PPS results and prospects

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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

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 ($\gamma\gamma \rightarrow X$), or QCD (exclusive dijets, …) processes
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 $15 + 40 + 60 \text{ fb}^{-1}$ collected in 2016, 2017, and 2018, as standard CMS subsystem

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**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*
Introduction – detector technologies along LHC run 2

2016 layout

- two stations of TOTEM silicon strips (10 planes), \( \sigma \sim 12 \, \mu m \), strips efficiency optimised for TOTEM operations at high-\( \beta^* \) (no multi-tracking, radiation damage: \( \Phi_{\text{max}} \sim 5 \times 10^{14} \, \text{p/cm}^2 \))
- 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), \( \sigma_x \sim 15 \, \mu m, \sigma_y \sim 30 \, \mu m, \Phi_{\text{max}} \sim 5 \times 10^{15} \, \text{p/cm}^2 \)
- timing: 1 station with 3 planes of single-layer diamond (first time installed at LHC!) with expected \( \delta t \sim 80 \, \text{ps/plane} + 1 \) plane of UFSD with \( \delta t \sim 30 \, \text{ps/plane} \), \( \Phi_{\text{max}} \sim 10^{15} \, \text{nev/cm}^2 \)

2018 layout

- two stations of 3D pixels (tracking component)
- hybrid single/double layer diamond (timing detectors)
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
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 \( pp \rightarrow pp \) **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](#)
“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** $L_y(\xi_0) = 0$ at which vertical impact points spread is minimal.
- Final result is a (non-linear) calibration of $\xi$ vs. the measured track $x$ position:

$$x = D_x(\xi) \cdot \xi$$

Overall uncertainty of **5.5%** in the $D_x(\xi)$ determination procedure
- added in quadrature to kinematic (angular/transverse) tracks kinematic uncertainties to extract the $\xi$ resolution

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)


\[
\gamma\gamma \rightarrow \ell^+\ell^- \quad \text{signals}
\]

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

$$a = 1 - |\Delta \phi / \pi| < \begin{cases} 0.009 (\mu^+\mu^-) \\ 0.006 (e^+e^-) \end{cases}$$
Selecting events with at least one track in **at least one** PPS arm

Accurate prediction of outgoing proton $\xi$ from central system kinematics:

$$\xi^{\pm}(\ell_1 \ell_2) = \frac{1}{\sqrt{s}} \left[ p_{T,\ell_1} e^{\pm \eta_{\ell_1}} + p_{T,\ell_2} e^{\pm \eta_{\ell_2}} \right]$$

... without experimental constraint/observation of second proton

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

Data-driven estimate of remaining background using inclusive $\text{DY} \rightarrow \ell^+\ell^-$ and $\text{DD} \gamma\gamma \rightarrow \ell^+\ell^-$ 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 $\xi(\ell\ell)$) and forward protons observed in data (inclusive $Z$ peak central selection)

Expected combined backgrounds expectations:

$$\begin{align*}
1.49 \pm 0.07 \text{ (stat.)} \pm 0.53 \text{ (syst.)} & \quad (\mu^+\mu^-) \\
2.36 \pm 0.09 \text{ (stat.)} \pm 0.47 \text{ (syst.)} & \quad (e^+e^-)
\end{align*}$$
Dimuon candidates (blue markers):

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

Dielectron candidates (red markers):

- **23 events** with $\xi(ee)$ consistent with RPs acceptance (triangles)
- **8 events** with matching $\xi(ee) / \xi(RP)$ (dots)
Central (semi-)exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ events

Signal significance: $4.3\sigma$ (2.6$\sigma$) over background-only hypothesis for dimuon (dielectron)

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

- mass range up to the EWK scale: $m_{\max}(\ell^+\ell^-) = 917$ 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, ...)

\[
\begin{align*}
\mu &= 50 \\
\mathbf{t}_s &= 14 \text{ TeV} \\
\mathbf{L} &= 300 \text{ fb}^{-1} \\
\mathbf{\zeta}_1 &= 10^{-12} \text{ GeV}^{-4} \\
\mathbf{\zeta}_2 &= 10^{-13} \text{ GeV}^{-4} \\
\mathbf{\zeta}_3 &= 10^{-12} \text{ GeV}^{-4} \\
\mathbf{\zeta}_4 &= 10^{-13} \text{ GeV}^{-4} \\
\end{align*}
\]

\[
\begin{align*}
\mathbf{m}_{\gamma\gamma} &> 600 \text{ GeV} \\
\mathbf{p}_{T,2}^{\gamma} / \mathbf{p}_{T,1}^{\gamma} &> 0.95, \mathbf{a} < 0.003 \\
\end{align*}
\]

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

**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 ($100 \text{ fb}^{-1}$): 2 orders of magnitude improvement wrt run 1 attempts (arXiv:1604.04464, arXiv:1607.03745)

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

![Graphs showing CMS-TOTEM and ATLAS simulations](image-url)
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