Search for exclusive or semi-exclusive $\gamma\gamma$ production and observation of exclusive and semi-exclusive e^+e^- production in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

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ABSTRACT: A search for exclusive or semi-exclusive $\gamma\gamma$ production, $\text{pp} \to \text{p}^{(*)} + \gamma\gamma + \text{p}^{(*)}$ (where p^* stands for a diffractively-dissociated proton), and the observation of exclusive and semi-exclusive e^+e^- production, $\text{pp} \to \text{p}^{(*)} + e^+e^- + \text{p}^{(*)}$, in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$, are presented. The analysis is based on a data sample corresponding to an integrated luminosity of $36\,\text{pb}^{-1}$ recorded by the CMS experiment at the LHC at low instantaneous luminosities. Candidate $\gamma\gamma$ or e^+e^- events are selected by requiring the presence of two photons or a positron and an electron, each with transverse energy $E_\text{T} > 5.5\,\text{GeV}$ and pseudorapidity $|\eta| < 2.5$, and no other particles in the region $|\eta| < 5.2$. No exclusive or semi-exclusive diphoton candidates are found in the data. An upper limit on the cross section for the reaction $\text{pp} \to \text{p}^{(*)} + \gamma\gamma + \text{p}^{(*)}$, within the above kinematic selections, is set at $1.18\,\text{pb}$ at 95% confidence level. Seventeen exclusive or semi-exclusive dielectron candidates are observed, with an estimated background of $0.85 \pm 0.28\,(\text{stat.})$ events, in agreement with the QED-based prediction of $16.3 \pm 1.3\,(\text{syst.})$ events.

KEYWORDS: Hadron-Hadron Scattering

Contents

1 Introduction

In central exclusive (hereafter referred to as "exclusive", for brevity) production in pp collisions, $pp \to p + X + p$, the colliding protons emerge intact from the interaction, carrying small transverse momentum ($\lesssim 2\,\text{GeV}$), and all the energy transferred from the protons goes into a color-singlet system at central rapidities. No other particles are produced aside from the central system, and large rapidity gaps, i.e. wide regions of rapidity devoid of particles, are present. The three main types of exclusive processes are due to $\gamma\gamma$ interactions (e.g. exclusive e^+e^- or $\mu^+\mu^-$ production [1]), $\gamma\mathbb{P}$ fusion (e.g. exclusive Υ production [2]) and $\mathbb{P}\mathbb{P}$ exchange (e.g. exclusive $\gamma\gamma$ or Higgs boson production [3]), where $\mathbb{P}$ denotes the pomeron, a strongly interacting color-singlet t-channel exchange with the vacuum quantum numbers [4, 5].

At the Large Hadron Collider (LHC), exclusive $\gamma\gamma$ (hereafter referred to as "diphoton") events can be produced by means of $\mathbb{P}\mathbb{P}$ exchange, interpreted in partonic terms as $gg \to \gamma\gamma$
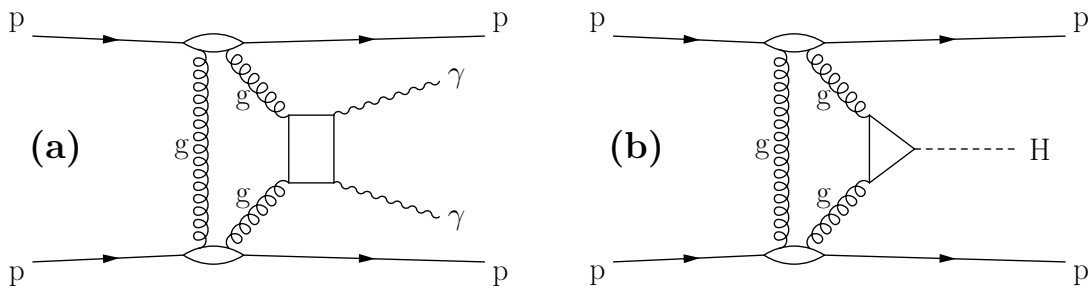
Figure 1. The dominant diagrams for (a) exclusive diphoton production and (b) exclusive Higgs boson production in pp collisions. Note the screening gluon that cancels the color flow from the interacting gluons and therefore allows the protons to stay intact. For exclusive $\gamma\gamma$ production, the contributions from $q\bar{q} \to \gamma\gamma$ and $\gamma\gamma \to \gamma\gamma$ are both theoretically estimated to be less than 1% of $gg \to \gamma\gamma$ [6].
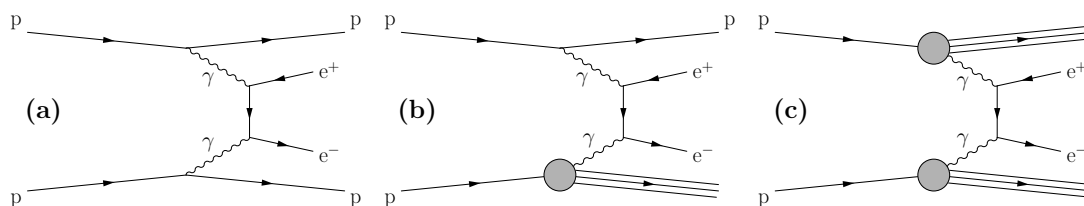

Figure 2. The Feynman diagrams for (a) exclusive e^+e^- production and semi-exclusive e^+e^- production with (b) either or (c) both protons dissociating in pp collisions.

via a quark loop, with an additional "screening" gluon exchanged to cancel the color of the interacting gluons, as shown in figure 1(a). The quantum chromodynamics (QCD) calculation of this diagram is difficult because the screening gluon has low four-momentum-transfer squared, Q^2. Furthermore, additional inelastic interactions between the protons may produce particles that destroy the rapidity gaps; this effect is taken into account by introducing the so-called rapidity-gap survival probability [7], which is poorly known theoretically. The study of exclusive diphoton production may shed light on diffraction and the dynamics of pomeron exchange. In addition, exclusive diphoton production is closely related to exclusive Higgs boson production (figure 1(b)), where the Higgs boson is produced via gg fusion dominantly through a top-quark loop [8–15]. Since the QCD part of the calculation, from which most theoretical uncertainties originate, is the same for H and $\gamma\gamma$ production, and only the calculable matrix elements $gg \to \gamma\gamma$ and $gg \to$ H are different, exclusive $\gamma\gamma$ production provides an excellent test of the theoretical predictions for exclusive Higgs boson production.

Exclusive e^+e^- (hereafter referred to as "dielectron") production via $\gamma\gamma$ interactions is a quantum electrodynamics (QED) process (figure 2(a)), and the cross section is known with an accuracy better than about 1%; the uncertainty is dominated by that on the proton electromagnetic form factor [16–18]. Detailed theoretical studies have shown that in this case the correction due to the rapidity-gap survival probability is well below 1% and can be safely neglected [19]. Exclusive e^+e^- events provide an excellent control sample for other exclusive processes with less certain theoretical predictions, such as exclusive $\gamma\gamma$ production.

Semi-exclusive $\gamma\gamma$ and e^+e^- production, involving single- or double-proton dissociation (figures 2(b) and 2(c) for the dielectron case), is also considered as signal in this analysis, as long as no particles from the proton dissociation have pseudorapidity $|\eta| < 5.2$. The pseudorapidity η is defined as $\eta = -\ln(\tan\frac{\theta}{2})$, where θ is the polar angle. This process has larger theoretical uncertainties. In the rest of this paper, exclusive events will be referred to as "el-el" events, while semi-exclusive events with either or both protons dissociated will be referred to as "inel-el" and "inel-inel" events, respectively. The term "non-exclusive events" will be used to indicate all other events with two photons or two electrons and additional activity.

Results on exclusive $\gamma\gamma$ production in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV were obtained by the CDF collaboration [20, 21], and the measured cross sections are consistent with the KMR [22] predictions. The CDF experiment also measured the exclusive e^+e^- and $\mu^+\mu^-$ production cross sections [23–25], and the results are in agreement with theory. Exclusive $\mu^+\mu^-$ production, which proceeds via the same mechanisms as exclusive e^+e^- production, was also measured by the Compact Muon Solenoid (CMS) experiment in pp collisions at $\sqrt{s} = 7$ TeV [26], and the result agrees with the QED-based prediction.

This paper presents a search for exclusive or semi-exclusive $\gamma\gamma$ production, and the observation of exclusive and semi-exclusive e^+e^- production in pp collisions at $\sqrt{s} = 7$ TeV. Since any other inelastic pp collision occurring in the same bunch crossing as the exclusive interaction ("pileup" events) would destroy the rapidity gaps and make the exclusive interaction unobservable, only a data sample with low pileup contamination is used. The data sample was collected in 2010 by the CMS experiment at the LHC, and corresponds to an integrated luminosity of $36\,\mathrm{pb}^{-1}$. The signal diphoton or dielectron event selection requires the presence of two photons or two electrons of opposite charge, each with transverse energy $E_T > 5.5$ GeV and pseudorapidity $|\eta| < 2.5$, and no other particles in the region $|\eta| < 5.2$. The two photons or electrons are expected to be balanced in E_T ($\Delta E_T \sim 0$) and to be back-to-back in azimuthal angle ϕ ($\Delta\phi \sim \pi$), a consequence of the very small Q^2 of the exchanged pomerons or photons.

2 The CMS detector

A detailed description of the CMS detector can be found in ref. [27]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors made by using three technologies: drift tubes (DT), cathode strip chambers (CSC), and resistive plate chambers. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle, θ, is measured from the positive z axis and the azimuthal angle, ϕ, is measured

in the x-y plane. The inner tracker measures charged particle trajectories with transverse momentum p_T from less than 100 MeV, and within the pseudorapidity range $|\eta| < 2.5$. The ECAL provides coverage in the pseudorapidity range $|\eta| < 1.479$ in the barrel region (EB) and $1.479 < |\eta| < 3.0$ in the two endcap regions (EE). The HCAL provides coverage for $|\eta| < 1.3$ in the barrel region (HB) and $1.3 < |\eta| < 3.0$ in the two endcap regions (HE). The two hadronic forward calorimeters (HF) cover the region of $2.9 < |\eta| < 5.2$. The CMS experiment selects data by using a two-level trigger system. The first level consists of custom hardware processors and uses information from the calorimeters and muon systems. The high-level trigger processor farm further decreases the event rate before data storage.

3 Simulation and reconstruction

The ExHuME 1.34 Monte Carlo (MC) event generator [28] is used to simulate exclusive diphoton events and to calculate their production cross section σ. The ExHuME package is an implementation of the KMR model [22]. In this model, the two gluons couple perturbatively to the protons, and produce the $\gamma\gamma$ system through a quark loop. The calculation includes the Sudakov factor, which accounts for the probability that no partons are emitted by the interacting gluons in the evolution up to the hard scale. The cross section is further suppressed by the rapidity-gap survival probability. A variety of parton distribution function (PDF) sets have been used, so as to assess the sensitivity of the cross section calculation to the low-x gluon density $g(x)$ ($\sigma \sim [g(x)]^4$, where x is the gluon fractional momentum) [29], which changes significantly in different PDF sets. Semi-exclusive diphoton production is not well known theoretically, and is not simulated in this analysis.

The LPAIR 4.0 event generator [30] is used to simulate both exclusive and semi-exclusive e^+e^- events and to calculate their production cross sections. For exclusive events, the cross section depends on the proton electromagnetic form factor. In the case of proton dissociation, the cross section calculation requires the knowledge of the proton structure function and the rapidity-gap survival probability. The latter is not included in LPAIR and is taken as 1 in this analysis. In order to simulate the fragmentation of the excited protons, LPAIR is interfaced to the JETSET 7.408 package [31], where the LUND fragmentation model [32] is implemented.

The generated events are further processed through a detailed simulation of the CMS detector based on GEANT4 [33] and are reconstructed in the same way as the collision data.

Photon candidates are reconstructed [34] from clusters of ECAL channels around significant energy deposits, which are merged into so-called superclusters. The clustering algorithm results in an almost complete recovery of the energy of photons converting in the material in front of the ECAL. In the barrel region, superclusters are formed from 5-crystal-wide strips in η centered on the locally most energetic crystal (seed), and have a variable extension in ϕ (up to ± 17 crystals from the seed). In the endcap, matrices of 5×5 crystals (which may partially overlap) around the most energetic crystals are merged if they lie within a narrow road in η ($\Delta\eta = 0.14$, $\Delta\phi = 0.6$ rad).

The reconstruction of electrons [35] combines the ECAL and inner-tracker information. It starts with clusters of energy deposits in the ECAL, which include the energy due to

electron-induced electromagnetic showers and that of the bremsstrahlung photons emitted along the electron trajectory. The clusters drive the search for hits in the pixel detector, which are then used to seed electron tracks. This is complemented by the usage of the tracker for the seeding, to improve the reconstruction efficiency at low p_T and in the transition regions between the ECAL detector elements. Trajectories in the tracker volume are reconstructed by using a dedicated model of the electron energy loss, and are fitted with a Gaussian sum filter (GSF) [35]. The four-momenta of electrons are obtained by using the angle from the associated GSF track and the energy from the combination of the tracker and ECAL information.

4 Event selection

The selection of signal events proceeds in three steps. Exactly two photons or two electrons of opposite charge, each with $E_\mathrm{T} > 5.5\,\mathrm{GeV}$ and $|\eta| < 2.5$, are required to be present in the triggered events. Then, the events are required to satisfy the cosmic-ray rejection criteria. Finally, the exclusivity selection is performed, based on the information from the tracker, the electromagnetic calorimeter, the hadron calorimeter, and the muon chambers; this selection requires no additional particles reconstructed in these subdetectors, and thus suppresses the contribution from semi-exclusive events and rejects non-exclusive events as well as pileup events.

4.1 Photon and electron selection

Both diphoton and dielectron candidate events were selected online by two different triggers corresponding to two subsequent data acquisition periods. Both triggers required the presence of two electromagnetic showers with $E_\mathrm{T} > 5\,\mathrm{GeV}$. In the second data acquisition period with higher instantaneous luminosities, the two showers were also required to be separated in azimuthal angle by at least $2.5\,\mathrm{rad}$, and a low-activity requirement of less than 10 hadronic towers with energy above $5\,\mathrm{GeV}$ and $|\eta| < 5.2$ was applied.

The first offline selection step is to require the presence of exactly two photon candidates or two electron candidates of opposite charge, each with $E_\mathrm{T} > 5.5\,\mathrm{GeV}$ and $|\eta| < 2.5$, for the diphoton and the dielectron analyses, respectively. These photon or electron candidates are subsequently required to satisfy the identification criteria described below.

For photons, the energy detected in the HCAL behind the photon cluster is required to be less than 2% of the ECAL energy, and the ECAL cluster-shape parameter [34] is required to be consistent with that of a photon. The photons are required to be isolated from other activity in the detector. The isolation parameter is defined as the scalar sum of the transverse energies of tracks or calorimeter deposits within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ of the direction of the photon, after excluding the contribution from the candidate itself. The isolation parameter is required to be less than $0.001 \times E_\mathrm{T} + 1.0\,\mathrm{GeV}$, $0.006 \times E_\mathrm{T} + 2.5\,\mathrm{GeV}$, and $0.0025 \times E_\mathrm{T} + 2.0\,\mathrm{GeV}$ for the tracker, ECAL, and HCAL, respectively, where E_T is the photon transverse energy in GeV. The absence of any hit patterns in the pixel tracker consistent with those of an electron track is also required in order to discriminate photons

from electrons. No explicit attempt is made to distinguish between photons and neutral pions when the showers of the two decay photons merge.

For electrons, the same requirements on the HCAL energy and the cluster shape are applied as in the photon case. The ratio between the isolation parameter described above (but with $\Delta R = 0.3$) and the electron p_T is required to be less than 0.05, 0.3, and 0.2 (barrel) or 0.1 (endcap), for the tracker, ECAL, and HCAL, respectively. The difference between the azimuthal angle of the cluster and that of the direction of the electron track at its vertex is required to be less than 0.3 rad; the corresponding difference in pseudorapidity is required to be less than 0.02 (EB) or 0.03 (EE). The number of missing hits in front of the first valid hit of the electron track is required to be ≤ 1 in order to reject electrons from photon conversions.

4.2 Cosmic-ray rejection

In order to remove cosmic-ray events, the timing of the two photons or electrons, as measured by the ECAL, is required to be consistent with that of particles originating from a collision, i.e. $|t_1| < 2\,\text{ns}$, $|t_2| < 2\,\text{ns}$, and $|t_1 - t_2| < 2\,\text{ns}$, where t_i is the timing of the i-th photon or electron. Furthermore, the two photon or electron candidates are required to be separated by more than 2.5 rad in ϕ, in order to reject the remaining cosmic-ray events in which the cosmic ray is far away from the interaction point in the x-y plane.

4.3 Exclusivity selection

Exclusivity selection criteria are designed to reject events with particles in the range $|\eta| < 5.2$ not associated with the two photon or electron candidates. More specifically, it is required that there should be no additional tracks in the tracker, no additional towers above the noise thresholds in the calorimeters (EB, EE, HB, HE, and HF), and no track segments in the DTs and CSCs. An additional track is defined as any track outside a region of $\Delta\eta < 0.15$ and $\Delta\phi < 0.7$ rad of the photons or the electrons. An additional tower in the EB is defined as a tower above the noise threshold and outside a region of $\Delta\eta < 0.15$ and $\Delta\phi < 0.7$ rad of the photons or the electrons, while in the EE the region is $\Delta\eta < 0.15$ and $\Delta\phi < 0.4$ rad. An additional tower in the HB, HE, and HF is defined as any tower above the noise thresholds. The noise thresholds are determined from non-interaction events. The values of the noise thresholds are 0.52 GeV, 2.18 GeV, 1.18 GeV, 1.95 GeV, and 9.0 GeV for the EB, EE, HB, HE, and HF, respectively, and are applied in energy rather than E_T.

The numbers of diphoton and dielectron candidates in the data sample remaining after each selection step are listed in table 1.

5 Efficiencies

The overall selection efficiency ε is defined as $\varepsilon = \varepsilon_{\gamma\gamma(e^+e^-)} \cdot \varepsilon_{\cos} \cdot \varepsilon_{\text{fsr}} \cdot \varepsilon_{\text{exc}}$, where $\varepsilon_{\gamma\gamma(e^+e^-)}$ is the efficiency for identifying the two photons or electrons; $\varepsilon_{\cos}$ is the efficiency for a signal event to pass the cosmic-ray rejection criteria; ε_{fsr} is the probability for a signal event not to be rejected by the exclusivity selection criteria because of final-state radiation; and ε_{exc}

Diphoton analysis		Dielectron analysis	
Selection criterion	Events remaining	Selection criterion	Events remaining
Trigger	3 023 496	Trigger	3 023 496
Photon reconstruction	1 683 526	Electron reconstruction	132 271
Photon identification	40 692	Electron identification	1 668
Cosmic-ray rejection	34 234	Cosmic-ray rejection	1 321
Exclusivity requirement	0	Exclusivity requirement	17

Table 1. Numbers of diphoton and dielectron candidates remaining after each selection step.

is the probability for a signal event not to be rejected by the exclusivity selection criteria because of pileup, calorimeter noise, or beam background.

5.1 Photon and electron efficiency

The diphoton efficiency $\varepsilon_{\gamma\gamma}$ is split into three parts: the reconstruction efficiency $\varepsilon_{\text{reco}}$, the identification efficiency ε_{id}, and the trigger efficiency $\varepsilon_{\text{trig}}$, i.e. $\varepsilon_{\gamma\gamma} = \varepsilon_{\gamma\gamma,\,\text{reco}} \cdot \varepsilon_{\gamma,\,\text{id}}^2 \cdot \varepsilon_{\gamma\gamma,\,\text{trig}}$. The reconstruction and trigger efficiencies are both denoted by the subscript "$\gamma\gamma$", rather than just "γ", to reflect the fact that these efficiencies must be calculated per event, rather than per photon, due to the strong E_{T} and ϕ correlations between the two photons (balanced in E_{T} and back-to-back in ϕ). All these efficiencies are calculated by using signal MC samples. The systematic uncertainty of the reconstruction efficiency is evaluated by shifting the E_{T} threshold by $\pm 5\%$, motivated by the energy scale uncertainty for low-E_{T} photons and electrons. The systematic uncertainty of the identification efficiency is evaluated by shifting the thresholds of the identification parameters by $\pm 10\%$. The systematic uncertainty of the trigger efficiency is estimated from the difference of the single-photon trigger efficiency calculated from interaction (minimum-bias) events in the data and in the MC samples. A summary of the photon efficiencies for exclusive diphoton events is listed in table 2.

For the dielectron analysis, the same procedure as in the diphoton analysis is used to determine the electron efficiencies and the corresponding systematic uncertainties. The results are listed in table 2 for both exclusive and semi-exclusive e^+e^- events.

5.2 Cosmic-ray rejection efficiency

For exclusive $\gamma\gamma$ and e^+e^- events, since the efficiency for the requirement of $\Delta\phi > 2.5\,\text{rad}$ is 100%, the cosmic-ray rejection efficiency ε_{cos} is equal to the efficiency for the timing requirements mentioned in section 4.2. This efficiency is determined by applying the timing requirements to a data sample of $\text{J}/\psi \to \text{e}^+\text{e}^-$ events with invariant mass $3.0 < M(\text{e}^+\text{e}^-) < 3.2\,\text{GeV}$, which has a negligible cosmic-ray contamination. This yields $\varepsilon_{\text{cos}} = 0.979 \pm 0.009$ for exclusive $\gamma\gamma$ and e^+e^- events. The quoted systematic uncertainty is evaluated by shifting the thresholds of the timing requirements by $\pm 5\%$, motivated by the uncertainty of the timing measurement of less than $100\,\text{ps}$. For semi-exclusive e^+e^- events, the efficiency

Diphoton analysis		Dielectron analysis			
			el-el	inel-el	inel-inel
$\varepsilon_{\gamma\gamma,\,\text{reco}}$	0.724 ± 0.087	$\varepsilon_{\text{e}^+\text{e}^-,\,\text{reco}}$	0.606 ± 0.055	0.663 ± 0.050	0.683 ± 0.045
$\varepsilon_{\gamma,\,\text{id}}$	0.941 ± 0.003	$\varepsilon_{\text{e},\,\text{id}}$	0.967 ± 0.005	0.966 ± 0.005	0.960 ± 0.005
$\varepsilon_{\gamma\gamma,\,\text{trig}}$	0.757 ± 0.050	$\varepsilon_{\text{e}^+\text{e}^-,\,\text{trig}}$	0.655 ± 0.024	0.708 ± 0.018	0.683 ± 0.013
$\varepsilon_{\gamma\gamma}$	0.485 ± 0.067	$\varepsilon_{\text{e}^+\text{e}^-}$	0.371 ± 0.037	0.438 ± 0.035	0.430 ± 0.030

Table 2. Summary of the photon and electron efficiencies with systematic uncertainties.

for the $\Delta\phi$ requirement is determined from MC to be 0.858 and 0.701 for inel-el and inel-inel events, respectively. A correction factor of 0.979 and 0.932 is subsequently applied for inel-el and inel-inel e^+e^- events in order to take into account the $\Delta\phi$ requirement at the trigger level. The cosmic-ray rejection efficiency for inel-el and inel-inel e^+e^- events is then estimated to be 0.822 ± 0.008 and 0.639 ± 0.006, respectively.

5.3 Final-state-radiation efficiency

As a consequence of the exclusivity requirements, signal diphoton events with either or both photons converting into e^+e^- pairs, as well as events that produce electrons in the tracker detector by Compton scattering, are vetoed if there are energy deposits above the noise thresholds outside the regions defined in section 4.3. The corresponding efficiency is the final-state-radiation efficiency ε_{fsr}, and is estimated by applying the exclusivity selection criteria to simulated signal events. The systematic uncertainty is evaluated by shifting the noise thresholds of the exclusivity selection criteria by the energy scale uncertainty for each subdetector. The uncertainty due to the tracker-material budget is negligible and is evaluated by using a set of realistic tracker-material modifications [36] in the simulation.

Likewise, for both exclusive and semi-exclusive dielectron production, if a final-state electron emits a high-energy bremsstrahlung photon, the event is vetoed by the exclusivity selection criteria. For the semi-exclusive case, the probability that a semi-exclusive event is not vetoed because of the particles from the proton dissociation is also folded into this efficiency, which results in a much lower final-state-radiation efficiency than for the exclusive case. The same procedure as in the diphoton analysis is used to determine the efficiencies and the uncertainties due to the energy scale. For the semi-exclusive case, the additional uncertainty coming from the proton fragmentation model is dominant, and is evaluated by using different programs to simulate the dissociation of the excited protons. The programs considered are PHOJET 1.12 [37, 38], PYTHIA 6.422 [39], PYTHIA 8.142 [40], and PYTHIA 8.165 with MBR [41].

5.4 Exclusivity efficiency

The exclusivity efficiency is the probability that a signal event is not rejected by the exclusivity selection criteria because of pileup, calorimeter noise, or beam background in the same bunch crossing, and is determined by using zero-bias events. Zero-bias events
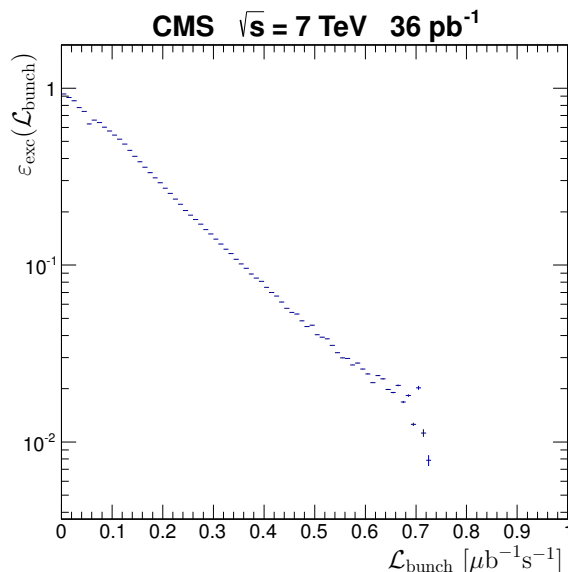
Figure 3. Exclusivity efficiency as a function of the bunch-by-bunch luminosity.

are those triggered solely on the bunch-crossing time. Since the number of inelastic proton-proton interactions in a given bunch crossing follows a Poisson distribution and the exclusivity efficiency is approximately equal to the probability of having no inelastic collision, the exclusivity efficiency is an exponential function of the bunch-by-bunch instantaneous luminosity:

$$\varepsilon_{\mathrm{exc}}(\mathcal{L}_{\mathrm{bunch}}) = \frac{N_{\mathrm{zero\text{-}bias}}^{\mathrm{exc}}(\mathcal{L}_{\mathrm{bunch}})}{N_{\mathrm{zero\text{-}bias}}(\mathcal{L}_{\mathrm{bunch}})} \approx \mathrm{e}^{-\overline{n}} = \mathrm{e}^{-\mathcal{L}_{\mathrm{bunch}}\cdot\sigma_{\mathrm{inelastic}}/f}$$

where $N_{\mathrm{zero\text{-}bias}}^{(\mathrm{exc})}$ is the number of zero-bias events with (exc) or without the exclusivity requirements, $\overline{n}$ is the average number of inelastic interactions per bunch crossing for a given bunch-by-bunch luminosity $\mathcal{L}_{\mathrm{bunch}}$, and $f = 11\,246\,\mathrm{Hz}$ is the LHC revolution frequency. The exclusivity efficiency is shown in figure 3 as a function of the bunch-by-bunch luminosity, calculated with a zero-bias data sample taken during the same data acquisition period as that of the signal sample.

The average exclusivity efficiency is calculated by using the following equation [23]:

$$\varepsilon_{\mathrm{exc}} = \frac{\int \frac{\mathrm{d}N_{\mathrm{zero\text{-}bias}}}{\mathrm{d}\mathcal{L}_{\mathrm{bunch}}} \cdot \mathcal{L}_{\mathrm{bunch}} \cdot \varepsilon_{\mathrm{exc}}(\mathcal{L}_{\mathrm{bunch}}) \cdot \mathrm{d}\mathcal{L}_{\mathrm{bunch}}}{\int \frac{\mathrm{d}N_{\mathrm{zero\text{-}bias}}}{\mathrm{d}\mathcal{L}_{\mathrm{bunch}}} \cdot \mathcal{L}_{\mathrm{bunch}} \cdot \mathrm{d}\mathcal{L}_{\mathrm{bunch}}}$$

where the weight $\mathcal{L}_{\mathrm{bunch}}$ in the integrations reflects the fact that the probability of a process taking place in a given bunch crossing is proportional to the corresponding bunch-by-bunch luminosity. The average exclusivity efficiency is $\varepsilon_{\mathrm{exc}} = 0.145\pm0.008$, where the uncertainty is evaluated by varying the noise thresholds of the exclusivity selection criteria by $\pm5\%$. This efficiency is dominated by the losses due to pileup.

Table 3 lists a summary of the efficiencies for both the diphoton and the dielectron analyses.

Diphoton analysis		Dielectron analysis			
			el-el	inel-el	inel-inel
$\varepsilon_{\gamma\gamma}$	0.485 ± 0.067	$\varepsilon_{e^+e^-}$	0.371 ± 0.037	0.438 ± 0.035	0.430 ± 0.030
$\varepsilon_{\mathrm{cos}}$	0.979 ± 0.009	$\varepsilon_{\mathrm{cos}}$	0.979 ± 0.009	0.822 ± 0.008	0.639 ± 0.006
$\varepsilon_{\mathrm{fsr}}$	0.972 ± 0.005	$\varepsilon_{\mathrm{fsr}}$	0.927 ± 0.005	0.666 ± 0.049	0.299 ± 0.041
$\varepsilon_{\mathrm{exc}}$	0.143 ± 0.008	$\varepsilon_{\mathrm{exc}}$	0.143 ± 0.008	0.143 ± 0.008	0.143 ± 0.008
ε	0.0660 ± 0.0099	ε	0.0481 ± 0.0055	0.0343 ± 0.0042	0.0117 ± 0.0019

Table 3. Summary of the efficiencies for both the diphoton and the dielectron analyses. The quoted uncertainties are systematic.

6 Backgrounds

For diphoton production, the following background processes are considered: non-exclusive events, exclusive e^+e^- production, cosmic-ray events, and exclusive $\pi^0\pi^0$ production.

The non-exclusive background consists of non-exclusive events with particles passing through the cracks between the calorimeter elements, or with energy deposits below the noise thresholds, so that they appear exclusive. In order to estimate the amount of this background, the two-dimensional distribution of the numbers of additional tracks and additional towers for diphoton events, with all selection criteria applied except the exclusivity requirements, is fitted and then extrapolated to the signal region, i.e. the bin with no additional tracks or towers. This yields a non-exclusive background of 1.68 ± 0.40 events.

Exclusive e^+e^- events can be misidentified as diphoton events if neither electron track is reconstructed or both electrons undergo hard bremsstrahlung. This contribution is estimated by assuming a single-electron misidentification probability of 8%, as determined from simulated exclusive e^+e^- events, for the 17 e^+e^- candidates found in the data (table 1), which results in a background of 0.11 ± 0.03 events.

The background from cosmic-ray events is evaluated by measuring the density of cosmic-ray events outside the signal region described in section 4.2 and then extrapolating that density into the signal region. This results in a probability of 0.46% that a diphoton candidate is due to a cosmic ray.

Exclusive $\pi^0\pi^0$ production ($\pi^0 \to \gamma\gamma$) [42] can be a background to diphoton production if the two pions are both misidentified as photons. A simulation carried out with the SUPERCHIC 1.41 event generator [43] is used to calculate the cross section and derive the selection efficiency. Fewer than 10^{-4} exclusive diphoton candidates are expected to originate from $\pi^0\pi^0$ events. Therefore, the background from exclusive $\pi^0\pi^0$ production, even with conservative theoretical uncertainties, is negligible. The background from exclusive pair production of other mesons, e.g. $pp \to p+\eta\eta+p$ ($\eta \to \gamma\gamma$), is also estimated to be negligible because of the low production cross sections (which are similar to that of exclusive $\pi^0\pi^0$ production). Exclusive $\gamma\pi^0$ or $\gamma\eta$ production is forbidden by C-parity conservation. Exclusive single-meson production, e.g. $pp \to p+\eta+p \to p+\gamma\gamma+p$, is completely removed

Diphoton analysis		Dielectron analysis	
Background	Events	Background	Events
Non-exclusive	1.68 ± 0.40	Non-exclusive	0.80 ± 0.28
Exclusive e^+e^-	0.11 ± 0.03	Exclusive $\Upsilon(1S,2S,3S) \to e^+e^-$	Negligible
Cosmic ray	Negligible	Cosmic ray	0.05 ± 0.01
Exclusive $\pi^0\pi^0$	Negligible	Exclusive $\pi^+\pi^-$	Negligible
Total	1.79 ± 0.40	Total	0.85 ± 0.28

Table 4. Background event yields expected for both the diphoton and the dielectron analyses. The quoted uncertainties are statistical.

by the requirement $E_{\mathrm{T}}(\gamma) > 5.5\,\mathrm{GeV}$, complemented by $\Delta\phi(\gamma\gamma) > 2.5\,\mathrm{rad}$, which selects events with $M(\gamma\gamma) \gtrsim 11\,\mathrm{GeV}$.

For dielectron production, the following background processes are considered: non-exclusive events, exclusive Υ production, cosmic-ray events, and exclusive $\pi^+\pi^-$ production.

The non-exclusive background is estimated by using the distribution of the numbers of additional tracks and additional towers for dielectron events with all selection criteria applied except the exclusivity requirements, after subtracting the contributions from both exclusive and semi-exclusive e^+e^- production expected from the simulation. This background is estimated to be of 0.80 ± 0.28 events.

The background from exclusive Υ production via $\gamma\mathbb{P}$ fusion ($\gamma\mathbb{P} \to \Upsilon(1S,2S,3S) \to e^+e^-$) [2] is completely removed by the $E_{\mathrm{T}} > 5.5\,\mathrm{GeV}$ requirement on the electrons, which corresponds to $M(e^+e^-) \gtrsim 11\,\mathrm{GeV}$, well above the $\Upsilon(3S)$ mass ($10.36\,\mathrm{GeV}$) even taking into account the e^+e^- mass resolution of $\sim 150\,\mathrm{MeV}$.

The cosmic-ray background contamination, estimated with the same method as for the diphoton analysis, is 0.3%, i.e. 0.05 ± 0.01 events.

Exclusive $\pi^+\pi^-$ production via $\mathbb{P}\mathbb{P}$ exchange [42] can be a background to e^+e^- production if the two pions are both misidentified as electrons. The cross section, calculated with SUPERCHIC, is less than 0.1% of that for exclusive e^+e^- production, which translates into a negligible background. This is consistent with the fact that no additional candidates are found, after removing the requirement of no HCAL energy behind the electron shower (a high-energy deposit in the HCAL is the signature of a pion).

A summary of the background processes for both the diphoton and the dielectron analyses is listed in table 4. The non-exclusive background is the largest contribution in both analyses.

7   Results

No diphoton events survive the selection criteria. An upper limit on the production cross section is set employing a CL_s approach [44, 45], taking into account the integrated lu-
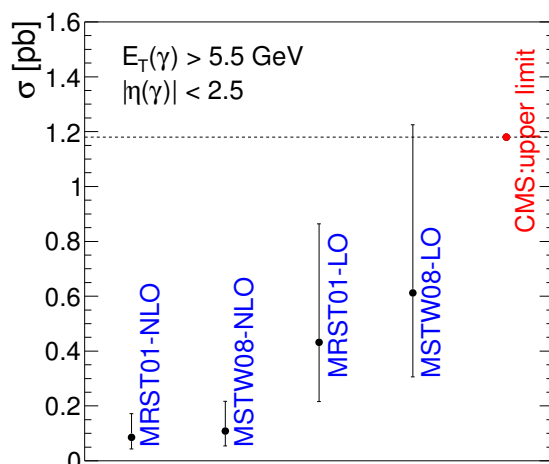
Figure 4. Comparison of the upper limit (at 95% CL) derived with the present data and four theoretical predictions. The upper limit is on the sum of the exclusive and semi-exclusive $\gamma\gamma$ production cross sections (where it is required that no particles from the proton dissociation have $|\eta| < 5.2$), while the theoretical predictions are for exclusive $\gamma\gamma$ production only. If the contributions from semi-exclusive production are included, the predictions increase by a factor of ~ 2 [49].

minosity, the selection efficiency, the background contributions, and their uncertainties. A log-normal prior is used for the integration over the nuisance parameters. This gives an upper limit on the production cross section at 95% confidence level (CL):

$$\sigma(E_{\mathrm{T}}(\gamma) > 5.5\,\mathrm{GeV},\ |\eta(\gamma)| < 2.5) < 1.18\,\mathrm{pb}.$$

The upper limit is on the sum of the exclusive (el-el) and semi-exclusive (inel-el and inel-inel) $\gamma\gamma$ production cross sections, with no particles from the proton dissociation having $|\eta| < 5.2$ for the semi-exclusive case. Figure 4 shows the comparison between the present upper limit and the predicted cross sections (el-el only) calculated with the ExHuME generator. Two different PDF sets, MRST01 [46, 47] and MSTW08 [48], from both leading-order (LO) and next-to-leading-order (NLO) fits, are considered. The difference between LO and NLO predictions reflects mostly the difference in the low-x gluon density. The uncertainties in these theoretical predictions (in addition to those due to the PDFs) are estimated to be a factor of about 2 [49], as shown in figure 4. The upper limit measured in this analysis is an order of magnitude above the predicted cross sections with NLO PDFs, while it provides some constraint on the predictions with LO PDFs. If the MSTW08-LO PDF is used, the probability of finding no candidate in the present data is less than 23%. The semi-exclusive $\gamma\gamma$ production cross section has larger theoretical uncertainties, but is expected to be of magnitude similar to that of the fully exclusive process [49].

Seventeen exclusive or semi-exclusive e^+e^- candidates are observed, with an expected background of 0.85 ± 0.28 (stat.) events, consistent with the theoretical prediction for the combined el-el, inel-el and inel-inel e^+e^- yield of 16.3 ± 1.3 (syst.) events (table 5). Figure 5 shows the comparison of the measured and simulated invariant-mass and p_{T} distributions of the e^+e^- pairs, while figure 6 shows that for the Δp_{T} and $\Delta\phi$ distributions. Both the

Process	$\mathcal{L}$ (pb^{-1})	σ (pb)	ε	Yield (events)
el-el		3.74	0.0481 ± 0.0055	6.51 ± 0.79 (syst.)
inel-el	36.2 ± 1.4	6.68	0.0343 ± 0.0042	8.29 ± 1.07 (syst.)
inel-inel		3.52	0.0117 ± 0.0019	1.49 ± 0.25 (syst.)
Total				16.3 ± 1.3 (syst.)

Table 5. Predicted e^+e^- yields for both exclusive and semi-exclusive e^+e^- production. The relative uncertainty of the integrated luminosity $\mathcal{L}$ is 4% [50]. The production cross sections σ are calculated with the LPAIR generator.
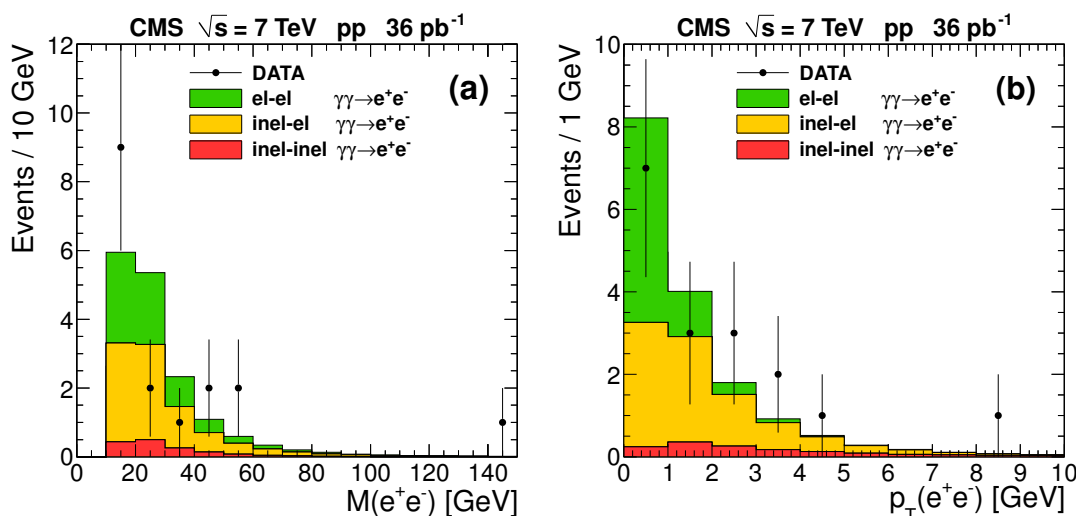
Figure 5. Distributions of (a) the invariant mass and (b) the transverse momentum of the e^+e^- pairs, compared to the LPAIR predictions (histograms) for the three processes contributing to exclusive and semi-exclusive $\gamma\gamma \rightarrow e^+e^-$ production, passed through the full detector simulation and reconstruction. The simulation is normalized to the integrated luminosity of the data sample (36 pb^{-1}), and does not include the estimated 0.85 ± 0.28 background events.

yield and the kinematic distributions are consistent with the assumption of exclusive and semi-exclusive e^+e^- production via the $\gamma\gamma \rightarrow e^+e^-$ process, which validates the analysis technique, notably the exclusivity selection.

8 Summary

A search for exclusive or semi-exclusive $\gamma\gamma$ production and the observation of exclusive and semi-exclusive e^+e^- production have been presented, based on a sample of pp collisions at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 36 pb^{-1}. Exclusive $\gamma\gamma$ production helps improve the understanding of diffraction and provides a test of the theoretical predictions for exclusive Higgs boson production. Exclusive e^+e^- production is dominantly a QED process and provides a means to check the selection procedure for other exclusive processes. No diphoton events satisfy the selection criteria. An upper limit on the cross
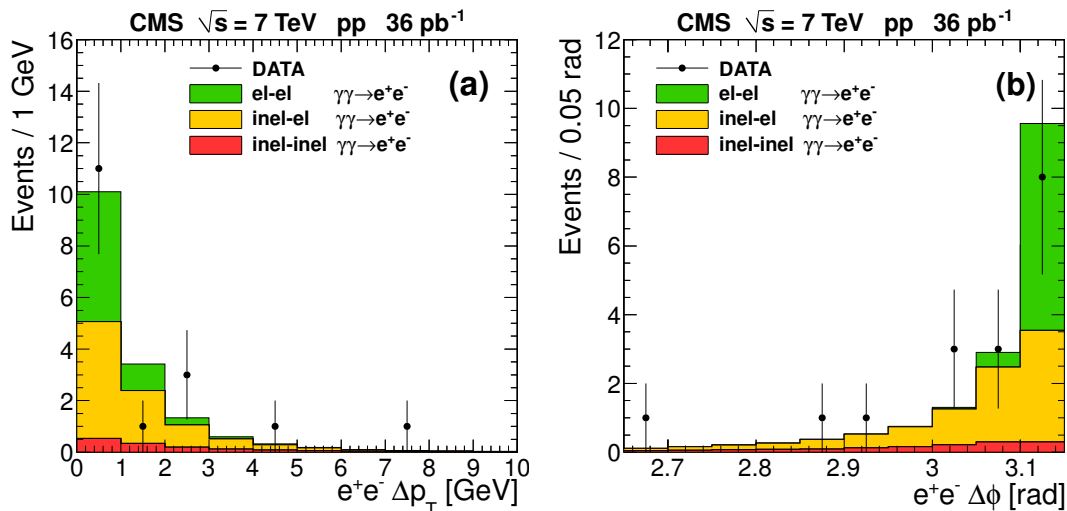
Figure 6. Distributions of the difference of (a) the transverse momentum and (b) the azimuthal angle of the e^+e^- pairs, compared to the LPAIR predictions (histograms) for the three processes contributing to exclusive and semi-exclusive $\gamma\gamma \to e^+e^-$ production, passed through the full detector simulation and reconstruction. The simulation is normalized to the integrated luminosity of the data sample $(36\,\text{pb}^{-1})$, and does not include the estimated 0.85 ± 0.28 background events.

section for the exclusive reaction $pp \to p + \gamma\gamma + p$ and the corresponding semi-exclusive processes (in which either or both protons diffractively dissociate and no particles from the proton dissociation have $|\eta| < 5.2$), with $E_T(\gamma) > 5.5\,\text{GeV}$ and $|\eta(\gamma)| < 2.5$, is set at 1.18 pb at 95% confidence level. Using a similar technique, 17 exclusive or semi-exclusive e^+e^- candidates are observed, with an expected background of 0.85 ± 0.28 (stat.) events, consistent with the LPAIR prediction of 16.3 ± 1.3 (syst.) events. Both the number of candidates and the kinematic distributions are in agreement with the expectation for exclusive and semi-exclusive e^+e^- production via the $\gamma\gamma \to e^+e^-$ process.

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