PROCEEDINGS OF SCIENCE

The CMS Precision Proton Spectrometer Project for the HL-LHC

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After the successful operation of the Precision Proton Spectrometer during Run-2, the CMS Collaboration has published an Expression of Interest to pursue the study of central exclusive production events, $pp \rightarrow p \oplus X \oplus p$, at the High-Luminosity Large Hadron Collider (HL-LHC) with detection of the very forward protons. Here the desired performance and the physics perspectives of a CMS near-beam proton spectrometer at HL-LHC are discussed along the plans for installation in the LHC tunnel.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

[*] Speaker

PoS(ICHEP2022)935

1. Physics Motivation

The CMS Precision Proton Spectrometer (PPS) [1] measures forward protons in Central Exclusive Production (CEP) events, $pp \to p \oplus X \oplus p$. Such events can originate in QCD/QED interactions and can be used to investigate rare processes in the Standard Model (SM). This detector may allow the evaluation of the coupling of the electroweak sector to new particles, thus extending the searches for New Physics.

CEP results in a central system X plus intact protons scattered in the forward direction at small angles [1]. While the CMS detector measures the invariant mass M_X and rapidity y_X of the central system, the PPS near-beam detectors measure the fractional momentum loss, $\xi = \Delta p/p$, of the outgoing protons, from which the information about the central state can also be reconstructed: $M_X = \sqrt{\xi_1 \xi_2 s}$ and $y_X = \frac{1}{2}\ln(\xi_1/\xi_2)$. This correlation between the central system and forward protons provides kinematic matching to reduce the background. Clean event tagging with intact protons is achieved by imposing transverse momentum balance and having an accurate longitudinal vertex position via proton Time of Flight, strongly suppressing pile-up events as seen in dilepton events collected during the Run-2 data [2].

2. Performance

The goal is to determine detector positions that allow the widest possible mass coverage, given that $M_{\mathrm{min(max)}} = |\xi|_{\mathrm{min(max)}}\sqrt{s}$. The PPS proposal foresees the installation of three stations on each side of CMS for Phase-2, comprising the region from 196 m to 234 m [3]. Horizontal detectors for tracking and timing are considered as well as vertical detectors at 220 m for alignment and calibration. These three stations would be based on Roman Pots positioned before the Q5 magnet (196-m region), in between the Q5-Q6 magnets (220-m region), and after the Q6 magnet (234-m region). Additional stations at 420 m are under consideration to extend the acceptance to lower masses, although this requires other technologies because these stations would be in the cold part of the LHC; in addition, the protons would have to be tagged in between the pipes.

Best detector acceptance is achieved with sensors approaching the beam horizontally. The minimum and maximum mass acceptances are derived from Phase-2 optics and machine parameters [4]. Figure 1 (left) shows the minimum accepted $|\xi|$ as function of the longitudinal distance, ς, from CMS for distinct beam crossing planes, where vertical crossing is the preferred option to achieve acceptance at lower masses. M_X and y_X acceptances are extracted for single- and double-arm proton tagging as shown by Fig. 1, with the center and right panels for horizontal and vertical crossings, respectively. The main factor altering M_{min} is the dispersion. Although single-arm provides acceptances at larger masses, clean events demand double-arm detection, which extends the lower M_X region down to ~100 GeV for three stations or ~40 GeV with all stations.

3. Physics perspectives

The PPS physics program includes high-mass beyond SM (BSM) searches, $\gamma\gamma \to VV$, exclusive pair production, diffractive CEP, Higgs physics, and Photo-production. This report will cover a few opportunities to be pursued with the data collected during the HL-LHC runs.

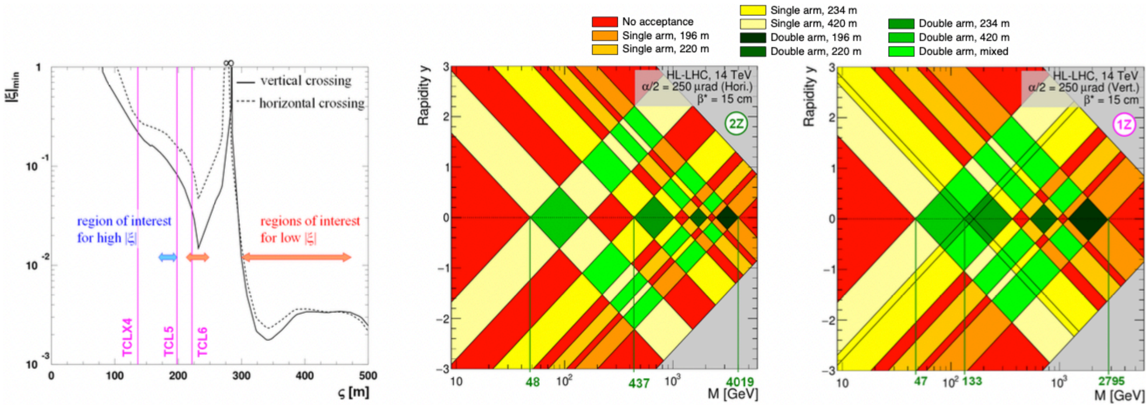

Figure 1: Left: Minimum mass acceptance as function of the longitudinal distance, ς, from CMS. The lines show two options for crossing planes. Center: Single- and double-arm kinematic acceptance for horizontal crossing (2Z). Right: Single- and double-arm kinematic acceptance for vertical crossing (1Z) [3].

3.1 Standard Model and Higgs boson production

While QCD-induced processes dominate at low invariant masses, the QED-mediated processes are dominant at high masses [3]. Acceptance at lower $\xi_{\min}$ values provides an increased rate of double-tagged events by $O(10^4)$ with respect to Run-2: 47 $\gamma\gamma\mu\mu$ events per fb^{-1} and 72 $\gamma\gamma WW$ events per 100 fb^{-1} with 2-arm acceptance are expected. For dimuons, the cross section would be increased by 3 orders of magnitude with the inclusion of the 420-m station.

CEP of the Higgs boson has not been observed yet, but becomes possible given the enhanced sensitivity provided by proton tagged events with stations at 420 m. The final state is strongly constrained to $J^{PC} = 0^{++}$, opening an opportunity to investigate the Higgs boson quantum numbers. $O(100)$ events per ab^{-1} for a Higgs boson of 125.4 GeV are expected, depending on the cross section, parton distribution functions, and survival factor. Given the high ξ resolution, the Higgs mass resolution goes down to ≈3 GeV, which is larger than the CMS detector mass resolution, however providing a unique measurement of a clean final state. Figure 2 (left) shows the generator-level ξ distribution for the CEP Higgs boson overlaid with the PPS acceptance for the 420-m stations (red boxes) with requirements in the central detector for the generator-level b quarks of $p_T(b) > 40$ GeV and $|\eta(b)| < 2.4$.

3.2 New Physics

The BSM scenarios may be explored with $\gamma\gamma$ processes at TeV scale, where sensitivity to heavy mediators may appear in the coupling to photons. This can give access to searches for axion-like particles (ALP). The ALP exclusion limits can be extended to TeV masses with PPS already with 300 fb^{-1} as shown in Fig. 2 (right). Searches for other predicted heavy systems, direct/indirect searches for SUSY, $Z + X$, and Dark Matter with invisible decays can profit from the $\gamma\gamma$ production mode for final states up to ~2 TeV.

Proton tagging may enhance the investigation of anomalous quartic gauge couplings (aQGC) in $\gamma\gamma VV$ processes. The longer tail in the mass distribution is dominated by aQGC events, where PPS provides good sensitivity at large ξ. In comparison to the Run-1 results, PPS could provide enough events to enhance such limits by $O(10^2)$ [3]. In addition, other rare processes like $\gamma\gamma\gamma\gamma$

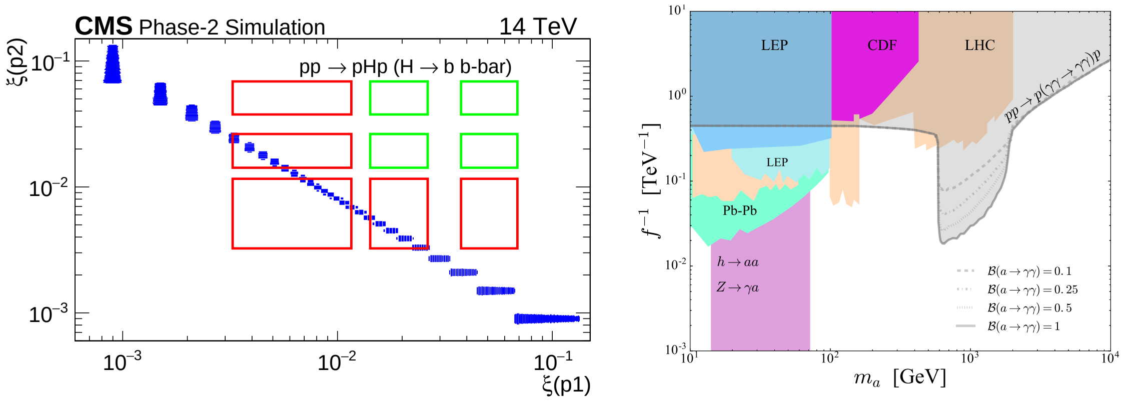

Figure 2: Left: Proton ξ at generator level for $pp \to p + H + p$, where blue boxes represent events after acceptance cuts, green boxes show the PPS acceptance with 220 and 234 stations, and red boxes with 420 stations. Right: Axion exclusion limits including the PPS acceptance for 300/fb [3].

and $\gamma\gamma\gamma Z$ could be investigated with proton tagged events. For instance, limits on the aQGC of $\gamma\gamma\gamma\gamma$ of 10^{-14} GeV^{-4} can be reached with 3000 fb^{-1} in the HL-LHC [5].

4. Conclusions

This report presents the proposal of the CMS experiment to extend its forward physics program by installing new stations along the LHC beamline, including one at 420 m. The performance studies have shown the ability to achieve coverage at lower and higher masses than in Run-2, which opens the possibility of precision tests of the Standard Model and further searches for New Physics.

References

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