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Photon-photon measurements in CMS

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Abstract
We discuss the measurements of exclusive photon-photon processes ($\gamma\gamma \to \ell^+\ell^-, \mathrm{W^+W^-}, \gamma\gamma$) using data collected by the CMS experiment in pp collisions at $\sqrt{s} = 7$ and 8 TeV and in PbPb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV.

Keywords
QED; Electroweak; New Physics; BSM; Light-by-light scattering

1 Introduction

Photon and photon (or "two photon") fusion processes have long been studied at e$^+$e$^-$, ep and hadron colliders, at the LHC they can be studied at much higher energies than available before [1]. Two photon processes provides a wide range of opportunities from testing fundamental Quantum Electro Dynamics (QED) to searches for physics beyond the Standard Model (SM). The results presented in this report are based on the data collected by the CMS experiment.

The central feature of the CMS detector is a superconducting solenoid that provides a magnetic field of 3.8 T, required to bend the charged particle's trajectory and measure it's momentum accurately. Within the solenoid volume are a silicon pixel and strip tracker, electromagnetic calorimeter (ECAL), hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid over the range $|\eta| < 2.4$. Two Hadron Forward (HF) calorimeters cover $2.9 < |\eta| < 5.2$, and two zero degree calorimeters (ZDC) are sensitive to neutrons and photons with $|\eta| > 8.3$. A more detailed description of the CMS detector can be found in Ref [2].

2 Exclusive two-photon production of lepton pairs in pp collisions at $\sqrt{s} = 7$ TeV

The higher energies and luminosities available at CMS allow for significant improvements in the measurement of exclusive two-photon production of lepton pairs. This process can be reliably calculated within QED, within uncertainties of less than 1% associated with the proton form factor. Exclusive two-photon production of lepton pairs provides an excellent control sample for photon fluxes and cross-sections for other exclusive processes.

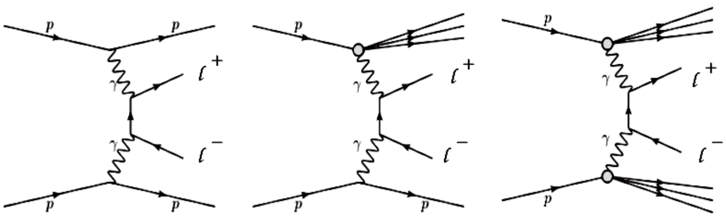

Fig. 1: Schematic diagrams for the elastic (left), single dissociative (center), and double dissociative (right) two-photon production of dilepton pairs.

Measurements of exclusive two-photon production of lepton pairs in pp collisions at $\sqrt{s} = 7$ TeV have been presented in [3, 4], collected by the CMS experiment. The measurement of $\gamma\gamma \to \mu^+\mu^-$ corresponds to an integrated luminosity of 40 pb^{-1} [3], and that of $\gamma\gamma \to e^+e^-$ to 36 pb^{-1} [4]. The

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LPAIR 4.0 [5] MC event generator was used to generate exclusive and semi-exclusive dilepton pair events. In semi-exclusive production, one or both the protons dissociate into a low mass system (Fig.1). The dimuon events are selected with a dedicated trigger that required the presence of two muons with minimum $p_T > 3$ GeV. In order to minimize the uncertainties related to the knowledge of the low p_T and larger η muon efficiencies, muons with $p_T > 4$ GeV and $|\eta| < 2.1$ are selected. In order to reduce the contamination from dimuon decays of the Upsilon meson, the invariant mass of the dimuon pair is required to be above 11.5 GeV. To suppress the proton dissociation background contribution, the muon pair is required to be back-to-back in azimuthal angle $(1-|\Delta\phi/\pi| < 0.1)$ and $\Delta p_T < 1.0$ GeV. The elastic pp $\rightarrow$ p$\mu^+\mu^-$p contribution is extracted by performing a binned maximum-likelihood fit to the measured p_T distribution (Fig.2) extracting a cross section of $\sigma = 3.38^{+0.58}_{-0.55}$ (stat.) ± 0.16 (syst.) ± 0.14 (lumi.) pb. The measured data-theory signal ratio is $0.83^{+0.14}_{-0.13}$ (stat.) ± 0.04 (syst.) ± 0.03 (lumi.) [3]. The measured cross-section is consistent with the predicted value from LPAIR event generator.

The electron pair events are selected with a dedicated trigger, which selects at least two electrons with $E_T > 5$GeV and $\Delta\phi$ between the two electrons greater than 2.5 rad. At the offline level, electrons with $E_T > 5.5$ GeV and $|\eta| < 2.5$ are required. In order to reduce the contamination from Upsilon meson decays, the invariant mass of electron pair is required to be above 11 GeV. The exclusive events are selected by requiring no additional tracks in the tracker and no additional tower above noise threshold in the calorimeters. Seventeen exclusive or semi-exclusive e^+e^- candidates are observed (Fig. 2), with an expected background of 0.85 ± 0.28 (stat.) events, consistent with the theoretical prediction for the combined elastic and inelastic yield of 16.3 ± 1.3 (syst.) events [4].

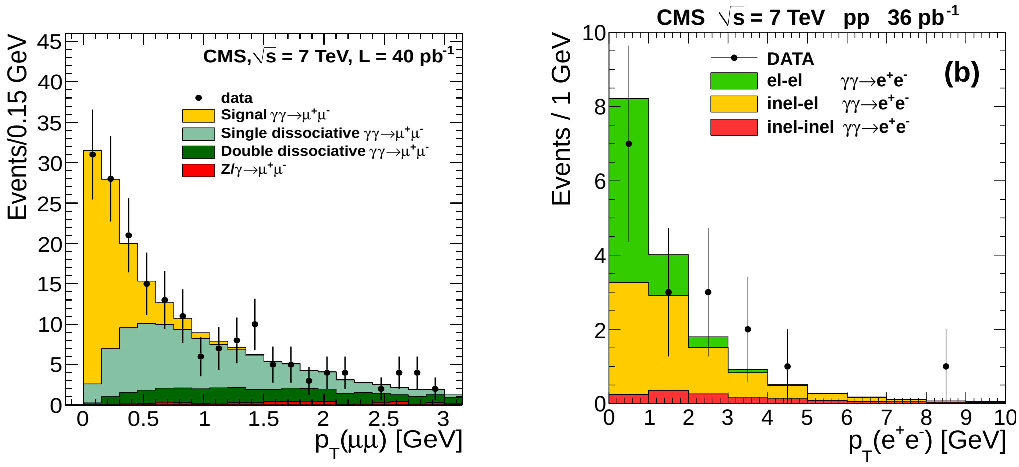


Fig. 2: Transverse momentum distributions for exclusive two-photon production of $\mu^+\mu^-$ (left) and e^+e^- (right) events. Histograms show the predictions for the exclusive, single and double-dissociative processes [3,4].

3 Measurement of W^+W^- pair production in pp collisions at $\sqrt{s} = 7$ and 8 TeV

High energy photon interactions at the LHC provide a unique opportunity to study exclusive production of W pairs. At leading order, quartic, t-channel and u-channel processes contribute to $\gamma\gamma \rightarrow W^+W^-$ production (Fig.3). The measurement of the quartic WW$\gamma\gamma$ coupling is particularly sensitive to deviations from the Standard Model (SM) and searches for new physics. A genuine anomalous quartic gauge coupling (AQGC) is introduced via an effective Lagrangian with two additional dimension-6 terms containing the parameters a_0^W and a_C^W. With the discovery of a light Higgs boson [6–8] a linear realization of the SU(2)$\times$U(1) symmetry of the SM, spontaneously broken by the Higgs mechanism, is possible. Thus, the lowest order operators, where new physics may cause deviations in the quartic gauge boson couplings alone, are of dimension 8. By assuming the anomalous WWZγ vertex vanishes, a direct relationship between the dimension-8 and dimension-6 couplings can be recovered [9]. In both dimension-6 and dimension-8 scenarios, the $\gamma\gamma \to W^+W^-$ cross section increases quadratically with energy, therefore a dipole form factor is introduced to preserve unitarity.

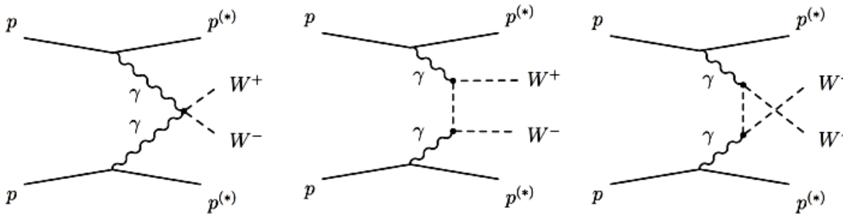


Fig. 3: Quartic (left), t-channel (center), and u-channel (right) diagrams contributing to the $\gamma\gamma \to W^+W^-$ process at leading order in the SM [10].

CMS has carried out a measurement of exclusive and quasi-exclusive $\gamma\gamma \to W^+W^-$ production, via $pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}\mu^\pm e^\mp p^{(*)}$ at $\sqrt{s} = 7$ and 8 TeV , corresponding to luminosities of 5.5 fb^{-1} and 19.7 fb^{-1}, respectively [10, 11]. The production of W pairs was measured in $\mu^\pm e^\mp$ final state, since $W^+W^- \to \mu^+\mu^-$ or $W^+W^- \to e^+e^-$ would be dominated by Drell-Yan events and $\gamma\gamma \to l^+l^-$ production. The $\mu^\pm e^\mp$ events were extracted from the data with a dedicated trigger that selects two leptons with transverse momentum $p_T > 17(8)$ GeV for the leading (subleading) lepton. Offline, the events with an opposite-charge electron-muon pair originating from a common primary vertex that has no additional tracks associated with it were selected to remove the underlying event activity. The events with transverse momentum of the pair $p_T(\mu^\pm e^\mp) > 30$ GeV were selected to suppress backgrounds from $\tau^+\tau^-$ production, including the exclusive and quasi-exclusive $\gamma\gamma \to \tau^+\tau^-$ processes.

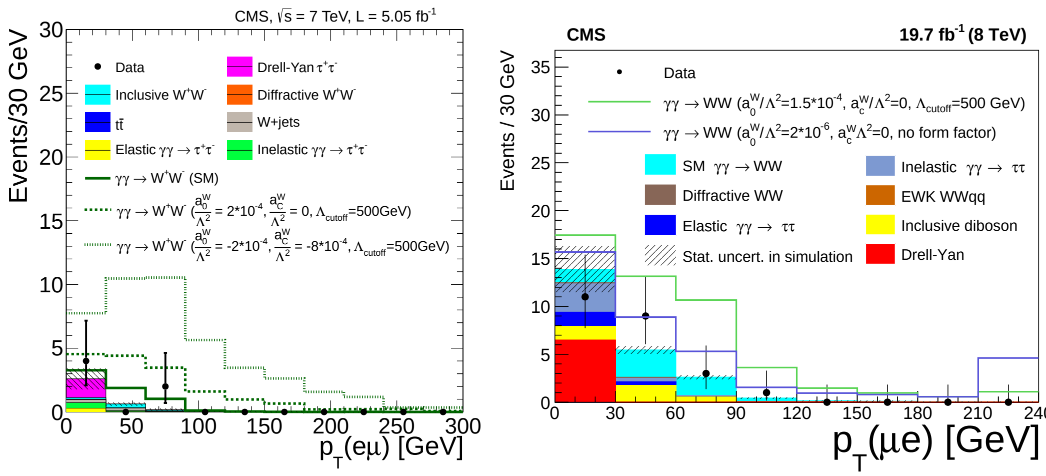


Fig. 4: The $p_T(\mu^\pm e^\mp)$ distribution for events with zero extra tracks at 7 TeV (left) [11] and at 8 TeV(right) [10].

Simulations show that in high-mass $\gamma\gamma$ interactions one or both of the protons dissociate, which may result in events being rejected by the veto on extra tracks. To estimate this effect from data, a sample is selected where the dilepton invariant mass is greater than 160 GeV so that W^+W^- pairs can be produced on shell. The ratio of the observed number of events to the calculated number of elastic $pp \to pl^+l^-p$ events is used as a scale factor to calculate, from the predicted elastic $pp \to pW^+W^-p$ events, the total number of $pp \to p^*\ W^+W^-\ p^*$ to be expected when including proton dissociation. The numerical value of the scale factor thus obtained is F = 4.10±0.43. Fig. 4 shows the $p_T(\mu^\pm e^\mp)$ distribution for events passing all other selection requirements. In the signal region with no additional tracks and $p_T(\mu^\pm e^\mp) > 30$ GeV, two events are observed at 7 TeV compared to the expectation of 2.2±0.4 signal events and 0.84±0.15 background events, corresponding to an observed (expected) significance of 0.8σ (1.8σ). While 13 events are observed at 8 TeV compared to the expectation of 5.3±0.7 signal events and 3.9±0.6 background events which corresponds to a mean expected signal significance of 2.1 σ. When combining the 7 and 8 TeV results, treating all systematic uncertainties as fully uncorrelated between the two measurements, the resulting observed (expected) significance for the 7 and 8 TeV combination is 3.4σ (2.8σ), constituting evidence for $\gamma\gamma \rightarrow W^+W^-$ production in proton-proton collisions at the LHC. Interpreting the 8 TeV results as a cross section multiplied by the branching fraction to $\mu^{\pm}e^{\mp}$ final states, corrected for all experimental efficiencies and extrapolated to the full space, yields : $\sigma(\mathrm{pp} \rightarrow \mathrm{p}^{(*)}\mathrm{W}^+\mathrm{W}^-\mathrm{p}^{(*)} \rightarrow \mathrm{p}^{(*)}\mu^{\pm}\mathrm{e}^{\mp}\mathrm{p}^{(*)}) = 11.9^{+5.6}_{-4.5}$ fb.

The corresponding 95% confidence level (CL) upper limit obtained from the 7 TeV data was <10.6 fb, with a central value of $2.2^{+3.3}_{-2.0}$ fb. The transverse momentum $p_T(\mu^{\pm}e^{\mp})$ distribution was also used to search for signals of anomalous quartic gauge couplings. A selection of $p_T(\mu^{\pm}e^{\mp}) > 100$ GeV is used at 7 TeV, while two bins, with boundaries $p_T(\mu^{\pm}e^{\mp})$ = 30–130 GeV and $p_T(\mu^{\pm}e^{\mp}) > 130$ GeV, are used to set the limit on aQGC. Fig. 5 shows the excluded values of the anomalous coupling parameters $a_0^W/\wedge^2$ and $a_C^W/\wedge^2$ with $\wedge_{cutoff}$ = 500 GeV. The exclusion regions are shown at 7 TeV (outer contour), 8 TeV (middle contour), and the 7+8 TeV combination (innermost contour). The areas outside the solid contours are excluded by each measurement at 95% CL. The cross indicates the one-dimensional limits obtained for each parameter from the 7 and 8 TeV combination, with the other parameter fixed to zero, more details can be found in [10].

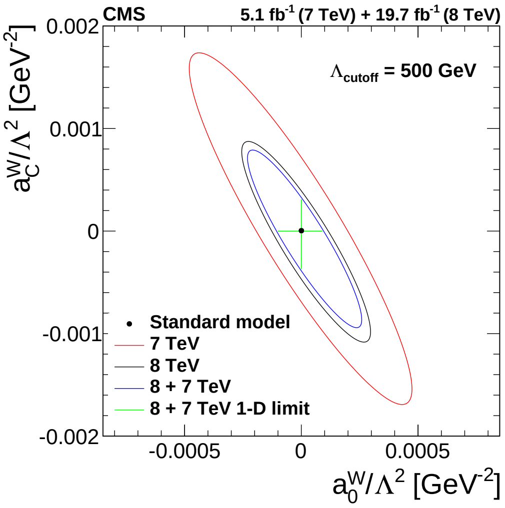
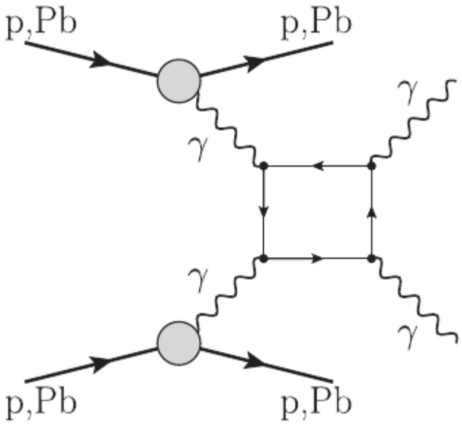


Fig. 5: Excluded values of the anomalous coupling parameters [10].

4 Search for Light-by-light scattering in PbPb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV

The elastic light-by-light (LbyL) scattering, $\gamma\gamma \rightarrow \gamma\gamma$, is a pure quantum mechanical process that proceeds at leading order in the fine structure constant, $\mathcal{O}(\alpha^4)$, via virtual box diagrams containing charged particles. In the standard model (SM), the box diagram of Fig. 6 involves charged fermions (leptons and quarks) and boson ($W^{\pm}$) loops. Despite its simplicity, LbyL scattering was unobserved before LHC because of its tiny cross section $\sigma_{\gamma\gamma} \propto \mathcal{O}~(\alpha^4) \approx 3 \times 10^{-9}$. The feasibility to study this process at LHC was provided in Ref. [12] and evidence for its observation has been claimed by the ATLAS collaboration [13] in ultra-peripheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV.

Fig. 6: Schematic diagram of elastic $\gamma\gamma \rightarrow \gamma\gamma$ collisions in electromagnetic proton or ion interactions at the LHC.



The final-state signature of interest here is the exclusive production of two photons, Pb-Pb $\rightarrow$ Pb$\gamma\gamma$ Pb where the diphoton final-state is measured in the central detector, and the incoming Pb ions survive the electromagnetic interaction and are scattered at very low angles with respect to the beam. Hence, it is expected to detect two low-energy photons and no further activity in the detector, in particular no reconstructed charged-particle tracks coming from the interaction region.

In this report, we introduce the methodology of an ongoing study of LbyL scattering, $\gamma\gamma \rightarrow \gamma\gamma$ using Pb-Pb collisions, recorded by the CMS experiment in 2015 at $\sqrt{s_{\rm NN}}$ =5.02 TeV, corresponding to an integrated luminosity of 388 μb^{-1}. The MADGRAPH V.5 MC event generator [14], modified as discussed in [12], was used to simulate the leading-order exclusive diphoton cross section including all quark and lepton loops. The exclusive QED, $\gamma\gamma \rightarrow e^+e^-$, background where electrons can be misidentified as photons, was generated with STARLIGHT [15]. The central-exclusive diphoton production gg$\rightarrow \gamma\gamma$ (CEP) is simulated using SUPERCHIC 2.0 [16], in which the proton-proton cross section has been scaled by $\mathrm{A}^2\mathrm{R}_g^4$, where A = 208 and $\mathrm{R}_g \approx 0.7$ is a gluon shadowing correction, and further normalized in a region of the PbPb data where such background is dominant. The events were selected by applying a dedicated UPC trigger, which requires at least two e/γ objects with $\mathrm{E_T} > 2$ GeV and at least one HF empty of hadronic activity. The photon reconstruction algorithm at CMS are optimized to reconstruct the photons with $\mathrm{E_T} > 10$ GeV, while most photons in this analysis have $\mathrm{E_T}$ between 2-10 GeV. Therefore, the thresholds of photon $\mathrm{E_T}$, electron p_T and supercluster seed $\mathrm{E_T}$ were reduced to 1 GeV from the default of 10 GeV. Exclusive $\gamma\gamma \rightarrow \gamma\gamma$ events are selected by requiring exactly two photons with $\mathrm{E_T} > 2$ GeV, no charged particle with p_T greater than 0.1 GeV and no additional tower above noise threshold in the calorimeter. In order to reduce the QED background, events with at least one hit in the pixel detector are vetoed. To suppress the CEP background, the photon pair is required to be back-to-back in azimuthal angle $(1-|\Delta\phi/\pi| < 0.01)$ and $\Delta\mathrm{E_T} < 2.0$ GeV. Since, gg$\rightarrow \gamma\gamma$ process has a large theoretical uncertainty, $\mathcal{O}(50\%)$, mostly related to the modelling of the rapidity gap survival probability, the absolute prediction of this process is estimated by normalizing the MC prediction to data for acoplanarity $(1-|\Delta\phi/\pi|) >$ 0.05. After applying all event selection criteria in the used Monte Carlo simulations, we can clearly observe the light by light signal over background and demonstrate the feasibility for a measurement of this process with the CMS experiment

5 Conclusions

Exclusive photon-fusion production of pairs of leptons and $\mathrm{W^+W^-}$, and of pairs of photons ("light-by-light" scattering) have been measured by the CMS experiment in "ultraperipheral" pp at $\sqrt{s} = 7$ and 8 TeV and in PbPb at $\sqrt{s_{\rm NN}}$ =5.02 TeV collisions, respectively. Such measurements provide novel access to electroweak physics in processes and/or at energies never studied before in the laboratory.

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