Exclusive processes in proton-proton collisions with the CMS experiment at the LHC

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Abstract

We present the recent measurements of exclusive processes performed in the CMS experiment at the LHC using data collected at a centre of mass energy of 7 TeV. These measurements include the double-pomeron production of photon pairs, the two-photon production of leptons pairs, and the previously undetected two-photon production of $W$ boson pairs. While in case of the two first processes that enables to set limits on production cross-section, in the later case it provides also stringent limits on the anomalous quartic gauge couplings.

1 Introduction

Central exclusive processes provide an interesting field of study in particle physics. With its excellent performance, the CMS experiment, whose full description can be found elsewhere,[1, 2] has managed by now to make a number of significant observations of these processes, hence to probe the Standard model in a unique way. A striking signature is expected for such processes, with two very forward (though undetected) scattered protons and two large rapidity gaps between these protons and the central exclusively produced system. An overview is hereby presented for some of these results, such as the search for central exclusive production of photon pairs, the exclusive two-photon production of lepton pairs, and the achieved limits on anomalous quartic gauge couplings in the two-photon production of $W$ pairs.

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2 Central-exclusive $\gamma\gamma$ production

The search for central exclusive production of two-photon events as represented on Fig. 1a constitutes a direct test for the QCD predictions involving the so-called double pomeron exchange. In perturbative calculations this process can be interpreted as a $gg \to \gamma\gamma$ subprocess involving an additional low-momentum gluon exchange enabling the cancellation of the colour flow involved by the interacting gluons.

With a data sample corresponding to an integrated luminosity of 36 $\text{fb}^{-1}$ collected in 2010 by the CMS detector, the limit on the cross-section of central exclusive production of two photons can be quoted for the first time at a centre of mass energy $\sqrt{s} = 7$ TeV after a measurement performed at $\sqrt{s} = 1.96$ TeV by the CDF experiment at the Tevatron [3]. The candidate events are requested to contain two energetic photons with a transverse energy higher than 5.5 GeV as measured by the electromagnetic calorimeter within its acceptance (corresponding to a pseudo-rapidity range $|\eta| < 2.5$). These two photons are furthermore expected to be balanced in their transverse deposited energy and be back-to-back in azimuthal angle. The exclusivity condition is then satisfied when no additional activity (apart from the two photons) is observed in the full detector (thus in the range $|\eta| < 5.2$). This allows a reduced observation of the proton-dissociative events, when one or both forward scattered proton dissociate in a hadronic system hence additional activity is expected in the forward region of the detector.

One of the sources of inefficiency considered in the analysis is due to the relatively high instantaneous luminosity delivered by the LHC machine, whose main drawback is the multiplication of the primary vertices in each event. This phenomenon, the “events pileup”, is expected to lower in a significant way the efficiency of the exclusivity condition with respect to the luminosity. This is shown in Fig. 2 in which the efficiency is evaluated using zero bias events collected parasitically during the data-taking.

No candidate events are observed with a background expectation of $1.79 \pm 0.40$ events arising from the multiple processes involving an inclusive or exclusive
Figure 2: Exclusivity condition efficiency with respect to the instantaneous luminosity of each protons bunch. This exclusivity efficiency is computed to be the ratio between the number of events passing the selection criteria and the total number of the so-called zero bias events collected in 2010 at $\sqrt{s} = 7$ TeV. Figure from [4].

production of photons, such as pairs of misidentified photons (from exclusive production of electron pairs) or from the exclusive $\pi^0\pi^0$ production. An upper limit on the exclusive production cross-section can therefore be set according to this result:

$$\sigma(E_T(\gamma) > 5.5 \text{ GeV}, |\eta(\gamma)| < 2.5) < 1.18 \text{ pb}.$$  

This limit is then compared to the theoretical prediction from various approaches using different orders in the perturbation theory, and parton densities functions (PDFs). A graphical view of this comparison can be found in Fig. 3, without the most recent prediction [5] computed at the leading order (LO) and the next-to-leading order (NLO), providing a production cross section of 0.180 pb for the former using the MSTW08 [6] PDF, and 0.039 pb for the latter using the MRST99 [7] PDF. These signal predictions are computed using the ExHuMe 1.34 [8] event generator implementing the KMR model [9] where the proton-gluon couplings are determined perturbatively. In this model, the two-photon system is then produced by the mean of a quark box, as represented on Fig. 1a.

This result shows that the theoretical predictions for this exclusive process, mediated by gluons only, are in good agreement with the observed upper limit on the cross-section.
3 Exclusive two-photon production of lepton pairs

Two different di-lepton exclusive analyses have been released using the data collected in 2010 at 7 TeV, namely for the measurements of $\gamma\gamma \rightarrow e^+e^-$ [4] and of $\gamma\gamma \rightarrow \mu^+\mu^-$ [10], such as represented on Fig. 1b.

The signal for such processes is simulated using the LPAIR [11, 12] Monte Carlo generator developed in the 1980s for the HERA ep collider experiments. It uses the full matrix element calculation for a $pp \rightarrow p^{(*)}\ell^+\ell^-p^{(*)}$ process, where the photon coupling to a proton is described by the proton electromagnetic form-factors, in case when a fully exclusive production is simulated and both incident protons survived the interaction. In the proton inelastic case the form-factor is replaced by the proton structure functions from HERA fits. The rapidity gap survival probability (due to re-scattering) is not modeled by LPAIR, and it is set to unity in these analyses.

The event selection is requiring two leptons which are energy- or momentum-balanced and back-to-back in the transverse plane. This corresponds to a $|p_T(\ell^+) - p_T(\ell^-)| < 1$ GeV as well as an acoplanarity describing the difference in azimuthal angles, $|1 - \Delta\phi(\ell^+,\ell^-)/\pi| < 0.1$. Furthermore, the dimuon analysis requires each of the two muons to carry a transverse momentum larger than 4 GeV in the range $|\eta(\mu)| < 2.1$. In order to reject the exclusive photoproduction of the low-mass resonances such as the $J/\psi$, the $\psi'$, and the $\Upsilon(1s,2s,3s)$, an invariant mass cut is applied $m(\mu^+\mu^-) > 11.5$ GeV. For the dielectron analysis, a electron-positron pair with a transverse energy deposit in the calorimeters $E_T > 5.5$ GeV are selected in the range $|\eta(e)| < 2.5$. No additonal invariant mass cut is needed in this case.

To ensure the exclusivity condition, the dimuon analysis requires no addi-
tional tracks within 2 mm in the longitudinal direction around the dimuon primary vertex, while the dielectron case rejects all events where any other particles are reconstructed within the full acceptance of the detector, |\(\eta| < 5.2\). This very tight condition, along with a noticeable difference in the collected integrated luminosity, results in large efficiency difference, hence in the number of dimuon candidates (184 events) and the dielectron ones (17 candidates), as represented in Fig. 4. Furthermore, the higher statistics provided by the dimuon channel allows an extraction of the elastic signal contribution as well as the correction to be applied on the theoretical yield predicted for the proton-dissociative part. These corrections are determined from a binned maximum-likelihood fit to the measured \(p_T(\mu^+\mu^-)\) distribution as represented on Fig. 4a.

![Figure 4: Muons (left) and electron (right) pairs transverse momentum distributions for the candidates selected in the two-photon production of leptons pairs.](image)

These two results allow to improve the understanding of this purely electromagnetic process, by observing 17 candidates for the dielectron channel and by a measurement of a production cross-section at \(\sqrt{s} = 7\) TeV for the dimuon channel:

\[
\sigma(pp \rightarrow p\mu^+\mu^-p) = 3.38^{+0.58}_{-0.55}\ \text{(stat.)} \pm 0.16\ \text{(syst.)} \pm 0.14\ \text{(lumi.) pb}
\]

which is consistent with the theoretical prediction.
4 Two-photon production of $W$ pairs and limits on anomalous quartic gauge couplings

Several processes beyond the Standard model predict an anomalous behaviour of the quartic gauge coupling, such as new gauge bosons production or heavy quarks exchanges\[13\]. These anomalous quartic gauge couplings (or AQGCs) can be translated into a higher production rate, or discrepancies in the kinematic distributions of multiple final state particles.

The LHC experiments have been predicted to be sensitive to such behaviours when involving the two-photon interactions \[14, 15\]. Hence, a search for these anomalous couplings is performed at high energies in the CMS experiment with the data collected in 2011 at $\sqrt{s} = 7$ TeV, using the challenging yet previously unobserved two-photon production of $W^\pm$ bosons pairs\[16\], where both the gauge bosons decay leptonically.

The channel of interest for this analysis is the different leptons flavours decay, and especially $e^\pm\mu^\mp\nu\bar{\nu}$. Indeed, since the high-statistics same-flavour channels are saturated with their main sources of background, the $e^+e^-\nu\bar{\nu}$ and $\mu^+\mu^-\nu\bar{\nu}$ final states are set aside in the current analysis. For the former, the dominant sources of background are the inclusive Drell-Yan and the exclusive two-photon productions of $\tau$ leptons pairs as well as the inclusive $W^+W^-$ production and the leptonic decay of $t\bar{t}$ events. On the other hand, the backgrounds for the later include the inclusive Drell-Yan production of same leptons pairs and exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ (as seen in section 3), which are predicted to be more than one order of magnitude larger than the exclusive $\gamma\gamma \rightarrow W^+W^-$. The two neutrinos being left undetected, the candidates are to contain two leptons with $p_T(\ell) > 20$ GeV reconstructed within the full detector acceptance, such as $|\eta(\ell)| < 2.4$, and matched to one single primary vertex from which no additional tracks originates. Indeed, the high luminosity conditions from the 2011 runs of the LHC giving rise to multiple interactions within the same bunch crossing (the so-called ”pileup”), this condition on the additional tracks is the only one ensuring a sufficient efficiency in the selection.

The leptons pair is required to have an invariant mass higher than 20 GeV, and two kinematic regions can be built to isolate the Standard model or the anomalous quartic gauge couplings search regions. For the former, a transverse momentum $p_T(e^\pm\mu^\mp) > 30$ GeV is imposed on the leptons pair, while the later is more stringent with a lower cut of 100 GeV.

In order to simulate the theoretical prediction of the Standard model and the anomalous scenarios in these two regions, extra diagrams have to be taken into account in the final computation. These additional processes are the protons single- and double-dissociative cases which cannot be untangled from the purely elastic contribution without the information on the outgoing protons. Hence, an estimation of these two contributions is given by using the high statistics $\mu^+\mu^-$ final state probed in the same phase space and extracting a ”scale factor”
which can then be applied on the $W^+W^-$ signal:

$$F = \frac{n(\mu\mu \text{ data}) - n(\mu\mu \text{ background})}{n(\mu\mu \text{ elastic})} \bigg|_{m(\mu\mu)>160 \text{ GeV}} = 3.23 \pm 0.53 \text{ (stat. + syst.)},$$

with the background events defined as the prediction of inclusive Drell-Yan production of muons and taus pairs, and the elastic $\gamma\gamma \rightarrow \mu^+\mu^-$ events number predicted by LPAIR.

Given that rescaling in the probed high mass region a theoretical production cross-section is extracted for two kinematic search regions using the CalcHEP \cite{CalcHEP} generator. The theoretical prediction cross-section for the first region (no acceptance cut, and with the $W\pm$ leptonic decay branching ratio included) is:

$$\sigma(pp \rightarrow p(\ast)W^+W^-p(\ast) \rightarrow p(\ast)\mu^+\nu\mu^-\bar{\nu}p(\ast)) = 4.0 \pm 0.7 \text{ fb}.$$ 

![Figure 5](image)

Figure 5: (a) Events passing the full $\gamma\gamma \rightarrow W^+W^-$ selection, with the lepton pairs’ transverse momentum relaxed. The filled histograms represent the backgrounds while the solid line represents the Standard model prediction of such exclusive two-photon production of $W^\pm$ pairs, and the dashed ones are two anomalous quartic gauge couplings examples given as a mean for comparison. (b) One- and two-dimensional limits on the two anomalous quartic gauge couplings parameters according to the CMS upper limits on the $\gamma\gamma \rightarrow W^+W^-$ production cross-section.

As seen in Fig. 5a which depicts the full selected events with the pair transverse momentum cut relaxed, a total of two $\gamma\gamma \rightarrow W^+W^-$ events candidates (displayed in Fig. 6) are observed in this Standard model region.

No events are observed in the AQGC search region. An upper limit on the production cross-section is set according to the theoretical predictions. A 95% confidence level interval is given for the Poisson mean for signal events in this window:

$$\sigma (p_T(\ell) > 20 \text{ GeV}, |\eta(\ell)| < 2.4, m(\mu^+\mu^-) > 20 \text{ GeV}, p_T(e^+\mu^+) > 100 \text{ GeV}) < 1.9 \text{ fb}.$$
Figure 6: Event displays of the two selected Standard model candidates are shown in a zoom over the inner tracking system of CMS. The numerous vertices present on these figures denote the hard events pileup conditions encountered during the 2011 data-taking period.

The two parameters controlling these AQGCs can finally be bounded in a tighter way than the previous limits by OPAL [18] and DØ [19]. These 1- and 2-dimensional CMS limits at 95% C.L. are drawn in Fig. 5b, and are approximately two orders of magnitude more stringent than the best limits obtained at the Tevatron, and at LEP. The one-dimensional bounds are:

\[
|a_0^W / \Lambda^2| < 1.5 \times 10^{-4} \text{ GeV}^{-2}, \quad \text{and} \quad |a_c^W / \Lambda^2| < 5.0 \times 10^{-4} \text{ GeV}^{-2}, \quad (\Lambda_{\text{cutoff}} = 500 \text{ GeV})
\]

\[
|a_0^W / \Lambda^2| < 4.0 \times 10^{-6} \text{ GeV}^{-2}, \quad \text{and} \quad |a_c^W / \Lambda^2| < 1.5 \times 10^{-5} \text{ GeV}^{-2}, \quad \text{(no form factor)}
\]

These results either include or not a dipole form factor with a cutoff scale \(\Lambda_{\text{cutoff}} = 500 \text{ GeV}\) to avoid the unitarity violation of the anomalous models at high two-photon energies. The case with no form factors is to be taken with care, as they are driven by high-energy two-photon interactions beyond the unitarity bound.

With two candidates on an undetected channel, the best limits on these anomalous quartic gauge couplings can be extracted. The limits exceed by two orders of magnitude the previous results, and are competitive with the current CMS analyses of such couplings based on tri-boson production [20].

5 Summary and outlook

In this note, several achievements were shown in the experimental search for exclusive processes at the LHC. First, the theoretical predictions for the central-exclusive \(\gamma\gamma\) production, mediated by gluons only, are in good agreement with the observed upper limit on the cross-section. This result goes hand in hand with the search for the two-photon production of leptons pairs, which enables
to improve the understanding of this purely electromagnetic process with an observation of 17 candidates for the dielectron channel and a measurement of a production cross-section at $\sqrt{s} = 7$ TeV consistent with the theoretical prediction for the dimuon channel. Finally, with two candidates on a previously undetected $\gamma\gamma \rightarrow W^+W^-$ process, the best limits on the anomalous quartic gauge couplings can be extracted. These limits, while exceeding two orders of magnitude more stringent results with respect to the previous attempts, are competitive with the current CMS analyses on such couplings.

The results presented in this note provide evidence both for the excellent performance of the CMS experiment, and its potential for future measurements of exclusive processes at the LHC.

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