PPS results and prospects

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on behalf of the CMS and TOTEM Collaborations

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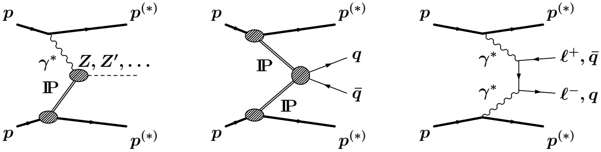
Introduction – PPS physics case



Central exclusive production

Very clean production processes at the LHC

- colour-singlet exchanges ($J^{PC} = 0^{++}$), with large rapidity gaps between the central system and scattered protons
- photoproduction, double-pomeron or two-photon exchanges yield a variety of processes accessible at LHC energies
  - 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)

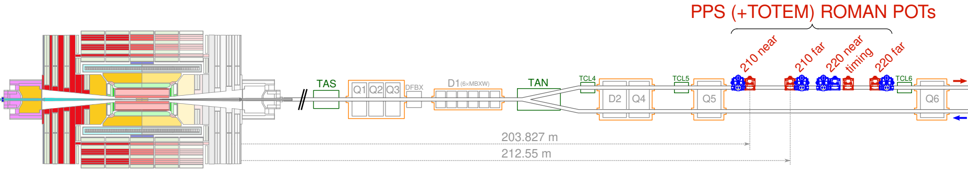
Tagging forward protons at the LHC

- over-constraint of event kinematics through central/forward systems matching
- proton dissociation cases (semi-exclusive processes) allow study of survival probability
- direct probe of BSM physics through EWK ($\gamma\gamma \to X$), or QCD (exclusive dijets, . . .) processes

Introduction – PPS apparatus

Joint **CMS + TOTEM project** including horizontal Roman Pots (RPs) within the CMS environment

- started in early LHC run 2 (2016), thanks to TOTEM silicon strips availability
- horizontal RPs equipped with RF shields
- several detection technologies used all along this period
- over **15 + 40 + 60 fb**$^{-1}$ collected in 2016, 2017, and 2018, as standard CMS subsystem



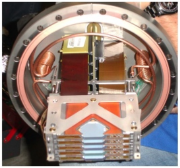
Principles of operation / detectors types

- **Tracking detectors**

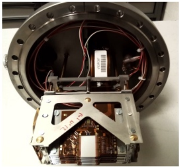
  measurement of proton tracks displacement with respect to the beam direction, translated into energy-momentum loss through knowledge of the beamline lattice

- **Timing detectors**

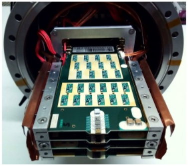
  2-arms measurement used in time-of-flight computation of interaction longitudinal position



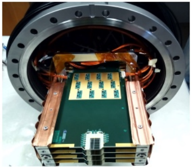
TOTEM strips



3D pixels



scCVD (diamond)



ultra-fast Si-detector

For each arm

2016 layout

- two stations of **TOTEM silicon strips** (10 planes), $\sigma \sim 12\ \mu$m, strips efficiency optimised for TOTEM operations at **high-**β^* (no multi-tracking, radiation damage: $\Phi_{\rm max} \sim 5 \times 10^{14}$ p/cm^2)
- **diamond timing detectors** in a cylindrical RP ; fully operational after 2016 TS2

2017 layout

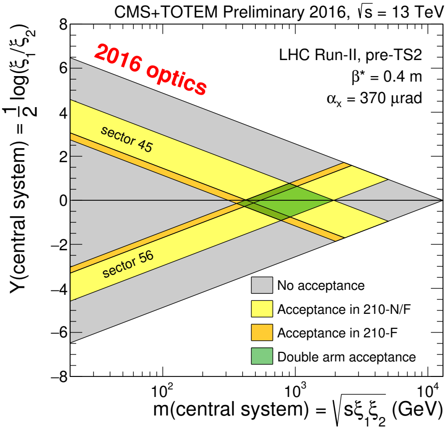
- tracking: 1 station of **strips**, 1 station of **3D pixels** (6 planes, same readout technology as CMS phase 1 central pixel), $\sigma_x \sim 15\ \mu$m, $\sigma_y \sim 30\ \mu$m, $\Phi_{\rm max} \sim 5 \times 10^{15}$ p/cm^2
- timing: 1 station with 3 planes of **single-layer diamond** (first time installed at LHC!) with expected $\delta t \sim 80$ ps/plane + 1 plane of UFSD with $\delta t \sim 30$ ps/plane, $\Phi_{\rm max} \sim 10^{15}$ nev/cm^2

2018 layout

- two stations of **3D pixels** (tracking component)
- **hybrid** single/double layer diamond (timing detectors)

PPS tracking detectors – single- and double-arm acceptance

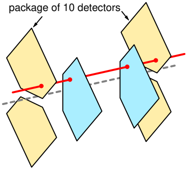
Physics observables: proton longitudinal momentum loss $\xi = \Delta p/p$, and squared 4-momentum loss t

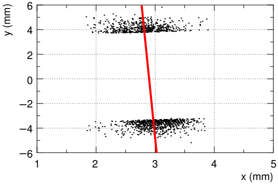


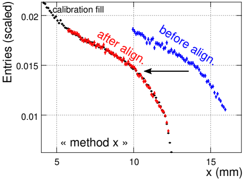
- In 2016, $360 < m(\text{central}) < 1950$ GeV (central $|y|$) for **double-arm tagging**
- From 2017 on, (horizontal) LHC **beams crossing angle variation** $\rightarrow$ time-dependent acceptance
- **Single-arm tagging** extends acceptance to low-mass, forward-region events (yellow bands)

PPS alignment and calibration

PPS detectors alignment







General **alignment technique** developed and **extensively used** by the TOTEM Collaboration, adapted to high-luminosity operation mode

Absolute Roman Pots alignment using dedicated low-intensity bunches (alignment runs):

- **beam-based absolute alignment** between LHC collimators and RPs (rate monitoring with BLMs of beam edge scraping with pots)
- use ***pp*** $\longrightarrow$ ***pp*** **scattering events** with both horizontal and vertical pots inserted very close to the beam to extract **absolute** and **relative** (in overlapping regions) **per-pot alignments** (incl. rotations)

Per-LHC fill pots alignment:

- one-dimensional match of hit distributions in **inclusive proton sample** from high-luminosity fills and from **alignment run**

Full documentation of the technique: CERN-TOTEM-NOTE-2017-001

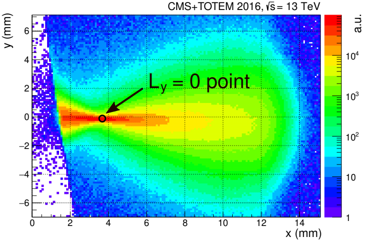
“$\boldsymbol{x}$-to-ξ” calibration

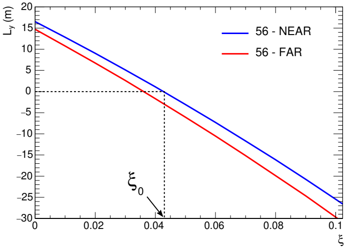
- Optics matching uses MAD-X modelling of full beamline optical components (quadrupole strengths, RPs/BPMs positions, ...)
- Dispersion calibration uses the **vertical pinch point** $\boldsymbol{L_y(\xi_0) = 0}$ at which vertical impact points spread is minimal.
- Final result is a (non-linear) calibration of ξ vs. the measured track x position:

$$\boldsymbol{x = D_x(\xi) \cdot \xi}$$

Overall uncertainty of **5.5%** in the $\boldsymbol{D_x(\xi)}$ determination procedure

- added in quadrature to kinematic (angular/transverse) tracks kinematic uncertainties to extract the ξ resolution



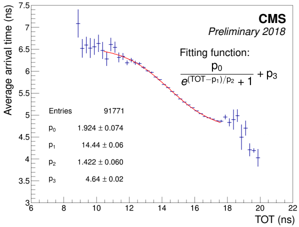


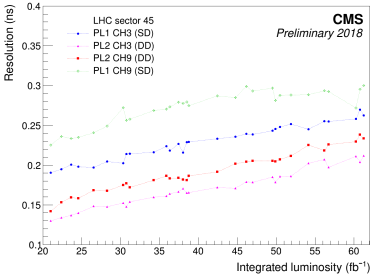
Full documentation: New J. Phys. 16 (2014) 103041, CERN-TOTEM-NOTE-2017-002

Timing detectors calibration

Two-steps **per-channel calibration** for single- and double-diamond pads:

- correction and alignment of measured time of arrival as a function of signal pulse width (TOT) from NINO ($\propto Q$)
- iterative computation of time precision for each pad





Double diamond sensors 70% more efficient than single diamonds

Two components identified in timing precision degradation:

- 20-50% damage for sensor and readout electronics (preamplification stage)
- region closest to the beam: metallisation/bulk creation of trapping centres, thus reducing signal yield

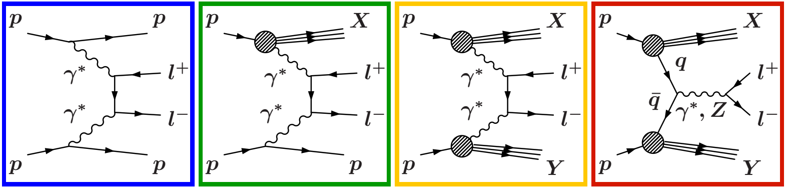
With this calibration technique, and improved knowledge of operational parameters, ultimate run 3 resolution goal of $<$ 30 ps per station within reach

Search for central exclusive production of lepton pairs

The analysis in a nutshell

Search for **two-photon production** of an opposite-charge **lepton pair** with forward **proton tagging** using PPS strips detectors (2016 pre-TS2 dataset, no timing detectors)

Analysis documentation: JHEP 07 (2018) 153 (arXiv:1803.04496 [hep-ex])



$\gamma\gamma \to l^+l^-$ *signals*

Elastic contribution:

- simple QED process, with low theoretical uncertainty (E-M proton form factors, . . .)

Single-dissociation component (SD):

- broader photon virtuality spectrum with respect to elastic production
- highly sensitive to proton survival probability

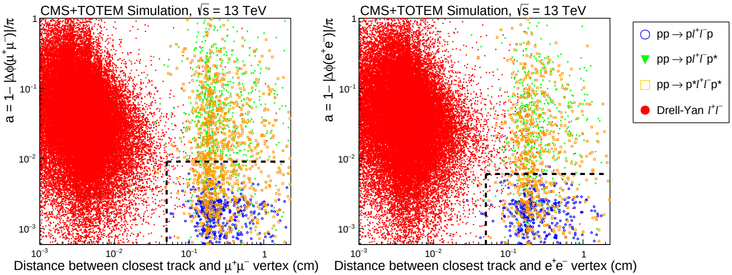
Backgrounds

Double-dissociation contribution (DD)

Inclusive contributions: Drell-Yan, VBF, . . .

- both background sources overlaid with protons from pileup

Central detector selection



Dataset: ~15 fb^{-1} (~10 fb^{-1} with RPs inserted) of pre-TS2 data collected at 13 TeV in 2016

Pre-selection:

- trigger: $\geq$ **2 leptons** with $\boldsymbol{p_T(\mu^\pm) > 38}$ **GeV**, $\boldsymbol{p_T(e^\pm) > 33}$ **GeV**
- offline selection: $\boldsymbol{p_T(l^\pm) > 50}$ **GeV**, $\boldsymbol{m(l^+l^-) > 110}$ **GeV** (above Z mass peak)
- refitted dilepton vertex ($\boldsymbol{\chi^2 < 10, |z| < 15}$ **cm**) clearly separated from neighbouring tracks (0.5 mm veto)
- leptons produced back-to-back in transverse plane,

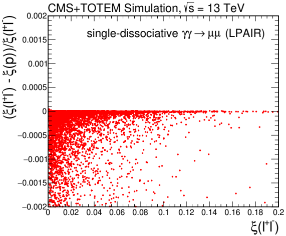
$$a \equiv 1 - |\Delta\phi/\pi| < \begin{cases} 0.009 \ (\mu^+\mu^-) \\ 0.006 \ (e^+e^-) \end{cases}$$

Selecting events with at least one track in **at least one PPS arm**

Accurate prediction of outgoing proton ξ from central system kinematics:

$$\xi^{\pm}(l_1 l_2) = \frac{1}{\sqrt{s}}\left[p_{\mathrm{T},l_1} e^{\pm\eta_{l_1}} + p_{\mathrm{T},l_2} e^{\pm\eta_{l_2}}\right]$$

... without experimental constraint/observation of second proton



Central-forward selection: 2-σ matching of $\xi(l^+l^-)$ and $\xi(\mathrm{RP})$

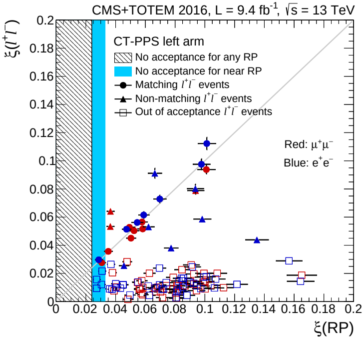
Data-driven estimate of remaining background using inclusive DY $\to l^+l^-$ and DD $\gamma\gamma \to l^+l^-$ events in coincidence with pileup protons

- extract yield of 2-σ matching events in Z peak control region
- for DY and DD accidental backgrounds, yields estimation using mixing of MC events (sampling of $\xi(ll)$) and forward protons observed in data (inclusive Z peak central selection)

Expected combined backgrounds expectations in the 2-σ matching region:

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

Results



Dimuon candidates (blue markers):

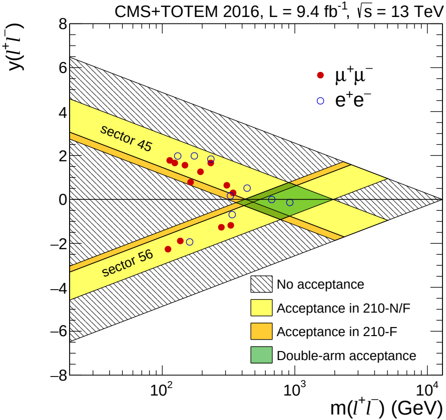
- **17 events** with $\xi(\mu\mu)$ consistent with RPs acceptance (triangles)
- **12 events** with matching $\xi(\mu\mu)$ / ξ(RP) (dots)

Dielectron candidates (red markers):

- **23 events** with $\xi(ee)$ consistent with RPs acceptance (triangles)
- **8 events** with matching $\xi(ee)$ / ξ(RP) (dots)

Signal significance: **4.3σ** (**2.6σ**) over background-only hypothesis for dimuon (dielectron)

- combined significance: **5.1σ** over the background
- first **observation** of central (semi-)exclusive (two-photon) production of dileptons with tagged protons



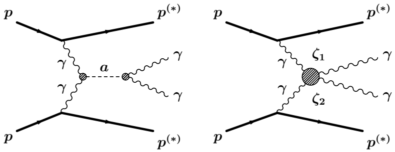
- mass range **up to the EWK scale**: $m_{max}(l^+l^-)$ = 917 GeV

Prospects and overview

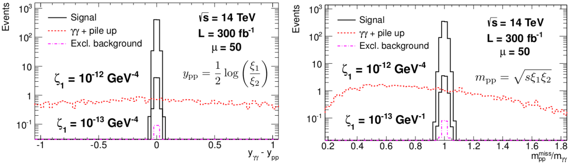
Search for two-photon production of a gauge boson pair

Addition of PPS within CMS allows to study numerous additional intermediate and final states

Search for exclusive two-photon production of a photon pair



- For double-tagging, very low background expected after kinematics match between central and forward two-proton systems
- Multiple SM extensions allow large range of predictions of discrepancies in yield/differential distributions (anomalous quartic gauge couplings, ALPs/new particle exchanges, . . .)



S. Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert (2015)

$m_{\gamma\gamma} > 600$ GeV, $p^{\gamma}_{T,2}/p^{\gamma}_{T,1} > 0.95$, $a < 0.003$

Search for anomalous $\gamma\gamma \to W^+W^-, \gamma\gamma \to \gamma Z, \ldots$

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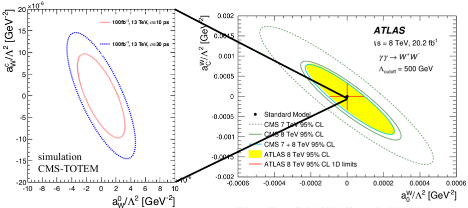
Addition of timing detectors opens the possibility to probe final states more complex than a dilepton system, even in a **high-$\langle\mu\rangle$ environment**

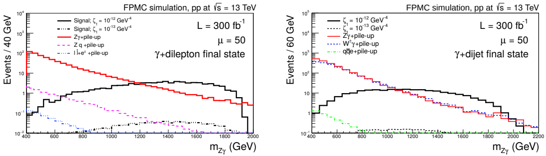
- for **exclusive W^+W^- production**, PPS TDR expectations (100 fb^{-1}): 2 orders of magnitude improvement wrt run 1 attempts (arXiv:1604.04464, arXiv:1607.03745)



CERN-LHCC-2014-021

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

- for **exclusive γZ production**, combined dilepton+dijet final states yields 3 orders of magnitude lower than inclusive limits on $Z \to \gamma\gamma\gamma$ BR (for 300 fb^{-1}, arXiv:1703.10600)



Summary

PPS in operation since 2016, first physics results published

- proven **for the first time** the feasibility of **operating a near-beam spectrometer** at a **high-luminosity hadron collider** on a regular basis
- multiple detector technologies, operated successfully over the full run 2 period
- first evidence at **more than 5σ** for electroweak-scale **single-proton tagged** two-photon production of a lepton pair at the LHC with **~10 fb^{-1}** collected in 2016
- rich physics programme ahead, with more (and increasingly complex) final states to be probed, and further precision tests of anomalous/BSM behaviours

More than **100 fb^{-1}** collected during LHC run 2, same scale as TDR expectations.

LHC run 3 preparation ongoing