PROCEEDINGS OF SCIENCE

The CMS-TOTEM Precision Proton Spectrometer and first physics results

Enrico Robutti*
INFN Genova
E-mail: enrico.robutti@ge.infn.it

on behalf of the CMS and TOTEM Collaborations

The CT-PPS (CMS-TOTEM Precision Proton Spectrometer) detector system consists of tracking and timing stations located along the LHC at CERN, on both sides of the CMS interaction point. Its purpose is to study Central Exclusive Production (CEP) in proton-proton collisions at LHC, where the two protons emerge intact from the interaction, while the energy lost is taken up by additional particles detected by the central CMS detectors. Channels of interest include photon-photon production of W and Z boson pairs, high-mass diphoton and dilepton production, high-p_{T} jet production, as well as searches for anomalous couplings and new resonances.

Data recorded by CT-PPS in 2016 at nominal LHC luminosity have been used to study dilepton production: on a sample corresponding to about 10 fb^{-1}, central exclusive production of high-mass dilepton pairs has been observed for the first time.

XXVI International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2018)
16-20 April 2018
Kobe, Japan

*Speaker.

PoS(DIS2018)040

1. The CMS-TOTEM Precision Proton Spetrometer

The CMS-TOTEM Precision Proton Spectrometer (CT-PPS) [1] is a joint project of the CMS and TOTEM Collaborations devoted to the study of central exclusive (or semi-exclusive) production processes at the LHC. In this kind of process, the two colliding protons (one, in the case of semi-exclusive reactions) remain intact after the interaction and are scattered at very small angles; the small energy fraction lost is turned into particles produced with sizable transverse momentum ("rapidity gap"). Processes can occur via photon-photon or gluon-gluon fusion (Fig. 1). Channels of interest include diboson production (with search for anomalous quartic gauge coupling [2]), dilepton production and multijet production [3]. The presence of new physics may induce deviations from theoretically known cross sections, or the appearance of new resonant structures.

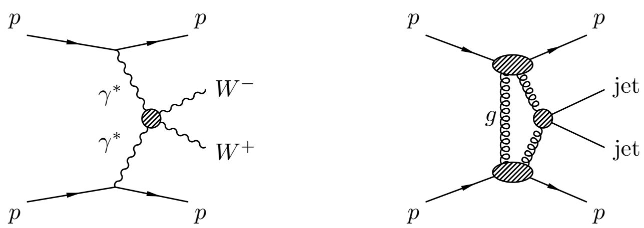

Figure 1: Example of diagrams for Central Exclusive Production processes. Left: photon-photon fusion; right: gluon-gluon fusion.

The CT-PPS experimental apparatus is designed to detect the emerging protons in their trajectory close to the circulating beams. It consists of a series of position and time detectors located along the LHC beam pipe, at a distance of about 200 m from the CMS interaction point (Fig. 2). On each side, two tracking stations and one timing station are hosted inside dedicated movable housings, called roman pots, which allow the detectors to approach the beam up to few times its tranverse size.

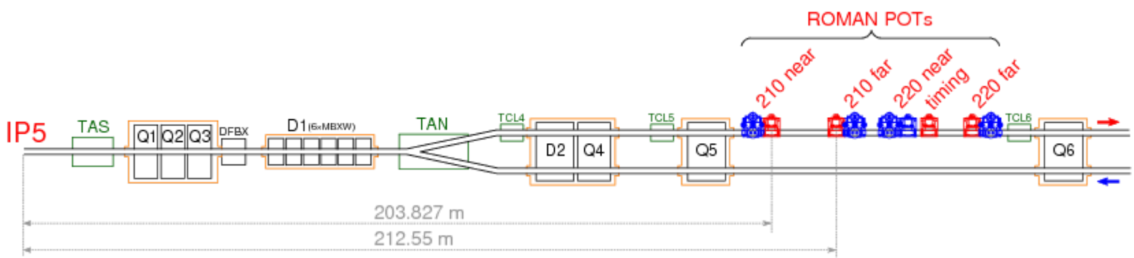

Figure 2: Schematic layout of the CT-PPS experimental apparatus (in red).

CT-PPS has been operating at nominal LHC luminosity since 2016. Tracking was provided initially by the TOTEM edgeless silcon strip detectors [4]; starting from 2017, they have been gradually replaced by new silicon pixel sensors with 3D technology. Timing detectors, installed to help rejecting the background due to pileup interactions, use diamond sensors, with a layer of ultra-fast silicon sensors (LGAD technology) in 2017.

2. Proton kinematics

The kinematics of protons detected by CT-PPS is defined by their four-momentum transfer squared, $t \equiv (p_\mathrm{f} - p_\mathrm{i})^2$, and their fractional momentum loss, $\xi \equiv (|p_\mathrm{f}| - |p_\mathrm{i}|)/|p_\mathrm{i}|$. The transverse (x, y) position of a proton track and its direction at a given point along the beam line can be related to the transverse position of the interaction point, the scattering angle, and ξ, through transport equations determined from the knowledge of the LHC lattice parameters ("beam optics"). With the settings used for high luminosity runs, the leading terms in the equations for x, y are:

$$\begin{aligned} x &\simeq D_x(\xi)\xi, \\ y &\simeq L_y(\xi)\theta_y^*, \end{aligned} \tag{2.1}$$

where (x, y) is the track impact point measured in the roman pots, θ_y^* is the proton vertical component of the scattering angle, and $D_x(\xi)$, $L_y(\xi)$ are two functions (horizontal dispersion and vertical effective length, respectively) determined by the machine lattice.

If the kinematics of the two protons is known, the kinematics of the central system, X, produced in the interaction can be determined by four-momentum conservation. In particular, its invariant mass and rapidity are given by

$$\begin{aligned} m_X^2 &= s\xi_1\xi_2, \\ y_X &= \tfrac{1}{2}\ln\tfrac{\xi_1}{\xi_2}, \end{aligned} \tag{2.2}$$

where 1 and 2 refer to the two protons, and s is the center-of-mass energy squared. They can be compared to the same quantities as measured directly by the central CMS detectors, their match thus providing a powerful signal signature. For each proton detector, the acceptance region in m_X and y_X is constrained on one side (lower m_X, y_X) by the minimum achievable distance from the beam, and on the other side (higher m_X, y_X) by the collimators in front of the pots.

In order to measure ξ from the reconstructed track parameters, it is crucial that the detector position with respect to the beam be known with precision. The alignment procedure [5] follows closely the technique extensively used by TOTEM. In a first part, performed once for each LHC setting, both horizontal (CT-PPS) and vertical (TOTEM) roman pots are moved very close to the beam during special low-luminosity fills. The shape of the proton hit distribution in vertical detectors for elastic scattering events, and the presence of a superposition region with the horizontal detectors, allows to determine the position of all detectors. Subsequently, for each regular physics fill, the x distribution of track impact points is corrected so that it matches that measured in the alignment fill.

3. Search for central exclusive dilepton production

The production of dilepton pairs at LHC via photon-photon fusion is a theoretically clean process, and its study can be used to test the theory predictions. So far, it has never been observed with the simultaneous detection of the scattered protons.

CT-PPS has searched for such a process [6] by looking at events where at least one proton is reconstructed in its detectors along the beam, and two leptons, either electrons or muons, are reconstructed by the central CMS detectors. Events where one of the two protons dissociates into a low-mass state and escapes undetected (semiexclusive production) are considered as signal, in order to enhance the event yield, since the expected cross section for exclusive production is very small in the acceptance region of CT-PPS. Fig. 3 shows the leading diagrams contributing to these processes, along with the diagram for double proton dissociation, which consitutes a background.

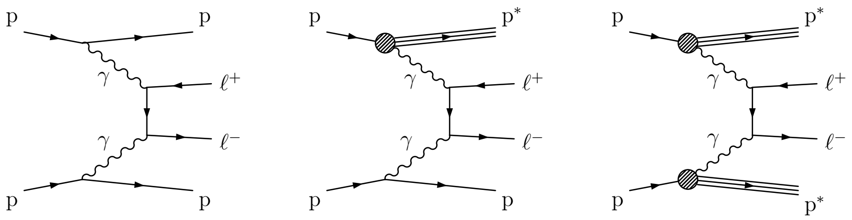

Figure 3: Leading diagrams for central dilepton production in proton-proton interactions via photon-photon fusion. Left: exclusive production; center: semiexclusive (single dissociation) production; right: double dissociation.

The analysis is based on data collected in 2016 at $\sqrt{s} = 13$ TeV; the total amount of data recorded with the roman pot inserted corresponds to an integrated luminosity of 9.4 fb^{-1}. For CT-PPS, only the strip trackers are used in the analysis.

Events are selected by a trigger requiring two muons (electrons) in the central CMS detectors with $p_{\mathrm{T}} > 38$ (33) GeV. The reconstructed dilepton vertex position is then required to be consistent with that of a proton-proton interaction; furthermore, the two leptons are required to have opposite charge, to pass standard CMS quality criteria, and to have $p_{\mathrm{T}} > 50$ GeV.

The main sources of background are double dissociation events and Drell-Yan events, where one additional proton from pileup interactions or beam-related background is reconstructed in the roman pots. Such events can be effectively rejected by vetoing additional tracks pointing to the dilepton vertex and by requiring the two leptons to be back-to-back in the transverse plane. To this end, a signal region is chosen in the d-a plane, where d is the distance of closest approach of any extra track to the dilepton vertex, and $a \equiv 1 - |\Delta\phi(\ell^+\ell^-)|/\pi$ is the lepton acoplanarity in azimuth ϕ (Fig. 4).

In the case of exclusive production, the value of ξ for the two protons can be calculated from the lepton kinematics:

$$\xi(\ell^+\ell^-) = \frac{1}{\sqrt{s}}\left[p_{\mathrm{T}}(\ell^+)e^{\pm\eta(\ell^+)} + p_{\mathrm{T}}(\ell^-)e^{\pm\eta(\ell^-)}\right], \tag{3.1}$$

where the two solutions for $\pm\eta$ correspond to the protons moving in the $\pm z$ direction. For semiexclusive production, it can be shown that one of the above solutions is approximately valid for the surviving proton: deviations comparable to the expected $\xi(\ell^+\ell^-)$ resolution only start to appear for values of m_X larger than about 400 GeV. For reconstructed protons, ξ is obtained by simply inverting the first of Eqs. 2.1. The final selection requires that $\xi(\ell^+\ell^-)$ is within the CT-PPS acceptance, and that it agrees within 2σ with the measured $\xi(p)$. Fig. 5 (left, center) shows the distribution of $\xi(\ell^+\ell^-)$ versus $\xi(p)$ for all selected events either passing or failing these last two requirements. After the final selection, 12 events are retained in the $\mu^+\mu^-$ channel, and 8 events in the e^+e^- channel. Fig. 5 (right) shows their distribution in the $(y(\ell^+\ell^-), m(\ell^+\ell^-))$ plane, superimposed to the CT-PPS acceptance region.

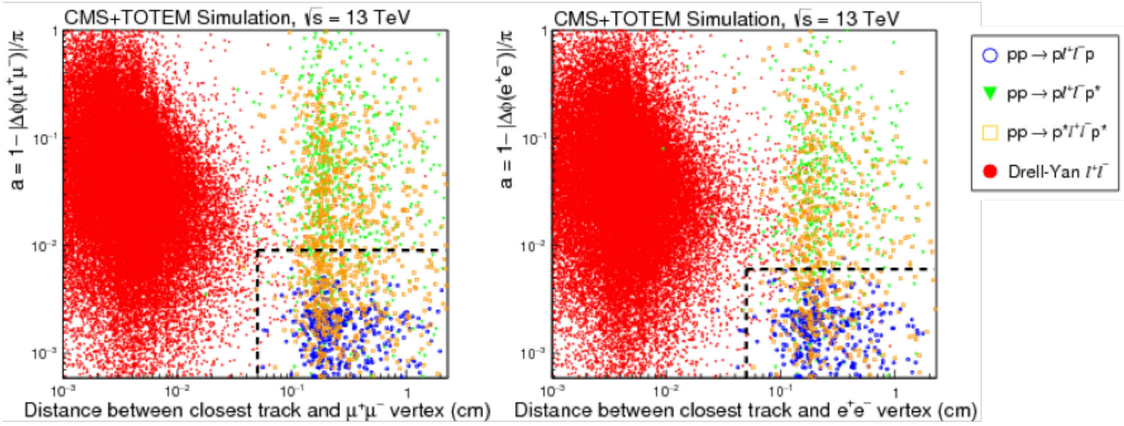

Figure 4: Distribution in the d-a plane (see text) for signal (blue and green points) and background (orange and red points) events. Left: $\mu^+\mu^-$; right: e^+e^-.The bottom right areas marked by the dashed lines define the signal region.

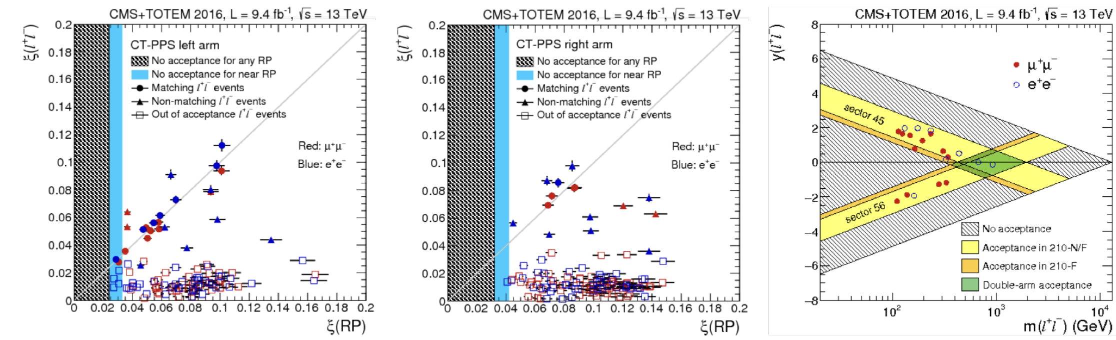

Figure 5: Distribution of kinematic variables for selected events. Left (center): $\xi(\ell^+\ell^-)$ vs. $\xi(p)$ for the left (right) arm of the spectrometer; right: $y(\ell^+\ell^-)$ vs. $m(\ell^+\ell^-)$ for events after the final selection, superimposed to the CT-PPS acceptance regions in both arms.

The number of background events surviving the selection is estimated with input from both data and simulated samples. Double dissociation and Drell-Yan events are taken into account: other sources are shown to contribute negligibly. Systematic uncertainties include contributions from statistics of the simulated samples, differences between data and simulated distributions, integrated luminosity, and the estimate of the rapidity gap survival probability [7]. A total of 11.0 ± 4.0 dimuon events and 10.5 ± 2.1 dielectron events are expected within the CT-PPS acceptance, when no requirement is made on the ξ matching; of these, 1.49 ± 0.53 and 2.36 ± 0.48 fall within the 2σ matching window in the dimuon and dielectron channel, respectively. The significance of the observed number of events over the expected background is estimated as 4.3σ and 2.6σ for the dimuon and dielectron channel, respectively; when combined, these result in an overall significance of 5.1σ, thus establishing the first observation of the process.

4. Plans and perspectives

From the start of the 2017 LHC run, CT-PPS has been operating regularly, with the roman pots inserted for most of the time, thus recording data for nearly all the available integrated luminosity. In 2018 all tracking stations are equipped with silicon pixel detectors, which feature higher radiation resistance and multi-track capability. Data analysis is ongoing to update the study of (semi)exclusive dilepton production with much larger statistics, as well as to pursue the studies of diboson ($\gamma\gamma$, WW, ZZ) and multijet production.

Extension of the project to continue its program in Run3 of the LHC is currently being considered.

References

[1] CMS and TOTEM Collaborations, "CMS-TOTEM Precision Proton Spectrometer", Technical Report CERN-LHCC-2014-021. TOTEM-TDR-003. CMS-TDR-13, 2014.

[2] T. Pierzchala and K. Piotrzkowski, "Sensitivity to anomalous quartic gauge couplings in photon-photon interactions at the LHC", Nucl. Phys. Proc. Suppl. 179-180 (2008) 257.

[3] R.A. Ryutin, "Exclusive double diffractive events: general framework and prospect" Eur. Phys. J. C 73 (2013) 2443.

[4] TOTEM Collaboration, "The TOTEM experiment at the CERN Large Hadron Collider", JINST 3, S08007 (2008).

[5] J. Kaspar, "Alignment of CT-PPS detectors in 2016, before TS2", CERN-TOTEM-NOTE 2017-001, 2017.

[6] CMS and TOTEM Collaborations, "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.

[7] L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, "The photon PDF in events with rapidity gaps", Eur. Phys. J. C 76 (2016) 255.