Status and perspective of the CMS Precision Proton Spectrometer timing system

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FAST 2023, La Biodola, Italy
31 May 2023

OUTLINE:

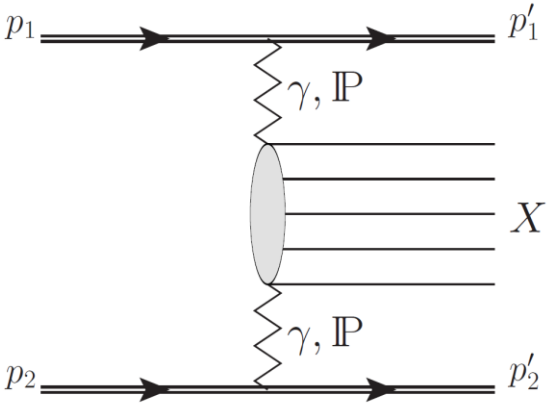
- PPS project overview
- Run 3 timing system
- Run2 performance & rad. hardness
- Current status
- PPS timing @ HL-LHC

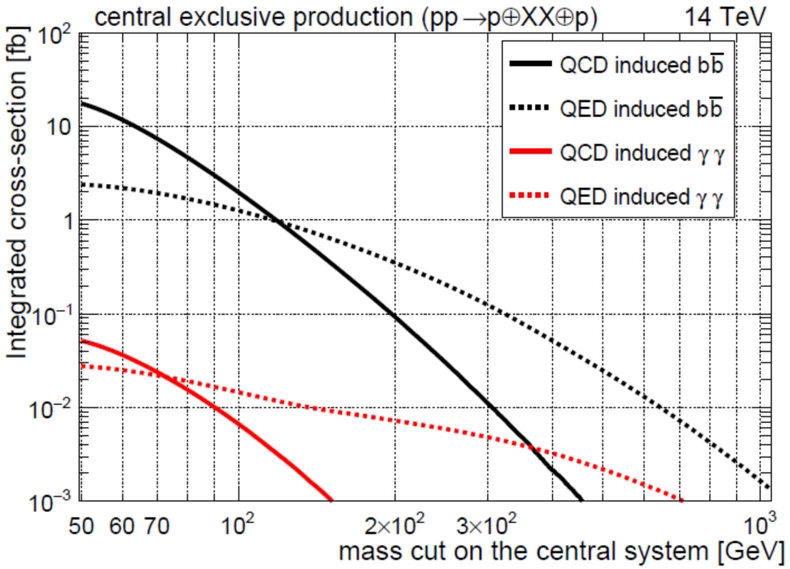
Physics motivation

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.

$pp \rightarrow p \oplus X \oplus p$ ($\oplus$= large 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
- …



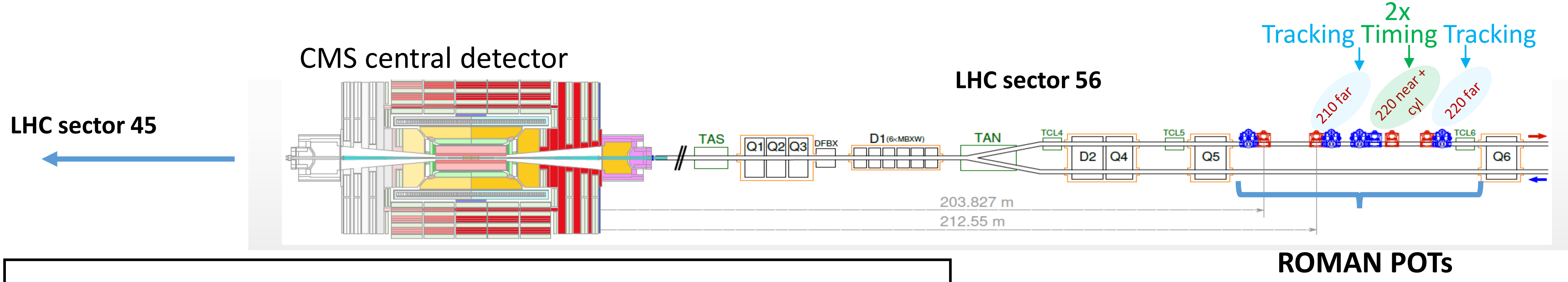


PPS can measure the proton kinematics; in conjunction with the information from the central CMS apparatus, the full event can thus be reconstructed.

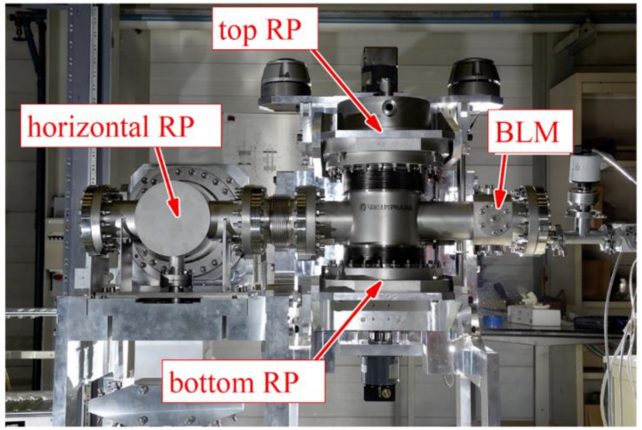
Reconstruction of mass and momentum of the central system X can be carried out from the proton information ($M_X = M_{PP} \sim \sqrt{\xi_1 \xi_2 s}$, where ξ is the proton fractional momentum loss) and compared with the central CMS measurements for background rejection.

PPS detector in Run 3

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



- Standard RP units composed of 3 Roman Pots (RP) with box housing: 2 vertical (used by TOTEM), 1 horizontal (used by PPS)
- 1 additional horizontal RP on each arm with cylindrical housing used as timing station
- Hosted detector brought to few mm from the beam
- RP infrastructure from TOTEM



Detectors operate in a secondary vacuum

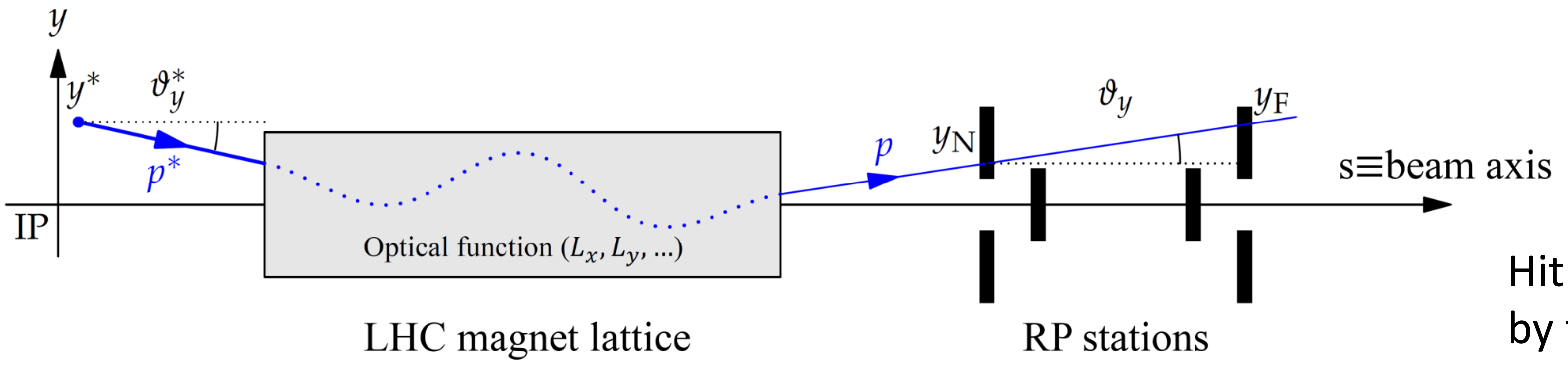
PPS RPs inserted at **12 σ_{beam}+ 0.3 mm (~1.5 mm) from the LHC beams**

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

Several technologies in use during Run 2, for both timing (single-side & double-side diamond, LGAD) and tracking (Si-strip, 3D pixel) stations.

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

Proton reconstruction: basic concepts



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

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

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.

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

➡

The solution relies on the measurements the time-of-flight of the two protons in the two sector. The difference can be used as a measurement of the longitudinal position of the interaction vertex:

$$Z_{PP} = c\Delta t/2$$

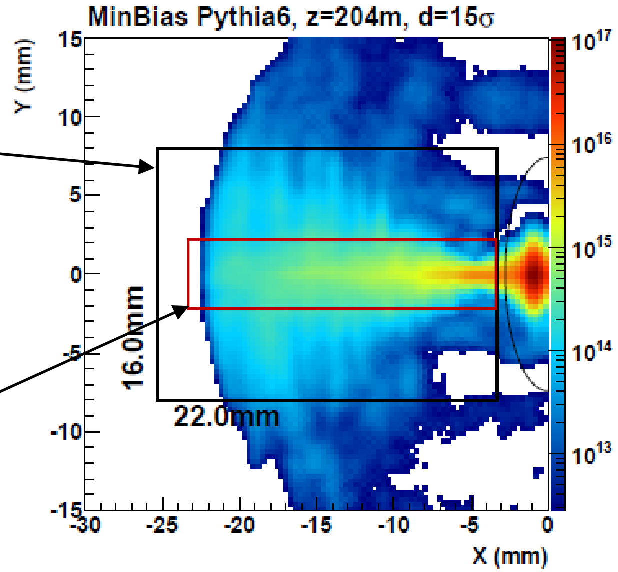
Timing detectors

PPS timing 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 shower probability)
- 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

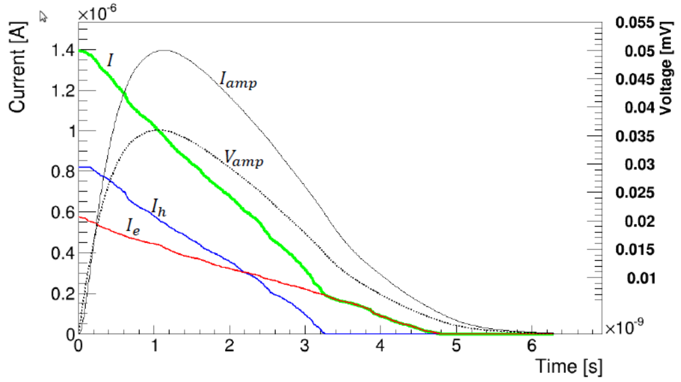


Simulated particle flux for 100 fb^{-1} (~300 fb^{-1} expected in Run 3).

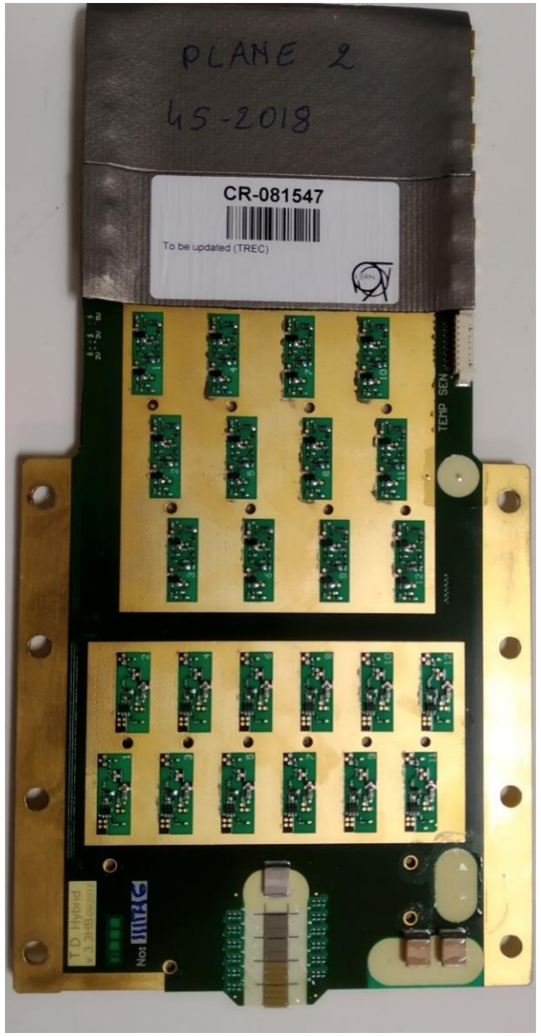
PPS timing sensor based on ultra pure single crystal CVD diamonds. Each crystal has dimensions 4.5x4.5x0.5 mm^3, with a total area coverage $\sim 80\ \mathrm{mm}^2$.

Main intrinsic signal characteristics:

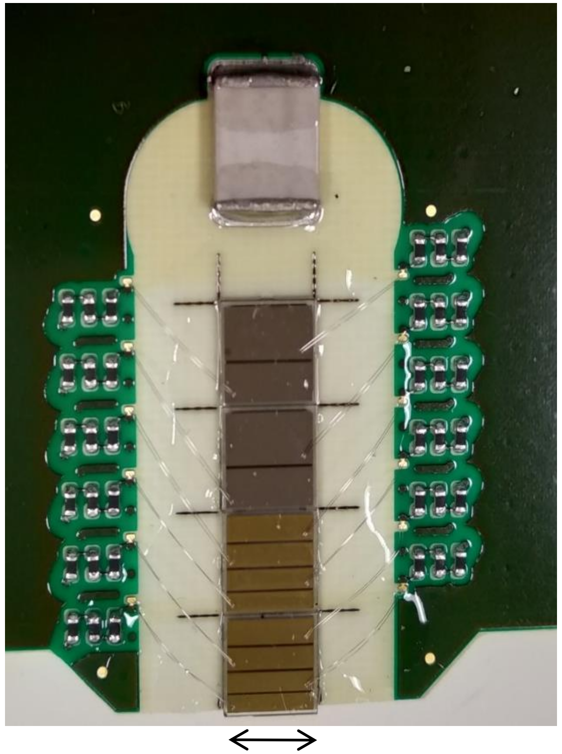
- Fast rise time (no gain, few ps)
- Very low noise (<nA) → Noise dominated by pre-amp input stage
- Low signal ~ 1 fC/MIP
- Electron/hole mobility nearly equal



PPS diamond sensors



- 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.

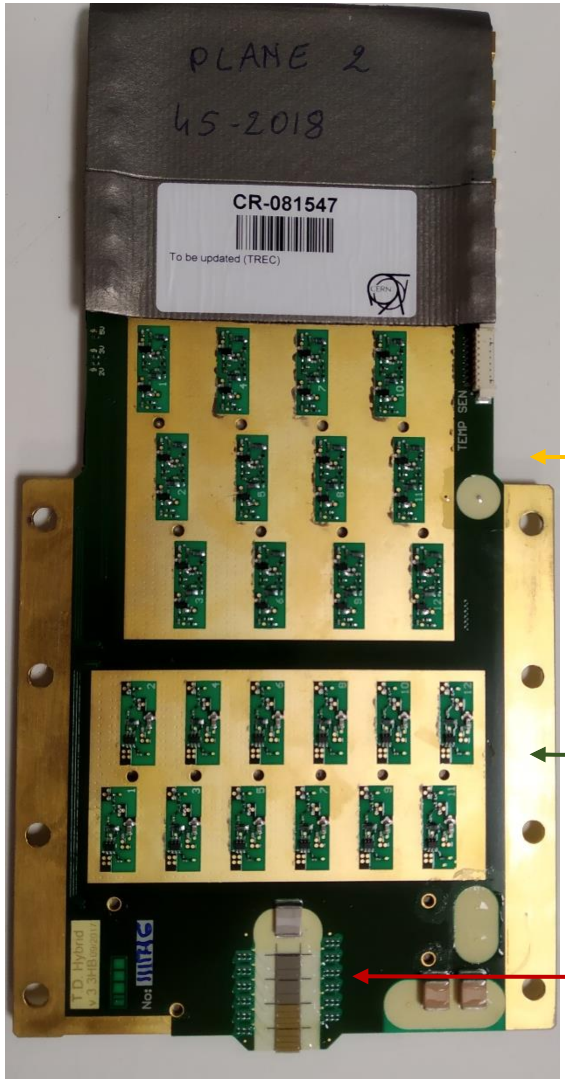


4.5 mm

- 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 (~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 ≥ 400 V)

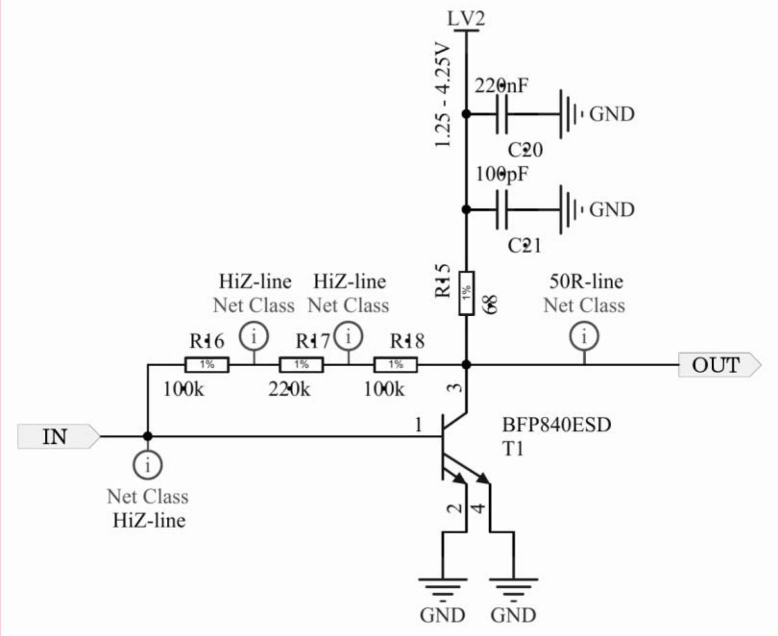
Diamond hybrid board

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



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

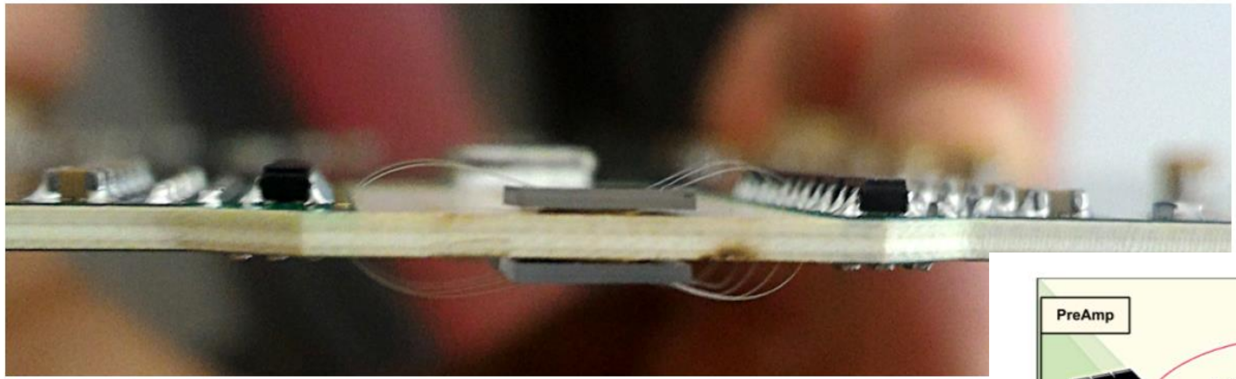
Amplifier:
Monolithic microwave integrated circuit ABA-53563, near linear phase, absolute stable amplifier

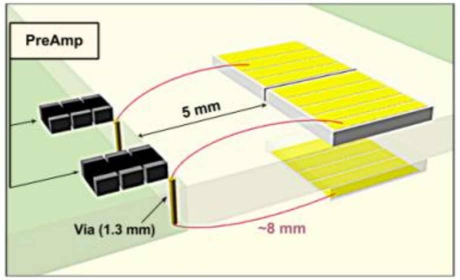


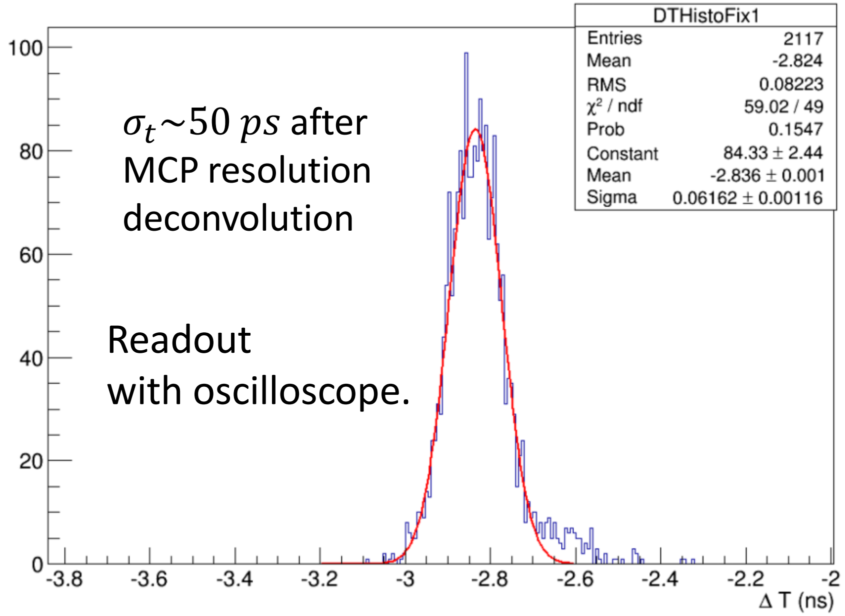
Pre-Amplifier:
stage BFP840 SiGe BJT with low-C feedback (~0.4 pF)

Double Diamonds (DD)

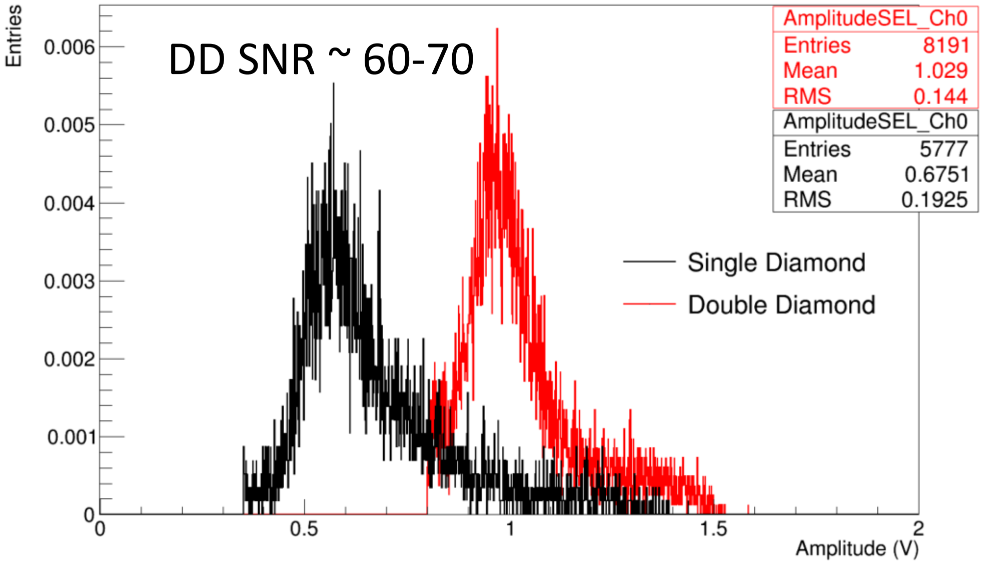
JINST 12 (2017) no.03, P03026







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



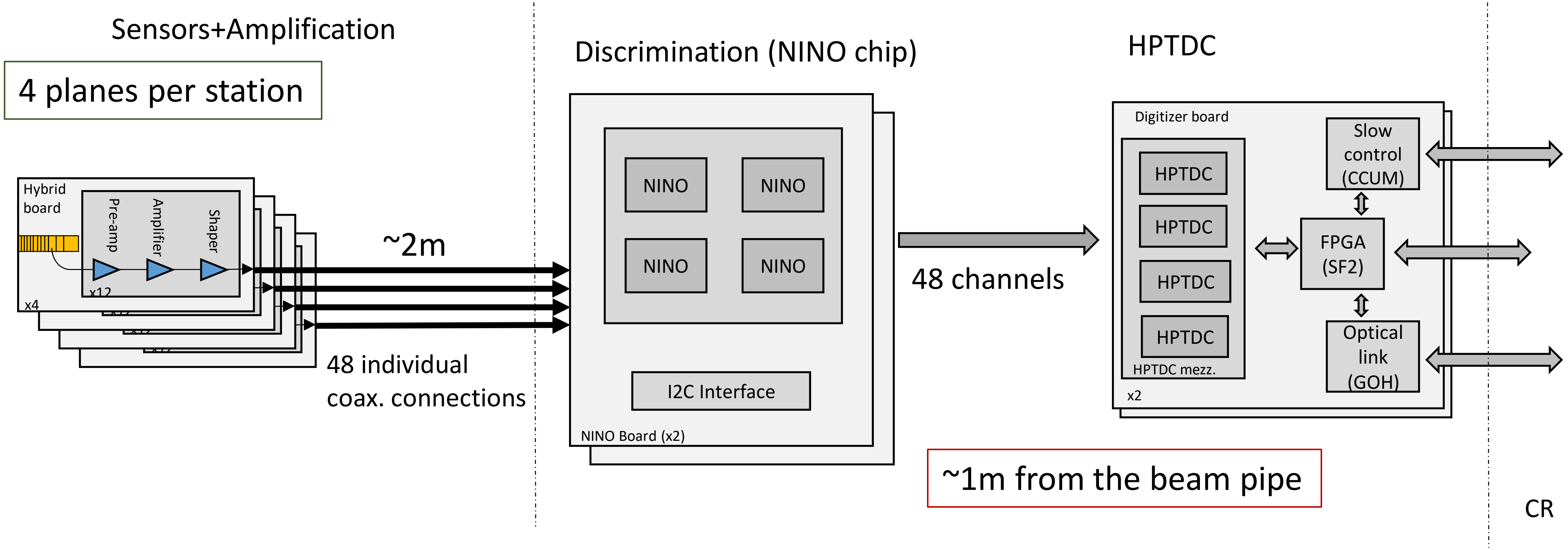
Signal amplitude comparison between DD and SD

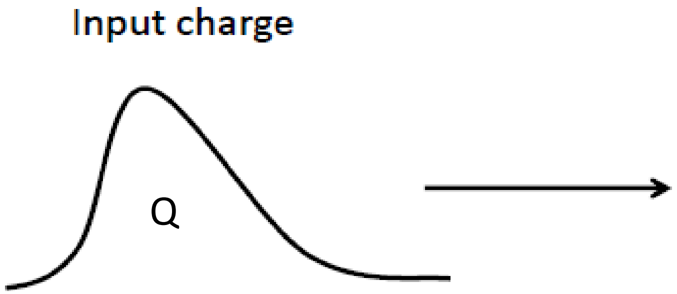
Signal from corresponding pads is connected to the same amplification channel:

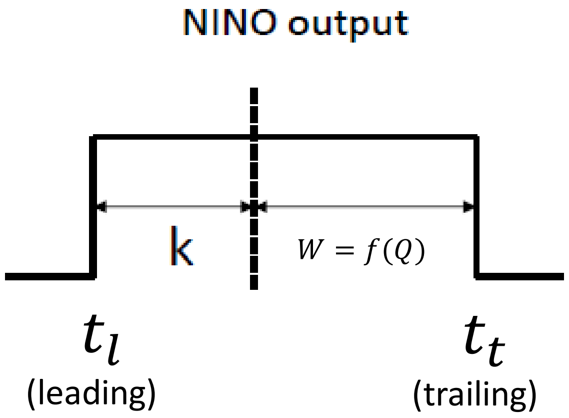
- Higher signal amplitude
- Same noise (pre-amp dominated) and rise time (defined by shaper)
- Higher sensor capacitance
- Need a very precise alignment

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

Run 3: main detector readout



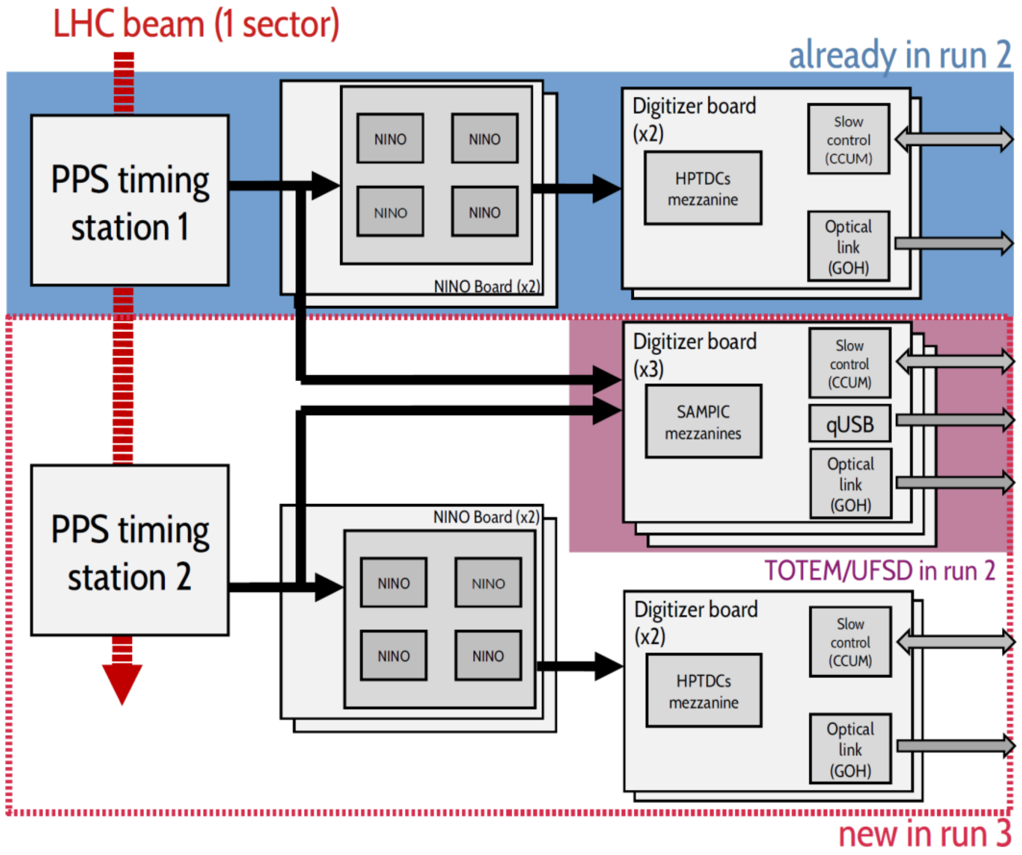


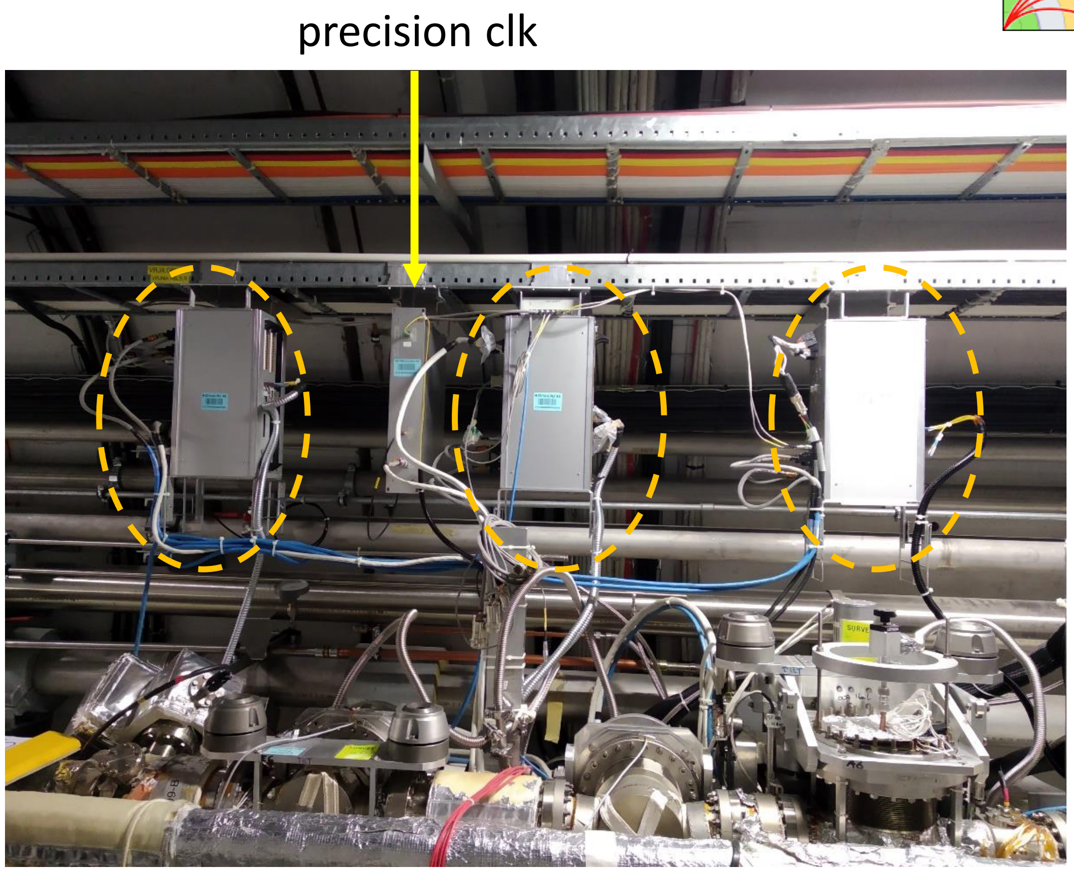


TOT = t_t-t_l = k+$f(Q)$

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

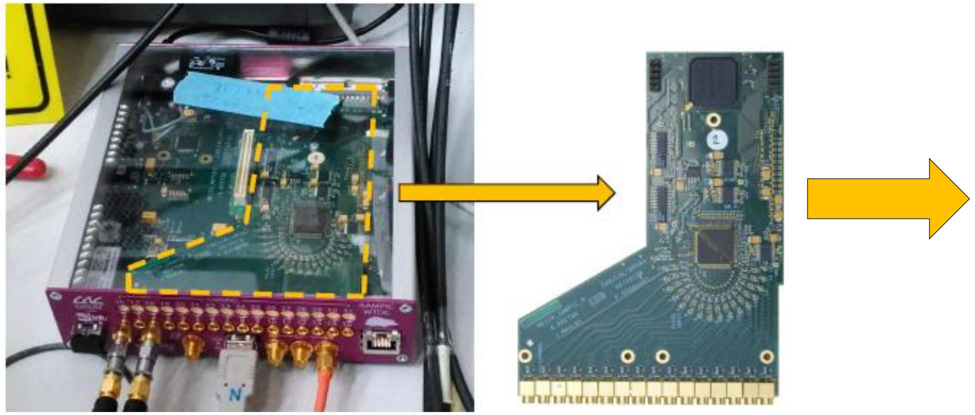
Run 3 : full system





Secondary readout available: sensor readout with SAMPIC (not the latest version) chip (fast sampler operated in PPS @ 7.8 Gsa/s) available for commissioning phase and sensor monitoring (cannot sustain hit rate at nominal luminosity, above 1 MHz/channel).

Readout with a sampler

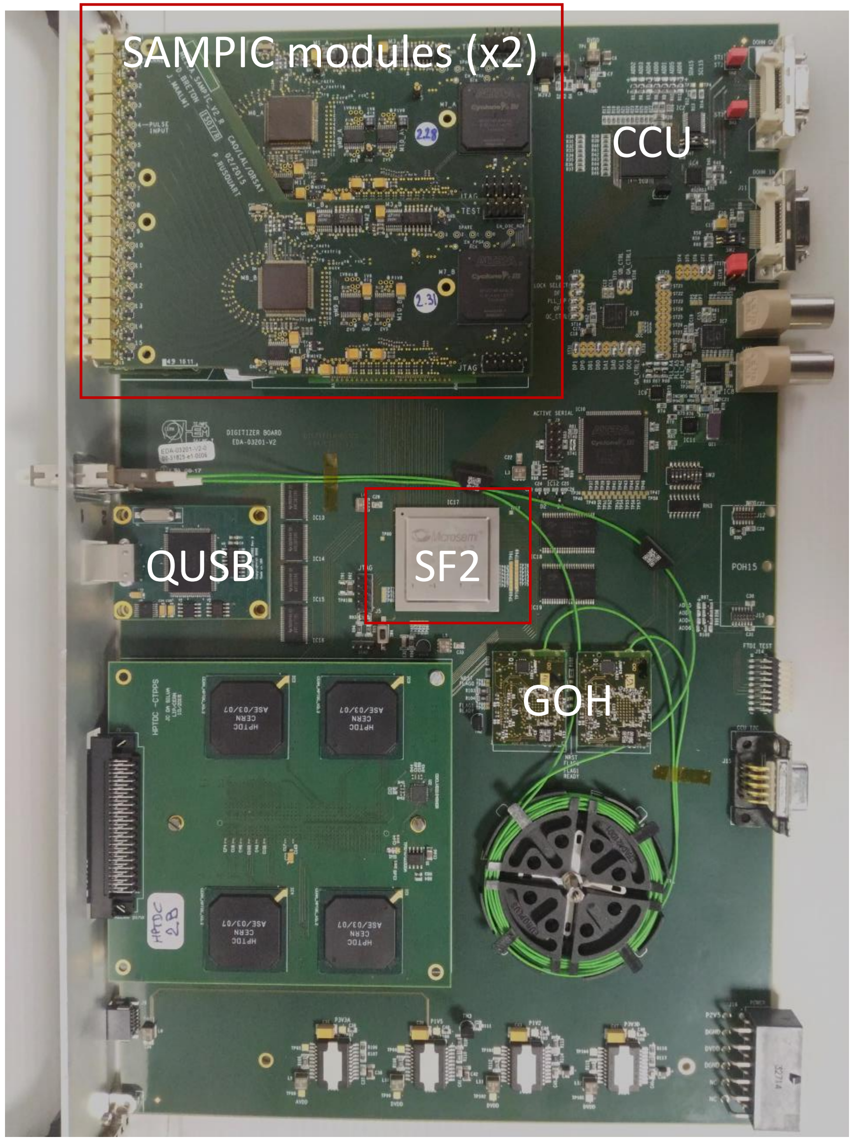


SAMPIC chip:
- 16 channel/chip
- Up to 64 sample/hit @ 10 GSa/s
- 1.5 GHz bandwidth
- 8-11 bit resolution
- 0.25-1.6 µs channel dead time

The TOTEM Digitizer is a general-purpose board designed to integrate different detector digitization systems to the TOTEM and CMS readout and control systems.

To be used in TOTEM/CMS additional capability are added through the Microsemi SF2 FPGA on the Digitizer board:

- Long data buffering capability (~10us)
- Event building
- Synchronization with central DAQ
- data compression

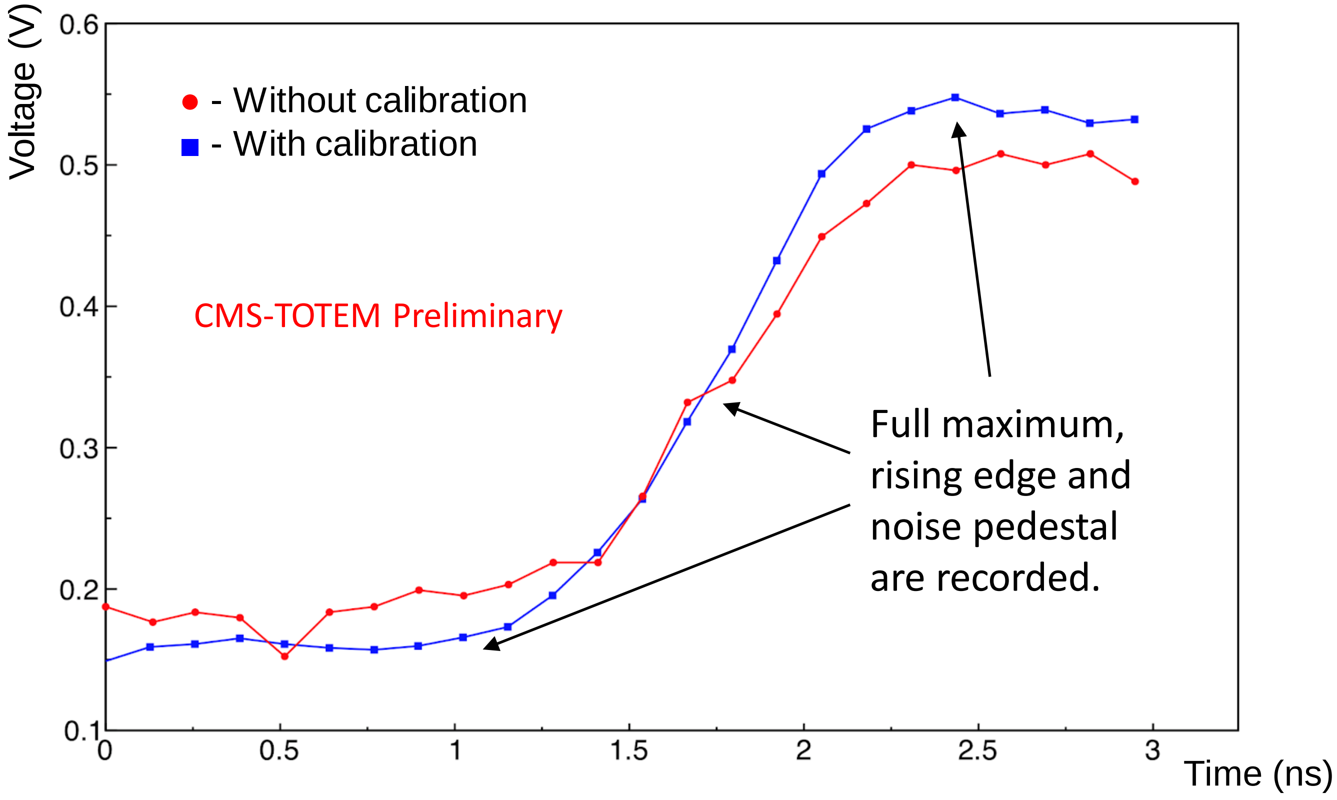


TOTEM/CMS Digitizer board

Timing readout with a sampler

The readout was originally developed and used for the TOTEM timing (based on LGAD Detectors) during the special TOTEM-CMS joint data taking in 2018 (High-β^* special optics -> Lower rate, on average ~50KHz/channel).

Example of waveform



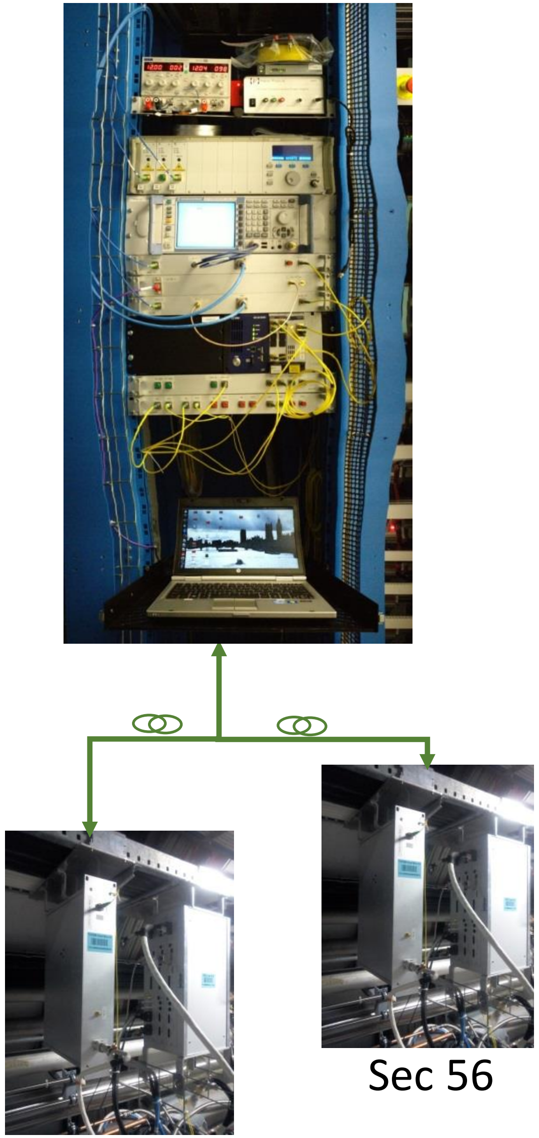
- Very good quality of the collected waveform
- Operations with CMS DAQ stable
- Efficiency of the readout above 99%
- No sizable timing degradation introduced

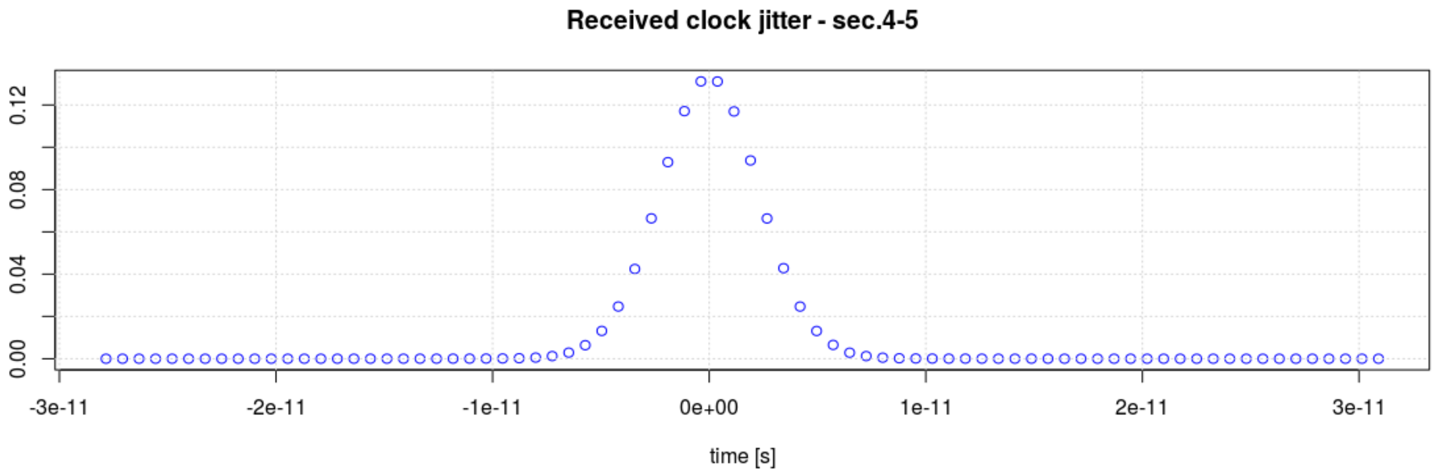
- SAMPIC operated at 7.8 Gsa/s, with 8 bit voltage resolution, to reduce payload size.
- 24 samples collected for each waveform (recording window of ~3.1 ns)

PoS TWEPP2018 (2019) 137

Clock system

- LHC clock is derived from CMS TCDS (Timing Control Distribution System)
- System delay changes over optical path are 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:

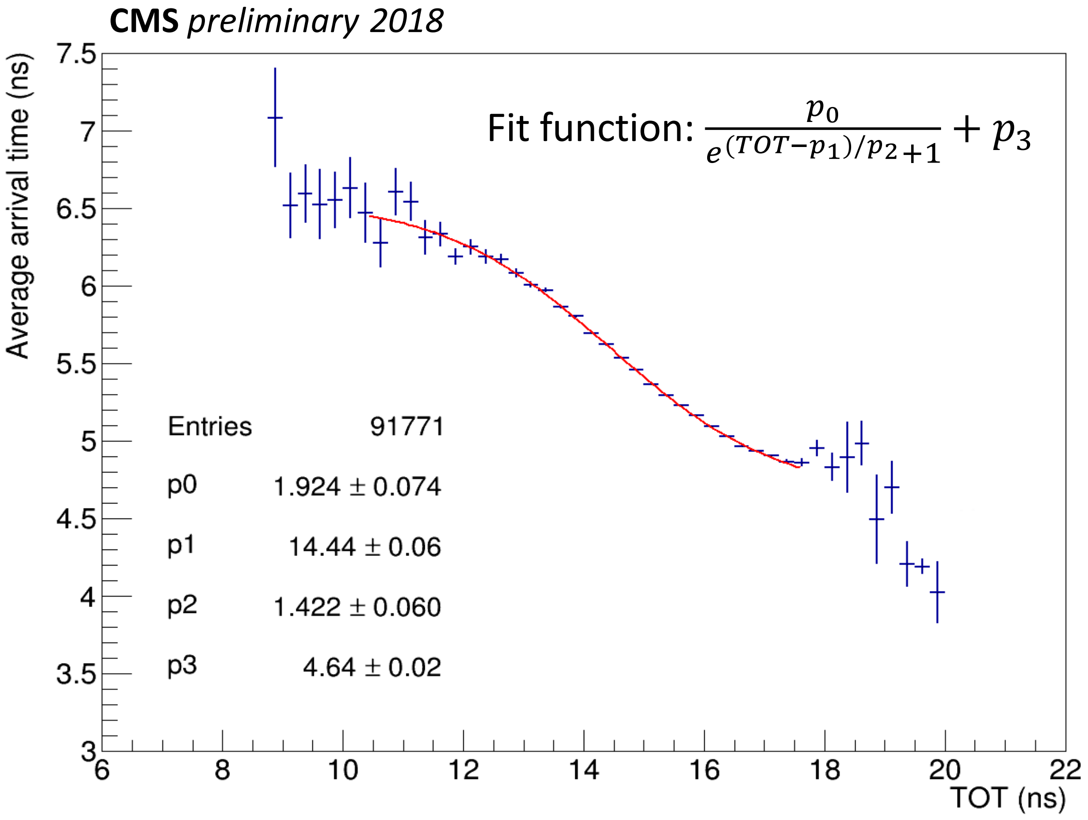
- Zero delay mode → constant phase delay between input and output
- Clock phase will be tuneable in ~18ps steps.

CMS DP-2019/034

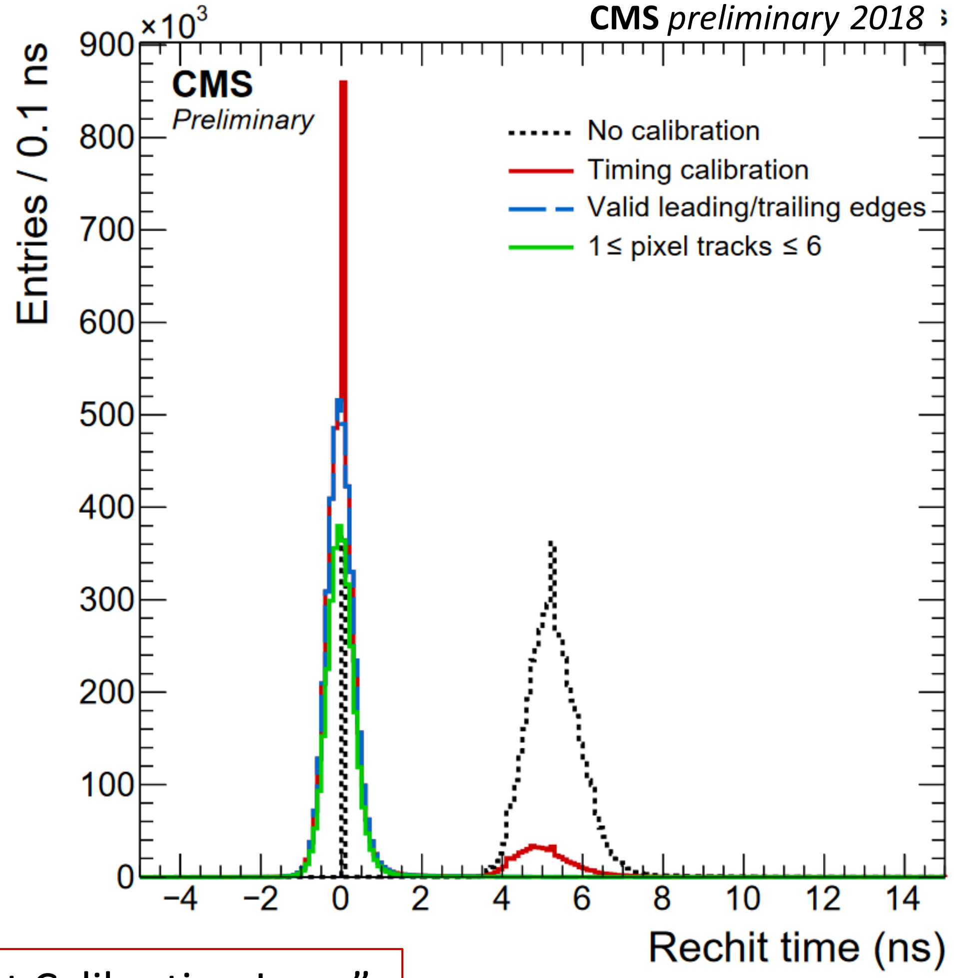
Calibrations & time reconstruction

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)

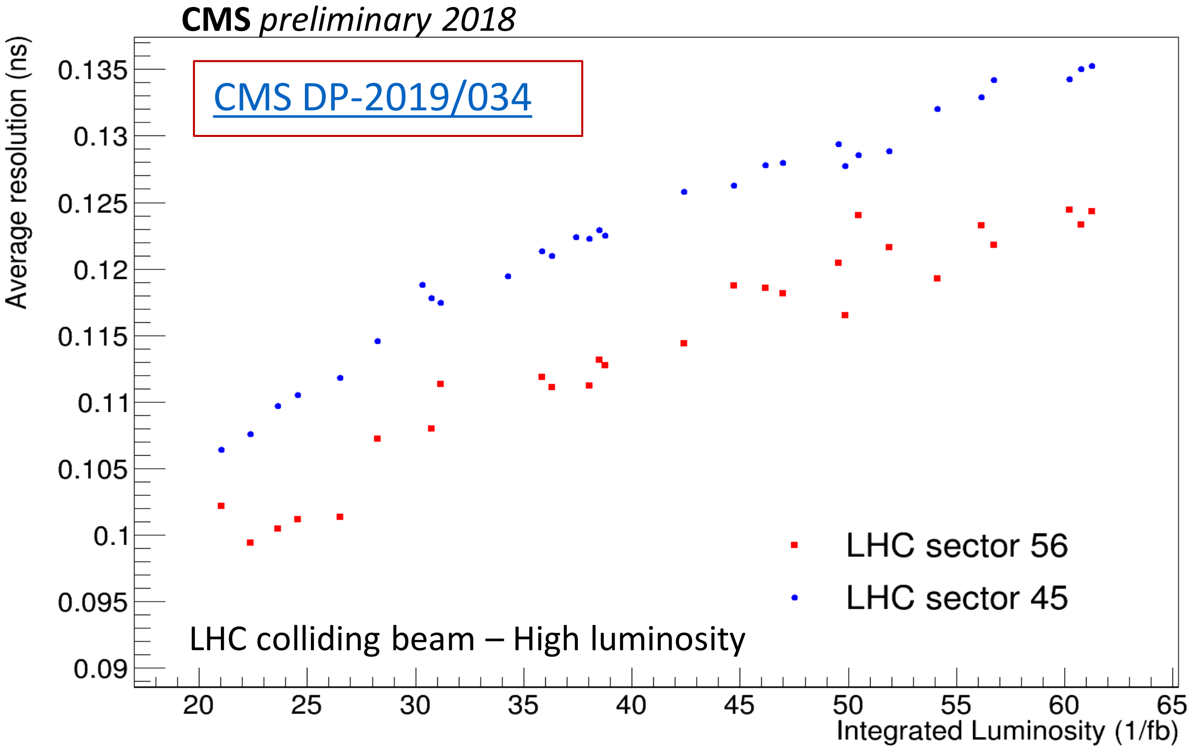


In Run 3 procedure included in "Prompt Calibration Loop"

What we learned (in the hard way) from Run 2

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
- Loss of signal amplitude from the amplifier



In 2018 2 single diamond (SD) and 2 double diamond (DD) planes were installed in each timing RP

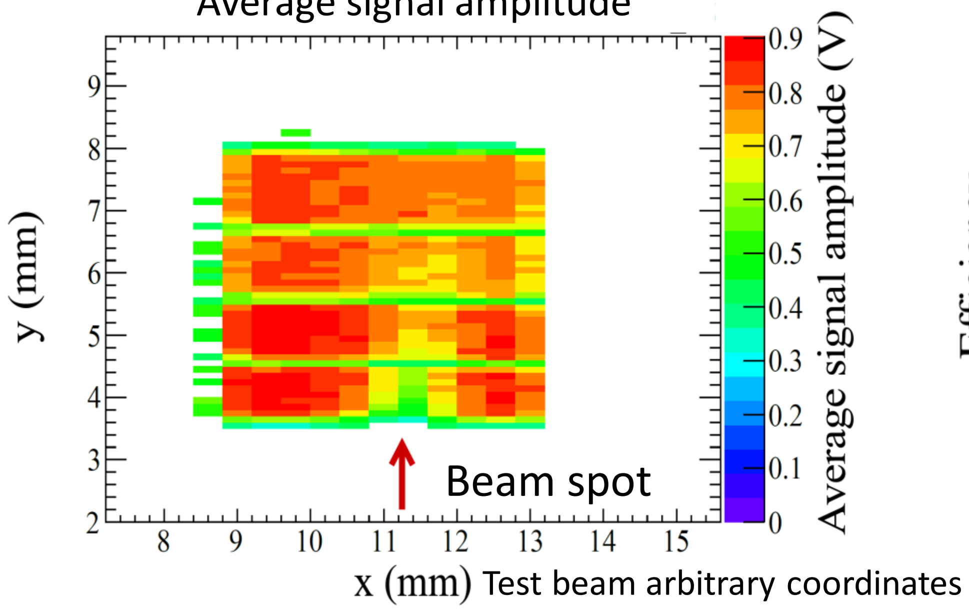
1. New version of Hybrid board produced:
   - improved RF stability
   - Pre-amp re-located further from beam
   - better HV isolation

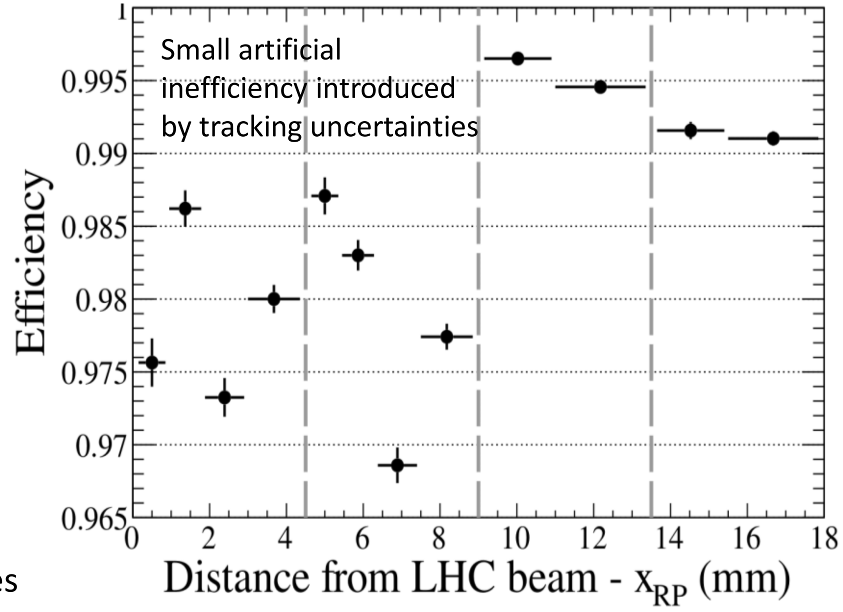
2. Remote control of amplifier gain implemented
3. New design of RF absorber to be used on the individual plane and on RP walls

New hybrid demonstrated to be fully stable at any amplifier gain, with or without beam presence. For the time being no degradation of pre-amp observed (based on the noise level).

Still we are suffering of some instabilities on HV. Detector conditioning and new recovery procedure being implemented.

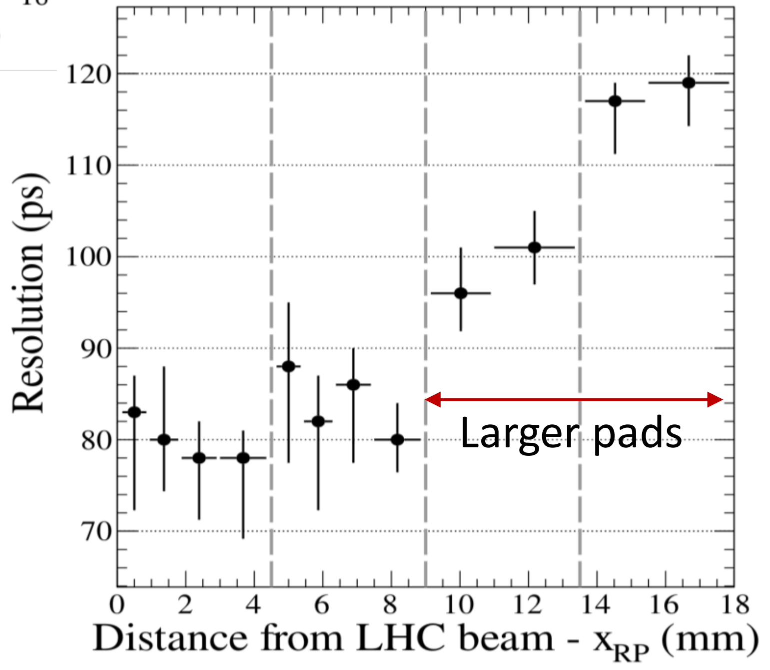
Study on Run 2 irradiated sensor





Run2 crystals reprocessed by TISCM (Russia) and used again in Run3.

They currently constitute ~30% of the Run 3 crystal.



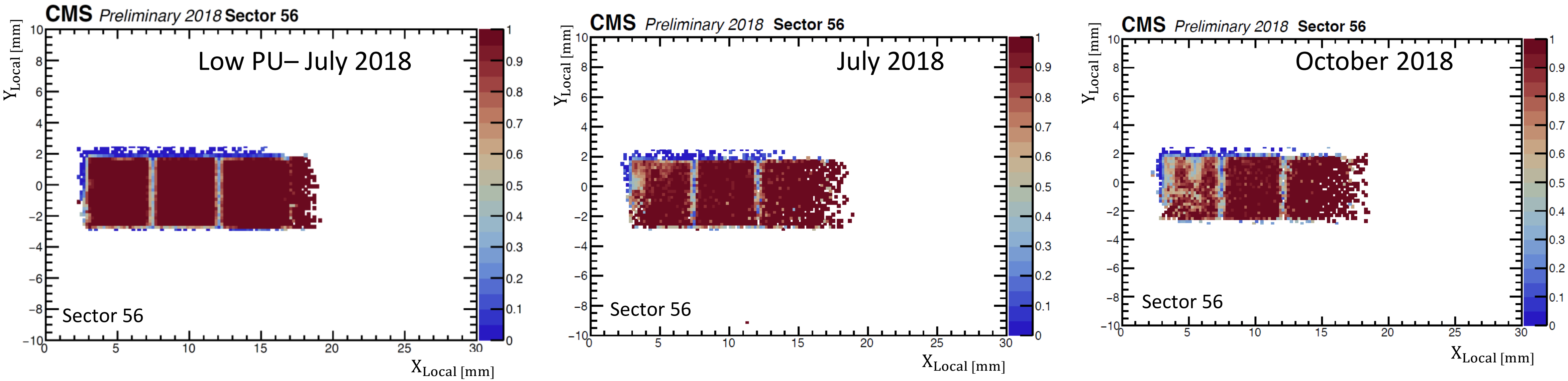
All timing planes dismounted and tested @ DESY with nominal LV/HV, SAMPIC (fast sampler) readout (CMS NOTE-2020/007):

- Radiation damage to crystals identified and characterized in small area ($\sim 1\ \mathrm{mm}^2$)
- 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)

CMS DP-2020/046

Run 2 detector efficiency

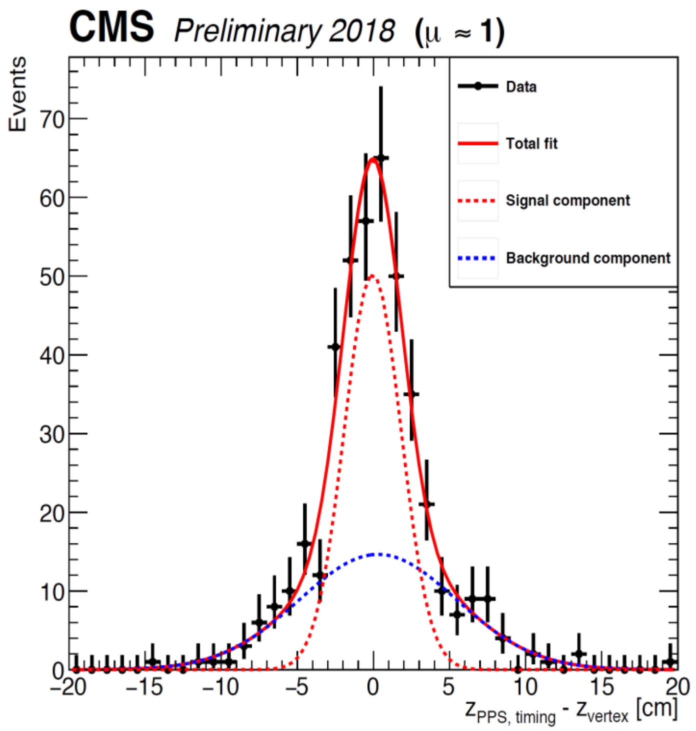


- The time-tracks, defined as a combination of at least 2 time measurements, have an efficiency near 100% in a low pileup fill from July 2018
- The evolution at the end of Run 2 (October 2018) shows a degradation of the efficiency
- Systematic lower efficiency is only visible in the regions between two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

CMS DP-2020/046

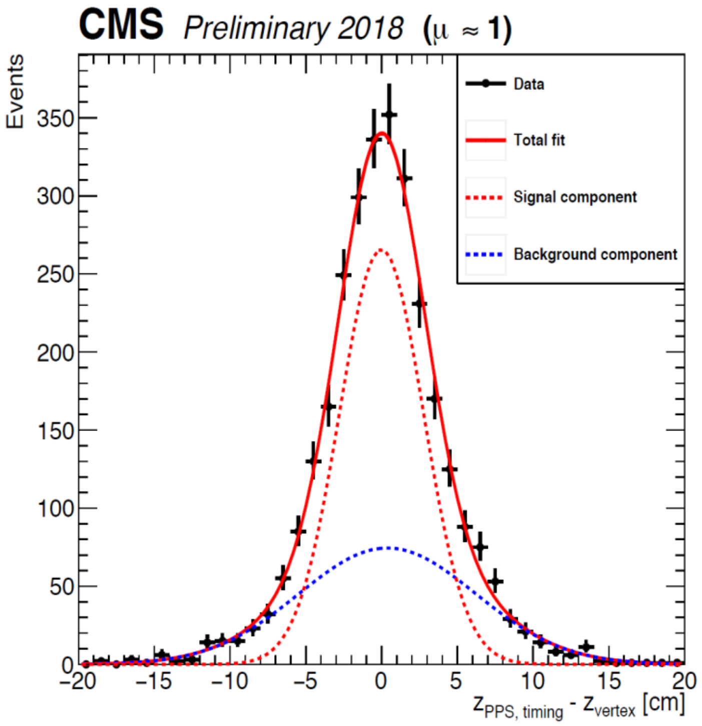
Run 2 vertex resolution

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



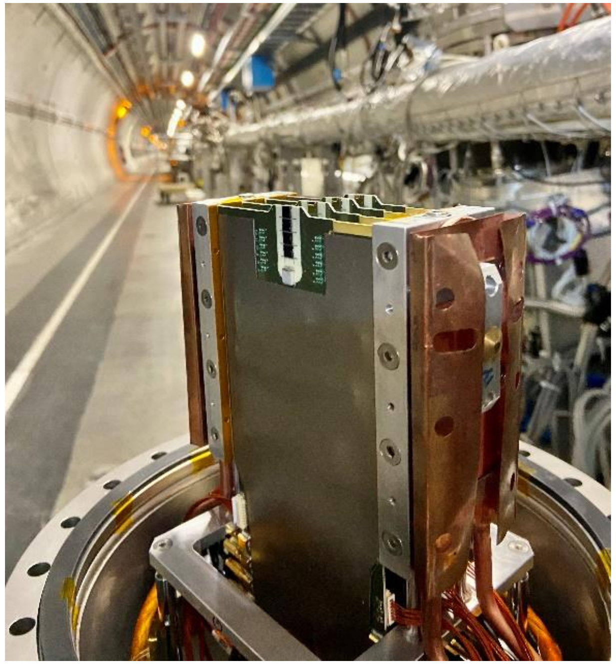
All timing tracks
$\sigma_{Zpp} = 2.77 \pm 0.17$ cm

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

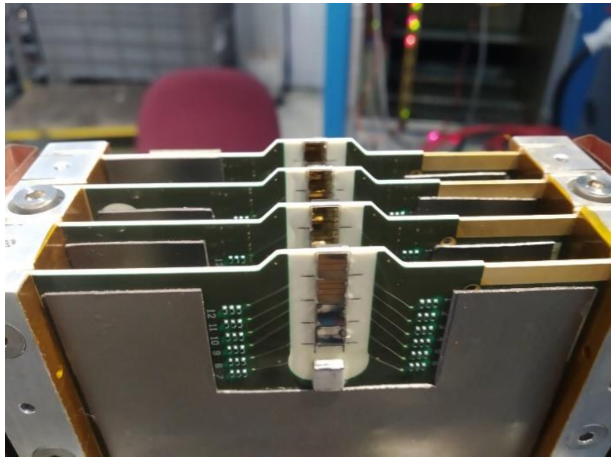


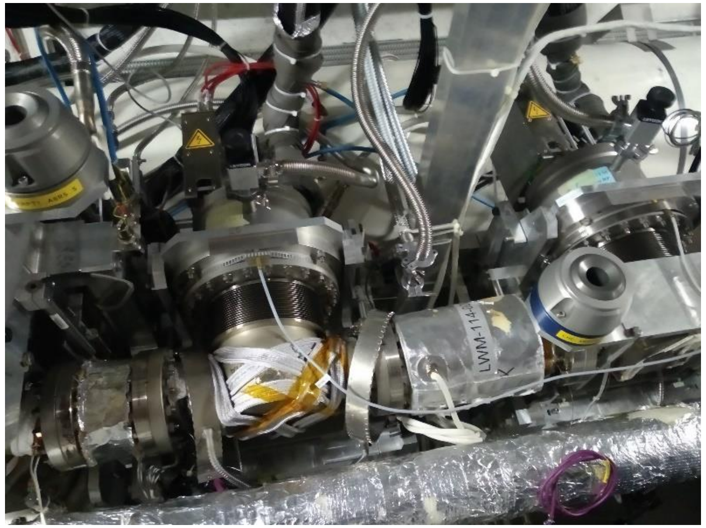
- A correlation is observed between the time difference of the protons detected in PPS, and the longitudinal vertex position reconstructed in the central CMS tracker
- The vertex resolution, inferred from the width of the correlation distribution, is consistent with the resolution predicted from the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

Run 3 operations and status



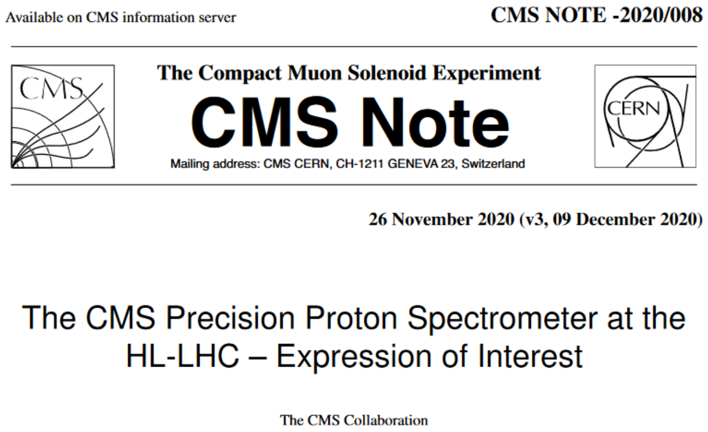
- All digital electronics has been installed and commissioned before the restart of LHC operation in 2022. Both read out systems (HPTDC & SAMPIC) are fully operational.
- One timing RP per sector installed and commissioned in 2022.
- 2nd set of timing stations installed and commissioned in March 2023. Due to several issues in diamond metallization/reprocessing the new stations have been equipped with only 3 planes. The missing plane could be installed during the next winter shutdown.
- All timing RPs in stable data taking in CMS runs. Work ongoing to optimize and study detector performance.





PPS for HL-LHC

Most measurements will be limited by statistical uncertainties with the full Run 2+3 dataset. In addition, searches for new phenomena will benefit from the higher integrated luminosities of HL-LHC.
The increased mass range available at HL-LHC would increase the acceptance for both direct and indirect searches for BSM physics and significantly enhance the statistics for all Standard Model and Higgs processes.



Available on CMS information server — CMS NOTE -2020/008

The Compact Muon Solenoid Experiment

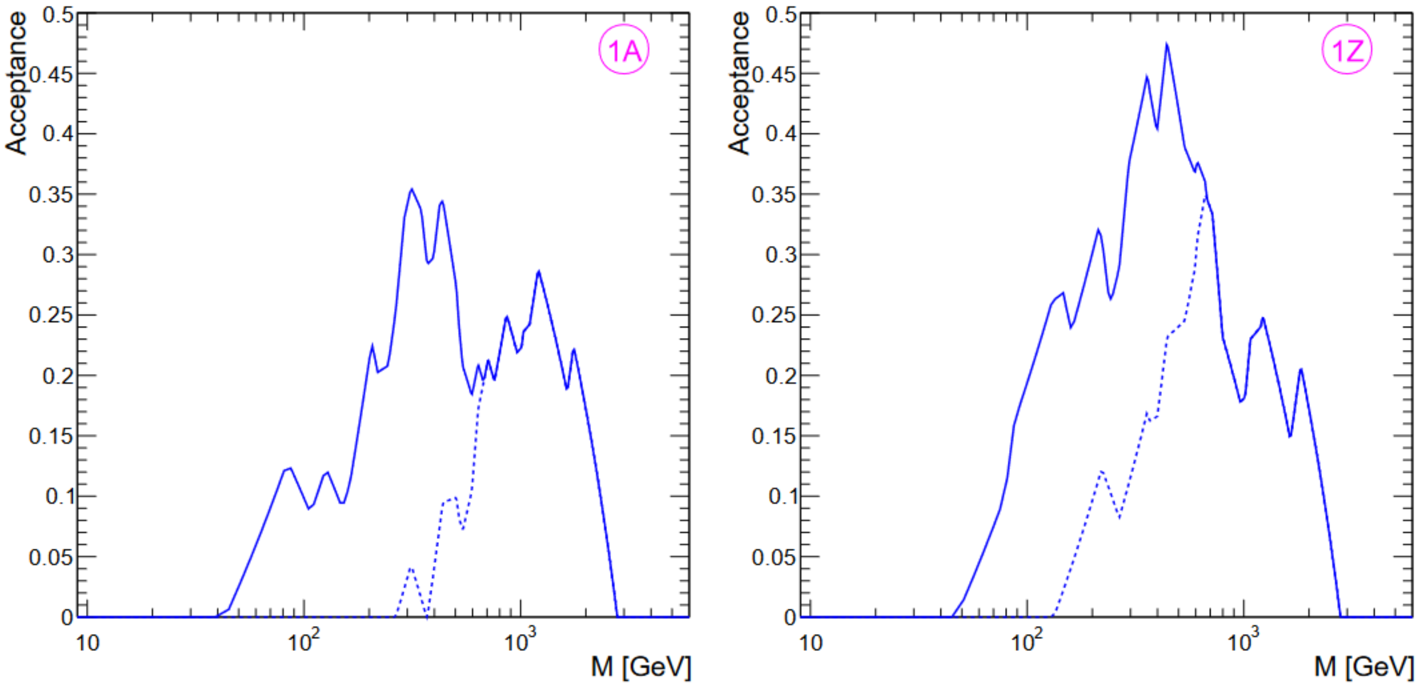
CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

26 November 2020 (v3, 09 December 2020)

The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest

The CMS Collaboration



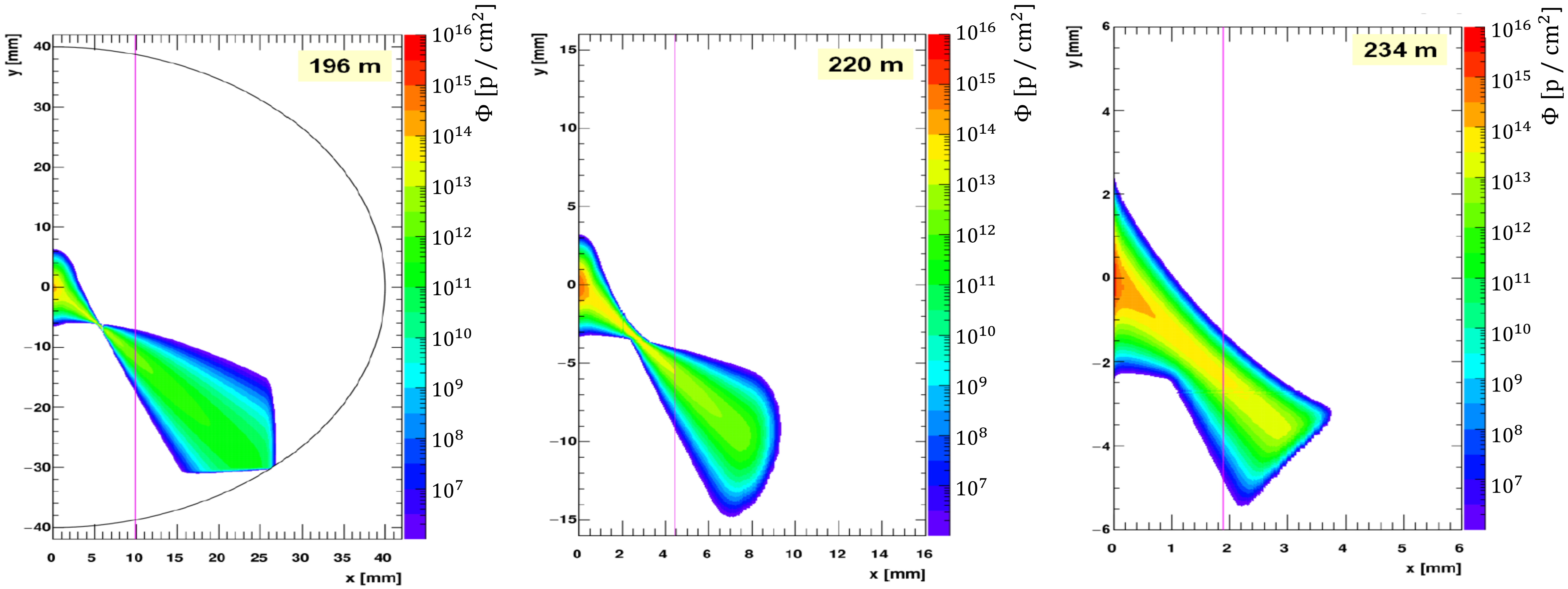
Expression of Interest document for PPS at HL-LHC available:
https://cds.cern.ch/record/2750358

HL-LHC mass range:

- 130 GeV < MX < 2.7 TeV
- 40 GeV < MX < 2.7 TeV (with 420m stations, not in Run4)

PPS @ HL-LHC : sensor dimension and hitmap

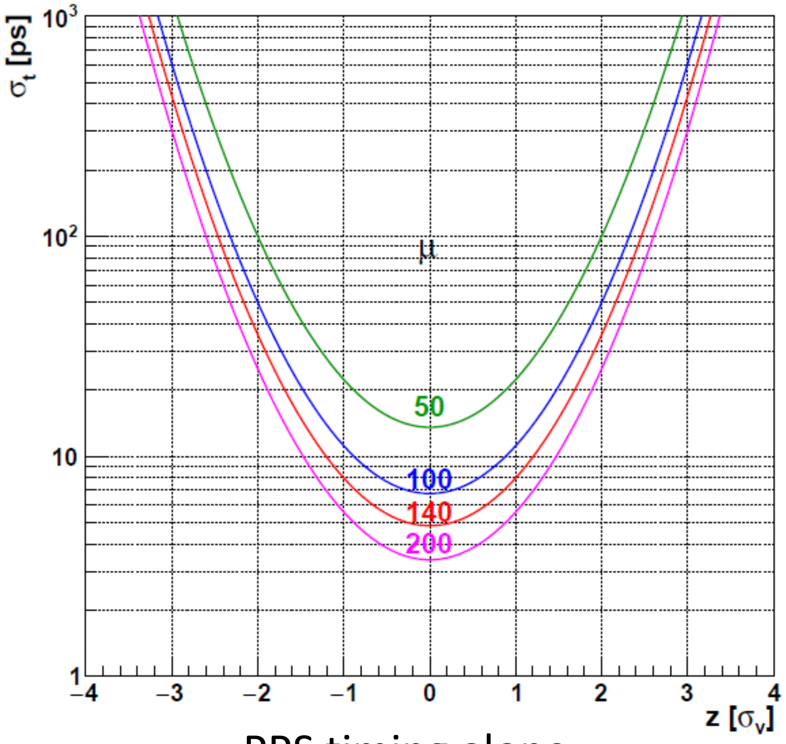
Simulated proton fluences per fb-1



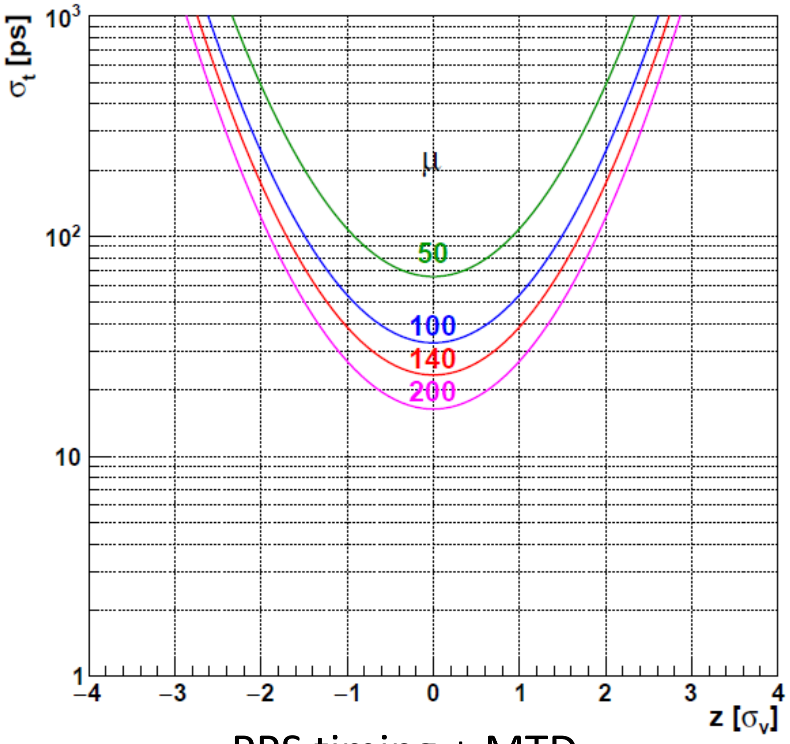
Minimal detector dimensions extrapolated from the simulated hitmap.
Larger area to be covered in 220m : ~<u>23 mm (2 x 33 mm)</u>
Factor 2 in y-dimension for the periodic flip of the vertical crossing angle. Does not consider the possible need of shifting the detector to mitigate radiation damage effects.

Station	$\Phi[\mathrm{p/cm^2}]$ (1 fb^{-1})	$\Phi[\mathrm{p/cm^2}]$ (300 fb^{-1})
196 m	$0.18\ (0.19) \times 10^{13}$	$5.4\ (5.7) \times 10^{14}$
220 m	$0.98\ (0.99) \times 10^{13}$	$2.9\ (3.0) \times 10^{15}$
234 m	$4.7\ (4.4) \times 10^{13}$	$1.4\ (1.3) \times 10^{16}$
420 m	$2.0\ (2.0) \times 10^{13}$	$6.0\ (6.0) \times 10^{15}$

PPS @ HL-LHC : timing requirements



PPS timing alone



PPS timing + MTD

HL-LHC, with pile-up in range 140-200, will require even more precise timing information.

A strong background suppression can be achieved without resolving each vertex, but some analysis will be required to completely suppress the contribution of pile-up.

Strategies to relax the extreme requirements on time precision (few ps with pile-up 140!) can be used:

- selection of a specific central event topology reduces the number of vertices to be combined with leading protons.
- The CMS Mip Timing Detector (MTD), placed between the tracker and the calorimeter in “central” region, can reduce the effective linear vertex density, by assigning a timestamp to the vertex.

Conclusions

- The CMS PPS group has developed a timing system based on scCVD diamonds, able to operate in the harsh condition of the Roman Pots.

- The system, operated during the LHC Run 2, has proved able to measure the longitudinal coordinate of the proton interaction vertex.
- Proton information contains the arrival time and the expected precision of the time measurement.

- With the Run 3 upgrades and the installation of a second set of timing stations, the system is expected to reach a vertex resolution better than 1 cm.

- All timing RPs are taking data. Work is ongoing to optimize and study detector performance.