The Role of Mesons in Light-by-Light Scattering at Low Transverse Momentum

Paweł Jucha[1,*] and *Mariola* Kłusek-Gawenda[1,**]

[1]Institute of Nuclear Physics Polish Academy of Sciences,
ul. Radzikowskiego 152, PL-31-342 Kraków, Poland

Abstract. Light-by-Light scattering involves the interaction of two strong electromagnetic fields, resulting in the emission of two photons. In the next years, the ALICE 3 experiment is going to measure photons in the transverse momentum range p_t = 1 - 50 MeV and 100 - 5000 MeV, which have not been investigated so far. Moving to a lower range of p_t imposes a consideration of low-energy meson resonances which decay into two-photon channel. Furthermore, experimental possibilities to investigate the VDM-Regge mechanism are discussed. The role of the vertical background in light-by-light scattering measurements is also shown.

1 Introduction

The light-by-light scattering was first described in a groundbreaking paper [1] in 1934. Depicted process is referred to fermionic loops (boxes). Despite representing tremendous progress towards the development of quantum field theory, this effect remained unobservable experimentally. It changed in 2017 when the ATLAS experiment published a paper presenting experimental evidence for light-by-light scattering for the first time [2]. The theoretical description of the obtained results was presented in the works [5, 6]. The observation of this subtle process was made possible by enhancing photon flux during ultrarelativistic, ultraperipheral heavy ion collisions. This enhancement scales the cross section with the fourth power of the atomic number of the colliding nuclei (Z^4).
Following the ATLAS group's article, two more papers presenting experimental results of light-by-light scattering were published [3, 4]. However, each of these measurements was conducted for photons with a transverse momentum greater than 2 GeV: ATLAS $p_t > 2.5$ GeV, CMS $p_t > 2$ GeV. As theoretical studies have shown [6], the cross section for light-by-light scattering dramatically increases for measurements at transverse momenta less than 1 GeV. In this limit of p_t, the possibility of observing processes that have not been explored so far arises, such as meson resonances or VDM-Regge.
The observation of photons with transverse momentum less than 1 GeV will be possible in the ALICE 3 experiment planned for the 2030s [7]. In this context, it is vital to not only generate predictions for light-by-light scattering but also to estimate the background. The primary component of this background is likely to be the creation of two π^0 mesons, as demonstrated in [8].

*e-mail: Pawel.Jucha@ifj.edu.pl
**e-mail: Mariola.Klusek@ifj.edu.pl

2 Formalism - Equivalent Photon Approximation

Describing ultraperipheral collisions of heavy ions, the Equivalent Photon Approximation was used. This formalism consists of two parts. The first part is the elementary cross section, describing the quantum effect of photon interaction. The second part is quasi-classical approximations of the electromagnetic field surrounding the accelerated ions using photon fluxes. The formula allowing for the determination of the nuclear cross section is presented below:

$$\sigma_{A_1A_2\to A_1A_2X_1X_2} = \int \frac{\mathrm{d}\sigma_{\gamma\gamma\to X_1X_2}(M_{\gamma\gamma})}{\mathrm{d}\cos\theta} \times N(\omega_1, b_1)N(\omega_2, b_2)S^2_{abs}(b) \times \frac{M_{\gamma\gamma}}{2} dM_{\gamma\gamma} dY_{X_1X_2} d\bar{b}_x d\bar{b}_y d^2b \times \frac{\mathrm{d}\cos\theta}{dy_{X_1}dy_{X_2}dp_t} \times dy_{X_1}dy_{X_2}dp_t. \quad (1)$$

Here X_1X_2 is a pair of produced particles. Di-photon energy $W_{\gamma\gamma} = \sqrt{4\omega_1\omega_2}$ is expressed through the energy of the single photon ω_i, b_i is an impact parameter related to photon-photon collision point where the components of impact parameter fulfil the relation: $b = b_1 - b_2$, y_{X_i} are rapidities of the outgoing particles. The surviving factor $S^2_{abs}(b)$ was modelled through Woods-Saxon potential. The photon flux $N(\omega_i, b_i)$ depends on Z^2. The photon flux formula is described by the realistic form factor of the nucleus which depends on the Fourier transform of the charge distribution.

3 Theoretical predictions

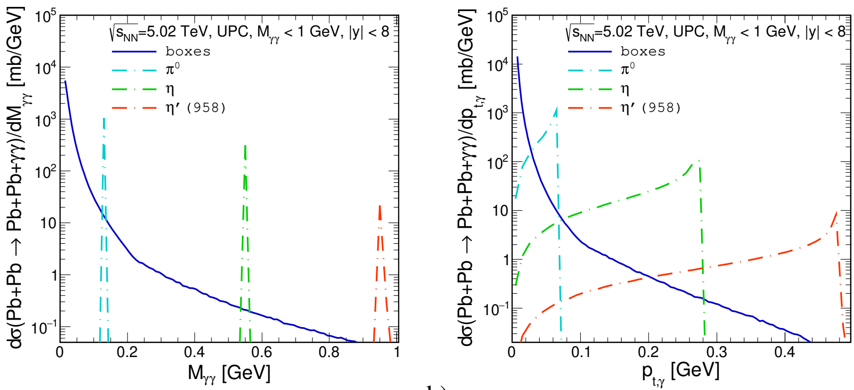
3.1 Resonances

The quantum description of the meson resonance phenomenon has been presented in [9]. Here are the formulas that were used to calculate the distribution of the elementary cross section:

$$\frac{\mathrm{d}\sigma_{\gamma\gamma\to R\to\gamma\gamma}(W_{\gamma\gamma})}{\mathrm{d}\cos\theta} = \frac{1}{32\pi W^2_{\gamma\gamma}} \frac{1}{4} \sum_{\lambda_1,\lambda_2} |\mathcal{M}_{\gamma\gamma\to R\to\gamma\gamma}(\lambda_1, \lambda_2)|^2 \quad (2)$$

$$\mathcal{M}_{\gamma\gamma\to R\to\gamma\gamma}(\lambda_1, \lambda_2) = \frac{\sqrt{64\pi^2 W^2_{\gamma\gamma}\Gamma^2_R Br^2(R\to\gamma\gamma)}}{\hat{s} - m^2_R - i m_R\Gamma_R} \times \frac{1}{\sqrt{2\pi}}\delta_{\lambda_1-\lambda_2} \quad (3)$$

where m_R represents the mass of the meson, Γ_R is the resonance width, and $Br(R \to \gamma\gamma)$ is the branching ratio for the $\gamma\gamma$ decay channel. Figure 1 shows the results of calculations of the cross section distribution for rapidity in the range -8 < y < 8, transverse momentum $p_t > 5$ MeV, and a di-photon mass $M_{\gamma\gamma} < 1$ GeV. In Figure 1a), the cross section distribution in invariant mass of two photons for resonances and light-by-light scattering continuum is presented. Here, characteristic peaks for π^0, η, and η' mesons are visible, dominating over the continuum. Figure 1b) presents the cross section distribution in transverse momentum. The maximum of the cross section distribution for individual resonances is seen for a half of the meson mass $p_t \approx m_R/2$. From an experimental standpoint, this predictions holds significant importance.



a) b)

Figure 1. Nuclear cross section for light-by-light scattering processes for photon transverse momentum $p_t > 5$ MeV, di-photon invariant mass $M_{\gamma\gamma} < 1$ GeV and photon rapidities $y_\gamma = (-8, 8)$: resonances vs boxes. a) Di-photon invariant mass distribution; b) Transverse momentum distribution.

3.2 VDM-Regge

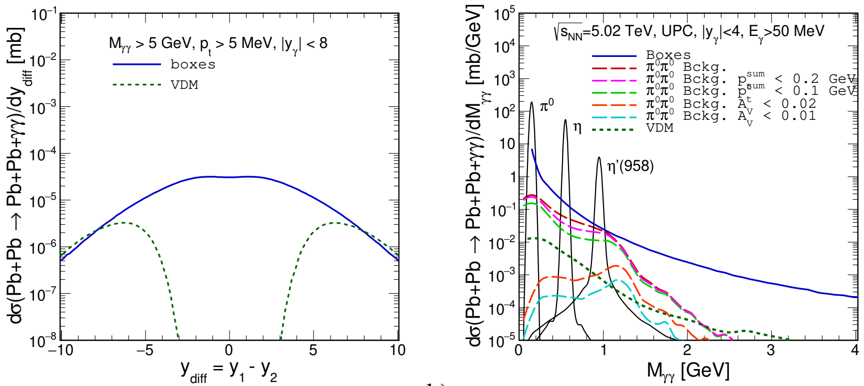
Fluctuations of photons' quantum numbers to vector meson states allow interactions between them by strong interaction. The description details of the VDM-Regge process in the context of light-by-light scattering and the details of calculations have been presented in the article [6]. It has been shown that observing the VDM mechanism requires high photon energies and small transverse momenta. It is also worth noting that there is a wide range of rapidity involved in this aspect. Measuring this process can facilitate the introduction of a new variable: the difference in photon rapidity. Such a distribution has been shown in Figure 2a). It can be seen that the cross section for VDM-Regge model reaches higher values than the boxes for large values of y_{diff}. This observation provides an opportunity to prepare an experiment to distinguish the process described by Regge theory in the future.

3.3 ALICE 3

The ALICE 3 experiment will feature two detectors enabling the measurement of photons. One with acceptance criteria of -1.6 $< y <$ 4, $p_t > 100$ MeV, while the other will cover the forward region: $3 < y < 5$, 1 MeV $< p_t <$ 50 MeV. The primary experimental challenge when observing light-by-light scattering appears to be the background from the $\pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma$ process. Details of determining the amplitude for this process were shown in [10]. The predicted results for ALICE 3 acceptance are presented in Figure 2b). According to the conducted analysis, it can be seen that the vertical background does not dominate over the light-by-light phenomena. The total cross section for boxes in ALICE 3 kinematical region ($p_t > 5$ MeV, $|y_\gamma| < 4$) is equal to 952.590 μb, versus background total cross section equal to 112.824 μb. Additionally, it can be further reduced by applying cuts on p_t^{sum} or vector asymmetry. A more detailed analysis for the ALICE 3 detectors is presented in an upcoming article [11].

4 Conclusion

Low mass mesons in the process of light-by-light scattering play a significant role in the limit of low transverse momentum. In particular, an important process is meson resonance.



a) b)

Figure 2. a) Distribution in y_{diff} for light-by-light scattering processes. The transverse momentum cut is equal to 5 MeV, the range of measured di-photon invariant mass is > 5 GeV. The blue solid line relates to the boxes, and the green dotted line to the VDM-Regge contribution. b) Di-photon invariant mass distribution for ALICE 3. Here the rapidity cut $y_\gamma = (-4, 4)$ and photon energy $E_\gamma > 50$ MeV. The blue solid line relates to the box contribution, the green line to the VDM component, the black solid line to meson resonances and the dashed lines relate to our double-pionic background contribution with different kinematical cut.

Resonances give a contribution superior to fermion loops for $M_{\gamma\gamma} < 1$ GeV, which are the only experimentally observed light-by-light scattering process to date. Extending the rapidity range of measured photons potentially provides the opportunity to observe the phenomenon described by Regge theory. Also discussed in the context of the future ALICE 3 experiment was the estimation of the background resulting from the creation of pairs of $\pi^0\pi^0$ mesons and their decay into four photons.

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