

# Importance of mesons in light-by-light scattering in ultraperipheral lead-lead collisions at the LHC

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**Abstract.** Possibility of PbPb→PbPb $\gamma\gamma$  measurement at smaller ( $< 5$  GeV) diphoton invariant mass will be presented. Analysis focuses only on ultraperipheral heavy-ion collisions. This estimate shows that the  $\gamma\gamma \rightarrow \gamma\gamma$  collisions can be measured at the LHC by ALICE and LHCb experiments for diphoton invariant mass  $> 2$  GeV. Predictions for the  $\gamma\gamma \rightarrow \eta, \eta' \rightarrow \gamma\gamma$  resonance scattering shows that these resonances can be measured with rather good statistics. A possible observation of peaks related to intermediate  $\eta, \eta'(958), \eta_c(1S), \eta_c(2S), \chi_{c0}(1P)$  mesons will be presented too. Attempts of reduction of background which comes from dipion production will be considered.

## 1 Introduction

Light-by-light scattering was realized experimentally only recently [1, 2] in ultraperipheral ultrarelativistic heavy ion collisions. For 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. ATLAS measured a fiducial cross section of  $\sigma = 70 \pm 24$  (stat.)  $\pm 17$  (syst.) nb and our theoretical calculations (including experimental acceptance) gave  $49 \pm 10$  nb [3]. ATLAS comparison of its experimental results to the predictions from Ref.[3] show a reasonable agreement. In comparison, the CMS Collaboration measured the same process but for smaller  $\gamma\gamma$  invariant mass ( $M_{\gamma\gamma} > 5$  GeV). Our theoretical calculations  $103 \pm 0.034$  nb are in the good agreement with the experimental fiducial cross section:  $\sigma = 122 \pm 46$  (stat.)  $\pm 29$  (syst.) nb.

This note will answer to a question whether we can go to lower  $\gamma\gamma$  scattering energies at the LHC. The calculations are directed to ALICE and LHCb experimental limitation. At lower energies ( $W_{\gamma\gamma} < 4$  GeV) meson resonances may play some role in addition to the Standard Model box diagrams [4] or double photon fluctuations into light vector mesons [3] or two-gluon exchanges [5].

## 2 Theory

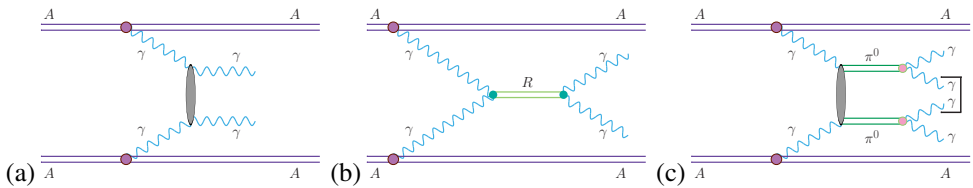
The phase space integrated cross section for nuclear ultraperipheral collisions (UPCs) in impact parameter space ( $b$ ) can be expressed through the five-fold integral

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$$\sigma_{PbPb \rightarrow PbPbX_1X_2}(\sqrt{S_{PbPb}}) = \int \sigma_{\gamma\gamma \rightarrow X_1X_2}(W_{\gamma\gamma}) N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) S_{abs}^2(\mathbf{b}) \times d^2b d\bar{b}_x d\bar{b}_y \frac{W_{\gamma\gamma}}{2} dW_{\gamma\gamma} dY_{X_1X_2}, \quad (1)$$

where here  $X_1X_2$  is a pair of photons or neutral pions. Incoming photons energy  $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$  is expressed through energy of the single photon  $\omega_i$  and  $Y_{X_1X_2} = (y_{X_1} + y_{X_2})/2$  is rapidity of the outgoing system.  $\mathbf{b}_1$  and  $\mathbf{b}_2$  are impact parameters of the photon-photon collision point with respect to parent nuclei 1 and 2, respectively, and  $\mathbf{b} = \mathbf{b}_1 - \mathbf{b}_2$  is the standard impact parameter for the  $A_1A_2$  collision. The absorption factor  $S_{abs}^2(\mathbf{b})$  assures UPC which means that the nuclei do not undergo nuclear breakup. The photon flux ( $N(\omega_i, \mathbf{b}_i)$ ) is expressed through a nuclear charge form factor of the nucleus. In our calculations we use a realistic form factor which is a Fourier transform of the charge distribution in the nucleus. More details can be found e.g. in [6]. The elementary cross section  $\sigma_{\gamma\gamma \rightarrow X_1X_2}$  in Eq. (1) for the  $\gamma\gamma \rightarrow \gamma\gamma$  scattering is calculated within LO QED with fermion loops (see left panel of Fig. 1 in Ref. [3]). The elementary cross section for  $\gamma\gamma \rightarrow \pi\pi$  was studied in detail in Ref. [7].



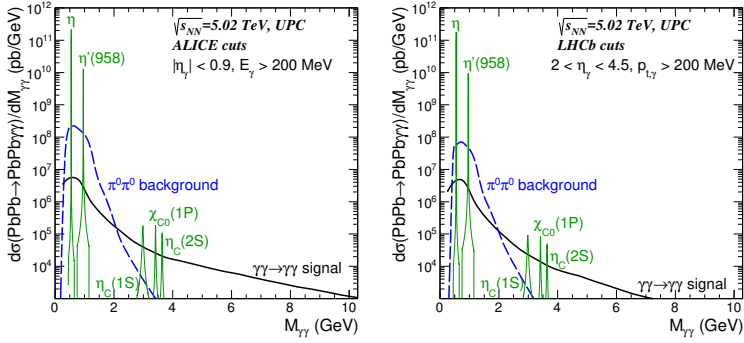
**Figure 1.** The continuum  $\gamma\gamma \rightarrow \gamma\gamma$  scattering (a) which includes box diagrams with leptons and quarks only [3]. Panel (b) shows diagram for  $s$ -channel  $\gamma\gamma \rightarrow$  pseudoscalar/scalar/tensor resonances which contribute to the  $\gamma\gamma \rightarrow \gamma\gamma$  process. Diagram (c) presents background related to the  $\gamma\gamma \rightarrow \pi^0\pi^0$  subprocess when only one photon from each  $\pi^0 \rightarrow \gamma\gamma$  decay is measured.

### 3 Theoretical predictions

Studies are dedicated to ALICE and LHCb detector. The limitation of the ALICE detector is given by the detector geometry:  $|\eta_\gamma| < 0.9$  and for LHCb we have:  $2.0 < \eta_\gamma < 4.5$ . Photons outside these regions are undetected. The ALICE experiment can measure photons for energies  $E_\gamma > 0.2$  GeV and LHCb:  $E_{t,\gamma} > 0.2$  GeV (taking into account  $m_\gamma = 0$  one gets  $E_{t,\gamma} = p_{t,\gamma}$ ). The calculations include effect of experimental energy resolution. For ALICE [8] and LHCb conditions [9] the resolution functions are parametrized as:

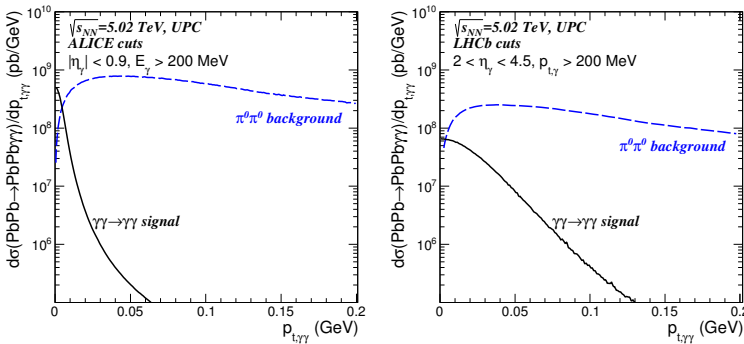
$$\left(\frac{\sigma_{E_\gamma}}{E_\gamma}\right)^{ALICE} = 1\%, \quad \left(\frac{\sigma_{E_\gamma}}{E_\gamma}\right)^{LHCb} = \frac{0.085}{\sqrt{E_\gamma}} + \frac{0.003}{E_\gamma} + 0.008. \quad (2)$$

In purely theoretical calculation both signal photons have the same transverse momentum values  $p_{t,\gamma}$  and transverse momentum of the diphoton pair is the Dirac-delta function  $\delta(p_{t,\gamma\gamma})$ . In order to include more realistic conditions, we can use Gaussian distribution to obtain a smearing in invariant mass or in scalar asymmetry ( $A_S = (|p_{t1}^2| - |p_{t2}^2|)/(|p_{t1}^2| + |p_{t2}^2|)$ ). Then the transverse momenta of each of the photons takes the form:  $p_{i,t} = p_t + \left(\frac{p_t}{E_i}\right)\delta E_i$ . Here  $\delta E_{i=1,2}$  is random number with Gaussian distribution with  $\sigma_{E_i}$  given by Eq. (2).



**Figure 2.** Diphoton invariant mass distribution for kinematical cuts which are given in the figure: left panel is for ALICE experiment and right panel corresponds to LHCb experiment. The black solid lines are the signal due to Standard Model box contribution, the blue dashed lines correspond to the  $\pi^0\pi^0$  background, while solid green lines are for resonant mesonic states.

Fig. 2 shows comparison of contributions which come from the continuum  $\gamma\gamma \rightarrow \gamma\gamma$  scattering and  $\gamma\gamma \rightarrow \text{resonances} \rightarrow \gamma\gamma$  as well as the background. The background means the cases when only two (out of four) photons pass the fiducial requirements. This contribution dominates at low invariant diphoton masses ( $< 2$  GeV). These figures suggest that one could be able to measure the  $\gamma\gamma \rightarrow \gamma\gamma$  scattering above  $W_{\gamma\gamma} > 2$  GeV. In the case of this 1-dimensional distribution, including experimental energy resolution modifies resonance signal. Total cross section is of course still the same but smearing of a resonance produces a peak about one order of magnitude smaller than without experimental resolution. The included energy resolution has a significance mainly at  $\eta$  and  $\eta'(958)$  peaks.



**Figure 3.** The differential cross section as a function of  $p_{t,\gamma\gamma} = (|\vec{p}_{t1} + \vec{p}_{t2}|)$  (transverse momentum of the diphoton pair) for the PbPb $\rightarrow$ PbPb $\gamma\gamma$  reaction at  $\sqrt{s_{NN}} = 5.02$  TeV.

The measurement of two out of four photons for the  $\pi^0\pi^0$  signal leads to relatively large transverse momenta of the measured  $\gamma\gamma$  pair as shown in Fig. 3. The left panel corresponds to the ALICE kinematical limitation and the right panel shows distribution for the LHCb cut. Theoretically, fermionic box signal takes a form of the Dirac-delta function, but due to experimental energy resolution, one can observe some smearing and one can see a very

limited region of very small  $p_{t,\gamma\gamma} = (|p_{t1}^{\vec{}} + p_{t2}^{\vec{}}|)$  where the  $\gamma\gamma \rightarrow \gamma\gamma$  signal is above the  $\pi^0\pi^0$  background. It seems more difficult to separate the background from the signal for the LHCb cuts (right panel). The situation for the ALICE fiducial region (left panel) looks a little bit better. By imposing extra cuts on  $p_{t,\gamma\gamma} < 0.005, 0.01$  and  $0.02$  GeV one can reduce the "unwanted" background [10], however no complete removing of the background is possible. The cut on  $p_{t,\gamma\gamma}$  seems the most efficient to reduce the  $\pi^0\pi^0$  background.

**Table 1.** Total nuclear cross section in nb. Only "standard" cuts for ALICE and LHCb are imposed.

Energy	$W_{\gamma\gamma} = (0 - 2)$ GeV		$W_{\gamma\gamma} > 2$ GeV	
	ALICE	LHCb	ALICE	LHCb
Fiducial region				
boxes	4 890	3 818	146	79
$\pi^0\pi^0$ background	135 300	40 866	46	24
$\eta$	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

The concluding section includes a Table with total cross section for ultraperipheral lead-lead collision at the LHC. As can be seen, the largest cross section is obtained for  $\eta$  resonant production. The Table 1 includes a list of total nuclear cross sections in two ranges of invariant mass: the first one is for the value of invariant mass from 0 to 2 GeV, second one for  $M_{\gamma\gamma}$  larger than 2 GeV. Here  $M_{\gamma\gamma}^{max} = 50$  GeV for fermionic boxes,  $M_{\gamma\gamma}^{max} = 5$  GeV for the  $\pi^0\pi^0$  background and  $M_{\gamma\gamma} = (m_R - 1 \text{ GeV}, m_R + 1 \text{ GeV})$  for resonances were assumed. The background contribution, as was discussed above, can be reduced. Here no extra cuts on the background are imposed. Due to large masses of  $\eta_c(1S)$ ,  $\chi_{c0}(1P)$  and  $\eta_c(2S)$  mesons, the contribution from these resonances appears only at "higher" energies. These cross sections are, however, very small in comparison to the other mechanisms. The  $\gamma\gamma$  scattering through  $\eta$  and  $\eta'$  resonances should be easily measurable. A precise measurement of the continuum part of the signal for  $W_{\gamma\gamma} < 2$  GeV is not completely clear and requires experimental studies.

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## References

- [1] ATLAS Collaboration (M. Aaboud et al.), *Nature Phys.* **13** 852 (2017)
- [2] CMS Collaboration, CMS-PAS-FSQ-16-012 (2018)
- [3] M. Kłusek-Gawenda, P. Lebedowicz and A. Szczurek, *Phys. Rev. C* **93** 044907 (2016)
- [4] P. Lebedowicz and A. Szczurek, *Phys.Lett. B* **772** 330 (2017)
- [5] M. Kłusek-Gawenda, W. Schäfer and A. Szczurek, *Phys.Lett. B* **761** 399 (2016)
- [6] M. Kłusek-Gawenda and A. Szczurek, *Phys.Rev. C* **82** 014904 (2010)
- [7] M. Kłusek-Gawenda and A. Szczurek, *Phys.Rev. C* **87** 054908 (2013)
- [8] F. Bock, *Neutral Pion and Eta Meson Production in pp and Pb-Pb Collisions at the LHC with the ALICE Detector*, <https://www.physi.uni-heidelberg.de/fbock/Masterthesis.pdf> (2012)
- [9] K. Govorkova, *Phys. Atom. Nucl.* **79** (2016) 1474
- [10] M. Kłusek-Gawenda, R. McNulty, R. Schicker and A. Szczurek, in preparation