PHOTON–PHOTON SCATTERING AT THE LHC IN COLLISIONS OF NUCLEI*

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This paper is focused on an analysis of the light-by-light scattering in ultraperipheral heavy-ion collisions at the energy available at the CERN Large Hadron Collider. Here, contribution from fermionic boxes, resonance scattering, VDM-Regge model, two-gluon exchange as well as pionic background will be compared. Each of these processes dominates at different ranges of two-photon invariant masses. The usage of the equivalent photon approximation in the impact parameter space gives results that are in good agreement with recently measured ATLAS and CMS data. Predictions including ALICE and LHCb experimental cuts for the next run at the LHC are shown.

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1. Introduction

Ultraperipheral heavy-ion collisions are a source of photons which can collide with each other producing *e.g.* a pair of particles. Physics of the ultraperipheral collisions (UPC) of heavy ions gives a nice opportunity to study electromagnetic processes. Due to the very strong electromagnetic field of colliding nuclei, reactions related to photon collisions can be studied. One can consider $\gamma\gamma$ fusion and photoproduction (Pomeron and/or Reggeon exchange) as a sub-process of heavy-ion UPC. These proceedings will pertain to light-by-light scattering. Diphoton processes have long been studied at e^+e^- collider. This tool allows testing a QED theory and a lot of aspects of meson spectroscopy. The first theory concerning the possibility of the light-by-light scattering was proposed more than 80 years ago *i.a.* by Heisenberg and his students: Euler and Kockel [1, 2] or by Akhieser, Landau and Pomeranchuk [3].

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Here, I present a theoretical approach to calculate cross section for $\gamma\gamma \to \gamma\gamma$ elastic scattering and for PbPb→PbPb$\gamma\gamma$ reaction, predictions as well as a comparison of our theoretical results with existing experimental data.

2. Theoretical approach

2.1. Elementary cross section

The leading order of elementary cross section for $\gamma\gamma \to \gamma\gamma$ process is well-known and one can use an available to the general public Mathematica package: FormCalc [4]. A so-called fermionic box includes scattering via quarks and leptons. At the energy larger than $2m_W$, the W^+W^- boson loop starts to dominate. Then the cross section is calculated within LoopTools package [5]. High-order contributions are possible too. The first one can be a non-perturbative mechanism of both photons fluctuation into vector mesons and their subsequent interaction [6]. This involves the Reggeon and Pomeron exchanges between ρ, ω or ϕ light mesons. The soft VDM-Regge contribution plays an important role only at the region of the very small p_{t} only weakly dependent on the energy $W = \sqrt{\hat{s}}$. The next mechanism is the same order in α_{em} as previous one but has higher order in α_{s}. The two-gluon exchange mechanism is a three-loop mechanism [7]. This type of process requires application of a so-called regularization parameter, $m_g = 0.75$ GeV as suggested by the lattice QCD [8]. One can predict the possibility of experimental identification of proposed mechanisms at facilities such as the International e^+e^- Linear Collider.

The authors of [9] study the role of mesons exchanges in light-by-light scattering. There several pseudoscalar, scalar, tensor and 4-spin mesons were taken into account. Contribution particularly from $\eta(548)$ and $\eta'(958)$ meson seems to be very important on the level of the elementary cross section. The implementation of ALICE or LHCb experimental limitation will give an answer to the question whether these very narrow resonances are still significant in light-by-light in heavy-ion UPC.

In addition, not trivial background from the $\gamma\gamma \to \pi^0(\to \gamma\gamma)\pi^0(\to \gamma\gamma)$ process should be considered in the context of light-by-light scattering. The excellent description of the Belle [10] and Crystal Ball [11] data for $\gamma\gamma \to \pi^0\pi^0$ reaction was done [12] within a multi-component model. There, for the first time, both the total cross section and angular distributions and significance of nine resonances, $\gamma\gamma \to \pi^+\pi^- \to \rho^\pm \to \pi^0\pi^0$ continuum, the Brodsky–Lepage and handbag mechanisms in these processes were studied. If only two photons from different neutral pions are measured at a given acceptance, such an event could be wrongly identified as $\gamma\gamma \to \gamma\gamma$ scattering if no extra cuts are imposed to eliminate such a background.

2.2. Nuclear cross section

A fast-moving heavy ion (with the velocity approximately equal to c) is surrounded by a strong electromagnetic field. This can be viewed as a cloud of photons that can collide with each other or with the other nucleus. To perform the calculation in the equivalent photon approximation, one should know the energy of emitted photon ($\omega_{1,2}$) from the first and second nuclei and the probability that these photons collide with each other to create a new final state. Technically, we use at least 5-dimensional integration in the impact parameter approach. Due to this approach, one can have control over the distance between colliding nuclei. The photon flux depends, especially at a small value of impact parameter, on the charge distribution in the nucleus. We try to include as many details that can have an impact on the final results as possible. Thus, in our calculation, we use a so-called realistic form factor which is a Fourier transform of the charge distribution in the nucleus.

3. Numerical results and conclusion

Light-by-light scattering was realized experimentally only recently [13, 14]. For collisions of ions of charges Z_1, Z_2, the cross section is enhanced by $Z_1^2 Z_2^2$ factor compared to proton–proton collisions, at least at low diphoton invariant masses equal to diphoton collision energies, where the initial photons are quasi-real with extremely low virtualities. On the other hand, a significant part of cross section is cut by absorption factor which ensures ultraperipheral character of the process.

Nuclear form factor kills large virtualities in UPC of heavy ion, therefore, the initial photon virtualities equal almost zero. In Ref. [6], one can find useful comparison of nuclear cross section that is calculated using the realistic and monopole form factor in the flux of photon formula. The cross section obtained with the monopole form factor is more than 10% bigger than that obtained with the form factor which is calculated as a Fourier transform of the charge distribution in the nucleus. The ratio between those two results becomes larger with the larger value of the diphoton invariant mass.

ATLAS measured a fiducial cross section of $\sigma = 70 \pm 24$ (stat.) ± 17 (syst.) nb [13] and our theoretical calculations (including experimental acceptance) gave 49 ± 10 nb [6]. The ATLAS comparison of its experimental results to the predictions from Ref. [6] shows reasonable agreement (see Fig. 3 in Ref. [13]). 13 events were observed by the ATLAS Collaboration. This detector recorded data using 480 $\mu\mathrm{b}^{-1}$ of lead–lead collision at the centre-of-mass energy per nucleon pair of 5.02 TeV. Measurement of diphoton pair was done in the midrapidity region. The $\gamma\gamma$ invariant mass was limited to

$M_{\gamma\gamma} > 6$ GeV. Similarly, the CMS group measured the same process but for somewhat lower threshold of invariant mass of the produced diphotons [14]. The measured fiducial light-by-light scattering cross section was $\sigma = 120 \pm 46$ (stat.) ± 28 (syst.) ± 4 (theo.) nb. We have recalculated this process including the CMS acceptance and obtained $\sigma = (103 \pm 0.034)$ nb which is in good agreement with the CMS result. Figure 1 shows the CMS preliminary experimental data (red points) together with our theoretical histogram (grey/blue area). Panel (a) depicts diphoton invariant mass and panel (b) corresponds to rapidity distribution of single outgoing photon. One can observe rather large statistical uncertainties. Our calculations are in agreement with the data but it seems to be important to further test the light-by-light scattering with a better precision.

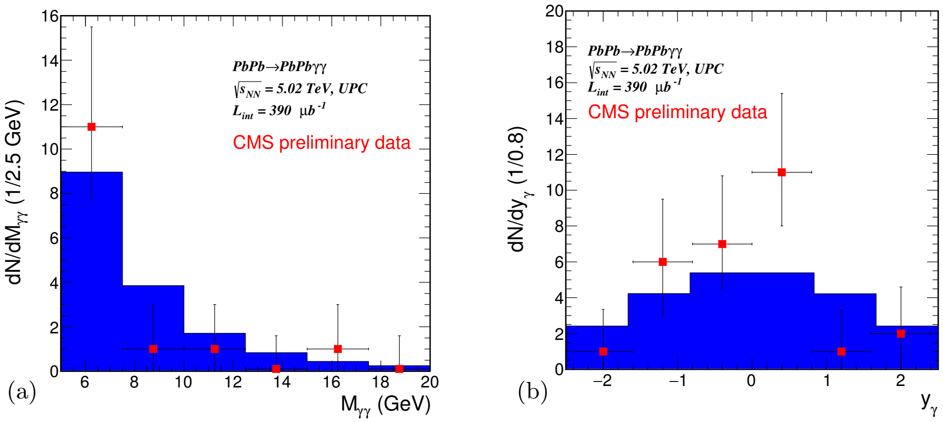

Fig. 1. (Colour on-line) Comparison of our results with existing CMS preliminary data [14]. (a) Distribution in invariant mass of diphoton pair. (b) Rapidity of single outgoing photon.

Due to relatively large cuts on the photon transverse momenta, only relatively large diphoton invariant masses were measured by the ATLAS and CMS collaborations. We believe that in the future, one could go to larger luminosity, higher collision energies, better statistics and smaller diphoton invariant masses.

Next, predictions for the ALICE and LHCb experiment will be shown. Calculations include experimental acceptance assuming that the ALICE detector facilitates measurement of outgoing photons at midrapidity region [15]. Photons with transverse energy smaller than 200 MeV cannot be detected. The above calculations will be compared with the results for more forward rapidity region: $2 < \eta < 4.5$ [16]. Here, we assume that any photon with $p_{\mathrm{t},\gamma} > 200$ MeV will be measured.

In Table I, one can find numerical values of the total nuclear cross section for fermionic boxes, pionic background and five types of intermediate mesons. The background is composed of events where exactly two of four outgoing photons are detected. The first one comes from the first pion, and the second one comes from the second pion. The two other photons, from the $\pi^0\pi^0 \to (\gamma\gamma)(\gamma\gamma)$ decays, are then outside of the detection area. Cross section in the table is given in two ranges of the diphoton invariant masses. The first one is from 0 to 2 GeV and the second one from 2 GeV to 50 GeV. Here, a cut on pseudorapidity and energy or transverse momentum of photons is included. The largest cross section is obtained for the $\gamma\gamma \to \eta \to \gamma\gamma$ resonance scattering. Results suggest that one could be able to measure the LO QED fermionic signal above $M_{\gamma\gamma} > 2$ GeV. In view of larger masses of $\eta_c(1S)$, $\chi_{c0}(1P)$ and $\eta_c(2S)$ resonance, the contribution from these resonant states occur only at the second considered range of energy. In addition, in the range of diphoton invariant mass $M_{\gamma\gamma} > 2$ GeV, comparison of cross sections for fermionic boxes and pionic background clearly shows almost fourfold dominance of boxes over the unwanted background.

TABLE I

Total nuclear cross section in nb for PbPb $\to$ PbPb $\gamma\gamma$ reaction, $\sqrt{s_{NN}} = 5.02$ TeV. ALICE and LHCb kinematical cuts are included.

Energy	$W_{\gamma\gamma} = (0–2)$ GeV		$W_{\gamma\gamma} > 2$ GeV	
Fiducial region	ALICE	LHCb	ALICE	LHCb
boxes	4 890	3 818	146	79
$\pi^0\pi^0$ background	135 300	40 866	46	24
η	722 573	568 499		
$\eta'(958)$	54 241	40 482		
$\eta_c(1S)$			9	5
$\chi_{c0}(1P)$			4	2
$\eta_c(2S)$			2	1

Figure 2 corresponds to the next run at the LHC. The energy (per nucleon) for $^{208}\mathrm{Pb}^{82+}$–$^{208}\mathrm{Pb}^{82+}$ collision is $\sqrt{s_{NN}} = 5.52$ TeV (Fig. 2 (a)) and for $^{40}\mathrm{Ar}^{18+}$–$^{40}\mathrm{Ar}^{18+}$, it is $\sqrt{s_{NN}} = 6.3$ TeV (Fig. 2 (b)). The analysis focuses on lower diphoton invariant masses. At lower energies ($W_{\gamma\gamma} < 4$ GeV), meson resonances may play important role in addition to the Standard Model box diagrams or proposed pionic background. The inclusion of energy resolution has a significance mainly at $\gamma\gamma \to \eta, \eta' \to \gamma\gamma$ resonance scattering and this contribution will be measured with good statistics. However, the resonance signal is modified including experimental energy resolution [17] and the η and $\eta'(958)$ peaks are about one order of magnitude smaller than without experimental resolution but the total cross section is, of course, still

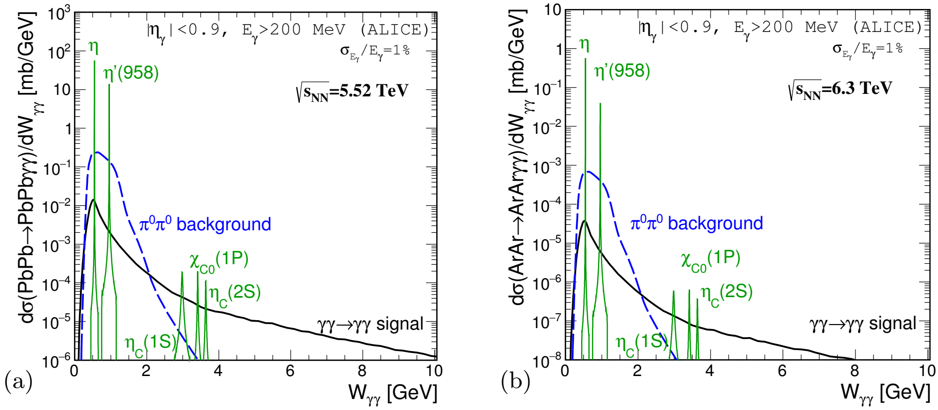

Fig. 2. Differential cross section as a function of $W_{\gamma\gamma} = M_{\gamma\gamma}$ for (a) PbPb→PbPb$\gamma\gamma$ and (b) ArAr→ArAr$\gamma\gamma$. The collision energy at the center-of-mass of the heavy-ion collision is 5.52 TeV and 6.3 TeV for lead–lead and argon–argon, respectively.

the same. Again, results suggest that one could be able to measure the $\gamma\gamma \to \gamma\gamma$ scattering above $W_{\gamma\gamma} > 2$ GeV. Comparing Fig. 2 (a) and (b), one can observe that the relevant distribution varies more than two orders of magnitude. In the case of argon–argon collisions, although the collision energy is larger, the predicted cross section is smaller. This is caused by the fourth power of the charge number of the nucleus in the cross section. The photon flux depends on Z_A^2 so the cross section is multiplied by Z_A^4. Thus, the total cross section for lead–lead collision is more than two orders of magnitude larger than for the argon–argon collision case. One can deduce that a collision of lighter nuclei is less favorable. However, we can hope that the luminosity in the run with Ar–Ar collision will be higher.

We try to find some way to reduce the rather large background contribution that occurs at smaller $W_{\gamma\gamma}$. One can use a cut on the diphoton transverse momenta or some quantity related to $p_{\mathrm{t},\gamma\gamma}$. We propose to use scalar or vector asymmetry [18] that can reduce the pionic background even by about an order of magnitude. In Ref. [19], the result shows that inclusion of experimental acoplanarity seems to be successful. Two cases with and without the acoplanarity cut ($A_{\mathrm{c}} < 0.01$) were considered. The acoplanarity requirement reduces the background contribution by a factor of five.

The ultraperipheral heavy-ion collisions give a possibility to measure the $\gamma\gamma \to \gamma\gamma$ scattering. I have presented the first predictions for integrated and differential cross section corresponding to ALICE and LHCb acceptance. The $\gamma\gamma \to \eta, \eta' \to \gamma\gamma$ resonance scattering can be measured with good statistics. With the help of a quantity that is a derivative of $p_{\mathrm{t},\gamma\gamma}$ kinematical variable, one can reduce the pionic background which was studied here for the first time.

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