PERFORMANCE OF THE CMS PRECISION PROTON SPECTROMETER DURING LHC RUN2 AND ITS UPGRADES FOR RUN3

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The CMS Precision Proton Spectrometer (PPS) 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. Special devices called Roman Pots are used to insert the detectors inside the LHC beam pipe to allow the detection of scattered protons close to the beam itself. They are located at around 200 m from the interaction point in the very forward region on both sides of the CMS experiment. The tracking system consists of 3D pixel silicon detectors while the timing system is made of diamond pixel detectors and Ultra Fast Silicon Detectors. PPS has taken data at high luminosity while fully integrated into the CMS experiment. The total data collected correspond to around 100 fb^{-1} during the LHC Run2. In this presentation, the PPS detector operation, commissioning and performance are discussed, as well as the upgrades foreseen for Run3.

Keywords: LHC, CMS, TOTEM, spectrometer, proton, tracking, timing

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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), that approach the beam down to a few mm. The idea is to measure the displacement of the scattered proton with respect to the beam by means of tracking detectors and their time-of-flight by means of timing detectors. The displacement measurement is converted into that of the proton momentum loss via the precise knowledge of the accelerator optics. The measurement of the TOF provides an estimation of the longitudinal position of the proton-proton interaction and can therefore be used to dramatically reduce the background induced by the pile-up. The PPS detectors have collected data corresponding to an integrated luminosity larger than 100 fb^{-1} during the LHC Run 2 (2016–2018). The PPS detector allows the study of central exclusive production (CEP), i.e. the process $pp \rightarrow p^{(*)}+X+p^{(*)}$, by detecting at least one of the outgoing protons. In the CEP process, that may occur through hadronic interaction or by photon-photon fusion, one or both protons may dissociate into a low-mass state (p^*). When both protons dissociate no signal is detected in PPS. The central system X may consist of W or Z boson pairs, photon or lepton pairs, high-p_T jet production, and in general states with $J^{PC}=0^{++}$ (also 2^{++} in case of γ–γ fusion).

2. The PPS experimental layout

Figure 1 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 RP's 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 RP's are hence used. The vertical RP's 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 RP's 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 proton TOF aims to reject background combinations with a proton from a pileup interaction, or a beam-halo particle. Three RP stations per arm were equipped during LHC Run2 with detectors in the horizontal pot. The configuration changed each year, reaching in 2018 the final

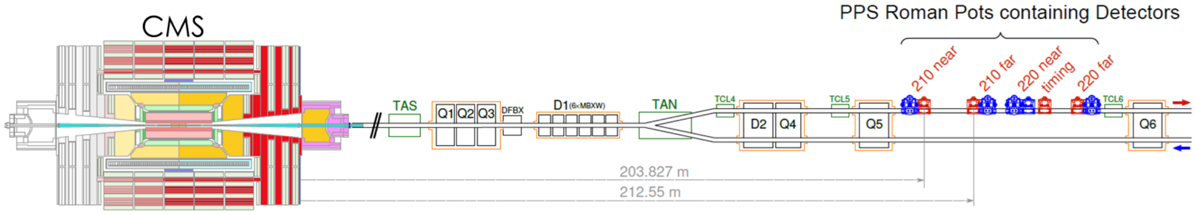

Figure 1. Schematic layout of the beam line between the interaction point and the location of the RP stations in the LHC (one side only).

(nominal) layout. The start of the PPS program, initially foreseen for 2017, was advanced to 2016; that year, the existing TOTEM Si strip detectors were used for tracking, while no timing detectors were installed. The Si strips, originally designed for low luminosity runs, were not able to sustain the high radiation dose taken during nominal runs, therefore only ~15 fb^{-1} of data could be written on disk. They were however sufficient to prove that PPS can actually operate and take data valid for physics analysis.

In 2017 an intermediate detector configuration was installed. One of the stations used for tracking and equipped with Si strip detectors was kept, while the other one was equipped with 3D pixel sensors [2]. Moreover, a special station between the previous two was equipped with timing detectors: diamonds [3] and Ultra Fast Silicon Detectors (UFSD) [4]. Finally, in 2018, both tracking stations were equipped with 3D silicon pixels and the timing station with diamond detectors. The details of the detectors used by PPS in the Run 2 are described in the following sections, focusing on the layout and performances of 3D pixels, for the tracking, and of the diamonds, for the timing [5, 6, 7].

3. The PPS tracking detector

Silicon strip sensors with a reduced insensitive region at the edge facing the beam have initially been used. A RP can host 10 silicon strip sensor planes, half at a +45° 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 in the same event. For this reason they have 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 that are read by 4 or 6 PSI46dig read out chips (ROC) [8], depending on the sensor size. The data collected by the ROC's are collected and serialized by a token bit manager (TBM) and sent to the front end (FE) electronics via an interface card (RPix portcard) that transforms the digital electrical signal into optical. The FE cards (FED for data and FEC for the controls) are the same as the ones used for the Phase-1 CMS Pixel Tracker [9]. The pixel dimensions are 150x100 μm^2 and provide a spatial resolution σ_x~17 µm, mainly due to the charge sharing between adjacent pixels. Because of the peculiarity of the shape of the signal, concentrated close to the beam region, see Figure 2 (left), the detector irradiation is dramatically non-uniform, as well as the correlated damage in the ROC's that are bump bonded directly on the sensor. As a consequence, the signal generated in the few most damaged pixels drifts in time more quickly than in the rest of the plane, causing a delay with the rest of the pixels that may become comparable to the bunch crossing time, jeopardizing the association of the hits to the event. In order to cope with this issue, when it was clear that the accumulated dose was creating the problem mentioned above, the pixel RP's have been slightly raised in position, thus moving the signal in a less damaged region of the detector. Apart from this problem, the detector performance was very high, with a ~98% average efficiency and more than 99% efficiency in most of the detector (see Figure 2 (right)).

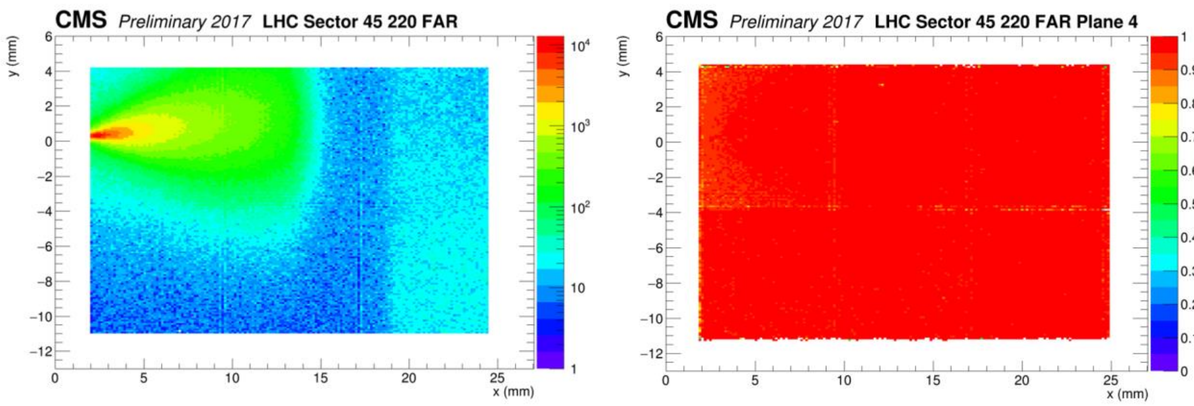

Figure 2. Left: impact point of the reconstructed tracks in a RP equipped with 3D pixels. Right: efficiency of a single pixel plane at the beginning of the data taking period in 2017.

4. The PPS timing detector

The timing detectors consisted of single-crystal CVD diamond sensor planes, with one plane of ultra-fast silicon sensors during the 2017 data taking, while in 2018 only diamond sensors were used. In the latter configuration, each timing RP was equipped with two planes of single diamond and two planes of double diamond detectors; in the latter, two diamond sensors were bonded to the same read out channel in order to double the amplitude of the signal. The signal is amplified and shaped a first time inside the RP itself, then it is sent to a NINO [1] chip that works as an amplifier and discriminator and finally to an HPTDC [1] that converts the time-over-threshold into a digital measurement. An accurate calibration of the detectors was needed to provide a definite estimation of the timing measurement uncertainty and a test beam campaign was carried out after the data taking to assess the damages due to the radiation. The test beam campaign confirmed that the timing resolution provided by the double diamond sensor itself is of the order of ~50 ps and that the radiation hardness of the detector is actually very good, with more than 94% efficiency after a year of data taking at the LHC. The evolution of the time resolution coming from the analysis of the LHC data is shown in Figure 3: a general degradation of the resolution by 20-50% is clearly visible and is due to the radiation damage of the sensor and of the readout electronics close to the beam.

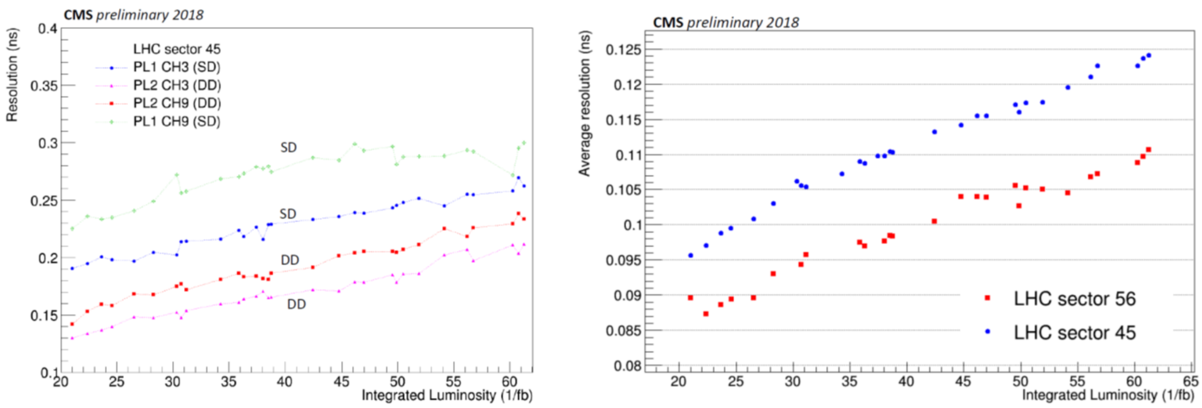

Figure 3. Evolution during 2018 data taking of the single channel timing resolution (left) and of the average time resolution from the track reconstruction in each of the timing RP (right).

5. Physics results

Central exclusive production of lepton pairs has been observed for the first time at the LHC in proton-proton collisions at $\sqrt{s}$=13 TeV, with data collected in 2016 corresponding to an integrated luminosity of 9.4 fb^{-1} [10]. The process considered is $pp \rightarrow p+l^+l^-+p^{(*)}$, where one proton may dissociate into a low-mass state and l=e,μ. Events are selected with $m(l^+l^-) > 110$ GeV/c^2. 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 at the l^+l^- vertex, and the two leptons be back-to-back in the transverse plane. Additionally, the reconstructed proton momentum loss ξ(RP) is required to agree within 2σ with the value calculated from the two leptons. Figure 4 shows the correlation of $\xi(l^+l^-)$ versus ξ(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 $\xi(l^+l^-)$ and ξ(RP), and those for which $\xi(l^+l^-)$ falls below the ξ(RP) acceptance, are indicated separately. A total of 12 matching events are observed in the $\mu^+\mu^-$ channel, and 8 events in the e^+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.

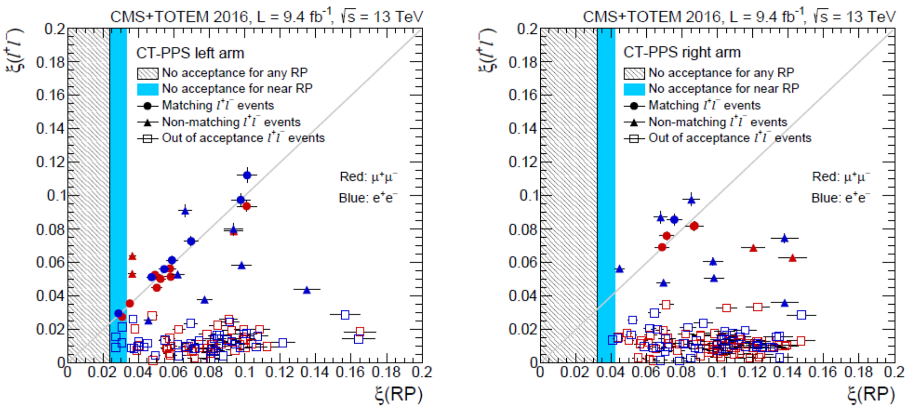

Figure 4. Correlations between the proton fractional momentum loss reconstructed indirectly from the two leptons $\xi(l^+l^-)$ and from the scattered protons ξ(RP) in sector 45 (left) and 56 (right) of the LHC.

6. Plans and prospects for Run 3

While Run 2 data are still being analyzed, the PPS group is preparing the new detectors for Run 3, that is scheduled to start in 2021. A new RP per side will be installed to add an additional set of timing detectors. Hence, the configuration for Run 3 will consist of two tracking and two timing RP's per side, equipped with 3D silicon pixels and double diamond detectors, respectively. The new tracking detectors will be bonded to PROC600 readout chips [11] that will replace the PSI46dig's. Moreover, the detector packages will be equipped with a remotely controlled motor that will be able to change their position inside the RP and therefore spatially distribute the radiation damage and reduce its impact. New double diamond timing detectors are being built and extensive optimization of the electronics is being carried out, aiming at a significant improvement of the timing resolution. The goal of PPS is to take data during the whole Run 3: a rich physics program lies ahead.

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