Timing detectors with scCVD diamond crystals: the CMS Precision Proton Spectrometer timing system.

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OUTLINE:

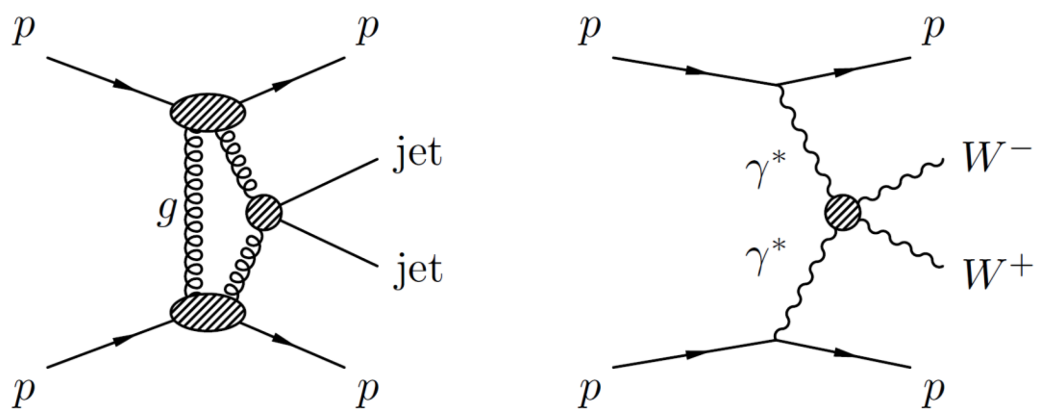
- PPS project overview
- Detector description
- Run 2 performance
- Radiation damage studies
- Run 3 perspectives

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]

PPS detector 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.

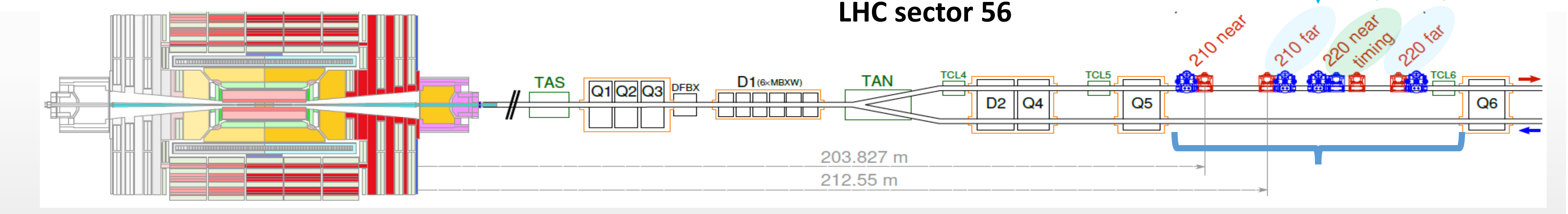
PPS detector

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

Tracking Timing Tracking

CMS central detector

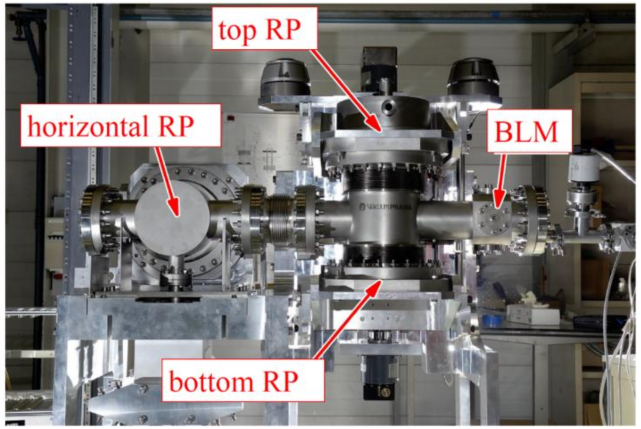
LHC sector 45



ROMAN POTs

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

Detector operate in a secondary vacuum



In 2017-2018 PPS RPs were 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 ~$5\text{x}10^{15}$ p/cm^2**(~ $2\text{x}10^{15}$ neq/cm^2) in Run 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 diamond planes (SD)

2017: 3 SD and 1 UFSD planes

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

Sensor for Run 3: 3D pixel (tracking) & Double 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:

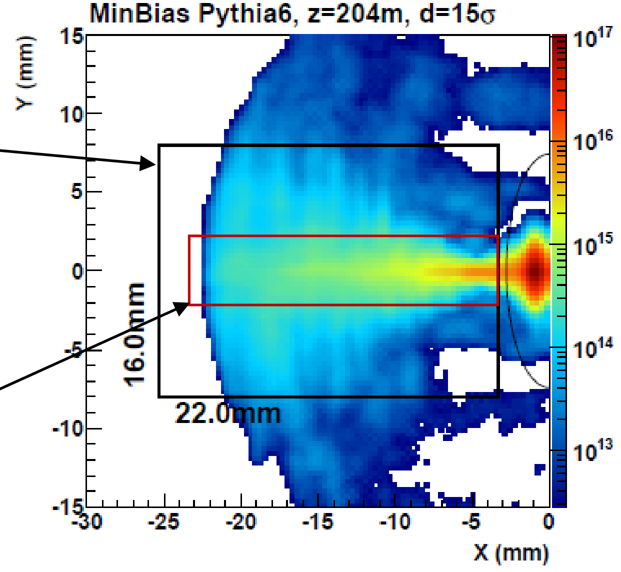
- $Z_{PP} = c\Delta t/2$
- Pile-up background reduction

PPS Detector requirements:

- Time precision <30 ps on MIP is the final goal.
- 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 hit on same pad
- Detector must operate in a vacuum

Area covered by tracking station

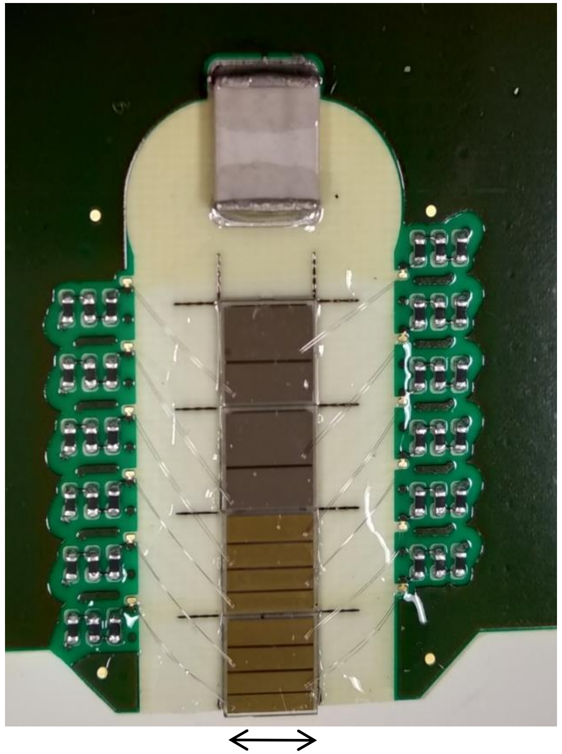
Area covered by timing station



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

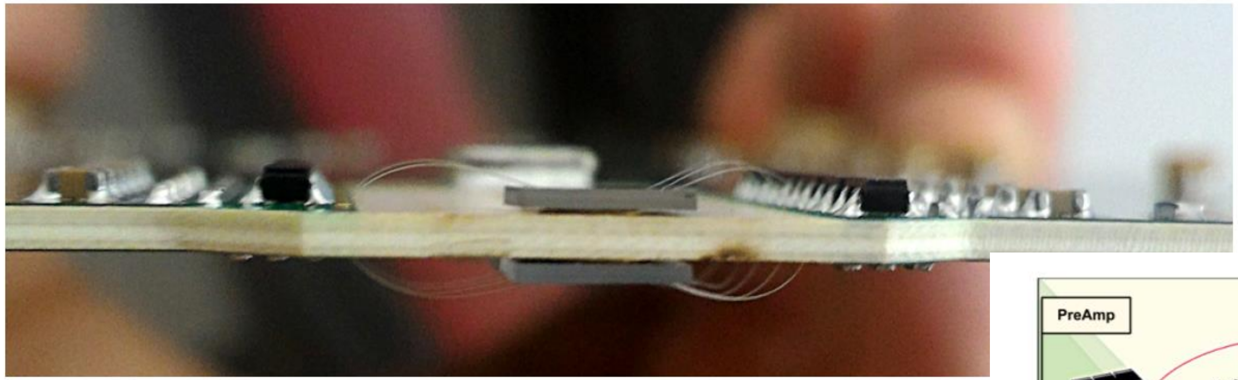


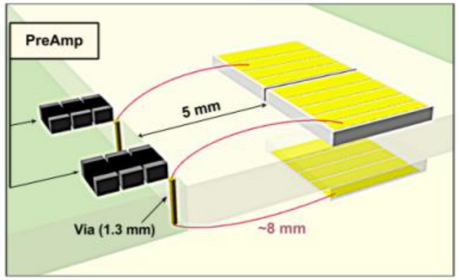
4.5 mm

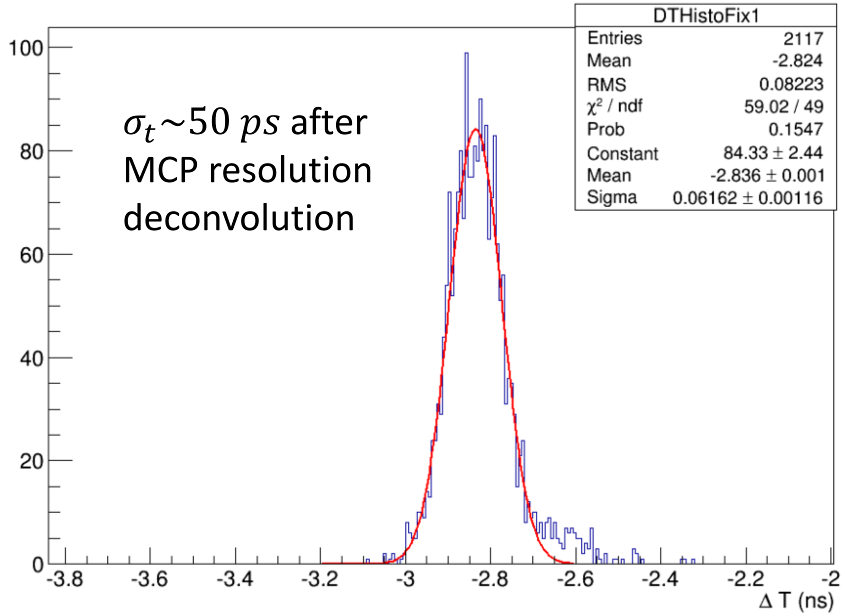
- Crystals are glued to a custom hybrid board. 12 discrete amplification channels, with a design adapted from the HADES collaboration, are available on each hybrid board [JINST 12 (2017) no.03, P03007]
- Pads are directly connected to pre-amplifier input to reduce input capacitance (~0.2 pF with 0.25 μm bonding wire diameter).
- Conformal coating is applied to sensitive areas to reduce HV discharges in vacuum (nominal HV ≥ 500 V)

Double Diamonds

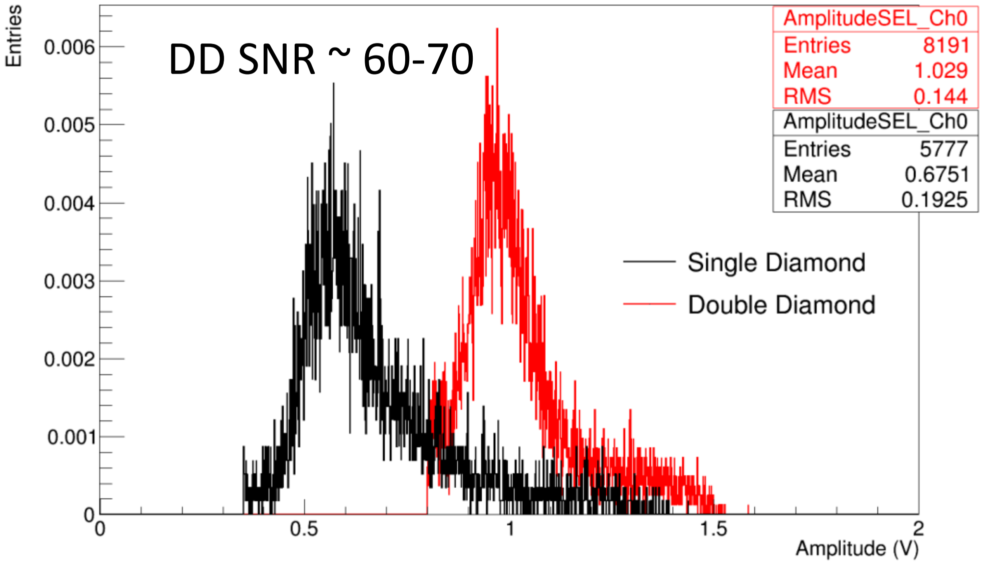
JINST 12 (2017) no.03, P03026 Sensor readout performed with oscilloscope.







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

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%.

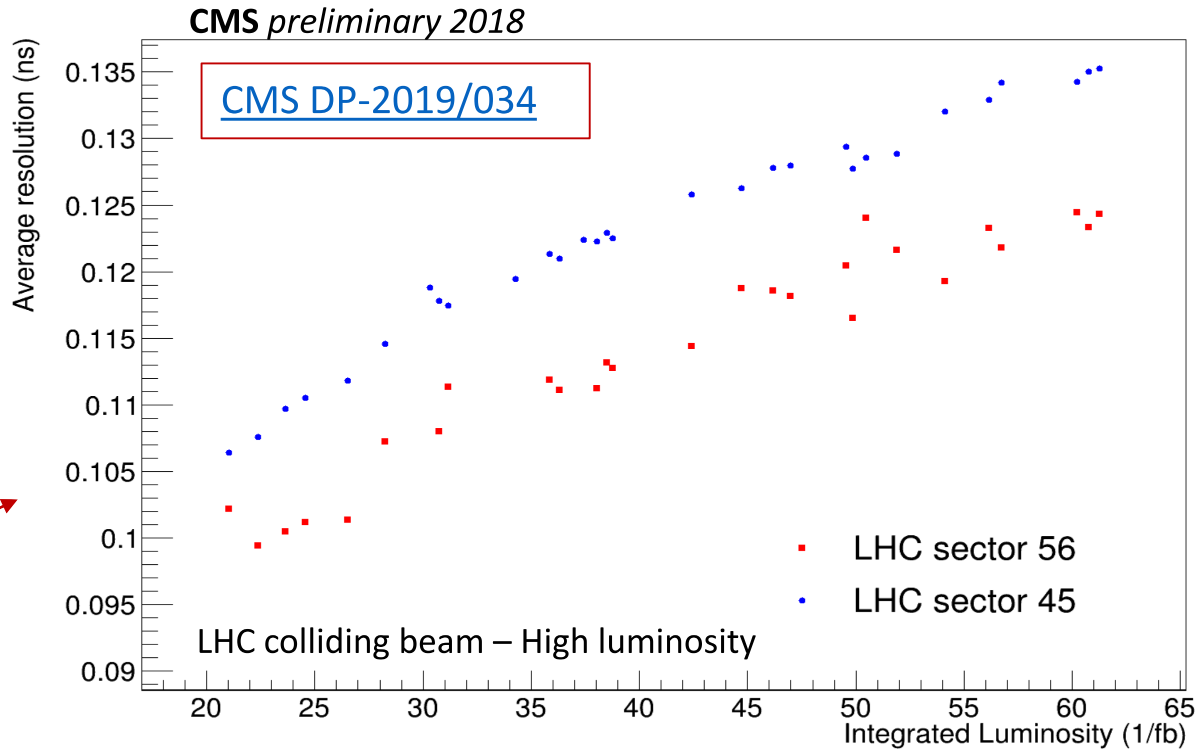
- Dedicated optical clock distribution with measured jitter < 2 ps and continuous phase monitoring
  - Online monitoring & offline shift correction
  - Clock phase tunable in ~18ps steps
  - In 2017 a clock system based on an RF distribution was also used.

- 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

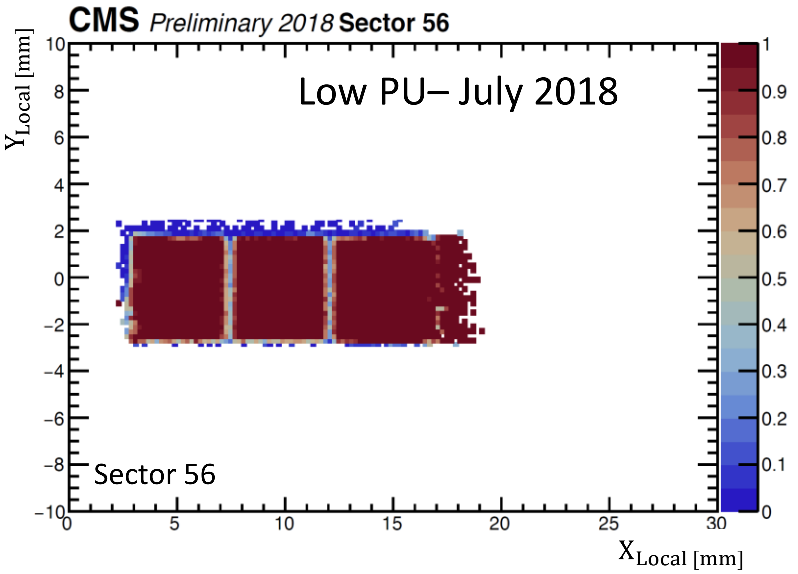
In Run 3 we will be able to remotely control the amplifiers gain.

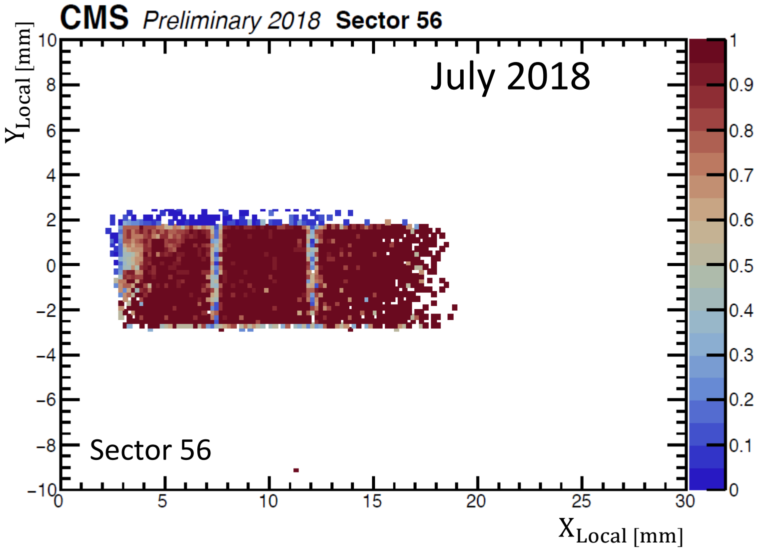


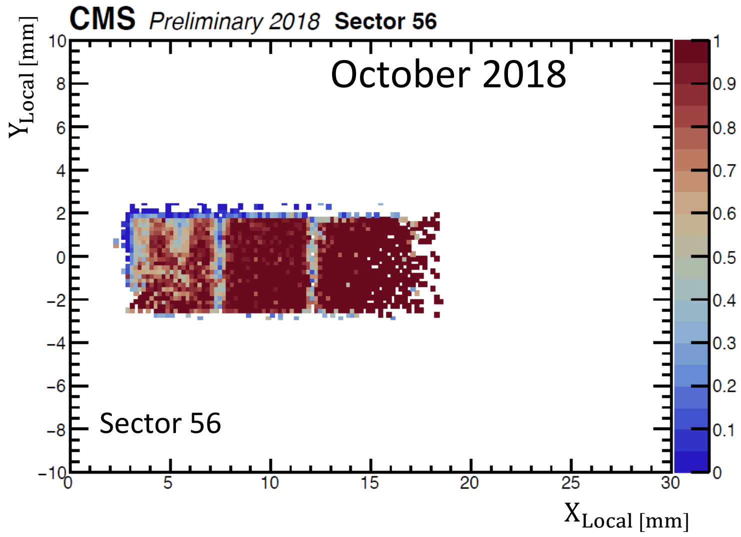
CMS DP-2020/046

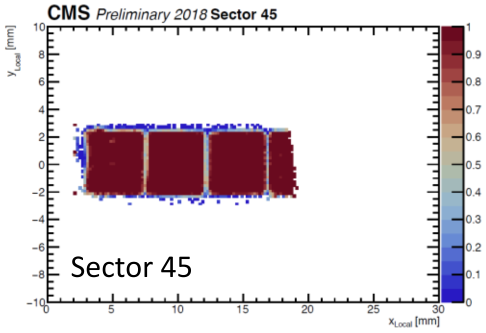
Run 2 detector efficiency

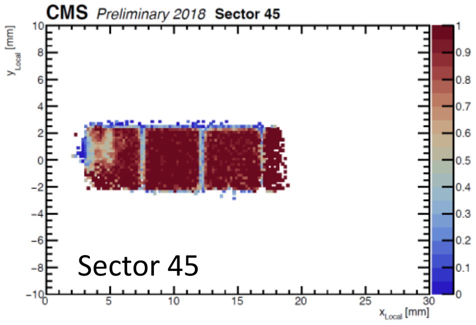
- The time-track efficiency in low pileup data from July 2018 is near 100%
- The evolution at the end of Run 2 (October 2018) shows a degradation of the efficiency

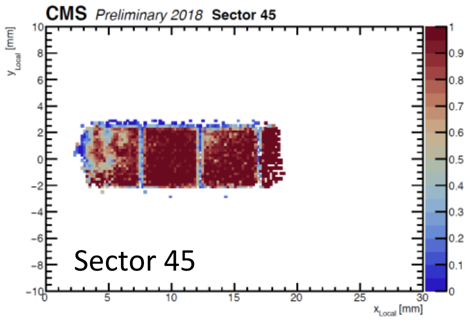










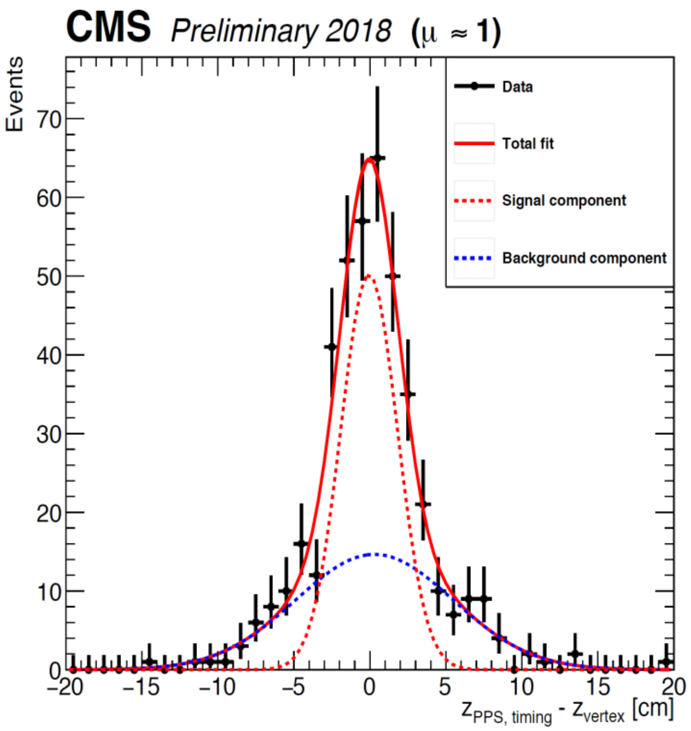


- A time-track is a combination of all (at least 2) measurements in the detection planes
- Systematic lower efficiency is only visible in the regions between two crystals, not between pad on the same crystal

CMS DP-2020/046

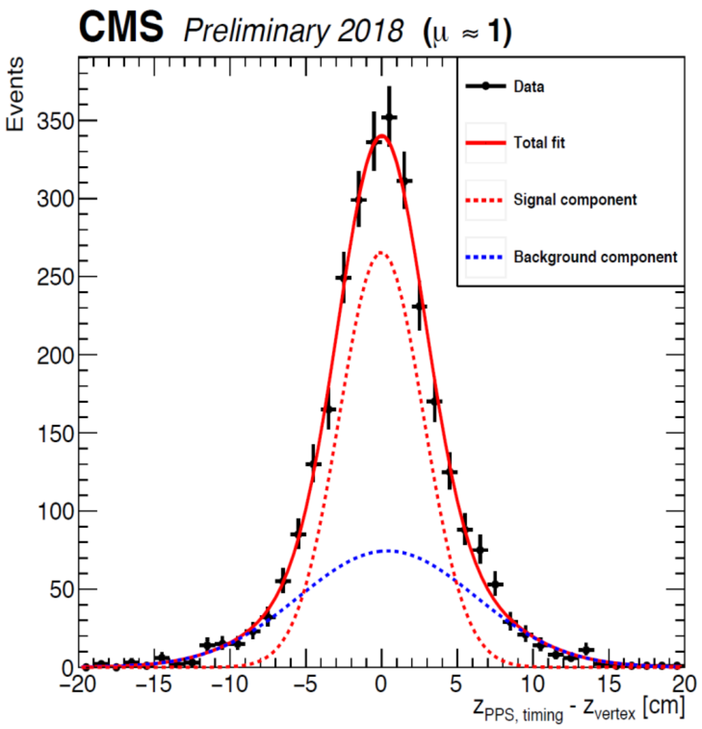
Run 2 vertex resolution

The resolution of the full PPS timing system has been checked in Central exclusive events collected in low pileup conditions during July 2018.



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

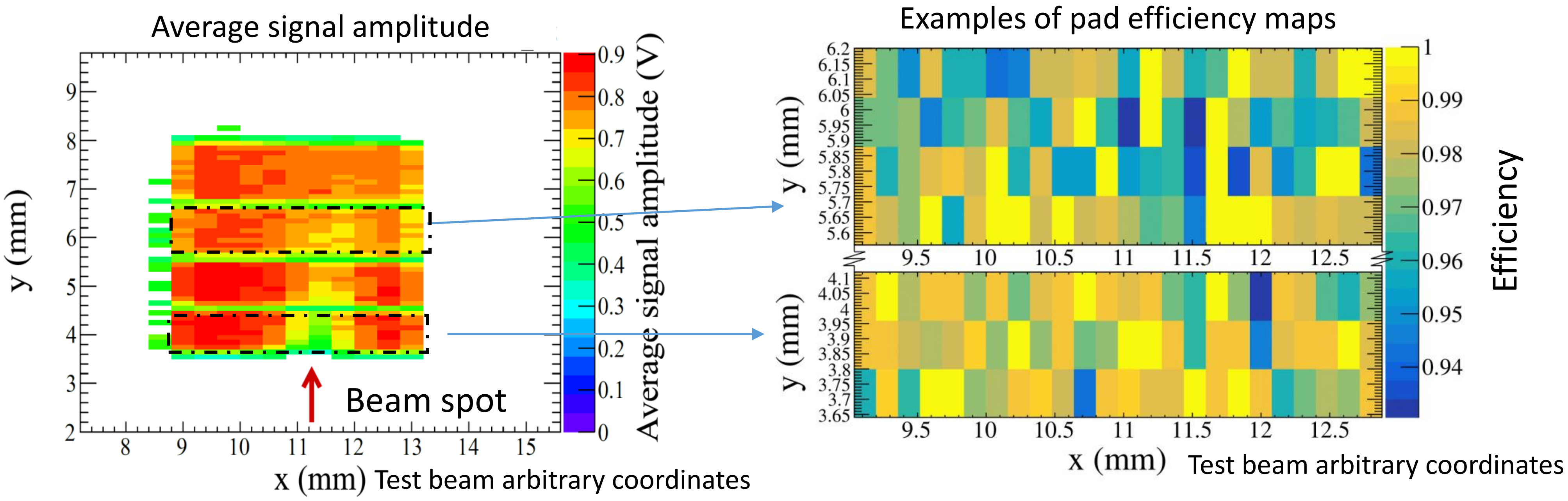
All timing tracks $\sigma_{Zpp} = 2.77 \pm 0.17$ cm



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

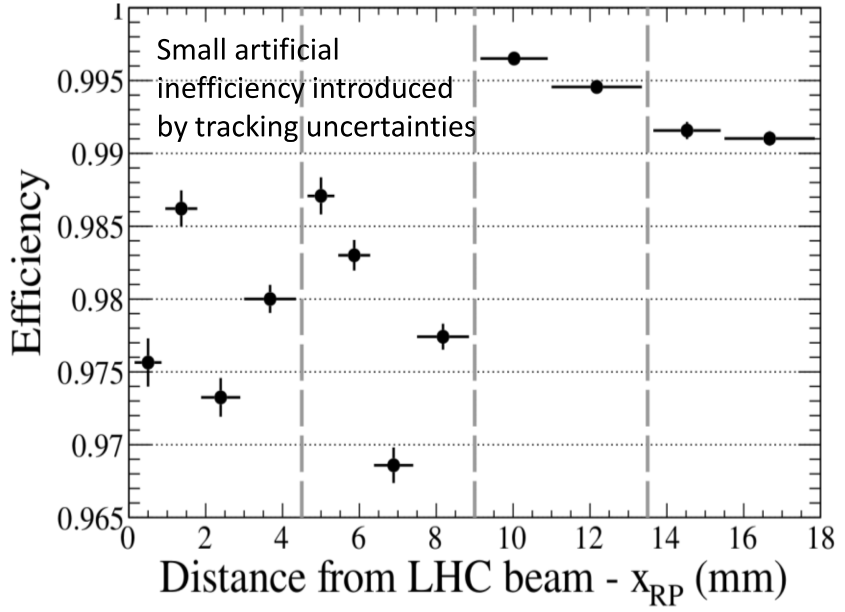
- A strong correlation is observed between the time difference of the protons detected in PPS, and the longitudinal vertex position reconstructed in the central CMS tracker
- The vertex resolution, inferred from the width of the correlation distribution, is consistent with the resolution predicted from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

Study on Run 2 irradiated sensor



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: 30%
- Sensors operated with nominal gain/bias show high efficiency also in the most irradiated area



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 NOTE-2020/007

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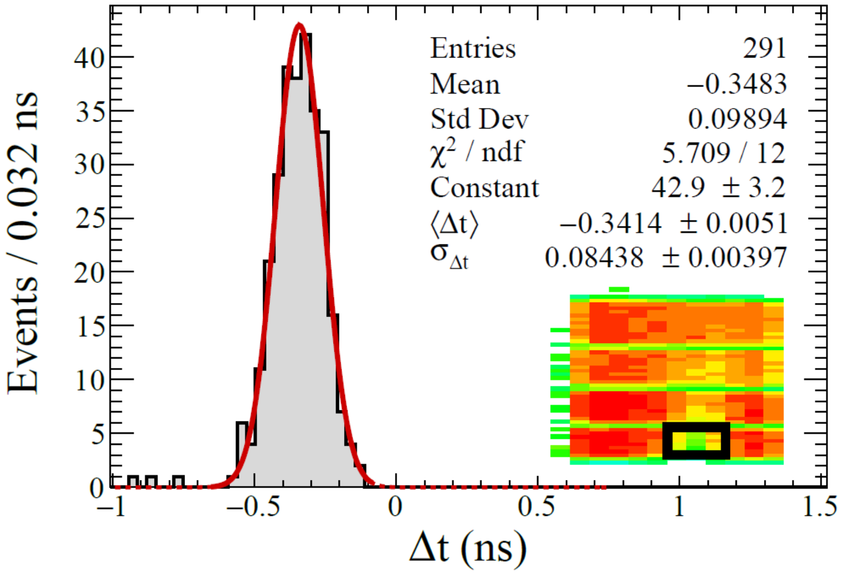

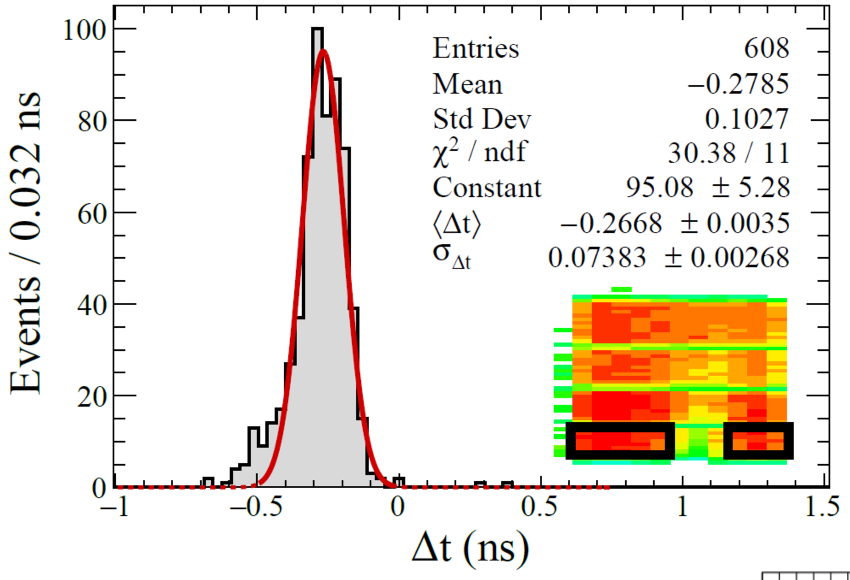

1. Run2 crystals will be reprocessed and used again in Run3
2. New version of Hybrid board:
   - RF stability
   - Pre-amp location
   - HV isolation

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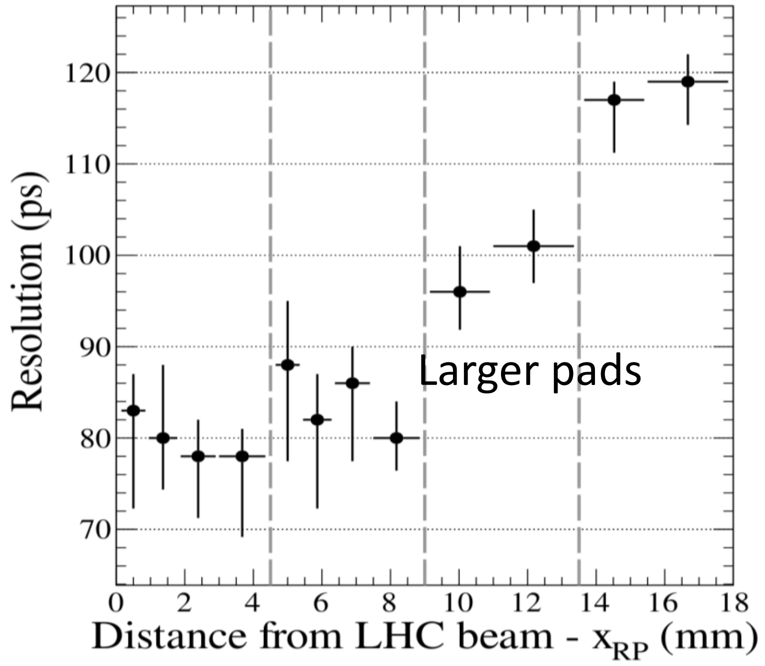
- Radiation damage to crystals identified and characterized in small area ($\sim 1\ \mathrm{mm}^2$)
- Confirmed overall loss of performance due to pre-amp irradiation: 30%
- Sensors operated with nominal gain/bias show high efficiency also in the most irradiated area
- Time resolution in the peak area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



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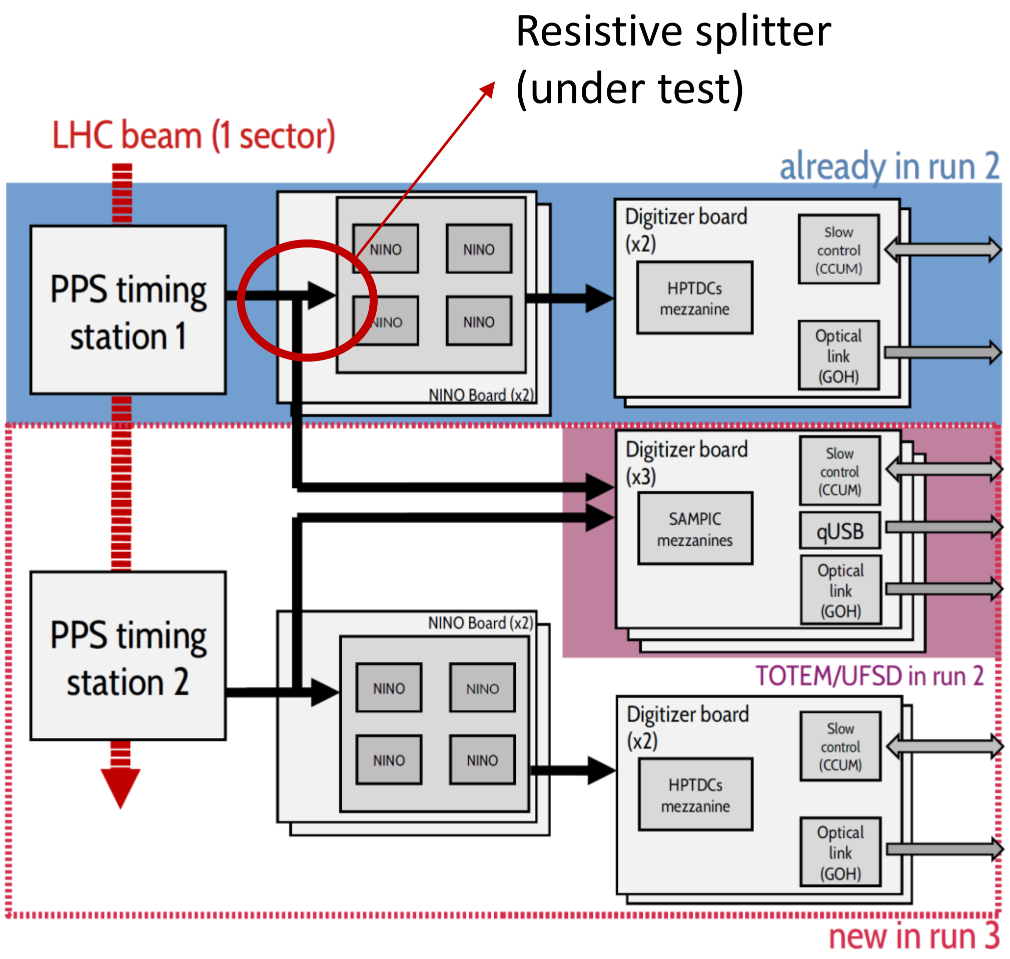
Main run 3 upgrades (sensors & readout electronics)

Important upgrade program ongoing for the timing system:

- 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 -> increase in amplification stability and HV isolation, further optimization of performance
- New NINO board -> reduce timing degradation in digitization phase and add secondary readout
- 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].



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 sensor arranged in DD architecture can reach a precision of 50 ps.

- The timing system was operated in Run2.
- Timing detector 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 TB and LHC data.

- The ongoing upgrades for Run 3 will give the possibility to reach a vertex resolution better than 1 cm.