POSSIBILITIES OF LIGHT-BY-LIGHT SCATTERING MEASUREMENT IN FoCal DETECTOR*

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The ATLAS Collaboration's 2017 article validated light-by-light scattering, showing photon pair production from strong electromagnetic field interactions during ultraperipheral collisions of heavy ions. The next phase in light-by-light scattering research involves an extension to smaller values of transverse momentum and diphoton invariant mass. An opportunity for scientific advancement will come with new ATLAS measurements with new rapidity acceptance, and with the FoCal detector, developed by the ALICE Collaboration, which will start taking data in 2027. Measurements with FoCal have the potential to measure low-mass meson resonances that evade modern detectors. Both acceptance and resolution of the FoCal detector were taken into account in the calculation presented here.

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1. Introduction

The first experimental measurement of light-by-light scattering took place in 2016. A year later, an article by the ATLAS group was published in Nature [1], confirming this key prediction of the quantum field theory from the early 20$^{\text{th}}$ century [2, 3]. This measurement was possible due to the enhancement of the cross section for the quantum process occurring in heavy-ion collisions, which depends on the fourth power of the atomic number. In the following years, experiments by CMS [4] and ATLAS [5] made further measurements of this effect within similar kinematic ranges: invariant mass $M_{\gamma\gamma} > 5$ GeV, photon rapidity $|y| < 2.4$, and transverse

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momentum of photon $p_t^\gamma > 2$ GeV by CMS, and with $p_t^\gamma > 2.5$ GeV by ATLAS. The theoretical description of the data was presented in publications [6, 7]. One can see the good agreement of the theory with the experiment in the invariant mass range above 10 GeV. Changing the kinematic ranges of the experiments may also allow for the observation of previously unregistered processes of $\gamma\gamma \to \gamma\gamma$, such as the production of η and η' meson resonances. Moreover, as shown in [8], for the invariant mass range below 1 GeV, cross sections for the light-by-light scattering via fermionic loop dramatically increase. Therefore, expanding the study of light-by-light scattering to additional kinematic ranges appears crucial for a full understanding of the discussed process. This article will present predictions for proposed new measurements by the ATLAS group. The potential of the FoCal detector, developed by the ALICE group, will also be discussed. Utilizing this detector may enable the first measurement of the light-by-light scattering phenomenon in the invariant mass range below 1 GeV.

2. Formalism

To describe the light-by-light scattering in ultraperipheral heavy-ion collisions, the so-called Equivalent Photon Approximation (EPA) formalism, was developed in 1934 independently by von Weizsäcker [9] and Williams [10]. The equation utilized in the calculation consists of the elementary cross section for light-by-light scattering and quasi-classical approximation of electromagnetic field surrounding relativistic heavy ion by photon flux. The complete equation used for calculation is presented below:

$$\begin{aligned} \sigma_{A_1A_2\to A_1A_2X_1X_2} \;=\; & \int \frac{\mathrm{d}\sigma_{\gamma\gamma\to X_1X_2}(M_{\gamma\gamma})}{\mathrm{d}\cos\theta} \times N(\omega_1,b_1)N(\omega_2,b_2)S^2_{abs}(b) \\ & \times \frac{M_{\gamma\gamma}}{2}\mathrm{d}M_{\gamma\gamma}\,\mathrm{d}Y_{X_1X_2}\,\mathrm{d}\bar{b}_x\,\mathrm{d}\bar{b}_y\,\mathrm{d}^2b \\ & \times \frac{\mathrm{d}\cos\theta}{\mathrm{d}y_{X_1}\,\mathrm{d}y_{X_2}\,\mathrm{d}p_{\mathrm{t}}} \times \mathrm{d}y_{X_1}\,\mathrm{d}y_{X_2}\,\mathrm{d}p_{\mathrm{t}}\,. \end{aligned} \tag{1}$$

Here, X_1X_2 means two produced particles. The diphoton energy $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ depends on the energy of photons $\omega_{1,2}$. Impact parameters $(b_{1,2})$ are related to the photon–photon collision point. These components fulfill the relation: $\boldsymbol{b} = \boldsymbol{b}_1 - \boldsymbol{b}_2$. Rapidities of outgoing particles are represented by y_{X_i}. The survival factor $S^2_{abs}(b)$ is expressed by the Woods–Saxon potential. Also, the photon flux $N(\omega_i, b_i)$ is described by the realistic form factor of the nucleus, which depends on the Fourier transform of the charge distribution [11].

In this paper, two quantum processes $\gamma\gamma \to \gamma\gamma$ are discussed. The first one is the fermionic loop, otherwise known as the box contribution. The amplitude of this process was calculated using the Mathematica-based software FeynCalc [12]. To determine the elementary cross section, five different combinations of helicity photons must be considered.

The second process is the formation of resonances due to the interaction of two photons and their subsequent decay. To describe the amplitude, relativistic Breit–Wigner functions were used

$$\mathcal{M}_{\gamma\gamma\to R\to\gamma\gamma}(\lambda_1,\lambda_2) = \frac{\sqrt{64\pi^2 W_{\gamma\gamma}^2 \Gamma_R^2 \,\mathrm{Br}^2(R\to\gamma\gamma)}}{\hat{s} - m_R^2 - i m_R \Gamma_R} \times \frac{1}{\sqrt{2\pi}}\delta_{\lambda_1-\lambda_2}\,. \tag{2}$$

The Γ_R parameter is the width of resonance, $\mathrm{Br}(R \to \gamma\gamma)$ is the meson branching ratio for decay to two-photon state, and m_R is the mass of produced meson. Details of the calculations are presented in works [13, 14]. Parameters of resonances are shown in Table 1.

Table 1. Parameters of resonances utilized in calculations.

Meson	m_R [MeV]	Γ^R [MeV]	$\mathrm{Br}(R \to \gamma\gamma)$
η	547.862	1.31×10^{-3}	0.3941
η'	957.78	0.188	0.0221

3. Calculations

3.1. ATLAS

According to the ATLAS detector's Internal Tracker improvement project [15], the rapidity range of measurements will change. The Pixel Detector should extend this range to $y = 4$. It will be almost double the present range, which is $|y| < 2.4$. However, there will be no change in the minimum threshold for transverse momentum and invariant mass, which will be 2.5 GeV and 5 GeV, respectively. Figure 1 shows the theoretical predictions together with a comparison to previous measurements. The change in the rapidity range should translate into an increase in the cross section by 30%. The total cross sections are summarised in Table 2. It is also worth mentioning the increased integrated luminosity of future experiments, which for the recent ATLAS measurement was 2.2 nb^{-1}. This should be expected to increase the number of detected light-by-light scattering events, significantly improving the statistics.

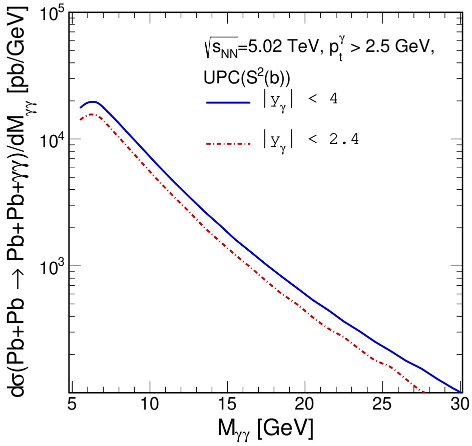


Fig. 1. Differential cross section as a function of diphoton invariant mass for future (blue solid line) and recent ATLAS measurement (red dashed line).

Table 2. Total cross section for light-by-light scattering in ultraperipheral heavy-ion collision with energy $\sqrt{s_{NN}} = 5.02$ TeV, in the range of photon transverse momentum $p_t^\gamma > 2.5$ GeV and diphoton invariant mass $M_{\gamma\gamma} > 5$ GeV.

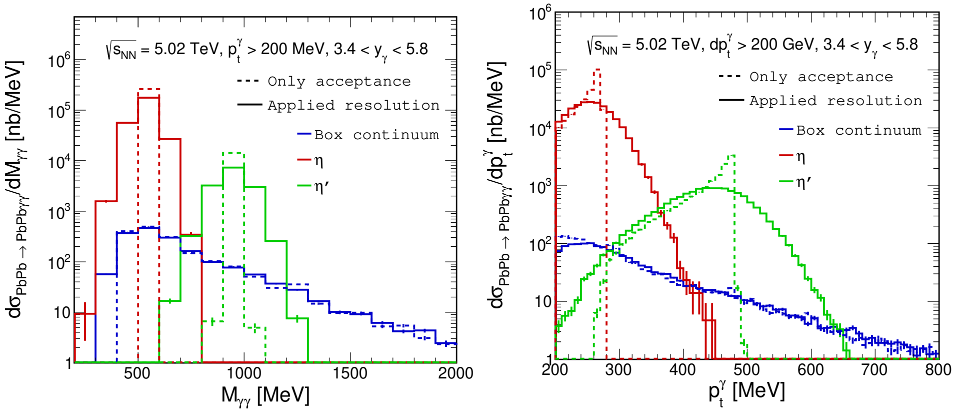
$\lvert y_\gamma \rvert <$	$\sigma_{\rm tot}^{\rm theo}$ [nb]	$\sigma_{\rm tot}^{\rm exp}$ [nb]
2.4	77.084 ± 0.005	120 ± 22
4	100.444 ± 0.027	planned

3.2. FoCal

In its conception, the Forward Calorimeter for the ALICE Collaboration is constructed to study the dynamics of hadronic matter at small x. In the present work, the detector's potential for studying photons in ultraperipheral collisions is explored due to its unique kinematic range. The light-by-light scattering analysis in the rapidity range of $3.2 < y < 5.8$ and invariant mass below 1 GeV would be an excellent opportunity to test theoretical predictions. Furthermore, it would allow meson resonances to be observed, as discussed in paper [8]. An obstacle that may hinder the measurement of the production of η and η' resonances in the $\gamma\gamma \to \gamma\gamma$ process may be the resolution of the detector. It is expressed by a formula [16]

$$\frac{\sigma_E}{E} = \frac{28.5\%}{\sqrt{E\ [\text{GeV}]}} + \frac{6.3\%}{E\ [\text{GeV}]} + 2.95\%\,. \tag{3}$$

Therefore, a Monte Carlo simulation was prepared to check the effect of resolution on photon measurements. Both energy and position resolution were included in the analysis. An effective calorimeter granularity of 1 mm^2 was taken as the position uncertainty of the measurements. Figure 2 shows the results of the analysis, both purely theoretical and with the blurring effect of detector resolution. Despite the significant impact on the peaks, resonances should be visible, however, they will interfere with the measurements of the light-by-light scattering continuum.



(a) (b)

Fig. 2. Results of combined theoretical predictions for light-by-light scattering and Monte Carlo simulation of energy and position resolution for the FoCal detector: (a) diphoton invariant mass, (b) transverse momentum of the measured photon.

4. Conclusion

Further experimental measurements of light-by-light scattering are the key to advancing the theory and, consequently, understanding interactions between photons. The above paper discusses the potential of upcoming measurements by the ATLAS and ALICE groups in Run 4 at the LHC. Expanding the rapidity range in the ATLAS group detector will provide additional validation of the current state of knowledge. The measurements of the FoCal detector seem highly promising. This detector should allow for the measurement of photons arising from the resonance decay of η and η' mesons, which have not been observed so far.

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