The CMS Precision Proton Spectrometer timing system: performance in Run 2, future upgrades and sensor radiation hardness studies.

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CERN

(on behalf of the CMS and TOTEM collaborations)

15th Topical Seminar on Innovative Particle and Radiation Detectors

OUTLINE:

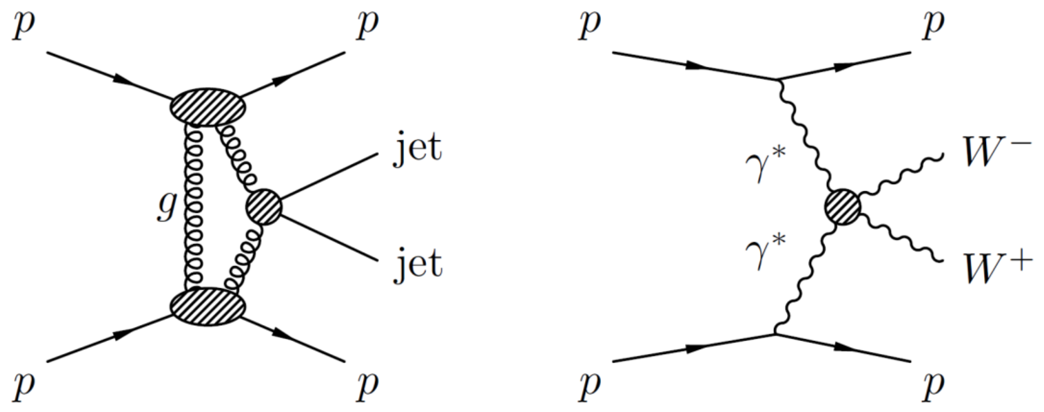
- PPS project overview
- Detector description
- Run 2 performance
- Test beam results
- Run 3 perspectives

Physics motivation

The PPS detector (previously CT-PPS, CMS-TOTEM Precision Proton Spectrometer) extends the physics program of CMS to Central Exclusive Production (CEP) processes, where both protons remain intact after the interaction.

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

- Photon or gluon exchanges
- Protons measured by PPS
- $\oplus$ rapidity gap
- X = High E_T jets, WW, ZZ, $\gamma\gamma$, …
- X measured in central detector



Examples of CEP process from PPS TDR [CERN-LHCC-2014-021]

First physics results published in JHEP 1807 (2018) 153

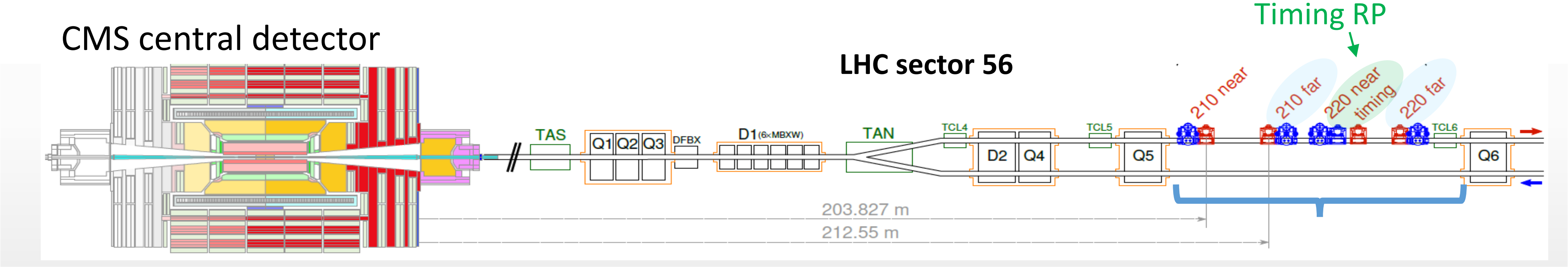
PPS can perform measurement of the proton kinematics.

Reconstruction of mass and momentum of the central system X can be carried out from the proton information ($M_X = M_{PP} \sim \sqrt{\xi_1 \xi_2 s}$, where ξ is the proton fractional momentum loss) and compared with the central CMS measurements for strong background rejection.

PPS detector

Symmetric experimental setup w.r.t. the interaction point

LHC sector 45



ROMAN POTs

Sensors in Run 2

Timing

2016: 4 single diamond planes(SD)

2017: 3 single diamond and
1 UFSD planes

2018: <u>2 single and 2 double (DD) diamond planes</u>

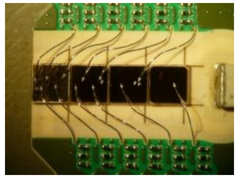
Tracking

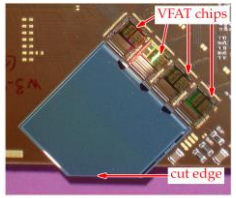
2016: 2 TOTEM strip detector stations

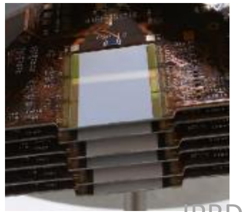
2017: 1 strip and 1 3D pixel stations

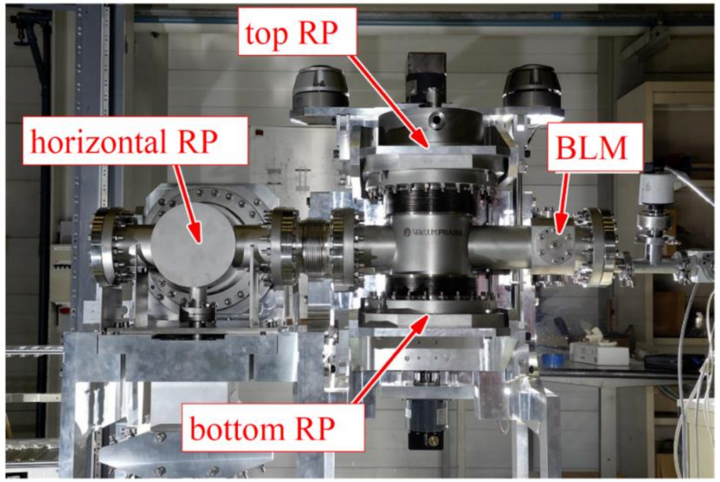
2018: 2 3D pixel stations

M.M.Obertino's talk on Monday









RP: Vacuum vessel entering the beam pipe, can be equipped with many types of detectors. Hosted detectors brought to few mm from LHC beam center.

Timing detectors

Average number of interactions per bunch crossing $\langle\mu\rangle$ in 2018 is ~35.
Beam longitudinal dimension $\sigma_z\sim7.5$ cm.
Tracking system cannot reconstruct the primary vertex of detected protons.

Solution: measure the proton time of flight in the two sectors:

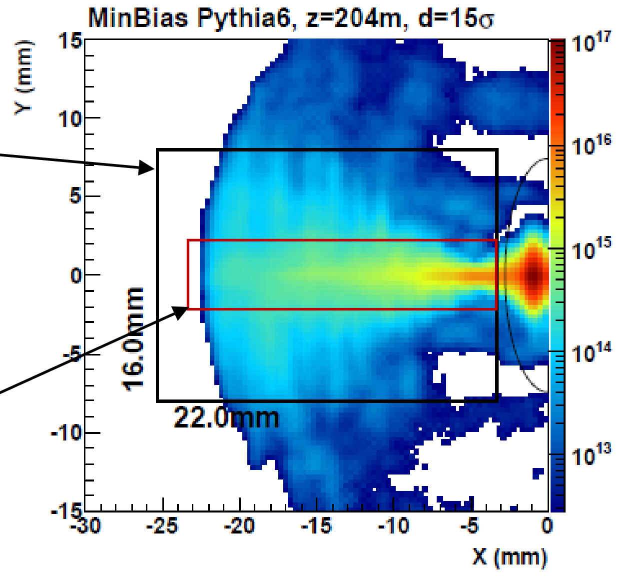
- $Z_{PP} = c\Delta t/2$
- Pile-up background reduction

<u>Detector requirements</u>:

- <u>Station</u> resolution of 10-30 ps is the final goal.
- High efficiency for MIP detection
- High radiation hardness (up to $\sim5\cdot10^{15}$ p/cm^2 for 100 fb^{-1}, highly non uniform)
- Low density/thickness detector (to fit more planes inside a RP and reduce material budget)
- Segmentation needed to avoid double hit on same pad
- Detector must operate in a vacuum

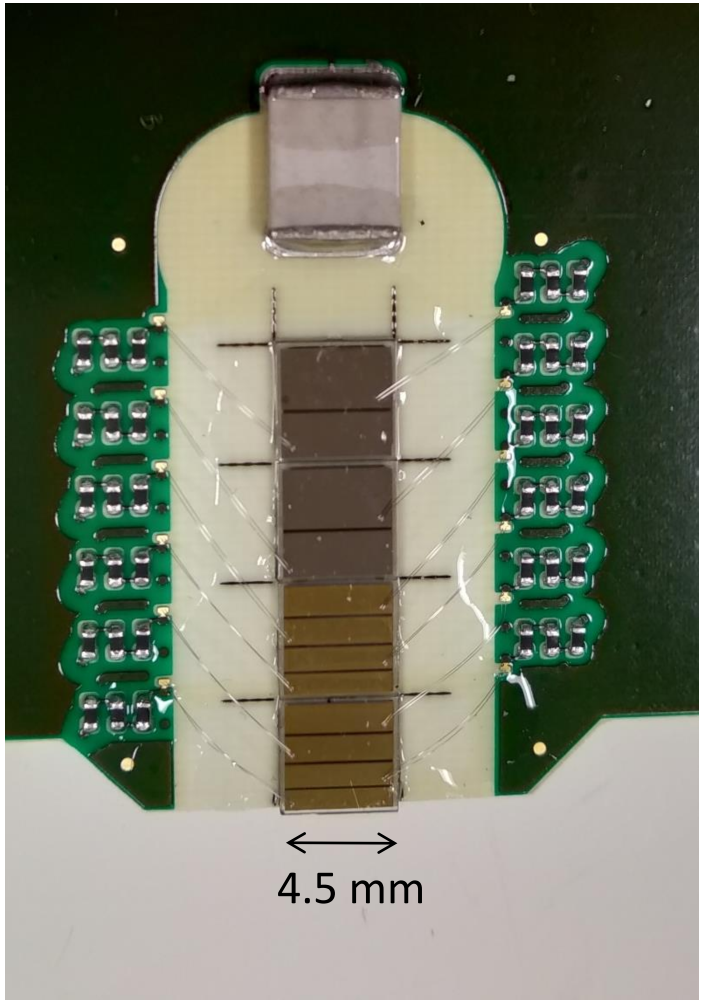
Area covered by tracking station

Area covered by timing station



Simulated particle flux for 100 fb^{-1} (full Run2)

PPS diamond sensors



Sensor based on ultra pure single crystal CVD diamonds. Each crystal has a dimensions 4.5x4.5x0.5 mm^3 , total area coverage ~ 80 mm^2.

Detector segmentation, optimized to reduce number of channels while keeping double hit probability low, is carried out in the metallization phase.
Metallization performed by GSI (Cr 50 nm + Au 150 nm) and Princeton University (100 nm TiW).

Pads are directly connected to pre-amplifier input to reduce input capacitance (~0.2 pF with 0.25 μm bonding wire diameter).

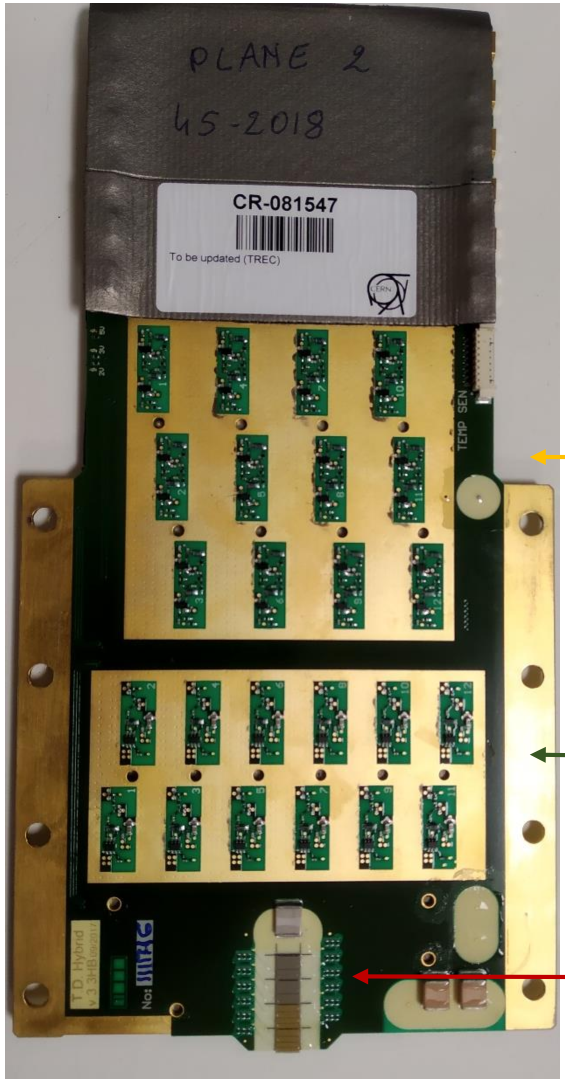
Coating is applied to sensitive areas to reduce HV discharges in vacuum (nominal HV ≥ 500 V)

Diamond hybrid board

4 crystals (8 in DD configuration) are mounted on custom hybrid board

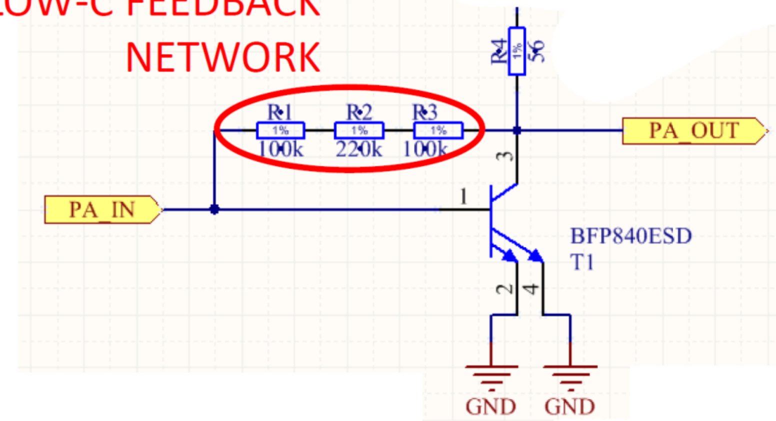
12 discrete amplification channels on each hybrid board, designed and optimized for diamond signals [**JINST 12 (2017) no.03, P03007**]:

- Fast intrinsic rise time (few ps)
- Very low noise (<nA) → Noise dominated by pre-amp input stage
- Low signal ~ 1 fC/MIP



<u>Shaper</u>:
2xBFG425 Si BJT matched amplifier for shaping the signal

<u>Amplifier</u>:
Monolithic microwave integrated circuit ABA-53563, near linear phase, absolute stable amplifier



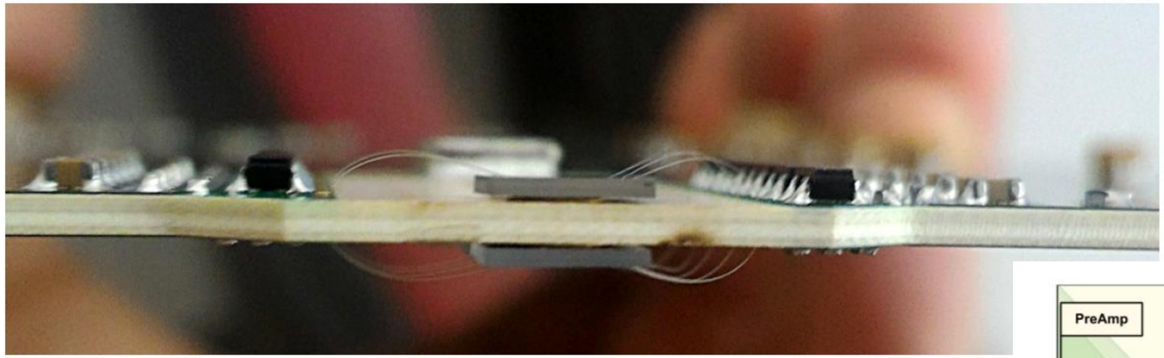
<u>Pre-Amplifier</u>:
stage BFP840 SiGe BJT with low-C feedback

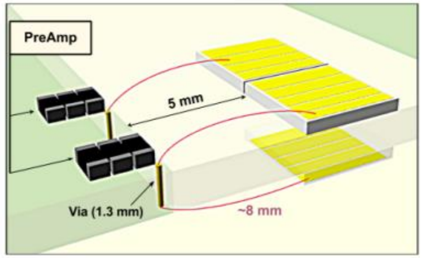
ABA-53563 (obsolete) will be replaced with GALI-39+ chip for run 3

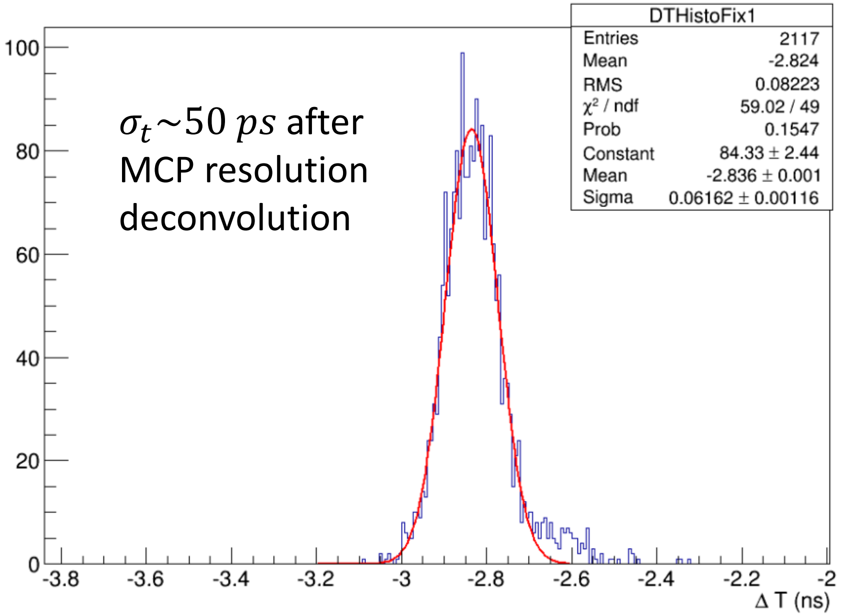
Double diamond performance

JINST 12 (2017) no.03, P03026

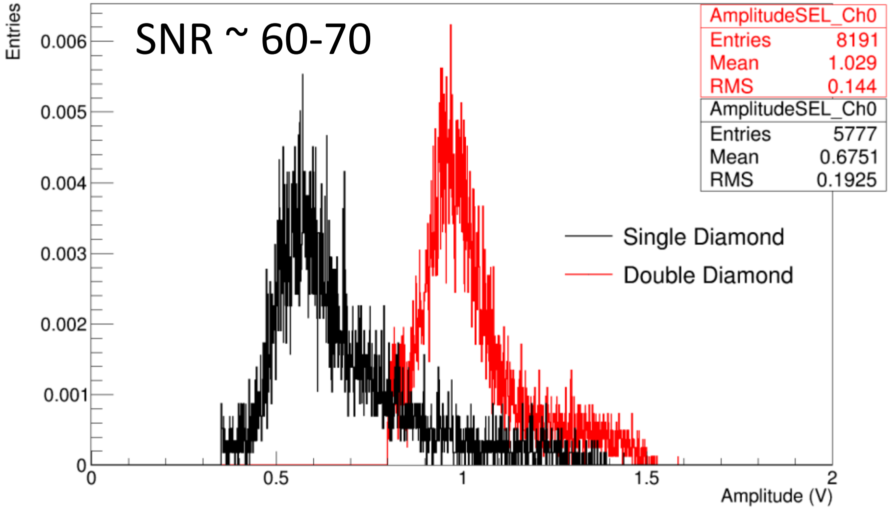
Sensor readout performed with oscilloscope. Actual sensor technology limit.







Time difference distribution between DD and reference MCP ($\sigma_{t,MCP} \sim 40\ ps$)



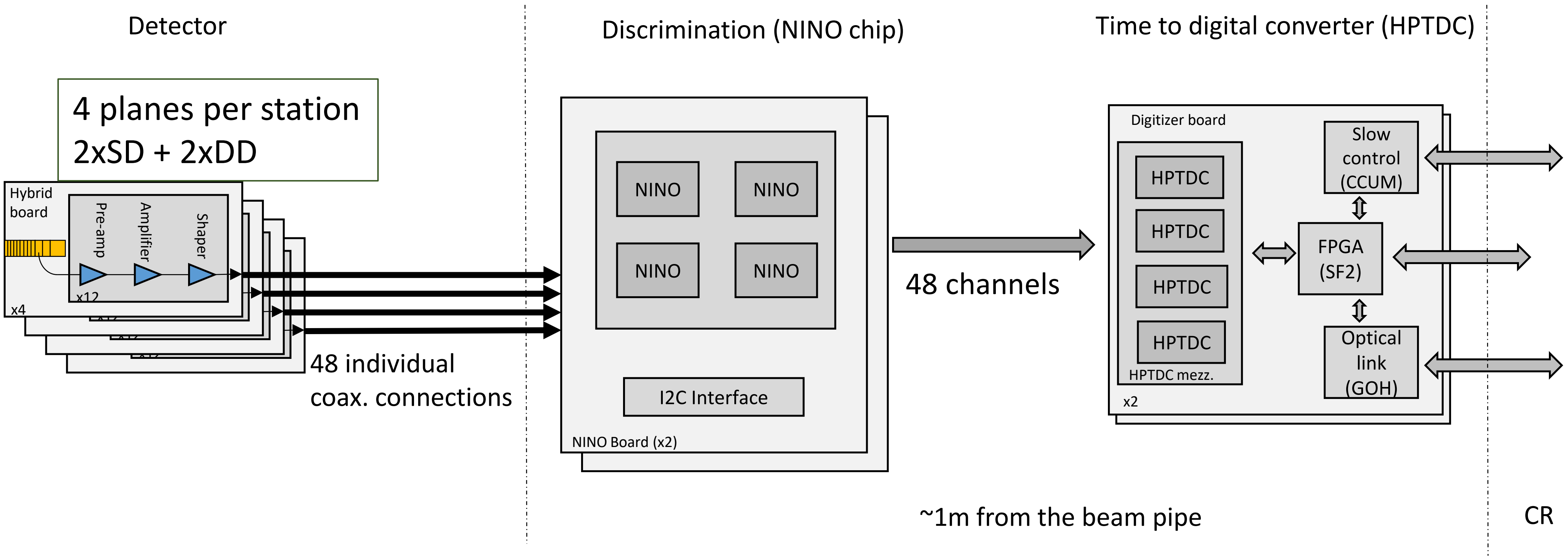
Signal amplitude comparison between DD and SD

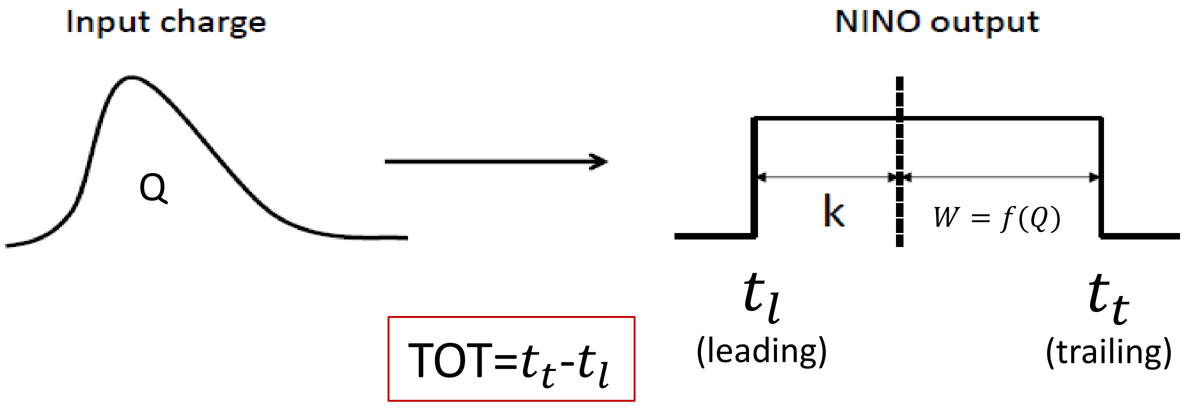
Signal from corresponding pads is connected to the same amplification channel:

- Higher signal amplitude
- Same noise (pre-amp dominated) and rise time (defined by shaper)
- Higher sensor capacitance
- Need a very precise alignment

Better time resolution (factor ~1.7) w.r.t SD

Run 2 layout





In Run 2 discrimination stage degraded timing performance by 30% (after time walk correction).

Optimization ongoing for Run 3

Operation and calibration

Timing system installed in late 2016.

PPS integrated luminosity in LHC-Run 2 (with timing): $\sim$100 fb^{-1}

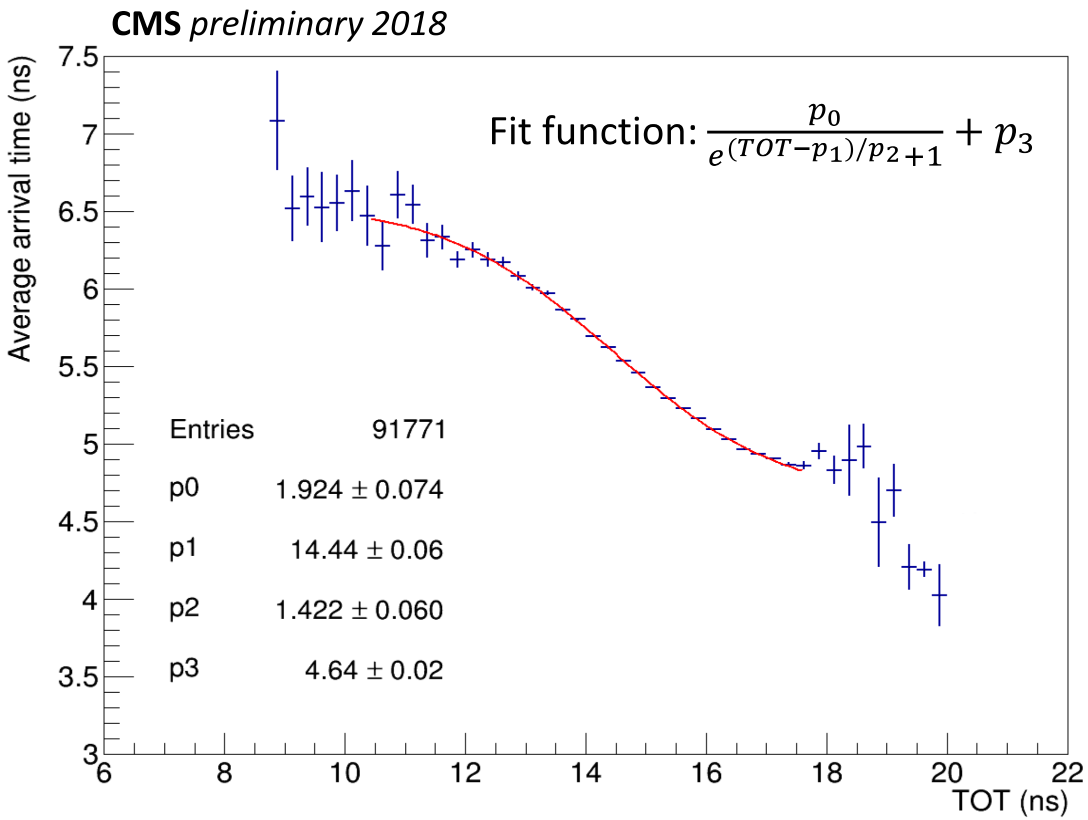
Run2 timing issues:

- RF noise pickup inside RP -> reduced LV
- Beam induced HV discharges -> reduced HV (350-400 V)
- Discrimination stage not fully optimized

Work ongoing for Run3.

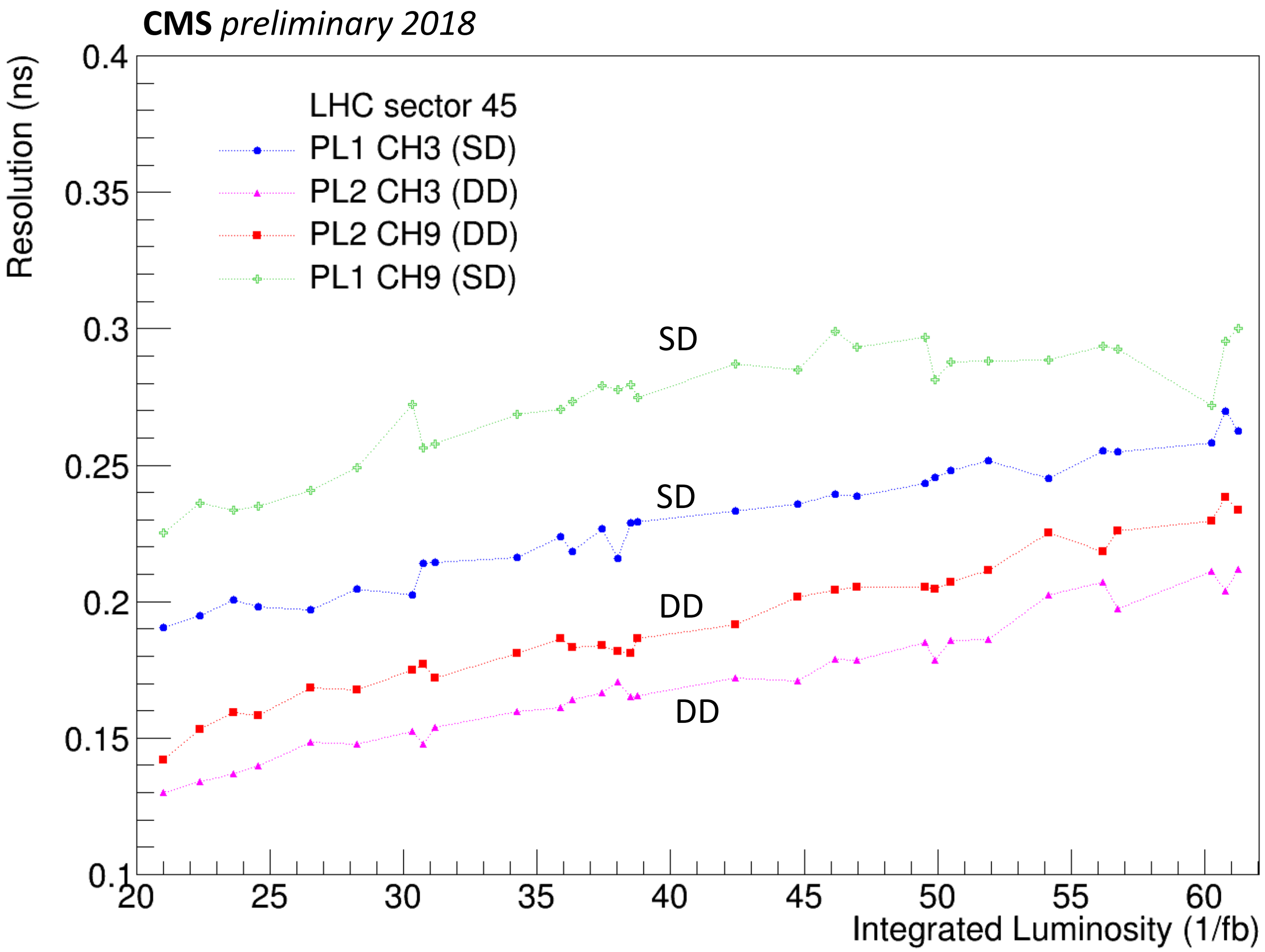
System calibration performed in 2 steps:

1. Correction and alignment of measured arrival time w.r.t. signal TOT (each channel treated independently)



2. Iterative procedure to compute resolution of each pad.

Resolution vs integrated Luminosity in Run2



Comparison of the resolution in two planes vs integrated luminosity in Run2. Calibration data available only after TS1.

Two types of degradation identified:

1. General resolution loss in the range 20-50%: radiation damage on sensor and electronics close to the beam (pre-amplification stage).

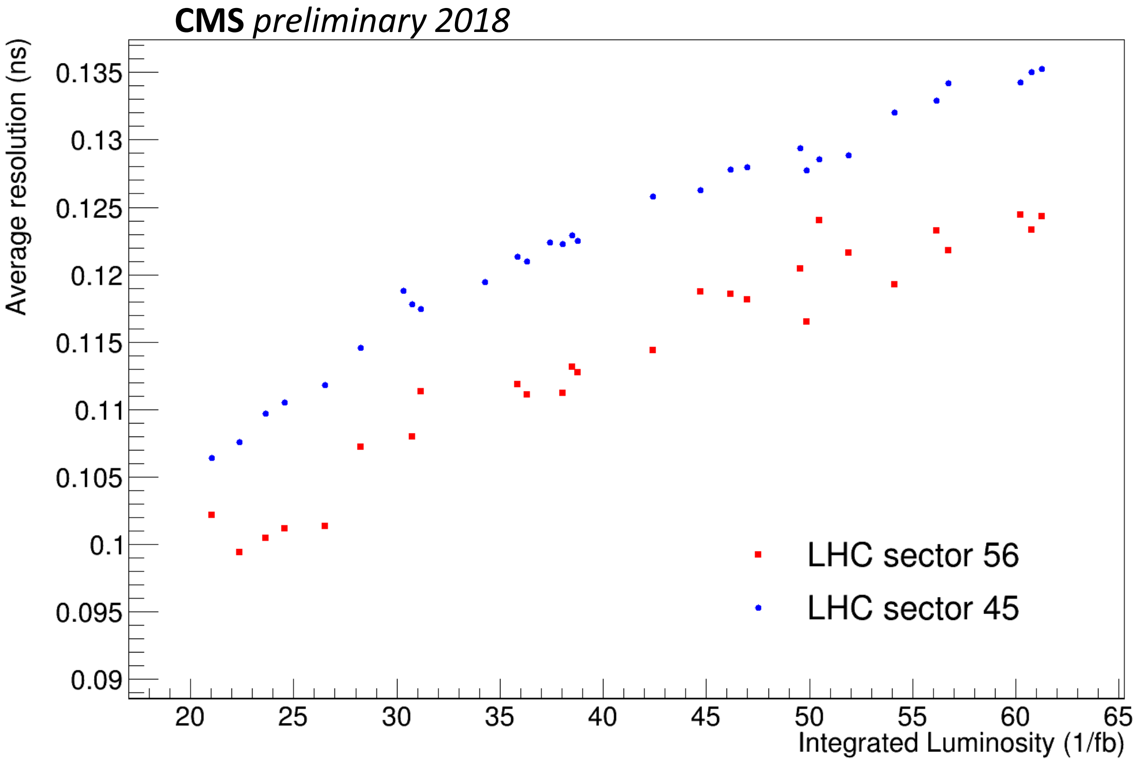
2. Localized damage on the sensor in the most irradiated area ($\sim 1\ \mathrm{mm}^2$). Damage could be due to creation of trapping centers in the bulk or at the metallization interface.

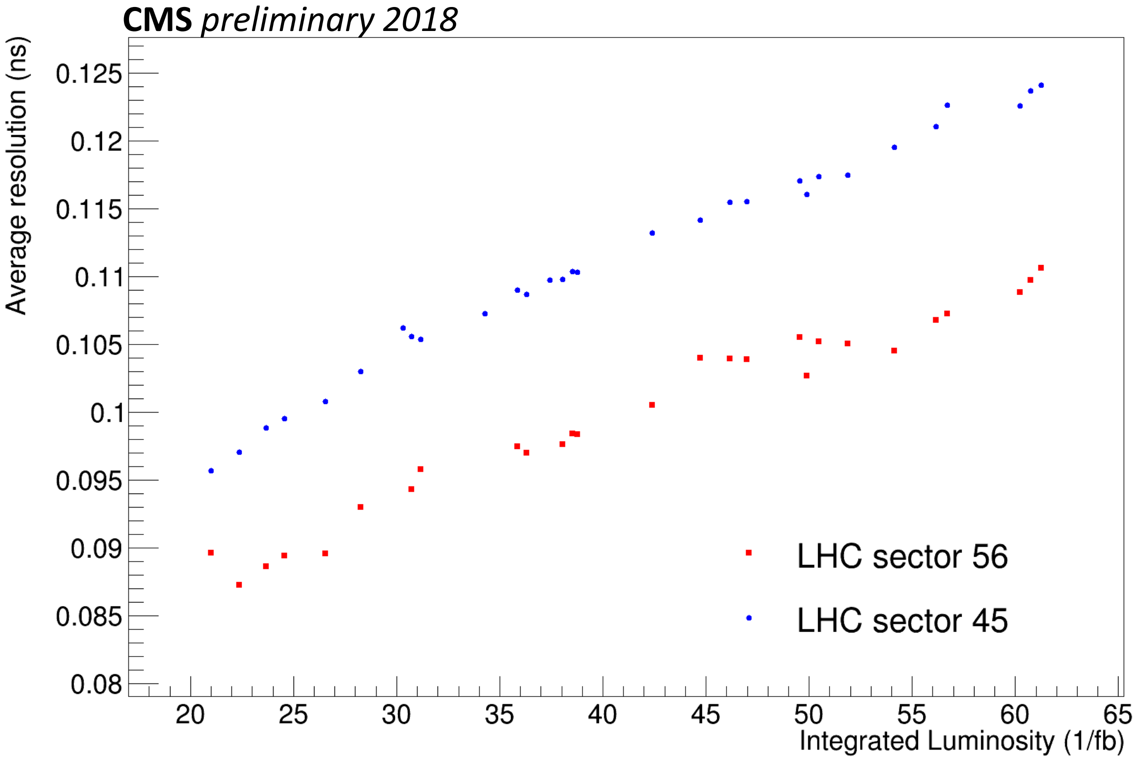
In Run 3 performance can be recovered raising the LV of the pre-amplification stage (LV remote control not implemented for Run 2).

Resolution in double diamond detectors factor 1.7 better, as expected.

2018 proton timing resolution

Once all channel resolutions are known it is possible to assign a time precision to each timing track.
This is a measure of the full station resolution (sensor + front-end + digitization + calibration).





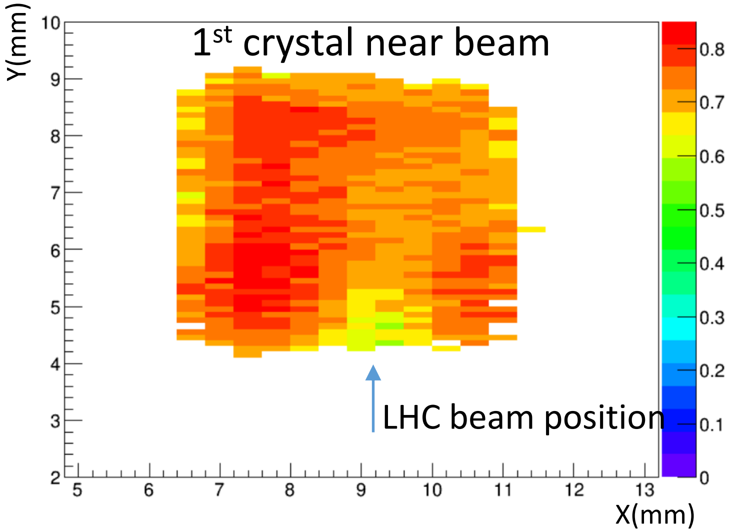
1 track in both pixel tracker stations & at least 3 diamond planes & 1 pad per plane

Timing detector can be used for physics. With 2018 performance important background reduction can be achieved.

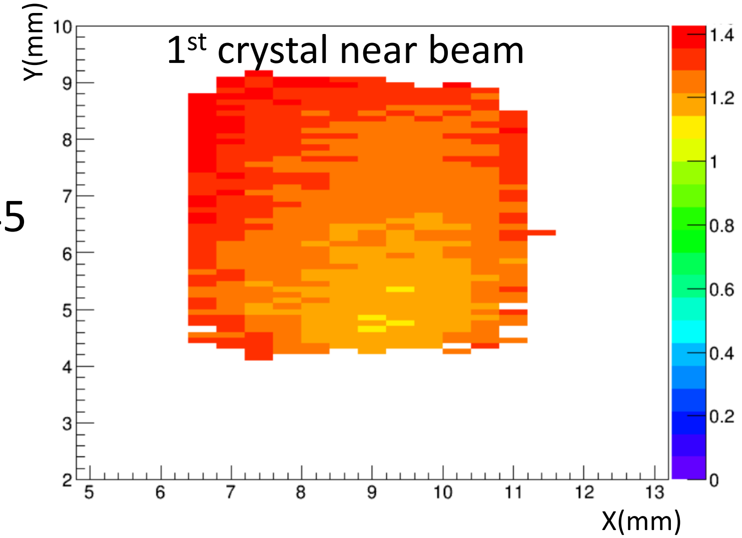
1 track in both pixel tracker stations & 4 diamond planes & 1 pad per plane

Localized damage (DD)

Average signal amplitude w.r.t. position (V)

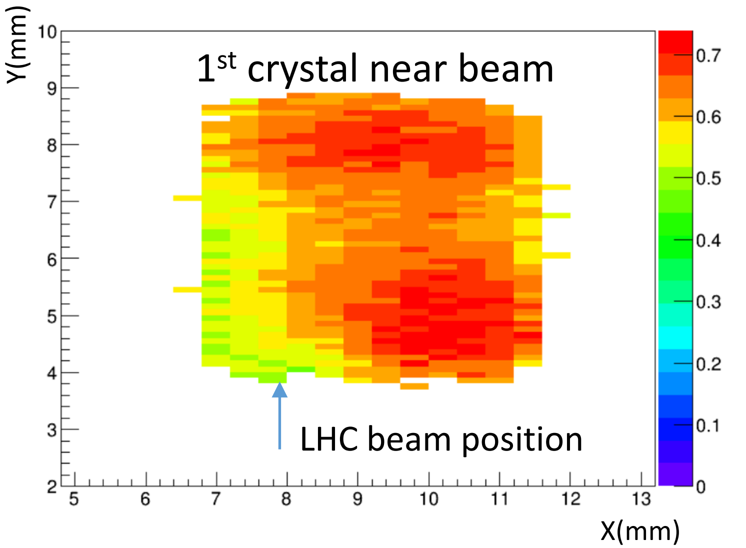


Average Rise Time w.r.t. position (ns)

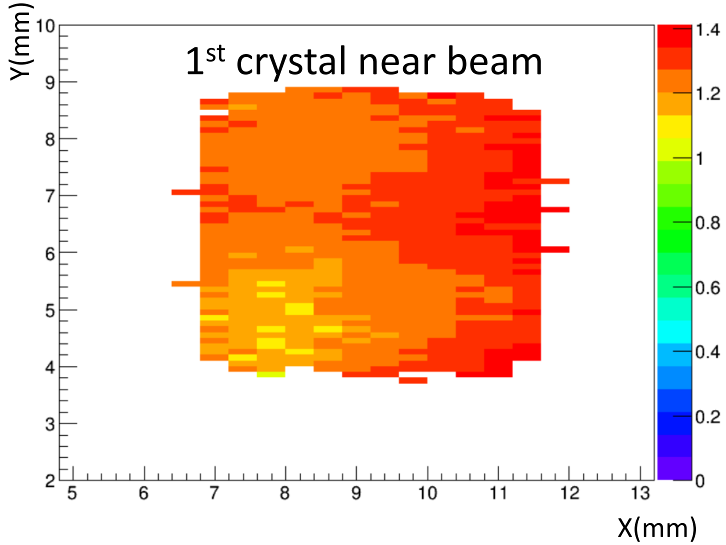


Sector 45

Average signal amplitude w.r.t. position (V)



Average Rise Time w.r.t. position (ns)



Sector 56

Sensors used in 2018 have been tested in DESY test beam facility with 4.8 GeV electrons. Tracker available to perform position dependent measurements.

Test beam settings:

- nominal LV
- HV @ 500V

Reduction of signal observed in the area with highest irradiation, partially compensated by faster rise time.

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

Run 3 perspectives

Important upgrade program ongoing for the timing system:

- New hybrid boards -> increase in amplification stability and HV isolation, further optimization of performance
- New discriminator board (still based on NINO chip) -> reduce timing degradation in digitization phase
- Amplification LVs will be remotely controlled
- Sensor readout with SAMPIC chip (fast sampler @ 7.8 Gsa/s) will be available for commissioning phase and sensor monitoring (cannot sustain hit rate at nominal luminosity). Successfully used as CMS-TOTEM timing sensor readout for a special run in 2018 (lower hit rate, Ultra Fast Silicon Detectors as sensor)[PoS TWEPP2018 (2019) 137] :
  - Improvement of calibration quality
  - Fast feedback from settings modification
  - Monitor of sensor performance (disentangled from digitization stages)
  - Parallel readout -> No impact on regular data acquisition

Run 3 perspectives

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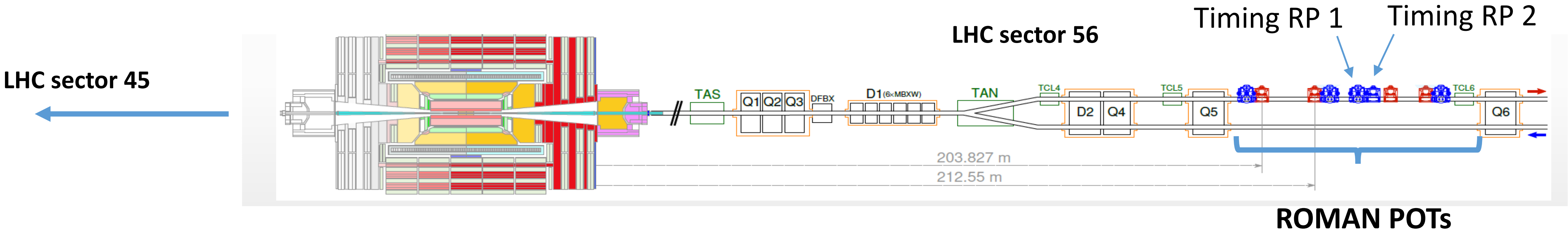
- An additional timing station will be built and installed in each sector. Each station will be equipped with 4 DD planes. → <u>8 DD planes in each sector</u>.

Ultimate resolution goal (< 30 ps) within reach



Conclusions

- TOTEM and CMS have developed new timing detectors based on scCVD diamonds.
- High improvement (factor 1.7) in performance is achieved using the double diamond architecture

- 2 RP stations based on this technology have been built and operated during LHC Run2.
- Readout is based on fast discriminator (NINO), coupled to a high precision TDC.

- Performance results in Run2 allow to use timing information to reduce pile-up background in CEP processes. Study of vertex resolution ongoing.

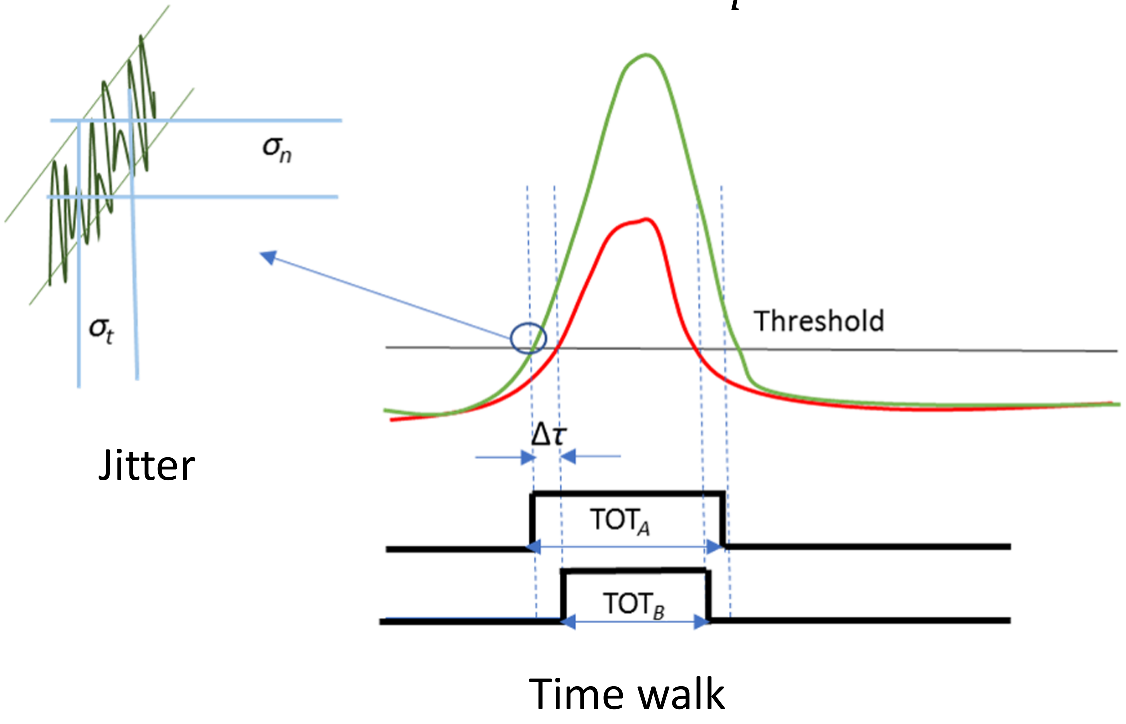
- The collaboration has performed important studies on the effect of radiation on crystals and electronics. Further studies will be carried out in the near future.
- Results will be extremely relevant due to the high level (up to $\sim 5 \cdot 10^{15} \mathrm{p/\,cm^2}$) and non uniformity of the particle flux.

- Important upgrades are ongoing for Run3, with the ultimate goal of a timing resolution < 30ps within reach.

Backup

Timing measurement

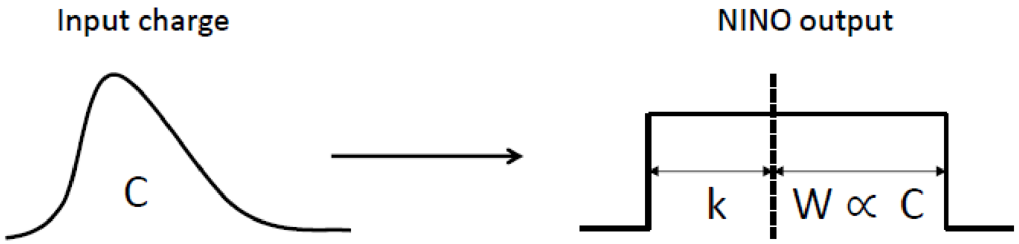
$$\sigma_t \approx \frac{RiseTime * NoiseRMS}{Amplitude}$$



Requirements for a good timng:

- High SNR and slew rate of the sensor signal
- Signal shape must be constant
- Possibility to perform time walk correction
    - Time over Threshold
    - CFD
    - Signal charge measurement
    - Signal sampling

$$\sigma_{tot}^2 = \sigma_{jitter}^2 + \sigma_{walk}^2 + \sigma_{digi}^2$$

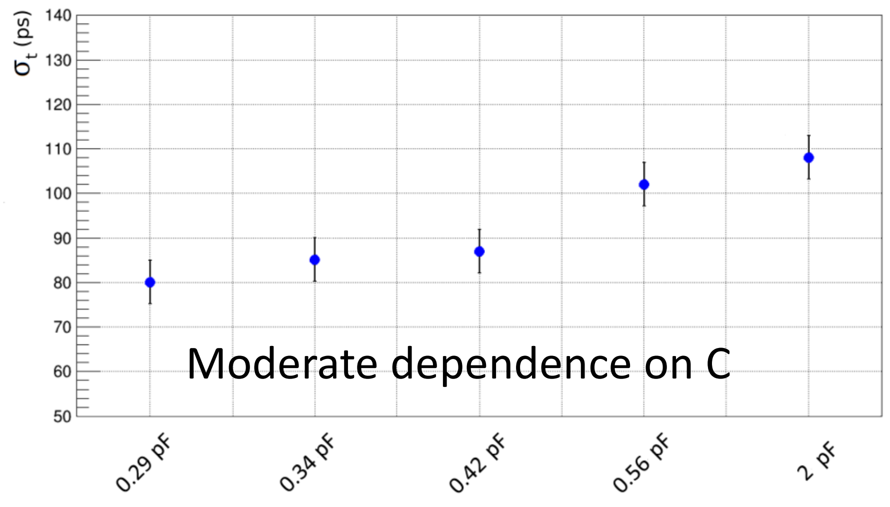


Single diamond performance

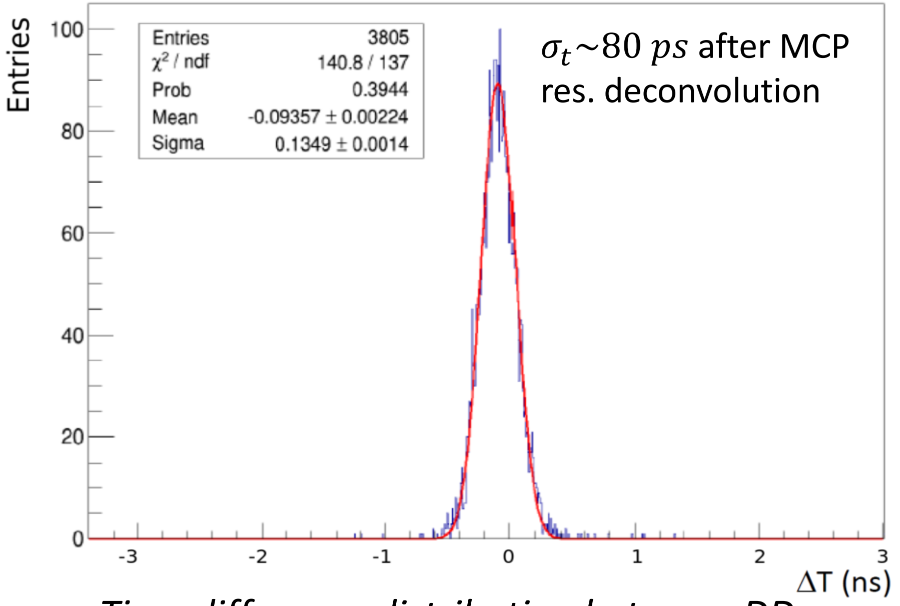
[JINST 12 (2017) no.03, P03007]

Signal characteristics (after amplification):
Rise time ~ 1.4 ns
Signal-to-noise ratio (SNR) ~ 30-40
Amplitude ~ 300-700 mV

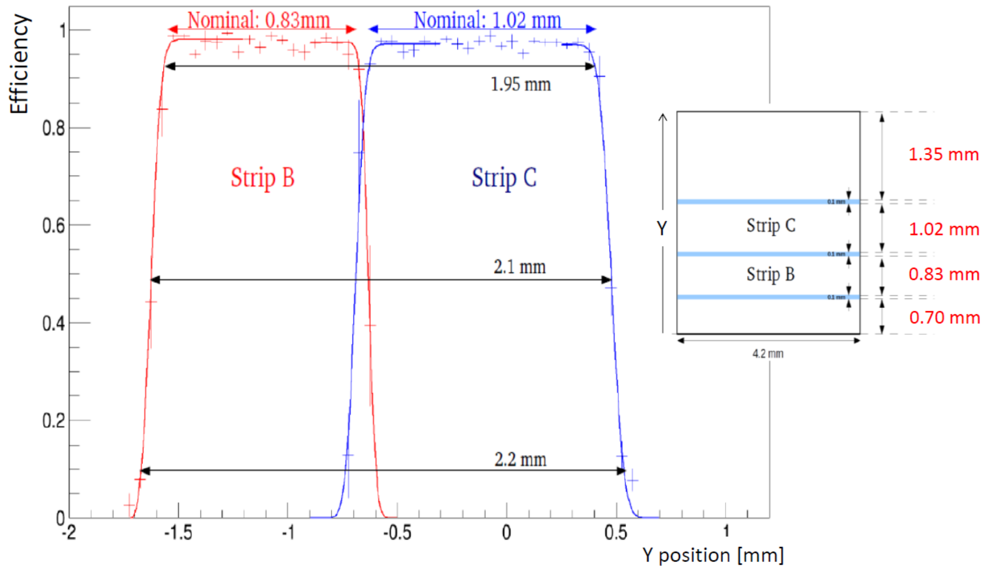
Sensor readout performed with oscilloscope or SAMPIC sampler.



Time resolution w.r.t. pad capacity (∝ pad size, 2pF = 4.2x4.2 mm2).



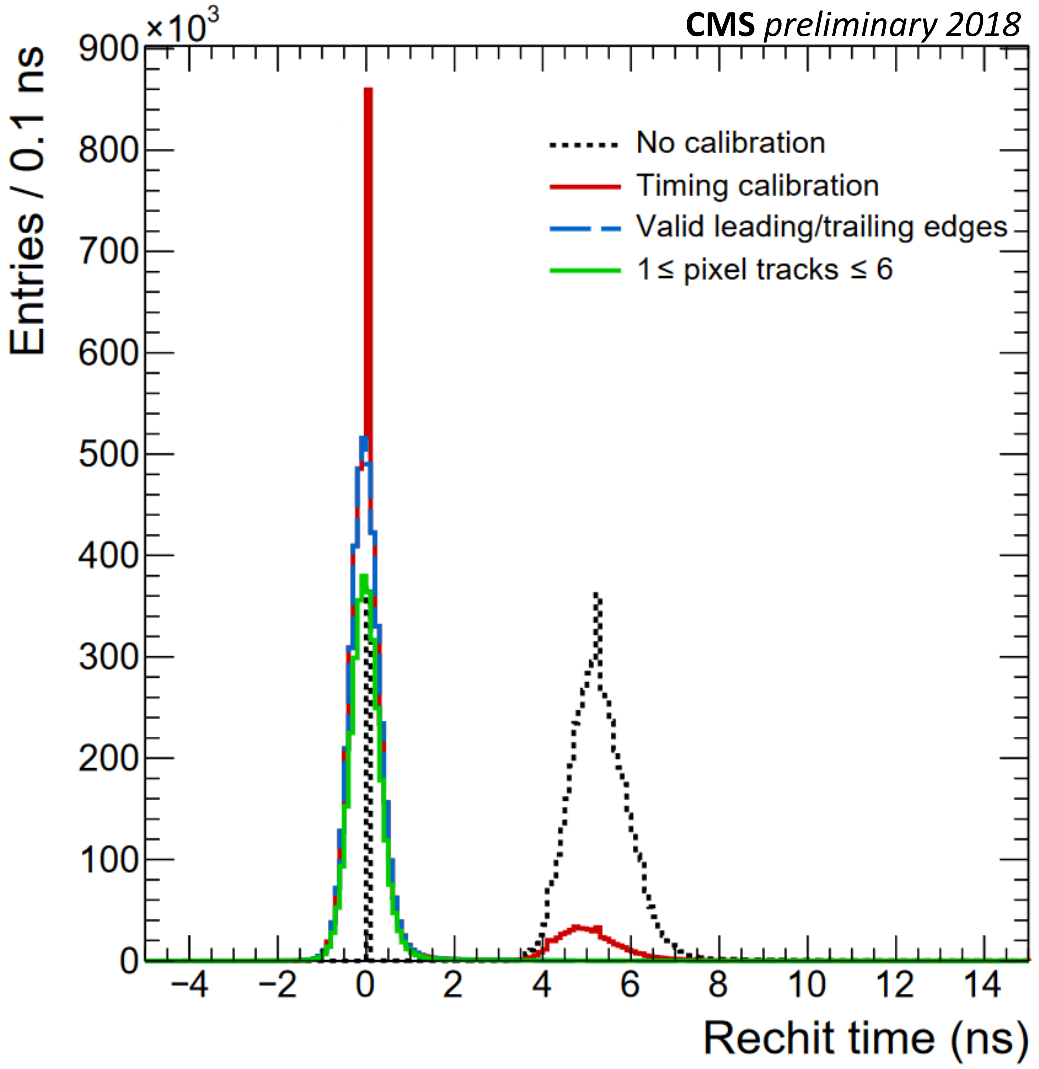
Time difference distribution between DD and reference MCP ($\sigma_{t,MCP} \sim 40\ ps$)



Efficiency between strips

Calibration effect

Calibration effect example: one run, all channels (LHC sector 45)



No timing calibration. Spike at $t = 0$ corresponds to events with missing leading edge.

Timing calibrations (from calibration step 1) applied for each channel. Spike at $t = 0$ and tail correspond to events with missing leading/trailing edge.

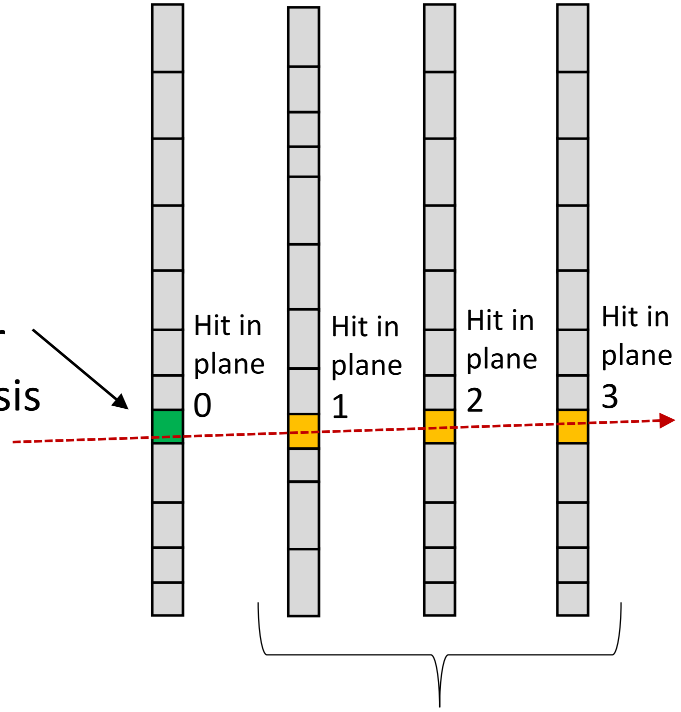
Timing calibration with quality cut: only hits with both leading and trailing edges and TOT>0 are considered valid.

Timing calibration with quality cut and pixel tracks multiplicity selection. Pixel multiplicity selection is used to reduce background.

Calibrated hit distribution shows a reduced RMS (it includes the effect of the beam longitudinal size).

Calibration procedure : channel resolution

For the 2018 data, the resolution is computed for each pad and used to calculate the track time (weighted mean).
Resolutions are computed with iterative procedure, where the weights computed at step n-1 are used the next step



t_k= corrected time measurement of plane k

w_k^j= weight computed at step j for the active pad in plane k ($w = 1/\sigma^2$)

$$T_{partial} = \frac{w_1^{n-1}t_1 + w_2^{n-1}t_2 + w_3^{n-1}t_3}{w_1^{n-1} + w_2^{n-1} + w_3^{n-1}}$$

$T_{partial}$ is the weighed mean of the measured times of the other pads

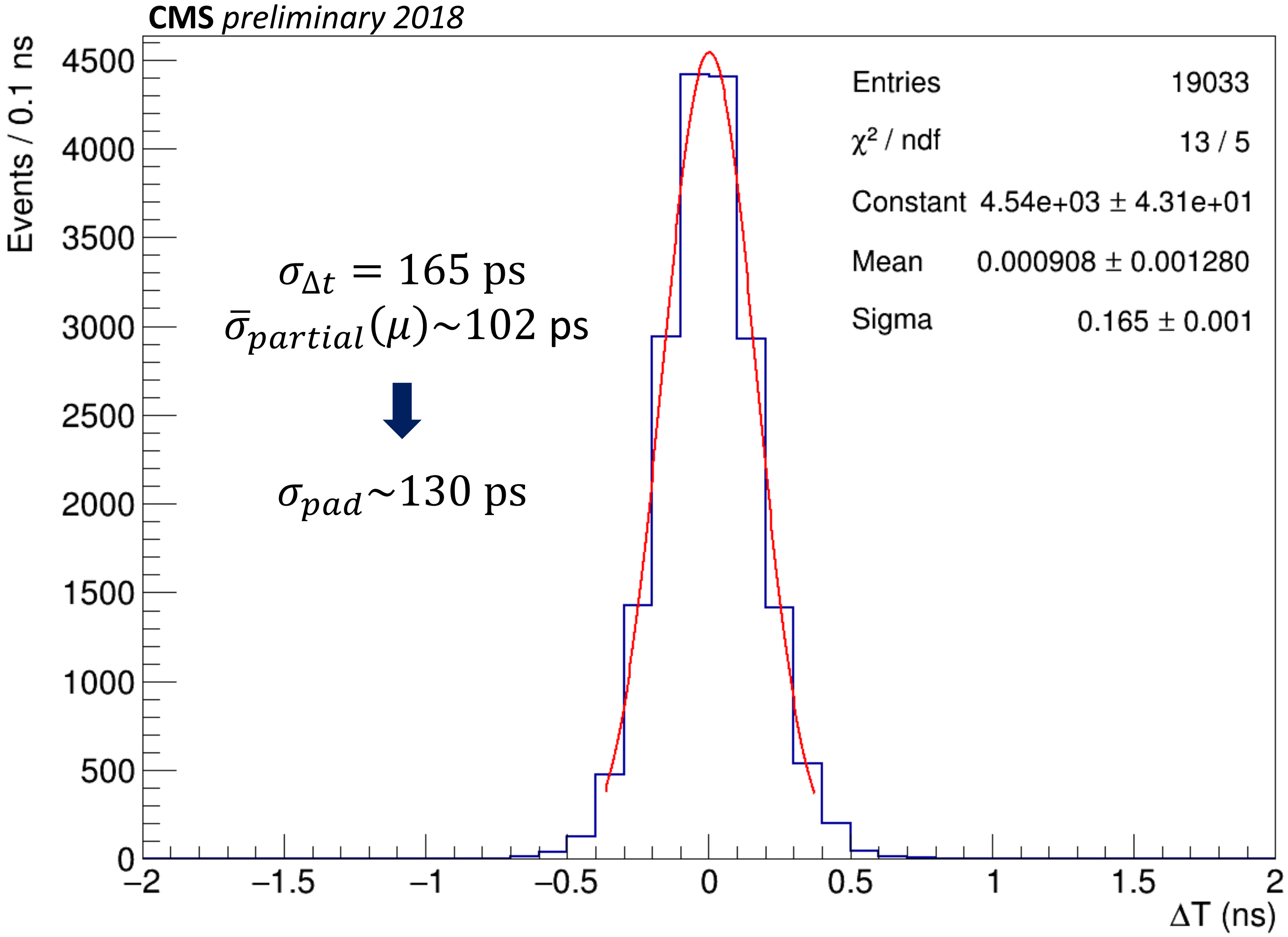
$$\sigma_{partial} = \sqrt{1/(w_1^{n-1}+w_2^{n-1}+ w_3^{n-1})}$$

Partial track resolution is computed with the resolutions extrapolated at the previous iteration step.

$$\Delta T = t_0 - T_{partial}$$

Calibration procedure : channel resolution example

ΔT distribution between channel 3 and partial time track computed with the other 3 planes.



$\sigma_{\Delta t} = 165$ ps
$\bar{\sigma}_{partial}(\mu) \sim 102$ ps

⬇

$\sigma_{pad} \sim 130$ ps

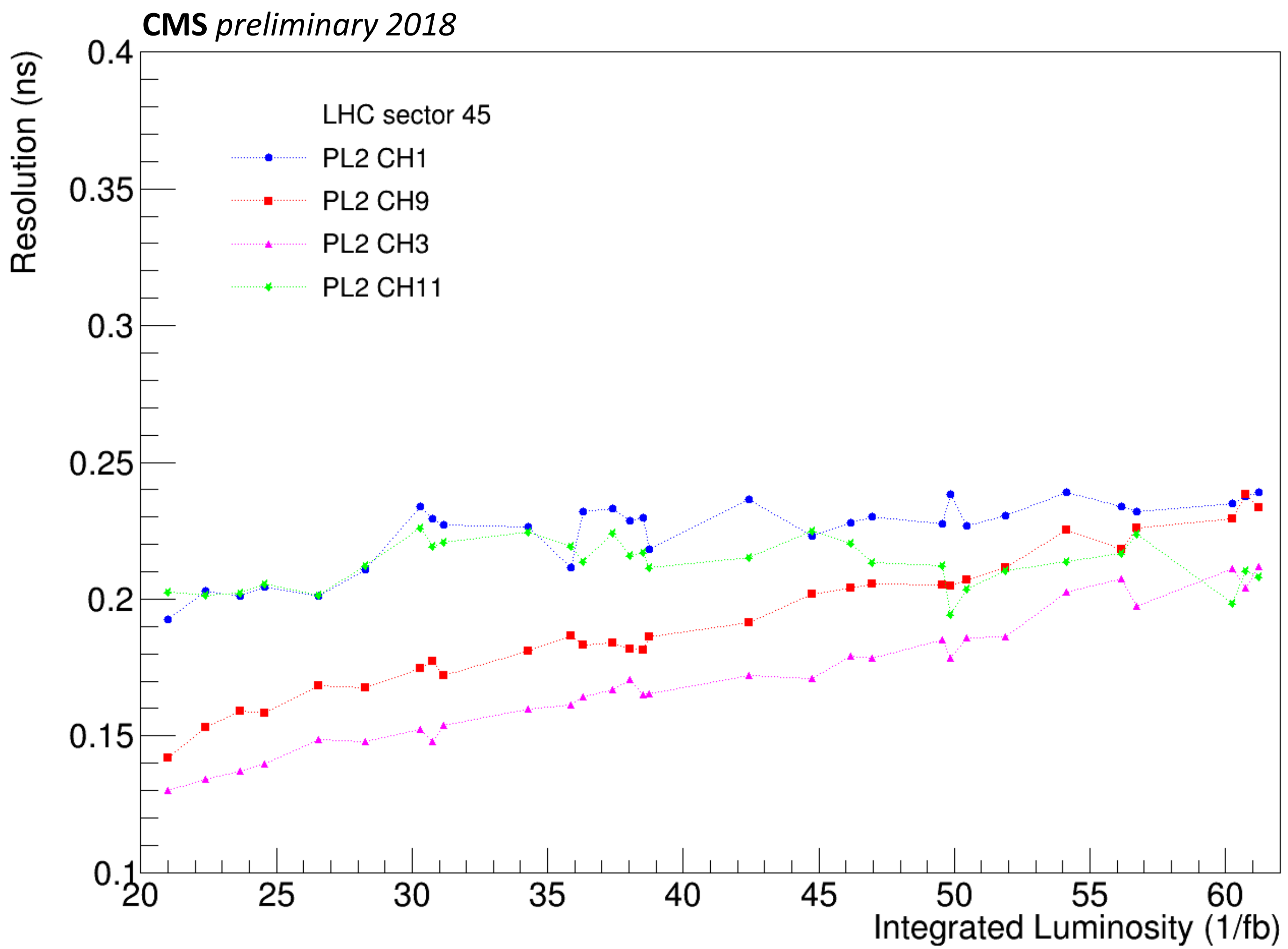
Average partial track resolution ($\sigma_{partial}(\mu)$) is deconvoluted from the σ of the ΔT distribution.

$$\sigma_{pad}^{n} = \sqrt{\sigma_{\Delta T}^{2} - \sigma_{partial}^{2}\,(\mu)}$$

Pad resolution

Statistical error negligible.
Systematic uncertainty (on the method) estimated ~10 ps

Resolution vs integrated Luminosity in Run2



Two types of degradation identified:

1. General resolution loss in the range 20-50%: radiation damage on sensor and electronics close to the beam (pre-amplification stage).

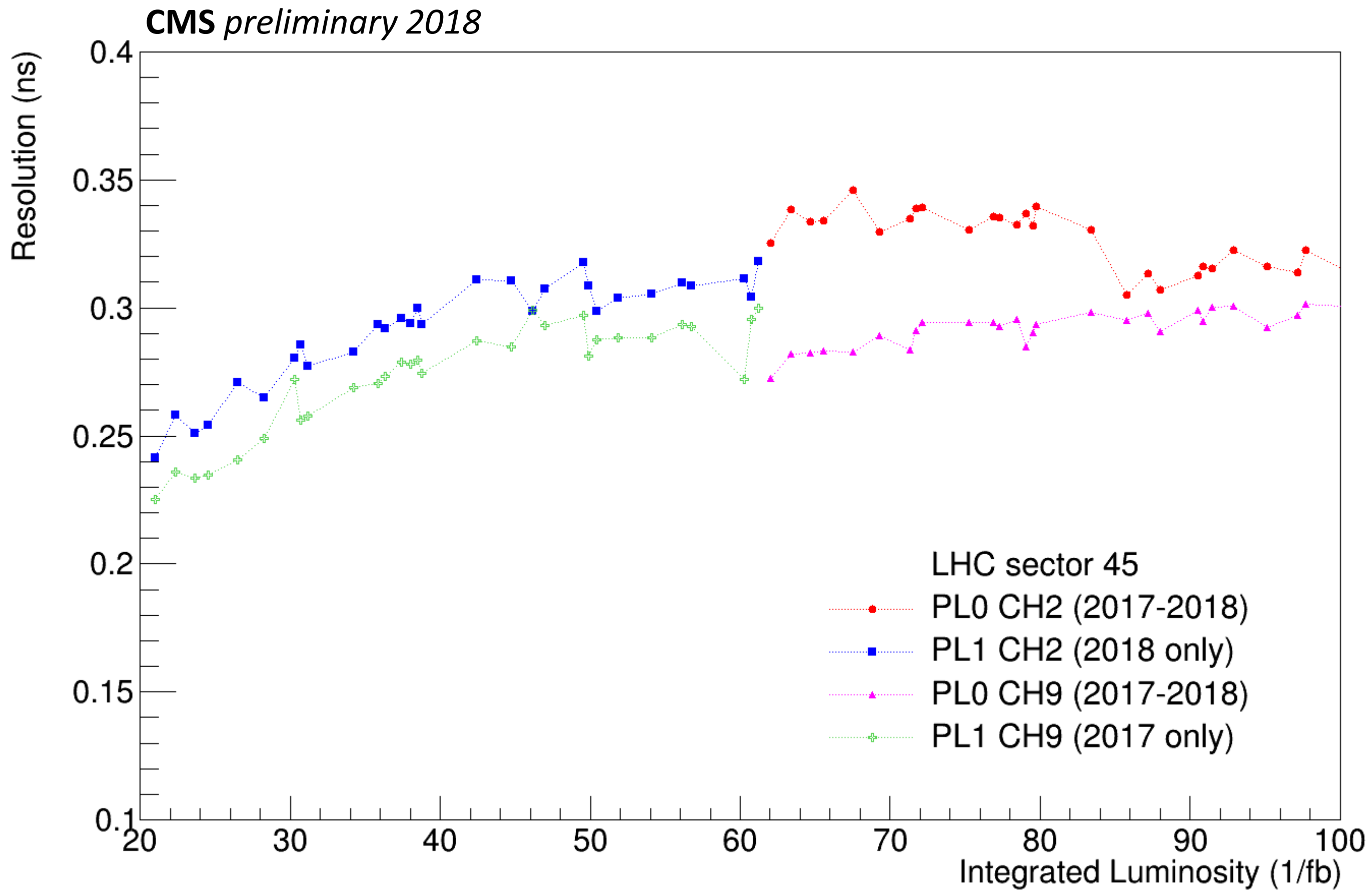
2. Localized damage on the sensor in the most irradiated area ($\sim 1\ \mathrm{mm}^2$). Damage could be due to creation of trapping centers in the bulk or at the metallization interface.

In Run 3 performance can be recovered raising the LV of the pre-amplification stage (LV remote control not implemented for Run 2).

Calibration data available only after TS1.

Resolution vs integrated Luminosity in Run2

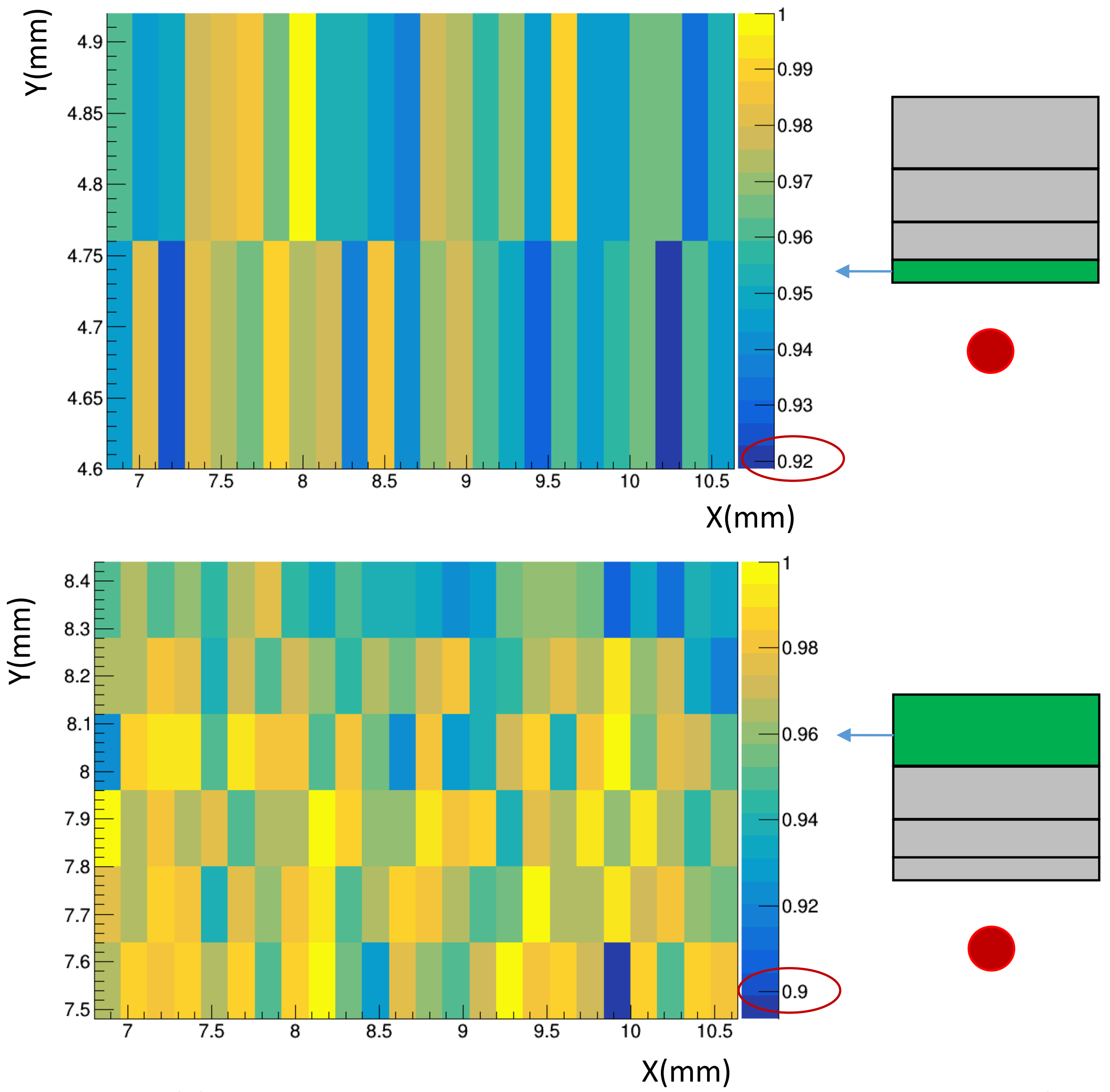
Comparison of the resolution in two SD planes vs integrated Luminosity in Run2



Plane 0 of each station was already used in 2017, accumulating an integrated luminosity of ∽40 fb^{-1}.

Data from such planes can be used to extend the resolution measurements on SDs up to ∽100 fb^{-1}: the comparison is done for same channels (∽ same distance w.r.t. the beam) of plane 0 and 1.

Core efficiency (DD)



Pad core is defined with a clearance of 300 μm in X and 200 μm in Y from metallization borders.

No evidence of efficiency loss in DD for the most irradiated pad (with test beam settings) .

Crystals used in Run2 will be removed from hybrid boards, etched and new metallization will be applied. New test campaign will clarify if the damage is in the crystal bulk or at the contact interface.

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)