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Results and prospects with the CMS-TOTEM Precision Proton Spectrometer

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The PPS (Precision Proton Spectrometer) detector system consists of silicon tracking stations as well as timing detectors to measure both the position and direction of protons and their time-of-flight with high precision. They are located at around 200–220 m from the interaction point in the very forward region on both sides of the CMS experiment. The PPS detector is built to study central exclusive production (CEP) in proton-proton collisions at the LHC, including the photon-photon production of W and Z boson pairs, high-mass photon and lepton pairs, high-p_T jet production, as well as searches for anomalous couplings and new resonances. The PPS detector system has taken data at high luminosity while fully integrated to the CMS experiment. The total data collected correspond to around 100 fb^{-1} during the LHC Run 2, from 2016–2018. For the first time, exclusive production of lepton pairs has been observed in the CMS detector while one outgoing proton is measured in PPS using roughly 10 fb^{-1} of data accumulated in 2016 during high-luminosity LHC operation. These first results show a good understanding, calibration and alignment of the PPS detectors.

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1. Introduction

The Precision Proton Spectrometer (PPS) detector system has been installed and integrated into the CMS experiment during the LHC Run 2 data taking period. It is a joint project by the CMS and TOTEM collaborations with the capability of measuring protons scattered at very small angles, operating at high instantaneous luminosity [1]. The scattered protons remain inside the beam pipe, displaced from the central beam orbit, and can be measured by detectors placed inside movable beam pipe insertions, called Roman pots (RP), which approach the beam down to a few mm. The PPS detectors have collected data corresponding to an integrated luminosity larger than 100 fb^{-1} during the LHC Run 2, from 2016–2018.

The PPS detector allows the study of central exclusive production (CEP), i.e. the process $\mathrm{pp} \to \mathrm{p}^{(*)} + \mathrm{X} + \mathrm{p}^{(*)}$, by detecting at least one of the outgoing protons. In the CEP process, one or both protons may dissociate into a low-mass state (p^{*}); when both protons dissociate no signal can be seen in the PPS detectors. The central system X may be formed by W and Z boson pairs, as well as photon and lepton pairs, high-p_{T} jet production, and in general states satisfying to good approximation the $\mathrm{J}^{\mathrm{PC}} = 0^{++}$ rule (e.g. [2, 3, 4, 5]). The CEP process may occur through a gluon-gluon colour-singlet exchange and by photon-photon fusion. The diagram of the latter process is shown in Figure 1.

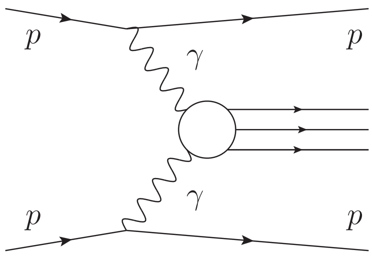

Figure 1: Schematic diagram of the photon-photon fusion process. The centrally produced system may consist of lepton, photon, W or Z boson pairs, or other particles. Figure reproduced from Ref. [4].

2. The PPS detectors

Figure 2 shows the layout of the RP stations installed at around 210 m from the CMS interaction point (IP5), along the beam line in LHC sector 56. A symmetric configuration is installed in LHC sector 45. The stations are comprised of RPs that approach the beam vertically from the top and bottom, and horizontally. During standard machine operation, scattered protons feature a large displacement in the horizontal direction and a small vertical displacement at the RP positions. The horizontal RPs are hence used. The vertical RPs are used in special configurations of the machine and in low intensity proton-proton fills for the calibration and alignment of the detectors.

Each detector arm consists of two RPs instrumented with silicon tracking detectors that measure the transverse displacement of protons with respect to the beam, and one RP station with timing detectors to measure their time-of-flight. The measurement of the difference between the arrival times of protons in the stations on both sides of the IP with high precision rejects background combinations with protons from pileup interactions, or beam-halo particles. Silicon strip

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sensors with a reduced insensitive region in the edge facing the beam have initially been used. An RP hosts 10 silicon strip sensor planes, half at a $+45^\circ$ angle and half at a -45° angle with respect to the bottom of the RP. These sensors cannot sustain a large radiation dose and cannot identify multiple tracks measured in the same event. They have for this reason been gradually replaced by new 3D silicon pixel sensors, with one RP station during the 2017 data taking run, and both RP tracking stations in 2018. Each RP hosts 6 3D pixel sensor planes [1]. Figure 3 shows the track impact point (x, y) distributions in silicon strip and 3D pixel detectors for data collected in two low intensity fills, during the 2017 and 2018 data taking runs. The timing detectors consisted of single- and double-sided single-crystal CVD diamond sensor planes [6], with one plane of ultra-fast silicon sensors [7] during the 2017 data taking.

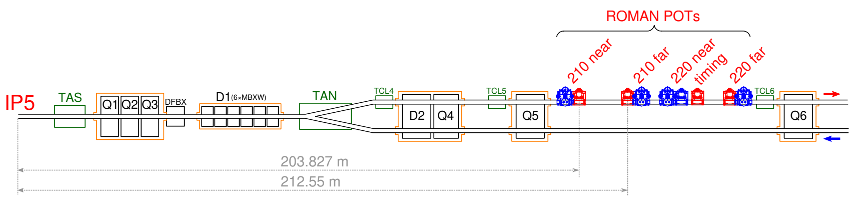

Figure 2: Schematic layout of the beam line between the interaction point and the location of the RP stations in LHC sector 56, corresponding to the negative z direction in the CMS coordinate system and the outgoing proton in the clockwise beam direction. The accelerator elements are indicated. The 210-near, 210-far, 220-far and timing stations where PPS detectors have been installed are marked in red. The 210-near and 210-far tracking stations have been used in the 2016 data taking, and the 210-far and 220-far stations in 2017 and 2018. Timing detectors were operational in 2017 and 2018. Figure reproduced from Ref. [8].

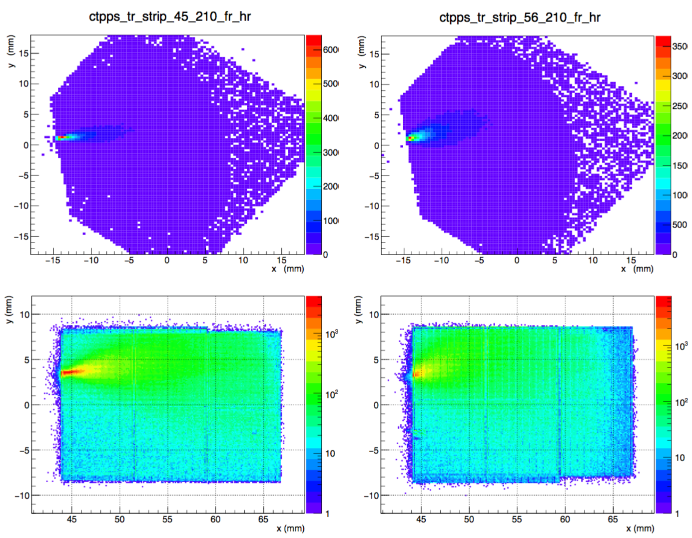

Figure 3: Track impact point distributions in silicon strip detectors in the 210-far station from data collected during a low intensity fill in 2017 (top row) and in 3D pixel detectors in the 220-far station from a low intensity fill in 2018 (bottom row), in LHC sector 45 (left) and sector 56 (right). The (x, y) coordinate systems are arbitrary. Figures reproduced from Ref. [9].

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3. Proton reconstruction

The proton reconstruction relies on the alignment of the sensor planes with respect to the LHC beam [10]. First, a special low intensity fill is required, with otherwise the same configuration as for standard operation. Horizontal and vertical RPs are inserted very close to the beam, at a distance of roughly 5σ, in units of the standard deviation of the beam transverse spatial distribution. The following steps are performed: i) Beam-based alignment, where the RPs are placed at a defined distance to the beam in units of σ, with the use of collimators that scrape the beam, leaving a sharp, detectable edge; ii) Relative alignment, by minimizing the residuals between hits in sensor planes and the track fits within each RP, and between different RPs when an overlap occurs; iii) Absolute alignment, from the measured (x,y) distribution in elastic scattering events in the vertical RPs, which has an elliptical shape centred on the beam position. Lastly, in high intensity physics fills the position of the detectors with respect to the beam needs to be redetermined. Only the horizontal RPs are inserted, at larger distances of around 15σ. The alignment in the horizontal direction is performed by matching the spatial distributions obtained in a physics fill with respect to those previously obtained in the low intensity fill, with the assumption that the physical distributions are the same. In the vertical direction, since the maximum of the hit distribution is visible in the detectors, the beam vertical position is obtained by a linear extrapolation of the (x,y) distribution towards $x = 0$.

The transverse position and direction of a proton track along the beam line are related to the transverse position of the primary interaction (x^*, y^*), the proton scattering angles in the horizontal and vertical directions $\left(\theta_x^*, \theta_y^*\right)$ and its momentum — or *momentum loss* $\xi = \Delta p/p$ —, by means of transport matrices which parametrise the LHC magnet lattice and are referred to as the beam optics. Figure 4 illustrates the proton transport from the IP to the RP stations.

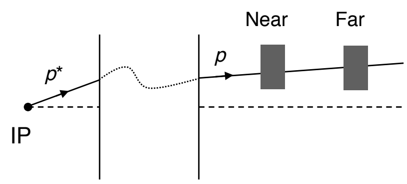

Figure 4: Sketch of the scattered proton transport traversing the LHC lattice from the IP to the RP stations.

The proton transport can be approximately described by the linear expression $\mathbf{d}(s) = T(s,\xi)\,\mathbf{d}^*$, where $T(s,\xi)$ is the single-pass transport matrix with s the distance from the IP and $\mathbf{d} = (x, \theta_x, y, \theta_y, \xi)$; the asterisk superscript denotes the proton kinematics at the IP. The transport matrix is calculated with the beam optics simulation program MAD-X, and additional constraints from the data [11]. The elements of the transport matrix are called optical functions. The transverse position of the proton traversing an RP with respect to the beam centre can be written as:

$$x(s_{\mathrm{RP}}) = v_x x^* + L_x \theta_x^* - D_x \xi,$$
$$y(s_{\mathrm{RP}}) = v_y y^* + L_y \theta_y^* - D_y \xi,$$

where $v_{x,y}$ are the horizontal and vertical magnifications, $L_{x,y}$ the effective lengths, and $D_{x,y}$ the horizontal and vertical dispersions. The convention where ξ is positive and $D_{x,y}$ are negative has been used.

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In the standard optics configuration for operation at high instantaneous luminosity, the leading terms for the above expressions are $x \approx |D_x|\,\xi$ and $y \approx L_y\,\theta_y^*$. In the horizontal direction, the dispersion D_x has a mild dependence on ξ, and the $L_x\,\theta_x^*$ term introduces fluctuations around the mean for a given value of ξ. The vertical dispersion D_y is considerably smaller than D_x. These approximate expressions can be used to partially reconstruct the proton kinematics with measurements in a single RP. By combining the measurements from both tracking RPs in a detector arm and the calculated transport matrix, the full proton kinematics with optimum resolution can be obtained.

4. Observation of central exclusive production of lepton pairs with PPS

Central exclusive production of lepton pairs has been observed for the first time at the LHC in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, with data collected in 2016 corresponding to an integrated luminosity of $9.4\,\mathrm{fb}^{-1}$ [8]. It corresponds to the process $\mathrm{pp} \to \mathrm{p}\ell^+\ell^-\mathrm{p}^{(*)}$, where one proton may dissociate into a low-mass state and $\ell = \mathrm{e}, \mu$. Events are selected with $m(\ell^+\ell^-) > 110\,\mathrm{GeV}$. A scattered proton is measured in one or both RP stations in either detector arm, in LHC sectors 45 or 56. The main background sources are Drell-Yan and double-dissociation events, combined with a proton from a pileup interaction or a beam-halo particle. They are suppressed by requiring that no extra tracks be present in the $\ell^+\ell^-$ vertex, and the two leptons be back-to-back in the transverse plane. Additionally, the reconstructed proton momentum loss $\xi\,(\mathrm{RP})$ is required to agree within 2σ with the analogous value calculated from the two leptons with the expression:

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

where the two solutions correspond to the protons moving in the $\pm z$ direction. This expression is exact for exclusive events when both protons remain intact and gives a good approximation when one proton dissociates, with discrepancies significant only at relatively large values of ξ.

Figure 5 shows the correlation of $\xi\,(\ell^+\ell^-)$ versus $\xi\,(\mathrm{RP})$, for protons measured in the detectors in sector 45 (left arm) and 56 (right arm). The regions outside acceptance for both near and far RPs in a detector arm, and only for the near RP, are shown. Events with matching and non-matching values of $\xi\,(\ell^+\ell^-)$ and $\xi\,(\mathrm{RP})$, and those for which $\xi\,(\ell^+\ell^-)$ falls below the $\xi\,(\mathrm{RP})$ acceptance, are indicated separately. A total of 12 matching events are observed in the $\mu^+\mu^-$ channel, and 8 events in the $\mathrm{e}^+\mathrm{e}^-$ channel, with a combined significance over the background estimate of 5.1σ. No events are observed with matching protons simultaneously in both arms, consistent with expectations of exclusive production of lepton pairs within the detector acceptance for these data.

Summary

The Precision Proton Spectrometer (PPS) detector system has been installed and integrated into the CMS experiment during the LHC Run 2 data taking period, and has collected over $100\,\mathrm{fb}^{-1}$ of data from 2016–2018. Radiation-hard 3D silicon pixel sensors with fine granularity for tracking and diamond as well as ultra-fast silicon sensors for timing measurements have been successfully commissioned and operated. The PPS detector allows the study of central exclusive production (CEP), including searches for anomalous couplings and new resonances, by measuring one or both

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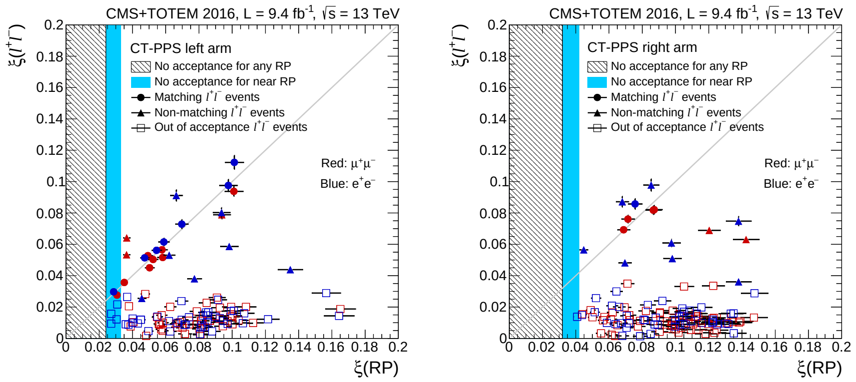

Figure 5: Correlations between the proton fractional momentum loss reconstructed indirectly from the two leptons, $\xi\,(\ell^+\ell^-)$, and that reconstructed from the scattered proton, $\xi\,(\mathrm{RP})$. Left: Events with a proton detected in LHC sector 45. Right: Events with a proton detected in sector 56. Figures reproduced from Ref. [8].

scattered protons. The proton kinematics can be correlated to that measured in the central detector, which provides a clean experimental signature. For the first time, exclusive production of lepton pairs has been observed in the CMS detector while one outgoing proton is measured in PPS using roughly 10 fb^{-1} of data accumulated in 2016 during high-luminosity LHC operation. These first results show a good understanding, calibration and alignment of the PPS detectors.

Acknowledgments

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