Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ and $\gamma p \rightarrow \Upsilon p \rightarrow \ell^+\ell^- p$

production at CMS

J. Hollar

Abstract

Exclusive dilepton events are characterized by the presence of two back-to-back leptons, and no other detector activity above threshold. In the CMS experiment, this signature can result from two-photon interactions ($\gamma\gamma \rightarrow \ell^+\ell^-$) or $\Upsilon$ photoproduction ($\gamma p \rightarrow \Upsilon p \rightarrow \ell^+\ell^- p$).

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PRODUCTION AT CMS

J. HOLLAR, ON BEHALF OF THE CMS COLLABORATION

Lawrence Livermore National Laboratory,
7000 East Avenue,
Livermore, CA 94550, USA
E-mail: jjhollar@llnl.gov

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1. Introduction

At the Large Hadron Collider, dilepton production through the processes $\gamma\gamma \rightarrow \ell^+\ell^-$ and $\gamma p \rightarrow \Upsilon p \rightarrow \ell^+\ell^- p$ (Figure 1) is characterized by the presence of two opposite-sign leptons, back-to-back in the azimuthal angle $\phi$ and balanced in transverse momentum $p_T$. In elastic interactions, the beam protons remain intact and escape undetected along the beam line. In the startup phase of the LHC, when the number of extra interactions per beam crossing (pileup) is small, these events can be produced exclusively, meaning that beyond the two signal leptons there is no additional detector activity above the noise threshold. A preliminary study of the prospects for observing these processes with the CMS detector (described in detail elsewhere) has been performed; zero pileup is assumed throughout. While this study considers $pp$ collisions at 14 TeV, similar $\gamma\gamma$ and $\gamma p$ simulation studies have been carried out in CMS for “ultraperipheral” Pb-Pb collisions at 5.5 TeV.

The two-photon interaction $\gamma\gamma \rightarrow \ell^+\ell^-$ is a nearly pure QED process, and can potentially be used for luminosity studies in the early LHC running. At high luminosity it will serve as a control sample for alignment of forward proton detectors, and for studies of non-Standard Model physics in $\gamma\gamma$ interactions. Beyond possible uses as a calibration and alignment sample, $\Upsilon$ photoproduction offers an opportunity to
Figure 1. Exclusive dileptons from elastic two-photon production (left) and \( \Upsilon \) photoproduction (right).

constrain models of QCD and diffraction. In particular, this process is sensitive to the generalised (or skewed) parton distribution functions (GPDs) of the proton. A measurement of \( \Upsilon \) photoproduction at LHC would extend the coverage in the effective \( \gamma p \) centre-of-mass energy by approximately one order of magnitude \(^{12,13}\).

2. Detector and event samples

The generated signal and background samples used in this study are processed through the full CMS analysis software unless otherwise noted. This includes detector simulation, trigger emulation, and offline reconstruction. The \textit{LPAIR} \(^{14}\) (two-photon) and \textit{STARLIGHT} \(^{15,16}\) (photoproduction) generators are used to generate the signal events. The largest source of irreducible background is dilepton production through inelastic (or dissociative) photon-exchange events. These events will appear exclusive when all products of the beam proton fragmentation escape detection. Although these events are expected to leave no activity within the central CMS hadronic calorimeter acceptance, they will often show activity in the \textit{CASTOR} \(^{17}\) or \textit{ZDC} \(^{18}\) forward calorimeters. These forward detector extensions can therefore be used to veto the inelastic events.

Other sources of dilepton backgrounds relevant to CMS include Drell-Yan production, quarkonium decays, heavy-flavor semileptonic decays, and \( W^+W^- \) production. The Pythia generator is used to generate all of these samples.

3. Event selection and background estimate

Starting from the sample of dileptons that satisfy the trigger requirements \( p_T > 3 \text{ GeV/c} \) (muons) and \( E_T > 6 \text{ GeV/c} \) (electrons), we require that the
offline reconstruction find exactly two same flavor opposite-sign dileptons in the event. Further selections on the acoplanarity and transverse momentum balance of the leptons are applied to suppress backgrounds. In the $\mu^+\mu^-$ channel, we require $|\Delta \phi(\mu^+\mu^-)| > 2.9 \text{ rad}$ and $|\Delta p_T(\mu^+\mu^-)| < 2.0 \text{ GeV}/c$. In the $e^+e^-$ channel, we require $|\Delta \phi(e^+e^-)| < 2.7 \text{ rad}$ and $|\Delta E_T(e^+e^-)| < 5.0 \text{ GeV}/c$.

A common exclusivity selection is applied for the dimuon and dielectron channels. The calorimeter exclusivity requirement is implemented by requiring that no more than 5 “extra” calorimeter towers have $E > 5 \text{ GeV}$, where extra towers are defined as those separated from either of the lepton candidates by $\Delta R > 0.3$ in the $\eta - \phi$ plane. A requirement that the
track multiplicity satisfy $N(\text{tracks}) < 3$ provides additional background suppression in the $|\eta| < 2.5$ region covered by the tracker. The distributions of all selection variables for the $\gamma\gamma \rightarrow \mu^+\mu^-$ signal and for the sum of backgrounds are shown in Figure 2.

The remaining background is dominated by the inelastic photon-exchange events. Generator-level acceptance studies show that approximately $2/3$ of this background can be removed by applying a veto against activity in the CASTOR and ZDC detectors. The residual background from non-photon exchange processes is estimated by performing an exponential fit to the sideband of the extra calorimeter towers distribution, in the region $5 < N(\text{towers}) < 25$. For an integrated luminosity of 100 pb$^{-1}$ this procedure results in a background estimate of approximately 39 events. In the signal region, the non-photon exchange background is small compared to the inelastic photon-exchange contribution, even after the forward detector vetos are applied.

4. Results

After all selections are applied, the expected $\gamma\gamma \rightarrow \mu^+\mu^-$ event yields in 100 pb$^{-1}$ are $N_{\text{elastic}}(\gamma\gamma \rightarrow \mu^+\mu^-) = 709 \pm 27$, and $N_{\text{inelastic}}(\gamma\gamma \rightarrow \mu^+\mu^-) = 223 \pm 15 \pm 42(\text{model})$. The statistical error is taken as $\sqrt{N}$ and a 19% model-dependent uncertainty on the inelastic cross-section is assumed.
based on studies by CDF. In the $\gamma\gamma \rightarrow e^+e^-$ channel, the samples are significantly smaller due to the higher trigger threshold and lower efficiency for reconstructing low $E_T$ electrons; the expected yields are $N_{\text{elastic}}(\gamma\gamma \rightarrow e^+e^-) = 67 \pm 8$, and $N_{\text{inelastic}}(\gamma\gamma \rightarrow e^+e^-) = 31 \pm 6 \pm 6$(model).

Due to the contribution of the theoretically less well understood inelastic events, the elastic signal cannot be extracted on an event-by-event basis. However, the $\Delta \phi$ and $\Delta p_T$ distributions provide a means of statistically separating the two contributions (Figure 3).

The $\Upsilon$ photoproduction signal can be extracted by performing a fit to the dimuon invariant mass distribution in the range $8 < m(\mu^+\mu^-) < 12$ GeV/$c^2$. The lines show the result of a fit, where the dashed line is the $\Upsilon$ component, the dotted line is the two-photon continuum, and the solid line is the sum of the two.

The $\Upsilon$ photoproduction signal can be extracted by performing a fit to the dimuon invariant mass distribution in the range $8 < m < 12$ GeV/$c^2$. The $1S$, $2S$, and $3S$ $\Upsilon$ resonances are fit to single Gaussians, while the sum of elastic and inelastic $\gamma\gamma \rightarrow \mu^+\mu^-$ contributions are fit to a second-order polynomial (Figure 4). For an assumed integrated luminosity of 100 pb$^{-1}$ and the cross-section prediction from $STARLIGHT$, the three $\Upsilon$ resonances are clearly visible above the $\gamma\gamma$ continuum. A measurement of the $t$ dependence of the cross-section is also possible; here $t$ indicates the squared four-momentum transfer at the proton vertex.
5. Conclusions

With 100 pb$^{-1}$ of integrated luminosity, a large sample of $\gamma\gamma \rightarrow \mu^+\mu^-$ and $\gamma p \rightarrow \Upsilon p \rightarrow \mu^+\mu^- p$ events can be triggered and reconstructed in the CMS experiment, using a common selection for both samples. A smaller sample of $\gamma\gamma \rightarrow e^+e^-$ events will also be collected. With minimal pileup these events can be distinguished using exclusivity requirements, and the inelastic backgrounds reduced using forward detector vetos. The $\Upsilon$ sample will allow measurements of cross-sections at significantly higher energies than previous experiments. The $\gamma\gamma \rightarrow \ell^+\ell^-$ sample will serve as a calibration sample for studies of luminosity and lepton reconstruction.

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