Detector performance of the **CMS Precision Proton Spectrometer** during LHC Run2 and its upgrades for Run3

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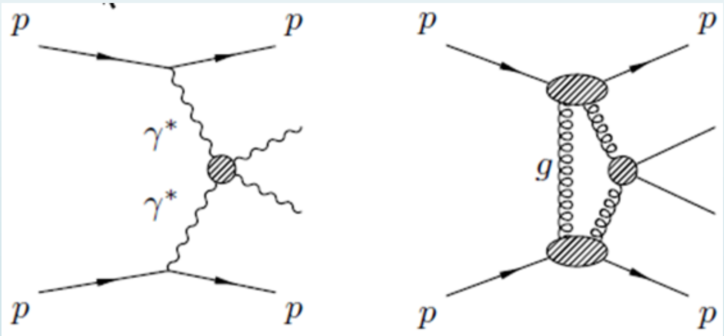
Physics motivations for a Precision Proton Spectrometer at the LHC

The importance of measuring the protons that survive the interaction

- **Central exclusive production** ($J^{PC} = 0^{++}$ central final state)
  - Colour-singlet exchanges with large rapidity gaps between the central system and the outgoing protons
  - Two-photon, photon-pomeron or two-pomeron exchanges at LHC energies allow access to a large variety of processes

- **Electroweak physics:** diboson and dilepton production, anomalous coupling searches
- **QCD:** dijet, trijet, ttbar production
- **BSM direct searches:** new resonances, missing mass, etc.



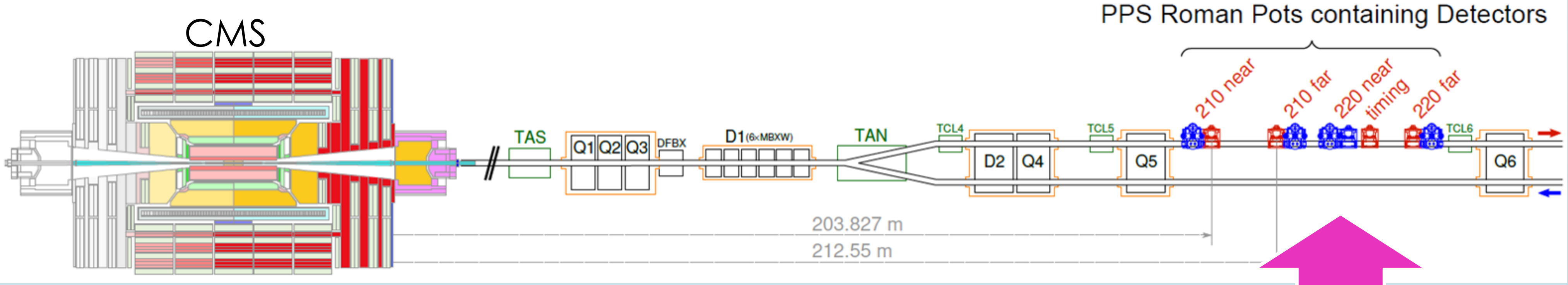
- **Advantages of the forward proton measurement**
  - Strong background suppression by requiring **kinematic match with the central system**
  - Reduced theory uncertainties related to proton dissociation

Experimental requirements

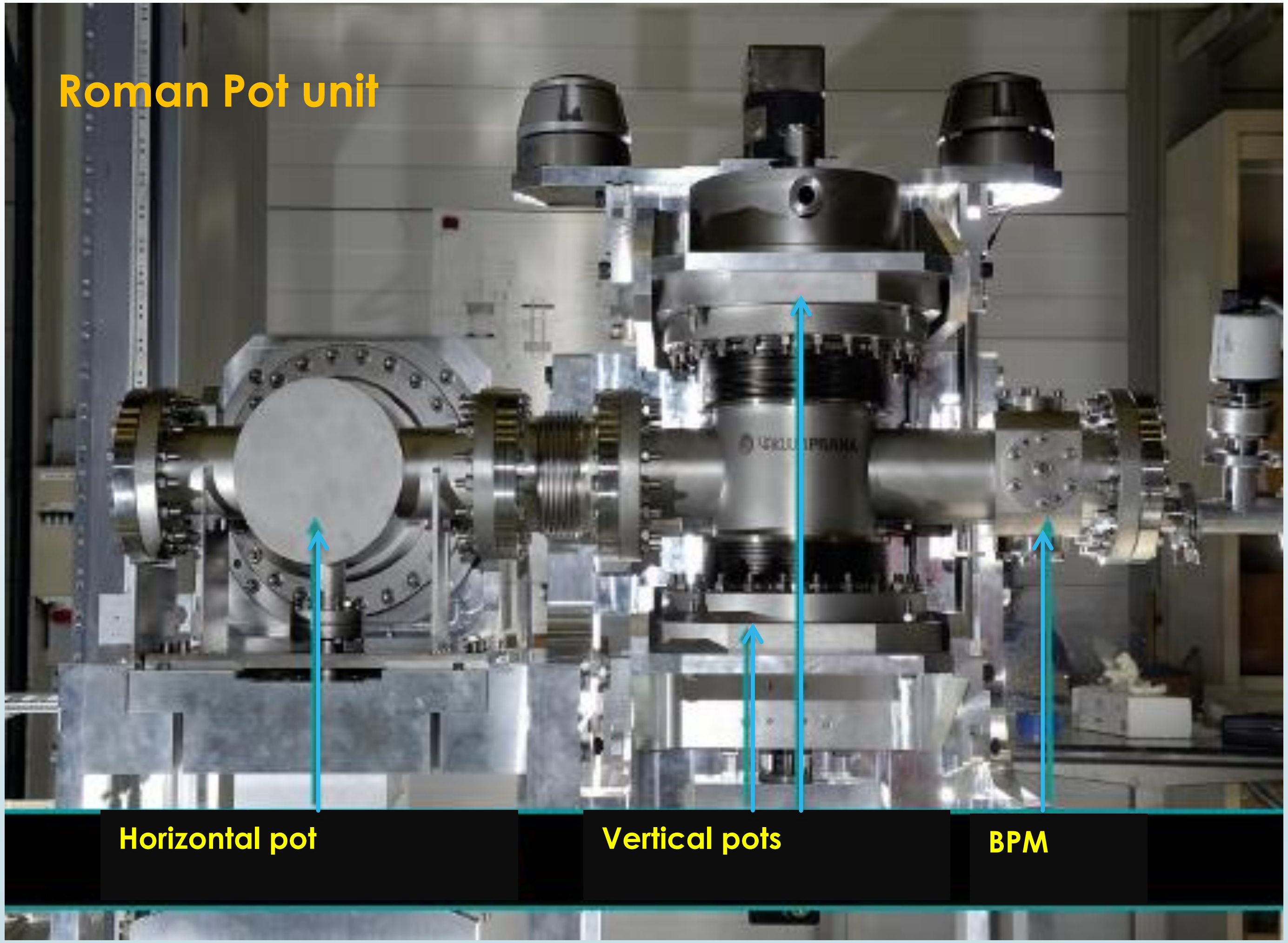
- Operate as close as possible to the beam line (~1.3 mm from the beam axis) without preventing LHC stable operation
- Run detectors in high radiation environment (proton flux up to 5 $10^{15}/cm^2$)
- Cope with high pile-up of standard LHC running (~38 average PU events in Run2)

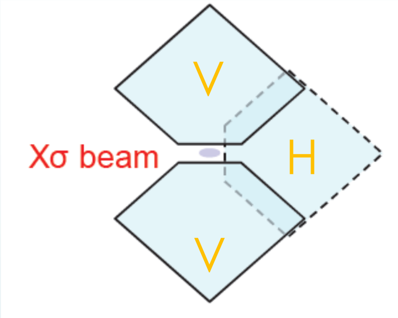
- **Two complementary measurements**
  - **Tracking detectors:** measure the proton displacement with respect to the beam ⇒ **proton momentum loss** via the knowledge of the beam optics
  - **Timing detectors:** measure the proton TOF in both arms w.r.t. a reference clock (for synchronization) ⇒ **longitudinal position of the pp interaction**

LHC magnets bend the protons. Roman Pot insertions in the beam line contain the detectors.

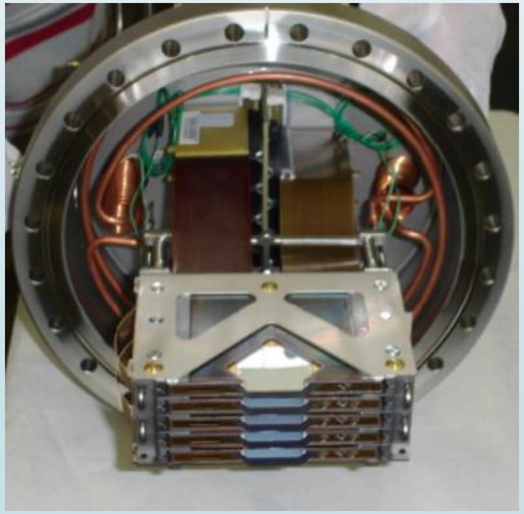


Roman Pot: a key device

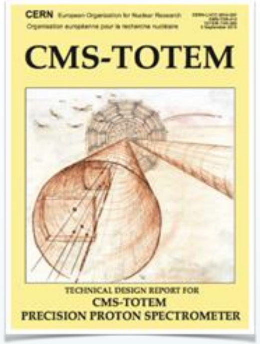




A typical detector package



PPS vs time

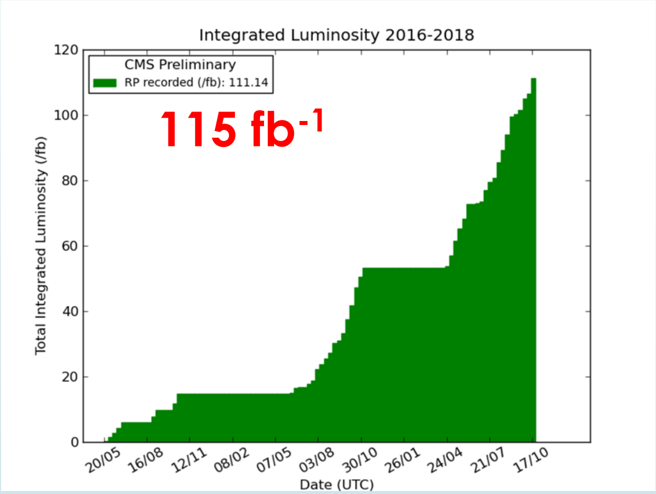


https://cds.cern.ch/record/1753795

Project approval in 2014 as a joint venture of TOTEM and CMS collaborations

Exploratory phase in 2016

Always inserted and taking data, fully integrated in CMS runs, in 2017 and 2018
Very high stability in both 2017 and 2018



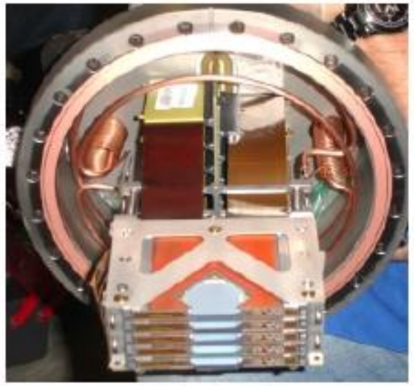
LHC Run2

	Tracking	Timing	Luminosity (wrt CMS)
2016	Si Strips		15 /fb (39%)
2017	Si Strips + 3D Pixels	Diamonds + UFSD	40 /fb (88%)
2018	3D Pixels	Diamonds	60 /fb (93%)

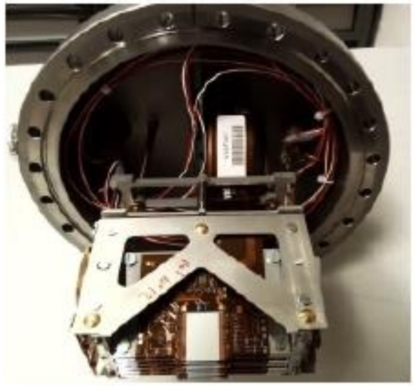
LHC Run3

2021	3D Pixels	Diamonds	…
…	…	…	…

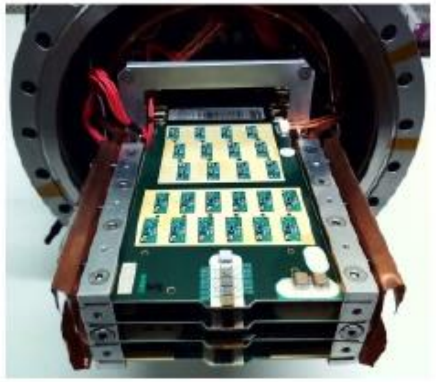
Detectors for Run2



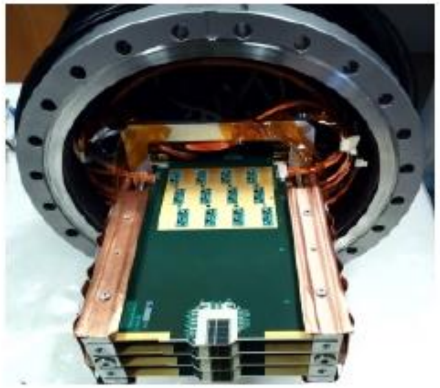
TOTEM si-strips



3D pixels



scCVD (diamond)



Ultra-fast silicon detectors

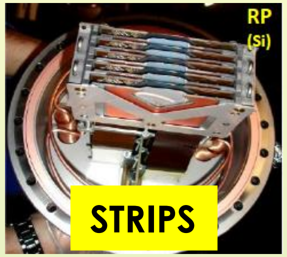
In both arms

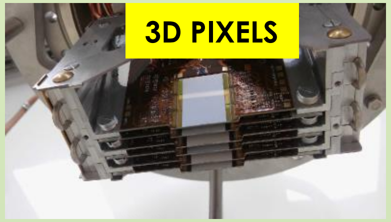
- **2016 Detectors**
  - Tracking: 2 stations of TOTEM **Si-strips** detectors (10 planes), 20 μm resolution. **Limited radiation resistance** ($\Phi_{max} \sim 5 \cdot 10^{14}$p/cm^2), **no multi-track capability**.
  - Timing: **diamond** detectors in cylindrical RP
- **2017 Detectors**
  - Tracking: 1 station of TOTEM **si-strips**, 1 station of silicon **3D pixels** (6 planes with CMS Phase 1 tracker readout chips), $\sigma_x \sim 15\ \mu m$ and $\sigma_y \sim 30\ \mu m$, $\Phi_{max} \sim 5 \cdot 10^{15}$p/cm^2
  - Timing: 1 station with 3 planes of single-layer **diamond** with expected $\delta_t = 80$ ps/plane and 1 plane of **UFSD** with expected $\delta_t = 30$ ps/plane ($\Phi_{max} \sim 10^{14}$p/cm^2)
- **2018 Detectors**
  - Tracking: two **3D pixels** stations
  - Timing: 1 station of **diamond** detectors (2 single-layer + 2 double-layer)

2017-2018 detector configuration

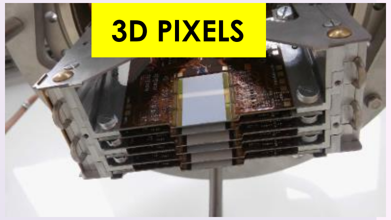
2017: an intermediate step towards design setup
2018: design setup

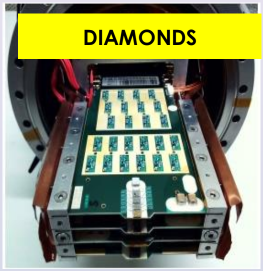
2017

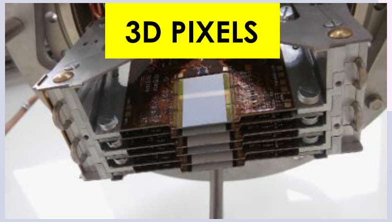


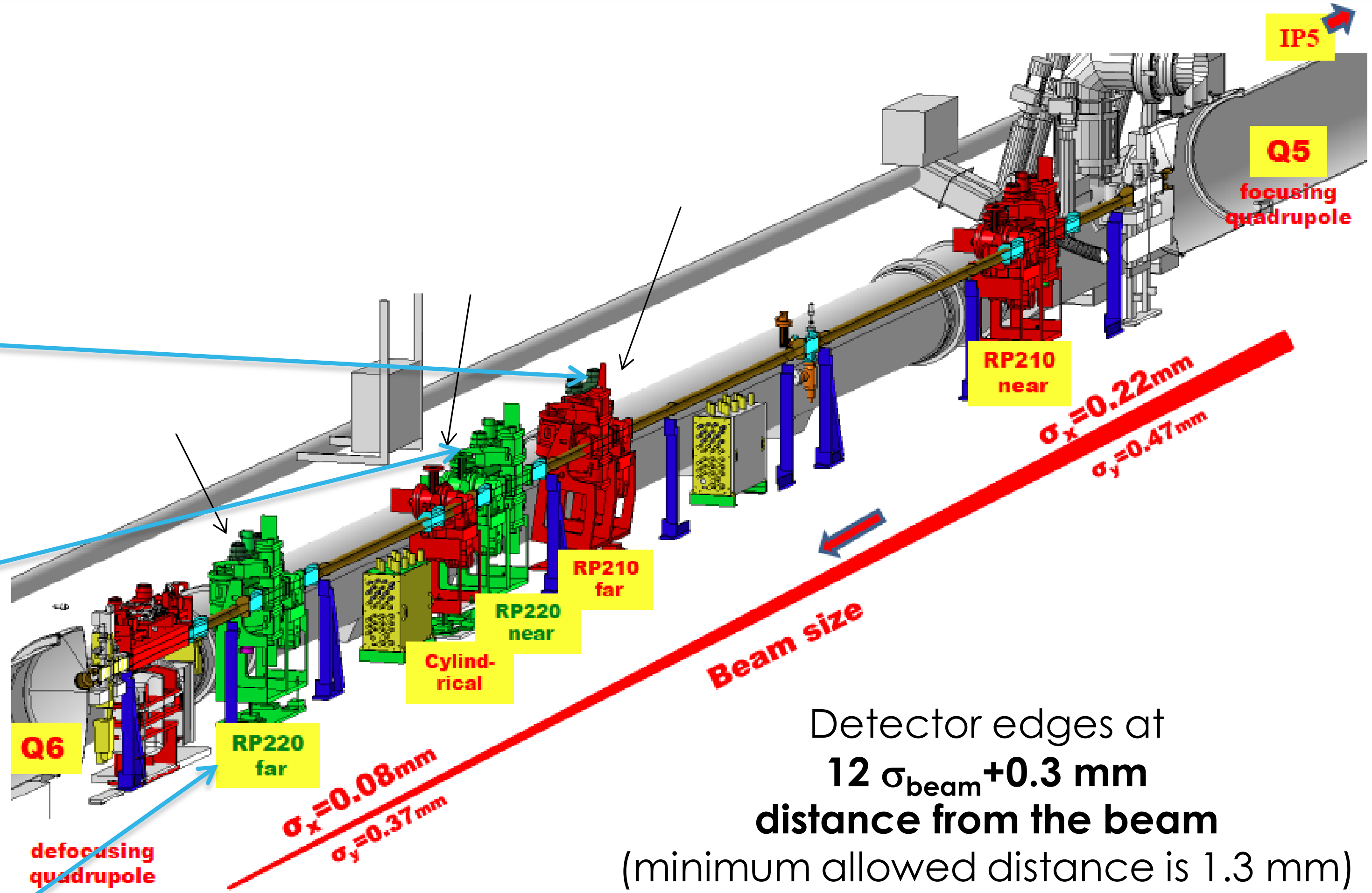


2018



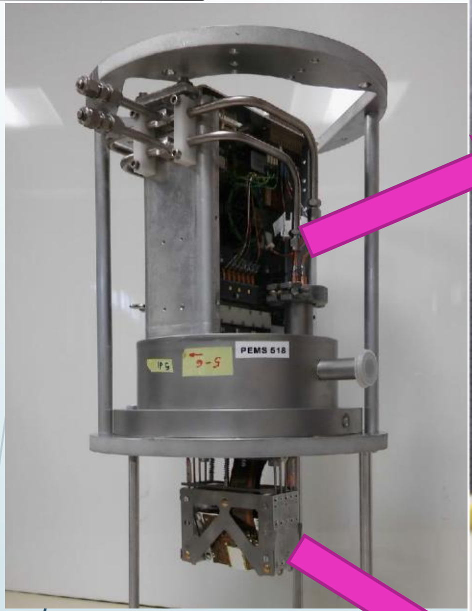


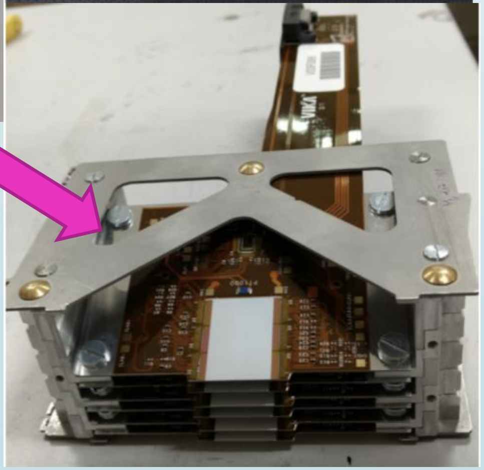




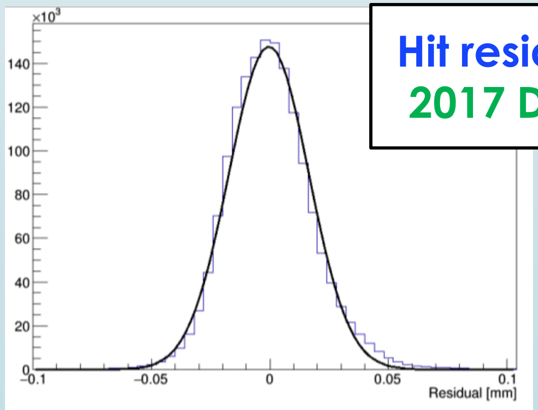
Detector edges at
12 σ_{beam}+0.3 mm
distance from the beam
(minimum allowed distance is 1.3 mm)

3D pixels





- ✓ **6 planes of 3D pixel silicon detectors per Pot**
- ✓ Sensors read out with 4 or 6 **PSI46dig ROCs**, depending on the sensor size
- ✓ Data collected and serialized by a TBM (token bit manager)
- ✓ Modules wire-bonded to a flex hybrid connected to the RPix portcard (interface between modules and FE electronics)
- ✓ Same front-end boards for data (FED) and control (FEC) as Phase I CMS pixel tracker
- ✓ Pixel dimension 150x100 μm



σ_x = 17 μm

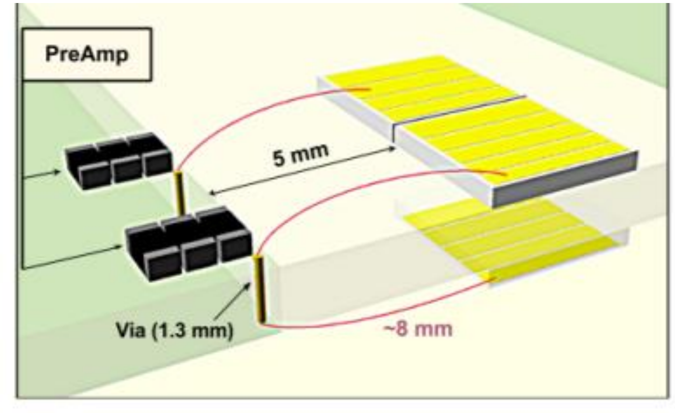
Double diamonds for timing

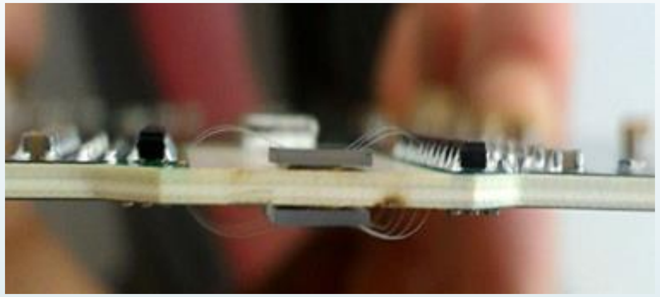
single-crystal CVD (Chemical Vapor Deposition) diamond detector

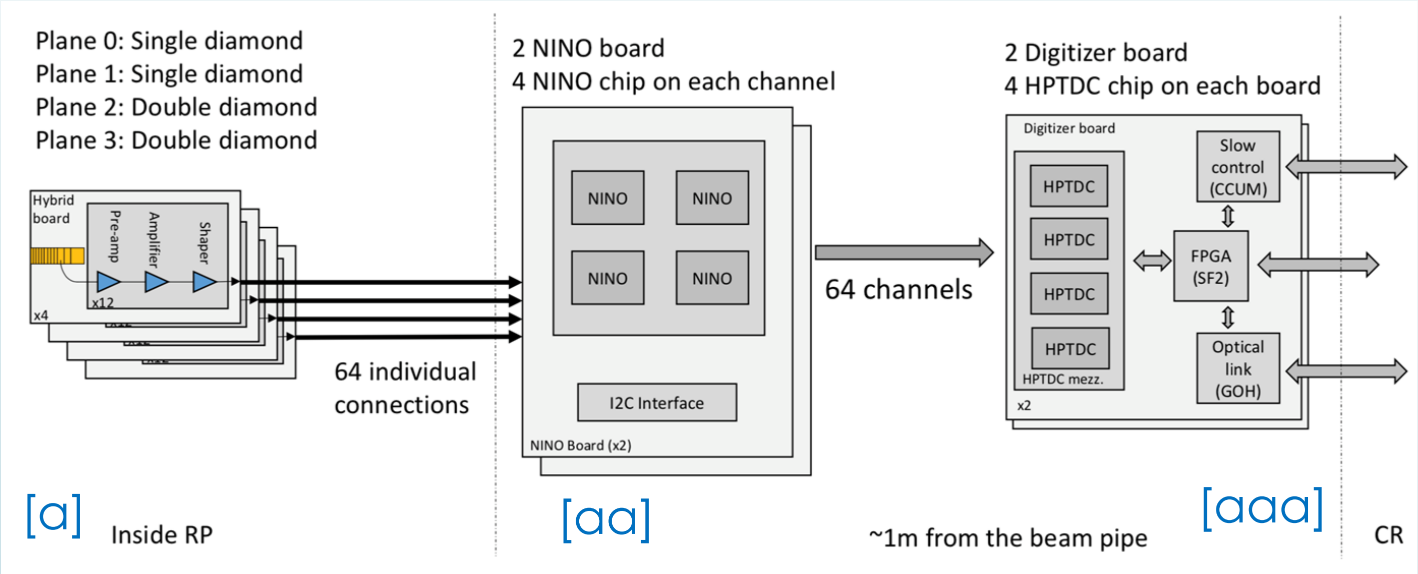
Two scCVD sensors installed back to back and connected in parallel to the same amplifier channel

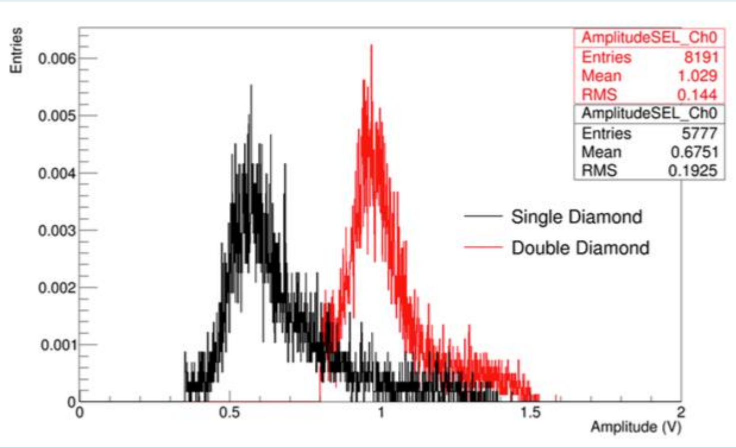
Sensor time resolution: ~50 ps per plane (measured in test beam)

Digitization stage (NINO+HPTDC) degrades resolution by 30% (low sensor S/N). Optimization work ongoing.







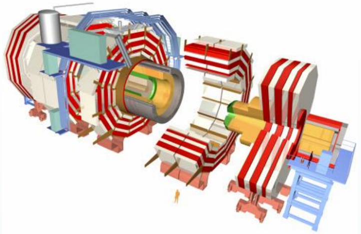


Signal almost doubled wrt single diamond

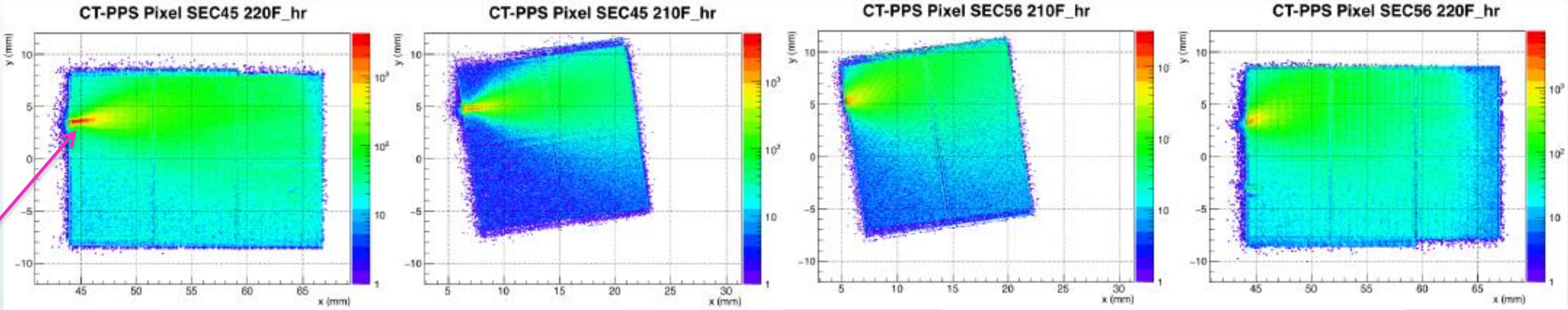
[a] TOTEM Coll., JINST 12 (2017) P03007
[aa] F. Anghinolfi et al., NIM A 533 (204) 183
[aaa] M. Mota and J. Christiansen, IEEE JSSC 34 (1999) 1360

2018 data: hit maps

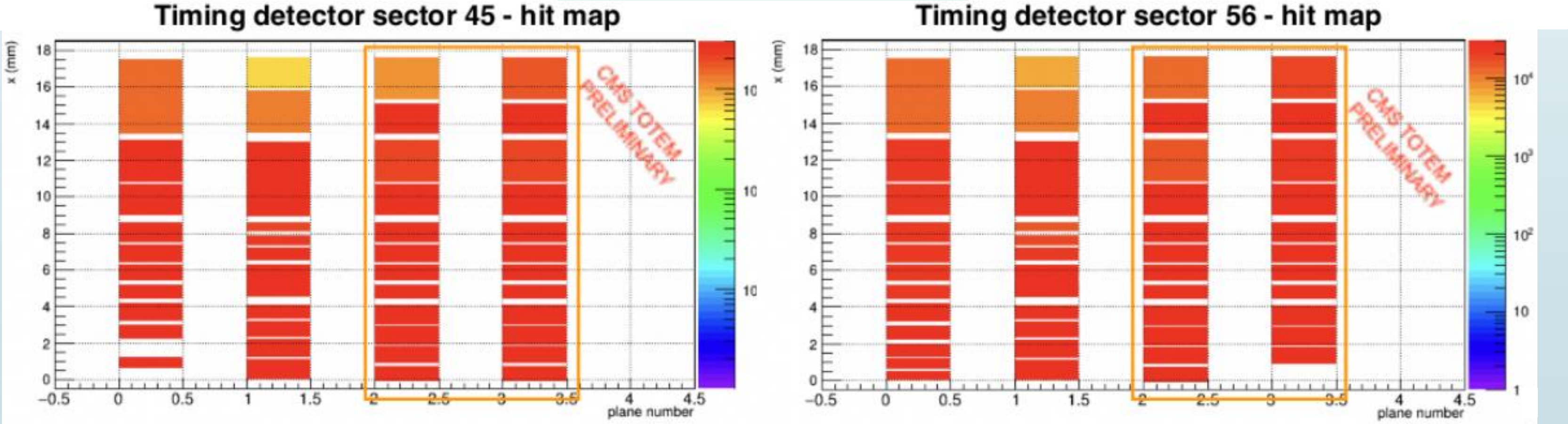
LHC Sector 45 ←



→ LHC Sector 56



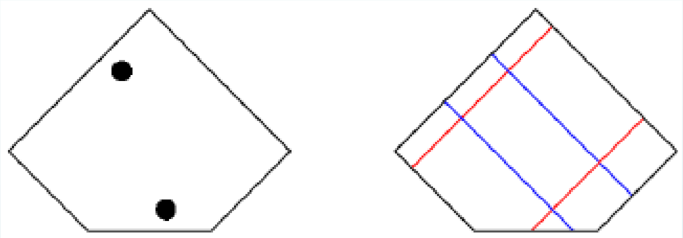
Remarkably non uniform signal distribution

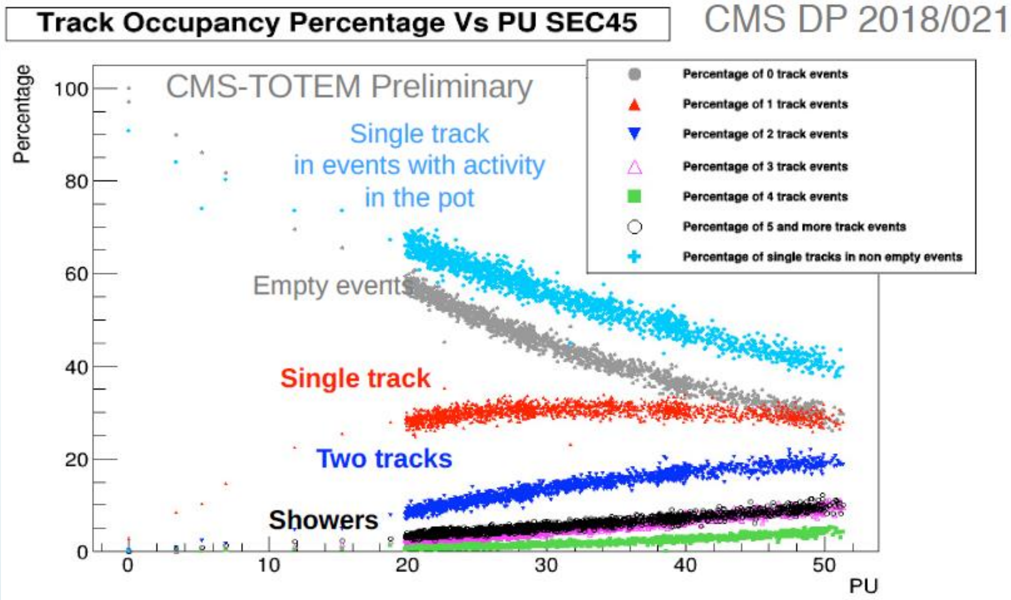


- Less than 0.05% bad or noisy pixels

Tracking efficiency studies

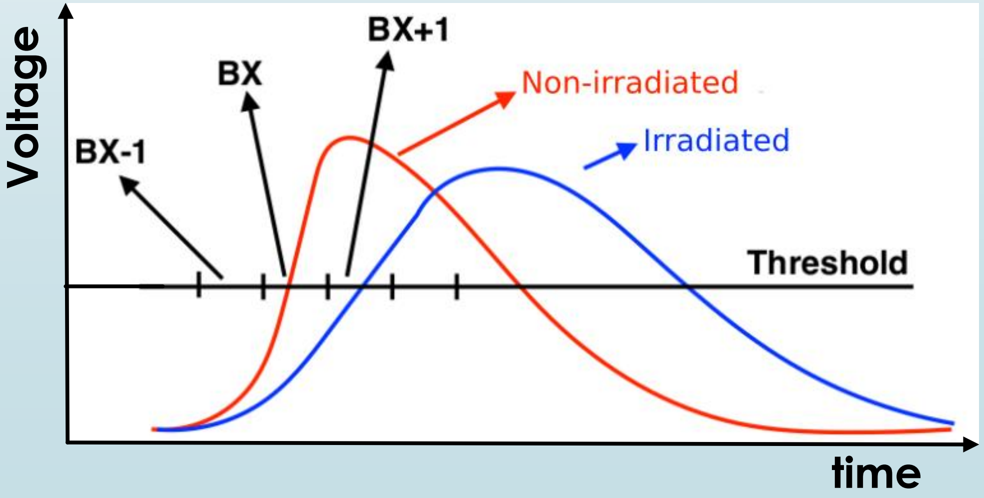
- **Main strips inefficiency due to no multi-tracking:**
  - **30% efficiency at pileup of 50**
  - **Solution: pixel detectors**





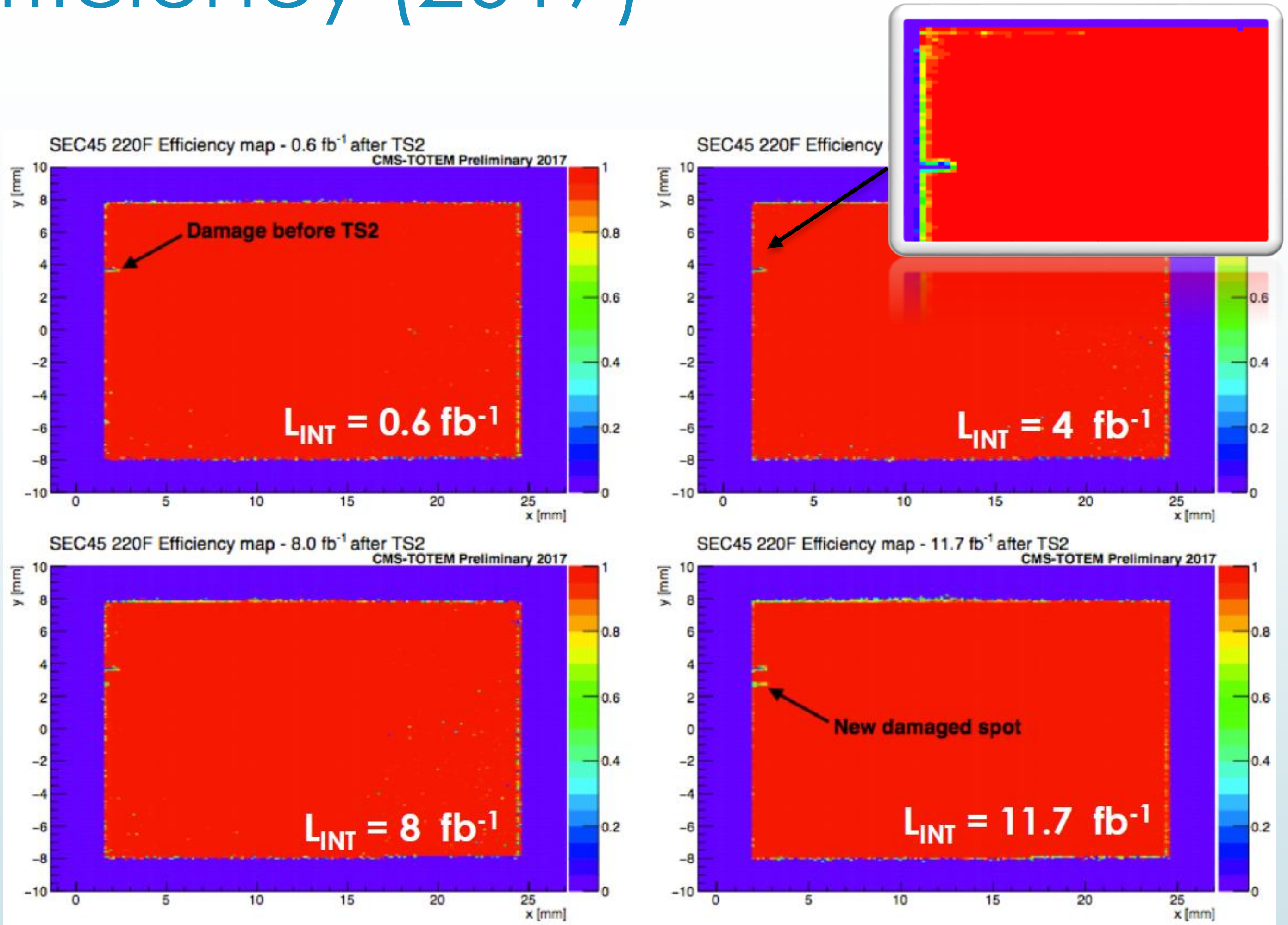
- **Radiation damage effects on the sensors reduced when moving to pixels:**
  - However, **non-uniform irradiation** affects the PSI46dig readout chip performance
  - Efficiency loss mitigated by **moving the stations** vertically during technical stops

Different response time in pixels with different irradiation



Pixel detector efficiency (2017)

- **Efficiency computed with tracks reconstructed within the same station**
  - Evolution of the radiation damage vs. integrated luminosity after LHC second Technical Stop (~18 fb^{-1} taken before TS2)
  - Inefficiency spot caused by radiation damage is moved away from the high-occupancy region when the station is lifted
  - The radiation effect starts to be visible at ~8 fb^{-1}

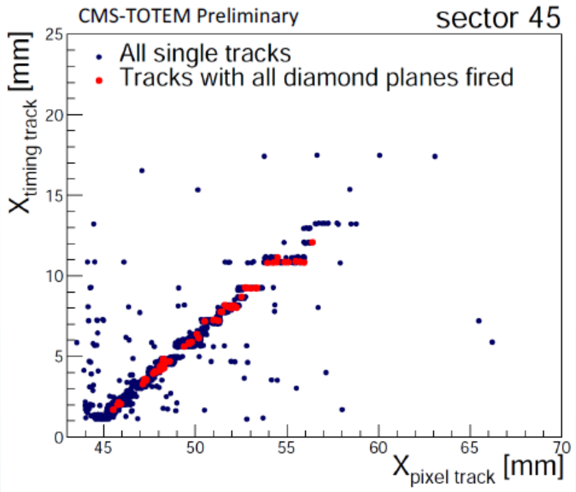


- **Very high performance overall: average efficiency ~98%**
  - Few damaged pixels: ~1.5×0.3 mm^2, caused by non-uniform irradiation of the readout chip

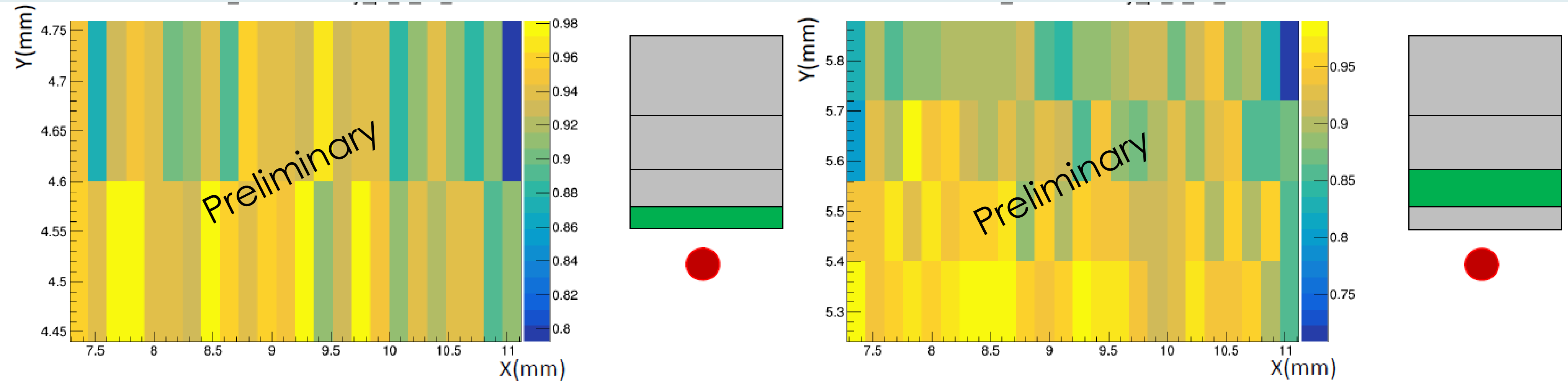
Timing perfomance

- Run 2 data being reprocessed with optimized calibration. Complete results on performance will be available soon.
- **σ_t ~ 50 ps** time resolution measured per plane in test beams per plane of double diamond detector (to be confirmed by analysis from Run 2, w.i.p.)
- First estimation of double-diamond sensor **efficiency** in after 2018 runs is still **> 94 %**

Diamond and pixel track correlation



Double Diamond efficiency on test beams (2019)

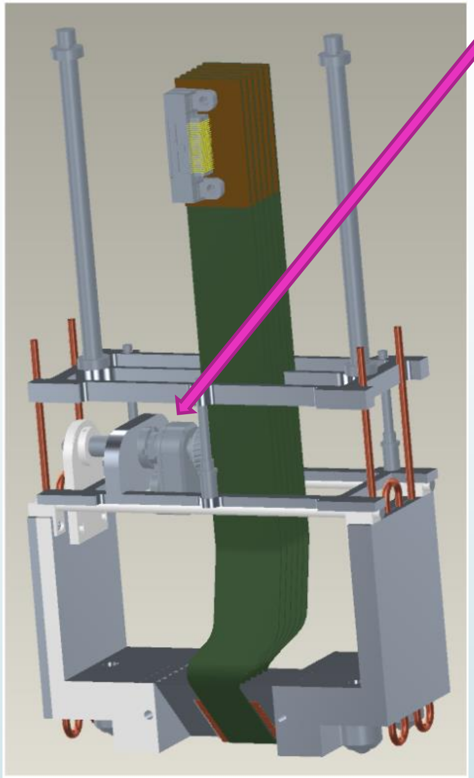


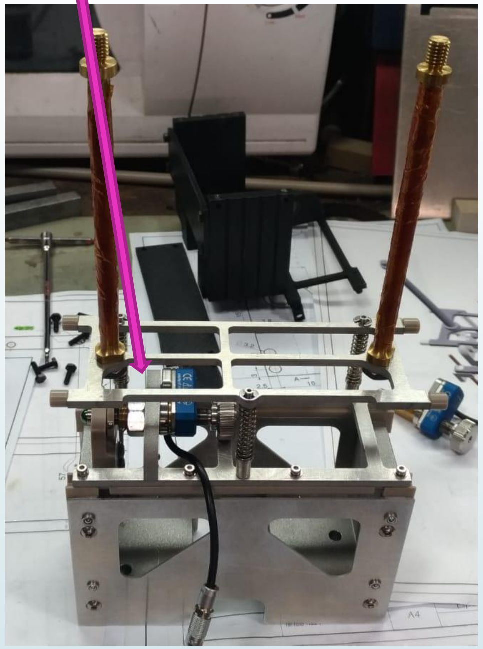
LHC Run 3 (2021-23) preparation

- Tracking:
  - 2 horizontal pots with silicon **3D pixels sensors** (sensor technology slightly different wrt Run2)
  - **PROC600 readout chip** instead of PSI46dig (same as CMS pixel detector layer 1)
  - **New internally motorized detector package**, to distribute the radiation damage and reduce its impact

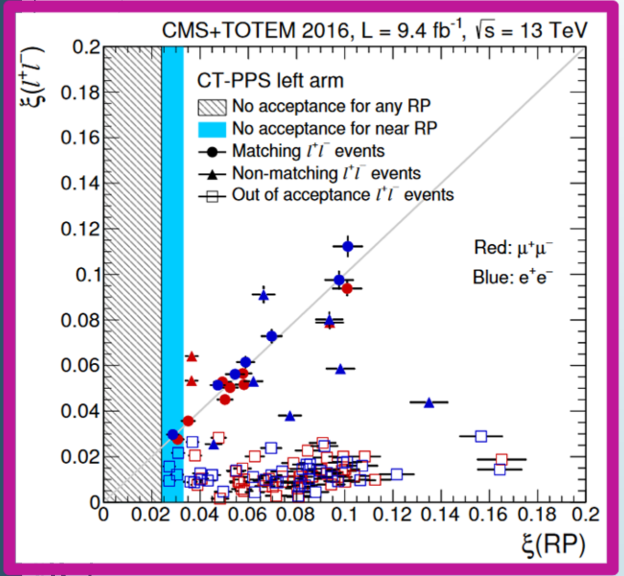
- Timing:
  - 2 horizontal pots (instead of 1) equipped with **double-layer diamond** sensors
  - Optimized readout electronics

Piezoelectric motor





Conclusions



- PPS has proven the feasibility of continuously operating a near-beam proton spectrometer at a high-luminosity hadron collider
- **PPS has successfully collected ~115 fb^{-1} of data** during LHC Run 2, with very good overall performance
- **CMS is publishing physics papers with data collected by PPS**
  - first paper https://link.springer.com/article/10.1007%2FJHEP07%282018%29153
- 2017 and 2018 detector performance studies are being finalized

- **The preparation for LHC Run 3 is ongoing**:
  - **New detectors are getting ready** to be installed for the future data taking
  - A **rich physics programme** lies ahead, with many final states to be studied