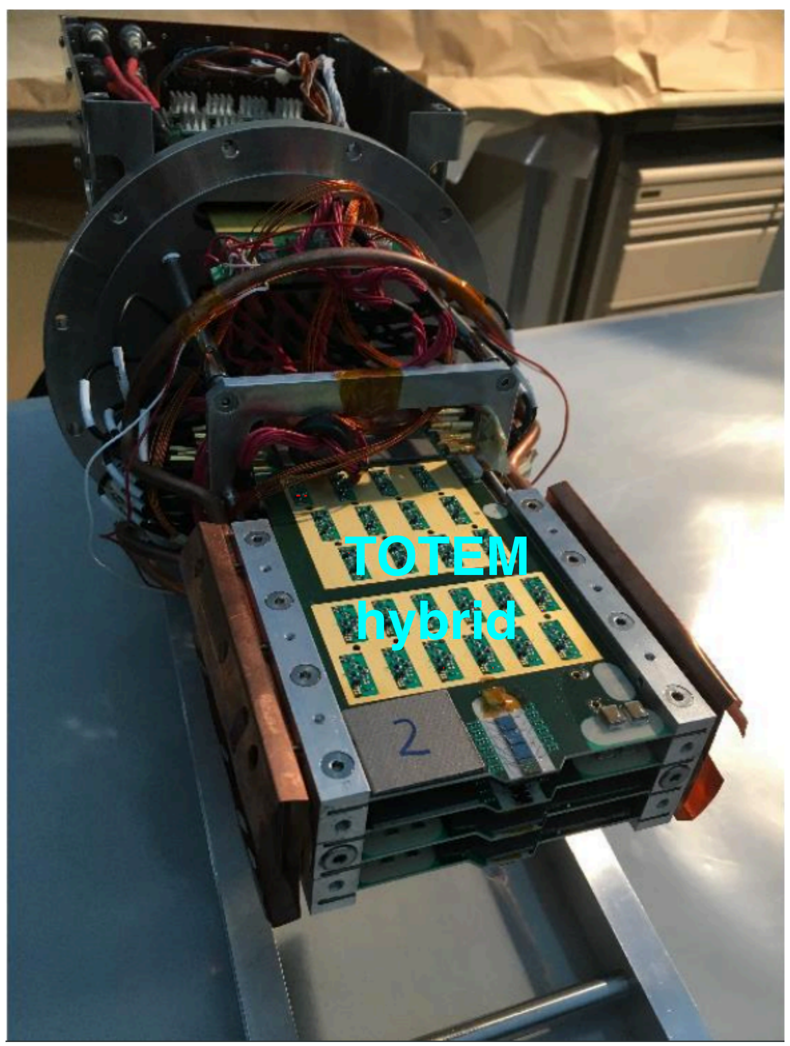


Very low number of bad pixels (eff<90%) = 129 (<0.05% of all channels)

Timing detectors

The average pile-up is expected to reach up to 50 interactions per bunch crossing





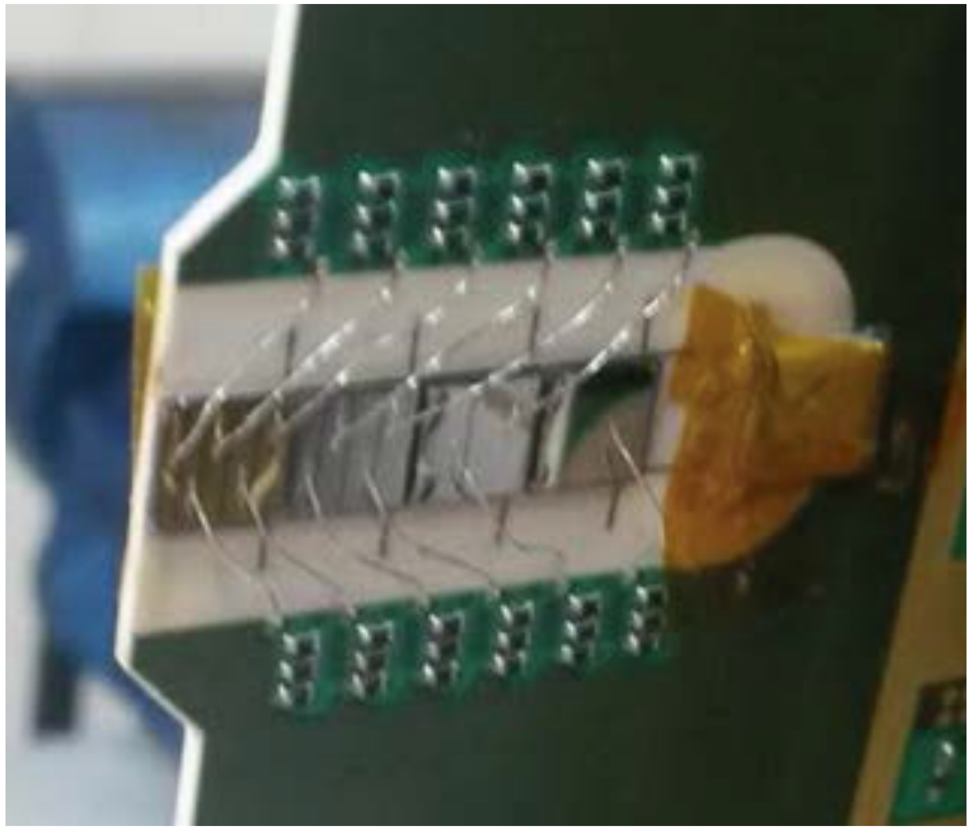
A resolution of ~ 10 ps on the proton arrival time allows to determine the vertex z position with $\sigma_z \sim 2$ mm ("z-by-timing" measurement $z = c\,(t1 - t2)/2$).

Each timing station hosts 3 scCVD diamond ($\sigma_t \sim 80$ ps) and one Ultra-Fast Silicon Detector ($\sigma_t \sim 35$ ps) planes.

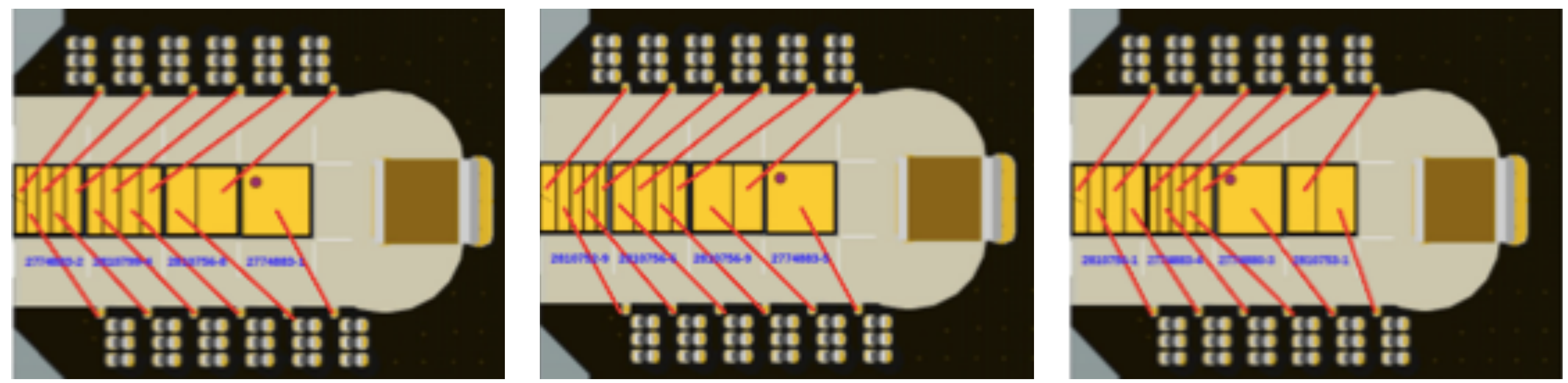
Digitization is done with NINO chip + HPTDC.

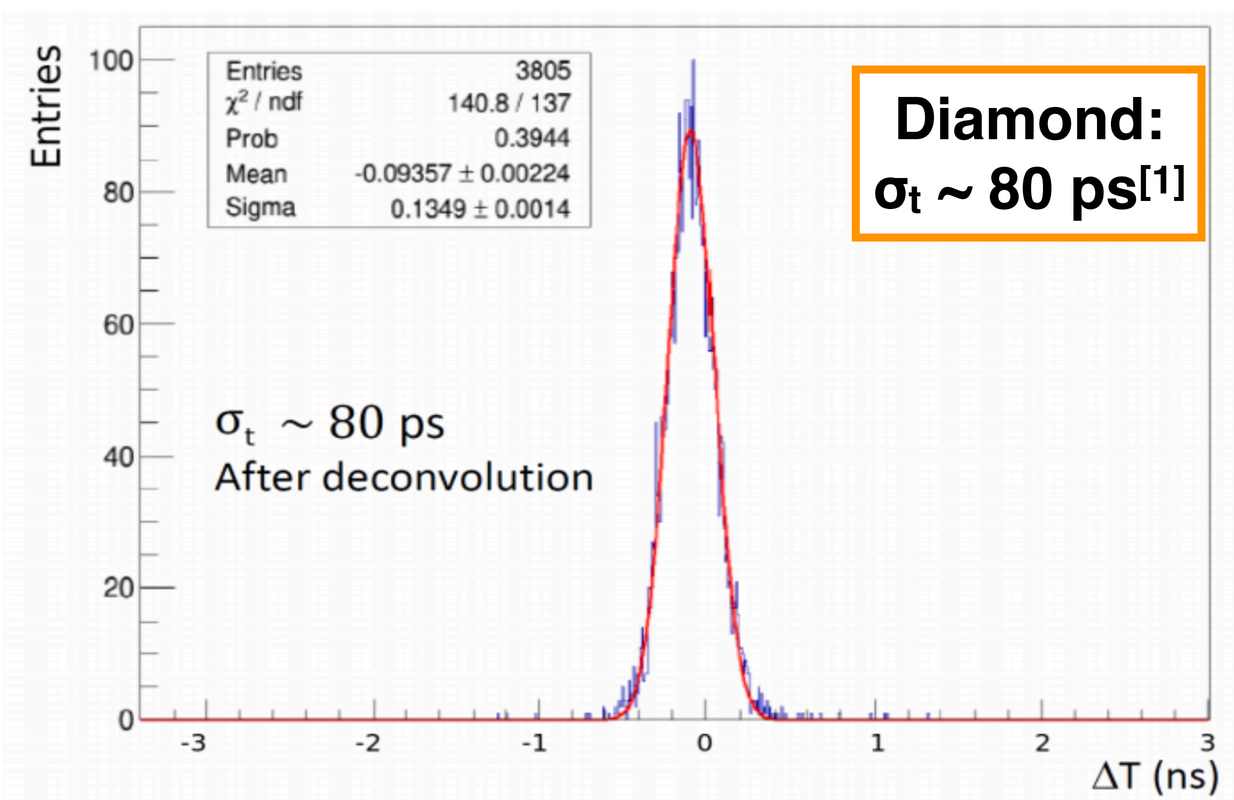
Precise clock distribution (few ps jitter) is obtained with a design adapted from the "Universal Picosecond Timing System" (optical network) or with RF-feedback with low-loss coaxial cable.

Diamond detectors



Four 4x4 mm² diamond sensors per plane, with different pad patterns to match the particle rate as a function of the distance from the beam.
Single sensors are mounted with a different order and rotation to improve the **spatial resolution to ~ 150 μm**.





Intrinsic radiation hardness → to withstand overall integrated flux of 5×10^{15} p/cm².

Triple stage amplification by SMD components on the TOTEM hybrid.

Allow for high granularity (wrt, e.g., quartz).
Time resolution ~ 80 ps per plane.

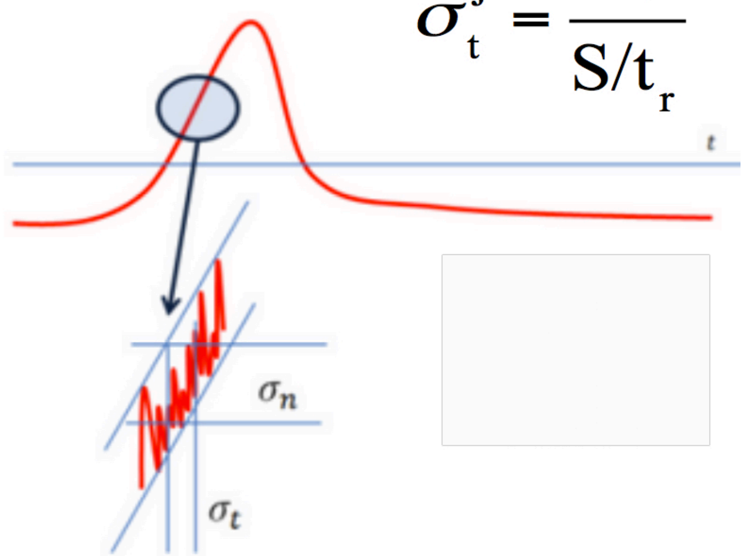
[1] G. Antchev et al.,JINST 12 (2017) P03007

Ultra-Fast Silicon Detectors (UFSD)

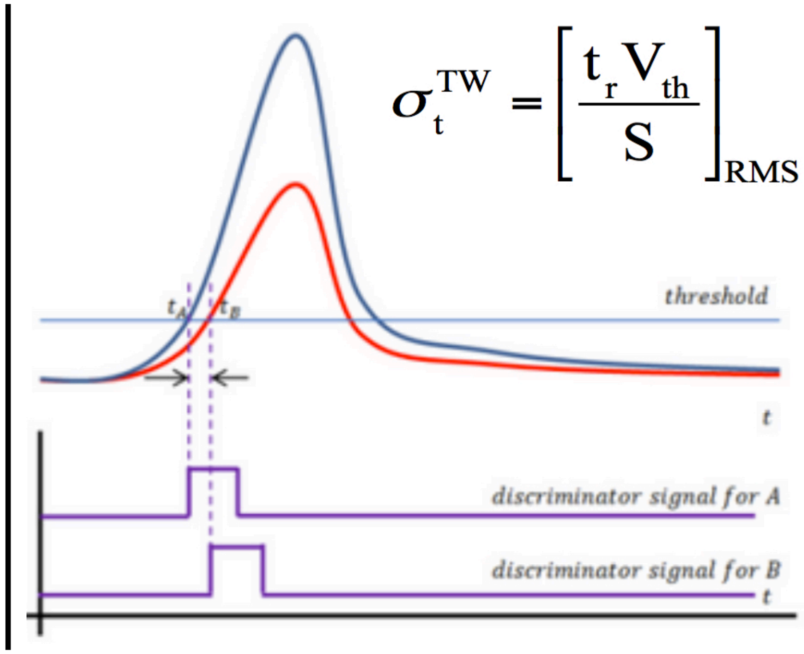
$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

Jitter: the noise is summed to the signal, causing amplitude variations

$$\sigma_t^J = \frac{N}{S/t_r}$$



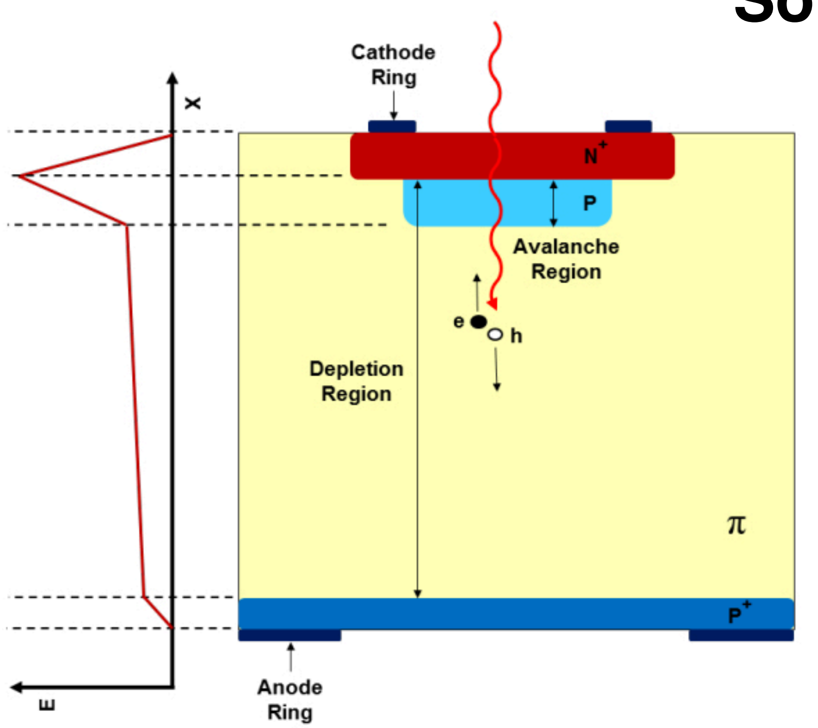
$$\sigma_t^{TW} = \left[\frac{t_r V_{th}}{S}\right]_{RMS}$$

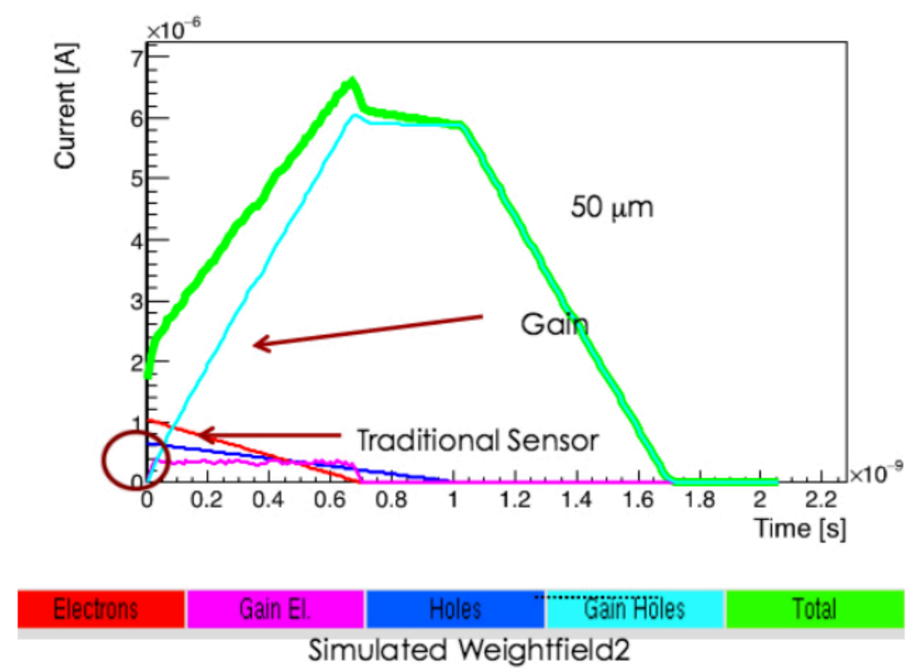


Time walk: the voltage value Vth is reached at different times by signals of different amplitude

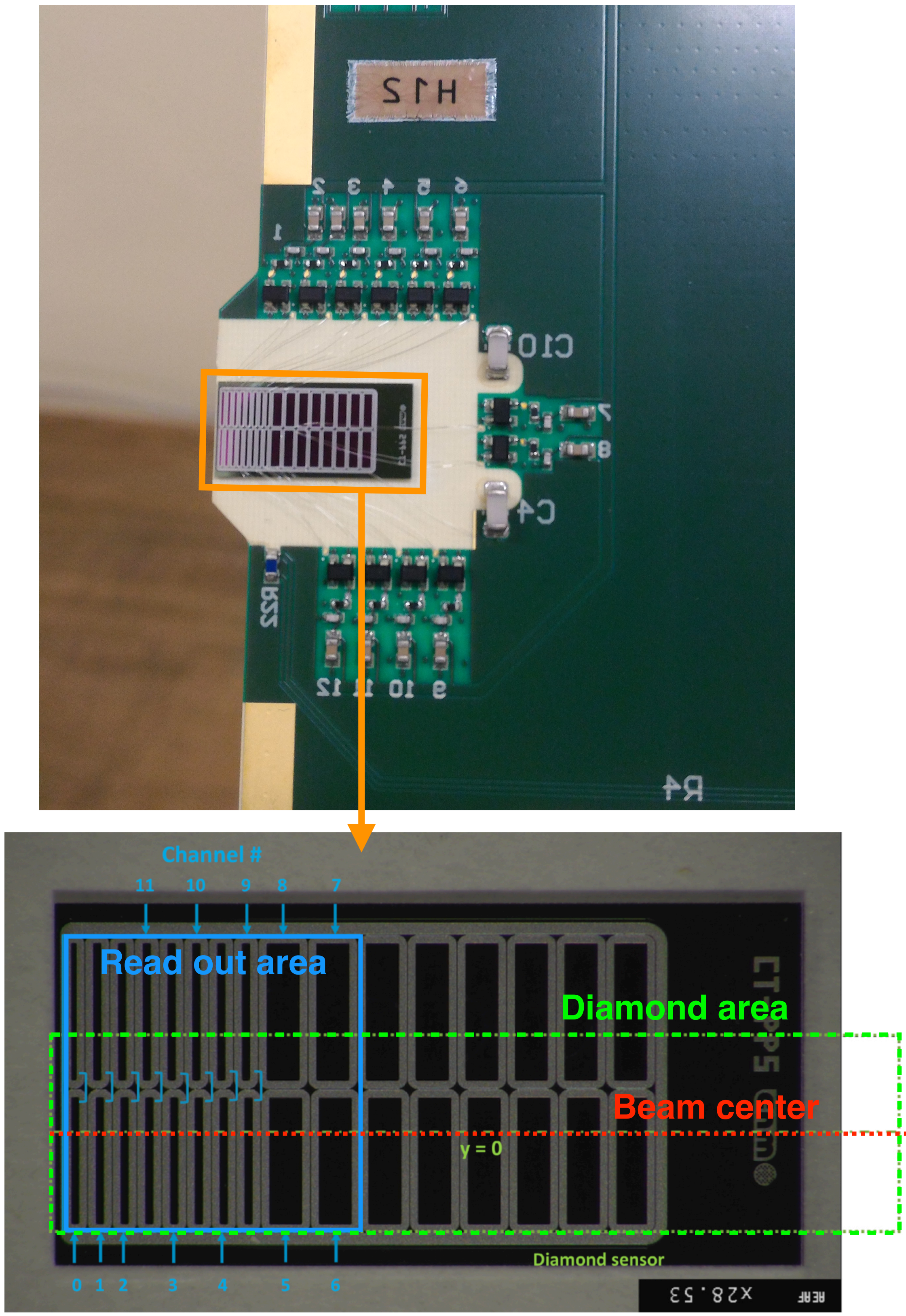
Time walk and jitter ~ $N^*(S/tr)^{-1} = N^*(dV/dt)^{-1}$

Solution: Gain!





UFSD in CT-PPS



1 plane of UFSD (**first installation in HEP**).

Pad readout adapted to that of the diamond readout board: eight 0.5x6mm^2 and four 1x3mm^2 pads.

Radiation hardness still an issue → in RP environment expected lifetime ~ 10^{14} p/cm^2 (R&D to improve rad-hardness still ongoing).

Allow for high granularity (wrt, e.g., quartz).

Double-stage amplification with modified TOTEM hybrid. **In Torino an ASIC (TOFFEE) is under development** to integrate the SMD components amplification and the NINO discrimination.

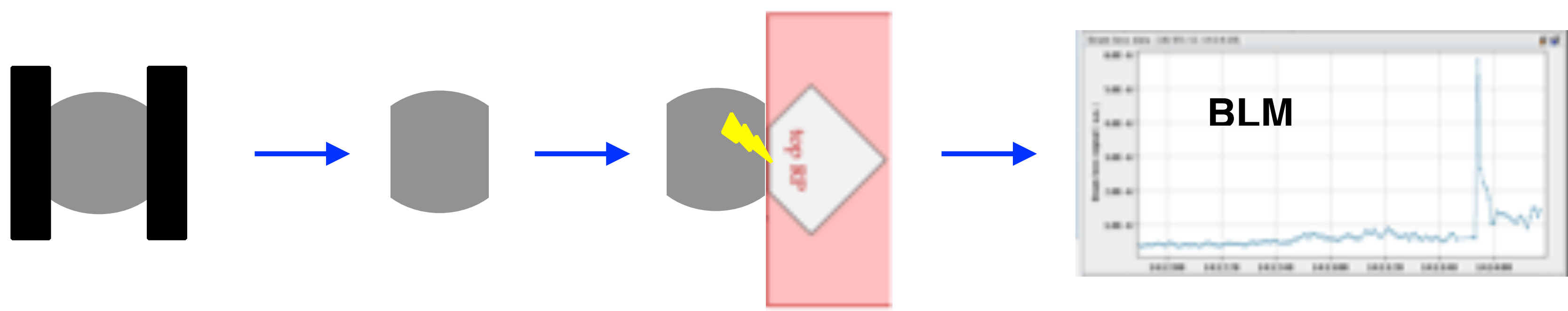
Time resolution ~ 35 ps[1]

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

Operational experience

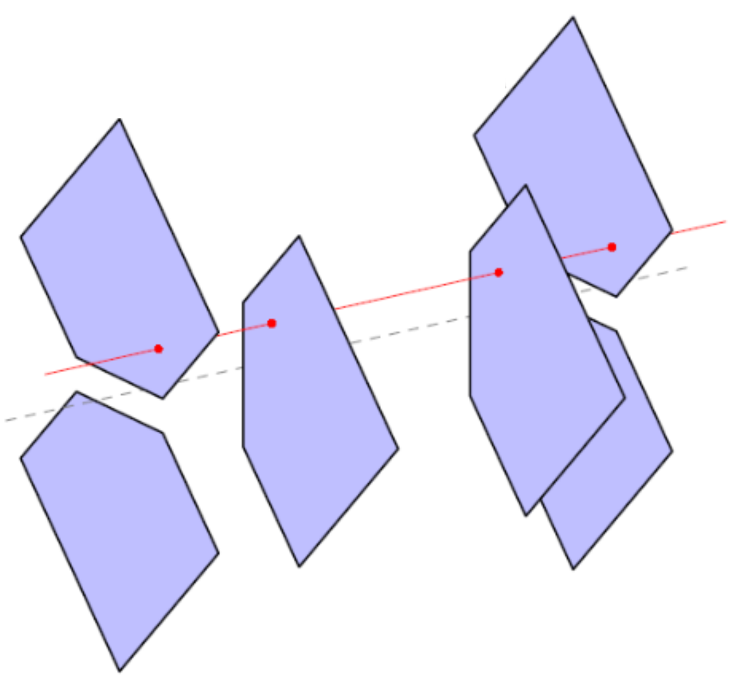
Alignment run procedure

- **Goal: RP alignment with respect to the collimators, relative alignment between the RPs, alignment with respect to the beam, optics determination**.
- Upstream collimators are closed to a given number of σ_{beam} from the beam (5 - 8.5). The RPs (both horizontal and vertical) are slowly approached one at a time and when a spike is observed in the downstream Beam Loss Monitor (BLM) it means that the RP reached the same position as the collimator in terms of beam sigmas.

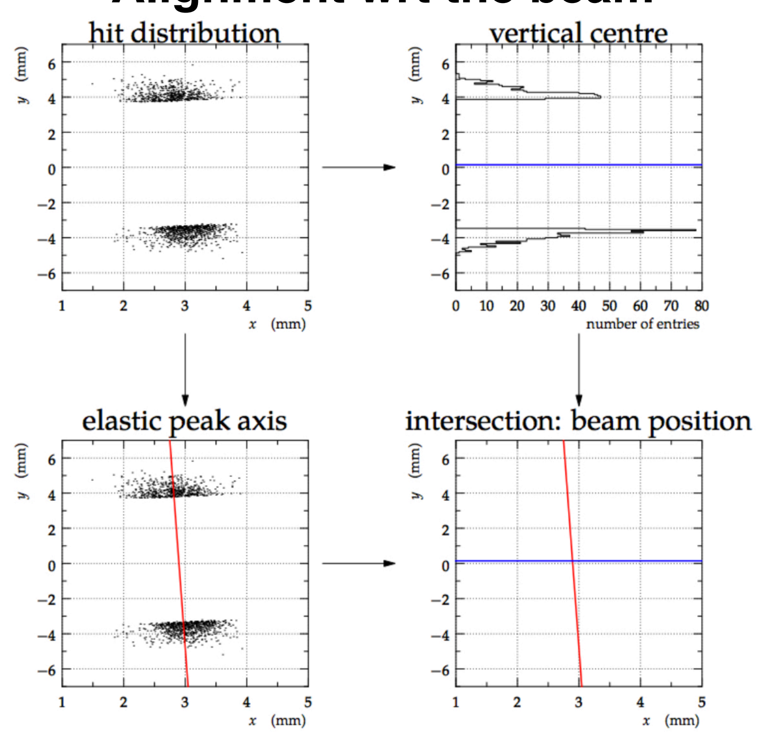


- Alignment with respect to the beam based on the elastic protons measured in the vertical RPs

RP relative alignment

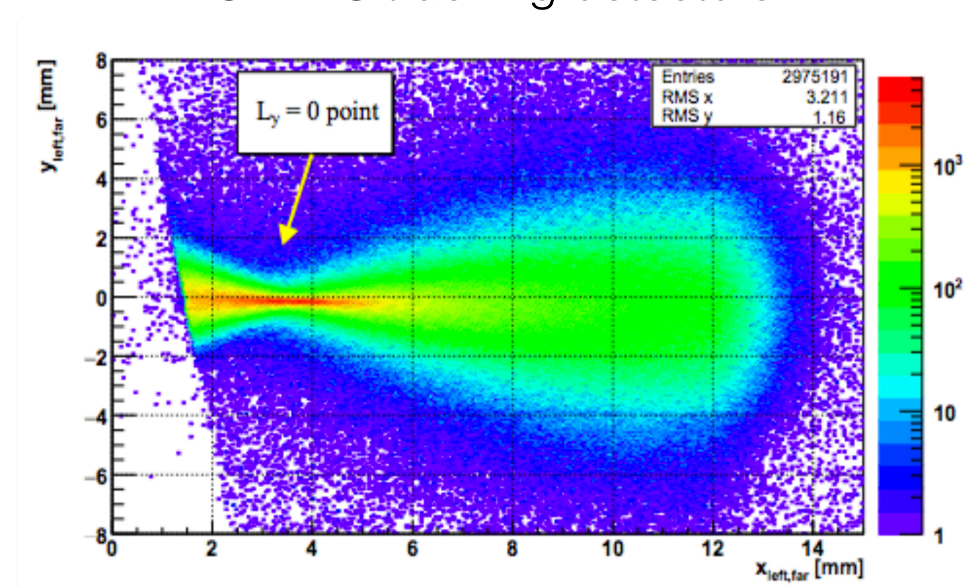


Alignment wrt the beam

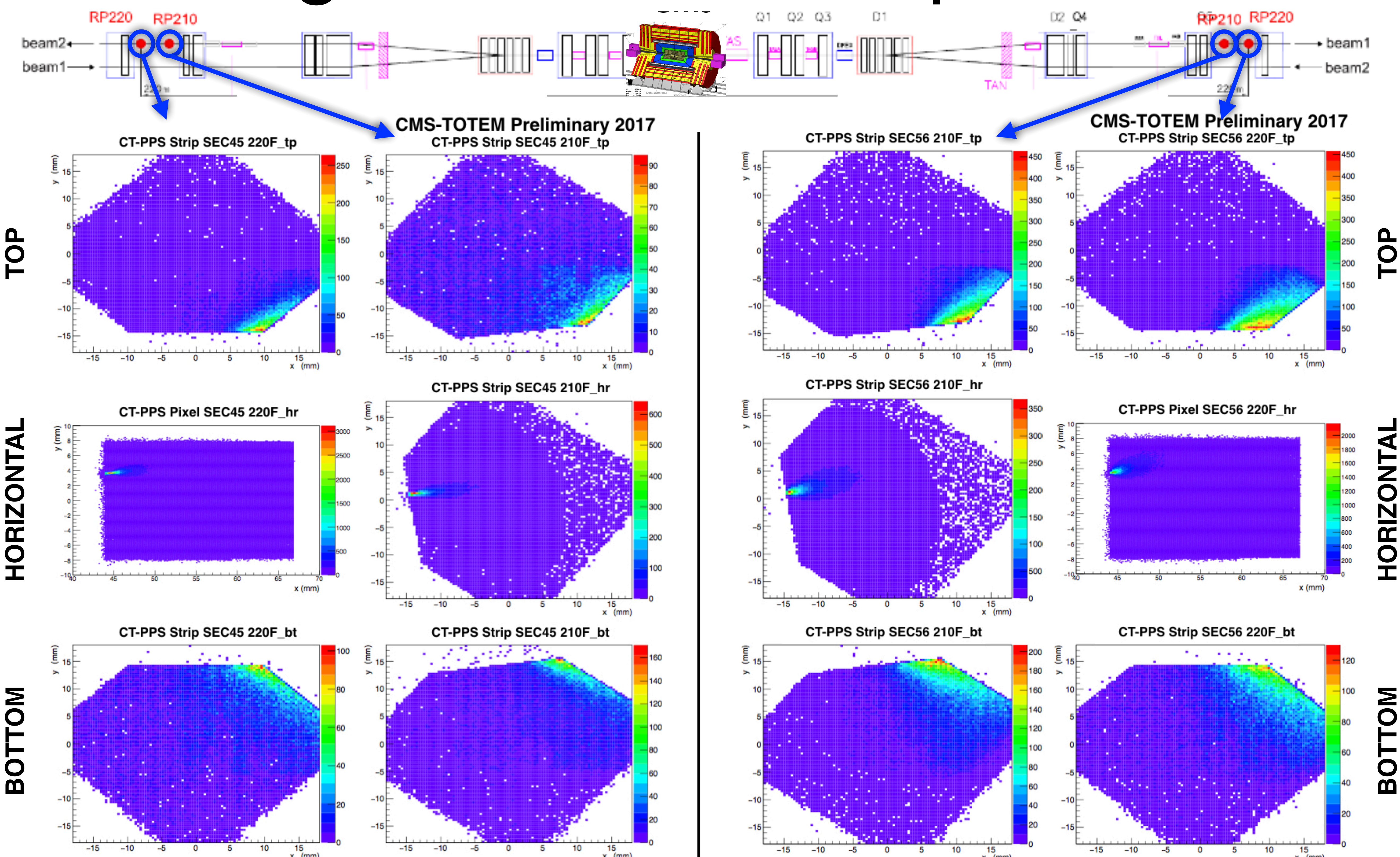


Optics tuning

Based on the hit profile on the CT-PPS tracking detectors

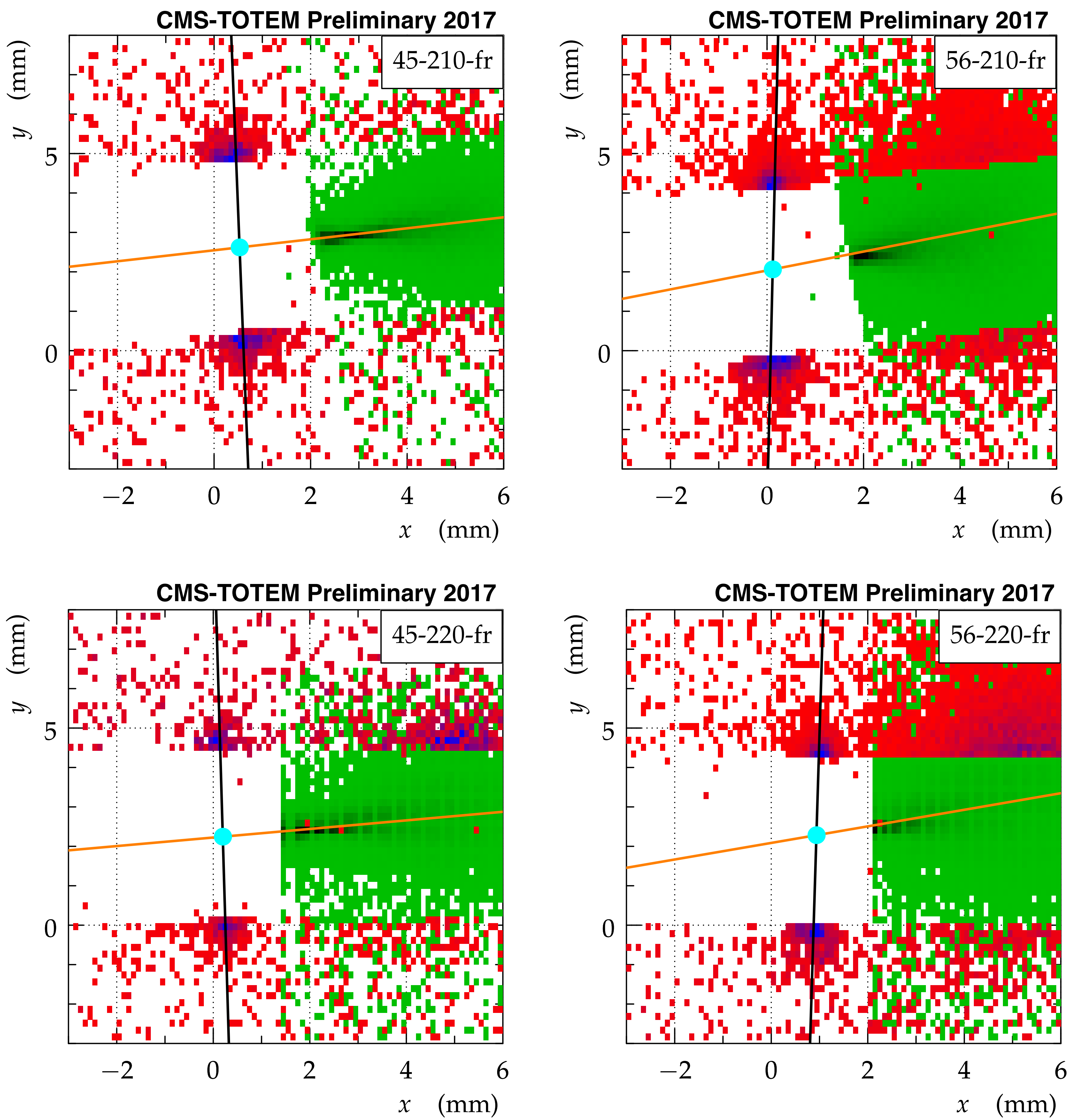


Tracking detector hit maps



Data collected during alignment run at end of May 2017
x-y coordinates relative to an arbitrary system of reference

RP relative and global alignment



Data of alignment runs are currently under study.

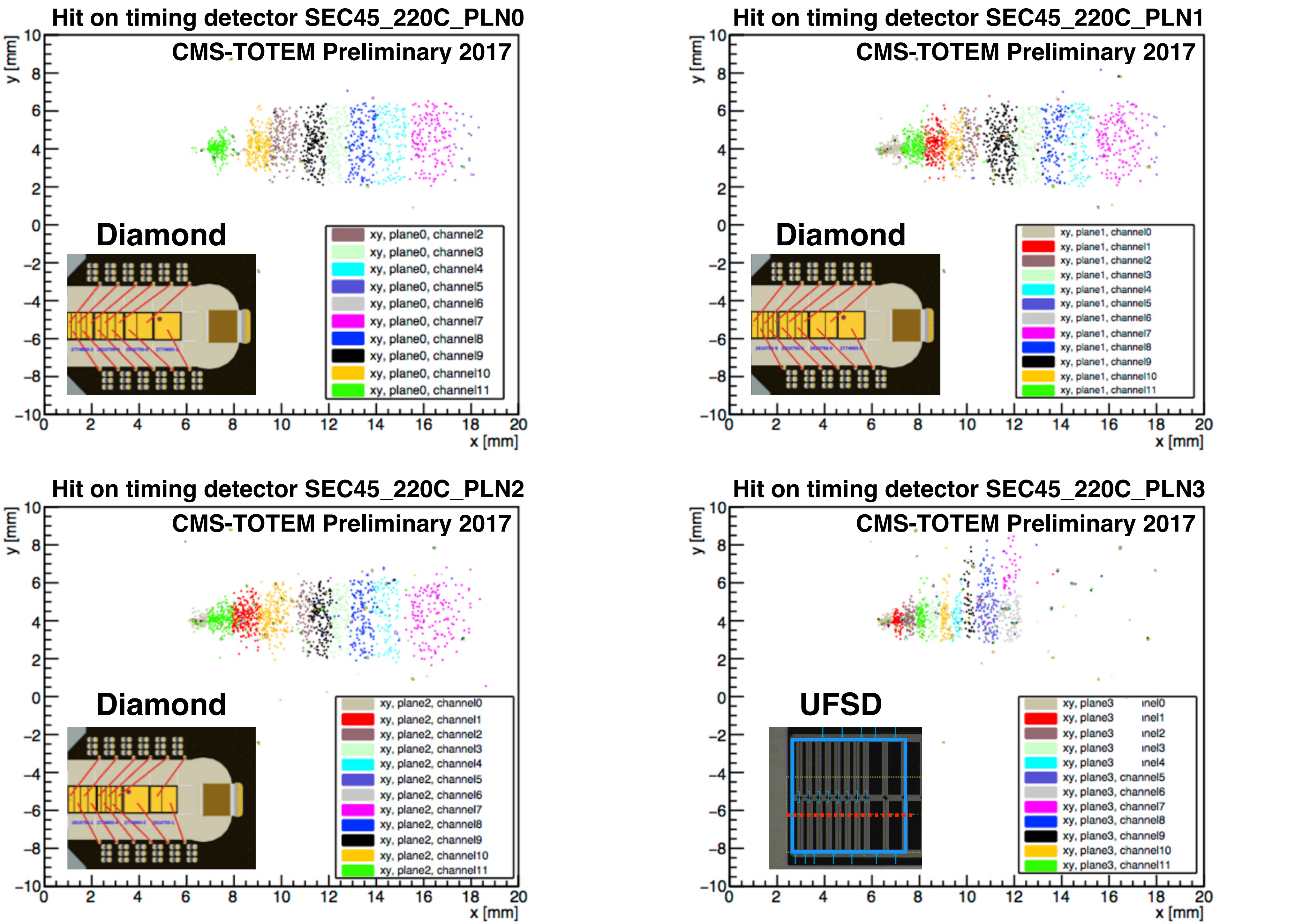
A first estimation of the Roman pot relative alignment and beam position is shown:

- 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

The fine determination of the optics parameters is ongoing and requires a more refined data analysis.

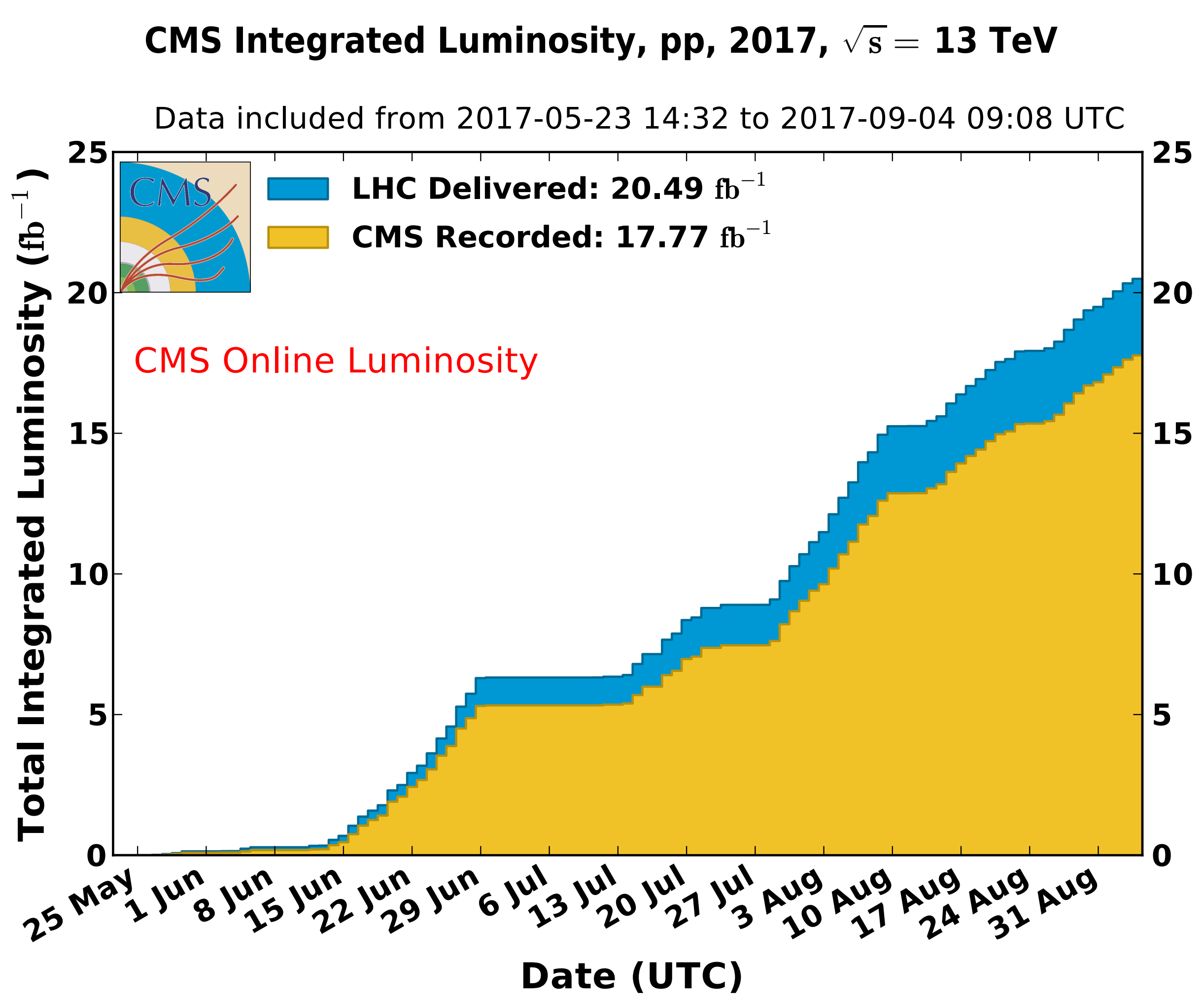
Timing status

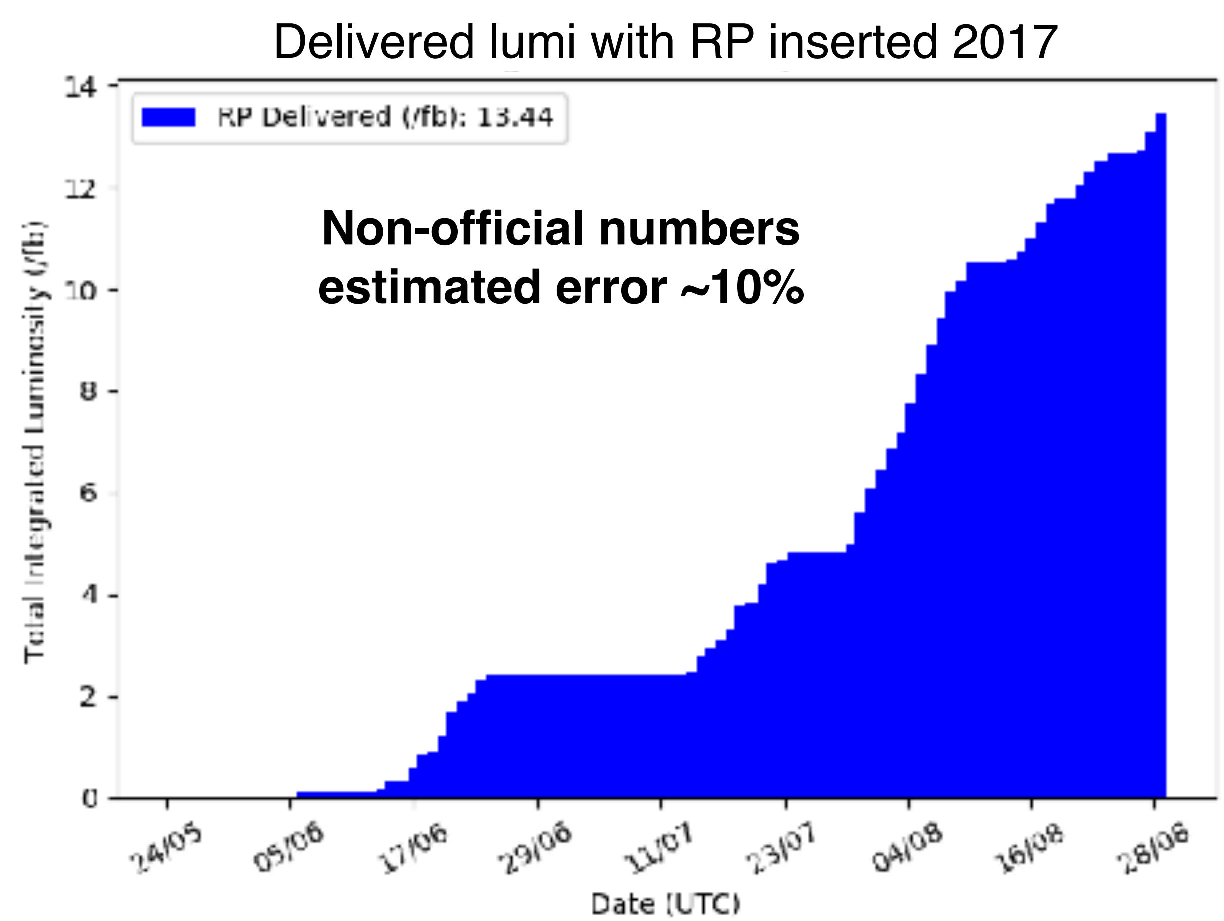
To ensure the consistency of the data collected with the timing detectors, hit maps as measured in the strips are plotted requiring a coincidence with timing detectors. Colours indicate the different channels. **A clear correlation is observed. Timing system being commissioned.**



Status of the data taking

- The Roman pots have been inserted during the LHC intensity ramp-up up to the maximum 2017 luminosity with ~2556 bunches. They have been certified for the 2017 data taking and they have been **inserted in all high luminosity fills since the Technical Stop 1** (beginning of July)
- **The CT-PPS detector is running stably** with very low impact on the CMS data taking.
- Up to now detectors have been inserted close to the beam for more than 13 fb^{-1}.





Summary and conclusions

- **2016 CT-PPS installation with an "accelerated program"**: silicon strips + diamond detectors → **15 fb^{-1} collected**. First data analysis: CMS-PAS-PPS-17-001
- **2017 CT-PPS installation completed in April 2017**, 4 different detector technologies
  - silicon strips for tracking
  - 3D silicon pixels for tracking (**first installation in CMS**)
  - scCVD diamonds for timing
  - Ultra-Fast Silicon Detectors for timing (**first installation in a HEP experiment**)
- **All detectors successfully integrated in the CMS central DAQ already from the first 2017 LHC fill**.
- Commissioning of tracking detectors completed. Commissioning of timing system in progress.
- The analysis of the alignment data is ongoing, the **relative and global alignments are being finalised**; efforts are ongoing to determine the LHC optics parametrisation.
- **More than 13 fb^{-1} of data have been collected so far at $\sqrt{s}$ = 13 TeV in 2017**. Many more are expected to be collected up to the end of 2018.

Backup

Physics motivations

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

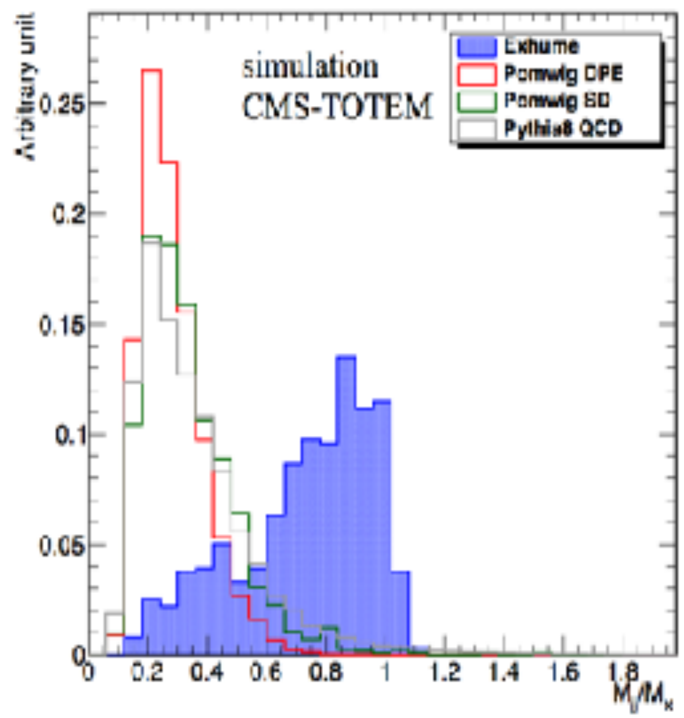
EWK: LHC used as photon-photon collider

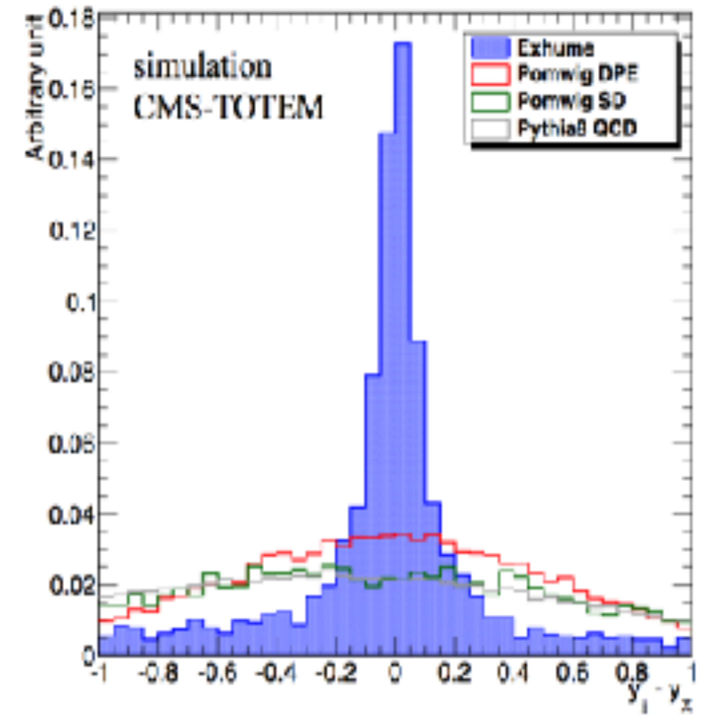
- Measurement of $\gamma\gamma \rightarrow W^+W^-$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
- Search for anomalous quartic gauge couplings (AQGCs) with high sensitivity

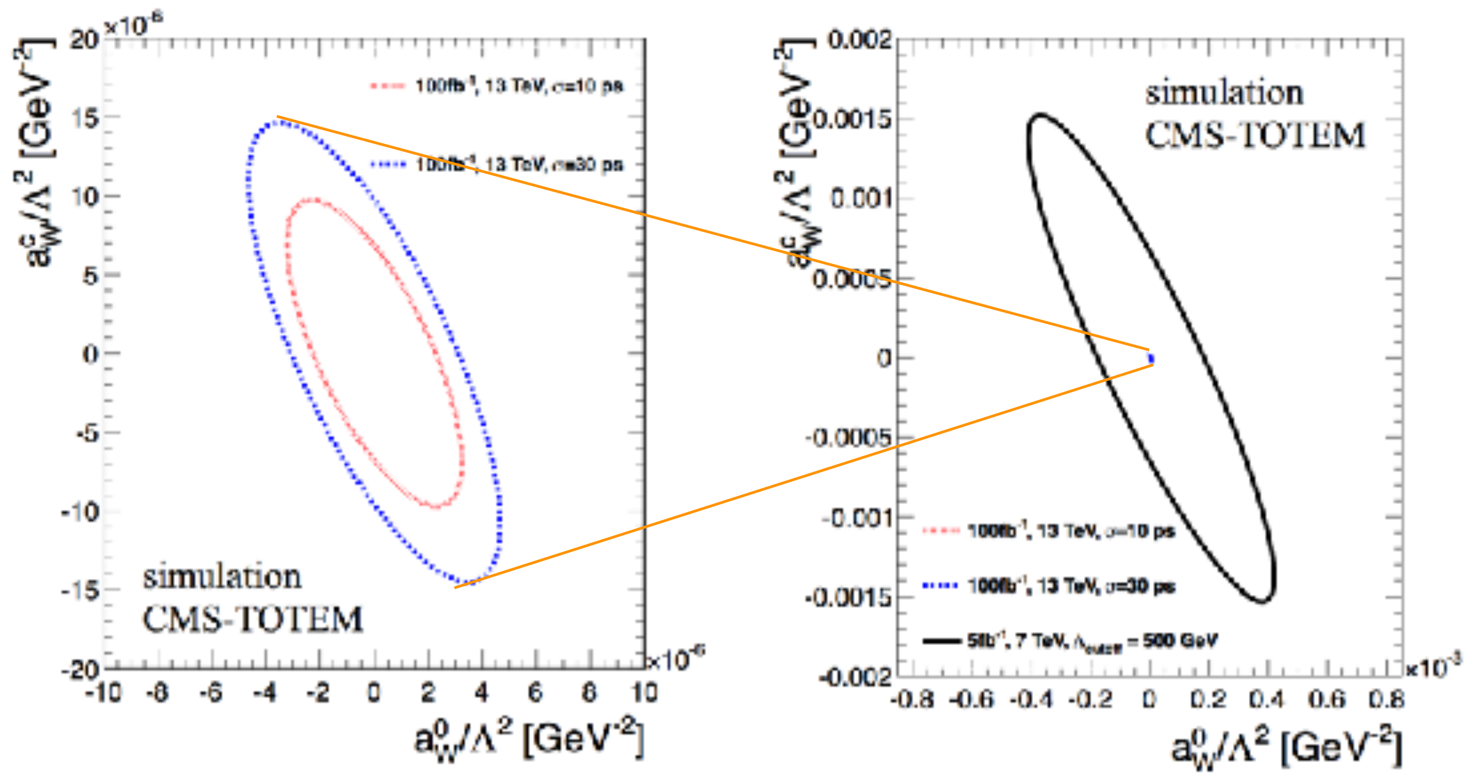
Beyond Standard Model:

- Clean events (no underlying event)
- Independent mass measurement by pp system
- JPC quantum numbers 0++, 2++

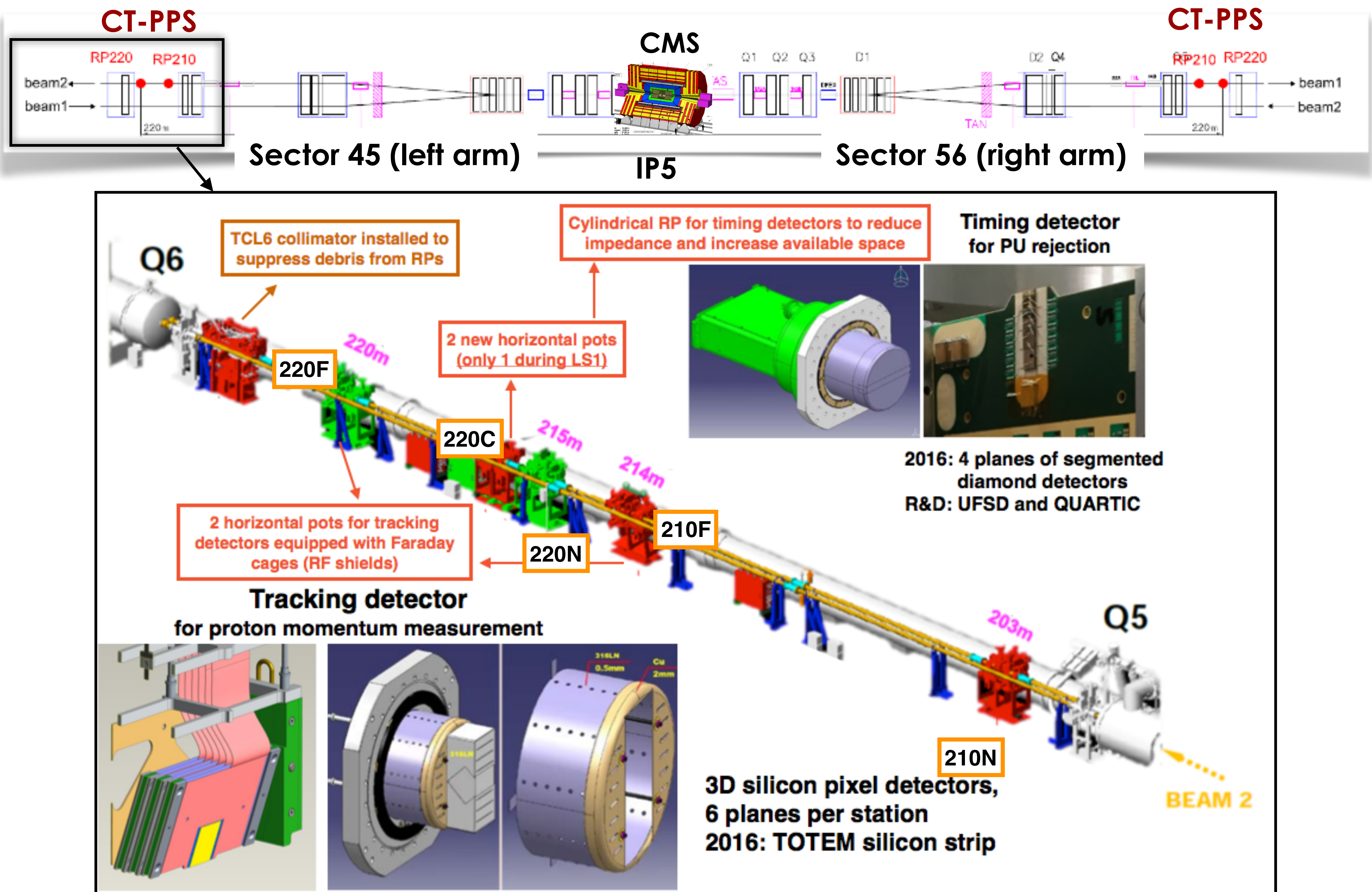
TDR studies







Detector setup in 2016



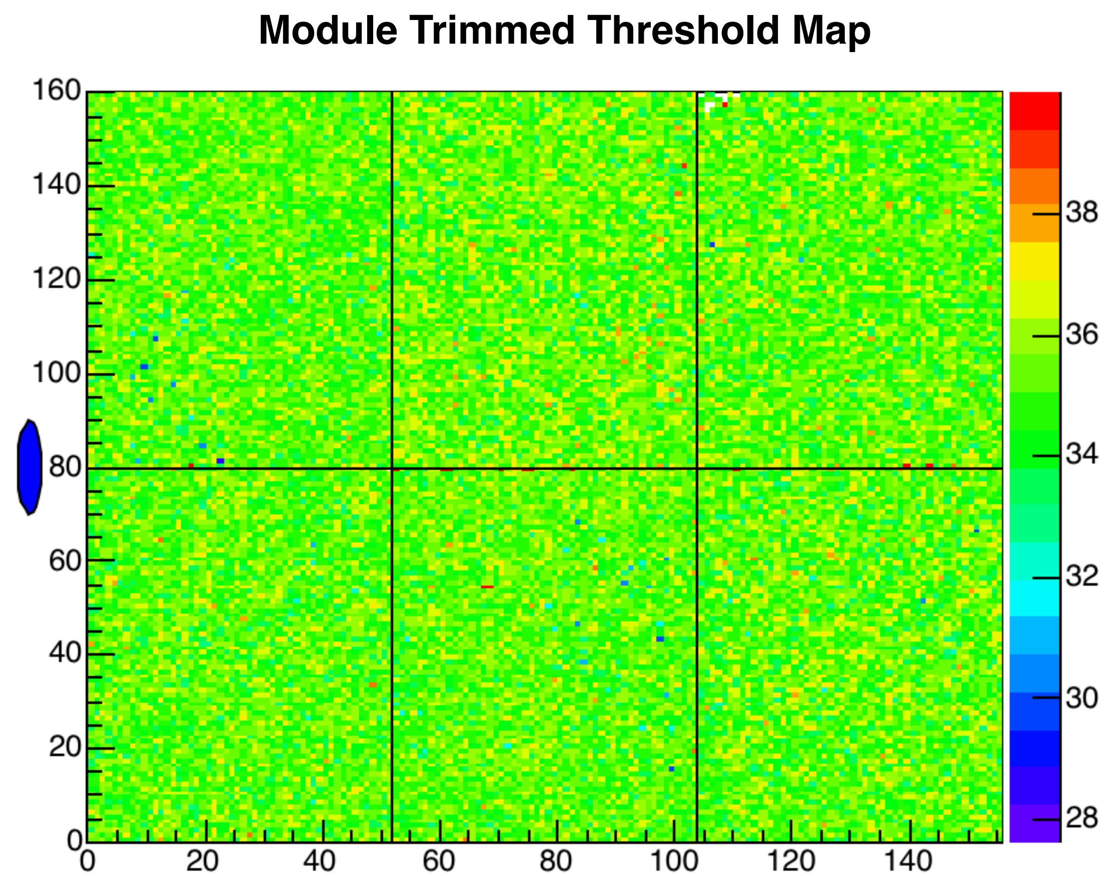
Module testing

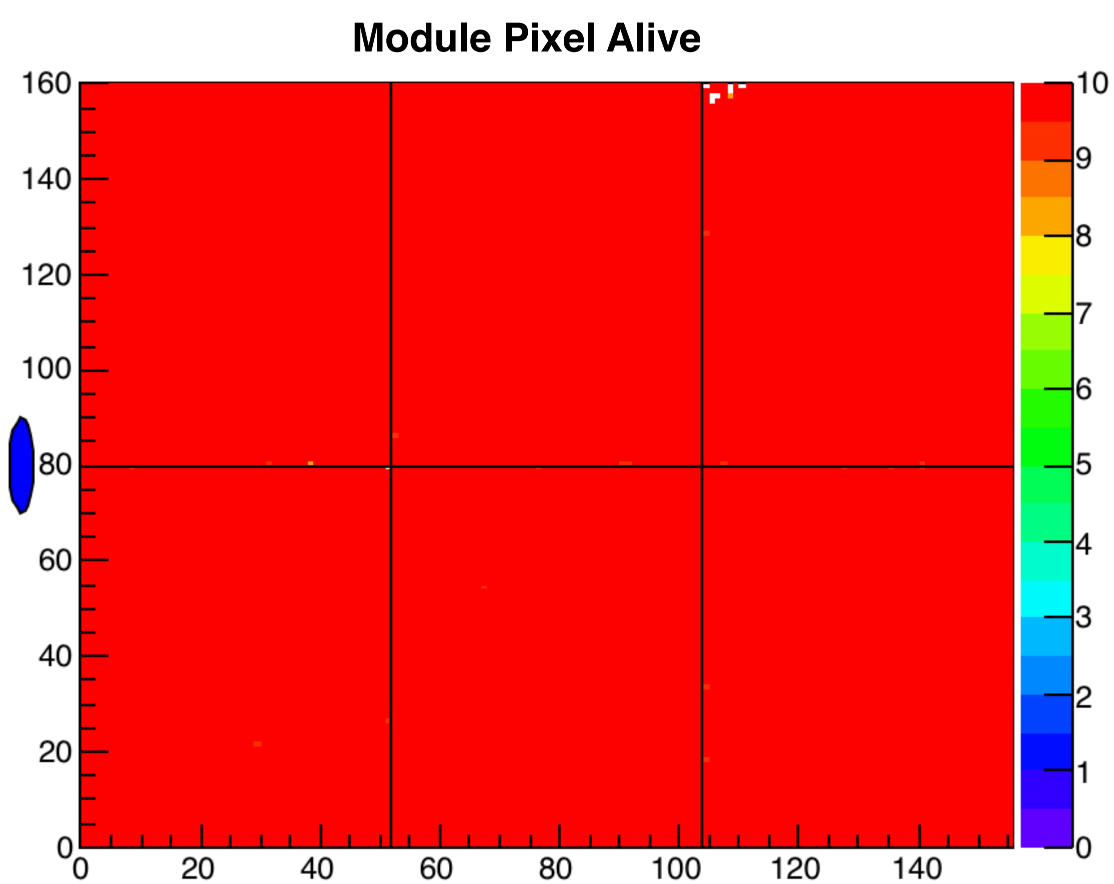
Detectors characterised and optimised in Torino and Genova by a temporary wire-bonding and gluing with gel-pak film on flex hybrid:

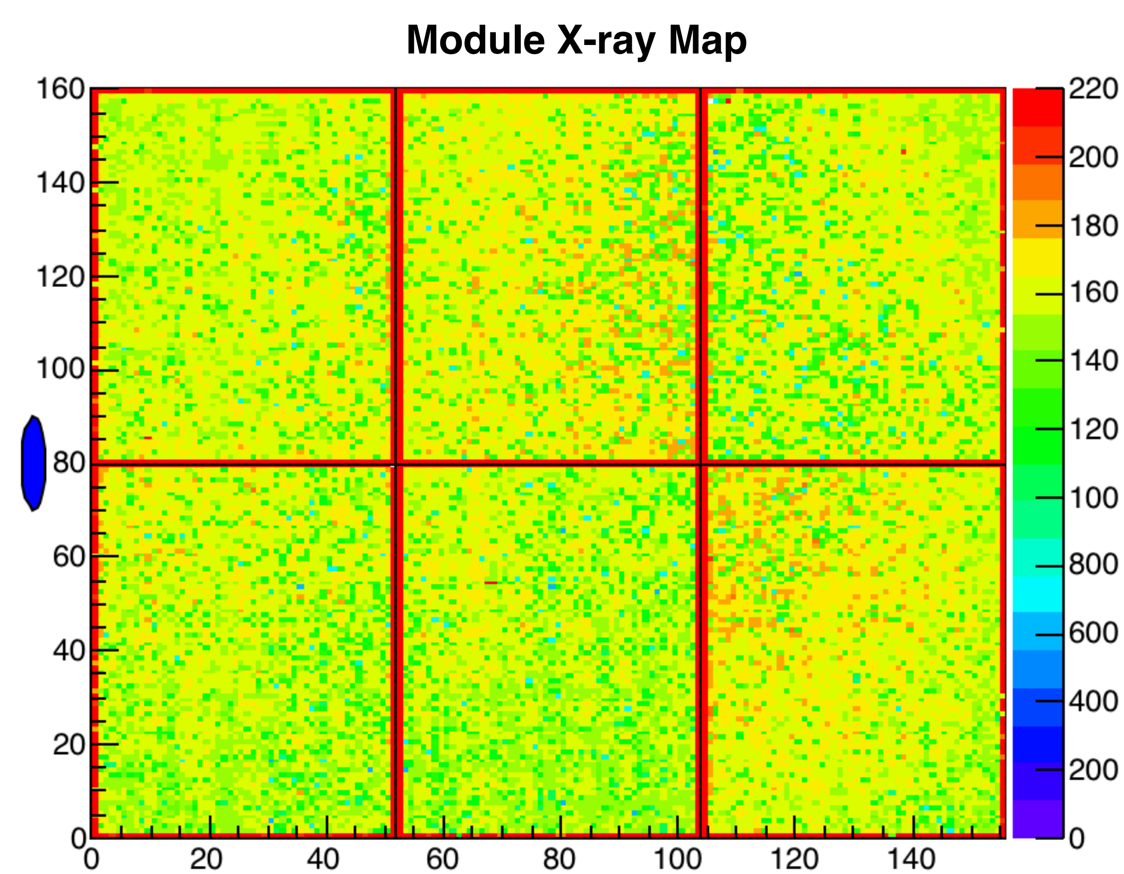
- IV curve
- ROC calibration and optimisation
- Threshold trimming to ~ 1800 e$^-$
- X-ray to check bump-bonding quality

No damage due to flip-chip observed, based on sensor IV curve comparison and ROC performance before and after bump-bonding.

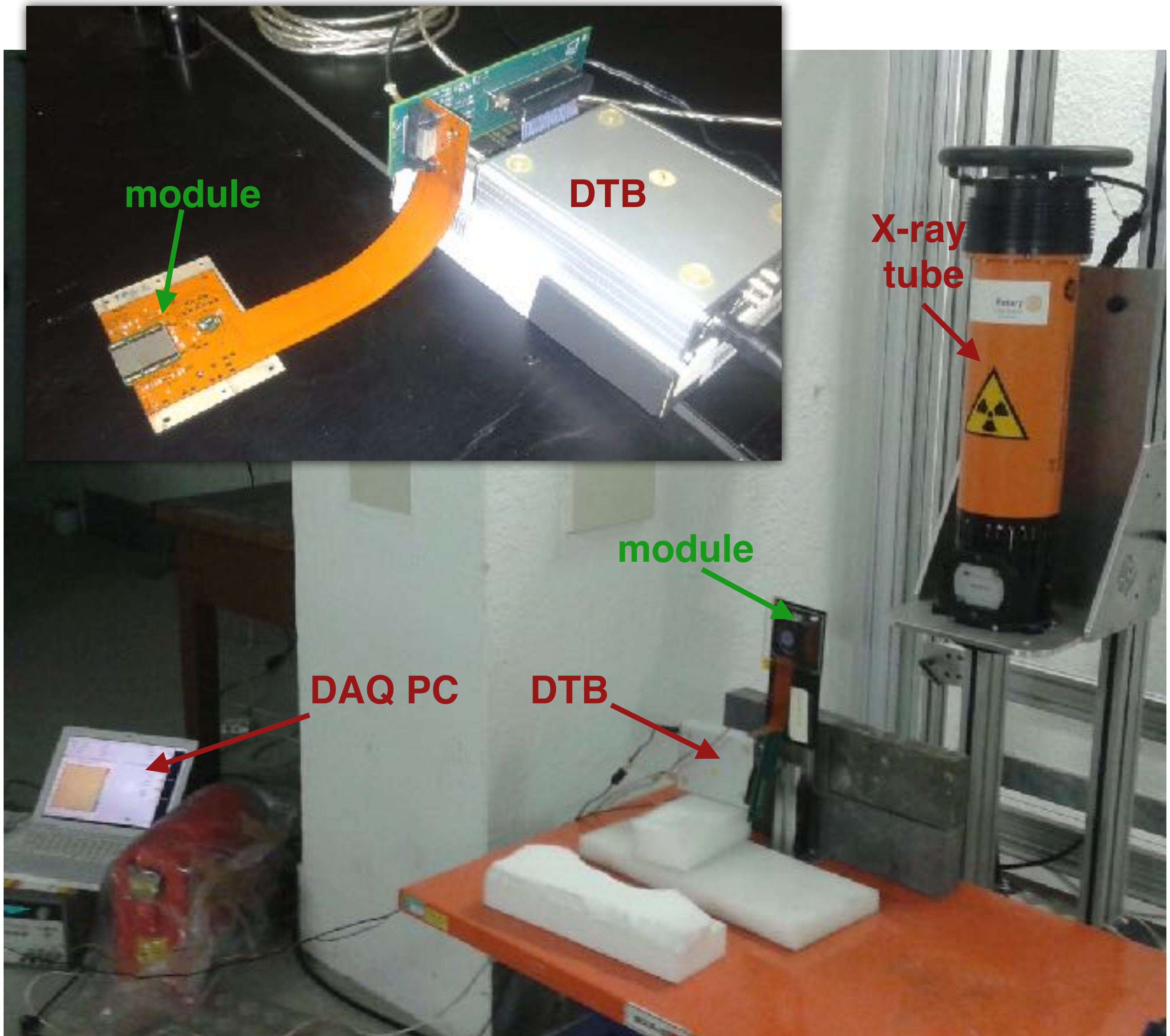
Good quality of bump-bonding

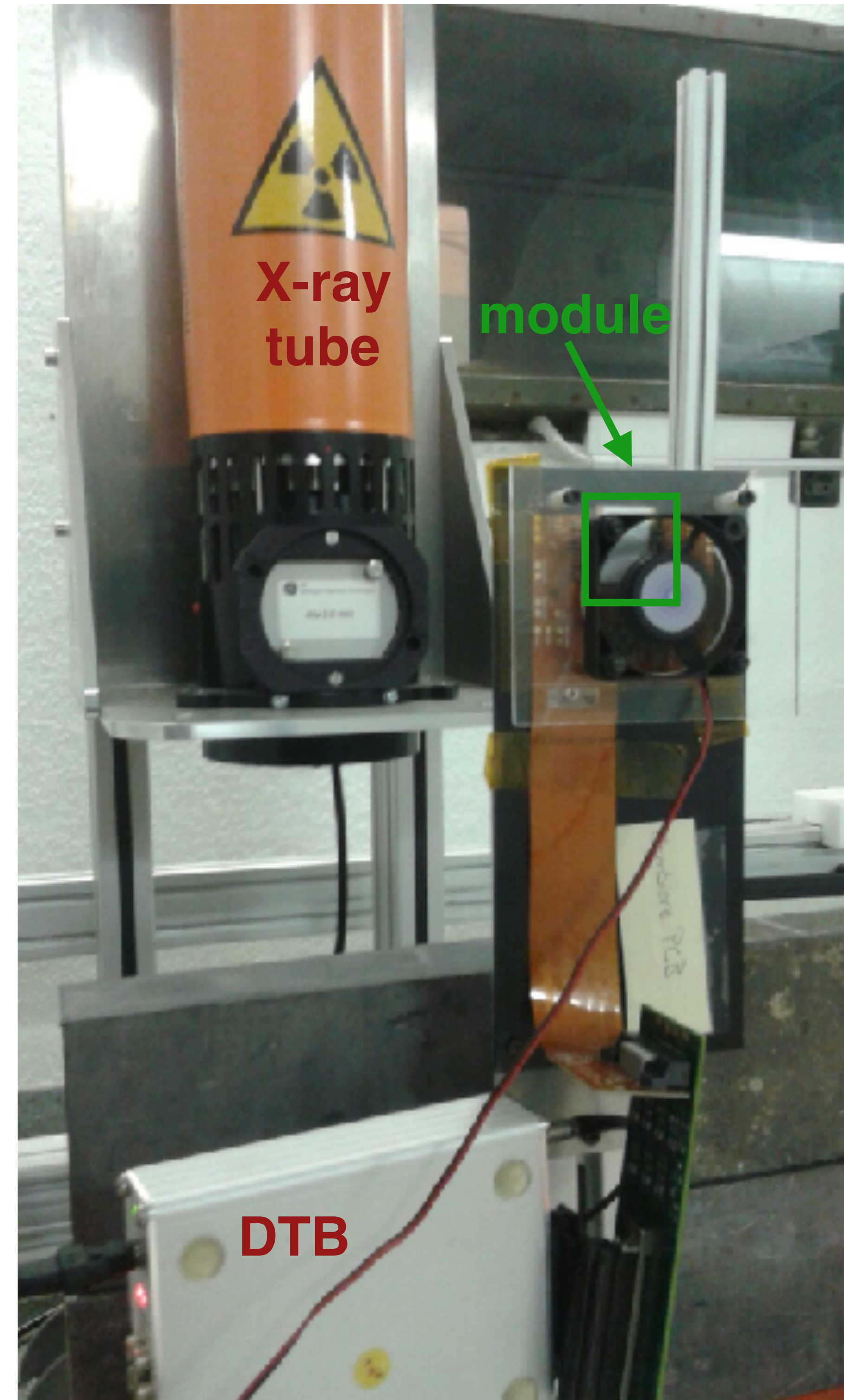






Torino X-ray setup





Status of module production - batch 1

3x2 module

Module	Layout	Class on wafer
3x2_b1w1d2	2E	B
3x2_b1w1d3	1E	B
3x2_b1w1d5	2E	B
3x2_b1w1d6	1E	B
3x2_b1w2d3	1E	A
3x2_b1w2d4	2E	B
3x2_b1w2d6	1E	A
3x2_b1w5d2	2E	B
3x2_b1w5d3	1E	A
3x2_b1w5d4	2E	B
3x2_b1w5d5	2E	B
3x2_b1w5d6	1E	A
3x2_b1w6d1	2E	B
3x2_b1w6d4	2E	B
3x2_b1w11d1	2E	B
3x2_b1w11d5	2E	B
3x2_b1w11d6	1E	A
3x2_b1w12d1	2E	A
3x2_b1w12d2	2E	A
3x2_b1w12d3	1E	A
3x2_b1w12d4	2E	A
3x2_b1w12d6	1E	A

2x2 module

Module	Layout	Class on wafer
2x2_b1w1d1	2E	B
2x2_b1w1d2	2E	B
2x2_b1w2d1	2E	B
2x2_b1w2d2	2E	A
2x2_b1w2d4	1E	A
2x2_b1w5d1	2E	B
2x2_b1w5d2	2E	A
2x2_b1w5d3	1E	A
2x2_b1w5d4	1E	A
2x2_b1w6d1	2E	B
2x2_b1w6d2	2E	B
2x2_b1w6d3	1E	B
2x2_b1w6d4	1E	B
2x2_b1w10d1	2E	A
2x2_b1w10d3	1E	B
2x2_b1w10d4	1E	A
2x2_b1w11d1	2E	B
2x2_b1w11d2	2E	B
2x2_b1w11d3	1E	A
2x2_b1w11d4	1E	A
2x2_b1w12d1	2E	B
2x2_b1w12d2	2E	A
2x2_b1w12d3	1E	B
2x2_b1w12d4	1E	B

Color code:

Green → Ok

Light green → few defects but still good

Light blue → timing issue, maybe usable but still under investigation

Orange → quite serious problems, better not to use it

Red → not usable

All red modules have been broken during handling or wire-bonding at the beginning of testing campaign.

Status of 3x2:
Tested 22/22
Good sensors 16/22 (7 2E)

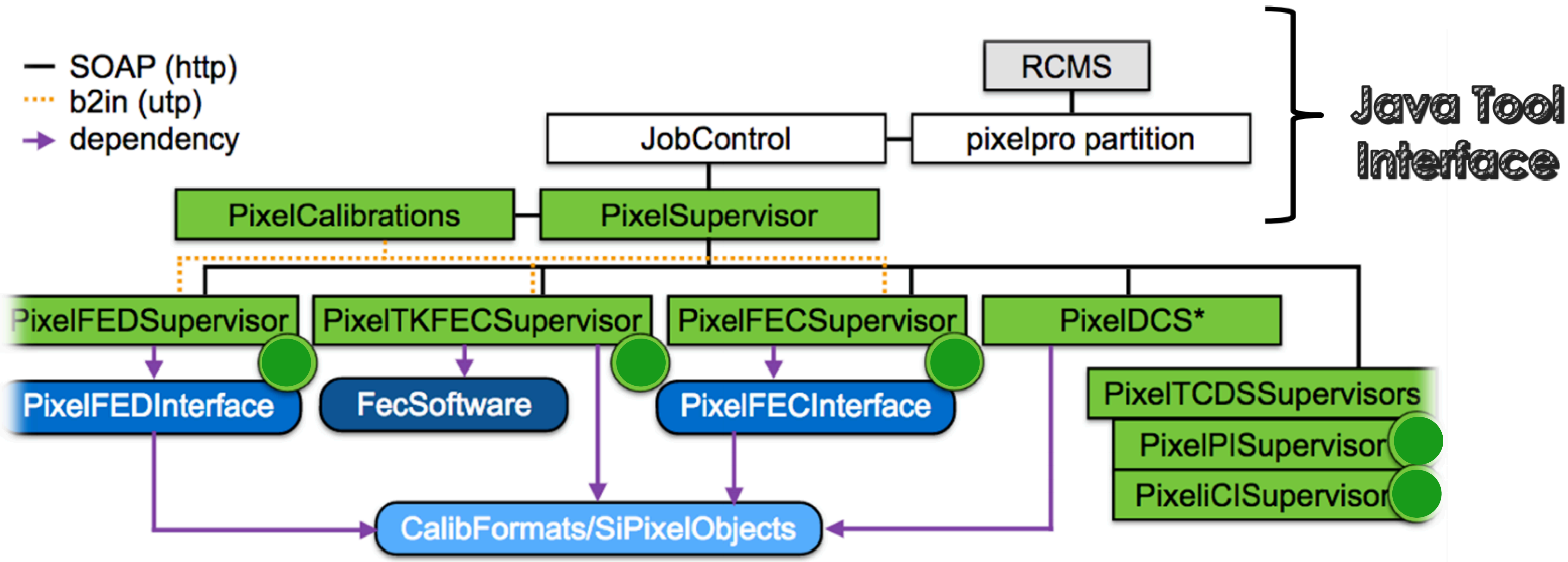
Status of 2x2:
Tested 22/24
Good sensors 18/22 (10 2E)

For the 2017 data taking only 2 pixel stations (one per each side) have been installed.

Mainly green 3x2 modules have been selected for the final station assembly.

CT-PPS pixel tracker DAQ

- The DAQ and calibration software for the CT-PPS pixel detector is based on the CMS Phase I Pixel Online Software (POS).
- **The software has been adapted to the CT-PPS electronics.**



- **The software has been fully tested in laboratory** and all the standard calibration procedures have been verified.
- The tests done on the modules during their qualification provided the initial setting which have been further optimised with the DAQ software.
- The software demonstrated to be reliable.

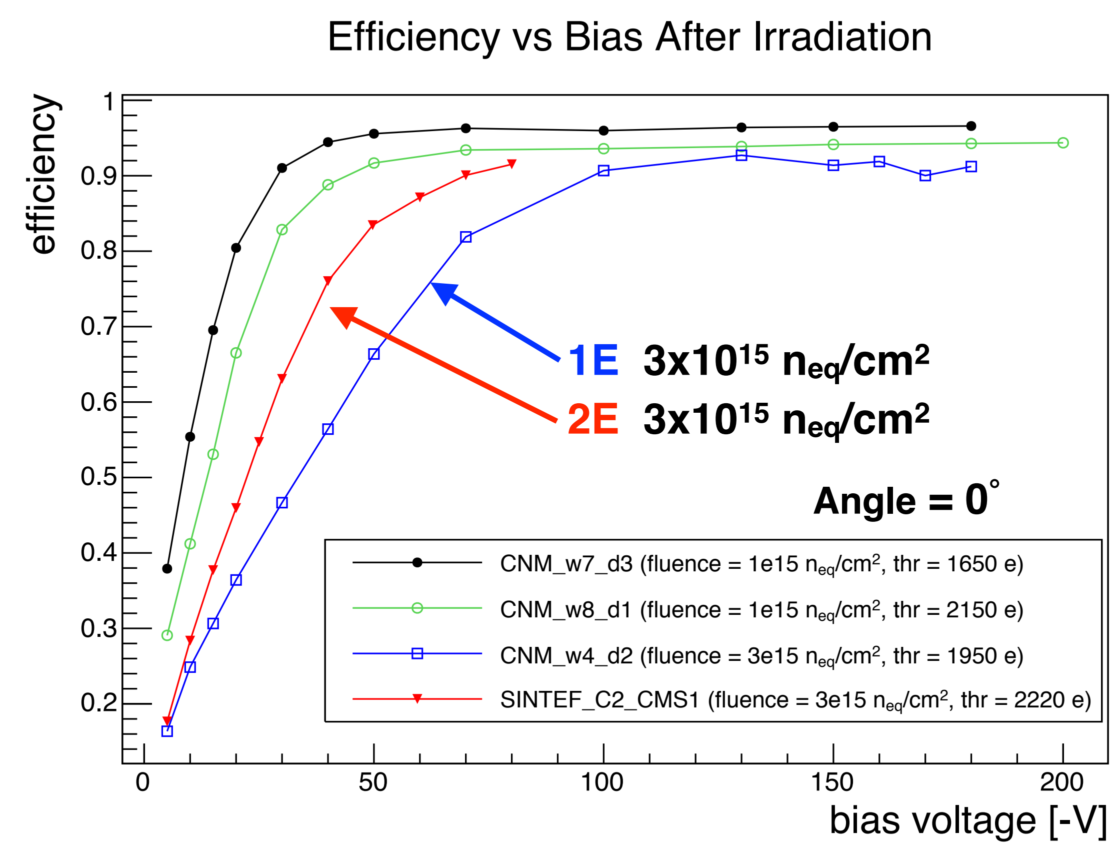
Performances after irradiation

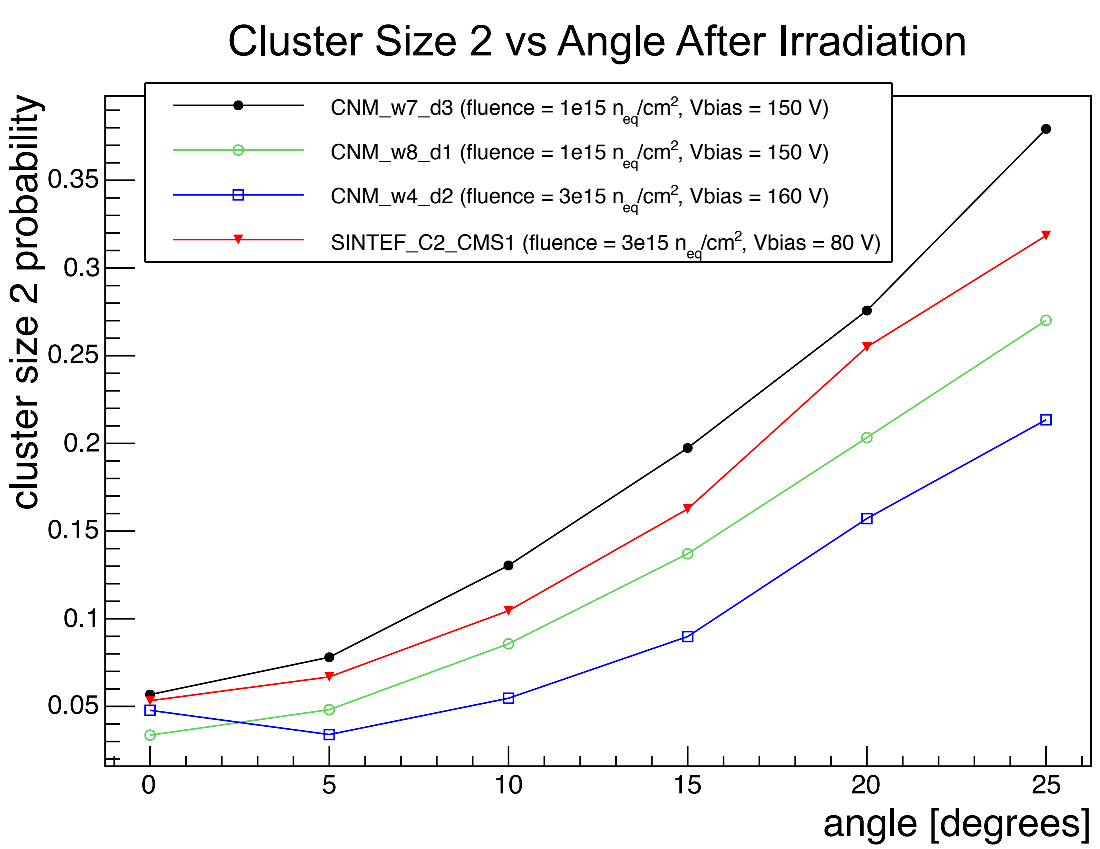
Preliminary

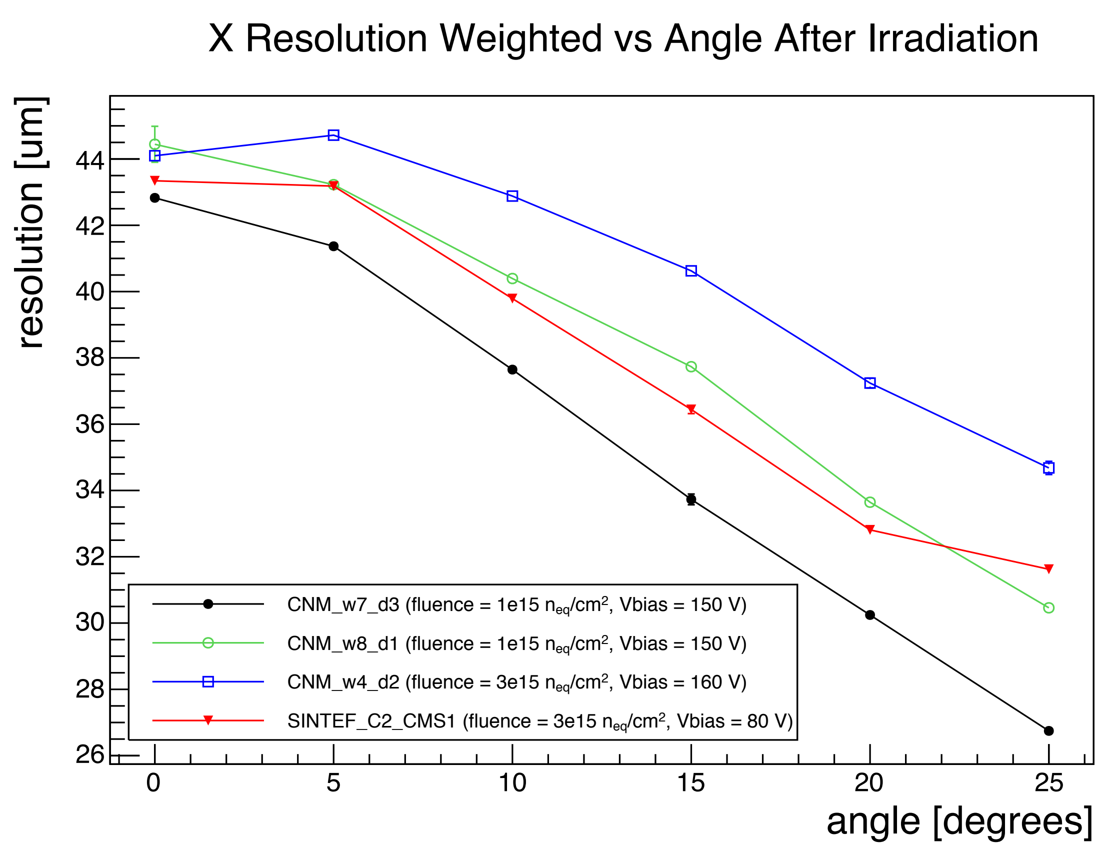
It is foreseen that **the detector will be irradiated during its life up to 5x10^{15} p/cm^2** which corresponds to ~1x10^{15} n$_{eq}$/cm^2.

3 1E CNM + 1 2E SINTEF sensors were irradiated at the CERN IRRAD Proton Facility with 24 GeV protons to fluences of 1x10^{15} and 3x10^{15} n$_{eq}$/cm^2 and tested in a beam at FNAL.

Results show the advantage of the 2E configuration after irradiation.







ξ and t resolution