The CMS Precision Proton Spectrometer timing system:
Run 2 performance and Run 3 upgrade status and perspective

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OUTLINE:

- PPS project overview
- Detector description
- Run 2 performance
- Run 3 upgrade
- Status & perspective

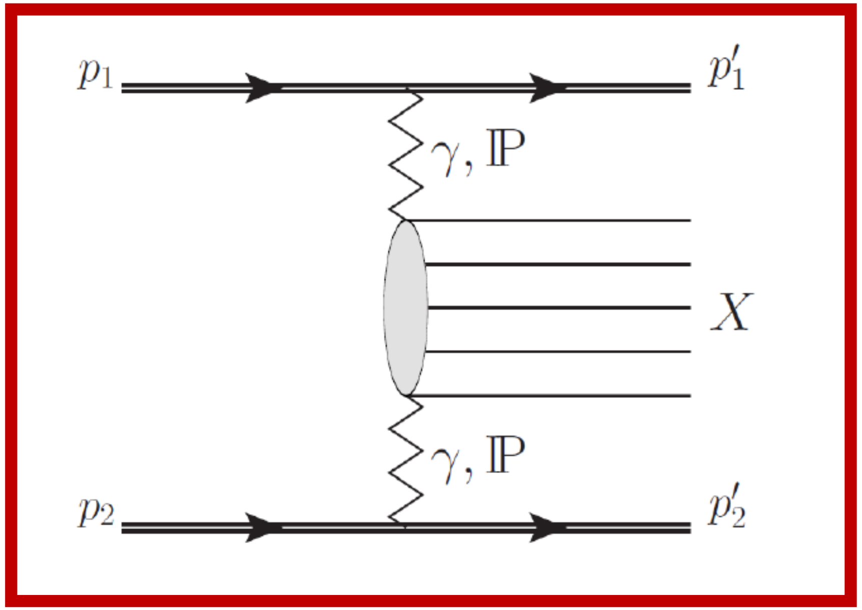
Physics motivation

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.

$pp \rightarrow p \oplus X \oplus p$ ($\oplus$= rapidity gap)

- Di-lepton central (semi)exclusive production
- CEP of top quark pairs
- LbyL scattering with proton tagging
- Missing mass searches for BSM physics
- Anomalous quartic couplings
- …

Latest results in A.Bellora's talk



PPS can measure the proton kinematics; in conjunction with the information from the central CMS apparatus, the full event can thus be reconstructed.

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 background rejection.

Proton reconstruction in M.Obertino's talk

PPS detector

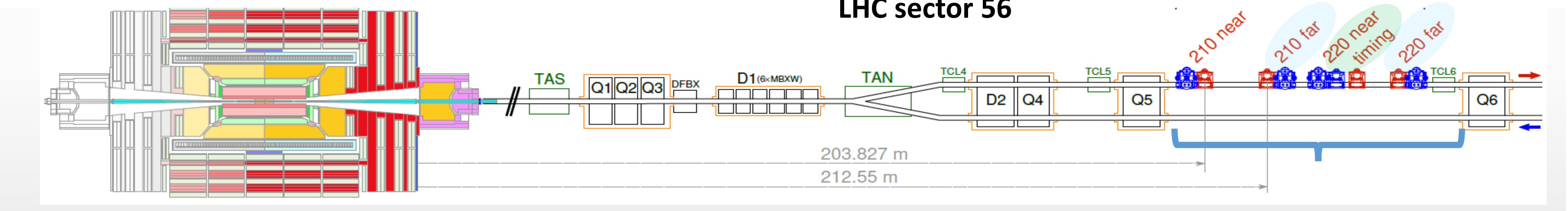
Symmetric experimental setup w.r.t. the interaction point to detect leading protons

Tracking Timing Tracking

CMS central detector

LHC sector 56

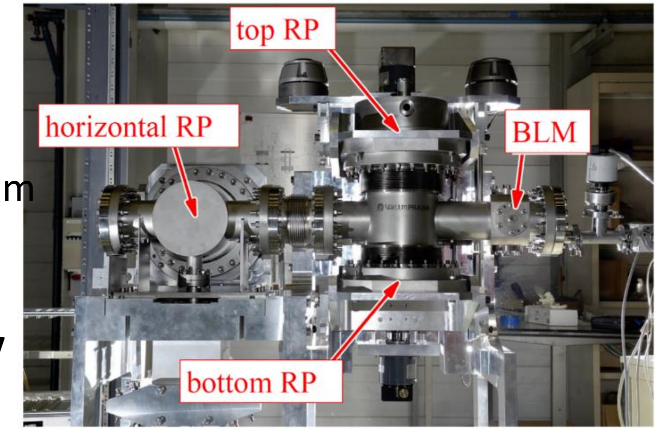
LHC sector 45



ROMAN POTs

- Standard RP units composed of 3 Roma Pots (RP): 2 vertical, 1 horizontal
- Hosted detector brought to few mm from the beam
- RP infrastructure from TOTEM

Detectors operate in a secondary vacuum



PPS RPs inserted at **12 σ_{beam}+ 0.3 mm (~1.5 mm) from the LHC beams**

Very high non-uniform irradiation field, with a **peak of ~5x10^{15} p/cm^2**

Sensors in Run 2

Tracking (2 stations per sector)

2016: 2 TOTEM strip detector stations

2017: 1 strip and 1 3D pixel stations

2018: 2 3D pixel stations

Timing (1 station/sector, 4 detection planes/station)

2016: 4 single-side diamond (SD) planes

2017: 3 SD and 1 UFSD planes

2018: 2 SD and 2 double-side diamond (DD) planes

Sensor for Run 3: 3D pixel (tracking) & Double-side Diamond (timing)

Timing detectors

Average number of interactions per bunch crossing $\langle \mu \rangle$ in 2018 is ~ 35.
Beam longitudinal dimension $\sigma_z \sim 7.5$ cm (~250 ps in the time domain).
Tracking system cannot reconstruct the primary vertex of detected protons.

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

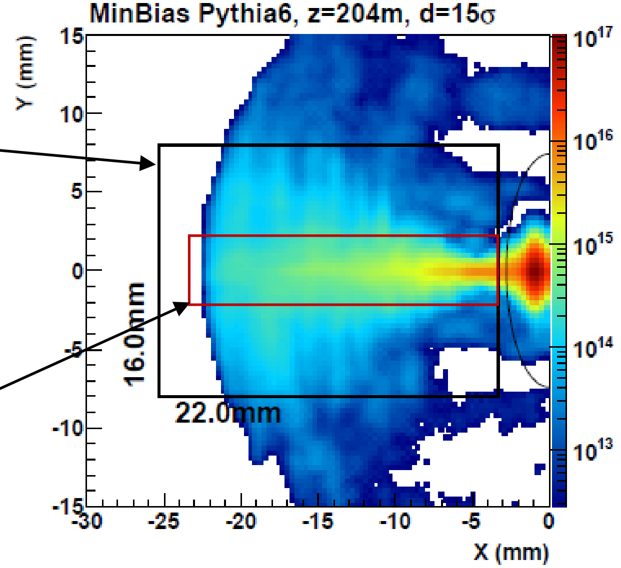
- $Z_{PP} = c\Delta t/2$
- Pile-up background reduction

PPS Detector requirements:

- Time precision <30 ps on MIP.
- High efficiency for MIP detection
- High radiation hardness (up to $\sim 5 \cdot 10^{15}$ 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 multiple hits on same pad
- Detector must operate in a vacuum

Area covered by tracking station

Area covered by timing station

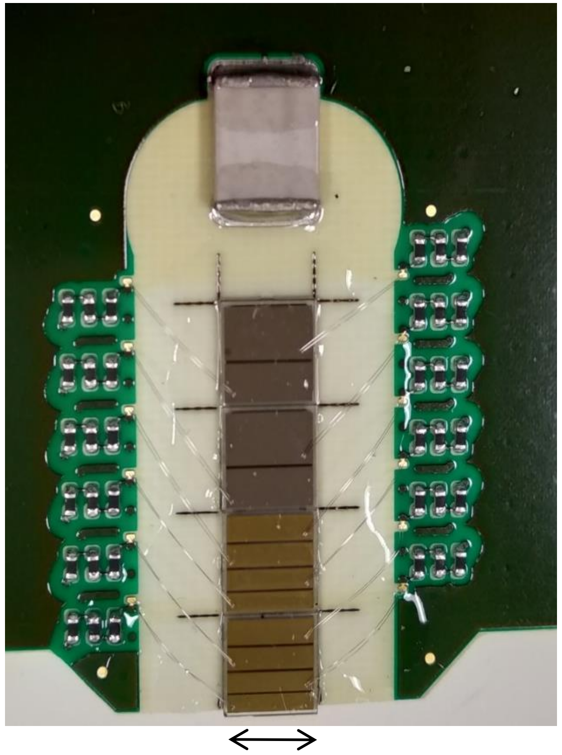


Simulated particle flux for 100 fb^{-1} (full Run2).
~300 fb^{-1} expected in Run 3

PPS diamond sensors

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

- Detector segmentation, optimized to reduce number of channels while keeping multiple hit probability low, is carried out in the metallization phase, with multiple pads created on the same crystal surface.



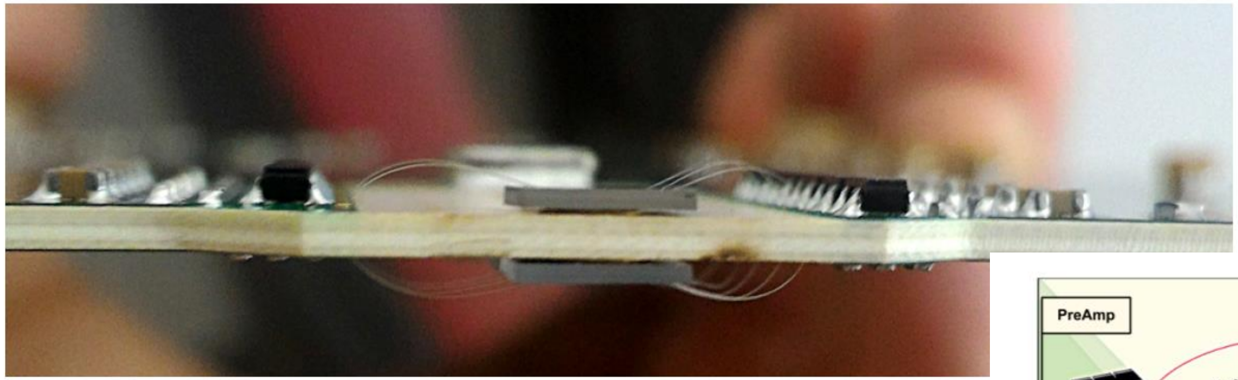
- Crystals are glued to a custom hybrid board. 12 discrete amplification channels, with a design adapted from the HADES collaboration, are available on each hybrid board [JINST 12 (2017) no.03, P03007]

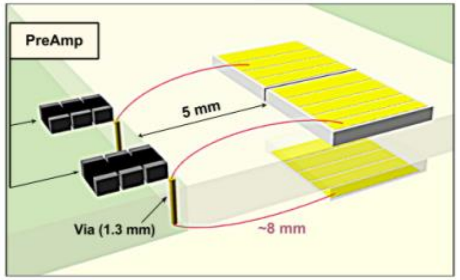
- Pads are directly connected to pre-amplifier input to reduce input capacitance ($\sim$0.2 pF with 0.25 μm bonding wire diameter).

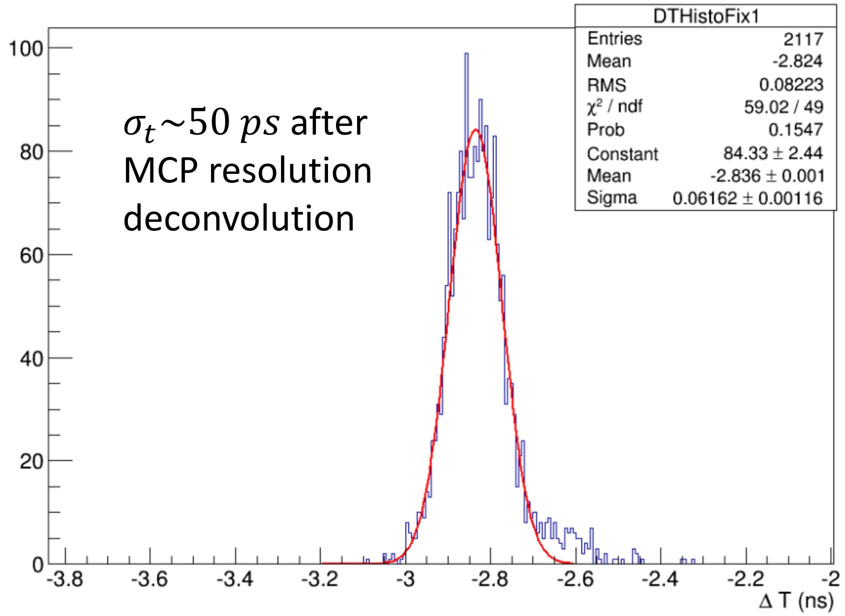
- Conformal coating is applied to sensitive areas to reduce HV discharges in vacuum (nominal HV $\geq$ 500 V)

Double Diamonds

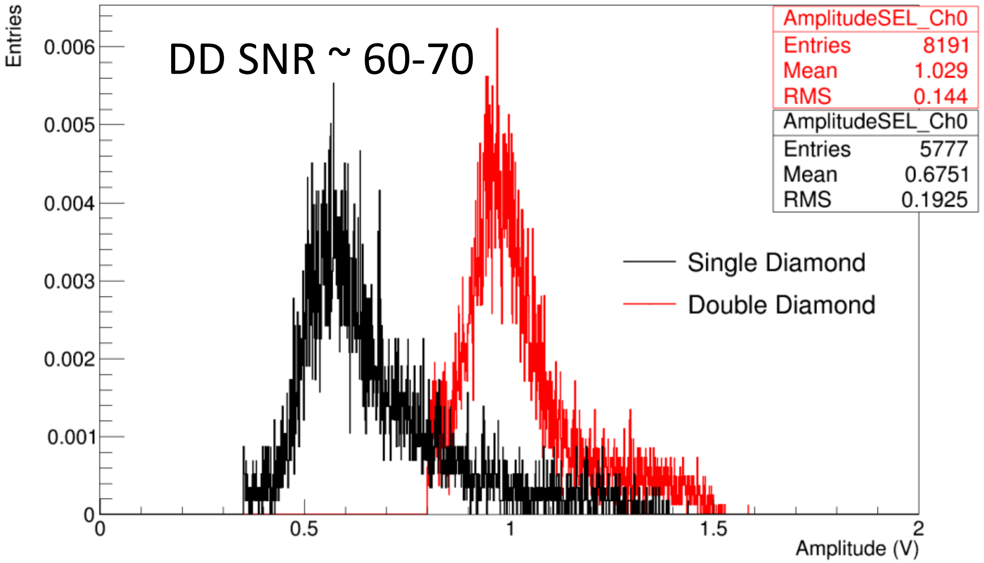
JINST 12 (2017) no.03, P03026 Sensor readout performed with oscilloscope.







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



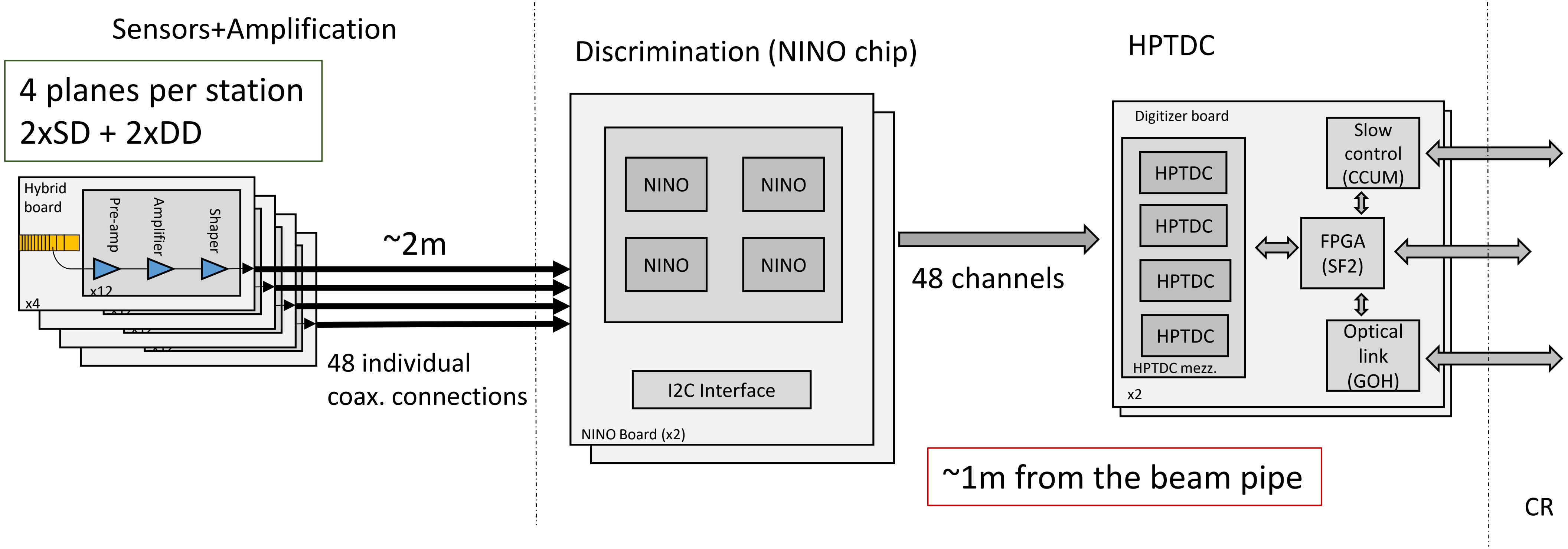
Signal amplitude comparison between DD and SD

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

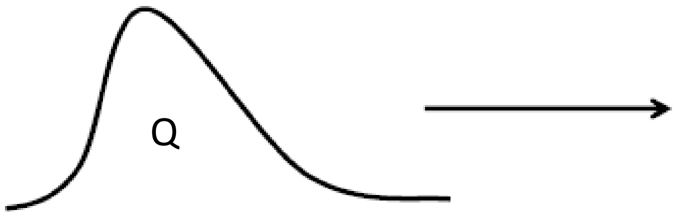
- Higher signal amplitude
- Same noise (pre-amp dominated) and rise time (defined by shaper)
- Higher sensor capacitance
- Need a very precise alignment

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

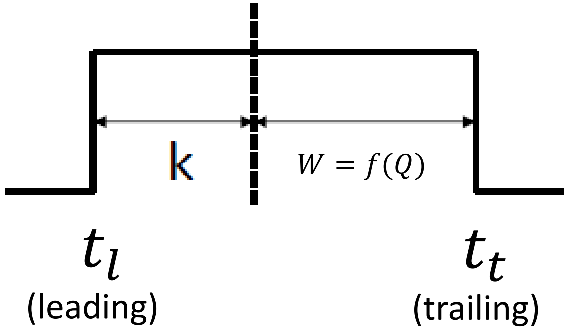
Run 2 read out



Input charge



NINO output



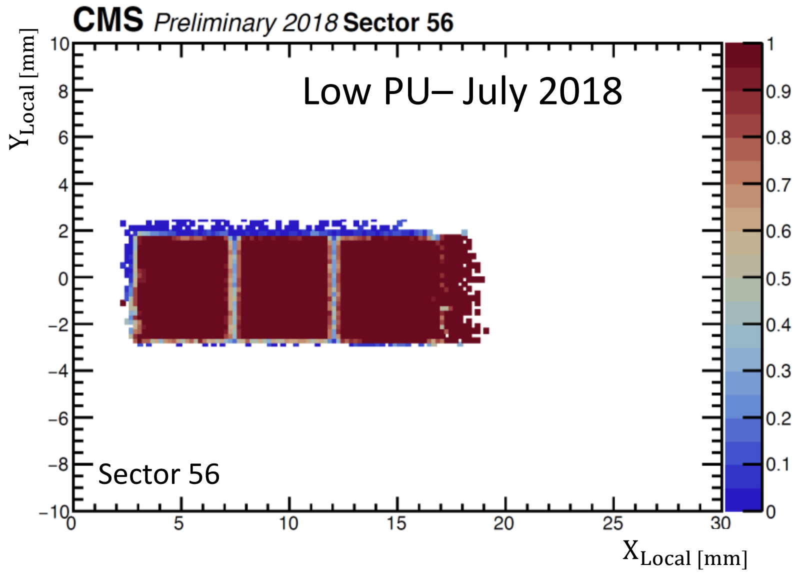
TOT = t_t-t_l = k+$f(Q)$

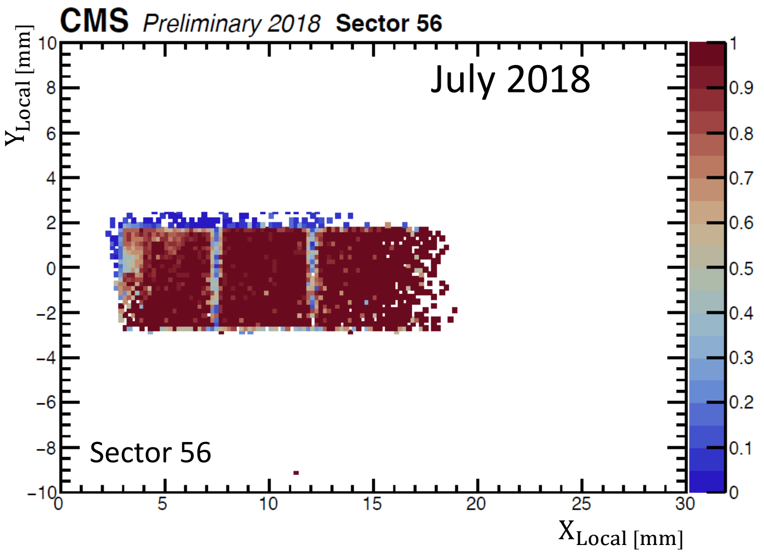
In Run 2 discrimination stage degraded timing performance by 30% (after time walk correction). Contribution of HPTDC (resolution <10ps) negligible.

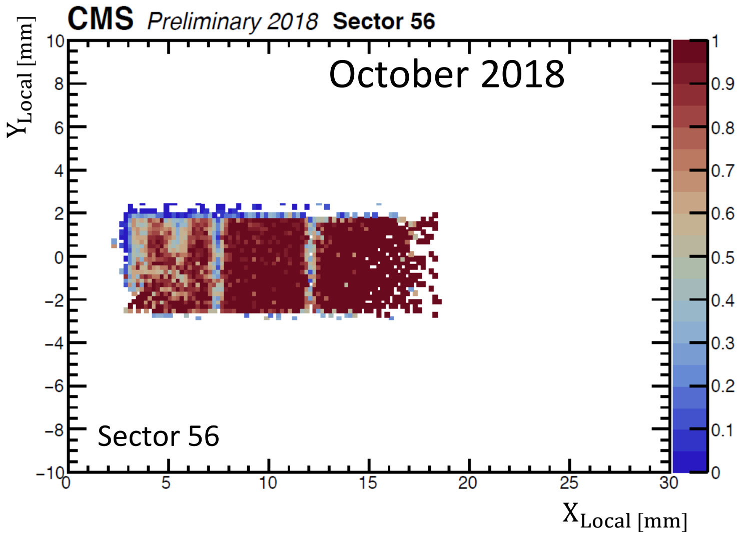
Run 2 detector efficiency

[CMS DP-2020/046](CMS DP-2020/046)

The timing system was operated @LHC in Run2. Best performance (section 5-6) was reached in 2018, limited by instabilities in amplification and HV discharges induced by the beam, forcing to operate below nominal bias and amplification level.







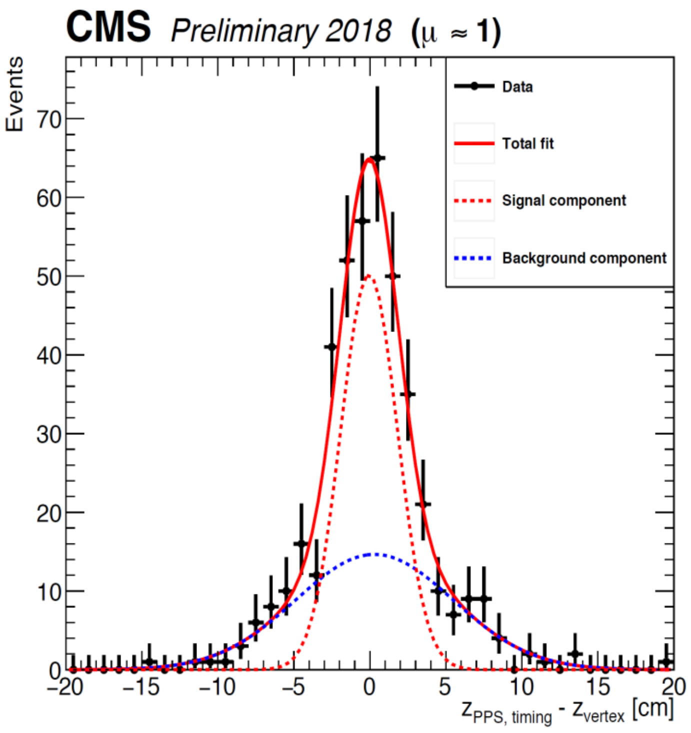
- The time-tracks, defined as a combination of at least 2 time measurements, have an efficiency near 100% in a low pileup fill from July 2018
- The evolution at the end of Run 2 (October 2018) shows a degradation of the efficiency
- Systematic lower efficiency is only visible in the regions between two crystals, not between pads on the same crystal

Detailed studies on radiation damage available:

- Test beam @ DESY (CMS NOTE-2020/007)
- LHC data (CMS DP-2019/034)

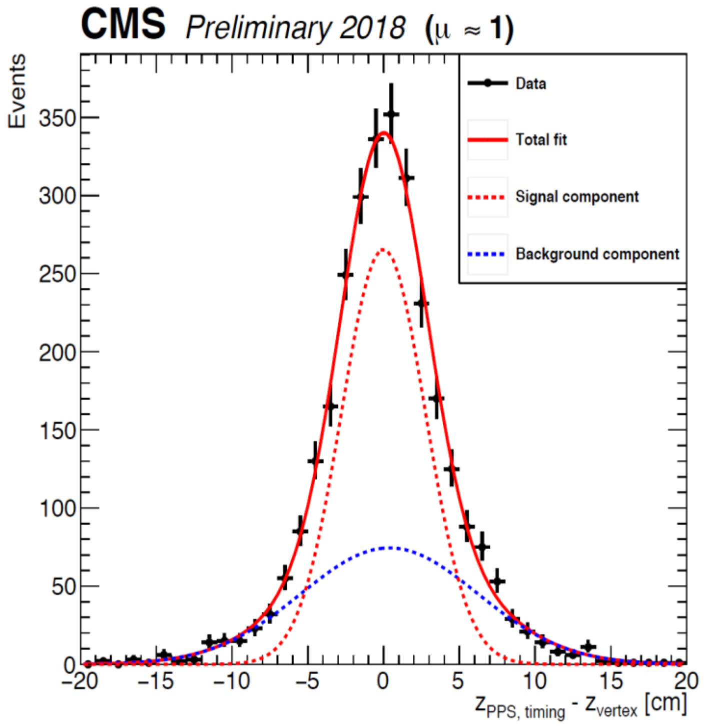
Run 2 vertex resolution

The resolution of the full PPS timing system has been measured in CEP events collected in low pileup conditions (July 2018).



High resolution tracks ($\sigma_{track} < 100\ ps$): $\sigma_{Zpp} = 1.87 \pm 0.21$ cm

All timing tracks $\sigma_{Zpp} = 2.77 \pm 0.17$ cm



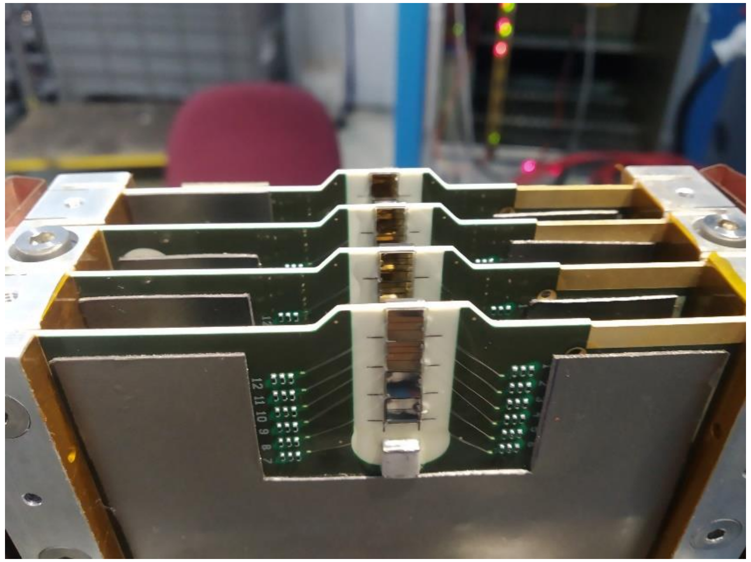
Timing information can be used in physics analysis to suppress pile-up background.

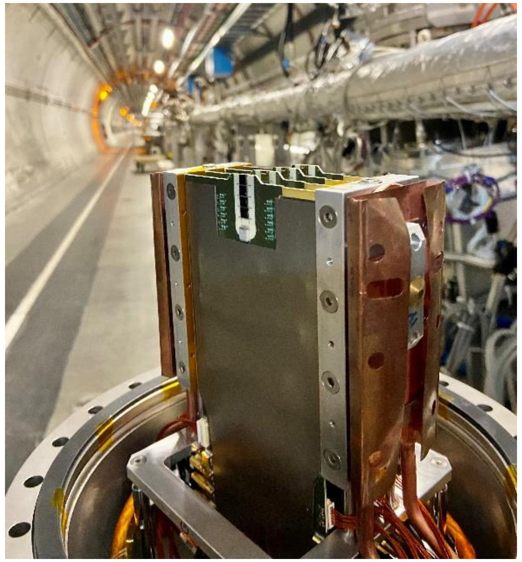
- A correlation is observed between the time difference of the protons detected in PPS, and the longitudinal vertex position reconstructed in the central CMS tracker
- The vertex resolution, inferred from the width of the correlation distribution, is consistent with the resolution predicted from the quadratic sum of the single-arm time-track resolutions.

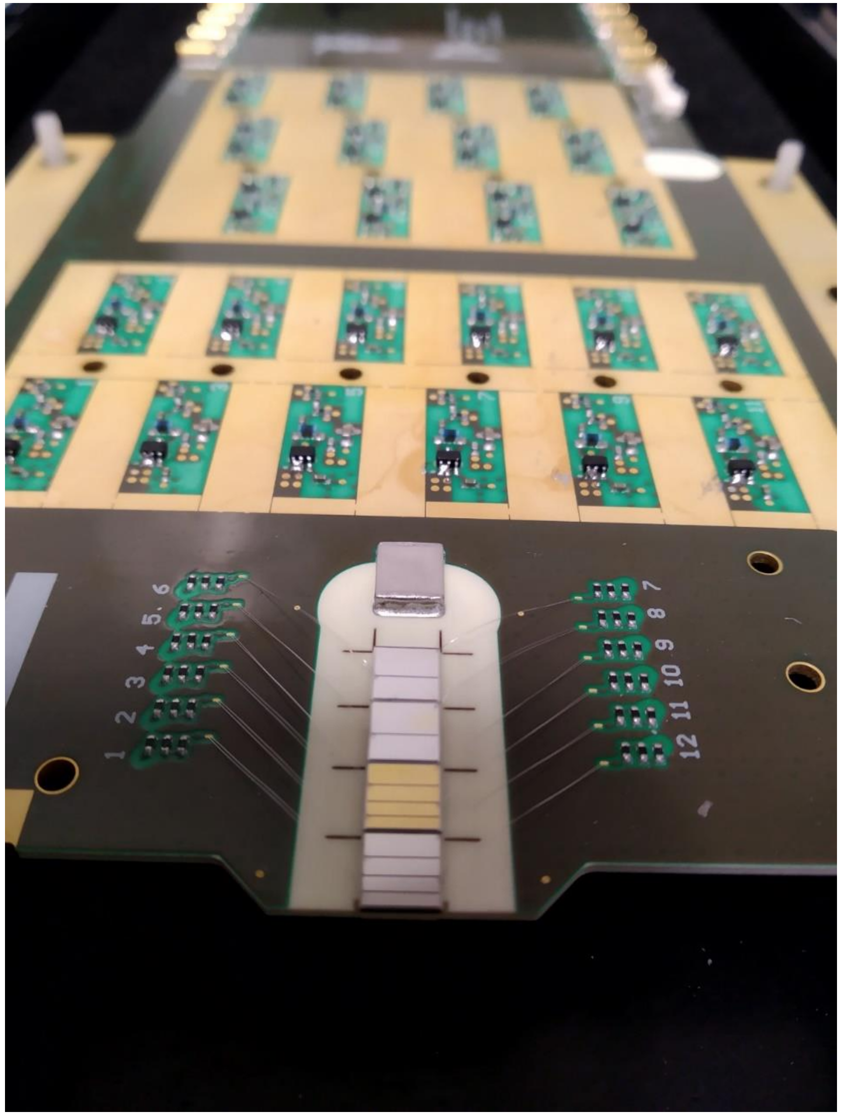
Main run 3 upgrades

Important upgrade program carried out for Run 3:

- An additional timing station will be built and installed in each sector. Each station will be equipped with 4 DD planes (2SD +2DD in 2018) → 8 DD planes in each sector + 70 ps/plane (including digitization) → 25 ps/arm.
- New hybrid boards & NINO board -> increase in amplification stability and HV isolation, further optimization of performance.







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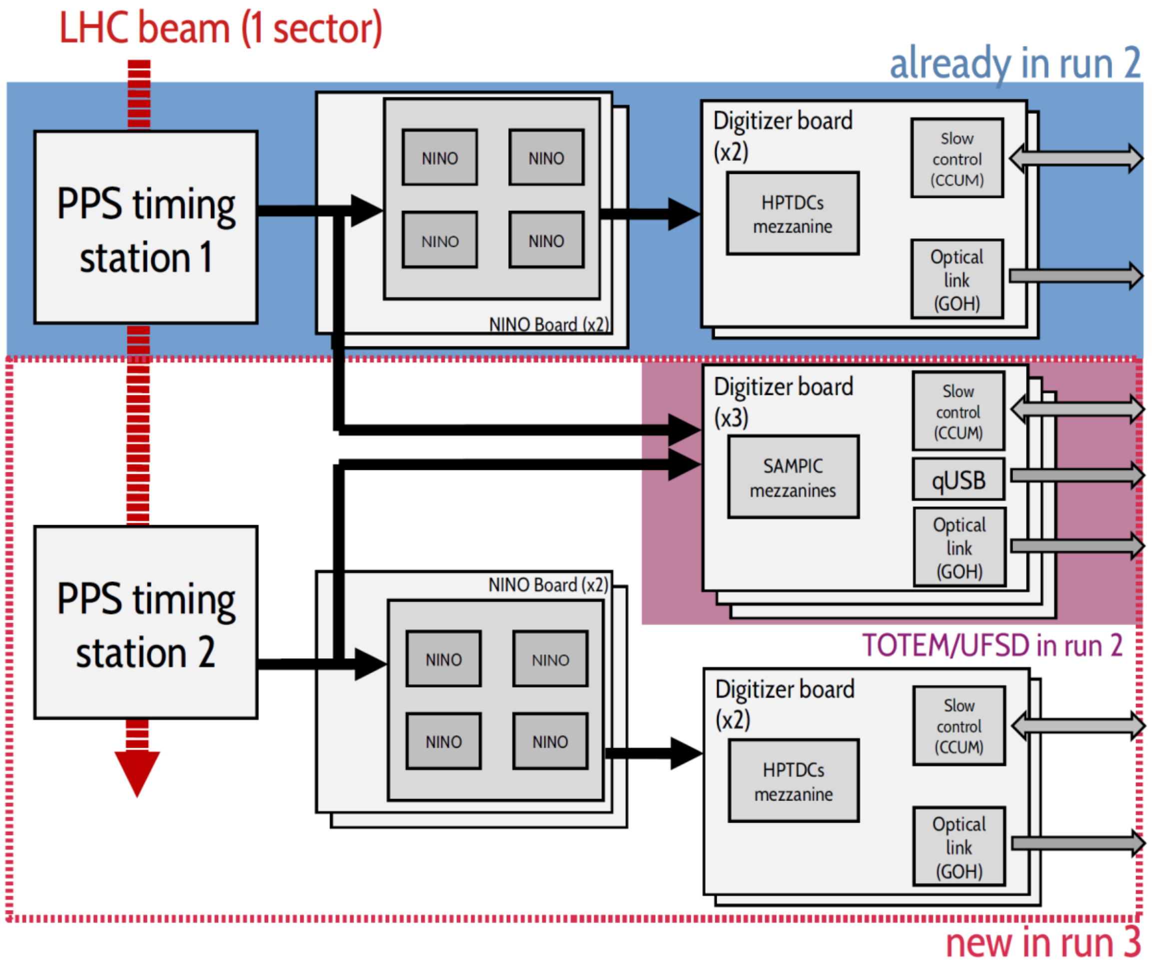

Run 3 upgrades & status

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STATUS:

- All digital electronics has been installed and commissioned. Both read out systems (HPTDC & SAMPIC) are fully operational.
- One timing RP per sector installed and commissioning well advanced. Detectors are collecting data during the LHC commissioning and intensity ramp-up.
- The timing system will be ready for the first high intensity physics beam.
- 2 additional stations foreseen by the end of 2022. The goal of a timing precision better than 30 ps (i.e. better then 1 cm in longitudinal vertex position) for protons in the TeV energy range is expected to be achieved after the installation of the second set of stations.

Conclusions

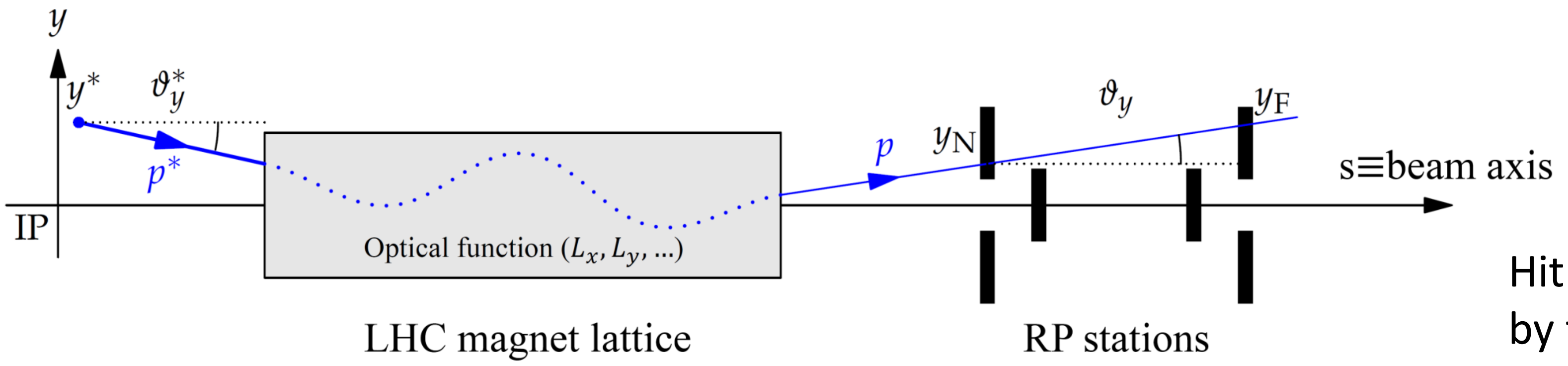
- The CMS PPS group has developed a timing system based on scCVD diamonds.
- Integration of the crystals and signal amplification is provided through a dedicated hybrid board, hosting 12 3-stage amplification channels.
- Test Beam data show that the sensors arranged in DD architecture can reach a precision of 50 ps.

- The timing system was operated in Run2.
- The system has proved able to measure the proton longitudinal vertex position and the proton timing information is now available. Timing information can be used for pile-up suppression.
- Performance and radiation damage to the detectors in run2 have been fully characterized with test beam and LHC data.

- Run 3 upgrades will give the possibility to reach a vertex resolution better than 1 cm, after the installation of the second set of timing RPs.
- Installation and commissioning of the new detectors are ongoing, with first data being collected during the LHC commissioning and intensity ramp-up.

Backup

Proton kinematics reconstruction



$$\boldsymbol{d}^*: (x^*, y^*, \theta_x^*, \theta_y^*, \xi) \longrightarrow \boldsymbol{d}: (x, y, \theta_x, \theta_y, \xi)$$

$$\boldsymbol{d}(s) = T(s, \xi)\boldsymbol{d}^*$$

Hit distribution on detectors determined by the optics -> With standard optics (PPS running scenario) only horizontal RPs are needed, with verticals used only for alignment.

Inversion of the transport matrix T needed for reconstruction of the proton kinematics. Main kinematic parameter is ξ, the fractional momentum lost by the proton. Measuring the ξ of both protons makes it possible to reconstruct the centrally produced mass.

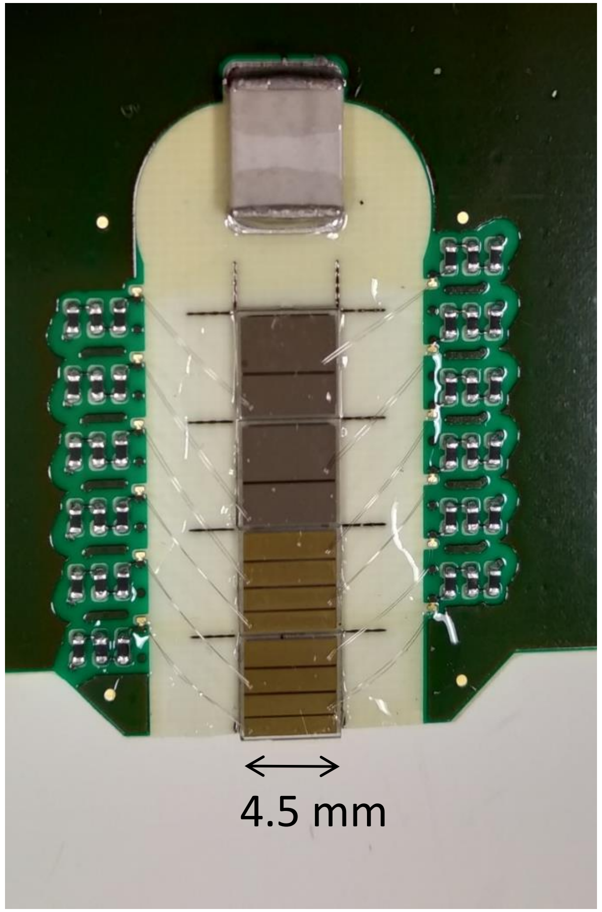
Tracking system cannot reconstruct the primary vertex of detected protons x^*, y^*. With high pile-up need of alternative method to fight pile-up.

Measure the proton time of flight in the two sectors:

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

PPS diamond sensors

Originally designed for TOTEM , then used in PPS.

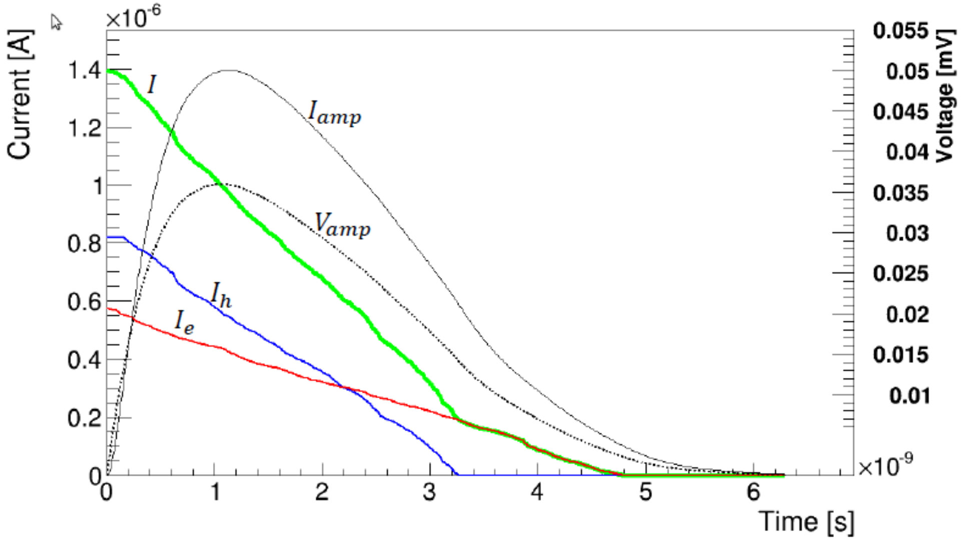


Sensor capacitance: 0.2-2 pF

Sensor based on ultra pure single crystal CVD diamonds. Each crystal has 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.

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

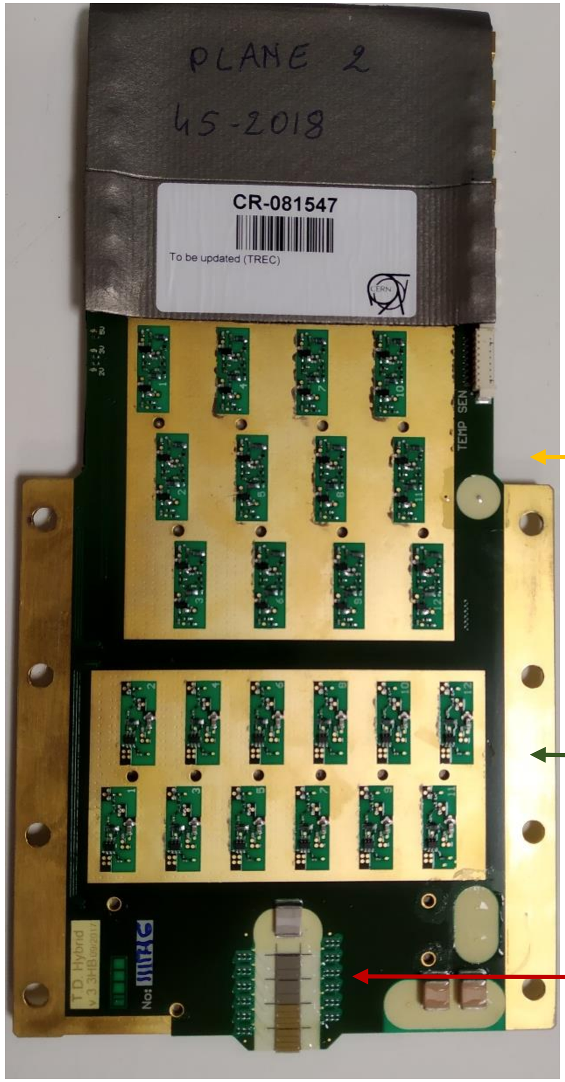


Main signal characteristics:

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

Front. in Phys., 8 (2020) p.248

Diamond hybrid board

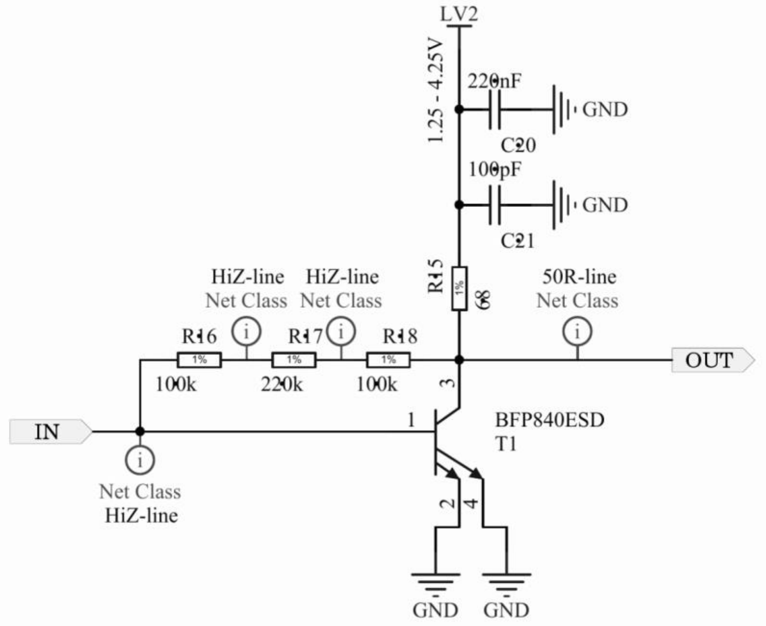


12 discrete amplification channels, with a design adapted from the HADES collaboration, on each hybrid board [JINST 12 (2017) no.03, P03007]

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

Shaper:
2xBFG425 Si BJT matched amplifier for shaping the signal

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

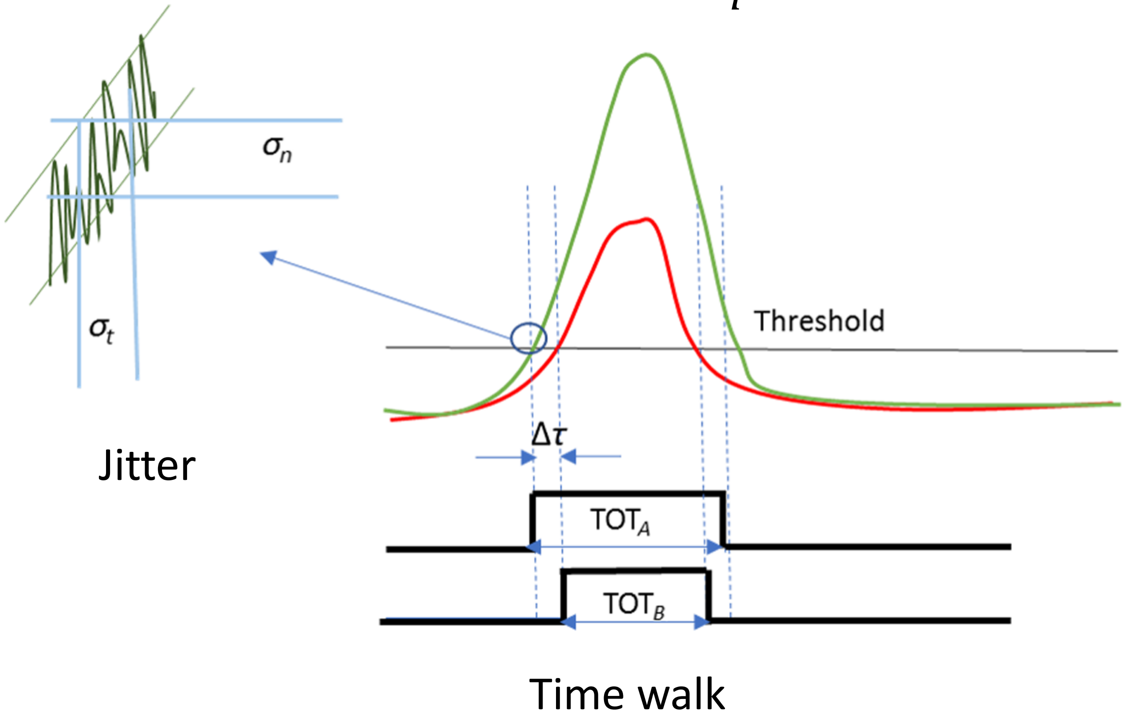


Pre-Amplifier:
stage BFP840 SiGe BJT with low-C feedback (~0.4 pF)

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

Timing measurement

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



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

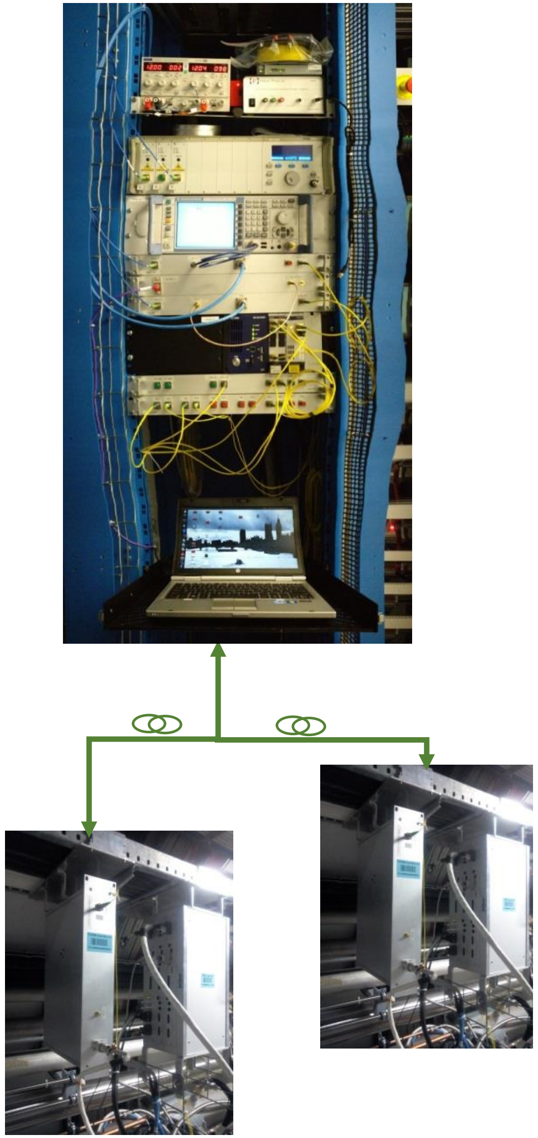
Requirements for good timing:

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

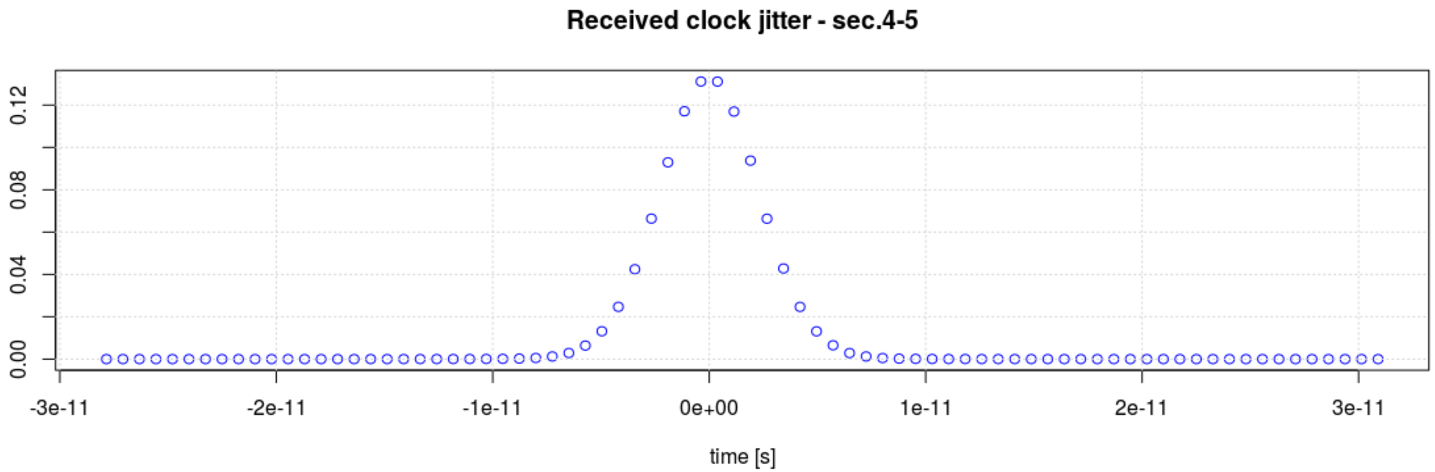
Rise time ~ 1-1.5 ns
SNR ~ 50-100
Amplitude ~ 300-700 mV

To cope with the high particle rate (~1MHz/channel) in the PPS application, a readout with a fast discriminator (NINO) and TDC (HPTDC) was chosen for the PPS timing system readout

Clock system



- LHC clock is derived from CMS TCDS (Timing Control Distribution System)
- System delay changes over optical path is constantly monitored -> 1 measurement every 10min.
- Data stored to files in csv format. File rotation system -> 1 file per day.
- Clock jitter measured at RP receiver <**2ps**



Clock source based on Silicon Lab 5344 chip:

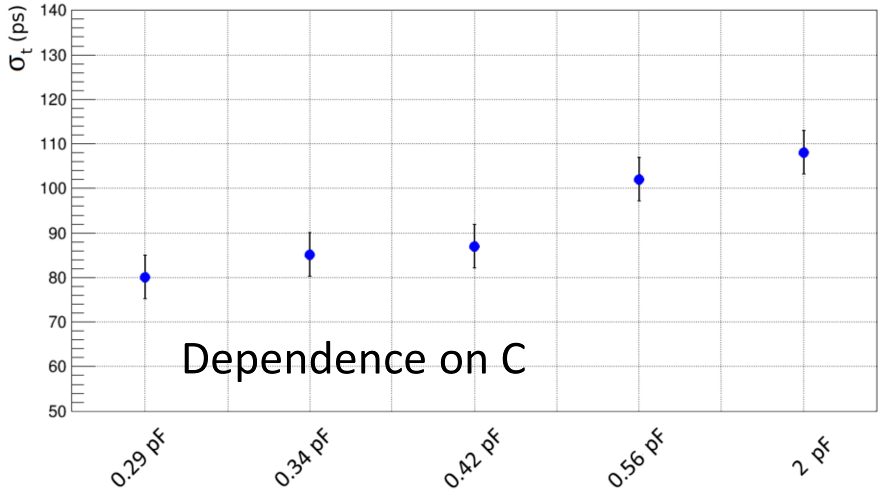
- Zero delay mode → constant phase delay between input and output
- Clock phase will be tuneable in ~18ps steps.

Single diamond performance

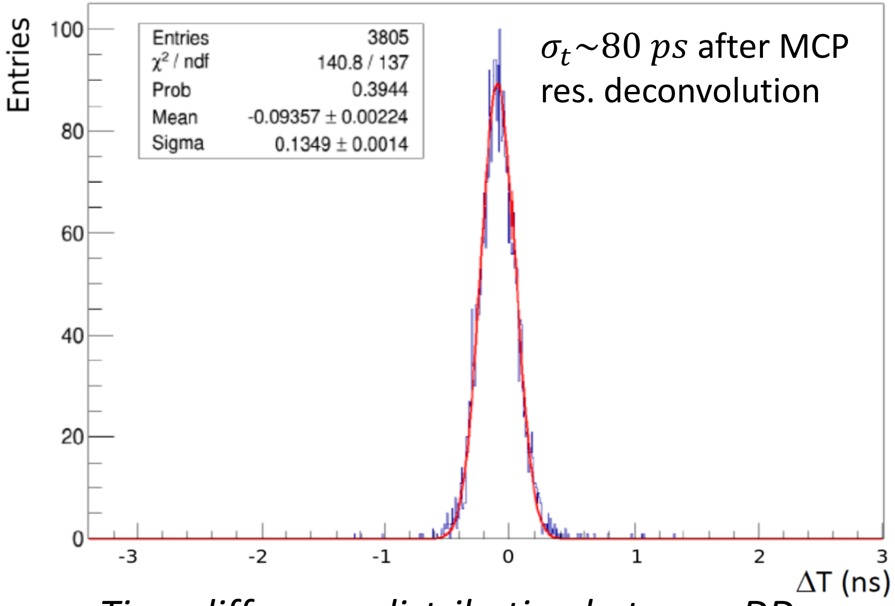
[JINST 12 (2017) no.03, P03007]

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

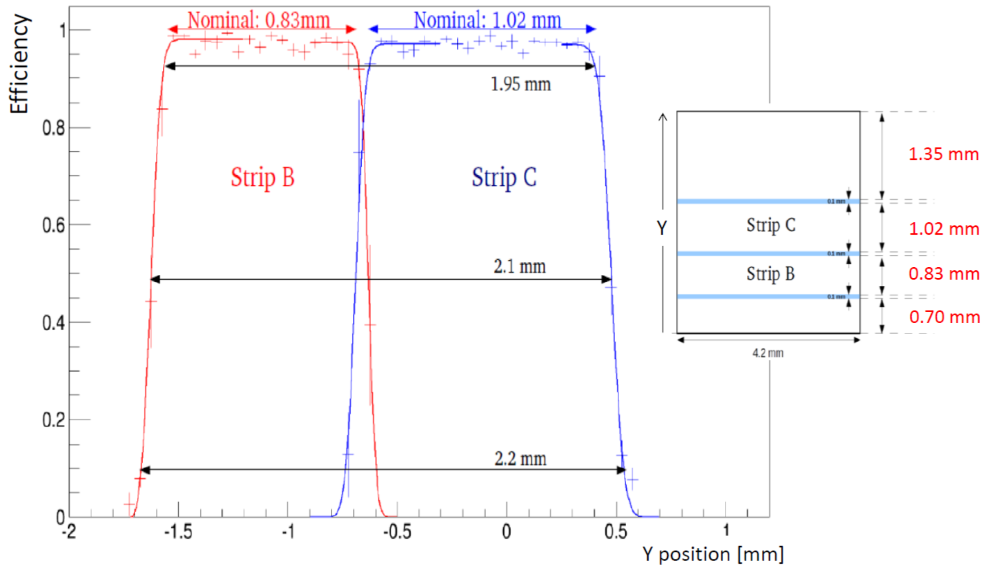
Sensor readout performed with oscilloscope or SAMPIC sampler.



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



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



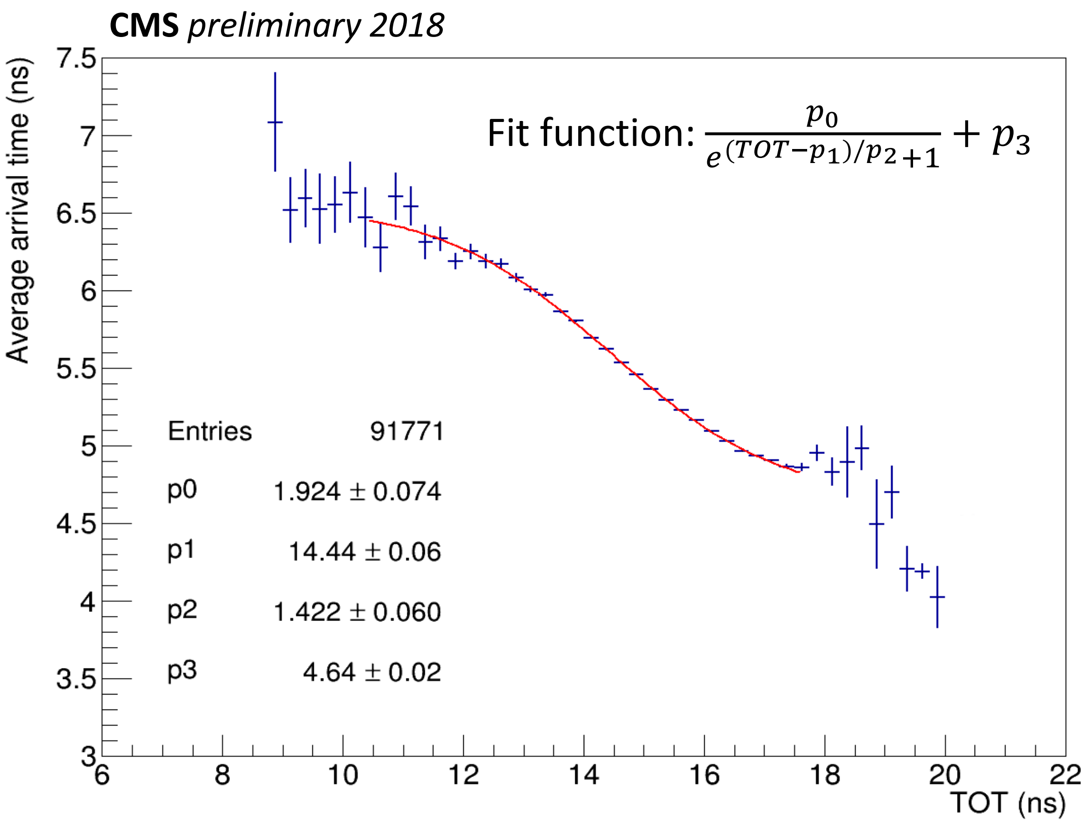
Efficiency between strips

CMS DP-2019/034

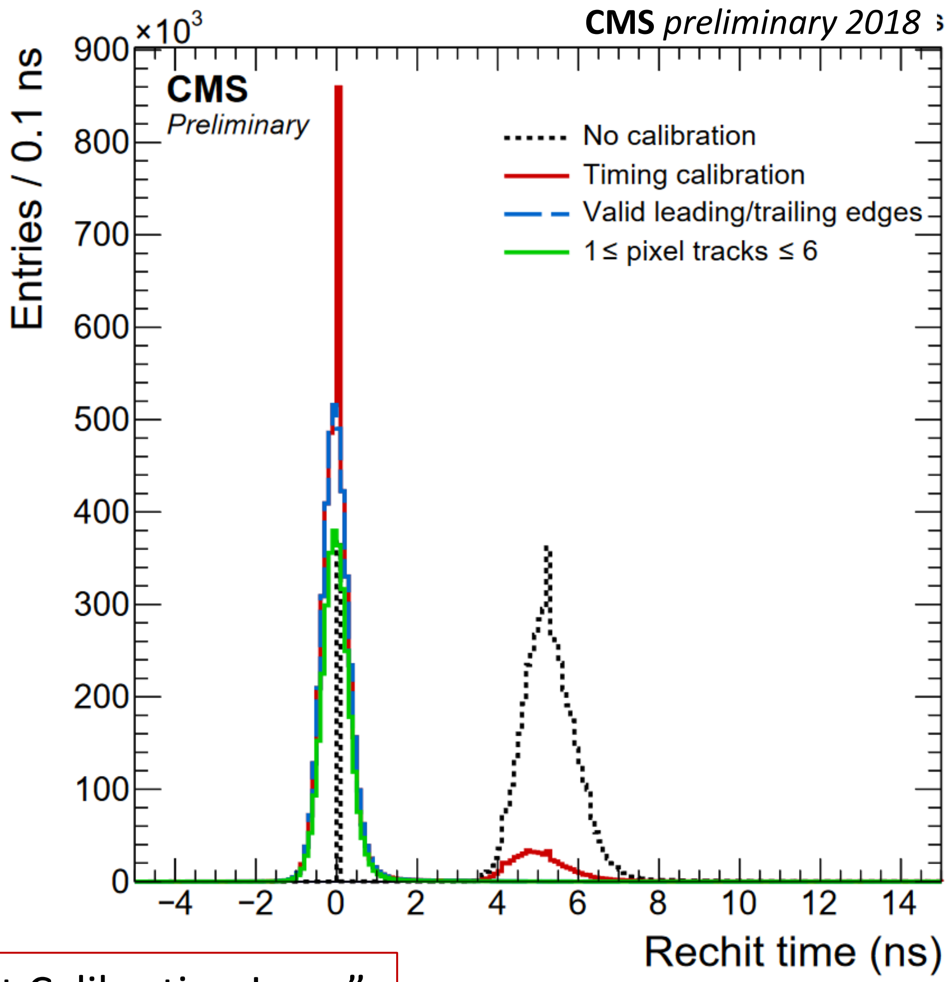
Run 2 timing calibrations

System calibration developed for Run 2 data, 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.



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



In Run 3 procedure included in "Prompt Calibration Loop"

PPS timing system:

<u>Readout & clock distribution</u>

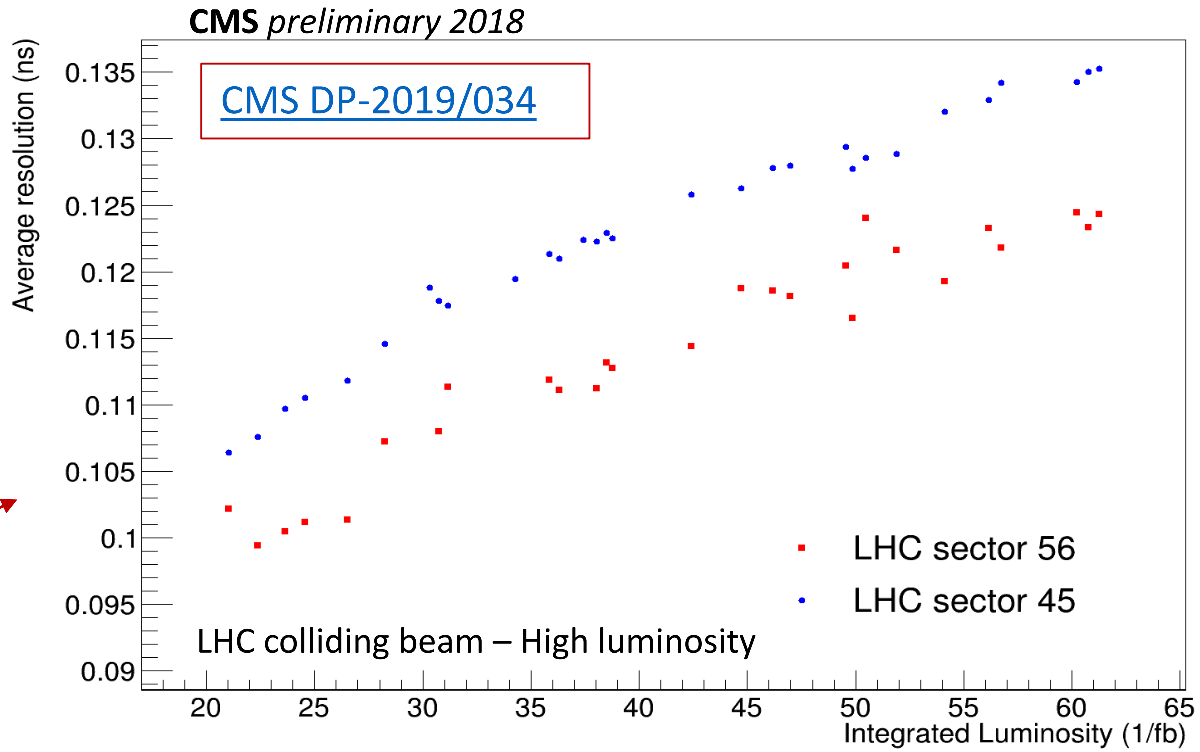
- ➢ Readout in LHC : discriminator (NINO) + TDC (HPTDC).
  - NINO chip encode input charge information in the output duration -> “Time walk” correction.
  - Can sustain the particle flow rate (~MHz/channel)
  - Reduction of time resolution 20-30%.
- ➢ Dedicated optical clock distribution with measured jitter < 2 ps and continuous phase monitoring
  - Online monitoring & offline shift correction
  - Clock phase tunable in ~18ps steps
  - In 2017 a clock system based on an RF distribution was also used.

- The time precision of each pad, computed through an iterative procedure, is used to estimate the precision of the proton time and to perform a weighted average of all measurements.
- In 2018 2 single diamond (SD) and 2 double diamond (DD) planes were installed in each timing RP

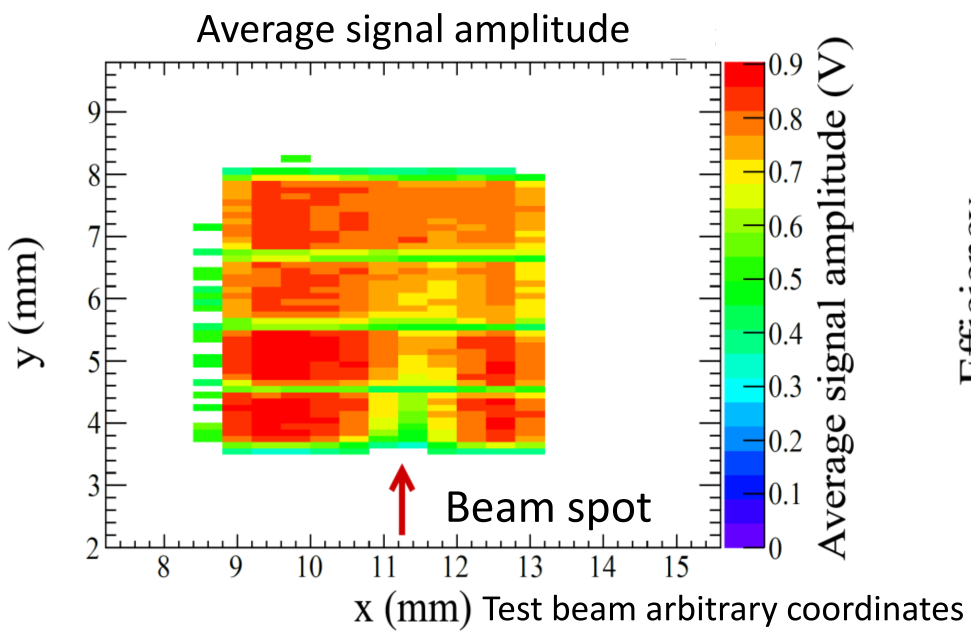
Some issues prevented exploiting the full potential of the detector:

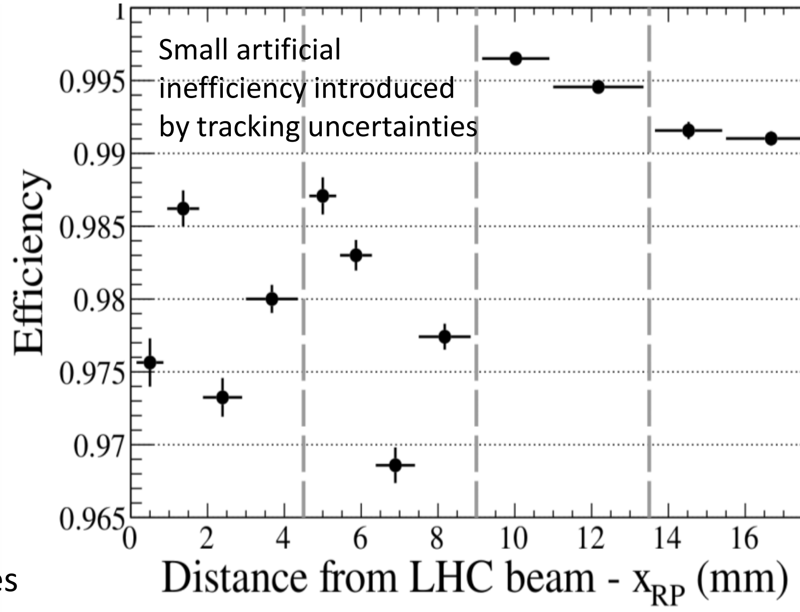
- RF noise pickup inside RP -> reduced amplifier gain
- Beam induced HV discharges -> reduced bias voltage

In Run 3 we will be able to remotely control the amplifiers gain.



Study on Run 2 irradiated sensor

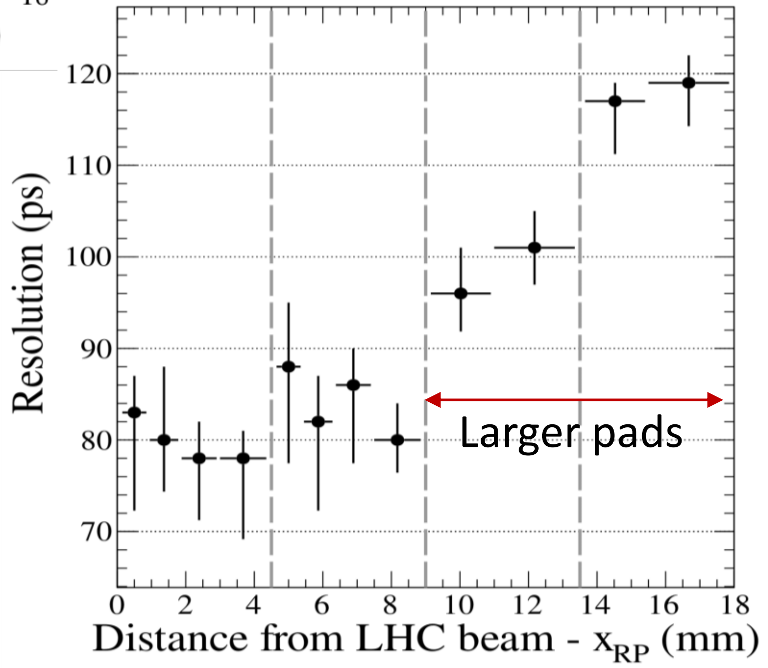




1. Run2 crystals will be reprocessed and used again in Run3
2. New version of Hybrid board:
   - RF stability
   - Pre-amp location
   - HV isolation

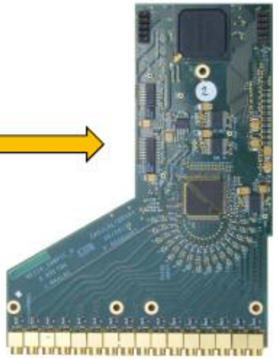
All timing planes dismounted and tested @ DESY with nominal LV/HV, SAMPIC (fast sampler) readout ([CMS NOTE-2020/007]):

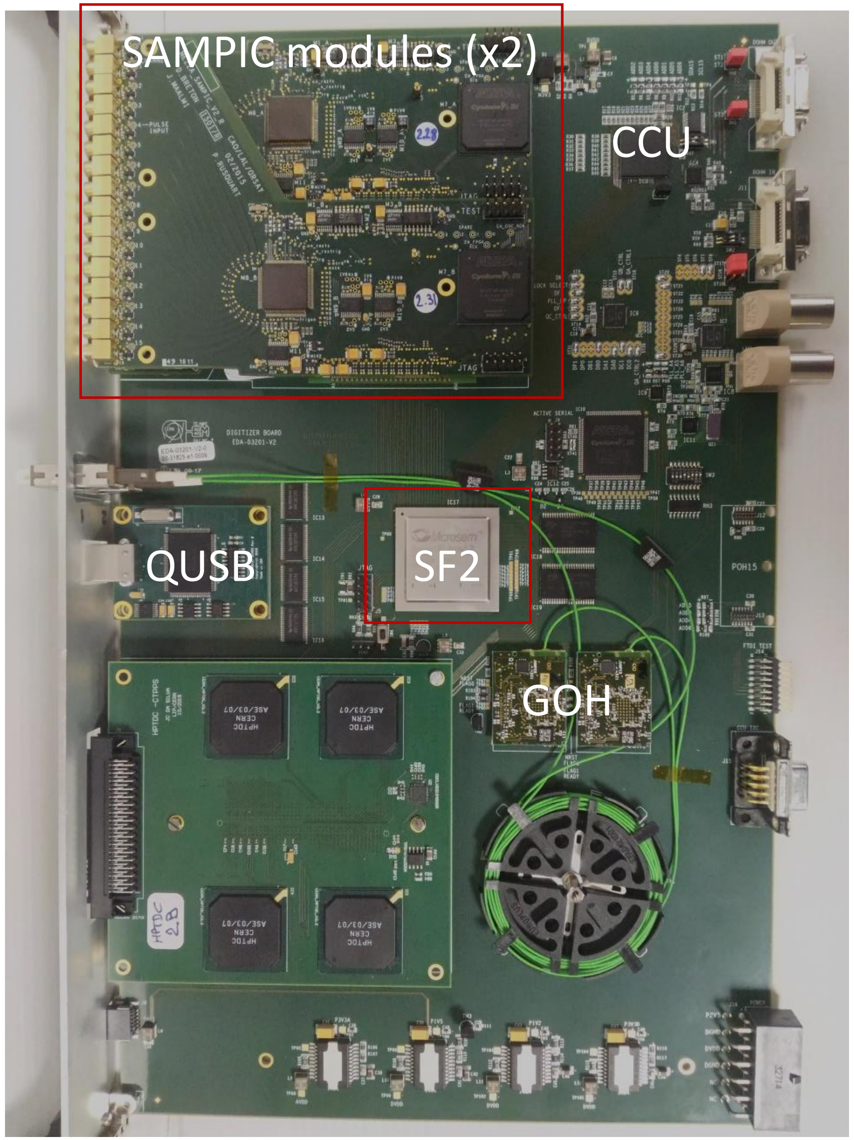
- Radiation damage to crystals identified and characterized in small area ($\sim 1\ \text{mm}^2$)
- Confirmed overall loss of performance due to pre-amp irradiation $\sim 30 - 40\%$
- Sensors operated with nominal gain/bias show high efficiency also in the most irradiated area
- Time resolution in the peak area only reduced by 10% w.r.t. the rest of the sensor



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)

Readout with a sampler





SAMPIC chip:

- 16 channel/chip
- Up to 64 sample/hit @ 10 GSa/s
- 1.5 GHz bandwidth
- 8-11 bit resolution
- 0.25-1.6 µs channel dead time

SAMPIC used as readout system for the TOTEM timing (UFSD) during the special TOTEM-CMS joint data taking in 2018.
Special optics -> Lower rate

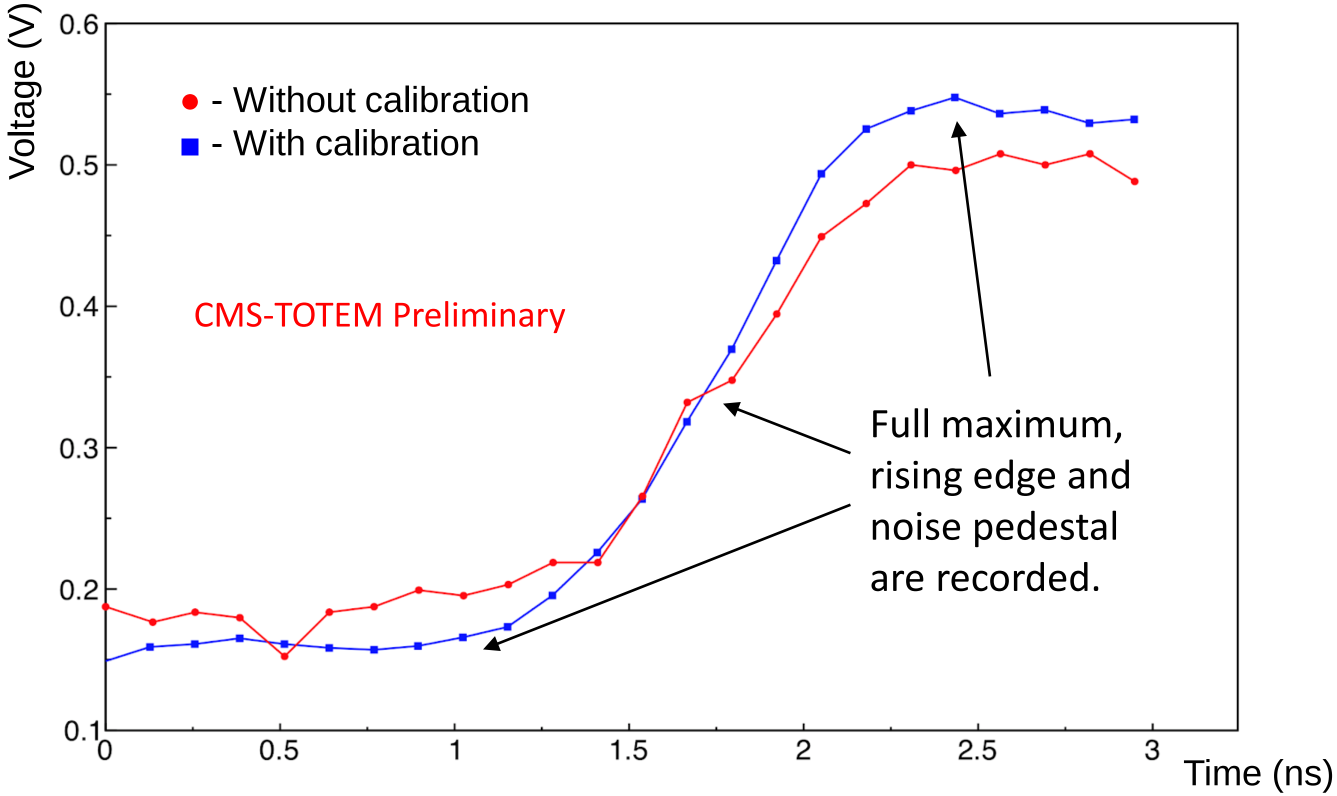
To be used in TOTEM/CMS needs additional capability:

- Event buffering
- Event building
- Synchronization with central DAQ
- Zero suppression and data compression

Timing readout with a sampler

A readout based on fast sampler (SAMPIC) was used for the TOTEM timing (based on UltraFast Silicon Detectors) during the special TOTEM-CMS joint data taking in 2018 (High-β^* special optics -> Lower rate, on average ~50KHz/channel).

Example of waveform



- Very good quality of the collected waveform
- Operations with CMS DAQ stable
- Efficiency of the readout above 99%
- No sizable timing degradation introduced

- SAMPIC operated at 7.8 Gsa/s, with 8 bit voltage resolution.
- 24 samples collected for each waveform (recording window of $\sim$3.1 ns)

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