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High energy $\gamma\gamma$ interactions at the LHeC

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The future Large Hadron-electron Collider (LHeC), operating at a center-of-mass energy of 1.2 TeV and delivering an integrated luminosity of 1 ab^{-1}, will offer unique opportunities for investigating high-energy $\gamma\gamma$ interactions. The clean experimental environment at the LHeC, combined with its high luminosity, suits perfectly studies of exclusive particle production. This paper discusses the exclusive production of pairs of charged particles via photon-photon fusion in electron-proton collisions at the LHeC, using $\gamma\gamma \to W^+W^-$, $\tau^+\tau^-$, and $\tilde{H}^+\tilde{H}^-$ cases as examples. Comparisons of the cross-section predictions from three different approaches to computing of two-photon production at the LHeC are also reported.

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1. Introduction

The proposed Large Hadron-electron Collider (LHeC) will operate at a center-of-mass energy of 1.2 TeV and is expected to deliver an integrated luminosity of about 1 ab^{-1} [1]. The clean experimental conditions at the LHeC, especially the low event pileup of a few percent, make it an ideal platform for investigating exclusive processes in general, and those involving the photon-photon fusion in particular.

To calculate the cross-sections for two-photon interactions in an electron-proton collision, the *Equivalent Photon Approximation* (EPA) [2] can be used. In the EPA framework, the cross-section at the electron-proton (ep) level for a given photon-photon process is computed by convoluting the equivalent photon fluxes, due to both electrons and protons, with the corresponding photon-photon cross-section [2, 3]. This convolution generates the photon-photon luminosity spectrum, $S_{\gamma\gamma}$, as a function of the photon-photon center of mass energy W, which effectively represents the relative rate of the photon-photon collisions in the electron-proton collisions, in a close analogy to the partonic luminosity spectra for proton-proton collisions.

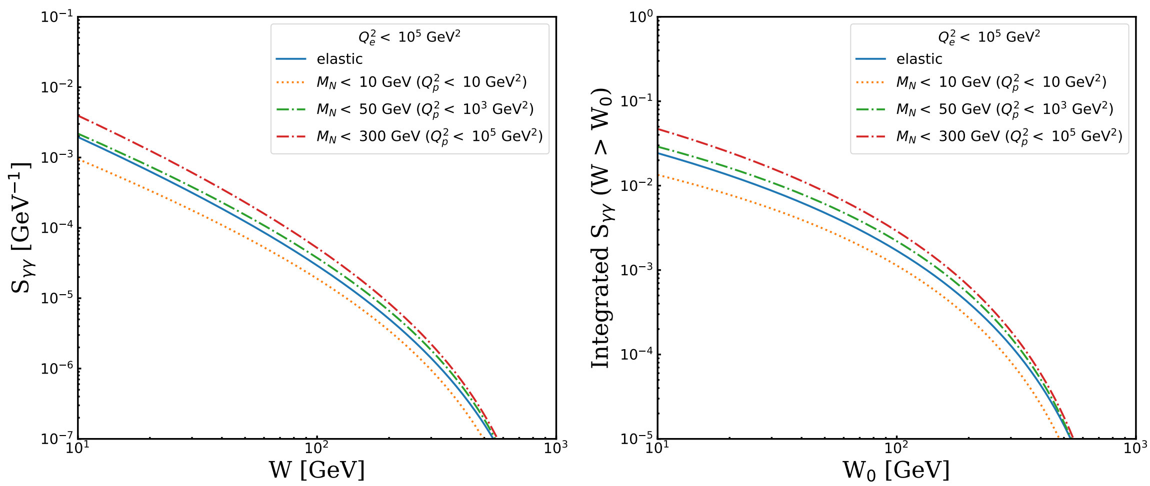

Figure 1: (Left) Elastic and inelastic luminosity spectra for photon-photon collisions at the LHeC; (Right) integrated luminosity spectra, $\int dW S_{\gamma\gamma}$, as a function of a minimal $\gamma\gamma$ center-of-mass energy W_0.

In Fig. 1 the photon-photon spectra are shown for the elastic, fully exclusive production as well as for the inelastic, semi-exclusive production when the incident proton dissociates into a state of mass M_N, where the photon virtuality at the electron vertex Q_e^2 is integrated up to 10^5 GeV^2 whereas Q_p^2 at the proton vertex up to three different values depending on the allowed maximal dissociative mass. It can be seen that on the one hand a significant $S_{\gamma\gamma}$ is expected for W well above 100 GeV and on the other hand, the effective integrated $S_{\gamma\gamma}$ luminosity for $W > 10$ GeV may reach 5% of the ep luminosity of 10^{34} cm^{-2}s^{-1}.

2. Two-photon exclusive production of pairs of charged particles at the LHeC

At high energies, well above a threshold energy, W-dependence of cross sections for the pair production via $\gamma\gamma$ fusion depends strongly on spin of produced particles: for charged vector particles, as W bosons, $\sigma_{\gamma\gamma\to VV}$ is asymptotically constant, for fermions is falling as $1/W$ and for scalars as $1/W^2$.

Assuming the integrated ep luminosity of 1 ab^{-1}, about 100'000 W boson pairs will be produced at the LHeC via photon-photon fusion. This will allow for unique high statistics studies of the coupling between the photon and W bosons. It should be noted here that such a two-photon production has a similar cross-section in pp collisions at the LHC but the exclusive measurements suffer there from very harsh conditions, in particular from ever increasing event pileups [4, 5]. In addition, the exclusive two-photon production is affected by big and not well controlled cross-section suppression due to strong re-scattering effects, which is absent in ep collisions. As a result, large backgrounds yields at the LHC highly compromise such measurements in contrast to the LHeC where the detection efficiencies are expected to be large for signal, and backgrounds very much reduced, allowing for precision studies using various decay channels.

3. Two-photon exclusive production of tau and higgsino pairs at the LHeC

Among the many photon-induced interactions of interest, the two-photon production of τ lepton pairs stands out as an important process – precision measurements of anomalous magnetic moment a_τ, and electric dipole moment d_τ of tauons could reveal deviations from the Standard Model (SM) predictions. Observations of $\gamma\gamma \to \tau^+\tau^-$ have been reported by the CMS and ATLAS Collaborations in ultra-peripheral collisions of heavy ions at the LHC [6, 7]. The first measurement of photon-induced τ pair production in proton-proton collisions at the LHC, along with strong constraints on a_τ and d_τ, was very recently reported by CMS [8]. Additionally, measurements of τ pair production via photon-photon fusion have been performed at the HERA experiment [9, 10], providing a strong foundation for future tauon studies at the LHeC.

In general, the exclusive production of tau pairs in ep collisions is predominantly governed by the two-photon Bethe-Heitler (BH) process, which can be precisely calculated within the SM [11]. This process dominates a large fraction of the accessible phase space. Schematic Feynman diagrams for such a production of τ pairs at the LHeC is illustrated in Fig. 2. However, aside from the Bethe-Heitler process, QED-Compton-like diagrams may become significant in regions with very low dilepton invariant masses. Additionally, processes involving Z boson exchanges are expected to contribute in the region of high invariant mass.

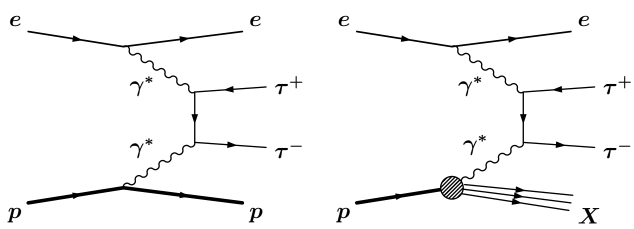

Figure 2: Feynman diagrams representing the exclusive, and semi-exclusive two-photon production of τ pairs at the LHeC.

With the two-photon luminosity spectrum $S_{\gamma\gamma}$ available, and using the photon-photon cross-section $\sigma_{\gamma\gamma\to\tau^+\tau^-}$, one can compute the production cross-sections at the LHeC by applying the EPA [2], as discussed above. To evaluate the precision of the general approach used in this work, the cross-sections calculated using the EPA are compared to those obtained from two available

Monte Carlo event generators for charged lepton pairs. We consider the LPAIR calculation, based on the diagrams of the two-photon BH process, dominant in a large fraction of the available phase space. As mentioned earlier, in the high-mass region, an additional Z-contribution is expected, and modeled in GRAPE. Additionally, GRAPE also includes the effects of initial state radiation (ISR), not negligible in the high energy electron-hadron collisions.

As shown in Tab. 1, the cross-section calculated using the EPA for a minimum two-photon invariant mass $W_0 = 10$ GeV are in a very good agreement with those obtained from the Monte Carlo generators: GRAPE [12], and the CEPGEN [13] implementation of LPAIR [14]. For the inelastic results, we present the EPA calculations based on two different sets of structure functions: the updated F_2 and F_L parameterization by Abramowicz *et al.* [15] (labelled as ALLM97), and a hybrid, "LUX-like" set of structure functions [13] modelling the (Q^2, x_{Bj}) kinematics space in three regions: resonances, partonic, and continuum. For the case of LPAIR, the results are computed using the structure functions from Suri & Yennie [16] (labelled as SY). GRAPE uses the parameterisation by Brasse *et al.* [17] for the invariant mass of the hadronic system smaller than 2 GeV (the proton resonance region), while for larger than 2 GeV it employs ALLM97 [15].

This comparison highlights that the EPA provides a reliable approximation for photon-photon interactions at LHeC, and that the corrections due to the ISR are small, of about 2%.

	$Q^2_{e,p} < 10$ GeV^2	$Q^2_{e,p} < 50$ GeV^2		$M_N < 3$ GeV; $Q^2_{e,p} < 10$ GeV^2
Calculation	σ_{el} [pb]	σ_{el} [pb]	Calculation	σ_{inel} [pb]
EPA (dipole FF)	46.32	49.74	EPA (ALLM)	12.29
LPAIR/CEPGEN	45.52	48.03	EPA (LUXlike)	11.72
GRAPE (BH)	46.30	48.82	GRAPE (BH)	11.52
GRAPE (BH+ISR)	46.88	49.58	LPAIR (SY)	12.74

Table 1: Elastic and inelastic $\tau^+\tau^-$ cross sections at the LHeC, calculated using the EPA for a minimum two-photon invariant mass of $W_0 = 10$ GeV. For the elastic case, the dipole parametrization of the proton electromagnetic form factors is used. Cross-section values obtained from the GRAPE [12] generator (both with and without ISR) and CEPGEN/LPAIR [13, 14] are also included for comparison.

To further support the above discussion, distributions are presented for the differential cross-sections $d\sigma/dW$ and $d\sigma/dY_{\tau^+\tau^-}$, calculated using the EPA, and compared to those obtained using the CEPGEN implementation of the LPAIR event generator [14]. These results are displayed in Fig. 3. Both the elastic and inelastic cases are shown, assuming $M_N < 3$ GeV for the dissociative mass and photon virtualities $Q^2_{\mathrm{e}} < 10$ GeV^2 and $Q^2_{\mathrm{p}} < 10$ GeV^2 at the electron and proton vertices, respectively.

As illustrated in Fig. 3, the EPA-based calculations show good agreement with LPAIR for both elastic and inelastic scenarios under the specified kinematic conditions. Despite minor corrections required in the higher-mass region due to additional effects due to Z-exchanges and ISR, the EPA remains a robust approximation for estimating exclusive two-photon production cross sections in electron-proton collisions across the broad kinematic range accessible at LHeC energies.

About 10^8 τ pairs will be exclusively produced and a large fraction of them within acceptance of a dedicated LHeC detector [18, 19]. This statistics is orders of magnitude larger than that available

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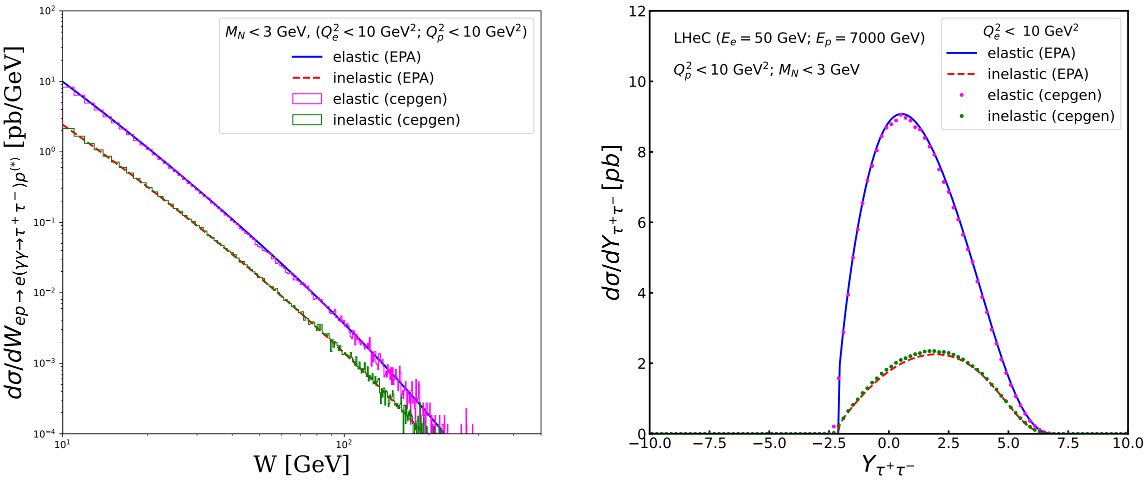

Figure 3: (Left) Differential cross section $d\sigma/dW$ for the $ep \to ep^{(*)}(\gamma\gamma \to)\tau^+\tau^-$ process as a function of the photon-photon center-of-mass energy W; (Right) Differential cross section $d\sigma/dY_{\tau^+\tau^-}$ as a function of the tau pair rapidity $Y_{\tau^+\tau^-}$.

at the LHC, and will largely improve sensitivities to a_τ and d_τ.

Similarly, the EPA-based calculations provided estimates for the two-photon exclusive production of pairs of 100 GeV higgsinos – the obtained total cross-section of almost 3 fb suggests an interesting potential also for verifying challenging predictions of the so-called compressed-mass supersymmetric theories (for more details see Ref. [20]).

4. Summary and Conclusions

The future Large Hadron-electron Collider (LHeC) – with its clean experimental environment, high luminosity, and extended kinematic reach – will be a unique platform for the deep exploration of high-energy photon-photon interactions. In this contribution, an initial overview is presented of the potential of $\gamma\gamma$ studies at the LHeC. Using the Equivalent Photon Approximation (EPA), we have computed $\gamma\gamma$ luminosity spectra, along with cross-sections for τ pair production. We also compared differential distribution for this process with results from the Grape, and Lpair/CepGen event generators. A good agreement between these approaches has been observed across a range of kinematic configurations.

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