

Exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ production in proton-proton collisions at $\sqrt{s} = 7$ TeV

The CMS collaboration

ABSTRACT: A measurement of the exclusive two-photon production of muon pairs in proton-proton collisions at $\sqrt{s} = 7$ TeV, $pp \rightarrow p\mu^+\mu^-p$, is reported using data corresponding to an integrated luminosity of 40 pb^{-1} . For muon pairs with invariant mass greater than 11.5 GeV, transverse momentum $p_T(\mu) > 4 \text{ GeV}$ and pseudorapidity $|\eta(\mu)| < 2.1$, a fit to the dimuon $p_T(\mu^+\mu^-)$ distribution results in a measured cross section of $\sigma(p \rightarrow p\mu^+\mu^-p) = 3.38_{-0.55}^{+0.58}$ (stat.) ± 0.16 (syst.) ± 0.14 (lumi.) pb, consistent with the theoretical prediction evaluated with the event generator LPAIR. The ratio to the predicted cross section is $0.83_{-0.13}^{+0.14}$ (stat.) ± 0.04 (syst.) ± 0.03 (lumi.). The characteristic distributions of the muon pairs produced via $\gamma\gamma$ fusion, such as the muon acoplanarity, the muon pair invariant mass and transverse momentum agree with those from the theory.

KEYWORDS: Hadron-Hadron Scattering

Contents

1	Introduction	1
2	The CMS detector	3
3	Simulated samples	3
4	Event selection	4
4.1	Trigger and muon reconstruction	4
4.2	Vertex and track exclusivity selection	4
4.3	Muon identification	5
4.4	Kinematic selection	5
5	Signal extraction	7
5.1	Efficiency corrections	7
5.2	Maximum likelihood fit	8
6	Control plots	11
7	Systematic uncertainties and cross-checks	11
7.1	Pileup correction systematic uncertainties	12
7.2	Muon efficiencies and momentum scale	14
7.3	Vertexing and tracking efficiencies	14
7.4	Crossing angle	14
7.5	Fit stability	14
7.6	Backgrounds	15
7.7	Summary of systematic uncertainties	15
8	Results	16
9	Summary	16
	The CMS collaboration	20

1 Introduction

The exclusive two-photon production of lepton pairs may be reliably calculated within the framework of quantum electrodynamics (QED) [1] (figure 1), within uncertainties of less than 1% associated with the proton form factor [2]. Indeed, detailed theoretical studies have shown that corrections due to hadronic interactions between the elastically scattered protons are well below 1% and can be safely neglected [3]. The unique features of this

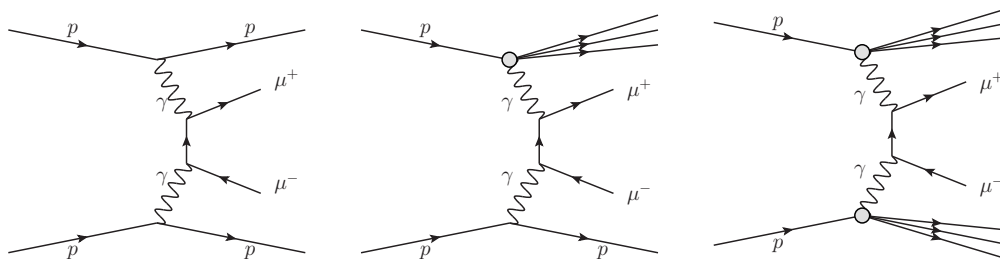


Figure 1. Schematic diagrams for the exclusive and semi-exclusive two-photon production of muon pairs in pp collisions for the elastic (left), single dissociative (center), and double dissociative (right) cases. The three lines in the final state of the center and right plots indicate dissociation of the proton into a low-mass system N .

process, like the extremely small pair transverse momentum and acoplanarity (defined as $1 - |\Delta\phi(\mu^+\mu^-)/\pi|$), stem from the very small virtualities of the exchanged photons.

At the Tevatron, the exclusive two-photon production of electron [4, 5] and muon [5, 6] pairs in $p\bar{p}$ collisions has been measured with the CDF detector. Observations have been made of QED signals, leading to measurements of exclusive charmonium photoproduction [6] and searches for anomalous high-mass exclusive dilepton production [5]. However, all such measurements have very limited numbers of selected events because the data samples were restricted to single interaction bunch crossings. The higher energies and increased luminosity available at the Large Hadron Collider (LHC) will allow significant improvements in these measurements, if this limitation can be avoided. As a result of the small theoretical uncertainties and characteristic kinematic distributions in $\gamma\gamma \rightarrow \mu^+\mu^-$, this process has been proposed as a candidate for a complementary absolute calibration of the luminosity of pp collisions [1–3].

Unless both outgoing protons are detected, the semi-exclusive two-photon production, involving single or double proton dissociation (figure 1, middle and right panels), becomes an irreducible background that has to be subtracted. The proton-dissociation process is less well determined theoretically, and in particular requires significant corrections due to proton rescattering. This effect occurs when there are strong-interaction exchanges between the protons, in addition to the two-photon interaction. These extra contributions may alter the kinematic distributions of the final-state muons, and may also produce additional low-momentum hadrons. As a result, the proton-dissociation process has significantly different kinematic distributions compared to the pure exclusive case, allowing an effective separation of the signal from this background.

In this paper, we report a measurement of dimuon exclusive production in pp collisions at $\sqrt{s} = 7$ TeV for the invariant mass of the pair above 11.5 GeV, with each muon having transverse momentum $p_T(\mu) > 4$ GeV and pseudorapidity $|\eta(\mu)| < 2.1$ (where η is defined as $-\ln(\tan(\theta/2))$). This measurement is based on data collected by the Compact Muon Solenoid (CMS) experiment during the 2010 LHC run, including beam collisions with multiple interactions in the same bunch crossing (event pileup), and corresponding to an integrated luminosity of 40 pb^{-1} with a relative uncertainty of 4% [7].

The paper is organized as follows. In section 2, a brief description of the CMS detector is provided. Section 3 describes the data and samples of simulated events used in the analysis. Section 4 documents the criteria used to select events, and section 5 the method used to extract the signal yield from the data. The systematic uncertainties and cross-checks performed are discussed in section 6, while section 7 contains plots comparing the selected events in data and simulation. Finally, the results of the measurement are given in section 8 and summarized in section 9.

2 The CMS detector

A detailed description of the CMS experiment can be found elsewhere [8]. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass/scintillator hadronic calorimeter. Muons are measured in gaseous detectors embedded in the iron return yoke. Besides the barrel and endcap detectors, CMS has extensive forward calorimetry. CMS uses a right-handed coordinate system, with the origin at the nominal collision 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 anticlockwise-beam direction. The azimuthal angle ϕ is measured in the x - y plane. Muons are measured in the window $|\eta| < 2.4$, with detection planes made using three systems: drift tubes, cathode strip chambers, and resistive plate chambers. Thanks to the strong magnetic field, 3.8 T, and to the high granularity of the silicon tracker (three layers consisting of 66 million $100 \times 150 \mu\text{m}^2$ pixels followed by ten microstrip layers, with strips of pitch between 80 and $180 \mu\text{m}$), the p_{T} of the muons matched to silicon tracks is measured with a resolution better than $\sim 1.5\%$, for p_{T} less than 100 GeV. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select (in less than $1 \mu\text{s}$) the most interesting events. The High Level Trigger processor farm further decreases the event rate from 50-100 kHz to a few hundred Hz, before data storage.

3 Simulated samples

The LPAIR 4.0 event generator [9, 10] is used to produce simulated samples of two-photon production of muon pairs. The generator uses full leading-order QED matrix elements, and the cross sections for the exclusive events depend on the proton electromagnetic form-factors to account for the distribution of charge within the proton. For proton dissociation, the cross sections depend on the proton structure function. In order to simulate the fragmentation of the dissociated proton into a low-mass system N , the LUND model shower routine [11] implemented in the JETSET software [12] is used with two different structure functions. For masses of the dissociating system $m_N < 2 \text{ GeV}$ and photon virtualities $Q^2 < 5 \text{ GeV}^2$, the Brasse “cluster” fragmentation is chosen [13], while for the other cases the Suri-Yenni “string” fragmentation is applied [14]. In the first case, the low-mass system N mostly decays to a Δ^+ or Δ^{++} resonance, which results in low-multiplicity states. In

the second case, the high-mass system usually decays to a variety of resonances (Δ , ρ , Ω , η , K), which produce a large number of forward protons, pions, neutrons and photons. No corrections are applied to account for rescattering effects. In general, these effects are expected to increase with the transverse momentum of the muon pair, modifying the slope of the $p_T^2(\mu^+\mu^-)$ distribution [3].

The inclusive Drell-Yan (DY) and quantum chromodynamic (QCD) dimuon backgrounds are simulated with PYTHIA v. 6.422 [15], using the Z2 underlying event tune [16]. All these samples are then passed through the full GEANT4 detector simulation [17] in order to determine the signal and background efficiencies after all selection criteria are applied.

4 Event selection

The analysis uses a sample of pp collisions at $\sqrt{s} = 7$ TeV, collected during 2010 at the LHC and corresponding to an integrated luminosity of 40 pb^{-1} . The sample includes 36 pb^{-1} of data passing the standard CMS quality criteria for all detector subsystems, and 4 pb^{-1} in which the quality criteria are satisfied for the tracking and muon systems used in the analysis. From the sample of triggered events, the presence of two reconstructed muons is required. Then the exclusivity selection is performed to keep only events with a vertex having no tracks other than those from the two muons. Finally, the signal muons are required to satisfy identification criteria, and kinematic constraints are imposed using their four-momentum. All selection steps are described in the following sections.

4.1 Trigger and muon reconstruction

Events are selected online by triggers requiring the presence of two muons with a minimum p_T of 3 GeV. No requirement on the charge of the muons is applied at the trigger level. Muons are reconstructed offline by combining information from the muon chambers with that on charged-particle tracks reconstructed in the silicon tracker [18], and events with a pair of oppositely charged muons are selected.

4.2 Vertex and track exclusivity selection

With single interactions, the exclusive signal is characterized by the presence of two muons, no additional tracks, and no activity above the noise threshold in the calorimeters. The presence of additional interactions in the same bunch crossing will spoil this signature by producing additional tracks and energy deposits in the calorimeters. In the 2010 data, less than 20% of the total luminosity was estimated to have been collected from bunch crossings where only a single interaction took place, leading to a significant decrease in signal efficiency if the conditions of no extra tracks or calorimeter energy are required.

The selection of exclusive events is therefore applied using the pixel and silicon tracker only, since the primary vertex reconstruction [19, 20] allows discrimination between different interactions within the same bunch crossing. The selection requires a valid vertex, reconstructed using an adaptive vertex fit to charged-particle tracks clustered in z [20, 21], with exactly two muons and no other associated tracks, and vertex fit probability greater

than 0.1%. The dimuon vertex is further required to have coordinates consistent with a collision in CMS, with a longitudinal displacement of less than 24 cm and a transverse displacement of less than 0.1 cm.

In order to reduce the background from inclusive DY and QCD dimuon production, which typically have many tracks originating from the same vertex as a prompt muon pair, the dimuon vertex is required to be separated in three dimensions by more than 2 mm from any additional tracks in the event. This value is selected to optimize the signal efficiency and background rejection found in events triggered only by the presence of colliding bunches (“zero-bias” events), and in DY Monte Carlo simulation. For the zero-bias data, this is accomplished by introducing an artificial additional dimuon vertex into each event as a proxy for an exclusive dimuon interaction. Thus, in this study, beam crossings with no real vertex present are counted as “single vertex” events, and crossings with one real vertex are counted as having an additional pileup event.

The effects of the track veto on the signal efficiency and on the efficiency for misidentifying background as signal are studied as a function of the distance to the closest track for the zero-bias sample and DY background (figures 2 and 3). With no extra vertices in the zero-bias events, the efficiency approaches 100% as expected for events with no pileup. With the addition of overlap events, the efficiency decreases, falling to $\sim 60\%$ with 8 extra vertices reconstructed. In the full data sample the average number of extra vertices is 2.1, with less than 10% of events having 4 or more extra vertices. The efficiency for misidentifying the DY background as signal increases sharply for distances less than 1 mm, consistent with the resolution of the single-track impact parameter in the longitudinal direction [20].

4.3 Muon identification

Each muon of the pair is required to pass a “tight” muon selection [22]. This selection consists of requesting that the reconstructed muon have at least one hit in the pixel detector, at least 10 hits in the silicon strip tracker, and segments reconstructed in at least two muon detection planes. In addition, a global fit to the combined information from the tracker and muon systems must include at least one muon chamber hit, and have a χ^2 per degree of freedom of less than 10.

4.4 Kinematic selection

In order to minimize the systematic uncertainties related to the knowledge of the low- p_T and large- η muon efficiencies, only muons with $p_T > 4$ GeV and $|\eta| < 2.1$ are selected. The p_T and $|\eta|$ requirements retain muon pairs from exclusive photoproduction of upsilon mesons, $\gamma p \rightarrow \Upsilon p \rightarrow \mu^+ \mu^- p$. This process occurs when a photon emitted from one proton fluctuates into a $q\bar{q}$ pair, which interacts with the second proton via a color-singlet exchange. This contribution is removed by requiring that the muons have an invariant mass $m(\mu^+ \mu^-) > 11.5$ GeV.

In order to suppress further the proton dissociation background, the muon pair is required to be back-to-back in azimuthal angle ($1 - |\Delta\phi(\mu^+ \mu^-)|/\pi < 0.1$) and balanced in the

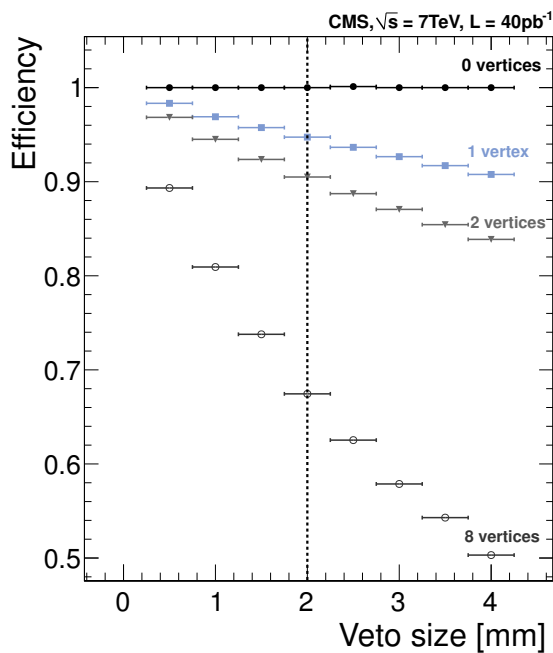


Figure 2. Efficiency of the zero extra tracks selection vs. distance to closest track computed with the artificial vertex method in zero-bias data. The points correspond to events with 0, 1, 2, and 8 real vertices in the event. Events to the right of the vertical dashed line are selected. The vertical error bars are negligible.

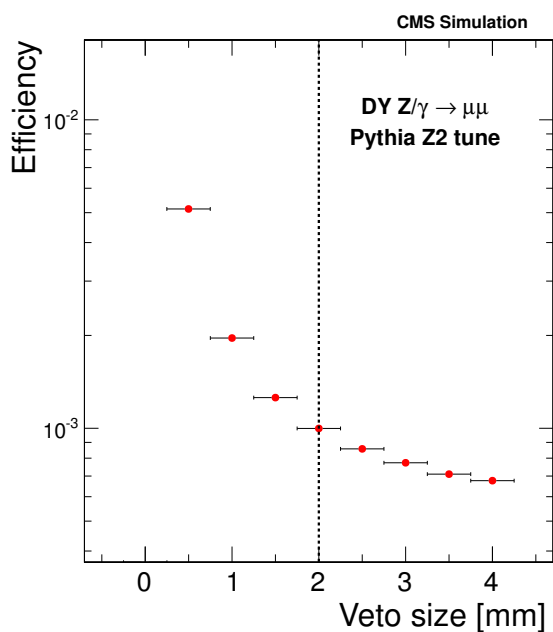


Figure 3. Efficiency of the zero extra tracks selection vs. distance to closest track computed for DY events in simulation. Events to the right of the vertical dashed line are selected. The vertical error bars are negligible.

Selection	Data	Signal	Single-pdiss.	Double-pdiss.	DY	Total
Vertex and track-exclusivity	921	247	437	197	56	937
Muon ID	724	193	336	160	53	741
$p_T > 4 \text{ GeV}$, $ \eta < 2.1$	438	132	241	106	20	499
$m(\mu^+\mu^-) > 11.5 \text{ GeV}$	270	95	187	86	13	380
$3D$ angle $< 0.95\pi$	257	87	178	83	12	361
$1 - \Delta\phi/\pi < 0.1$	203	87	126	41	8	263
$ \Delta p_T < 1.0 \text{ GeV}$	148	86	79	16	3	184

Table 1. Number of events selected in data and number of signal and background events expected from simulation at each selection step for an integrated luminosity of 40 pb^{-1} . The last column is the number of events expected from the sum of the signal, DY, and proton dissociation backgrounds in the simulation. The relative statistical uncertainty on the sum of simulated signal and background samples in each row is $\leq 0.5\%$. The contribution from exclusive resonance production of Υ or χ_b mesons is not simulated, and thus contributes only to the data column before requiring $m(\mu^+\mu^-) > 11.5 \text{ GeV}$. For entries in the line “Muon ID” and below, the simulation is corrected for effects related to event pileup, muon identification, trigger, and tracking efficiencies, as described in the text.

scalar difference in the p_T of the two muons ($|\Delta p_T(\mu^+\mu^-)| < 1.0 \text{ GeV}$). A possible contamination could arise from cosmic-ray muons, which would produce a signature similar to the exclusive $\gamma\gamma \rightarrow \mu^+\mu^-$ signal. The three-dimensional opening angle of the pair, defined as the arccosine of the normalized scalar product of the muon momentum vectors, is therefore required to be smaller than 0.95π , to reduce any contribution from cosmic-ray muons.

The effect of each step of the selection on the data and simulated signal and background samples is shown in table 1. After all selection criteria are applied, 148 events remain, where from simulation, approximately half are expected to originate from elastic production. The number of events selected in data is below the expectation from simulation, with an observed yield that is roughly 80% of the sum of simulated signal and background processes. The deficit could be caused by a lower-than-expected signal yield, or by a smaller proton-dissociation contribution than expected from simulation.

5 Signal extraction

5.1 Efficiency corrections

A correction is applied to account for the presence of extra proton-proton interactions in the same bunch crossing as a signal event. These pileup interactions will result in an inefficiency if they produce a track with a position within the nominal 2 mm veto distance around the dimuon vertex. This effect is studied in zero-bias data using the method described in section 4.2. The nominal 2 mm veto is then applied around the dimuon vertex, and the event is accepted if no tracks fall within the veto distance. The efficiency is measured as a function of the instantaneous luminosity per colliding bunch. The average efficiency is calculated based on the instantaneous luminosities to be 92.29% for the full 2010 data set, with negligible statistical uncertainty.

The trigger, tracking, and offline muon selection efficiencies are each obtained from the tag-and-probe [22, 23] method by using samples of inclusive $J/\psi \rightarrow \mu^+\mu^-$ and $Z \rightarrow \mu^+\mu^-$ events from data and Monte Carlo simulation. These control samples are triggered on one muon such that the other muon is unbiased with respect to the efficiency to be measured. For $p_T < 20$ GeV muons from J/ψ decays are used, while above 20 GeV muons from Z decays are used. The trigger and offline muon selection efficiencies are measured using J/ψ events by requiring a muon tag that, when combined with a track reconstructed using only the silicon detectors, is consistent with a J/ψ . These efficiencies are measured in bins in p_T and η , separately for the two muon charges. The tracking efficiency is measured similarly using J/ψ events by requiring a muon tag that, when combined with a muon reconstructed using only the muon systems, is consistent with a J/ψ . The tracking efficiency is then measured on the unbiased muon probe. In contrast to the trigger and muon identification efficiencies, the tracking efficiency is measured in data and Monte Carlo simulation averaged over $|\eta| < 2.1$ and $p_T > 4$ GeV, and is taken to be uncorrelated between the two tracks. The resulting ratio of efficiencies in data and simulation for the pair $(99.18 \pm 0.14)\%$ is applied as a correction to the efficiency.

The effect of the vertexing efficiency is studied both in inclusive dimuon data and signal simulation, by performing an independent selection of all muon pairs with a longitudinal separation of less than 0.5 mm. A Kalman filter [24] algorithm is then applied to estimate the best position of the dimuon vertex, without using information from any tracks other than the two muons. Among events with a valid dimuon vertex and for which no additional tracks exist within 2 mm in z , the efficiency for the default adaptive vertex fitter to reconstruct a primary vertex with only two muons attached and matching with the Kalman vertex is computed. The ratio of the vertexing efficiency in data to that in simulation is 99.97%, and therefore no correction is applied.

5.2 Maximum likelihood fit

The elastic $pp \rightarrow p\mu^+\mu^-p$ contribution is extracted by performing a binned maximum-likelihood fit to the measured $p_T(\mu^+\mu^-)$ distribution. Shapes from Monte Carlo simulation are used for the signal, single-proton dissociation, double-proton dissociation, and DY contributions, with all corrections described in section 4.4 applied.

Three parameters are determined from the fit: the elastic signal yield relative to the LPAIR prediction for an integrated luminosity of 40 pb^{-1} ($R_{\text{El-EI}}$), the single-proton dissociation yield relative to the LPAIR single-proton dissociation prediction for 40 pb^{-1} ($R_{\text{diss-EI}}$), and an exponential modification factor for the shape of the p_T distribution, characterized by the parameter a . The modification parameter is included to account for possible rescattering effects not included in the simulation, as described in section 3. Given the small number of events expected in 40 pb^{-1} , the double-proton dissociation and DY contributions cannot be treated as free parameters and are fixed from simulation to their predicted values. The contribution from exclusive $\gamma\gamma \rightarrow \tau^+\tau^-$ production is estimated to be 0.1 events from the simulation, and is neglected.

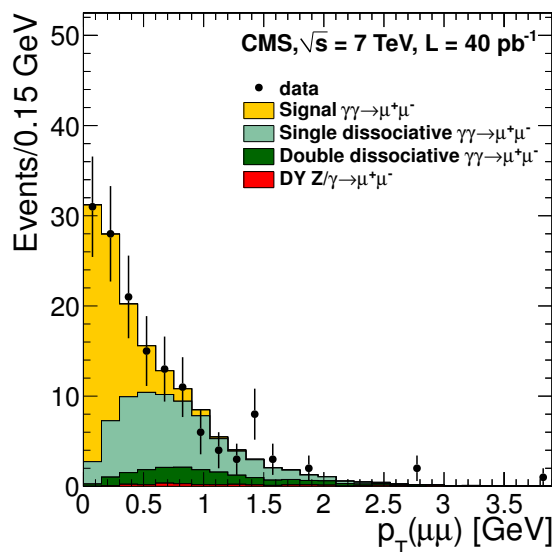


Figure 4. Distribution of $p_T(\mu^+\mu^-)$ for the selected sample. Data are shown as points with statistical error bars. The histograms represent the simulated signal (yellow), single (light green) and double (dark green) proton dissociative backgrounds, and DY (red). The yields are determined from a fit using the distributions from simulation.

The $p_T(\mu^+\mu^-)$ distribution in data is shown overlaid with the result of the fit to the shapes from Monte Carlo simulation in figure 4. The result from the best fit to the data is:

$$\begin{aligned}
 \text{data-theory signal ratio:} & & R_{\text{El-El}} &= 0.83^{+0.14}_{-0.13}, \\
 \text{single-proton dissociation yield ratio:} & & R_{\text{diss-El}} &= 0.73^{+0.16}_{-0.14}, \\
 \text{modification parameter:} & & a &= 0.04^{+0.23}_{-0.14} \text{ GeV}^{-2},
 \end{aligned}
 \tag{5.1}$$

with asymmetric statistical uncertainties computed using MINOS [25]. The corresponding value of the signal cross section is $3.38^{+0.58}_{-0.55}$ (stat.) pb. The resulting 1σ and 2σ contours projected onto each pair of fit variables are displayed in figure 5. For any values of the proton dissociation ratio and slope within the 1σ contour, the extreme values of the data-theory signal ratio are 0.64 and 1.03. The upper value of 1.03 for the signal ratio would correspond to the single-proton dissociation component having a ratio to the prediction of approximately 0.65. The best fit does not require a significant modification parameter. However, the statistical uncertainty on this parameter is chosen to play the role of a non-negligible systematic uncertainty, to take account of the neglect of the rescattering effects in the simulation.

As a cross-check, a fit to the $1-|\Delta\phi(\mu^+\mu^-)|/\pi$ distribution is performed, with the signal and single-proton dissociation yields as free parameters, and the shape of the single-proton dissociation component fixed from the simulation. The resulting value of the data-theory signal ratio is $0.81^{+0.14}_{-0.13}$, consistent with the nominal fit result.

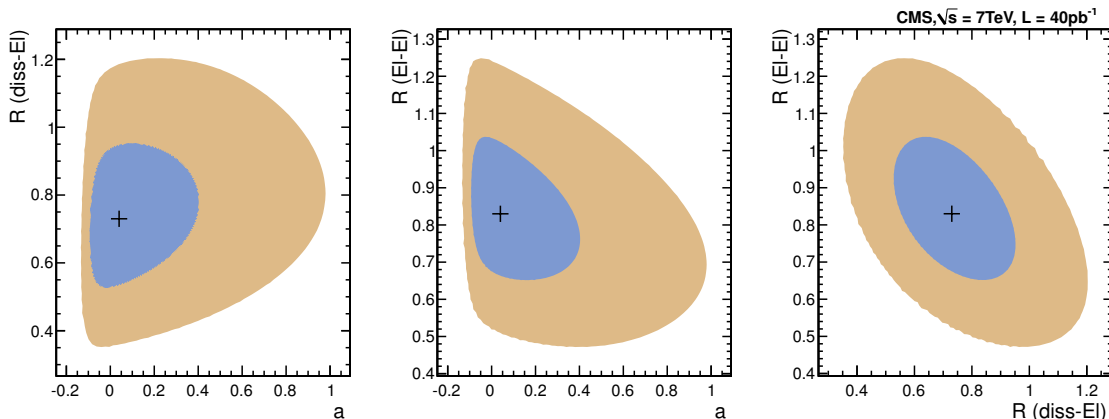


Figure 5. One and two standard-deviation contours in the plane of fitted parameters for the proton-dissociation yield ratio vs. modification parameter a (left), the data-theory signal ratio vs. modification parameter a (center), and the data-theory signal ratio vs. proton-dissociation yield ratio (right). The contours represent 39.3% and 86.5% confidence regions, where the cross indicates the best-fit point.

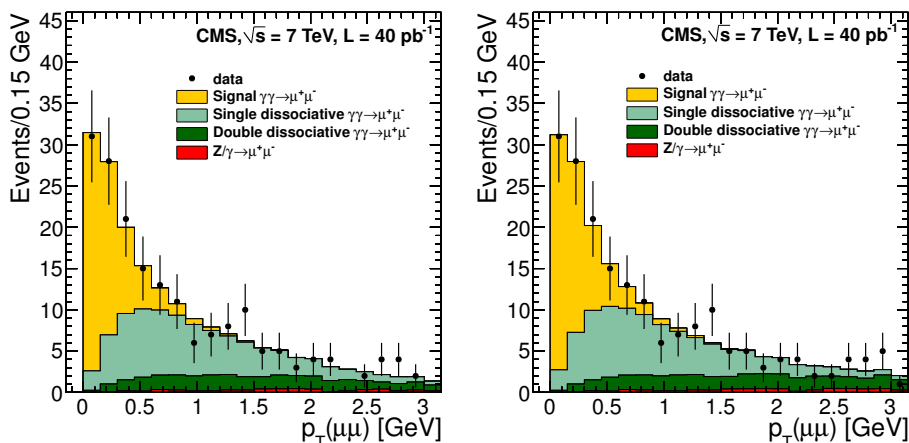


Figure 6. Result of fit to the $p_T(\mu^+\mu^-)$ distribution with requirements on $|\Delta p_T(\mu^+\mu^-)|$ (left) and on both $|\Delta p_T(\mu^+\mu^-)|$ and $1 - |\Delta\phi(\mu^+\mu^-)|/\pi$ (right) removed. The points with error bars represent the data. The histograms are the result of fitting the simulated distributions to the data.

The central values of the signal and single-proton dissociation yields from the fit are both below the mean number expected for 40 pb^{-1} , consistent with the deficit shown in table 1. This is investigated by repeating the fit, first with the $\Delta p_T(\mu^+\mu^-) < 1.0 \text{ GeV}$ requirement removed, and then with both the $\Delta p_T(\mu^+\mu^-) < 1.0 \text{ GeV}$ and $1 - |\Delta\phi(\mu^+\mu^-)|/\pi < 0.1$ selections removed. From simulation this is expected to have negligible effect on the signal efficiency, while enhancing the background. The double-proton dissociation and DY contributions in particular are expected to be small with the nominal selection, but their sum becomes comparable in size to the signal with the $\Delta p_T(\mu^+\mu^-)$ and $1 - |\Delta\phi(\mu^+\mu^-)|/\pi$ requirements removed.

Selection	$R_{\text{El-EI}}$	$R_{\text{diss-EI}}$
All selection criteria applied	$0.83^{+0.14}_{-0.13}$	$0.73^{+0.16}_{-0.14}$
No $ \Delta p_T $ requirement	$0.82^{+0.13}_{-0.13}$	$0.63^{+0.11}_{-0.10}$
Both $ \Delta p_T $ and $1 - \Delta\phi/\pi $ requirements removed	$0.81^{+0.13}_{-0.13}$	$0.45^{+0.08}_{-0.07}$

Table 2. Best-fit values of $R_{\text{El-EI}}$ and $R_{\text{diss-EI}}$ for the nominal selection, and with the requirements on $|\Delta p_T(\mu^+\mu^-)|$ and $1 - |\Delta\phi(\mu^+\mu^-)/\pi|$ removed.

The fits to the data with these looser selection requirements are shown in figure 6, and the resulting best-fit yields for the signal and single-proton dissociation are shown in table 2; the single-proton dissociation yield is observed to be significantly lower relative to the prediction with the looser selections. In all variations, the normalizations of the double-proton dissociation and DY yields are fixed, although the double-dissociation contribution is expected to be significant at large $p_T(\mu^+\mu^-)$ with the looser selection. With additional data, a more precise comparison of the single and double dissociation yields to the theoretical expectation may be made. In spite of the lower single-proton dissociation yield, the data-theory ratio for the signal is stable in all three variations.

6 Control plots

The dimuon invariant mass and acoplanarity distributions for events passing all selection criteria listed in table 1 are shown in figure 7, with the simulation predictions normalized to the best-fit signal and background yields. The event with the largest invariant mass has $m(\mu^+\mu^-) = 76 \text{ GeV}$. No events consistent with $Z \rightarrow \mu^+\mu^-$ are observed. This is expected for exclusive production, since the $\gamma\gamma \rightarrow Z$ process is forbidden at tree-level.

In figure 8, the $|\Delta p_T(\mu^+\mu^-)|$ and η distributions are plotted. In figures 9–10, the data and simulation are similarly compared for the p_T and η of single muons passing all other selection requirements. Agreement between the data and simulation is observed in the distributions of all dimuon and single-muon quantities.

7 Systematic uncertainties and cross-checks

Systematic uncertainties related to the pileup efficiency correction, muon trigger and reconstruction efficiency corrections, momentum scale, LHC crossing angle, and description of the backgrounds in the fit are considered. The systematic uncertainties related to the muon identification, trigger, and tracking efficiencies are determined from the statistical uncertainties of the J/ψ and Z control samples used to derive the corrections. The remaining systematic uncertainties are evaluated by varying each contribution as described in the following sections, and repeating the fit with the same three free parameters $R_{\text{El-EI}}$, $R_{\text{diss-EI}}$, and the shape correction a . The relative difference of the data-theory signal ratio between the modified and the nominal fit result is taken as a systematic uncertainty.

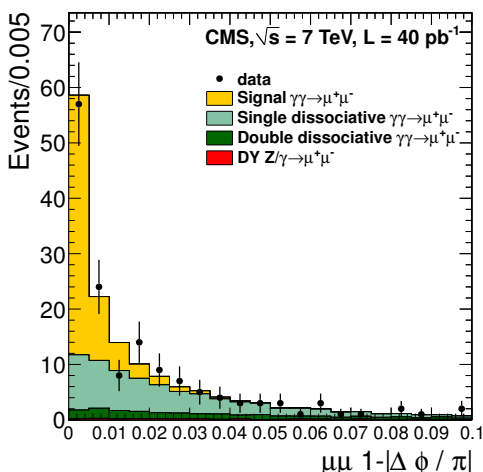


Figure 7. Muon pair invariant mass spectrum (left) and acoplanarity (right), with all selection criteria applied and the simulation normalized to the best-fit value. Data are shown as points with statistical error bars, while the histograms represent the simulated signal (yellow), single (light green) and double (dark green) proton dissociative backgrounds, and DY (red).

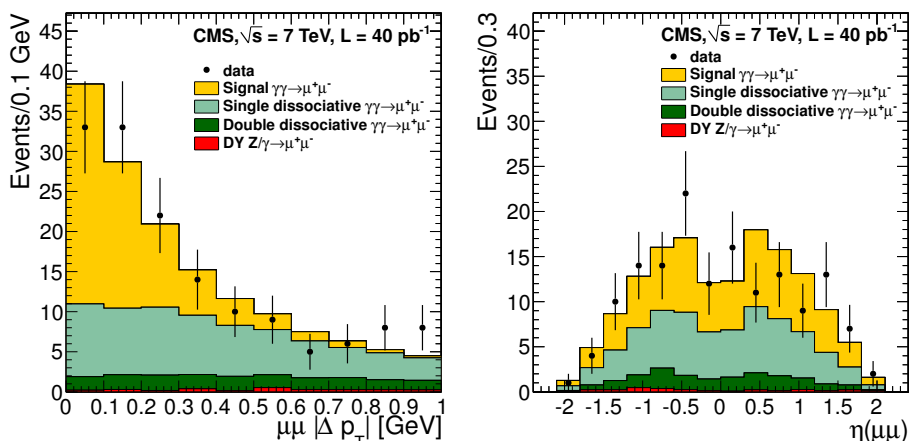


Figure 8. Muon pair transverse momentum difference (left) and pair pseudorapidity (right), with all selection criteria applied and the simulation normalized to the best-fit value. Data are shown as points with statistical error bars, while the histograms represent the simulated signal (yellow), single (light green) and double (dark green) proton dissociative backgrounds, and DY (red).

7.1 Pileup correction systematic uncertainties

Charged tracks from pileup interactions more than 2.0 mm from the dimuon vertex may induce a signal inefficiency, if they are misreconstructed to originate from within the 2.0 mm veto window. The η -dependent single-track impact parameter resolution in CMS has been measured to be less than 0.2 mm in the transverse direction, and less than 1.0 mm in the longitudinal direction [20]. The track-veto efficiency is studied in zero-bias data by varying the nominal 2.0 mm veto distance from 1.0 to 3.0 mm. The maximum relative variation is

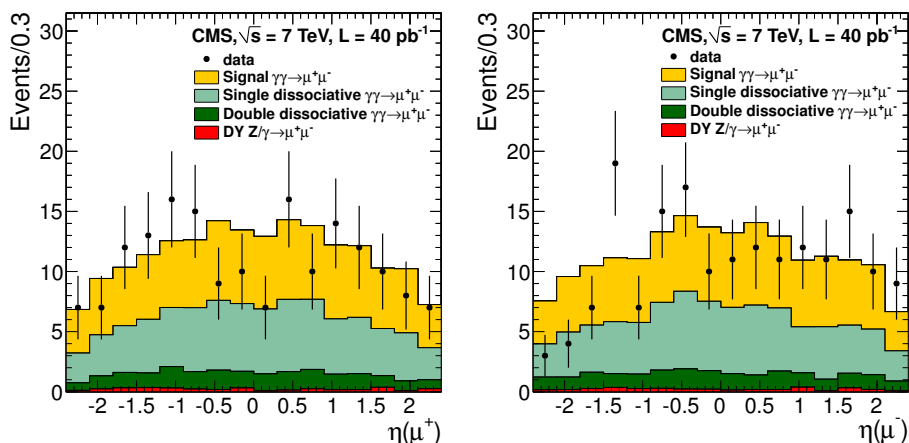


Figure 9. Single-muon pseudorapidity distribution with all other selections applied for μ^+ (left) and μ^- (right) and the simulation normalized to the best-fit value. Data are shown as points with statistical error bars, while the histograms represent the simulated signal (yellow), single (light green) and double (dark green) proton dissociative backgrounds, and DY (red).

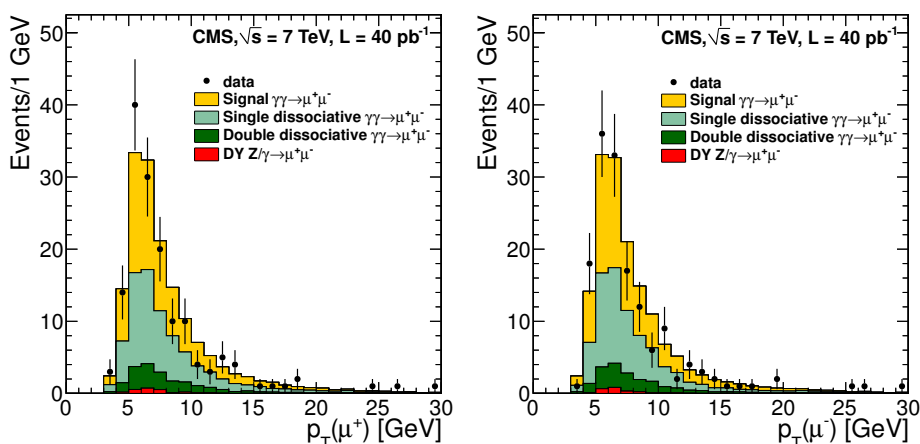


Figure 10. Single-muon transverse momentum with all other selections applied for μ^+ (left) and μ^- (right) and the simulation normalized to the best-fit value. Data are shown as points with statistical error bars, while the histograms represent the simulated signal (yellow), single (light green) and double (dark green) proton dissociative backgrounds, and DY (red).

found to be 3.6%, when enlarging the veto size to 3.0 mm. In addition, the veto is modified to use high-quality tracks having at least seven consecutive layers hit in the tracker, in place of the default veto based on all charged tracks. This is found to result in a 2.5% variation in the signal yield, which is taken as a systematic uncertainty.

As a further check, the same variations are applied to the selected sample of dimuon events, removing the Υ mass cut $m < 11.5$ GeV to increase the statistics with photo-produced exclusive upsilon events. The change in the number of events selected in the dimuon sample is found to be consistent with the expectation from the zero-bias sample.

7.2 Muon efficiencies and momentum scale

The statistical uncertainty on the muon efficiency correction is evaluated by performing a fast Monte Carlo study in which each single-muon correction evaluated from the tag-and-probe study is varied independently using a Gaussian distribution having a width equal to the measured uncertainty. The r.m.s. of the distribution of the resulting variations in the overall dimuon efficiency correction is taken as the systematic uncertainty. From 1000 pseudo-experiments, this results in an uncertainty of 0.8%. In addition, we study the effect of correlations in the dimuon efficiency. The tag-and-probe study is only sensitive to single-muon efficiencies. Since we take the dimuon efficiency as the product of the single-muon efficiencies, the effect of correlations in the efficiency are not modeled. To evaluate the size of this effect, the efficiency corrections are computed after removing events in the J/ψ control sample in which the two muons bend towards each other in the r - ϕ plane, potentially becoming very close or overlapping. Such events may introduce larger correlations in the efficiency of the dimuon pair than would be present in the well separated signal muons. Repeating the signal extraction with this change results in a relative difference of 0.7% from the nominal efficiency, which is taken as a systematic uncertainty.

Using studies of the muon momentum scale derived from $Z \rightarrow \mu^+\mu^-$ [23], the muon p_T is shifted by the observed p_T -dependent bias, and the nominal fit is performed again. The resulting relative change in the signal yield is 0.1%, which is taken as a systematic uncertainty. As a cross-check using a sample kinematically closer to the signal, we apply all the selections except for the veto on the Υ mass region, and perform a fit to the $\Upsilon(1S)$ resonance. The resulting mass is consistent with the PDG value [26], within an uncertainty of 20 MeV. Applying a 20 MeV shift to the mass and p_T scales of the data and performing the fit again results in no change from the nominal efficiency.

7.3 Vertexing and tracking efficiencies

Since the study described in section 4.4 shows no significant difference in the vertexing efficiency between data and simulation, the 0.1% statistical uncertainty of the measurement in data is taken as a systematic uncertainty. For the tracking efficiency, the difference between data and simulation is applied as a single correction without binning in p_T or η . The statistical uncertainty of 0.1% on the correction for the dimuon is taken as a systematic uncertainty.

7.4 Crossing angle

The non-zero crossing angle of the LHC beams leads to a boost of the dimuon system in the x direction. Consequently, the p_T of the pair is over-estimated by a few MeV, especially for high-mass dimuon events. This effect is estimated by applying a correction for the Lorentz boost, using a half-angle of $100 \mu\text{rad}$ in the x - z plane. This results in a 1.0% variation from the nominal fit value, and is taken as an additional systematic uncertainty.

7.5 Fit stability

Checks of the fit stability are performed by testing different bin widths and fit ranges. Starting from the nominal number of 20 bins in the range 0-3 GeV, variations in the bin width from 0.1 to 0.2 GeV and fit range $[0, 2]$ to $[0, 4]$ GeV show deviations by at most

3.3% with respect to the nominal yield. The fit bias is studied by performing a series of Monte Carlo pseudo-experiments for different input values of the signal and proton-dissociation yields, using events drawn from the fully simulated samples. The means of the pull distributions are found to be consistent with zero. Since the pseudo-experiments with the nominal binning and fit range show no significant bias, no additional systematics are assigned in this case.

7.6 Backgrounds

The yields of the double-proton dissociation and DY contributions are fixed in the nominal fit. To estimate the systematic uncertainty from this constraint, the fit is repeated with each of these varied independently by a factor of 2. The resulting changes in the fitted signal yield are 0.9% and 0.4%, respectively, where because of the similar shapes of the single and double proton dissociation components, this variation is partly absorbed into the fitted single-proton dissociation yield. As a cross-check of this procedure, the $|\Delta p_T(\mu^+\mu^-)|$ and $1 - |\Delta\phi(\mu^+\mu^-)/\pi|$ requirements are inverted to select samples of events expected to be dominated by double-proton dissociation and DY backgrounds. The agreement between data and simulation in these regions is found to be within the factor of 2 used as a systematic variation.

The possibility of a large contamination from cosmic-ray muons, which may fake a signal since they will not be correlated with other tracks in the event, is studied by comparing the vertex position and three-dimensional opening angle in data and simulations of collision backgrounds. A total of three events fail the vertex position selection in data, after all other selection criteria are applied. All three also fail the opening angle selection, which is consistent with the expected signature from cosmic muons. We conclude that the opening angle requirement effectively rejects cosmic muons, and do not assign a systematic uncertainty for this possible contamination.

A similar check for contamination from beam-halo muons is performed by applying the nominal analysis selection to non-collision events triggered by the presence of a single beam. Within the limited statistics, zero events pass all the analysis selections, and therefore no additional systematic uncertainty is assigned in this case.

7.7 Summary of systematic uncertainties

The individual variations in the definition of the track-veto are taken as correlated uncertainties, with the largest variation taken as a contribution to the systematic uncertainty. The largest variation related to the track quality, obtained when requiring high-purity tracks with > 10 hits instead of the nominal value of > 3 hits, is also taken as a contribution. The larger variation resulting from increasing or decreasing the double-proton dissociation background normalization by a factor of 2, and the larger variation resulting from increasing or decreasing the DY background normalization by a factor of 2, are each taken as contributions to the systematic uncertainty. The variation in the crossing angle, muon identification and trigger efficiencies, tracking efficiency, bias due to correlations in the J/ψ control sample, and vertexing efficiency are treated as uncorrelated uncertainties. Summing quadratically all uncorrelated contributions gives an overall relative systematic uncertainty of 4.8% on the signal yield (table 3).

Selection	Variation from nominal yield
Track veto criteria	3.6%
Track quality	2.5%
DY background	0.4%
Double-proton dissociation background	0.9%
Crossing angle	1.0%
Tracking efficiency	0.1%
Vertexing efficiency	0.1%
Momentum scale	0.1%
Efficiency correlations in J/ψ control sample	0.7%
Muon and trigger efficiency statistical uncertainty	0.8%
Total	4.8%

Table 3. Relative systematic uncertainties.

8 Results

For muon pairs with invariant mass greater than 11.5 GeV, single-muon transverse momentum $p_T(\mu) > 4$ GeV, and single-muon pseudorapidity in the range $|\eta(\mu)| < 2.1$, 148 events pass all selections. Approximately half of these are ascribed to fully exclusive (elastic) production. The number of events expected from Monte Carlo simulation of signal, proton dissociation, and DY backgrounds for an integrated luminosity of 40 pb^{-1} is 184.

The resulting visible cross section from a fit to the $p_T(\mu^+\mu^-)$ distribution is $\sigma(\text{pp} \rightarrow \text{p}\mu^+\mu^-\text{p}) = 3.38_{-0.55}^{+0.58}$ (stat.) ± 0.16 (syst.) ± 0.14 (lumi.) pb, and the corresponding data-theory signal ratio is $0.83_{-0.13}^{+0.14}$ (stat.) ± 0.04 (syst.) ± 0.03 (lumi.), where the statistical uncertainties are strongly correlated with the single-proton dissociation background.

9 Summary

A measurement is reported of the exclusive two-photon production of muon pairs, $\text{pp} \rightarrow \text{p}\mu^+\mu^-\text{p}$, in a 40 pb^{-1} sample of proton-proton collisions collected at $\sqrt{s} = 7$ TeV during 2010 at the LHC. The measured cross section

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

is consistent with the predicted value, and the characteristic distributions of the muon pairs produced via $\gamma\gamma$ fusion, such as the pair acoplanarity and transverse momentum, are well described by the full simulation using the matrix-element event generator LPAIR. The detection efficiencies are determined from control samples in data, including corrections for the significant event pileup. The signal yield is correlated with the dominant background from two-photon production with proton dissociation, for which the current estimate from a fit to the $p_T(\mu^+\mu^-)$ distribution can be improved with additional data. The efficiency for the exclusivity selection is above 90% in the full data sample collected by CMS during the

2010 LHC run. With increasing instantaneous luminosity this efficiency will decrease, but without possible improvements to the selection remains above 60% with up to 8 additional pileup vertices. Since the process may be calculated reliably in the framework of QED, within uncertainties associated with the proton form factor, this represents a first step towards a complementary luminosity measurement, and a reference for other exclusive production measurements to be performed with pileup.

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