# PHYSICS AT THE HL-LHC WITH PROTON TAGGING*

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The High-Luminosity Large Hadron Collider (HL-LHC), a major upgrade of the LHC, is set to operate in 2029. The HL-LHC aims to achieve higher instantaneous luminosities to allow exploration of the rarest production processes of the Standard Model (SM). The central exclusive production (CEP) process in proton–proton collisions at the HL-LHC can only be explored using a forward proton spectrometer (FPS), a set of near-beam detectors located a few hundred meters from the proton–proton interaction point. During LHC Run 2, the ATLAS and CMS collaborations installed FPSs delivering a broad range of physics results. The accelerator complex will be rearranged for the HL-LHC, and a new FPS detector design is under development. The CEP study offers a unique opportunity to observe the rarest SM processes and search for physics beyond the SM, including axion-like particles or anomalous gauge couplings.

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## 1. Introduction

Diffractive and exclusive processes in proton–proton collisions are extensively studied at the Large Hadron Collider (LHC) at CERN. These interactions are mediated by the $t$-channel exchange of colour-neutral particles and identified by a large rapidity gap or an intact proton. Different collaborations at the LHC target these processes, covering a broad range of topologies and scales. The lowest scales correspond to the elastic proton–proton scattering measured by the TOTEM [1–6] and ATLAS collaborations [7–9]. ATLAS has also reported measurements of the single- and double-diffractive processes [10]. Photo-production of vector mesons in the $p$–Pb collision, where the heavy ion serves as a photon source, was studied by the ALICE [11, 12] and CMS collaborations [13] targeting mainly a few GeV scales. The central exclusive production (CEP) was reported by the LHCb Collaboration [14, 15] for the production of a few GeV final states, while

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hard scattered events were studied by ATLAS [16] and the CMS [17–21]. Additionally, TOTEM and the CMS have measured the Mueller–Tang jet topology with and without proton tagging [22], and ATLAS has measured exclusive pion pair production using proton tagging [23]. Figure 1 shows diagrams of different production modes of a central system in association with two forward protons.

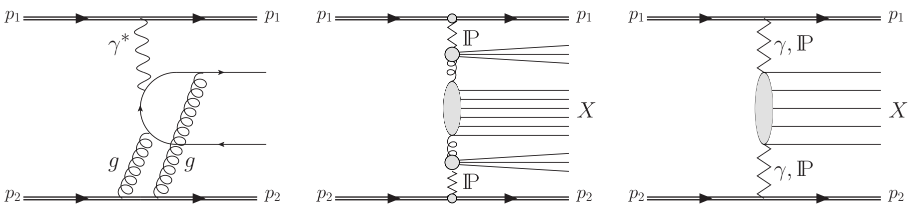


Fig. 1. The three main production processes of a central system in association with two intact protons: photo-production of quark pair (left), double Pomeron exchange (middle), and central exclusive production (right).

The Forward Proton Spectrometer (FPS) is a powerful instrument for tagging interactions with an intact proton at the final state. Installed approximately 200 meters from the interaction point of the ATLAS and CMS experiments, these near-beam detectors are typically housed in Roman Pots vessels [24]. There are different types of proton spectrometers, including those that approach the LHC beam vertically, such as ALFA [25] and TOTEM [26]. These can tag elastic and diffractive protons with $p_{\mathrm{T}} > 0.15$ GeV. Detec-

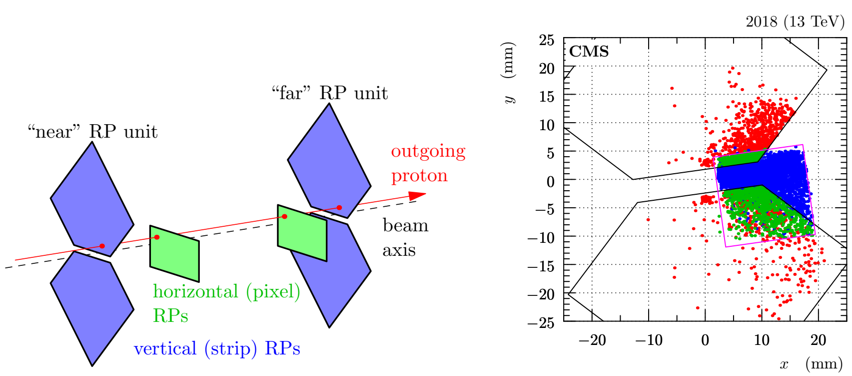


Fig. 2. (Colour on-line) Left: Illustration of a proton crossing both the vertical (blue/gray) and the horizontal (green/light gray) RPs. Right: Hit map of tracks reconstructed from vertical RPs only (red/gray), horizontal RPs only (blue/black), and both vertical and horizontal RPs (green/light gray). The RP sensors are represented schematically by the black (vertical RPs) and magenta/thick gray (horizontal RPs) boundaries. Taken from [29].

tors that approach the LHC beam horizontally are sensitive to protons with momentum loss between 3% and 15%, and can tag exclusive production processes with central masses above a few hundred GeV. Examples of these detectors include the ATLAS Forward Proton detector (AFP) [27] and CMS–TOTEM Precision Proton Spectrometer (CT-PPS) [28]. Figure 2 displays a hit map recorded from vertical and horizontal stations during the 2018 standard data-taking period with the CT-PPS detectors. The horizontal stations are designed to operate during the standard LHC running conditions and are planned to be used during the High Luminosity LHC (HL-LHC) phase, which will be discussed in Section 2. Section 3 is dedicated to physics with tagged protons, and the article concludes in Section 4.

## 2. Experimental apparatus and methodology

The ATLAS Forward Proton (AFP) and the CMS–TOTEM Precision Proton Spectrometer (CT-PPS) are near-beam detectors equipped with tracking and timing stations that allow for precise measurement of forward protons. The AFP consists of two stations, positioned approximately 205 and 217 meters on either side of the ATLAS interaction point, each equipped with four planes of edgeless silicon pixel sensors providing 6 $\mu$m spatial resolution [30]. The farthest station also has a time-of-flight detector. In 2017, the AFP recorded integrated luminosity of approximately 15 fb$^{-1}$ of $pp$ collisions. The CT-PPS was integrated in 2016 during the LHC Run 2, based on the combined expertise of CMS and TOTEM collaborations [28]. It comprises two tracking stations, located about 210 and 220 meters from the CMS interaction point, with a timing detector placed in between them. The tracking detectors can measure protons produced in central exclusive production in processes with central masses ranging from 350 GeV to 2 TeV. During LHC Run 2, the CMS collected more than 100 fb$^{-1}$ of integrated luminosity in $pp$ collisions with operational CT-PPS detectors.

### *2.1. Proton kinematics*

Protons participating in diffractive interaction can remain intact, lose a fraction of their longitudinal momentum, and scatter at small angles. These protons will be deflected away from the beam centre and can be detected by the FPS. Each proton can be described in terms of its momentum loss, denoted $\xi = \Delta p_z/p$, as well as two scattered angles at the interaction point $\left(\theta^*_x, \theta^*_y\right)$, and the proton–proton collision vertex on the plane perpendicular to the beam axis $(x^*, y^*)$. The deflection in position is expressed as

$$\begin{aligned} \delta x &= x_{\rm D}(\xi) + v_x(\xi) \cdot x^* + L_x(\xi) \cdot \theta_x^* \,, \\ \delta y &= y_{\rm D}(\xi) + v_y(\xi) \cdot y^* + L_y(\xi) \cdot \theta_y^* \,, \end{aligned} \tag{1}$$

where $x_{\rm D}$, $y_{\rm D}$, $v_x$, $v_y$, $L_x$, and $L_y$ are functions of proton momentum loss at different positions from the IP and are determined by simulating proton trajectory in the LHC magnetic field (more details can be founded in Ref. [29]).

In order to determine all five parameters of a proton, it is necessary to make at least five independent spatial measurements of the scattered proton at the position of the proton detectors, which requires having at least three tracking stations. However, the FPS design described in this section has only two tracking stations, resulting in the measurement of four independent spatial coordinates. This requires an approximation of equation (1). For instance, in [29], the $x^*$ parameter is neglected, and reconstruction of proton track parameters from two stations is sufficient for tracking back to the proton impact parameters.

## 3. Physics with tagged protons at the LHC

Central exclusive production processes arise from exchanging colour singlets via quantum chromodynamics (Pomeron exchange) or quantum electrodynamics (photon exchange). Figure 3 compares the production cross section of central exclusive $b\bar{b}$ and $\gamma\gamma$ final states for Pomeron–Pomeron and photon–photon interactions. At central masses above the electroweak scale, photon–photon interactions dominate. By tagging CEP at high masses, the LHC can be viewed as a photon collider, providing a means to explore the electroweak sector with high precision.

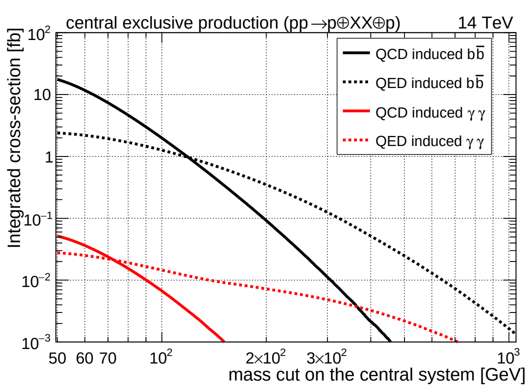


Fig. 3. Integrated cross sections of different exclusive processes with intact protons at $\sqrt{s} = 14$ TeV, plotted as a function of the required minimum central system mass. Taken from [31].

The CEP studies encounter a significant challenge in dealing with a large combinatorial background. During the standard LHC runs, a few tens of proton–proton interactions occur per bunch crossing, with at least one proton undergoing diffractive scattering in about 20% of these interactions. As a result, the inclusive process accompanied by protons produced from pileup interaction can mimic the exclusive final state (central system with protons detected on both sides). To address this problem, matching the proton kinematics and the kinematics of the central system is necessary for tagging CEP. Proton kinematics can be inferred from the central system using the following expression:

$$\xi_{\pm} = \frac{1}{\sqrt{s}} \left( \Sigma E \pm p_z \right) , \tag{2}$$

where $\xi_+$ and $\xi_-$ are the proton momentum loss computed for proton in positive and negative directions, respectively, $E$ and $p_z$ are the energy and the longitudinal momentum of all the particles of the central system, respectively. By matching the kinematics of the proton and the central system, it becomes possible to select CEP events at the LHC. An example of matching between the proton momentum loss ($\xi_{\mathrm{AFP}}$) and of the proton momentum loss derived from the di-lepton system ($\xi_{\ell\ell}$) is demonstrated in figure 4.

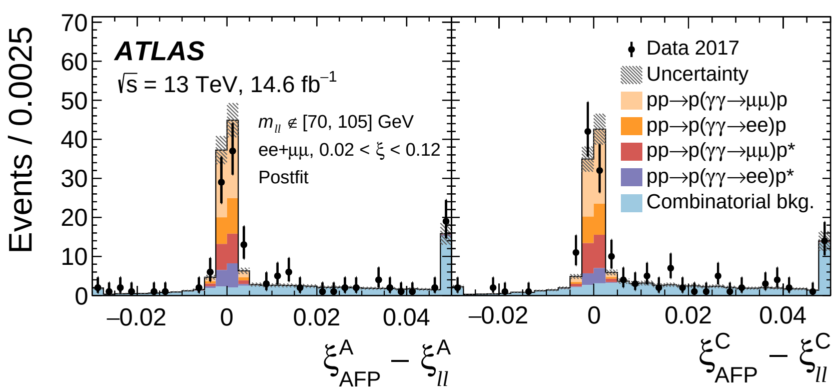


Fig. 4. Distributions of $\xi_{\mathrm{AFP}} - \xi_{\ell\ell}$ for side A (left) and side C (right) of the ATLAS detector. The total prediction comprises the signal and combinatorial background processes, where $p^*$ denotes a dissociated proton. Taken from [16].

In addition to the matching technique, the "missing mass" technique can be used to search for unknown particles produced in CEP. This technique was first implemented at the LHC by the CMS Collaboration in a search for new particles in the $pp \to pp + Z/\gamma + \chi$ production process, based on a bump hunt of $\chi$ particle by utilizing the supreme resolution of the central mass measurement [18].

### *3.1. Physics perspectives at the HL-LHC*

The HL-LHC is an upgraded design of the LHC accelerator, scheduled to begin operation in 2029, targeting to deliver about 3000 $\mathrm{fb}^{-1}$ of total integrated luminosity over 10–12 years. This upgrade will enable the study of the rarest processes in the SM [32], including CEP of various SM final states, which can only be targeted using the FPS during the HL-LHC [33]. To accommodate the HL-LHC targets, the accelerator layout will be rearranged, and a new detector design of FPS is currently under development by the CMS Collaboration [31]. The new location of the forward detectors is selected in three positions, at $z = \pm 196$, $\pm 220$, and $\pm 234$ meters from the CMS interaction point, targeting mass ranges of centrally produced final-state particles between 133 GeV and 2.7 TeV. Including a fourth station located at $z = \pm 420$ m, CEP with masses down to 43 GeV can be measured. Table 1 shows the fiducial cross section of SM CEP processes in $pp$ collisions at $\sqrt{s} = 14$ TeV for two scenarios, with and without the 420 m station.

Table 1. Fiducial cross sections of photon-induced CEP processes in $pp$ collisions at $\sqrt{s} = 14\,\mathrm{TeV}$, computed using EPA [34] and gap survival probability of 90%. The cross sections were obtained using central detector selection cuts of $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, and two scenarios are considered: with and without the station at $\pm 420$ m. Taken from [31].

| Process | Fiducial cross section [fb] | |
|---|---|---|
| | all stations | w/o 420 |
| $jj$ | 60 | 2 |
| $W^+W^-$ | 37 | 15 |
| $\mu\mu$ | 46 | 1.3 |
| $t\bar{t}$ | 0.15 | 0.1 |
| $H$ | 0.07 | 0 |
| $\gamma\gamma$ | 0.02 | 0.003 |

#### 3.1.1. Production of jets

Systematic studies of screening effects in central exclusive di-jet production have not been carried out. The CEP of $b\bar{b}$ quark pairs, the primary background for exclusive Higgs boson searches, has been extensively discussed in the literature but not measured. Pair production of top quarks, characterized by a large final-state mass (above the $m_{t\bar{t}}$ threshold), can be detected with high acceptance using two-proton-tagged events. Although the cross section is relatively low (of the order of 0.1 fb), the production of top quarks with intact protons has recently attracted considerable phenomenological interest [35–38]. In addition to the exclusive production of top-quark pairs, inclusive diffraction may have a signal significance of three standard deviations above the background fluctuation at a pileup rate of 200 and an integrated luminosity of 4 $\mathrm{ab}^{-1}$ [35].

#### 3.1.2. Production of leptons

Measurement of exclusive di-lepton production has a cross section of the order of a few fb with stations located at about 200 m from the interaction point and requires integrated luminosities above $\mathrm{ab}^{-1}$. However, using single-tagged events, semi-exclusive production of lepton pairs provides significant statistics and can be used to calibrate proton spectrometers during the run. The production of the di-$\tau$ final state is particularly interesting as it allows for measuring photon-$\tau$ SM coupling, providing strong constraints on the anomalous magnetic moment of the $\tau$ lepton [39]. The final state with two leptons in association with protons can also serve to search for supersymmetric particles in difficult scenarios with highly compressed spectra [40, 41].

#### 3.1.3. Production of $W$-bosons

The CEP of $W$-boson pairs is a highly clean channel in fully leptonic decay mode. Although the measurement of $\gamma\gamma \to W^+W^-$ with the LHC Run 2 and 3 acceptances is insignificant, the acceptance for 2-arm events would be significantly improved at the HL-LHC with the three-station configuration. This increase in acceptance would allow for the measurement of the SM cross section and serve as a benchmark for probing the high-mass tails of the distribution, which are sensitive to the presence of anomalous quartic gauge couplings.

#### 3.1.4. Higgs physics

The main production mechanism of Higgs boson in CEP is through the exchange of Pomerons, with a cross section of a few fb. To detect a Higgs boson with a mass of 125 GeV in association with two intact protons, at least one proton should be detected in the 420 m station. Without the 420 m stations, there is no acceptance for the SM Higgs bosons. The only detectable production mode of the Higgs bosons is in association with a $W^+W^-$ vector-boson pair. Although the production cross section at the tree level is 0.04 fb, a high acceptance is expected due to high $\xi$ distributions. The production rate of the $HW^+W^-$ process can be measured regardless of the Higgs boson decay mode by reconstructing the protons and the $W$ bosons in semi- or fully-hadronic decay modes. Therefore, an independent measurement of the Higgs boson branching ratio to the dominant decay modes is possible.

#### 3.1.5. Production of photons

Measuring light-by-light scattering in the SM is challenging due to its low cross section, requiring the full HL-LHC statistics and four stations. However, FPS offers the best sensitivity to anomalous couplings and can probe high di-photon masses, searching for axion-like particles (ALPs) ranging from tenths to a few TeV. Recently, advancements in the proper modelling of single and double dissociation processes [42] allow for exploring the semi-exclusive processes and searching for ALPs with masses as low as a few hundred GeV.

## 4. Conclusion

The FPS at HL-LHC will provide an unprecedented opportunity to extend the current HL-LHC physics perspectives by extensively studying CEP. The improved acceptances and higher integrated luminosity will enable measuring a few SM processes in CEP mode and holds great potential for new physics discoveries. However, the challenging environment, with large radiation doses and a pileup of up to 200, poses significant technical challenges and sets a high bar for existing detector technologies. The CMS Collaboration has proposed a staged installation program, starting with three stations installed approximately 200 m from the interaction point during LHC Run 4 and adding a 420 m station for Run 5 or beyond. The ATLAS/AFP upgrade program also plans to reserve space for Run 5. In conclusion, the proton spectrometers at HL-LHC offer a promising avenue for advancing our understanding of CEP and searching for physics beyond SM.

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