PROCEEDINGS OF SCIENCE

$\gamma\gamma \to \gamma\gamma$ in heavy ion collisions - new results and prospects

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So far light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) was not accessible for experiments because the corresponding cross section is rather low. Measurements of diphotons in ultra-peripheral collisions (UPCs) of lead-lead have been reported recently by the ATLAS and CMS Collaborations. Our theoretical results based on the equivalent photon approximation in the impact parameter space are in good agreement with the current data. We will discuss how to extend such studies to lower $\gamma\gamma$ energies where photoproduction of pseudoscalar and scalar resonances contribute to the two-photon final state. In addition, we consider the dominant background that arises from $\gamma\gamma$ fusion into pairs of neutral pions. Such π^0-pairs contribute to the background when only two of the four decay photons are within the experimental acceptance, the other two photons escape undetected. We will discuss in detail how to reduce the unwanted background. We will present differential distributions and total cross section in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.05$ and 5.52 TeV and cross section for Ar-Ar collisions at the energy equal to 6.3 TeV. Results for ALICE and LHCb acceptance will be presented.

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1. Theory

Physics of the ultra-peripheral collisions (UPC) of heavy ions gives a nice opportunity to study electromagnetic processes [1]. Due to the very strong electromagnetic field of colliding nuclei, reactions related to photon collisions can be studied. This study will concern the light-by-light scattering. The first theory concerning the possibility of the light-by-light scattering was proposed more than 80 years ago i.a. by W. Heisenberg and his students: H. Euler and B. Kockel [2, 3] or by A. Akhieser, L. Landau and I. Pomeranchuk [4].

The leading order of the elementary cross section for $\gamma\gamma \to \gamma\gamma$ process is well-know and one can use a Mathematica package available to the general public: `FormCalc` [5]. The (a) diagram in Fig. 1 shows the so-called fermionic box (scattering via quarks and leptons is taken into account). The next diagram presents the W^+W^- boson loop and this cross section is calculated within `LoopTools` [6]. Fig. 1(c) presents the diagram for the non-perturbative mechanism of both photons fluctuation into vector mesons and their subsequent interaction. This involves the Reggeon and Pomeron exchanges between ρ, ω or ϕ light mesons. The (d) diagram of Fig. 1 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]. The finite fermion masses, the full momentum structure in the loops and all helicity amplitudes are included. When considering processes with gluon exchange, one can use the so-called regularization parameter, m_g, which can be: $m_g = 0$ for usual gluon exchange, however $m_g = 0.75$ GeV is suggested by lattice QCD [8]. Panel (e) shows a diagram for s-channel $\gamma\gamma \to$ pseudoscalar/scalar/tensor resonances which also contributes to the $\gamma\gamma \to \gamma\gamma$ process.

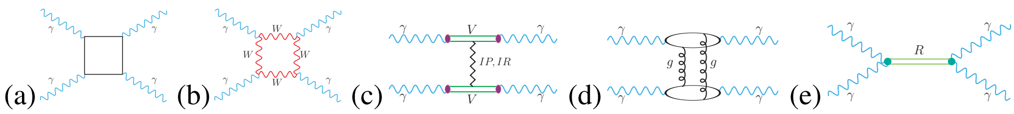

Figure 1: $\gamma\gamma \to \gamma\gamma$ scattering: (a) fermionic boxes, (b) one-loop W box, (c) the VDM-Regge, (d) two-gluon exchange mechanism and (e) resonance scattering.

In the present analysis we take into account pseudoscalar and scalar mesons that decay into two-photons: η, $\eta'(958)$, $\eta_c(1S)$, $\eta_c(2S)$, $\chi_{c0}(1P)$. The amplitude for the $\gamma\gamma$ production through the s-channel exchange of a pseudoscalar/scalar mesons is the same as in Ref. [9]. In addition, also background from the $\gamma\gamma \to \pi^0(\to \gamma\gamma)\pi^0(\to \gamma\gamma)$ process is considered. In Ref. [9] we constructed a multi-component model which described e.g. the Belle [10] and Crystal Ball [11] data for $\gamma\gamma \to \pi^0\pi^0$. In [9] both $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to \pi^0\pi^0$ reactions were considered 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, Brodsky-Lepage and handbag mechanisms in these processes was studied. A detailed formalism and the description of these sub-processes can be found in [9]. If only two photons from different neutral pions are detected within the given experimental range of rapidities and transverse momenta such an event could be wrongly identified as $\gamma\gamma \to \gamma\gamma$ scattering if no extra cuts are imposed to reduce or eliminate such a background.

The nuclear cross section for each above process is calculated with the help of equivalent photon approximation (EPA). Here we consider only ultra-peripheral collisions, that is the impact parameter (b) determining the distance between the centres or the midpoints of the colliding nuclei is bigger than the sum of the radii. In our approach, we use the equivalent photon approximation in the impact parameter space.

The current analysis concerns the production of diphoton pairs originating from

- boxes, VDM-Regge mechanism and two-gluon exchange,
- resonances which decay into $\gamma\gamma$ state,
- pionic background.

2. Results and conclusion

Light-by-light scattering was realized experimentally only recently [12–15]. About one year before the first experimental results which were obtained by the ATLAS collaboration, we have studied light-by-light scattering via the fermion loop and with the help of the non-perturbative mechanism of photons fluctuation into light vector mesons (VDM-Regge model) [16]. We have considered only ultra-peripheral lead-lead collisions. For ions of charges Z_1, Z_2, the cross section is enhanced by a factor of $Z_1^2 Z_2^2$ 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.

ATLAS measured a fiducial cross section of $\sigma = 78 \pm 13$ (stat.) ± 7 (syst.) ± 3 (lumi.) nb [12] [13] and our theoretical calculations (including experimental acceptance) gave 51 ± 0.02 nb [16]. The ATLAS comparison of its experimental results to the predictions from Ref.[16] show a reasonable agreement (see Fig. 3 in Ref. [12]). The ATLAS detector recorded data of lead–lead collision at a center-of-mass energy per nucleon pair of 5.02 TeV. The measurement of the diphoton pair was carried out in the midrapidity region. The $\gamma\gamma$ invariant mass was limited to $M_{\gamma\gamma} > 6$ GeV. Similarly as the ATLAS collaboration, the CMS collaboration measured the same process but for a somewhat lower threshold of invariant mass of the produced diphotons [14]. The fiducial light-by-light scattering cross section was measured to be $\sigma = 120 \pm 46$ (stat.) ± 28 (syst.) ± 4 (theo.) nb. We have recalculated this process including the CMS acceptance and we obtained $\sigma = (103 \pm 0.034)$ nb which is in a good agreement with the CMS result. Due to relatively large cuts on the photon transverse momenta, only large diphoton invariant masses ($M_{\gamma\gamma} > 5$ GeV) were measured by the ATLAS and CMS collaborations. We believe that in a future one could go to larger luminosity, higher collision energies and smaller diphoton invariant masses [17].

Next, predictions for the ALICE and LHCb experiment will be shown. The ALICE detector facilitates a measurement of outgoing photons in the midrapidity region ($|\eta_\gamma| < 0.9$). Photons with a transverse energy smaller than 200 MeV cannot be detected. The above calculations will be compared with the results for the more forward rapidity region ($2 < \eta < 4.5$), i.e. for LHCb acceptance. Here we assume that any photon with $p_{t,\gamma} > 200$ MeV will be measured.

Fig. 2 illustrates contribution of $\gamma\gamma \to \gamma\gamma$ signal (black line), background (blue dashed line) and resonances (green lines) to the diphoton invariant mass distribution for ALICE (a) and LHCb conditions (b). 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. Contributions suggest that one could be able to measure the LO QED fermionic signal above $M_{\gamma\gamma} > 2$ GeV. Below this value, two very clear peaks show up, corresponding to η and $\eta'(958)$

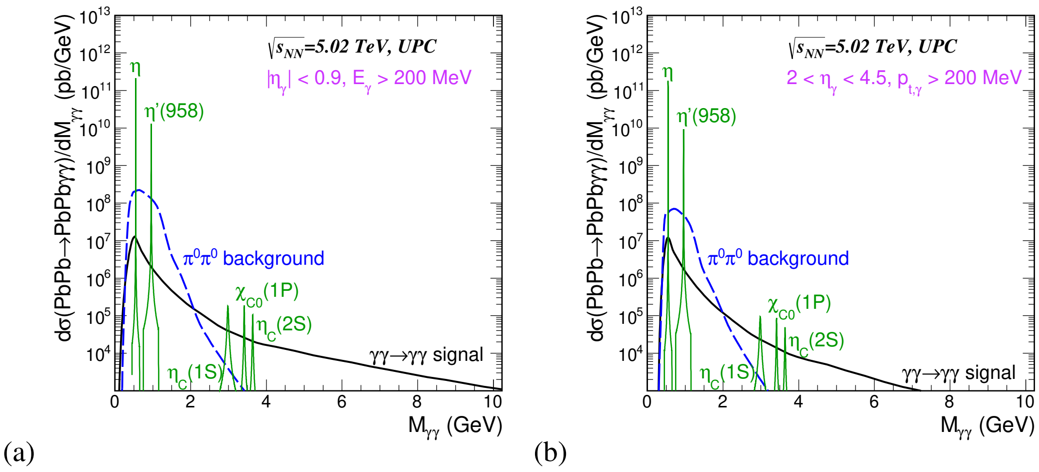

Figure 2: Differential nuclear cross section for $PbPb \to PbPb\gamma\gamma$ as a function of $\gamma\gamma$ invariant mass. (a) ALICE and (b) LHCb kinematical cuts are included. In addition, the energy experimental resolution is taken into account. Here $\sqrt{s_{NN}}$ = 5.02 TeV.

mesons that decay into two-photon final state. Inclusion of the Gaussian distribution to simulate experimental energy resolution causes only a little smearing of the resonant signals. Then the transverse momenta of each of the photons takes the form: $p_{i,t} = p_t + \left(\frac{p_t}{E_i}\right)\delta E_i$. It seems worth mentioning that the peak corresponding to a resonance very strongly depends on the number of bins. The maximum value of the differential cross section emerges exactly at m_R.

Table 1: Total nuclear cross section in nb.

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

In Table 1 one can find values of the total nuclear cross section for fermionic boxes, pionic background and five types of mesons. The cross section is given in two ranges of the diphoton invariant masses [17]. 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 the transverse momentum of photons is included. The largest cross section is obtained for the $\gamma\gamma \to \eta \to \gamma\gamma$ resonance scattering. Additionally, 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 non-wanted background.

Fig. 3 corresponds to the next run at the LHC. Predicted values for lead-lead collision is

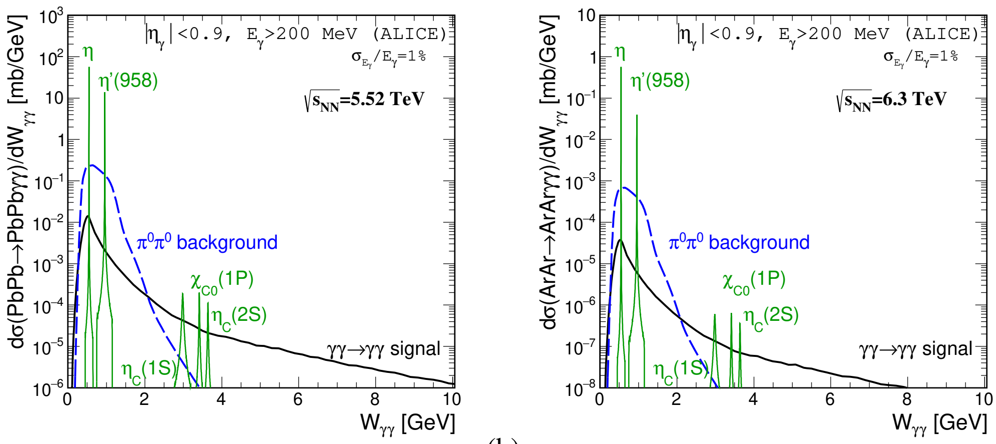

Figure 3: Differential cross section as a function of $W_{\gamma\gamma} = M_{\gamma\gamma}$ for (a) PbPb→PbPb$\gamma\gamma$ and (b) ArAr→ArAr$\gamma\gamma$. The collision energy at the center-of-mass of the heavy ion collision is 5.52 TeV and 6.3 TeV for lead-lead and argon-argon respectively.

$\sqrt{s_{NN}}$ = 5.52 TeV (Fig. 3(a)) and for argon-argon it is $\sqrt{s_{NN}}$ = 6.3 TeV (Fig. 3(b)). The analysis focuses on lower diphoton invariant masses again. At lower energies ($W_{\gamma\gamma} < 4$ GeV) meson resonances may play an important role in addition to the Standard Model box diagrams or proposed pionic background. The inclusion of energy resolution has a significance mainly for $\gamma\gamma \to \eta, \eta' \to \gamma\gamma$ resonance scattering and this contribution will be measured with a good statistics. However, the resonance signal is modified when including experimental energy resolution 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 the same. These figures suggest that one could be able to measure the $\gamma\gamma \to \gamma\gamma$ scattering above $W_{\gamma\gamma} > 2$ GeV. Comparing Fig. 3 (a) with (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 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. Comparing contributions for lead-lead and argon-argon collisions, one can deduce that the collision of lighter nuclei is less favorable. However, we can hope the luminosity in the run with Ar-Ar collision will be higher.

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