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LIGHT-BY-LIGHT SCATTERING IN ULTRAPERIPHERAL HEAVY-ION COLLISIONS AT THE LHC*

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We present cross sections for diphoton production in (semi)exclusive PbPb collisions, relevant for the LHC. The calculation is based on equivalent photon approximation in the impact parameter space. The cross sections for elementary elastic scattering $\gamma\gamma \to \gamma\gamma$ subprocess are calculated including two mechanisms: box diagrams with leptons and quarks in the loops and a mechanism based on vector-meson dominance (VDM-Regge) model with virtual intermediate vector-like excitations of the photons. We get measureable cross sections in PbPb collisions. We present many interesting differential distributions which could be measured by the ALICE, CMS or ATLAS collaborations at the LHC. We study whether a separation of box and VDM-Regge contributions is possible. We find that the cross section for elastic $\gamma\gamma$ scattering could be measured in the heavy-ion collisions for subprocess energies smaller than $W_{\gamma\gamma} \approx 15$–20 GeV.

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1. Introduction

In the classical Maxwell theory waves do not interact. In contrast, in quantal theory, photons can interact via quantal fluctuations. So far, only inelastic processes, *i.e.* production of hadrons or jets via photon–photon fusion could be measured *e.g.* in e^+e^- collisions.

The light-by-light scattering to the leading and next-to-leading order was discussed earlier in the literature, see [1–3], also in the context of search for effects beyond the Standard Model [4, 5]. The cross section for elastic

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$\gamma\gamma \to \gamma\gamma$ scattering is very small, so till recently, it was beyond the experimental reach. In e^+e^- collisions, the energies and/or couplings of photons to electrons/positrons are rather small and the corresponding $\gamma\gamma \to \gamma\gamma$ cross section is extremely small. A proposal to study helicity-dependent $\gamma\gamma \to \gamma\gamma$ scattering in the region of MeV energies with the help of high power lasers was discussed recently *e.g.* in Ref. [6].

Ultraperipheral collisions (UPC) of heavy ions provide a nice possibility to study several two-photon induced processes such as: $\gamma\gamma \to l^+l^-$, $\gamma\gamma \to \pi^+\pi^-$, $\gamma\gamma \to$ dijets. It was realized only recently that ultraperipheral heavy-ion collisions can be also a good place for testing elastic $\gamma\gamma \to \gamma\gamma$ scattering experimentally [7, 8].

In this communication, we present our recent results obtained in [8]. We shall show some differential distributions not discussed before [8]. In Ref. [8], we included both box mechanisms as well as a new soft mechanism relying on simultaneous fluctuation of both photons into virtual vector mesons. This mechanism was not discussed before [8] in the literature in the context of photon elastic scattering.

2. $\gamma\gamma \to \gamma\gamma$ elementary cross section

The lowest order QED mechanisms with elementary particles in the loop are shown in Fig. 1. The diagram in the left panel is for lepton and quark (elementary fermion) loops, while the diagram in the right panel is for W (spin-1) boson loops. The mechanism on the left-hand side was shown to dominate at lower photon–photon energies, while the mechanism on the right-hand side becomes dominant at higher photon–photon energies (see *e.g.* [9, 10]). In numerical calculations, we include box diagrams with fermions only. The inclusion of W bosons becomes important only at $W > 50$ GeV which, as will be shown below, is practically impossible to observe at present with heavy-ion collisions.

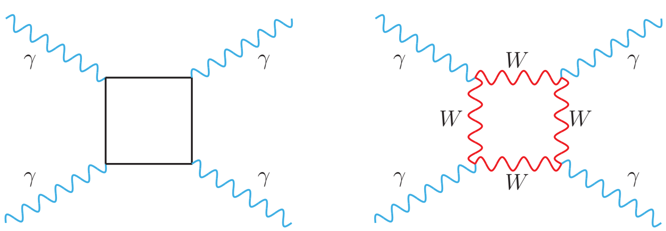

Fig. 1. Light-by-light scattering mechanisms with the lepton and quark loops (left panel) and, as an example, one diagram for intermediate W-boson loop (right panel).

Two-loop corrections turned out to be small [3]. However, higher-order processes are potentially interesting. In Fig. 2 (left panel), we show a process which is of the same order in α_{em} but of higher order in α_{s}. This mechanism is formally three-loop type but can be calculated in high-energy approximation [11]. Here, we shall not discuss the higher-order contributions, instead, we shall discuss "a kinematically similar" process shown in the right panel where both photons fluctuate into virtual vector mesons (three different light vector mesons are included). In this approach, the interaction "between photons" happens when both photons are in their hadronic (vector-meson) states.

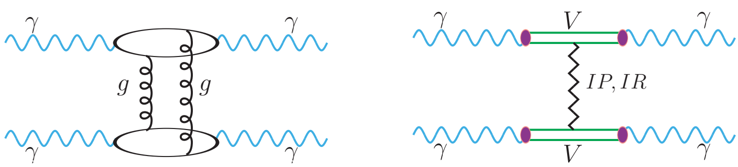

Fig. 2. Other elementary $\gamma\gamma \to \gamma\gamma$ processes. The left panel represents two-gluon exchange and the right panel is for VDM-Regge mechanism.

Details of differential cross section and the amplitude for the VDM-Regge mechanism can be found in [8].

The elementary angle-integrated cross section for the box and VDM-Regge contributions is shown in Fig. 3 as a function of the photon–photon subsystem energy. Lepton and quark amplitudes interfere in the cross section for the box contribution. At energies $W > 30$ GeV, the VDM-Regge contribution becomes larger than that for the box diagrams.

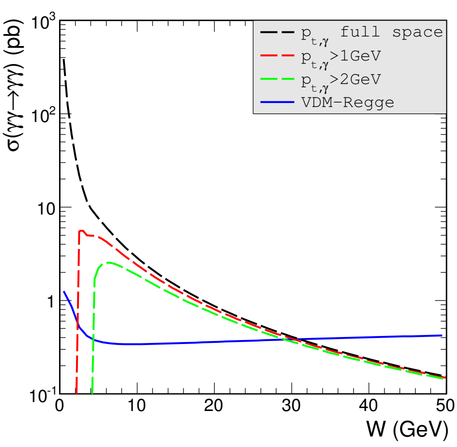

Fig. 3. Integrated $\gamma\gamma \to \gamma\gamma$ cross section as a function of the subsystem energy. The dashed lines show contribution of boxes and the solid line represents result of the VDM-Regge mechanism.

3. Production of pairs of photons in ultraperipheral heavy-ion collisions

At present (LHC), the photon–photon elastic scattering can be studied in $pp \to pp\gamma\gamma$ and $AA \to AA\gamma\gamma$. In Ref. [8], we concentrated on heavy-ion collisions. Here, we shall show some results obtained in [8] for the diphoton production in ultrarelativistic heavy-ion collisions at the LHC.

The general situation for $AA \to AA\gamma\gamma$ is sketched in Fig. 4. In our equivalent photon approximation (EPA) in the impact parameter space, the total cross section is expressed through the five-fold integral

$$\sigma_{A_1A_2\to A_1A_2\gamma\gamma}\left(\sqrt{s_{A_1A_2}}\right) = \int \sigma_{\gamma\gamma\to\gamma\gamma}\left(W_{\gamma\gamma}\right) N\left(\omega_1, \boldsymbol{b}_1\right) N\left(\omega_2, \boldsymbol{b}_2\right) S^2_{\rm abs}\left(\boldsymbol{b}\right) \times 2\pi b\mathrm{d}b\,\mathrm{d}\bar{b}_x\,\mathrm{d}\bar{b}_y\,\frac{W_{\gamma\gamma}}{2}\mathrm{d}W_{\gamma\gamma}\,\mathrm{d}Y_{\gamma\gamma}\,. \tag{1}$$

More details can be found in [8, 12].

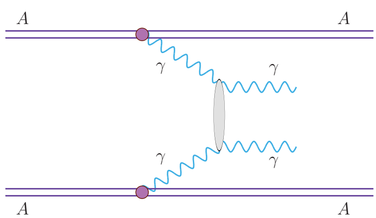

Fig. 4. $AA \to AA\gamma\gamma$ in ultrarelativistic UPC of heavy ions.

Can the elastic photon–photon collisions be measured with the help of LHC detectors? In Fig. 5, we show numbers of counts in the 1 GeV intervals expected for assumed integrated luminosity of 1 nb^{-1}, where in addition to the lower cut on photon–photon energy, we have imposed cuts on (pseudo)rapidities of both photons. It seems that one can measure invariant mass distribution up to $M_{\gamma\gamma} \approx 15$ GeV.

The cuts on subsystem energies are, in principle, not obligatory. What are energies of photons in the laboratory frame? In Fig. 6, we show distribution of energies of both photons, separately for the two mechanisms: boxes (left panel) and VDM-Regge (right panel). In this calculations, we do not impose cuts on $W_{\gamma\gamma}$ but only minimal cuts required by experiments on energies of individual photons ($E_\gamma > 3$ GeV). Slightly different distributions are obtained for box and VDM-Regge mechanisms. For the box mechanism, we can observe a pronounced maximum when both energies are small. For both mechanisms, one observes an enhancement of the cross section for rather asymmetric configurations: $E_1 \gg E_2$ or $E_1 \ll E_2$.

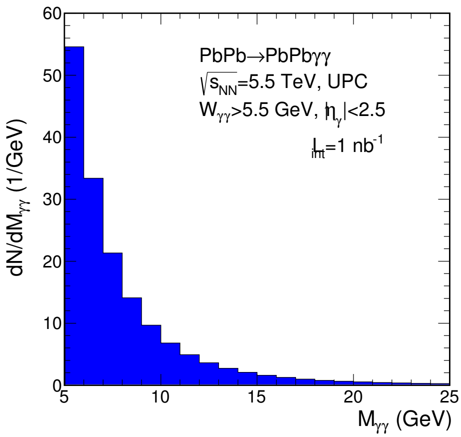

Fig. 5. Distribution of expected number of counts in 1 GeV bins for cuts specified in the figure legend. This figure should be compared with a similar figure in [7].

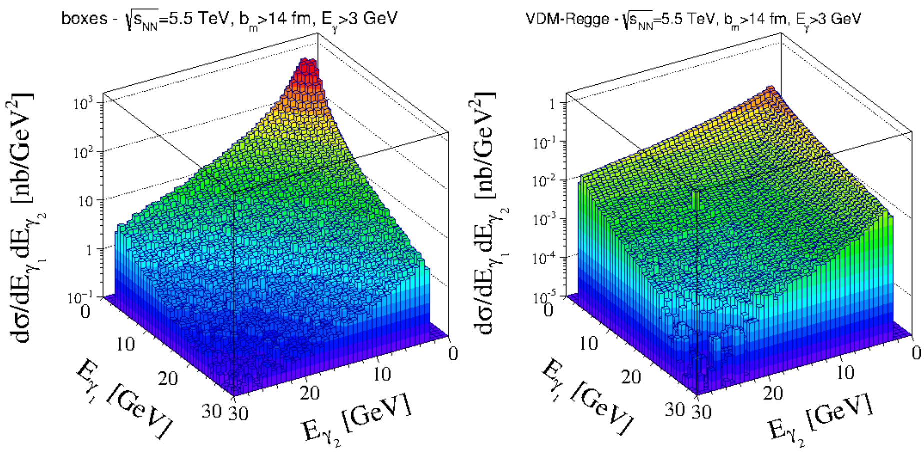

Fig. 6. Two-dimensional distribution in energies of the two photons in the laboratory frame for box (left panel) and VDM-Regge (right panel) contributions.

In Fig. 7, we show two-dimensional distributions in photon rapidities with explicitly shown experimental limitations ($y_{\gamma 1}, y_{\gamma 2} \in (-2.5, 2.5)$). These distributions are very different for the box and VDM-Regge contributions. In both cases, the influence of the imposed cuts is significant. In the case of the VDM-Regge contribution, we observe a non-continues behaviour which is caused by the strong transverse momentum dependence of the elementary cross section which causes that some regions in the two-dimensional space are almost not populated. The empty areas in the upper-left and lower-right corners for the box case are caused by a finite number of points in a grid at $z \approx \pm 1$. For the case of the VDM-Regge contribution, we show distribution for only one half of the $(y_{\gamma_1}, y_{\gamma_2})$ space. Clearly, the VDM-Regge contribution does not fit to the main detector and extends towards large rapidities. In Ref. [8], we investigated whether the photons originating from this mechanism can be measured with the help of zero-degree calorimeters (ZDCs) associated with the ATLAS or CMS main detectors. In the case of the VDM-Regge contribution (right panel), we show much broader range of rapidity than for the box component (left panel). The maxima of the cross section associated with the VDM-Regge mechanism are at $|y_{\gamma_1}|, |y_{\gamma_2}| \approx 5$. Unfortunately, this is below the limitations of the ZDCs $|\eta| > 8.3$ for ATLAS [13] or 8.5 for CMS [14].

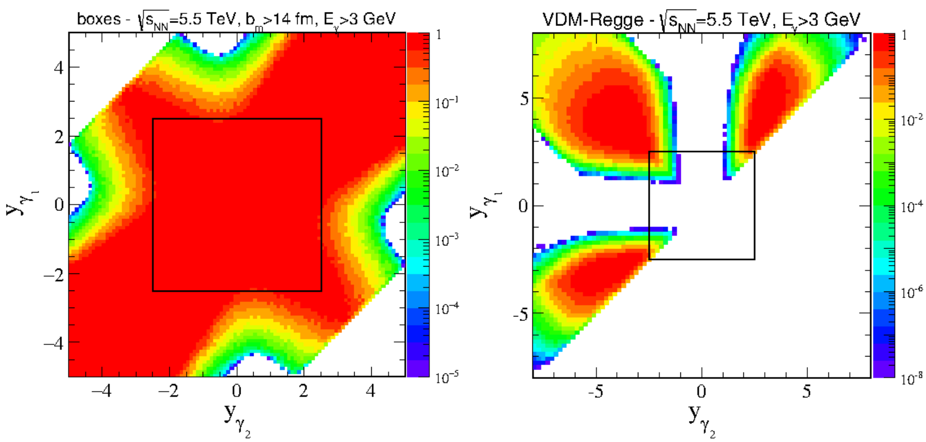

Fig. 7. Contour representation of two-dimensional ($d\sigma/dy_{\gamma_1}dy_{\gamma_2}$ in nb) distribution in rapidities of the two photons in the laboratory frame for box (left panel) and VDM-Regge (right panel) contributions together with experimental rapidity coverage of the ATLAS or CMS main detectors. Only one half of the $(y_{\gamma_1}, y_{\gamma_2})$ space is shown for the VDM-Regge contribution. The second half can be obtained by reflection around the $y_{\gamma_1} = y_{\gamma_2}$ line.

4. Conclusion

Recently, in Ref. [8], we performed detailed feasibility studies of elastic photon–photon scattering in ultraperipheral heavy-ion collisions at the LHC. The calculation was performed in equivalent photon approximation in the impact parameter space. This method allows to remove those cases when nuclei collide and, therefore, break apart. Such cases are difficult in interpretation and were omitted here.

In Ref. [8], we proofed that the observation of the dominant box contribution should be feasible as far as statistics is considered. We also investigated whether the VDM-Regge contribution could be observed. We found that the VDM-Regge contribution reaches a maximum of the cross section when ($y_{\gamma_1} \approx 5$, $y_{\gamma_2} \approx -5$) or ($y_{\gamma_1} \approx -5$, $y_{\gamma_2} \approx 5$). This is a rather difficult region which cannot be studied *e.g.* with zero degree calorimeters installed at the LHC.

So far, we have studied only two mechanisms of diphoton continuum. The two-gluon exchange contribution, not discussed in Ref. [8], will be discussed soon in [11]. The resonance mechanism could be also included in the future. In the present studies, we have concentrated on the signal. Future studies should also include estimation of the background. The dominant background may be expected from the $AA \to AAe^+e^-$ when both electrons are misidentified as photons.

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