The Precision Proton Spectrometer at CMS

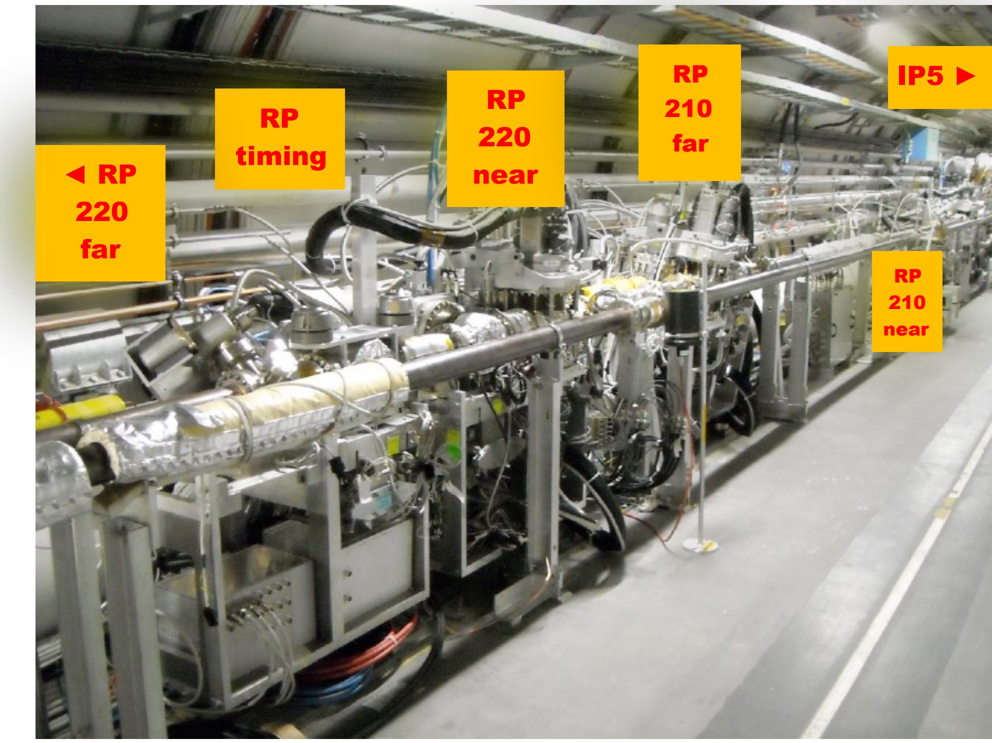
Jonathan Hollar (LIP - Lisboa)
Jornadas 2020
Feb. 15, 2020

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

LIP — LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS — partículas e tecnologia

PPS (“Precision Proton Spectrometer”)

- **Near-beam tracking and timing detectors, housed in moveable “Roman Pot” installations in the LHC beam-line**
  - ~210-220 m from the CMS interaction point
  - **Detectors must be moved to within ~2mm of the LHC beam at top energies - extreme constraints on control/safety systems**

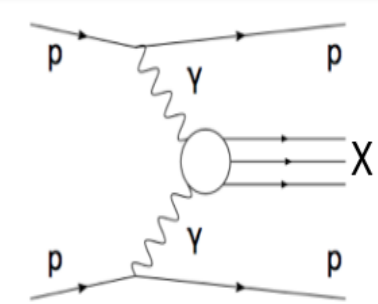


- **Selects intact protons from “exclusive” interactions**
  - Currently PPS acceptance mostly sensitive to γγ collisions
  - Allows reconstruction of the γγ collision energy and kinematics in proton-proton collisions

Proton kinematics:

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|} \quad M_X = \sqrt{s\xi_1\xi_2}$$

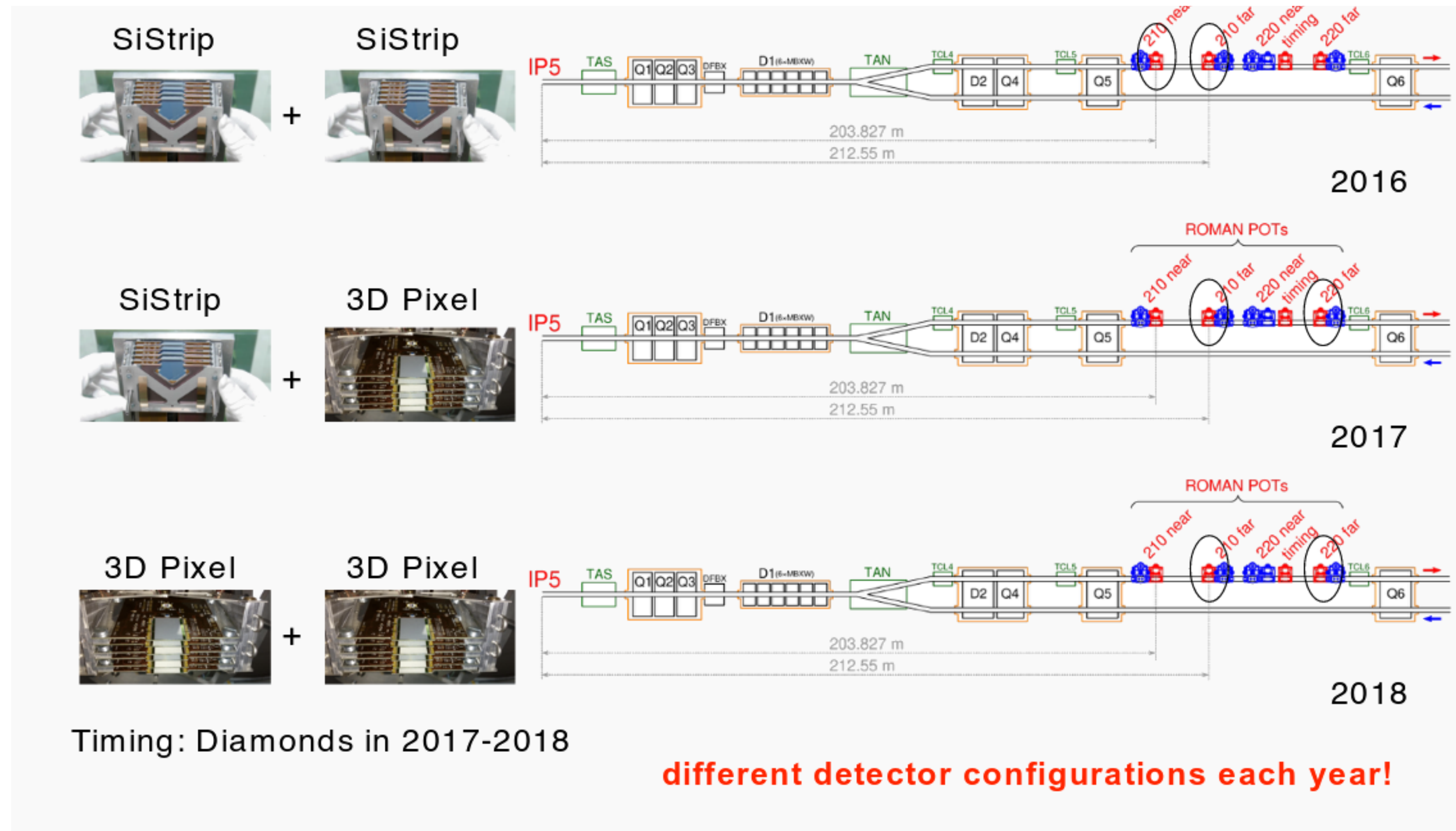
$$t = (p_f - p_i)^2 \quad y_X = \frac{1}{2}\log\left(\frac{\xi_1}{\xi_2}\right)$$



- **Unique ability to cleanly probe Electroweak and Beyond Standard Model physics in γγ collisions at very high energies (Anomalous Gauge Couplings, direct production of resonances/exotics, etc.)**

PPS in LHC Run 2

- **Initially a joint project of CMS+TOTEM - TDR in 2014, started taking data at the beginning of 2016**
    - Full CMS sub-detector project since 2018
- **Small detectors - periodic upgrades every year**
    - Tracking evolved from non-radiation hard Si-strips to 3D pixels from 2016-2018
    - Timing detectors (diamonds) operated in 2017-2018 to allow matching of protons with central vertex

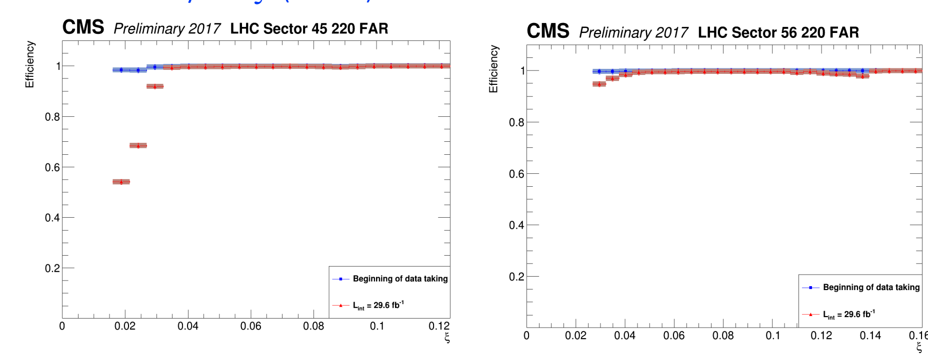


- **Total of >100fb^{-1} recorded in Run2 (PPS + rest of CMS), with increasing availability every year:**
    - 2016: ~41% of CMS total
    - 2017: ~90% of CMS total
    - 2018: ~93% of CMS total

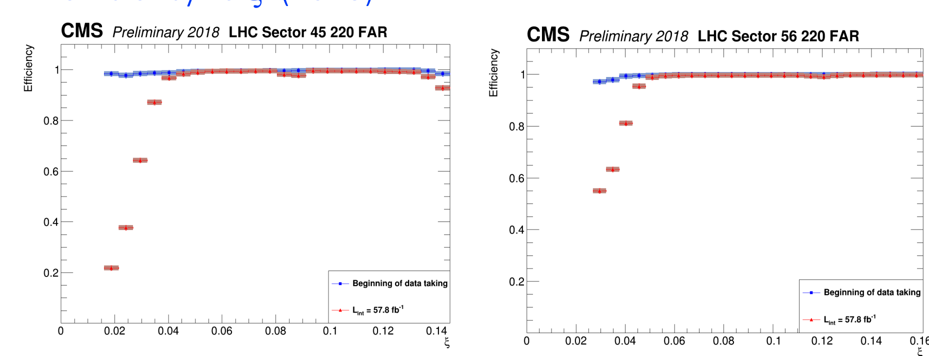
PPS detectors, performance, and reconstruction

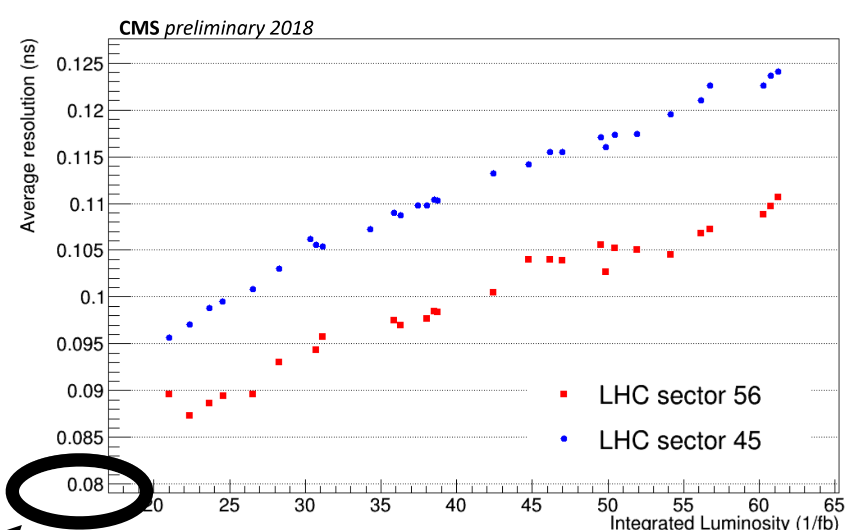
- **First use of rad-hard "3-d" pixel tracking detectors in CMS**
  - Good experience with sensors - 2 years of data-taking with ~100% efficiency over most of the active area
  - Inefficiencies at low proton momentum loss "ξ" due to non-uniform irradiation of readout chips near the beam

RP efficiency vs ξ (2017)



RP efficiency vs ξ (2018)





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

Suppressed zero

- **First dedicated fast timing detector in CMS (single-crystal synthetic diamond)**
  - Major challenges in commissioning and understanding performance of full system
  - Reached ~90-120ps resolution for 2018 data

LIP highlights: Electronics/DAQ, Operations, proton reconstruction

- **Major LIP contribution to PPS DAQ/ online software+electronics**
  - Design of HPTDC mezzanine boards for timing, firmware for timing digitizer boards, + contributions to online SW for timing, tracking, & DAQ
  - Most components tested in LIP@CERN facilities before installation in LHC

- LIP responsibility for overall data-taking operations in LHC Run 2, plus many 24-hour on-call shifts

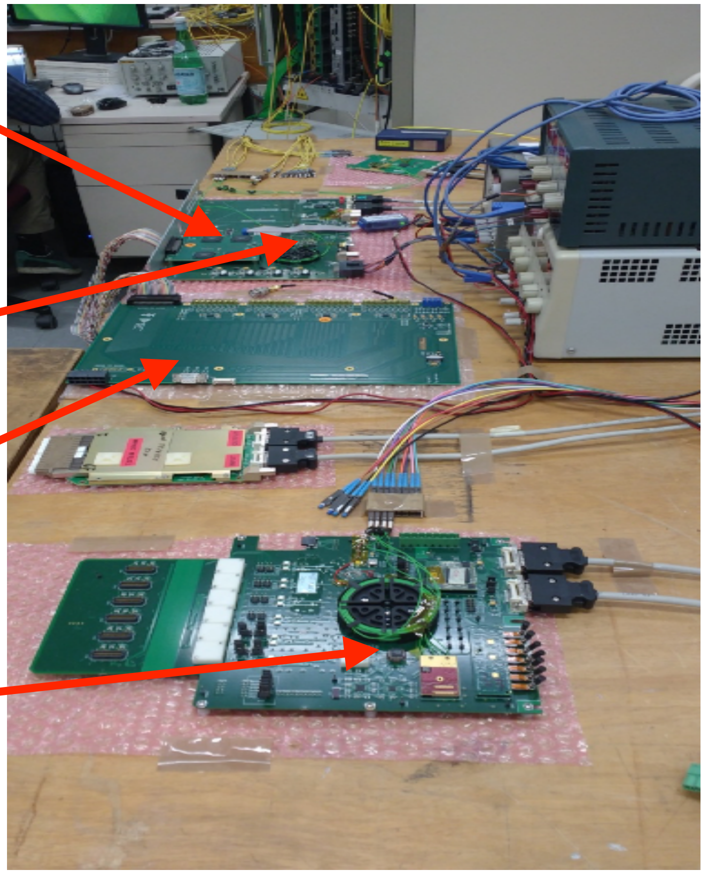
LIP lab @CERN B20

Timing: HPDTC mezzanine board (LIP design)

Timing: Digitizer motherboard (LIP firmware, control software)

Timing: NINO discriminator board (LIP contributions to control software, testing)

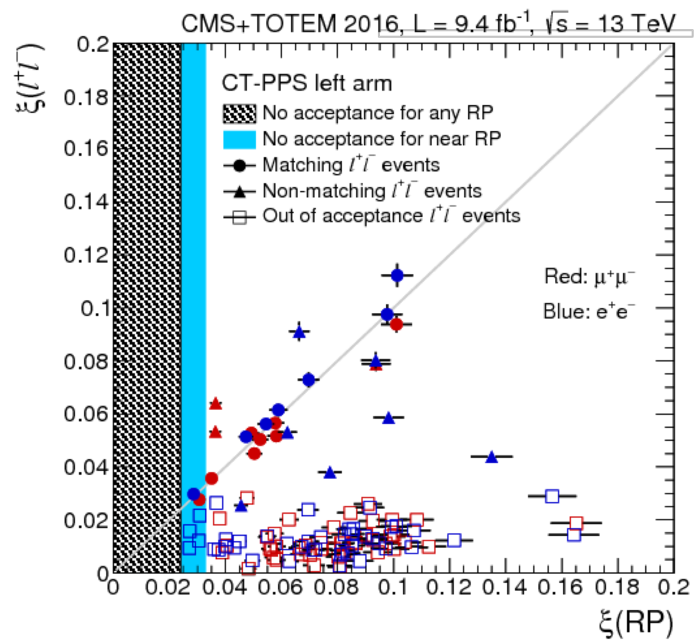
Tracking: Pixel portcard (LIP contributions to control software, testing)

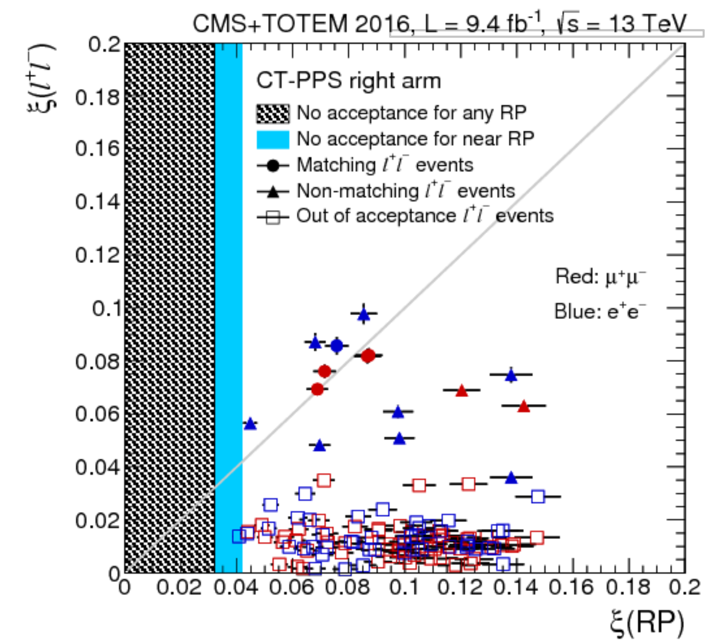


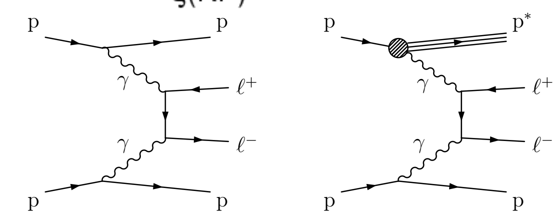
- After Run 2, large effort to put reconstructed protons on the same footing with other physics objects in CMS (muons, electrons, jets, etc.) - Leadership from LIP group since 2019
  - **On-going "Ultra-legacy" reconstruction of Run 2 CMS data includes PPS protons as a standard physics object for the first time**
  - Several improvements for Run 3 under development - High-level triggers, automated calibrations, etc.

Physics with PPS

- First CMS paper using PPS for physics: Observation of γγ→μμ and γγ→ee with single-arm protons (**JHEP 1807 (2018) 153**) based on 2016 data
  - Important “standard candle” for high-mass γγ interactions with intact protons
    - Now used as a calibration sample with 10x more data
  - **Leading contribution from LIP members**: K. Shchelina, J. Hollar, L. Llorett (former)





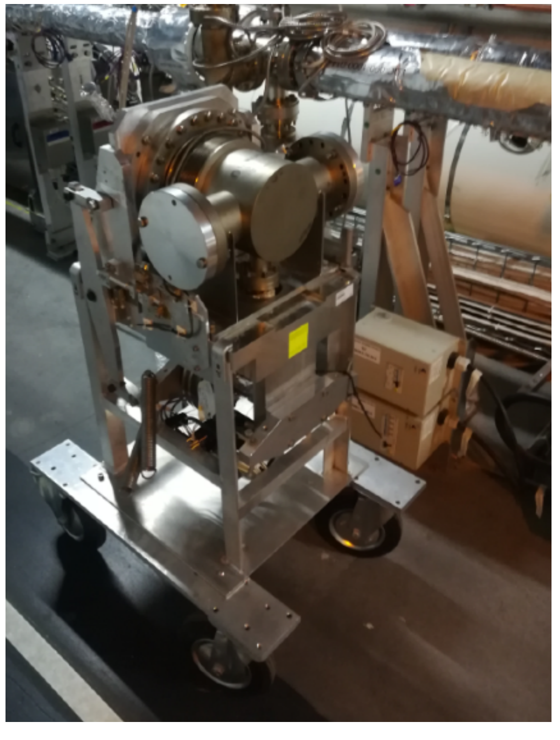


- **Several Beyond-SM searches and Standard Model analyses now started using PPS Run 2 data in CMS**
  - **Example: Exclusive t-tbar with leptonic decays in 2017 data**
    - **MS thesis by B. Ribeiro (LIP, now at DESY) + M. Gallinaro (supervisor)**
  - Other analyses in progress : searches for γγ, WW, ZZ, missing masses, t-tbar (semi-leptonic), plus μμ/ee cross sections

The future

- LHC finished Run 2 in 2018 and is currently in "Long Shutdown 2" until 2021

- **PPS will continue running as a standard CMS sub-detector through at least LHC Run 3 (2021-2024)**



- **Program of upgrades for Run 3 ongoing**
  - RP's moved for installation of a second timing station: 8 double-diamond planes in total
  - Optimization of front-end boards/amplifiers for timing readout
    - Aim for improved timing resolution in Run 3

- Addition of vertical movement system for pixel-tracking detectors, to mitigate radiation on ROCs

- Development of High-level triggers using protons, automated calibration procedures

Summary

- **PPS was the first new high-luminosity detector installed/commissioned/integrated by CMS since the LHC startup in 2010**

- **During LHC Run 2 PPS established the ability to operate near-beam Roman Pot detectors in the LHC at the highest luminosities, from 2016-2018**

    - **Over 100fb^{-1} collected for physics during Run 2**

        - One physics paper and several performance notes already public, other analyses ongoing/in internal review

    - Operated technologies/concepts considered for HL-LHC (3-D pixels, fast timing detectors)

- Upgrades for Run 3 in progress, with focus on improving timing resolution, radiation mitigation for tracking

- **LIP has had a major impact on almost all aspects of PPS (coordination/DAQ/electronics/timing/operations/reconstruction/physics…)**

LIP-CMS role in PPS

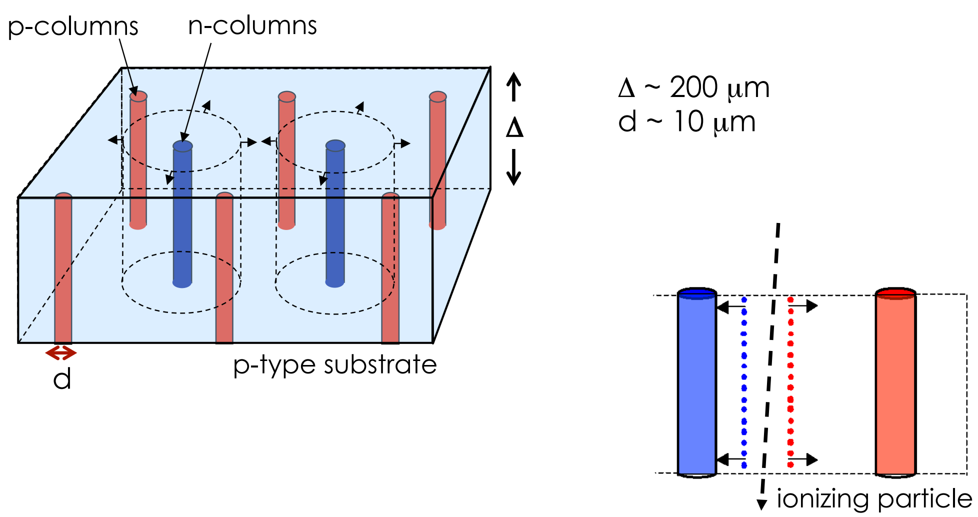
- **Current** and **former** group members
  - Project manager: **J. Varela** (2014-2018)
  - Deputy Project manager: **J. Hollar** (2018-present)
  - Proton Physics Object Group convenor: **K. Shchelina** (2019-present)
  - Timing detector coordinator: **M. Gallinaro** (2014-2018)
  - DAQ and detector operations coordinator: **J. Hollar** (2016-2018)
  - Electronics/firmware/DAQ/online software: **J. Carlos Da Silva**, **C. Carpinteiro**, **L. Llorett**, **B. Galinhas**
  - Proton reconstruction, High-level trigger: **K. Shchelina, M. Araujo**, **C. Da Cruz E Silva**
  - Alignment, timing detector testbeams: **G. Strong**, **A. Toldayev**
  - Detector on-call shifts: **K. Shchelina**, **C. Carpinteiro** , **L. Llorett**, **J. Hollar**
  - Physics analyses: **K. Shchelina, M. Gallinaro,** **B. Ribeiro, L. Llorett, P. Silva**

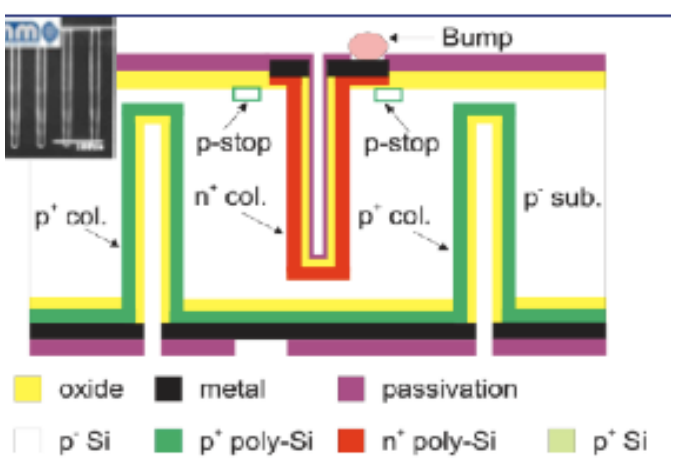
Extra

References

- “CMS-TOTEM Precision Proton Spectrometer”: CERN-LHCC-2014-021, TOTEM-TDR-003, CMS-TDR-13 [link]
- “Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS-TOTEM precision proton spectrometer”: JHEP 1807 (2018) 153 [arXiv:1803.04496]
- “Efficiency of the Pixel sensors used in the Precision Proton Spectrometer: radiation damage”: CMS-DP-2019-036 ; CERN-CMS-DP-2019-036 [link]
- “Time resolution of the diamond sensors used in the Precision Proton Spectrometer”: CMS-DP-2019-034 ; CERN-CMS-DP-2019-034 [link]

"3-d" silicon pixels for tracking

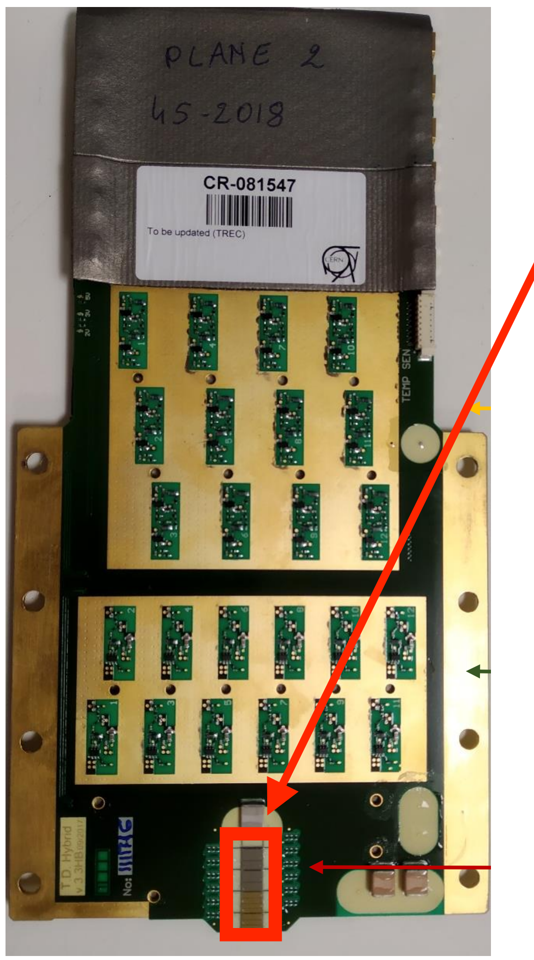




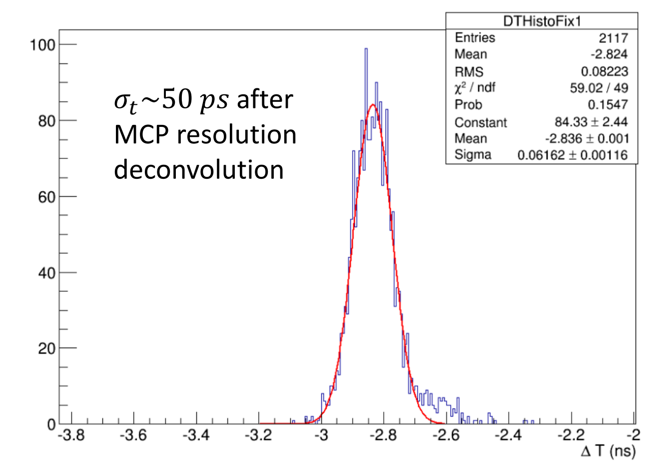
M. M. Obertino

- Electrodes in vertical columns through the substrate, instead of planes
  - Small collection distance without reducing wafer thickness/signal amplitude
  - Low trapping probability - high radiation hardness
    - Est. up to ~$5*10^{15}$ protons/cm^2 in 100 fb^{-1}
  - Low power dissipation
- Efficiency losses mainly due to highly non-uniform irradiation of readout chips, not sensors
  - Mitigated by vertically shifting detectors manually in Run 2, to be automated in Run 3

Diamond timing detectors



- Based on synthetic single-crystal carbon vapor deposit diamonds
- In 2017: 3 planes/arm of “single-diamonds” + 1 plane of ultra-fast silicon sensors
- In 2018: 2 planes of single-diamonds + 2 planes of double-diamonds/arm

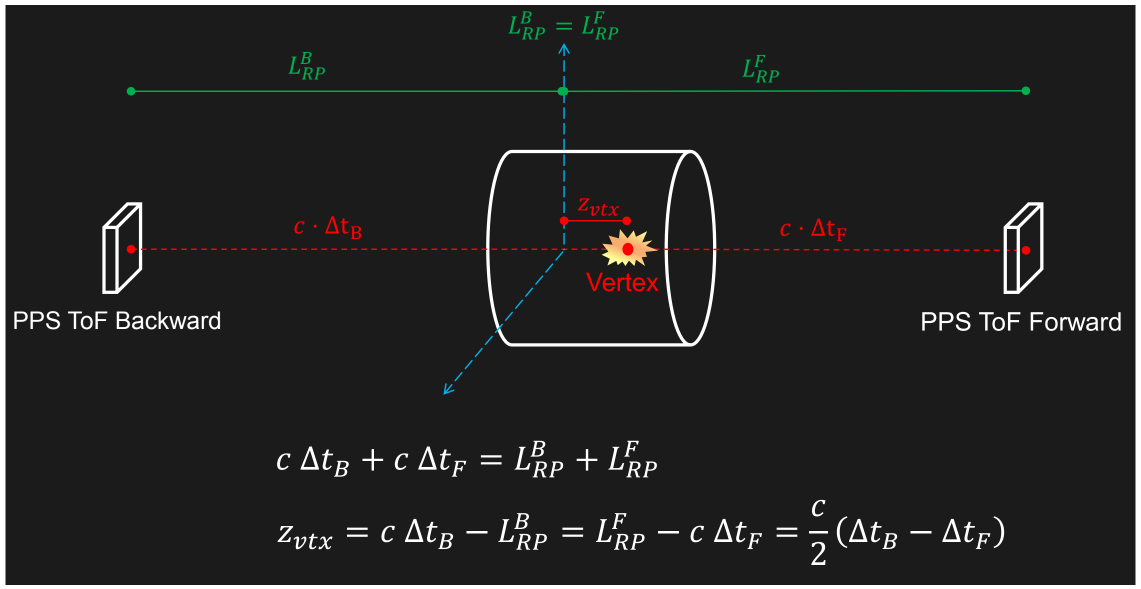


Time difference distribution between DD and reference MCP ($\sigma_{t.MCP} \sim 40\ ps$)

E. Bossini

- Double diamonds: signal from 2 diamonds connected to same amplification channel
  - Larger signal amplitude => improved timing resolution
  - Up to 50ps/plane in ideal testbed conditions (oscilloscope readout, nominal LV and HV)
- For Run 3: 8 planes of double-diamonds/arm (in 2 stations)

Proton timing-vertex matching



- Basic idea: the time-of-flight difference (Δt) of the 2 protons is correlated with the z position of the vertex
    - For real signal events with 2 protons

- Studies in simulation:
    - Strong correlation for signal events
    - Random distribution for combinatoric background events