PROCEEDINGS OF SCIENCE

Measurement of exclusive $\gamma\gamma \to \ell\ell$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

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Measurement of the exclusive cross section for the process $\gamma\gamma \to \ell^+\ell^-$ $(\ell = e, \mu)$ in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC is presented. The cross section in the electron channel is determined to be $\sigma^{\text{excl}}_{\gamma\gamma\to e^+e^-} = 0.428 \pm 0.035\,(\text{stat}) \pm 0.018\,(\text{sys})$ pb in the phase space region with the invariant mass of the electron pair greater than 24 GeV and in which both electrons have transverse momenta $p_T > 12$ GeV and pseudorapidity $|\eta| < 2.4$. For muon pairs with invariant mass greater than 20 GeV and both muons having $p_T > 10$ GeV and pseudorapidity $|\eta| < 2.4$, the cross section is determined to be $\sigma^{\text{excl}}_{\gamma\gamma\to\mu^+\mu^-} = 0.628 \pm 0.032\,(\text{stat}) \pm 0.021\,(\text{sys})$ pb. The measured cross sections are consistent with QED predictions only if the proton absorptive effects due to finite size of the proton are taken into account.

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1. Introduction

The exclusive two-photon production of lepton pairs in proton-proton collisions can be reliably calculated within the framework of quantum electrodynamics (QED) [1, 2] with the uncertainty of 2% associated with the proton elastic form-factor. The schematic view of the process is shown in the left panel of Fig. 1. Unless both outgoing protons are detected, the semi-exclusive two-photon production, involving single or double proton dissociation (middle and right panels of Fig. 1), becomes an irreducible background that has to be subtracted.

Calculations of the cross section for exclusive two-photon production of lepton pairs in proton-proton collisions are based on the Equivalent Photon Approximation (EPA) [2], and the appropriate formula reads:

$$\sigma^{\mathrm{EPA}}_{pp(\gamma\gamma)\to pp\ell^+\ell^-} = \iint P(x_1)P(x_2)\sigma_{\gamma\gamma\to\ell^+\ell^-}(m^2_{\ell^+\ell^-})dx_1dx_2$$

where $P(x_1)$ and $P(x_2)$ are the equivalent photon spectra for protons, x_1 and x_2 are the fractions of the proton energy carried out by the emitted photons and $m_{\ell\ell}$ is the invariant mass of the lepton pair. In the kinematic region under study, the photons are quasi-real ($Q^2 \ll m^2_{\ell\ell}$), and the EPA gives the same results as full leading order (LO) QED calculations.

Such photon-induced reactions, in particular exclusive di-lepton production, require significant corrections due to proton absorptive effects. These effects are mainly related to pp strong-interaction exchanges that accompany the two-photon interaction and that lead to the production of additional hadrons in the final state. Recent phenomenological studies suggest that the exclusive $\gamma\gamma \to \ell\ell$ cross-section is suppressed by a factor that depends on the mass and rapidity of the system produced [5]. For the kinematic range relevant for the measurement presented here the suppression factor is about 20%. This factor includes both the strong pp absorptive correction (8% suppression) and the photon-proton (γp) coherence condition ($b_{\gamma p} > r_p$, where $b_{\gamma p}$ is the γp impact parameter and r_p is the transverse size of the proton).

In the following the recent measurement of the two-photon production of di-electron and di-muon pairs is presented. For more details the reader is refered to the original publication by the ATLAS Collaboration [3]. A similar measurement has been also performed by the CMS Collaboration [4].

The data are corrected for detector inefficiencies and possible background contribution using Monte Carlo samples. The signal event samples for exclusive $\gamma\gamma \to \ell\ell$ production are generated using the HERWIG++ 2.6.3 event generator, which implements the EPA formalism in pp collisions. The dominant background, photon-induced single-dissociative dilepton production, is simulated

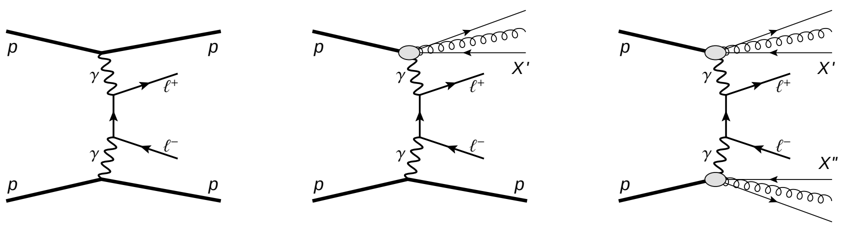

Figure 1: Schematic diagrams for (left) exclusive, (middle) single-proton dissociative and (right) double-proton dissociative two-photon production of lepton pairs in proton-proton collisions. The symbols X' and X'' in the final states indicate dissociation of the proton into a low-mass system.

using LPAIR 4.0 with the Brasse and Suri-Yennie structure functions for proton dissociation. The HERWIG++ and LPAIR generators do not include any corrections to account for proton absorptive effects. For double-dissociative reactions, PYTHIA 8.175 is used with the NNPDF2.3QED parton distribution functions (PDF). The absorptive effects in double-dissociative MC events are taken into account using the default multi-parton interactions model in PYTHIA 8. For estimation of Drell-Yan, $Z/\gamma \to \ell\ell$, backgrounds the POWHEG 1.0 generator is used. The other sources of background turned out to be negligible.

2. Event selection

The measurement is based on proton-proton data collected by the ATLAS experiment [6] in 2011 at the centre-of-mass energy of $\sqrt{s} = 7$ TeV and corresponds to the luminosity of 4.6 fb^{-1}.

Exclusive dilepton events have a clean signature that helps discriminate them from background: there are only two identified muons or electrons, without any other activity in the central detectors, and the leptons are back-to-back in the azimuthal angle.

Events in the electron channel were selected online by requiring a single-electron or di-electron trigger. For the single-electron trigger, the transverse momentum threshold was set to 22 GeV. The di-electron trigger required a minimum transverse momentum of 12 GeV for each electron candidate. Electron candidates are reconstructed from energy deposits in the calorimeter matched to Inner Detector (ID) tracks. The electrons are required to have a transverse momentum $p_{\mathrm{T}}^{e} >$ 12 GeV and pseudorapidity $|\eta^{e}| < 2.4$ with the calorimeter barrel/end-cap transition region $1.37 < |\eta^{e}| < 1.52$ excluded. Electron candidates are required to meet so called “medium" identification criteria based on shower shape and track-quality variables [7].

Events in the muon channel were selected online by a single-muon or di-muon trigger, with a transverse momentum threshold of 18 GeV or 10 GeV, respectively. Muon candidates are identified by matching complete tracks in the Muon Spectrometer to tracks in the ID [8], and are required to have $p_{\mathrm{T}}^{\mu} > 10$ GeV and $|\eta^{\mu}| < 2.4$. Only isolated muons are selected by requiring the scalar sum of the p_{T} of the tracks with $p_{\mathrm{T}} > 1$ GeV in a $\Delta R = 0.2$ cone in (η, ϕ) around the muon to be less than 10% of the muon p_{T}.

Di-lepton events are selected by requiring two oppositely charged same-flavour leptons with an invariant mass $m_{e^+e^-} > 24$ GeV for the electron channel and $m_{\mu^+\mu^-} > 20$ GeV for the muon channel. After these preselection requirements 1.57×10^{6} di-electron and 2.42×10^{6} di-muon candidate events are found in the data.

In order to select exclusive $\gamma\gamma \to \ell\ell$ candidates, a veto on additional charged-particle track activity is applied. This exclusivity veto requires that no additional charged-particle tracks with $p_{\mathrm{T}} > 400$ MeV are associated with the dilepton vertex, and that no additional tracks or vertices are found within a 3 mm longitudinal isolation distance, $\Delta_{\mathrm{vtx}}^{\mathrm{iso}}$, from the dilepton vertex. These conditions are primarily motivated by the rejection of the Z/γ^{*} and multi-jet events, which typically have many tracks originating from the same vertex. The charged-particle multiplicity distribution in Z/γ^{*} MC events is reweighted to match the UE observed in data, following the same procedure as in Ref. [9]. Uncorrected Z/γ^{*} MC models overestimate the charged-particle multiplicity distributions observed in data by 50% for low-multiplicity events. In order to estimate the relevant weight, the events in the window of the Z boson region, defined as 70 GeV $< m_{\ell\ell} <$ 105 GeV, are used. This

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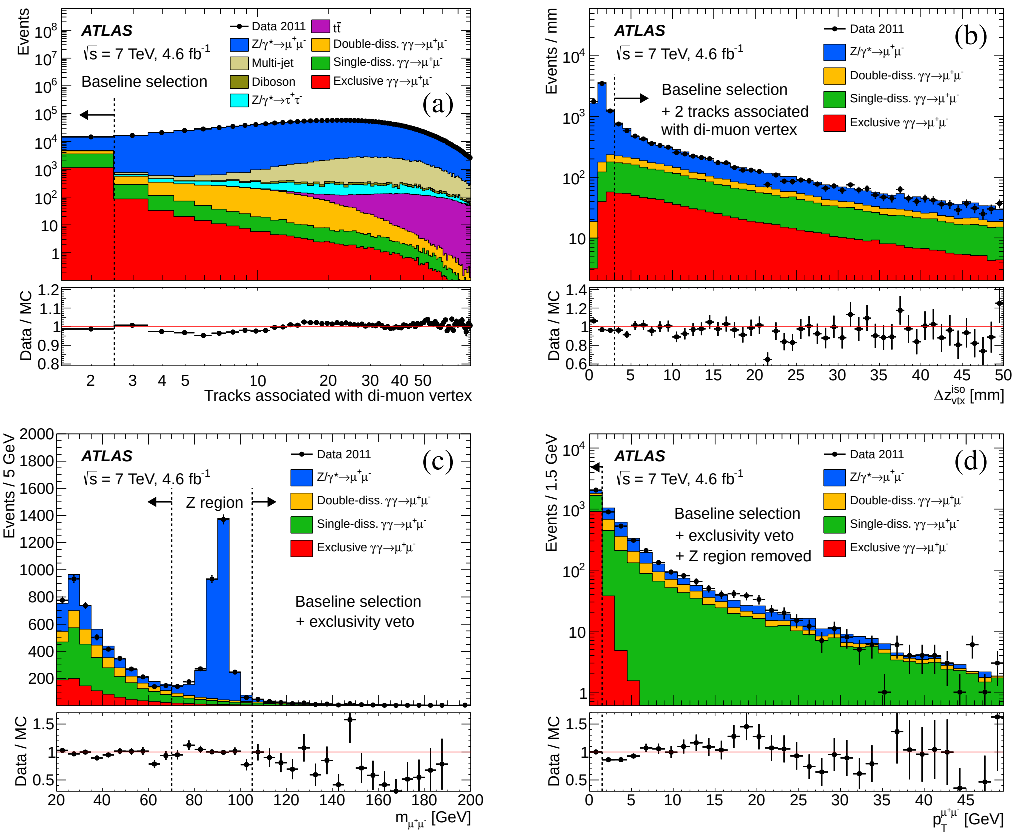

Figure 2: Subsequent requirements in the exclusive di-muon selection [3]. (a) Number of tracks associated with the di-muon vertex, (b) longitudinal distance between the di-muon vertex and any other tracks or vertices, (c) di-muon invariant mass, and (d) transverse momentum of the di-muon system, after application of subsequent selection criteria (indicated by the dashed lines). Data are shown as points with statistical error bars, while the histograms represent the expected signal and background contributions, corrected using the scale factors described in the text.

region is expected to include a large DY component. The correction procedure also accounts for the effect of tracks originating from pile-up and ID track reconstruction ineffciency. The requirement of no additional tracks associated with the dilepton vertex completely removes multi-jet, $t\bar{t}$ and diboson backgrounds. The influence of the subsequent requirements discussed above on the di-muon sample is presented in Fig. 2.

After the final exclusive event selection, there is still a significant contamination from DY, single- and double-dissociative processes. Scaling factors for signal and background processes are estimated by a binned maximum-likelihood fit of the sum of the simulated distributions contained in the MC templates for the various processes, to the measured dilepton acoplanarity $(1 - |\Delta\phi_{\ell^+\ell^-}|/\pi)$ distribution. The fit determines two scaling factors, defined as the ratios of the number of observed to the number of expected events based on the MC predictions, for the exclusive (R^{excl}) and single-dissociative ($R^{\text{s-diss}}$) templates. The double-dissociative and DY contributions are fixed to the MC predictions in the fit procedure. Contributions from other background processes are found to be negligible. Figure 3 shows the e^+e^- and $\mu^+\mu^-$ acoplanarity distributions in data overlaid with the result of the fit to the shapes from MC simulations for events satisfying all selection requirements.

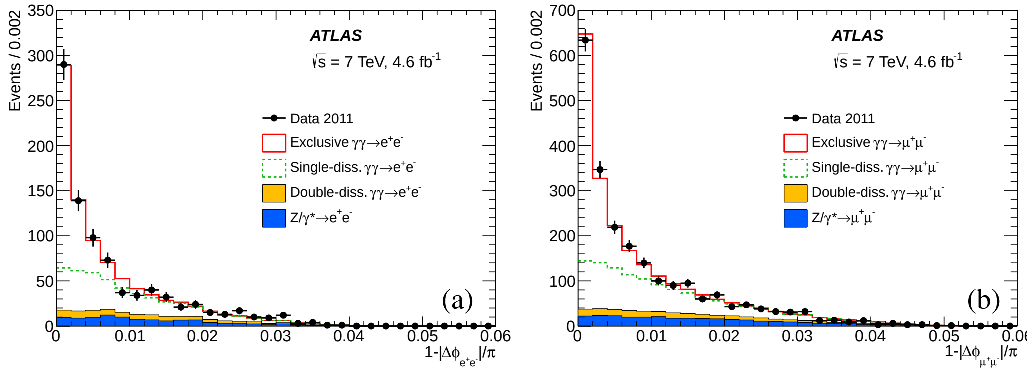

Figure 3: (a) Di-electron and (b) di-muon acoplanarity distributions for the selected sample after exclusivity requirements [3]. Data are shown as points with statistical error bars. The stacked histograms, in top-to-bottom order, represent the simulated exclusive signal, and the single-dissociative, double-dissociative and DY backgrounds. The exclusive and single-dissociative yields are determined from the fit described in the text.

3. Results

The exclusive $\gamma\gamma \to \ell\ell$ cross sections are measured in the fiducial regions defined as: $p_T^e >$ 12 GeV, $|\eta^e| < 2.4$, $m_{e^+e^-} >$ 24 GeV and $p_T^\mu >$ 10 GeV, $|\eta^\mu| < 2.4$, $m_{\mu^+\mu^-} >$ 20 GeV, for the electron and muon channels, respectively. The fiducial cross-sections are given by the product of the measured signal scale factors by the exclusive cross-sections predicted, in the fiducial region considered, by the EPA calculations based on HERWIG++:

$$\sigma^{\text{excl}}_{\gamma\gamma\to\ell^+\ell^-} = R^{\text{excl}}_{\gamma\gamma\to\ell^+\ell^-} \cdot \sigma^{\text{EPA}}_{\gamma\gamma\to\ell^+\ell^-}$$

The scale factors obtained from the fits to acoplanarity distributions, for the electron and muon channels read (for completeness also the values of $R^{\text{s-diss}}$ are given):

$$R^{\text{excl}}_{\gamma\gamma\to e^+e^-} = 0.863 \pm 0.070\,(\text{stat}) \pm 0.037\,(\text{sys}) \qquad R^{\text{s-diss}}_{\gamma\gamma\to e^+e^-} = 0.759 \pm 0.080\,(\text{stat})$$
$$R^{\text{excl}}_{\gamma\gamma\to\mu^+\mu^-} = 0.791 \pm 0.041\,(\text{stat}) \pm 0.026\,(\text{sys}) \qquad R^{\text{s-diss}}_{\gamma\gamma\to\mu^+\mu^-} = 0.762 \pm 0.049\,(\text{stat})$$

Several sources of systematic uncertainties have been considered (for details see [3]). The total systematic uncertainties are 4.3% and 3.3% for the electron and muon channels, respectively. The resulting measured fiducial cross sections read:

$$\sigma^{\text{excl}}_{\gamma\gamma\to e^+e^-} = 0.428 \pm 0.035\,(\text{stat}) \pm 0.018\,(\text{sys})\ \text{pb}$$
$$\sigma^{\text{excl}}_{\gamma\gamma\to\mu^+\mu^-} = 0.628 \pm 0.032\,(\text{stat}) \pm 0.021\,(\text{sys})\ \text{pb}$$

The ratios of measured to EPA predicted cross sections for the electron and muon channels are shown in Fig. 4 and are consistent with the CMS measurement [4]. However there is clear suppression of the exclusive production mechanism in data with respect to the EPA prediction. The observed cross-sections are about 20% below the nominal EPA prediction, and consistent with the suppression expected due to proton absorption contributions [5]. The MC predictions for the shapes of the dilepton kinematic distributions, including both the exclusive signal and the background dominated by two-photon production of lepton pairs with single proton dissociation, are

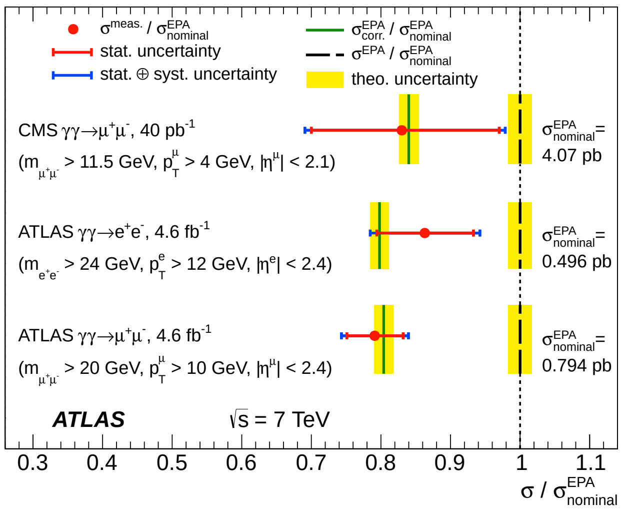

Figure 4: Comparison of the ratios of measured (red points) and predicted (solid green lines) cross-sections to the uncorrected EPA calculations (black dashed lines) [3]. Results for the muon and electron channels are also compared with a similar CMS measurement [4]. The inner red error bar represents the statistical error, and the blue bar represents the total error on each measurement. The yellow band represents the theoretical uncertainty of 1.8% (1.7%) on the predicted (uncorrected EPA) cross-sections, assumed to be uniform in the phase space of the measurements.

also found to be in good agreement with the data. In summary, with its improved statistical precision compared to previous measurements, this analysis provides a better understanding of the physics of two-photon interactions at hadron colliders.

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