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Study of central exclusive production processes by proton-proton collisions at $\sqrt{s} = 13$ TeV with the CMS experiment(*)

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Summary. — In this paper the reader is introduced to the physics of central exclusive production (CEP) processes. Furthermore, an overview of many CEP processes studied with the CMS experiment during Run2 will be given, including $t\bar{t}$, e^-e^+, $\mu^-\mu^+$ and $\gamma\gamma$ central exclusive production.

1. – Central exclusive production processes

A Central Exclusive Production (CEP) event is characterised by the presence of undissociated protons in the final state: during the interaction the incoming protons lose energy, which is used to create a new system of particles, which will be called X ($pp \to p + X + p$). As a result of the interaction, protons are deflected from their original path. The proton interaction that is responsible for the creation of the X system can be mediated by photon-photon fusion ($\gamma\gamma \to X$) or by pomeron-pomeron exchange ($PP \to X$). As it will be mentioned in the next sections, in the analyses studied the $\gamma\gamma \to X$ process is by far dominant. The X system is produced orthogonal to the beam, and therefore can be detected by the CMS [1, 2] central detector. On the other hand, protons are slightly deflected from the beam line, and are detected in the forward Precision Proton Spectrometer (PPS) that was specifically built to tag the outgoing protons. PPS took data during Run 2. As detailed in sect. **2**, PPS can measure the fraction of momentum lost by the protons during the interaction. This quantity is related to the energy of the X system. The PPS setup changed during the Run and the performance was studied in detail in ref. [4].

2. – The Precision Proton Spectrometer

The Precision Proton Spectrometer (PPS) [4] was originally developed as a joint project of the CMS and TOTEM collaborations. Some of the PPS detectors are located in the pre-existing TOTEM Roman Pots (RPs), and some others are located in new pots built along the LHC beam line. RPs are located at a distance of ≈ 200 m from the interaction point at the center of CMS (interaction point 5 - IP5), and the detectors

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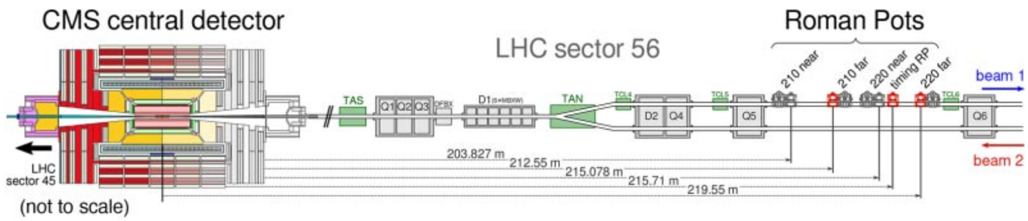

Fig. 1. – The Precision Proton Spectrometer is a symmetrical apparatus located at ±200 m from the IP5. In the picture just one arm of PPS is shown.

inside the RPs are placed at a distance of about 3 mm from the beam line. This allows to tag protons slightly deflected.

The set of PPS detectors is represented in fig. 1. PPS is a symmetrical apparatus composed by 6 stations, three of them located at the distance of $\approx +200$ m from IP5 (arm 0) and three of them at ≈ -200 m (arm 1).

Each arm is composed of two tracking stations and one timing station. The tracking stations have the crucial role to tag the outgoing proton and reconstruct the fraction of momentum lost during the interaction ($\xi = \frac{p_i - p_f}{p_i}$). However, along the years, the technology of the detectors installed in the stations changed. In 2016, the tracking stations were all equipped with silicon strips. Strips are affected by heavy radiation damage and, therefore, the efficiency of PPS in that year was low. From 2017 to 2018 the silicon pixel detectors were introduced. In 2017 each arm had one RP still equipped with strips and the other RP was equipped with pixels. This improved the PPS sensitivity. Finally, in 2018 all the RPs were equipped with pixel detectors. This allowed to improve the resolution of PPS detectors and, on top of that, made possible to reconstruct the trajectory of more than one proton passing through the RPs at the same time.

Reconstructing the fraction of momentum lost by the protons is crucial: the invariant mass (M_X) and the rapidity (Y_X) of the central system, measured by CMS central detector, are related to the fraction of momentum lost by the two outgoing protons ($\xi_1,\ \xi_2$) and measured by PPS: $M_X = \sqrt{s\xi_1\xi_2}$ and $Y_X = \frac{1}{2}\log\frac{\xi_1}{\xi_2}$. More details about proton reconstruction can be found in ref. [8].

In Run2, PPS could resolve protons characterized by $\xi \in (0.015,\ 0.15)$. Due to the relation $M_X = \sqrt{s\xi_1\xi_2}$, this means that PPS can tag protons coming from central interactions characterized by $M_X \in (300,\ 2000)$ GeV. Therefore, PPS is sensitive to Beyond Standard Model (BSM) scenarios at high energies. On the other hand, timing station should measure the time in which the central interaction happened, however their resolution is still not optimal and therefore they were not used in the Run2 analyses.

3. – Proton Pile Up

The central system Pile Up (PU) is a well known issue: during Run2, on average, 33 interactions happened in the same bunch crossing. These interactions cannot by resolved by CMS central system and, therefore, the particles from these "simultaneous" collisions appear in the same recorded event. PPS shows a similar problem: several protons may be deflected during the same bunch crossing. Therefore, several issues may arise:

- Inclusive backgrounds ($pp \to X$), which are not characterized by the presence of protons in the final state, may be reconstructed as exclusive processes, since extra protons can come from PU;

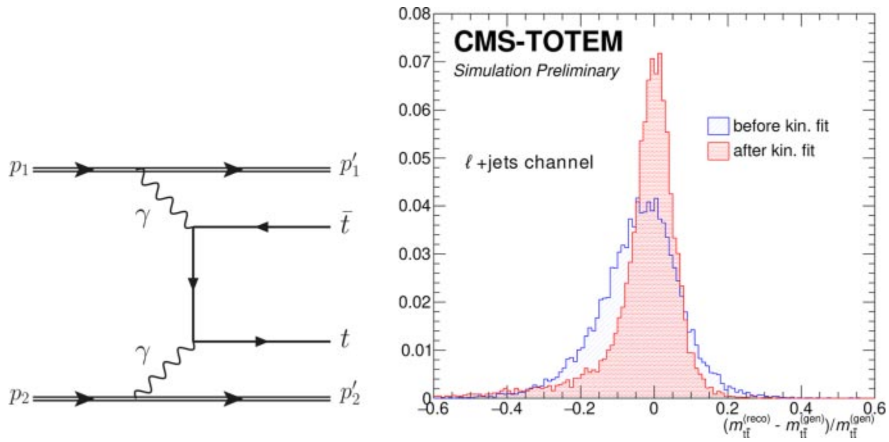

Fig. 2. – Left: Sketch diagram of the central exclusive production of $t\bar{t}$ pairs ($pp \to p + t\bar{t} + p$) via photon-photon interaction (dominant contribution). Right: Invariant mass of the $t\bar{t}$ pair before the kinematic fit (blue) and after the fit (red). The resolution is improved.

- Proton PU can add "extra protons" to the signal: even if the signal is characterized by one proton per arm, additional protons can be reconstructed by PPS due to PU.

These issues reduce the sensitivity of CEP analyses: in principle the exclusive backgrounds (usually the ones characterized by highest cross sections) should be rejected a-priori, since they do not have protons in the final state. Anyhow, there is a probability of 13% to get a set of 2 protons (one per arm) coming from PU.

Finally, proton PU forces us to develop a strategy to select the protons coming from signal: in case of PU, we have multiple protons in the signal samples. In 2017 this was a severe issue, since all events with multiple protons could not be resolved by PPS and were rejected. In 2018, analyzers developed techniques to select the proton coming from the CEP event. The strategy depends on the analysis considered.

4. – Central exclusive production

In this section the reader is introduced to several exclusive analyses developed by the CMS collaboration.

4˙1. *Central exclusive production of $t\bar{t}$ pairs.* – In this kind of process the incoming protons interact by photon-photon fusion and create a $t\bar{t}$ pair in the final state: $pp \to p + t\bar{t} + p$ ($\gamma\gamma \to t\bar{t}$). The pomeron-pomeron exchange is also possible, but its contribution to the cross section is one order of magnitude smaller [3, 5]. In fig. 2 (left) one can find the sketch diagram of the interaction.

The most challenging background is the inclusive production of $t\bar{t}$ pairs ($pp \to p + t\bar{t} + p$) since the central system is equal to signal. The final state is quite challenging since the top quarks are not stable and may decay hadronically ($t \to bq\bar{q}'$) or leptonically ($t \to bl\nu$, being l a charged lepton). In the analysis presented, just the semi-leptonic and di-leptonic decay channels are exploited. On the other hand, the full hadronic decay mode was discarded due to the massive presence of jets.

The high number of particles in the final state (six in total) makes it hard to reconstruct the invariant mass of the $t\bar{t}$ pair. For this reason, a kinematic fit was introduced for the semi-leptonic decay mode to improve the $t\bar{t}$ resolution. The kinematic fit considers

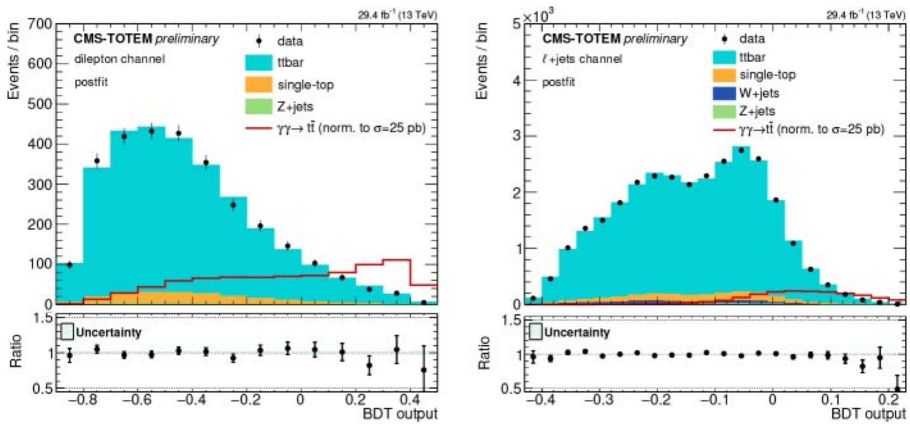

Fig. 3. – Test statistics output for the dilepton (left) and lepton+jet (right) final state.

the components $p_x,\ p_y,\ p_z$ of the momentum of the final state particles. Each kinematic quantity is affected by a statistical uncertainty $(\Delta p_x,\ \Delta p_y,\ \Delta p_z)$. We let $p_x,\ p_y,\ p_z$ freely move in the ranges $p_x \in (p_x - \Delta p_x, p_x + \Delta p_x)$, $p_y \in (p_y - \Delta p_y, p_y + \Delta p_y)$ and $p_z \in (p_z - \Delta p_z, p_z + \Delta p_z)$. For each set of $(p_x,\ p_y,\ p_z)$ it was verified if the conservation principles (invariant mass conservation and momentum conservation) hold. The set of $(p_x,\ p_y,\ p_z)$ that best satisfies the conservation principles mentioned above is chosen. In fig. 2 (right) one can compare the reconstructed invariant mass of the $t\bar{t}$ pair obtained considering the components $p_x,\ p_y,\ p_z$ before and after applying the kinematic fit. Finally, a multivariate analysis tool was developed to maximise the significance of the analysis. In fig. 3 one can find the distributions of the test statistics obtained for the semi-leptonic and di-leptonic decay modes (the classifier trained is a Boosted Decision Tree).

The final observed limit [5] on the cross section is 0.59 pb (at 95% CL), being the theoretical value $O(0.1\text{ fb})$ [9].

4·2. *Central (semi)exclusive production of electron/positron and muon/anti-muon pairs.* – The study of the CEP of $t\bar{t}$ pairs did not allow to set a strict limit since the double proton acceptance of PPS is reduced. As mentioned in sect. **2**, PPS is sensitive to protons characterized by $\xi \in (0.015,\ 0.15)$. This means that it is not sensitive for events with invariant mass lower than 300 GeV. On the other hand, if we consider events with just one proton tagged by PPS, the acceptance at low masses increases. This kind of events are called semi-exclusive events.

The analysis presented in this sub-section aims at tagging pairs of e^+e^- and $\mu^+\mu^-$ produced exclusively or semi-exclusively [6]. Looking for semi-exclusive events makes PPS sensitive for events characterized by an event mass of 100 GeV and above. On top of that, the final state studied is "cleaner", since both electrons and muons can be directly reconstructed by the CMS central system and it is not necessary to reconstruct their decay products. Figure 4 shows the invariant mass and rapidity of the 12 muon/anti-muon and 8 electron/positron pairs observed. Please note that just 2 electron/positron pairs were observed in an exclusive production (green shaded area).

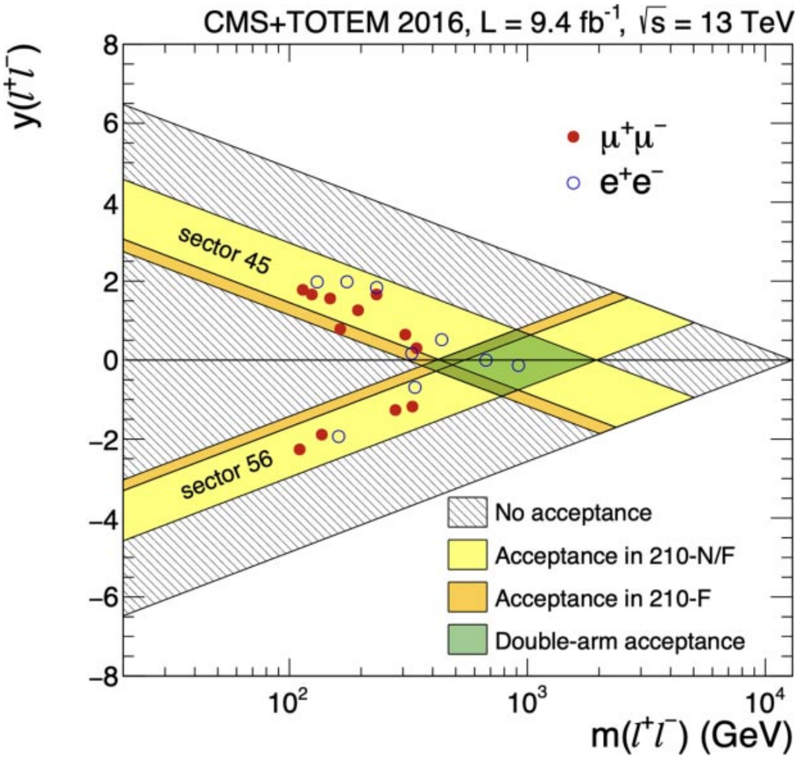

Fig. 4. – Invariant mass and rapidity of the 12 muon/anti-muon and 8 electron/positron pairs observed by the collaboration. In yellow, the single arm PPS acceptance is shown, while in green the PPS double arm acceptance is shown.

4·3. *Exclusive production of $\gamma\gamma$ pairs*. – The CEP of $\gamma\gamma$ pairs ($\gamma\gamma \rightarrow \gamma\gamma$) is an interesting process that can lead to study couplings not described by the SM [7]. As shown in fig. 5 (left), this process is sensitive to the $4-\gamma$ coupling, which is not allowed by standard electromagnetism.

It is also possible that high energy photons produce pairs of opposite sign particles. These particles can subsequently interact and create a new $\gamma\gamma$ pair. Therefore, the process $\gamma\gamma \rightarrow \gamma\gamma$ can indeed be described introducing a particle/anti-particle loop. The anomalous coupling is described by the coefficients ζ_1, ζ_2. The values (ζ_1, ζ_2)=(0,0) correspond to the SM values. In fig. 5 (right), one can appreciate the limits set on these two coefficients.

5. – Conclusions

This article showed several analysis about CEP processes developed by the CMS collaboration. This is a promising field of physics since PPS acceptance is sensitive to processes characterized by high invariant mass. Therefore, studying CEP process with PPS is a way to look for BSM scenarios, characterized by high energy, and allow us to set strict limits on exotic couplings.

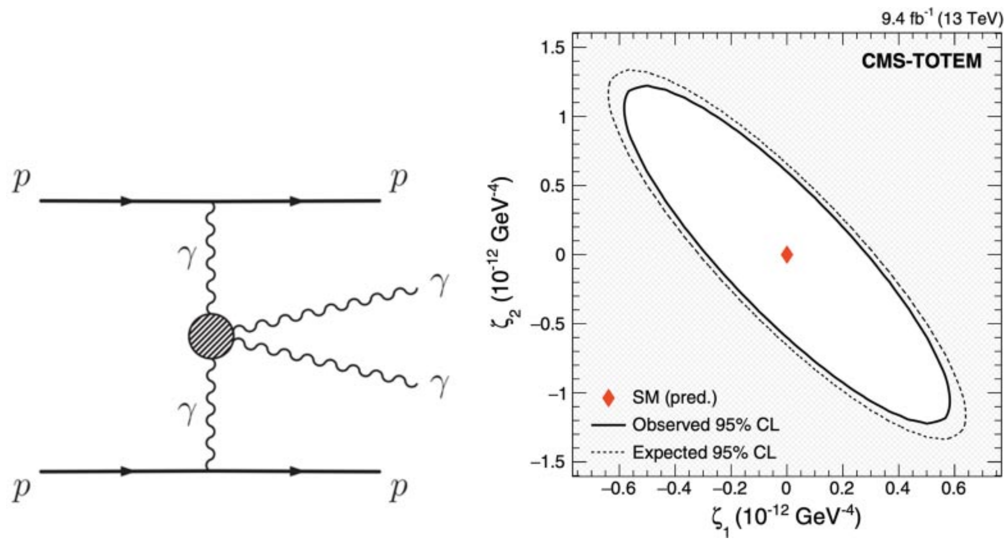

Fig. 5. – Central exclusive production of $\gamma\gamma$ pairs. This process is sensitive to the 4-photon coupling. Sketch diagram (left); Observed and expected limits on the ζ_1, ζ_2 coefficients at the 95% CL (right).

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