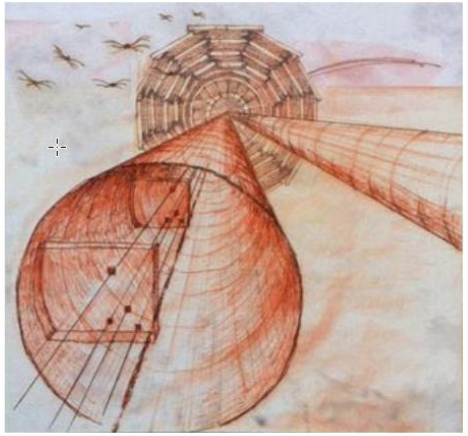


The CMS Precision Proton Spectrometer (PPS): results, status and prospects

Andrea Bellora (Università degli Studi di Torino and INFN)

on behalf of the CMS and TOTEM Collaborations

Low-x 2019, Nicosia, Cyprus

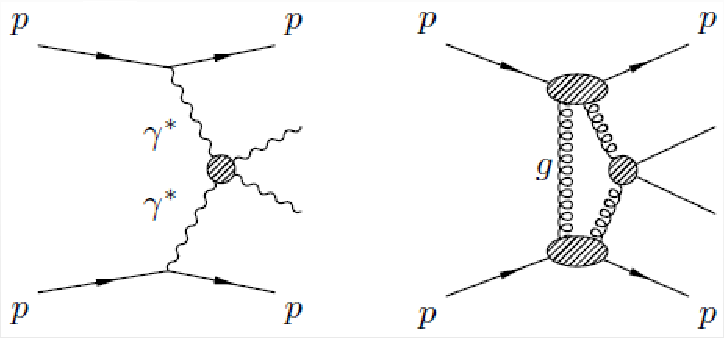
August 26-30, 2019

Outline

- PPS physics case
- Experimental apparatus
- Operation in LHC Run 2
- Tracking efficiency
- Detector alignment and proton reconstruction
- (Semi)Exclusive $\gamma\gamma \rightarrow \ell^{+}\ell^{-}$ results with 2016 data
- Prospects for LHC Run 3

PPS physics case

- **Central exclusive production** ($J^{PC} = 0^{++}$ central final state)
  - Colour-singlet exchanges with large rapidity gaps between the central system and the outgoing protons
  - Two-photon, photon-pomeron or two-pomeron exchanges at LHC energies allow access to a large variety of processes
    - see e.g. *JHEP 1608 (2016) 119, Phys.Lett. B777 (2018) 303-323* (in pp), *Nature Phys. 13 (2017) no.9, 852-858, arXiv:1810.04602* (UPC in PbPb)

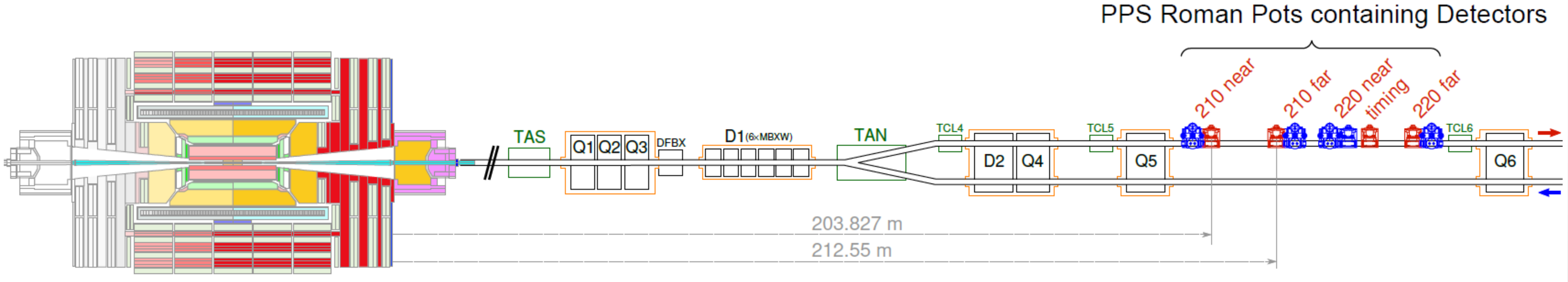


- **Electroweak physics:** diboson and dilepton production, anomalous coupling searches
- **QCD:** dijet, trijet, $t\bar{t}$ production
- **BSM direct searches:** new resonances, missing mass…

- **Advantages of the forward proton measurement**
  - Strong background suppression by requiring kinematic match with the central system
  - Reduced theory uncertainties related to proton dissociation

Introduction to PPS

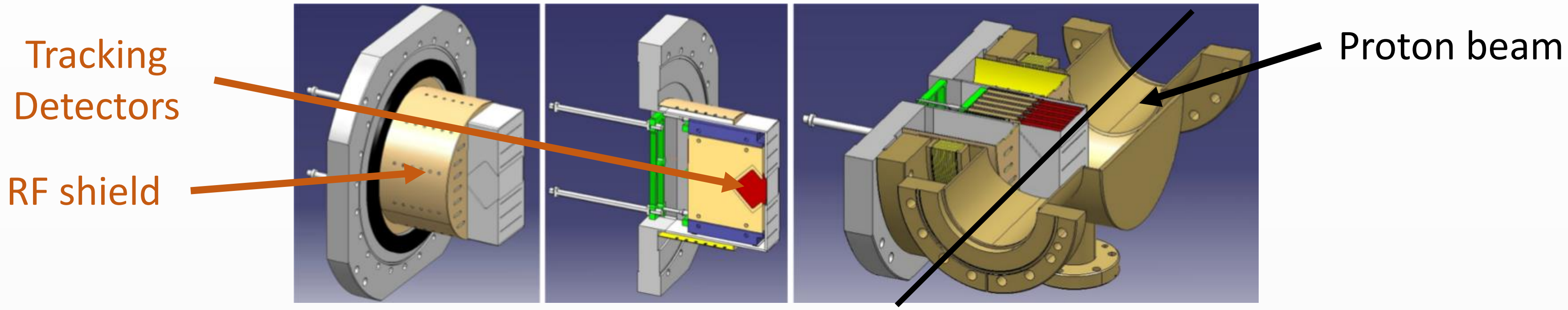
- **Near beam magnetic spectrometer at IP5 of the LHC**
  - Joint CMS+TOTEM project to include horizontal Roman Pots in the standard, high luminosity, CMS data taking, TDR in 2014 [*CERN-LHC-2014-021*]
  - Started in 2016 (one year early) thanks to the availability of the legacy TOTEM silicon strips detectors
  - Collected data throughout the whole LHC Run 2



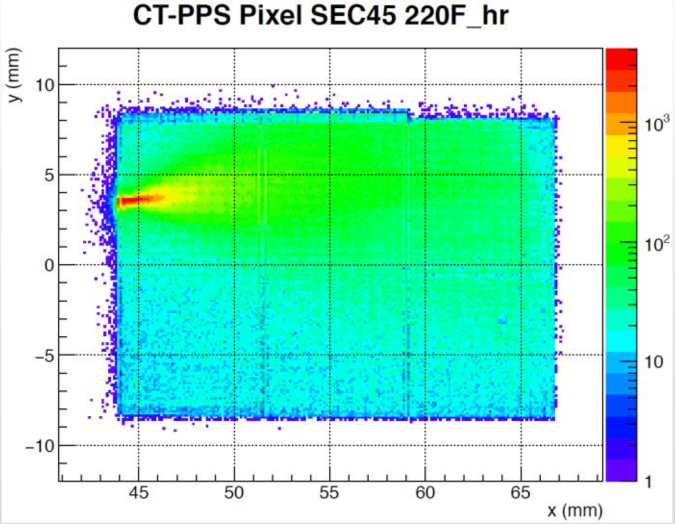
- **Two complementary measurements**
  - **Tracking detectors** measure the proton displacement with respect to the beam, which is translated into energy-momentum loss thanks to the knowledge of the beam optics
  - **Timing detectors** measure the proton arrival time in both arms w.r.t. the reference clock that keeps the two stations synchronized, allowing the calculation of the longitudinal position of the interaction

Experimental challenges

- **Roman Pots need to operate at few mm from the beam to maximize acceptance**
  - RF shielding installed to limit the impedance caused by the RP insertion



- **Detectors must tolerate high levels of non-uniform irradiation**
  - For ~100 fb^{-1} (Run 2): $\sim 5 \cdot 10^{15}$ protons/cm^2 in tracking detectors
  - Spatial resolution required: ~10-30 μm
  - Timing resolution required: ~ 20 ps, to reject high pileup



PPS physics case

Experimental apparatus

Operation in LHC Run 2

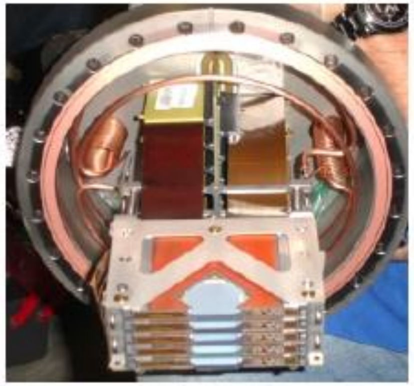
Tracking efficiency

Detector alignment and proton reconstruction

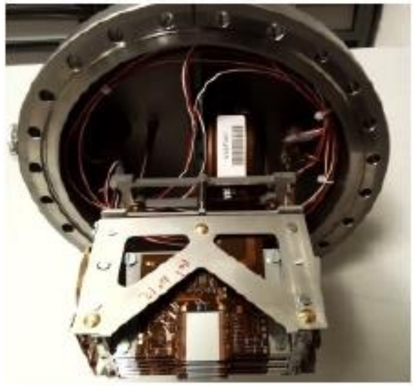
(Semi)Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ 2016 results

Prospects for LHC Run 3

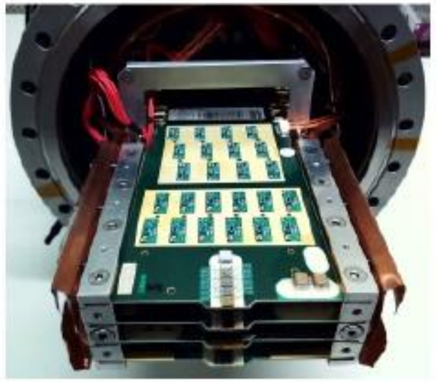
PPS detectors for Run 2



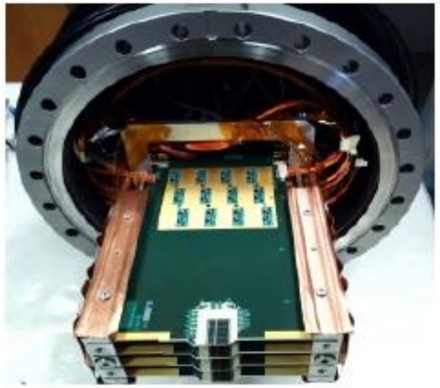
TOTEM si-strips



3D pixels



scCVD (diamond)

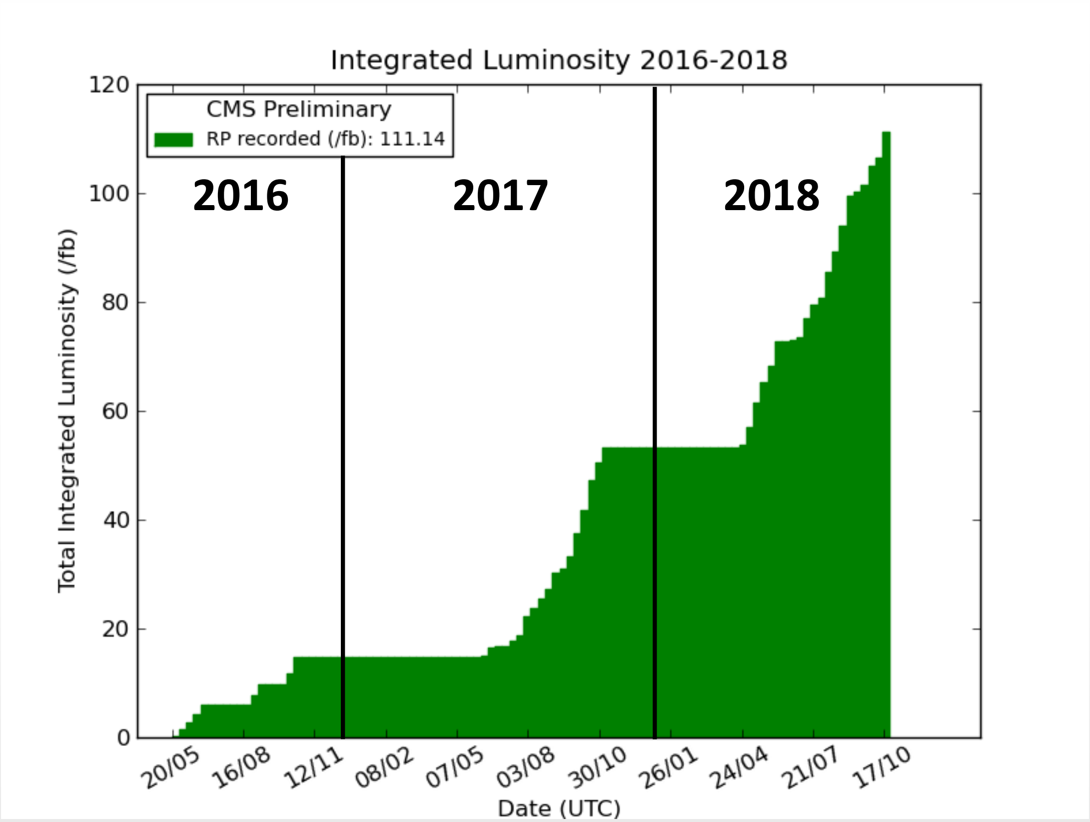


Ultra-fast silicon detectors

In both arms

- **2016 Detectors**
  - Tracking: 2 stations of TOTEM Si-strips detectors (10 planes), 20 μm resolution. Limited radiation resistance ($\Phi_{\max} \sim 5 \cdot 10^{14}$p/cm^2), no multi-track capability.
  - Timing: diamond detectors in cylindrical RP
- **2017 Detectors**
  - Tracking: 1 station of TOTEM si-strips, 1 station of silicon 3D pixels (6 planes with CMS Phase 1 tracker readout chips), $\sigma_x \sim 15\ \mu m$ and $\sigma_y \sim 30\ \mu m$, $\Phi_{\max} \sim 5 \cdot 10^{15}$p/cm^2
  - Timing: 1 station with 3 planes of single-layer diamond with expected $\sigma_t = 80$ ps/plane and 1 plane of UFSD with expected $\sigma_t = 30$ ps/plane ($\Phi_{\max} \sim 10^{14}$p/cm^2)
- **2018 Detectors**
  - Tracking: two 3D pixels stations
  - Timing: 1 station of diamond detectors (2 single-layer + 2 double-layer)

LHC Run 2 operation



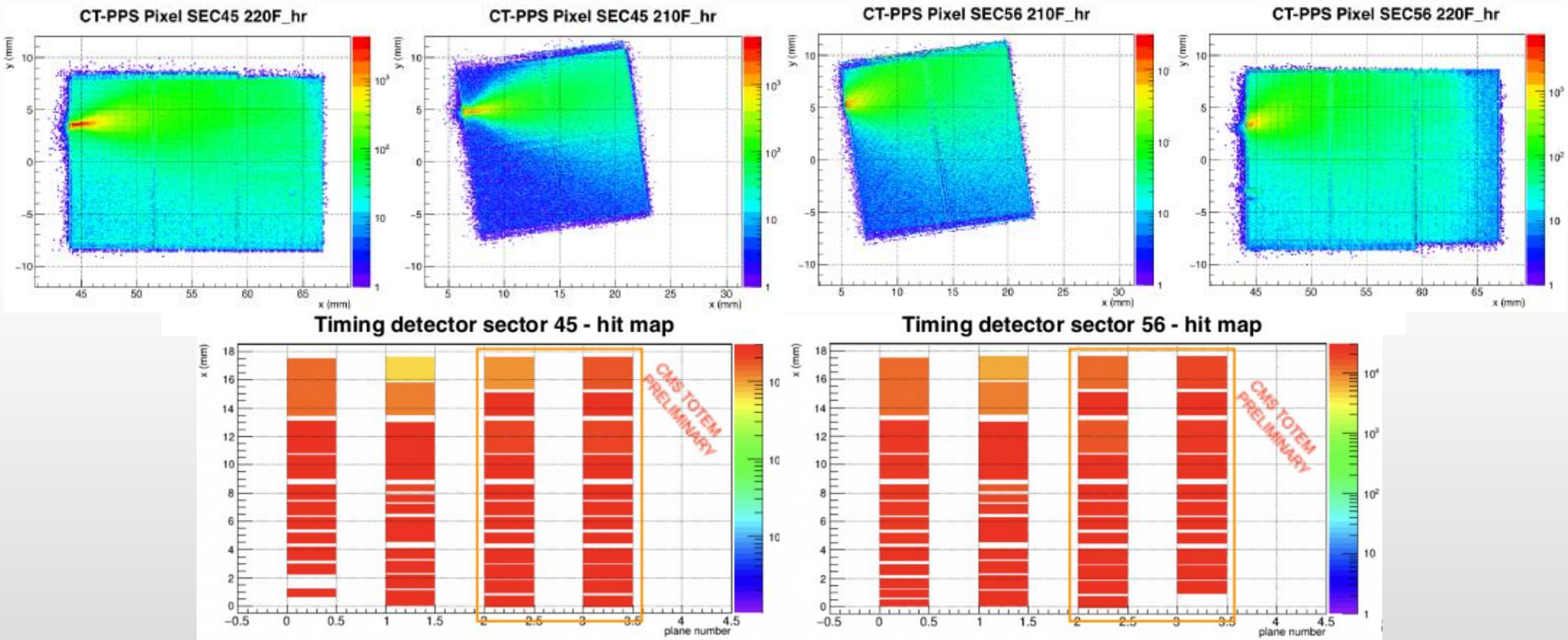
2016: 40% of the CMS statistics
2017: 88% of the CMS statistics
2018: 92% of the CMS statistics

- **$\sim$ 115 fb^{-1} collected by PPS during Run 2**
  - Always inserted and taking data, fully integrated in CMS runs, in 2017 and 2018
  - Very high stability in both 2017 and 2018

2018 data: hit maps

Sector 45 ← **IP5** → **Sector 56**

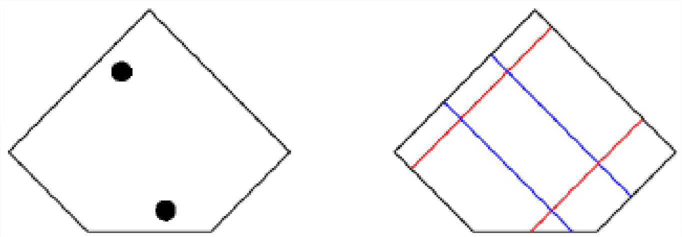
2018 Layout

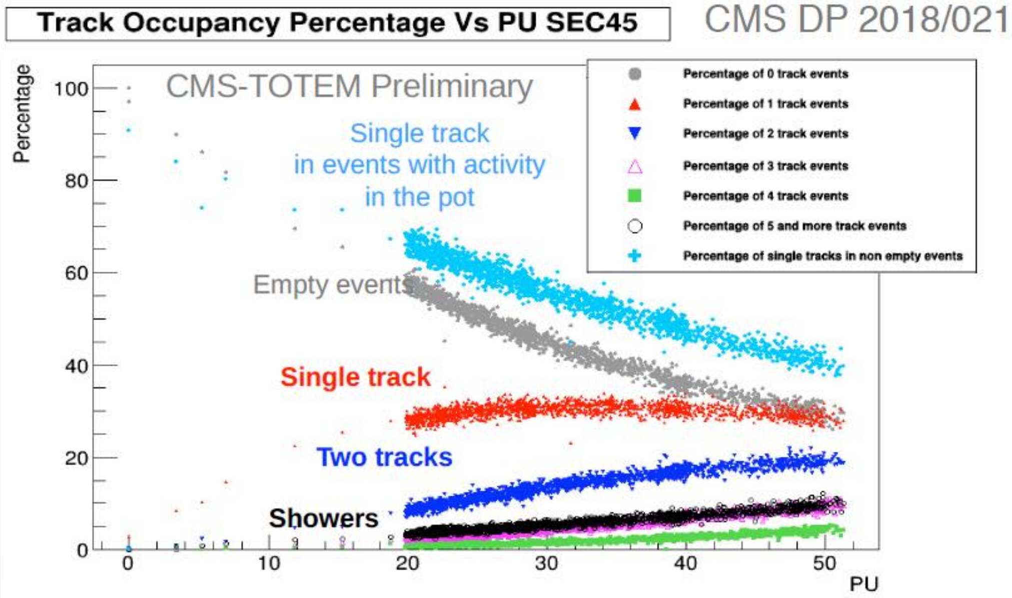


- Less than 0.05% bad or noisy pixels

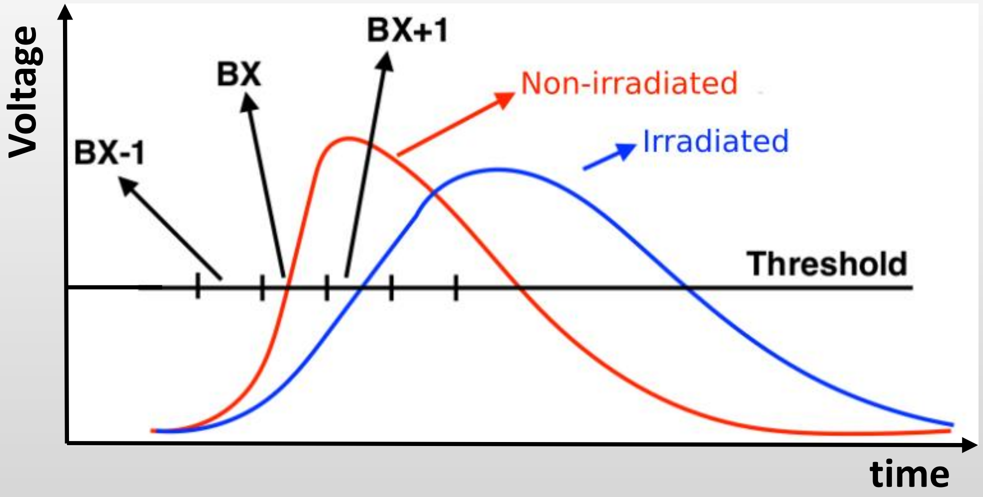
Tracking efficiency studies

- **Main strips inefficiency due to no multi-tracking:**
  - 30% efficiency at pileup of 50
  - No problem for pixel detectors



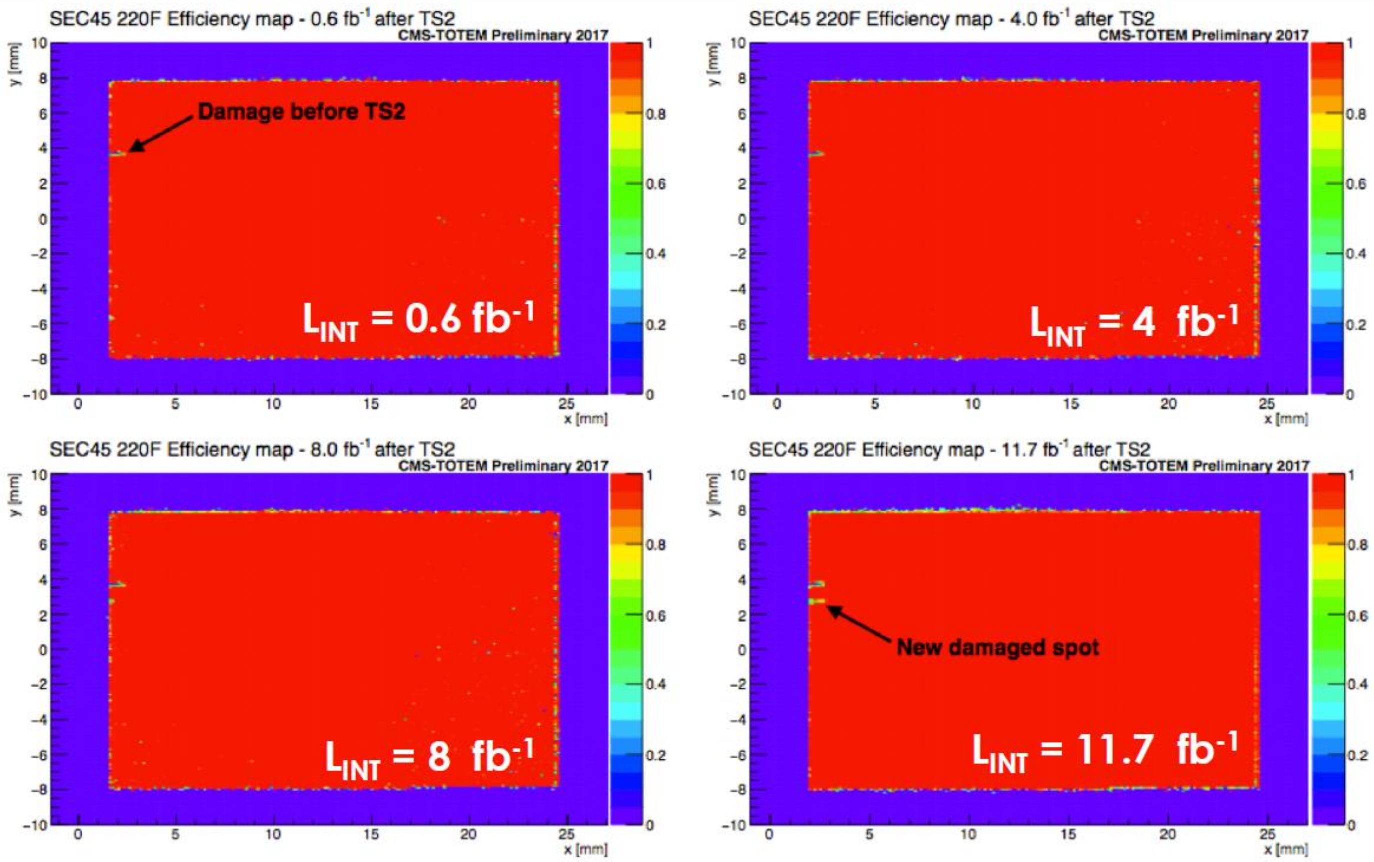


- **Radiation damage effects on the sensors reduced when moving to pixels:**
  - However, non-uniform irradiation does affect the readout chip performance
  - Efficiency loss mitigated by moving the stations vertically during technical stops



2017 Pixel detector efficiency

- **Efficiency computed with tracks reconstructed within the same station**
  - Evolution of the radiation damage vs. integrated luminosity after LHC second Technical Stop ($\sim$18 fb^{-1} taken before TS2)
  - Inefficiency spot caused by radiation damage is moved away from the high-occupancy region when the station is lifted
  - The radiation effect starts to be visible at $\sim$8 fb^{-1}



- **Very high performance overall: average efficiency $\sim$98%**
  - Few damaged pixels: $\sim 1.5 \times 0.3$ mm^2, caused by non-uniform irradiation of the readout chip

PPS physics case

Experimental apparatus

Operation in LHC Run 2

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Detector alignment and proton reconstruction

(Semi)Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ 2016 results

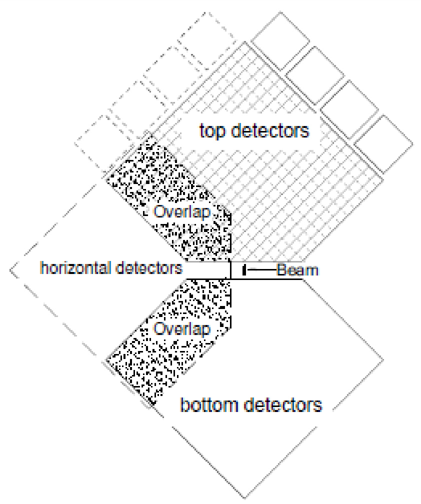
Prospects for LHC Run 3

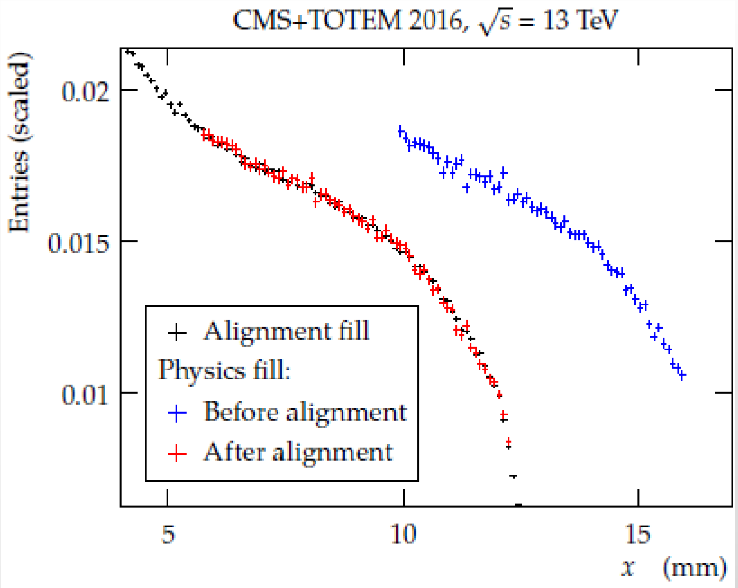
Detector alignment

Two step detector alignment procedure:

- <u>Absolute RP alignment</u> in dedicated low-luminosity runs:
  - Beam-based alignment, to establish the position of the RPs w.r.t. the LHC collimators and the beam
  - Exploit the geometrical properties of elastic scattering events (pp → pp) to extract positions of all the RPs, with both horizontal and vertical pots inserted very close to the beam
- <u>Fill-by-fill</u> alignment:
  - Need to redetermine the RPs positions w.r.t. the beam: the RP position during standard data taking differs from that of the alignment run; the beam position may also change due to the RP or beam movement
  - Use inclusive sample of protons and match the proton tracks distribution with those of the alignment run

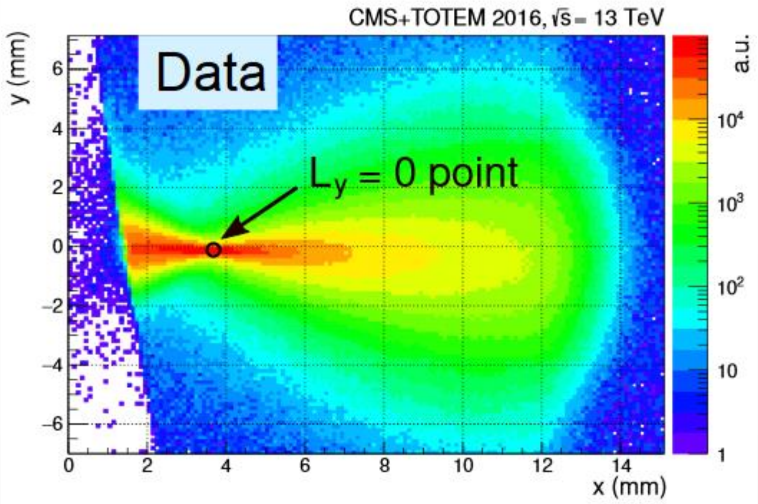
See CERN-LHC-2014-021 and CERN-TOTEM-NOTE-2017-001 for further details

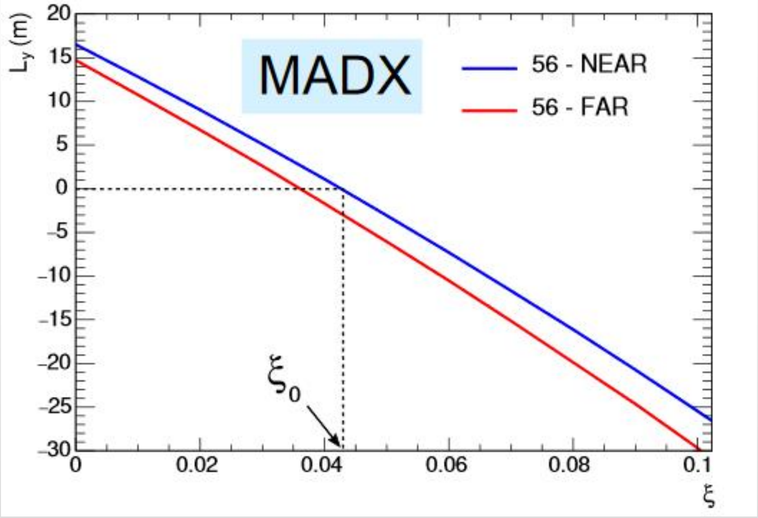




LHC optics and dispersion corrections

- **Very good knowledge of the LHC beam optics is needed in order to correctly reconstruct the proton fractional momentum loss ξ**
    - Significant data-driven corrections need to be made to the nominal optics
        - MADX software is used to simulate LHC optics
        - The model parameters are tuned to measurements performed with RPs and beam-position monitors
    - The dispersion is calibrated by using the effective length pinch point ($L_y(x) = 0$)
- In the end: **non-linear calibration of ξ vs. the measured track position, ξ=x/D_x(ξ)**
- *For the full documentation, see:*
  New J. Phys. 16 (2014) 103041, CERN-TOTEM-NOTE-2017-002





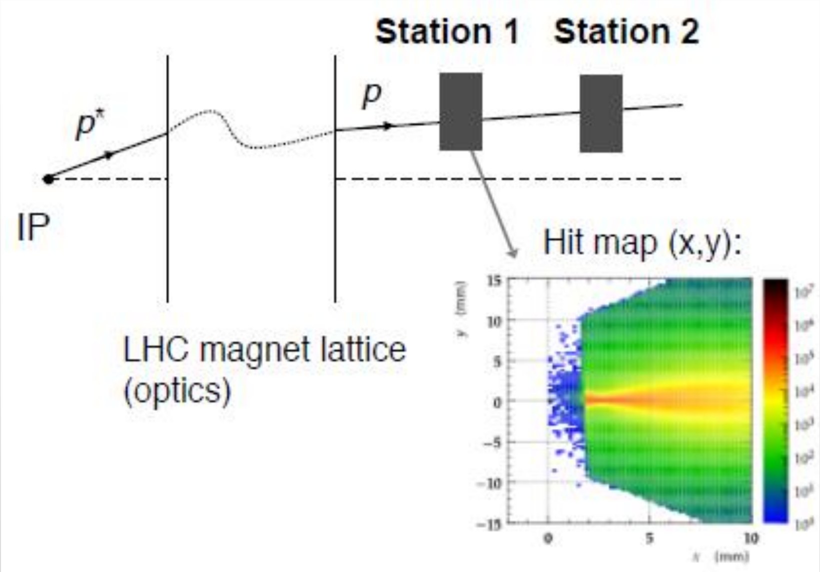
Proton reconstruction

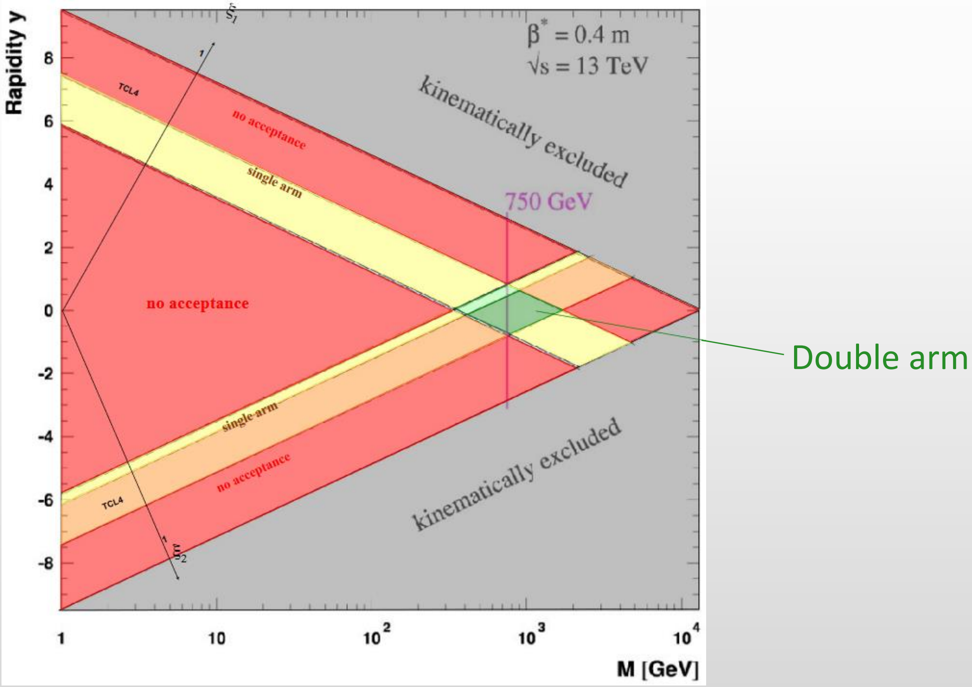
- **Knowledge of beam optics allows the proton fractional momentum loss ξ to be computed:**
  - From ξ the invariant mass and rapidity of the centrally produced state X is determined
- **Double arm mass acceptance in the $\sim 400 - 2000$ GeV range**
  - Lower limit mainly due to the minimum distance from the beam (can vary depending on beam conditions, e.g. crossing angle)
  - Upper limit due to collimators

$$\xi = 1 - \frac{|\mathbf{p}_f|}{|\mathbf{p}_i|}$$

$$M_X = \sqrt{s\xi_1\xi_2}$$

$$y_X = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$$



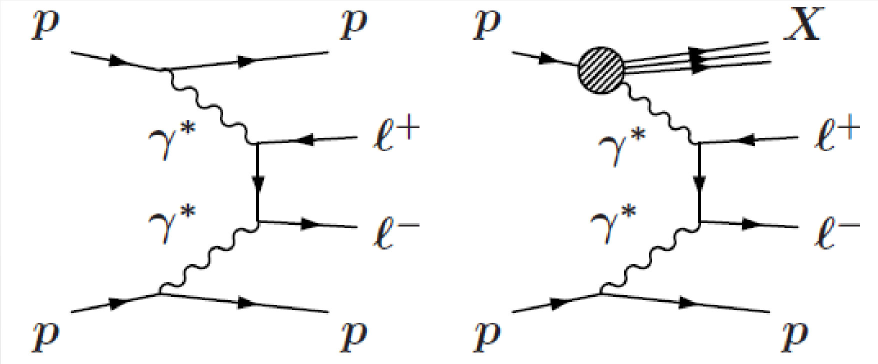


(Semi)exclusive $\gamma\gamma \to \ell^+\ell^-$

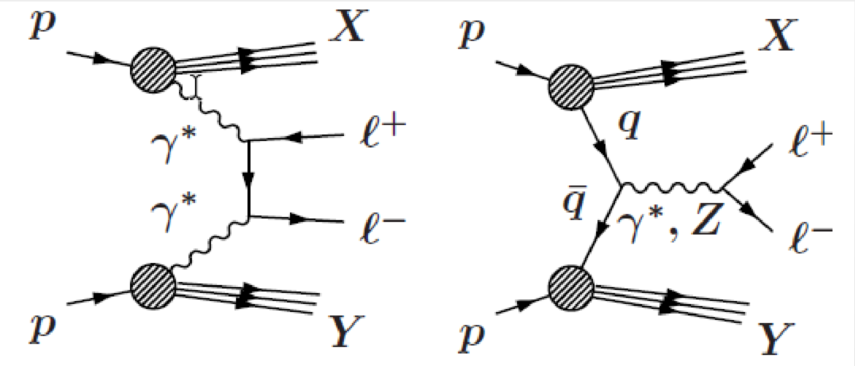
- Search for **opposite-charge lepton pairs produced by two photons, with forward proton tagging**
  - *See (JHEP 07 (2018) 153 (arXiv:1803.04496 [hep-ex]))*
- **Known EWK process:**
  - **Proton ξ related to p_T and η of the leptons:** $\xi(\ell^+\ell^-) = \frac{1}{\sqrt{s}}[p_T(\ell^+)e^{\pm\eta(\ell^+)} + p_T(\ell^-)e^{\pm\eta(\ell^-)}]$
  - **Elastic contribution:** low theoretical uncertainty (E-M proton form factors, …)
  - **Single dissociation component:**
    - Wider photon virtuality spectrum than for exclusive production
    - Sensitive to rapidity gap survival probability
    - Provides acceptance towards lower masses
- **Backgrounds:**
  - **Double dissociation** contribution
  - **Inclusive** (Drell-Yan, VBF) contribution

} **+ pileup proton**

Signal



Backgrounds



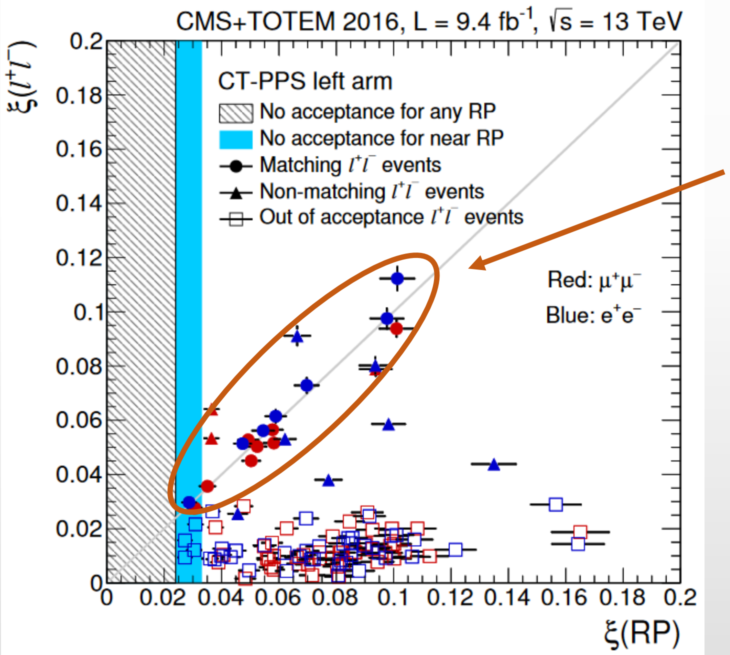
(Semi)Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ data selection

- **9.4 fb^{-1} of 2016 data used**
- **Pre-selection:**
  - Trigger: >= 2 leptons with $p_T(\mu^\pm) > 38$ GeV and $p_T(e^\pm) > 33$ GeV
  - Offline selection: $p_T(\ell^\pm) > 50$ GeV, $m(\ell^+\ell^-) > 110$ GeV (above Z mass peak),
    well-reconstructed protons with $\xi(\ell^+\ell^-)$ in PPS coverage >= 1
  - Refitted dilepton vertex ($\chi^2 < 10$, $z < 15$ cm) separated from neighbouring tracks (0.5 mm veto)
  - Leptons produced back-to-back in transverse plane: $a \equiv 1 - \left|\frac{\Delta\Phi}{\pi}\right| < \begin{cases} 0.009\ (\mu^+\mu^-) \\ 0.006\ (e^+e^-) \end{cases}$
- Strong background suppression by **requiring 2σ matching between ξ measurements** (central tracker vs. PPS)
- **Data-driven background estimation**, using inclusive $\mathrm{DY} \rightarrow \ell^+\ell^-$ data and double dissociative simulated events together with randomly selected protons from the data passing the ξ match requirement
- **Expected background:**

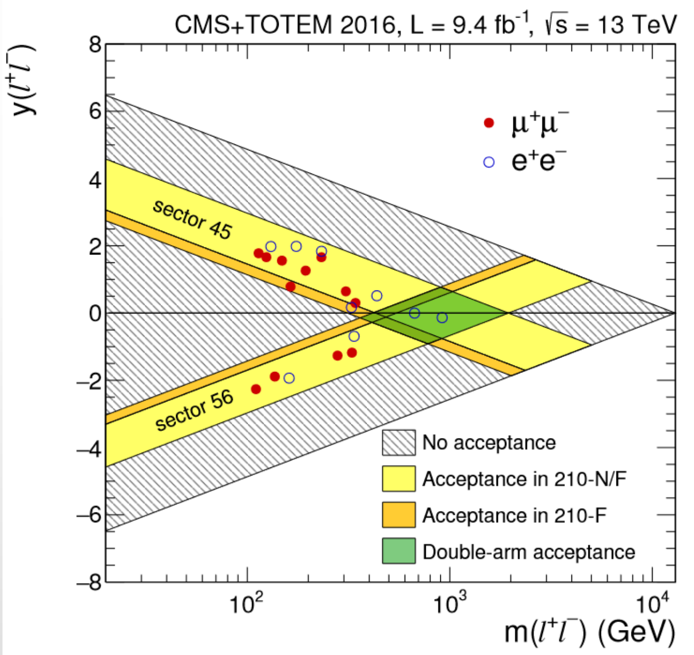
$$\begin{cases} \mathbf{1.49 \pm 0.07\ (stat.) \pm 0.53\ (syst.)\ (\mu^+\mu^-)} \\ \mathbf{2.36 \pm 0.09\ (stat.) \pm 0.47\ (syst.)\ (e^+e^-)} \end{cases}$$

(Semi)Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ 2016 results

- **First observation of (semi)exclusive (two-photon) production of dileptons with tagged protons**
  - 20 matching events, with a total estimated background of 3.85 events
  - Combined significance of 5.1σ over background only hypothesis



Events matched in Sector 45 (Left arm)



<u>**This measurement proves that PPS performs according to expectations**</u>

PPS physics case

Experimental apparatus

Operation in LHC Run 2

Tracking efficiency

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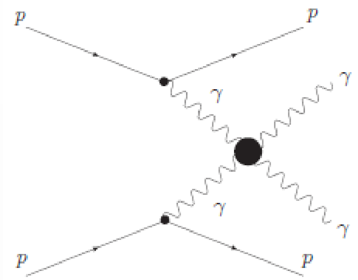
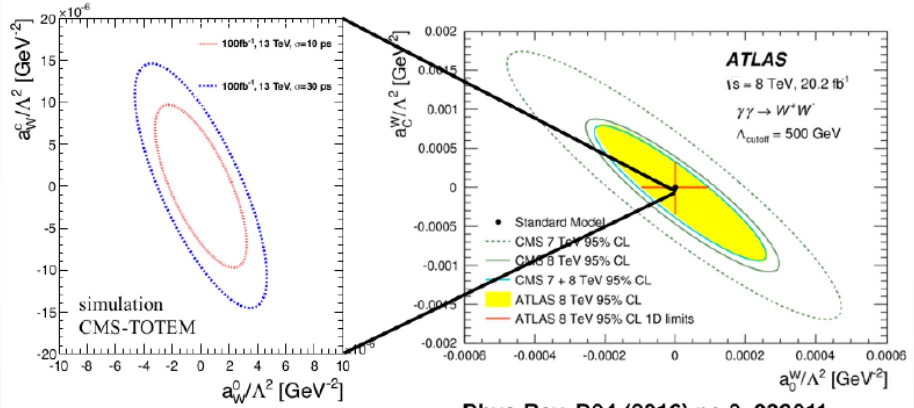
(Semi)Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ 2016 results

Prospects for LHC Run 3

PPS analysis prospects

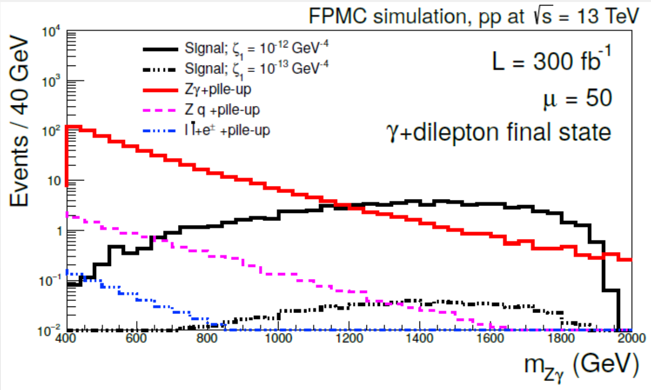
- **Search for two-photon production of a boson pair:**
  - Study neutral quartic gauge coupling, suppressed in SM
  - Sensitive to resonances (axion-like particles, new particle exchanges)
  - Provides model-independent bounds on massive charged particles, only parameterized by spin, mass and "effective charge"
    - *See arXiv: 1411.6629*
- **Search for anomalous quartic gauge couplings:** $\boldsymbol{\gamma\gamma \to W^+W^-, \gamma\gamma \to \gamma Z, \gamma\gamma \to ZZ \dots}$
  - $\gamma\gamma \to W^+W^-$: PPS TDR expectations with two order of magnitude improvement w.r.t. Run 1 searches
    - *See arXiv: 1604.04464, arXiv: 1607.03745*
  - $\gamma\gamma \to \gamma Z$: the combined sensitivity in the γZ channel, for 300 fb^{-1}, goes beyond the one expected for $Z \to \gamma\gamma\gamma$ decay searches by ~3 orders of magnitude
    - *See arXiv: 1703.10600*





CERN-LHCC-2014-021

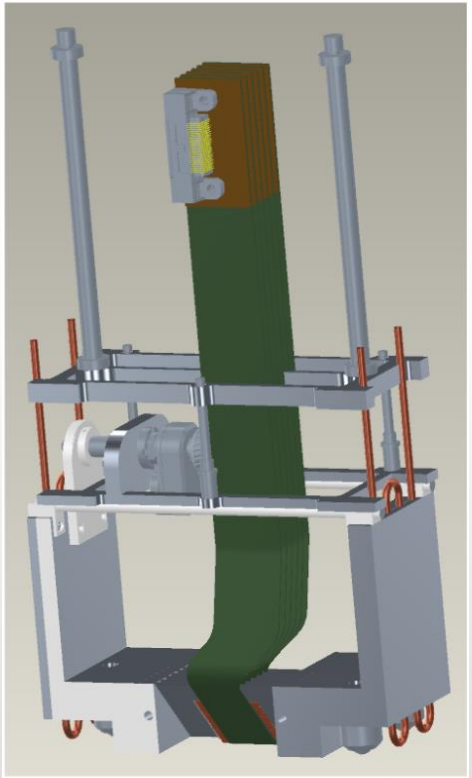
Phys.Rev. D94 (2016) no.3, 032011



PPS prospects for Run 3

- **PPS approved for operation as standard CMS subsystem in LHC Run 3 (2021-2023)**

- **Experimental apparatus:**
  - Tracking:
    - 2 horizontal stations with silicon 3D pixels sensors (similar to the 3D pixels designed for the CMS Phase2 Tracker R&D)
    - PROC600 readout chip (same as CMS pixel detector layer 1)
    - New internally motorized detector package, to distribute the radiation damage and reduce its impact
  - Timing:
    - 2 horizontal stations equipped with double-layer diamond sensors
    - Optimized readout electronics



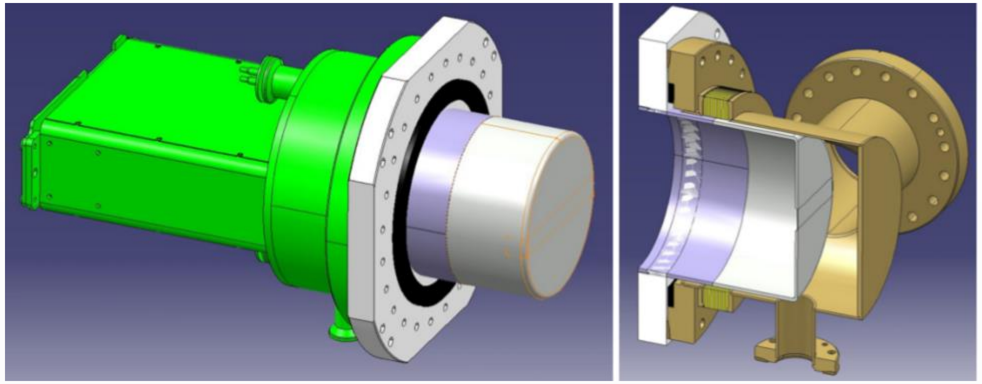
Summary

- PPS has proven the feasibility of continuously operating a near-beam proton spectrometer at a high-luminosity hadron collider
- **PPS has successfully collected $\sim$115 fb^{-1} worth of data** during LHC Run 2, with very good overall performance
- **PPS has for the first time observed at more than 5σ significance the proton-tagged two-photon production of lepton pairs** with $\sim$10 fb^{-1} of 2016 data
- 2017 and 2018 detector performance studies are being finalized

- **The preparation for LHC Run 3 is ongoing**:
  - **New detectors are getting ready** to be installed for the future data taking
  - A **rich physics programme** lies ahead, with many final states to be studied

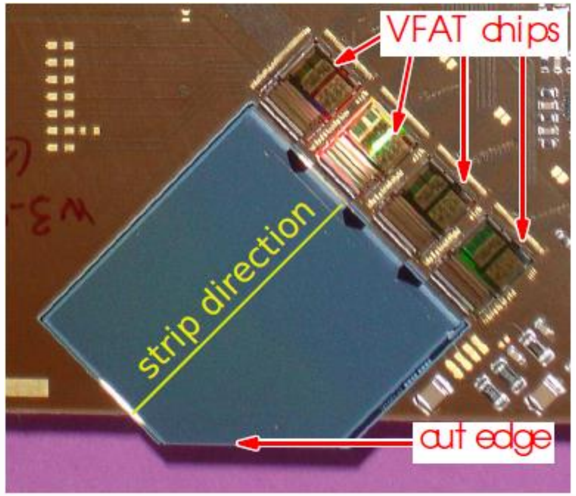
Backup Slides

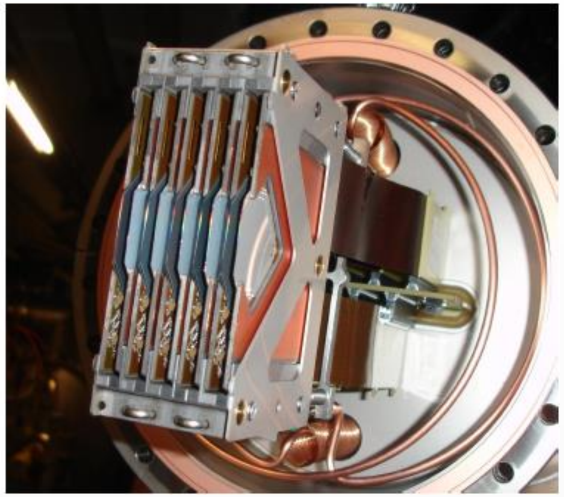
RPs for timing detectors



- **New cylindrical RP design to host larger detectors and reduce the impedance**
- Timing RPs are **equipped with a 300 µm thick window towards the beam**
  - The thickness is required to compensate the pressure gradient on the larger window
  - No vertical stations needed because the alignment is done by propagating tracks from the tracking stations

Silicon strips detectors

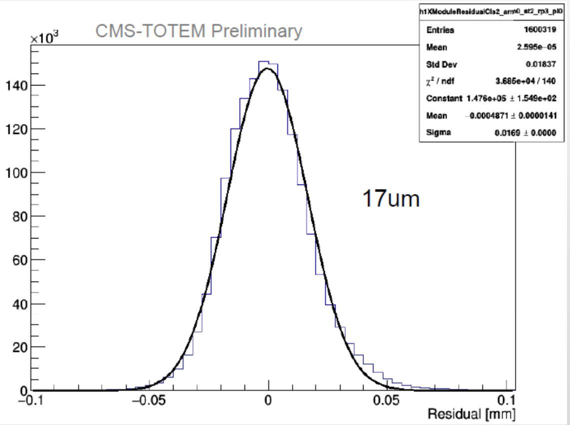


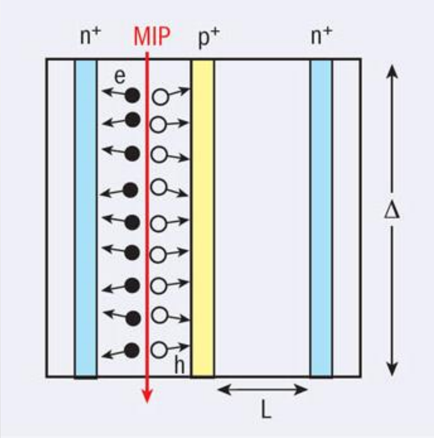


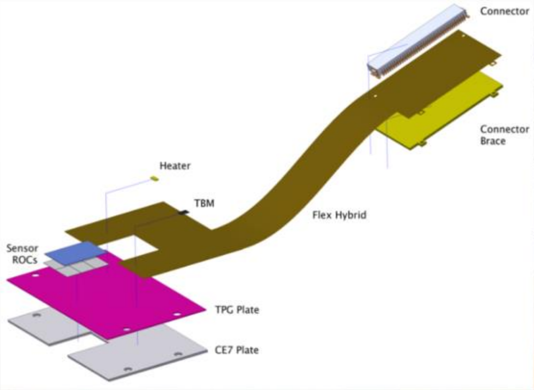
- 300 μm thickness
- 66 μm pitch
- strips oriented at 45° w.r.t. edge facing beam
- Dead area close to the cut edge: only ~50 μm
- operated at −20 °C, bias voltage ~100 V
- 5+5 planes per RP (2 strip orientations for 2D reconstruction)

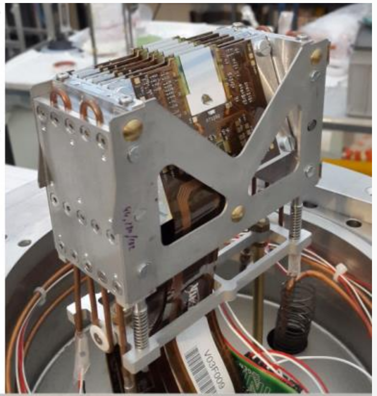
3D pixel detectors

- 3D technology grants high radiation hardness (up to $\sim 5 \cdot 10^{15}$ p/cm^2)
- Pixel size 100×150 μm, 230 μm thickness
- Low dead region close to the edge (~ 50 μm)
- 6 planes per RP
  - 18° planes tilt to improve hit cluster size
- Operation at -20 °C and in vacuum (P < 20 mbar)
- Pixel tracker works as expected
  - Residuals according with test beam measurements









Timing detectors

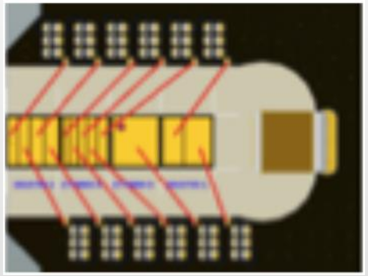
Diamond Sensors

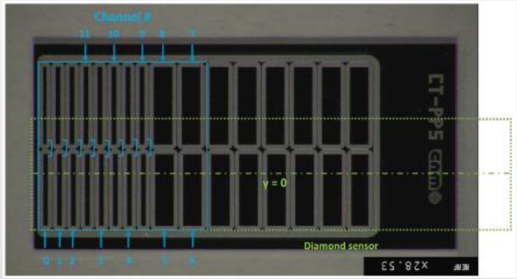
- CVD diamond sensors
- Radiation hard
- Macro-pixels of varying size
- Single-plane resolution in test-beam: $\sigma_t \sim 80$ ps

Ultra-Fast Silicon Detectors

- Based on LGAD technology
- Limited radiation hardness
- Macro-pixels of varying size
- Single-plane resolution in test-beam: $\sigma_t \sim 30$ ps

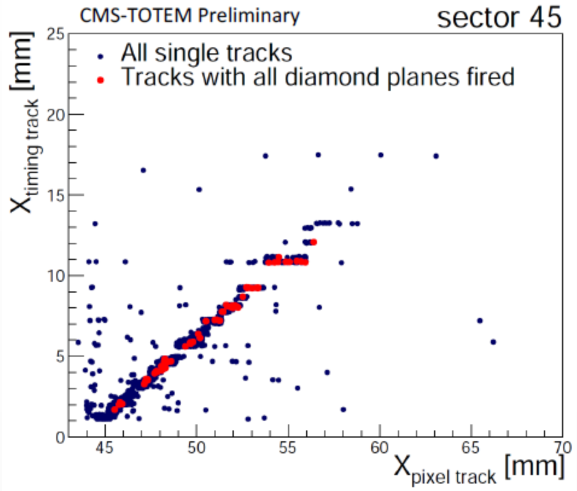
Common readout electronics



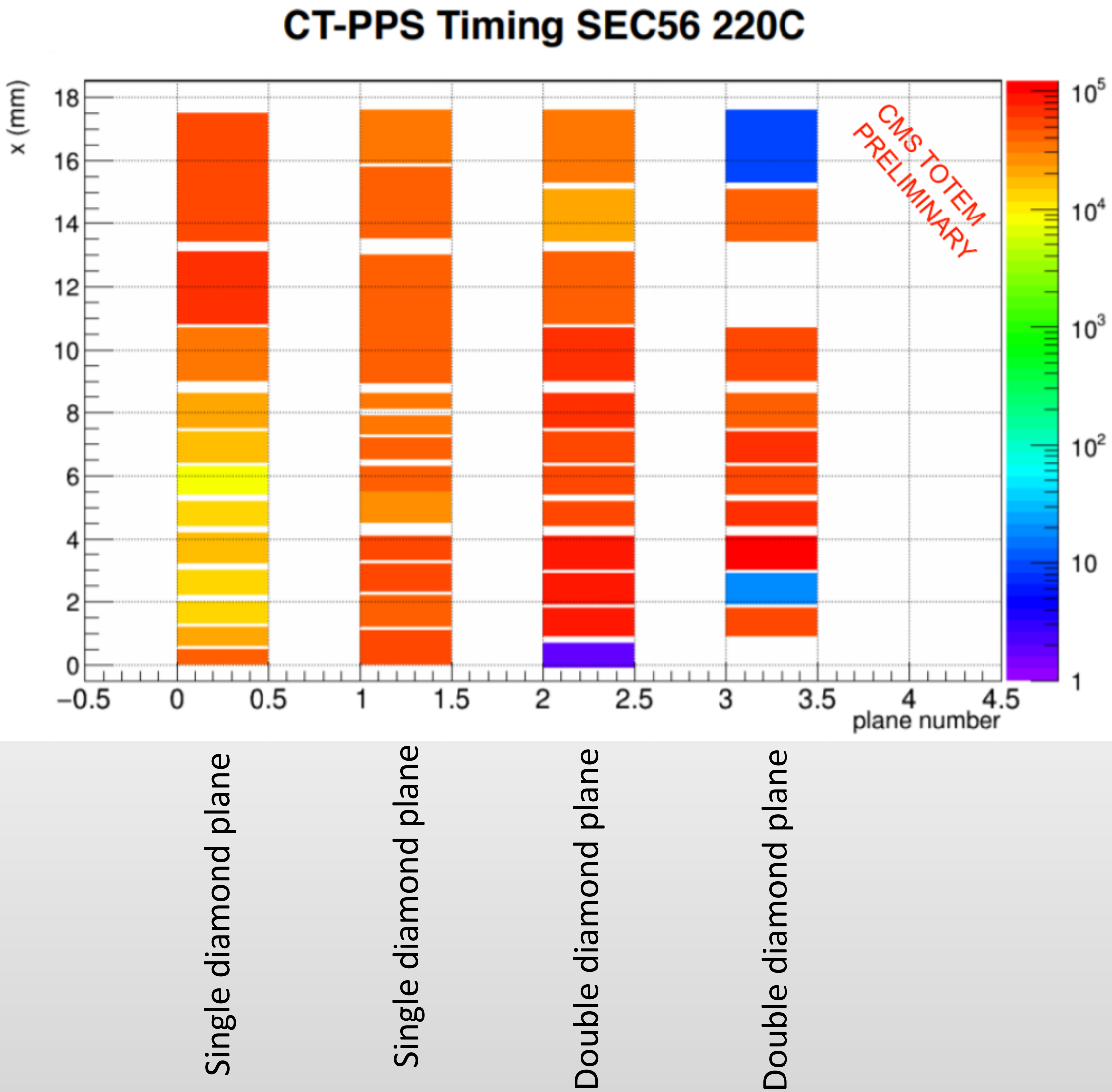


Timing detectors performance

2017



2018



- Horizontal position of the reconstructed track in the PPS pixels vs. horizontal position of in the PPS timing in low pile-up data (<PU> ~ 0.8)
- The data sample is selected requiring a single vertex reconstructed in CMS, a single track reconstructed in the PPS pixels in each of the arms and a single track reconstructed in the PPS timing in each of the arms
- **Blue points** show all the events passing the double arm selection
- **Red points** represent the subsample with a single hit per diamond detector plane and all the diamond planes firing

Proton transport model

- The propagation of the proton from the IP to the RPs is approximately modeled with this linear formula:

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

where $\boldsymbol{d} = \left(x, \theta_x, y, \theta_y, \frac{\Delta p}{p}\right)^T$, the * symbol refers to quantities at the IP,

$$\mathrm{T} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ \frac{dv_x}{ds} & \frac{dL_x}{ds} & m_{23} & m_{24} & \frac{dD_x}{ds} \\ m_{31} & m_{32} & v_y & \mathrm{L_y} & \mathrm{D_y} \\ m_{41} & m_{42} & \frac{dv_y}{ds} & \frac{\mathrm{dL_y}}{\mathrm{ds}} & \frac{\mathrm{dD_y}}{\mathrm{ds}} \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}, \quad \begin{matrix} v_{x,y} = \sqrt{\beta_{x,y}/\beta^*} \cos(\Delta\mu_{x,y}) \\ L_{x,y} = \sqrt{\beta_{x,y} \cdot \beta^*} \sin(\Delta\mu_{x,y}) \end{matrix}$$

β is the betatron amplitude and $\Delta\mu_{x,y}$ is the relative phase advance ($\Delta\mu_{x,y} = \int_{IP}^{RP} \frac{ds}{\beta_{x,y}}$)

The leading terms are:

- $x \approx D_x(\xi) \cdot \xi$
- $y \approx L_y(\xi) \cdot \theta_y^*$