PROCEEDINGS OF SCIENCE

New physics results with the CMS Precision Proton Spectrometer

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The Precision Proton Spectrometer (PPS) is a subdetector of CMS introduced for the LHC Run 2, which provides a powerful tool for advancing BSM searches. The talk discussed the new results on exclusive diphoton, Z+X, and diboson production explored with PPS, illustrating the unique sensitivity which can be achieved using proton tagging.

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

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PoS(ICHEP2022)863

1. Introduction

The Precision Proton Spectrometer (PPS) is a subdetector of the Compact Muon Solenoid (CMS) experiment [1] at the CERN Large Hadron Collider (LHC). It consists of a set of near-beam detectors, symmetrically located at $\sim$ 200 m distance from the CMS interaction point, which perform tracking and timing measurements on scattered protons that remain intact after the collision (Fig. 1). The detectors are installed in beam pipe insertions called Roman Pots (RP), which approach the LHC beam within a few mm.

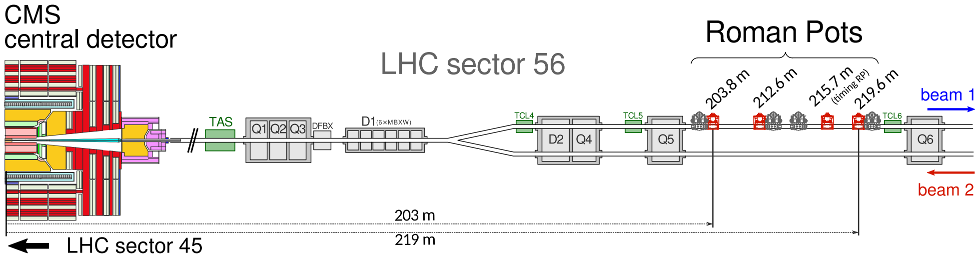

Figure 1: Schematic layout of the beam line between the interaction point and the RP locations in LHC sector 56, corresponding to the negative z direction in the CMS coordinate system and the outgoing proton in the clockwise beam direction. The accelerator magnets are indicated as grey boxes and the collimator system elements in green. The horizontal RPs, which belong to PPS, are marked in red. Figure from Ref. [2].

PPS successfully took data during the years 2016–2018 of the LHC Run 2, collecting an integrated luminosity of $\sim$ 100 fb^{-1} in proton-proton (pp) collisions at 13 TeV.

2. Physics measurements with PPS

The focus of the PPS detector is the measurement of central exclusive production (CEP) processes. This family of processes is characterised by the interacting protons exchanging a neutral colour-singlet (e.g. photons, Pomerons, Z bosons) and remaining intact while producing a state X (Fig. 2). The X state is usually referred to as central system, as it is detected by the central CMS detectors. Conversely, the outgoing protons are measured by PPS. For high masses in central system, photon exchange is favoured over the Pomeron one.

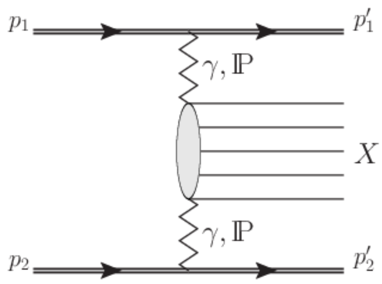

Figure 2: Schematic diagram for central exclusive production, pp $\to$ pXp. Figure from Ref. [3].

From the measurement of the outgoing protons, the fractional momentum loss ξ can be reconstructed:

$$\xi = (p_{\rm nom} - p)/p_{\rm nom}, \tag{1}$$

where p_{nom} and p are the nominal beam momentum and the scattered proton momentum, respectively.

Correlations of the proton ξ with the mass and rapidity of the central system arise from the four-momentum conservation, and can be expressed as:

$$m_{\mathrm{X}} = \sqrt{E_{cm}\xi_{+}\xi_{-}}, \qquad y_{\mathrm{X}} = \frac{1}{2}\log\frac{\xi_{+}}{\xi_{-}}, \tag{2}$$

where E_{cm} is the pp centre-of-mass energy and the + (−) sign refers to the quantity measured for the proton moving towards the positive (negative) direction of the z-axis.

The proton reconstruction relies on the thorough understanding of the proton transport from the CMS interaction point to the RP location, which is determined by the LHC magnetic fields. The techniques developed to calibrate and perform the proton reconstruction are described in detail in Ref. [2].

The measurement of the outgoing protons provides a unique handle to tag CEP events. This allowed CMS to extend its searches for physics beyond the standard model (BSM) by looking at multiple final states using the LHC Run 2 data. In the following sections, the searches for anomalous exclusive production of vector boson pairs (WW/ZZ) and exclusive diphoton production are presented. Furthermore, a search for a resonance in the missing mass spectrum in association with a Z boson or a photon is also illustrated.

A search for the top quark anti-quark pair exclusive production foreseen in the standard model was also performed with 2017 data, and is described by B. Ribeiro Lopes and D. Muller in these proceedings.

3. Search for anomalous vector boson pair production

A search for the anomalous exclusive production of vector boson pairs was performed using the data collected in LHC Run 2 at $\sqrt{s}$ = 13 TeV [4], which correspond to an integrated luminosity of 100.0 fb^{-1}. The fully hadronic decay channel, in which both bosons decay into large-radius boosted and merged jets was explored.

The analysis looks for enhancements in the region of high masses of the central system, and interprets the results in an effective field theory (EFT) framework where anomalous quartic gauge couplings (AQGC) between photons and vector bosons modify the standard model lagrangian.

Events passing a combination of several jet triggers are first selected based on their substructure and transverse momentum. The mass of the two-jet system formed with the highest p_T jets is required to be larger than 1126 GeV, to ensure $>$ 99% trigger efficiency. Further selection criteria on the jets are imposed, requiring them to be back-to-back, thus with low acoplanarity $a = |1 - \Delta(\phi)/\pi|$, and balanced in transverse momentum. In these equations $\Delta(\phi)$ is the difference in azimuthal angle between the two jets, and $j1(j2)$ refers to the leading (subleading) jet in terms of p_T.

Events are further subdivided in the WW and ZZ categories based on the sum of the mass of the two jets, which is found to be an efficient discriminator, independent of the anomalous coupling value.

The main background contribution is given by jet production via QCD processes with protons coming from soft diffractive interactions in the same bunch crossing (pileup). Matching criteria between the mass and rapidity of the central system reconstructed with the jets and with protons (cf. Eqs. 2) were imposed, thus suppressing non-exclusive contributions.

The signal sensitivity was studied as a function of the AQGC parameter values. No excess over the background was observed and bidimensional exclusion regions were derived as a function of the dimension six AQGC operator parameters (Fig. 3). Unitarity-safe limits were also set in the WW channel by excluding events with mass higher than 1.4 TeV, following the so-called clipping procedure. Unidimensional limits on the dimension six and dimension eight AQGC operators are also available in the publication [4].

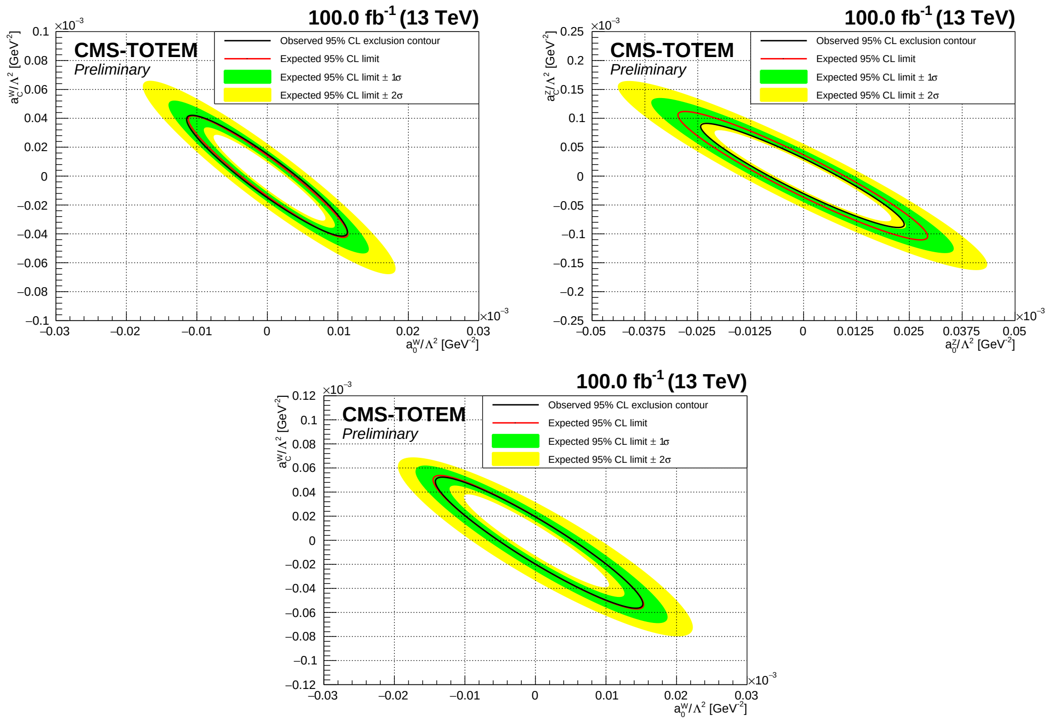

Figure 3: Expected and observed limits in the two-dimensional plane of a_0^W/Λ^2 vs. a_C^W/Λ^2 (above left), a_0^Z/Λ^2 vs. a_C^Z/Λ^2 (above right), and a_0^W/Λ^2 vs. a_C^W/Λ^2 with unitarization imposed by clipping the signal model at 1.4 TeV (below).

4. Search for high-mass exclusive diphoton production

A search for high-mass exclusive diphoton production (light-by-light scattering) with proton tagging was recently extended to the full Run 2 dataset (102.7 fb^{-1}) [5].

The analysis searched for BSM contributions to diphoton production in events where the diphoton system mass and rapidity match the ones reconstructed from the tagged protons (cf. Eq. 2). Recent results use a multivariate analysis approach to improve the photon identification performance. Photon pairs with mass greater than 350 GeV and low acoplanarity are selected. The main background contribution is given by inclusive $\gamma\gamma$ + jets events in which scattered protons from pileup interactions randomly satisfy the mass and rapidity match requirements.

One exclusive diphoton candidate was observed with a background prediction of 1.1 events. Results were interpreted with two approaches: the former describes the 4γ interaction in an EFT scenario, under the assumption of a new physics scale heavier than the energy reachable experimentally. The latter assumes the s-channel production of a neutral pseudo-scalar such as an axion-like particle (ALP). Limits on the 4γ coupling and ALP parameters are illustrated in Fig. 4. The limits on the ALP-photon coupling in the ALP mass range of 500–2000 GeV are the strongest to this date.

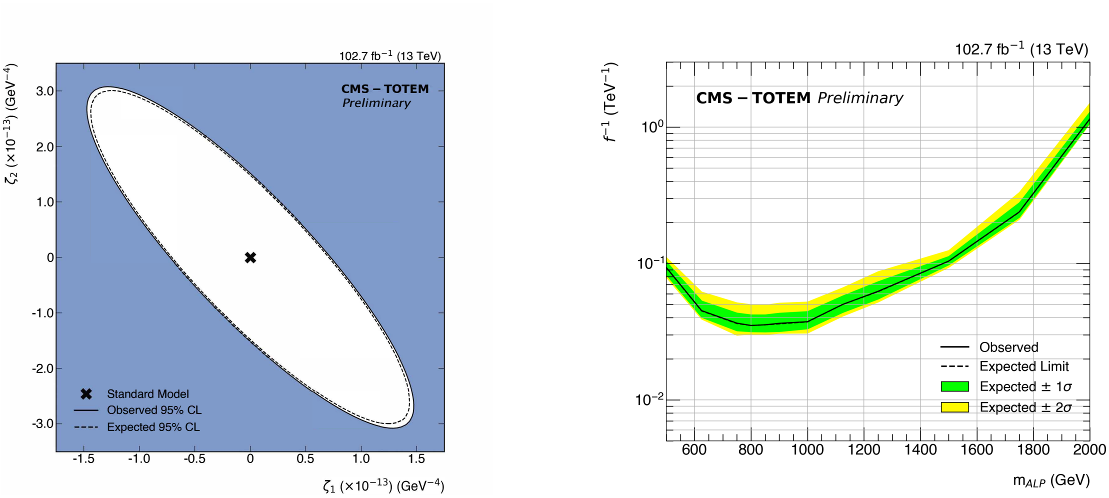

Figure 4: On the left: observed and expected exclusion limits on the anomalous coupling parameters ζ_1 and ζ_2. On the right: limits on ALP production in the plane of the ALP mass and the coupling strength. The shape of the limit curve follows the PPS acceptance times efficiency curve. Figures from Ref. [5].

5. Search for a resonance in the missing mass spectrum in association with Z/γ production

An innovative search for the production of a generic particle X in association with a Z-boson or a photon was performed using data collected in 2017 corresponding to 37.2 and 2.3 fb^{-1}, respectively.

The technique relies on the missing mass (m_{miss}) observable, which corresponds to the mass of the hypothetical particle X, and is defined as:

$$m_{\mathrm{miss}} = \left[(p^{\mathrm{in}}_{\mathrm{p_1}} + p^{\mathrm{in}}_{\mathrm{p_2}}) - (p_{\mathrm{V}} + p^{\mathrm{out}}_{\mathrm{p_1}} + p^{\mathrm{out}}_{\mathrm{p_2}})\right]^2, \quad (3)$$

where p_{V} is the four-momentum of the boson and $p^{\mathrm{out,in}}_{\mathrm{p}_i}$ (i=1,2) are the four-momenta of the outgoing and incoming protons, respectively.

Events with a central signature compatible either with a Z-boson leptonic decay or with a single photon are selected. In both cases, one proton in each PPS arm is required. The leading background contribution is given by inclusive SM processes (Z + jets or γ + jets) in combination with two protons from pileup.

The acceptance and selection efficiency are studied in the 600–1600 GeV m_{X} mass range, for the Z-boson and photon channel separately. The observed m_{miss} spectra are found in good agreement (better than 10%) with the background expectations and 95% CL upper limits on the pp → ppZ/γX cross section are set as a function of m_X (Fig. 5).

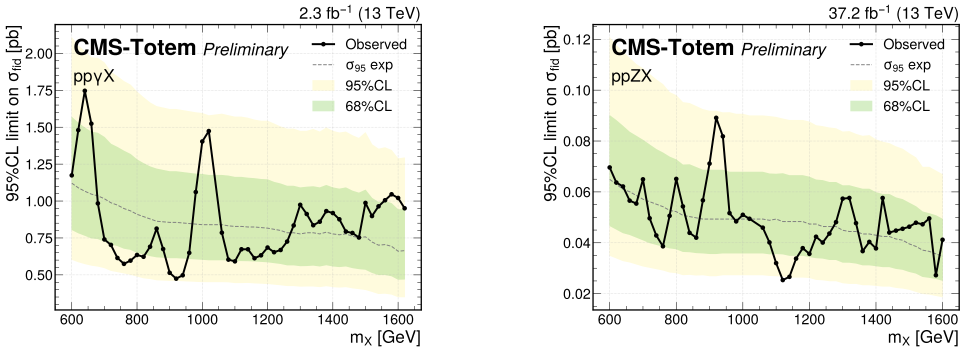

Figure 5: Upper limits on the pp → ppZ/γX production cross section at the 95% CL, as function of m_X. The 95% and 68% CL quantiles of the expected limits are represented by the bands, while the observed limit is superimposed as a curve. The left and right plots correspond to the Z and γ analyses. Figures from Ref. [6].

6. Summary

The most recent results of CMS analyses using proton tagging were shown, including vector boson pair exclusive production, high-mass diphoton exclusive production, and the search of a generic new particle with the missing mass technique, produced in association with a photon or Z-boson.

The present analyses show good agreement with the SM prediction and the results have been used to set constraints on BSM models.

References

[1] CMS Collaboration, JINST 3 S08004 (2008)

[2] CMS and TOTEM Collaboration, arXiv:2210.05854, submitted to JINST (2022).

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[6] CMS and TOTEM Collaborations, CMS Physics Analysis Summary CMS-PAS-EXO-19-009, TOTEM-NOTE-2022-003 (2022).