FEASIBILITY STUDIES OF LIGHT-BY-LIGHT SCATTERING IN ALICE WITH FoCal PHASE SPACE*

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Received 28 March 2025, accepted 9 April 2025,
published online 26 June 2025

The ALICE experiment has significantly upgraded its detectors, enabling new measurements in ultra peripheral collisions of lead nuclei with an integrated luminosity of $\mathcal{L} = 7/\mathrm{nb}$ and 6/nb during Run 3 and Run 4, respectively. Investigation of light-by-light scattering in the low diphoton invariant mass is studied in this paper. The predictions presented here take into account the acceptance of the current EMCal and PHOS electromagnetic calorimeters, TPC and ITS tracking devices in the central barrel, as well as the future Forward Calorimeter, FoCal. Results from the SuperChic and UPCgen Monte Carlo generators are compared across all possible reconstruction topologies.

DOI:10.5506/APhysPolBSupp.18.5-A36

1. Introduction

The light-by-light scattering phenomenon has been confirmed by both ATLAS [1, 2] and CMS [3] at the LHC energies in kinematic ranges of diphoton invariant mass $M_{\gamma\gamma} > 5$ GeV$/c^2$, photon rapidity $|\eta| < 2.4$, and full photon azimuthal angle φ coverage. The measurements have been made in the ultraperipheral collisions (UPCs) of heavy ions, where the flux of photons is proportional to the fourth power of the atomic number of the ion as described with the Weizsäcker–Williams formula [4]. In the ALICE experiment [5], one can expand the study of light-by-light scattering to the unique, lower invariant mass range $M_{\gamma\gamma} < 5$ GeV$/c^2$ in the central region. In addition, this process can be investigated using the potential of the future forward calorimeter, FoCal [6], which will be installed in the next Long Shutdown 3. Described prospects for measuring the light-by-light scattering in ALICE's unique invariant mass range will be discussed, showing the results

* Presented at the 31$^{\mathrm{st}}$ Cracow Epiphany Conference on the *Recent LHC Results*, Kraków, Poland, 13–17 January, 2025.

predicted by two Monte Carlo (MC) generators: SuperChic 5.4 [7] (SC) and UPCgen [8], analyzed across all possible reconstruction topologies in central and forward rapidity phase spaces.

2. Used topologies and MC generators

2.1. Topologies

The analysis benefits from multiple reconstruction techniques using both existing and future ALICE detectors. One can measure the energy deposit of the electromagnetic cascade, which develops in the calorimeter due to the incident photon, or utilize the Photon Conversion Method (PCM) [9], where the photon is reconstructed from electron–positron pairs produced through photon conversion in the detector's material. The Electromagnetic Calorimeter EMCal [10] and the Photon Spectrometer PHOS [11] were considered in the central rapidity region. The EMCal kinematic ranges are $|\eta| < 0.68$ and $80^\circ < \varphi < 187^\circ$ or $0.22 < |\eta| < 0.7$ and $260^\circ < \varphi < 320^\circ$, or $|\eta| < 0.7$ and $320^\circ < \varphi < 327^\circ$ with the minimum transverse momentum of a photon $p_{\mathrm{T}}^{\min} = 0.5$ GeV$/c$ and $p_{\mathrm{T}} > 2.5$ GeV$/c$ for the EMCal trigger. The PHOS covers $|\eta| < 0.13$ and $70^\circ < \varphi < 190^\circ$ with $p_{\mathrm{T}}^{\min} = 0.3$ GeV$/c$. One can use the PCM method to reconstruct photons in the full azimuth and $|\eta| < 0.9$. However, only $\sim 5\%$ of signal photons are registered due to the conversion probability. The minimum $p_{\mathrm{T}}^{\min} = 0.5$ GeV$/c$ is chosen in the PCM.

Both signal light-by-light scattering photons must be registered in the EMCal, PHOS or reconstructed by the PCM. It can also be a hybrid case, when, for example, one photon is reaching EMCal phase space, while the other one is in the PHOS acceptance. To summarise, photons can be detected within the following topologies: EMCal + EMCal, EMCal + EMCal trigger, PCM + PCM, EMCal + PHOS, EMCal + PCM, PHOS + PCM. PHOS + PHOS topology is not accessible due to the low acceptance.

The installation of the Forward Calorimeter, FoCal, is planned for the Long Shutdown 3. The cuboidal-shaped FoCal will be located 7 meters away from the interaction point and will cover the forward rapidity range of $3.2 < \eta < 5.8$. The lowest photon transverse momentum is set to be $p_{\mathrm{T}}^{\min} = 0.5$ GeV$/c$. Two scenarios have been considered for the FoCal acceptance, the full FoCal and the slightly reduced by 4 modules from each side, to show the predicted yield as a precaution. In such a case, the FoCal y coordinate was reduced to $|y| < 31.2$ cm and $\eta < 5.3$. In the case of FoCal, both photons have to fulfill the acceptance criteria in the forward rapidity.

The total integrated luminosity for the central rapidity region is estimated to reach $\mathcal{L}^{\mathrm{Run}\ 3} = 6/\mathrm{nb}$ and $\mathcal{L}^{\mathrm{Run}\ 4} = 7/\mathrm{nb}$ for Run 3 and Run 4, respectively, whereas at the time this analysis was performed, the total integrated luminosity of $\mathcal{L} \simeq 3/\mathrm{nb}$ had already been accumulated. Thus, several integrated luminosity scenarios, which may represent realistic expectations for data collected in the central barrel region, are considered in this analysis: $\mathcal{L}^{\mathrm{tot}} = 3/\mathrm{nb}$, $10/\mathrm{nb}$, and $13/\mathrm{nb}$. For the forward rapidity region, the expected integrated luminosity is approximately $\mathcal{L}^{\mathrm{tot}} = 6/\mathrm{nb}$, as data collection will begin at a later stage.

2.2. Events generators

The light-by-light scattering events have been simulated in SuperChic and UPCgen MC generators. The signal $\gamma\gamma \to \gamma\gamma$ process has been simulated in the ultraperipheral Pb–Pb collisions of energy $\sqrt{s_{NN}} = 5.36$ TeV available during Runs 3 and 4. The 50 000 signal events have been generated with SuperChic in the central region with the photon rapidity $|\eta^{\gamma}| < 0.9$, photon transverse momentum $p_{\mathrm{T}}^{\gamma} > 0.3$ GeV$/c$, and invariant mass $M_{\gamma\gamma} > 0.5$ GeV$/c^2$ with the cross section $\sigma^{\mathrm{SC}} = (2332 \pm 1)$ nb. In the case of UPCgen, 150 000 events have been generated in the similar kinematic region with the cross section of $\sigma^{\mathrm{UPCgen}} = 2538$ nb. For the forward rapidity region of FoCal, 50 000 signal events have been simulated in both generators with $3.2 < \eta^{\gamma} < 5.8$, $p_{\mathrm{T}}^{\gamma} > 0.5$ GeV$/c$, and $M_{\gamma\gamma} > 0.5$ GeV$/c^2$. The generated cross sections are $\sigma^{\mathrm{SC}} = 216.92 \pm 0.07$ nb and $\sigma^{\mathrm{UPCgen}} = 165.55$ nb for SuperChic and UPCgen[1], respectively.

The main difference between these two generators may arise from the flux modeling. It is significantly different in the forward region, while in the central region, it remains the same.

3. Results

Figure 1 shows the expected signal yield of the light-by-light scattering in the central barrel region in the ALICE detector for the total integrated luminosity $\mathcal{L} = 13$ nb^{-1} for the SuperChic and UPCgen MC generators. Although initial distributions differ in tails between both generators, the yield in the lower invariant mass range is similar for the central region. The total predicted number of events for $M_{\gamma\gamma} < 10$ GeV$/c^2$ which fulfills selections criteria for different topologies alltogether (described in Section 2) is 1147 ± 34 and 1232 ± 35 for SuperChic and UPCgen, respectively. It is evident that the number of events increases with a decreasing diphoton invariant mass. Therefore, it is crucial to measure the light-by-light scattering in the lowest possible invariant mass region of $M_{\gamma\gamma} < 5$ GeV$/c^2$ to increase the signal yield.

[1] The UPCgen generator does not provide uncertainty of the cross section.

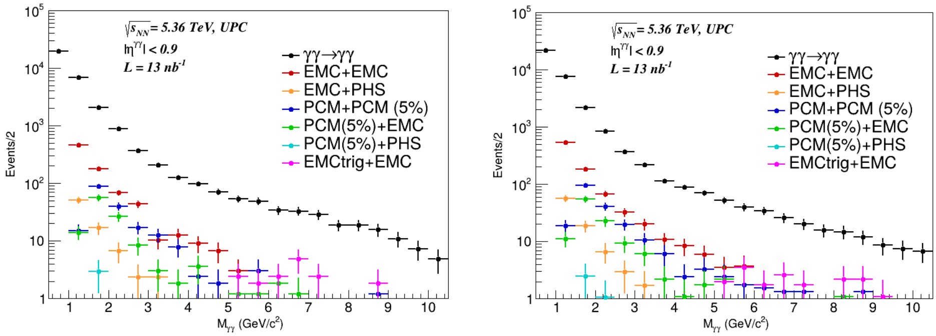

Fig. 1. Expected light-by-light scattering yield measured in different topologies in the ALICE detector in the central region for $\mathcal{L} = 13$ nb^{-1} as a function of the diphoton invariant mass coming from SuperChic 5.4 (left-hand side) and UPCgen (right-hand side) Monte Carlo generators.

Similar spectra have been obtained for the forward rapidity region in the FoCal detector, as shown in Fig. 2. In this case, the yield predicted by both generators differs slightly. The number of events within the full FoCal acceptance (blue lines in the plots from Fig. 2) is 1074 ± 33 for SuperChic and 925 ± 30 for UPCgen. The number of events above $M_{\gamma\gamma} = 2$ GeV$/c^2$ is 81 ± 9, while only 4 ± 2 events are observed above $M_{\gamma\gamma} = 4$ GeV$/c^2$ (generated by SuperChic) as indicated by the red vertical lines in Fig. 2. Therefore, it is crucial to measure the signal in the lowest possible invariant mass region.

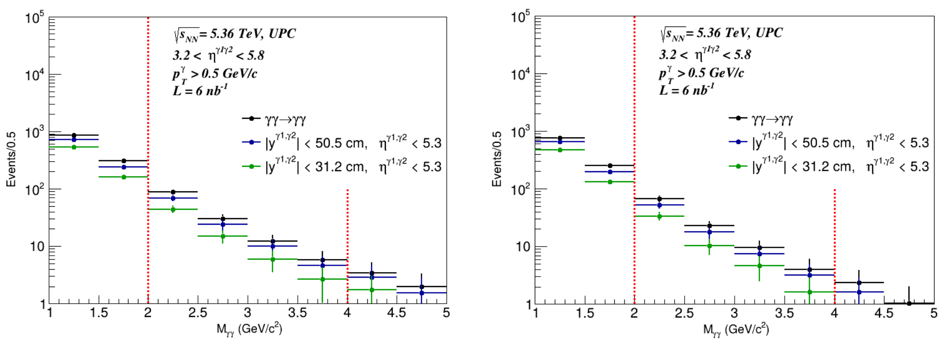

Fig. 2. Expected light-by-light scattering yield measured in different topologies in the ALICE FoCal detector in the forward region for $\mathcal{L} = 6$ nb^{-1} as a function of the diphoton invariant mass coming from SuperChic 5.4 (left-hand side) and UPCgen (right-hand side) Monte Carlo generators.

An important observation is the significant difference between initial spectra delivered by the SuperChic 5.4 and UPCgen MC generators. While predictions for the central region are similar in the low invariant mass range $1 < M_{\gamma\gamma} < 5$ GeV$/c^2$, noticeable differences appear in the forward rapidity region of FoCal. The spectra, as well as the ratios of predicted invariant mass distributions coming from both generators, are shown in Fig. 3.

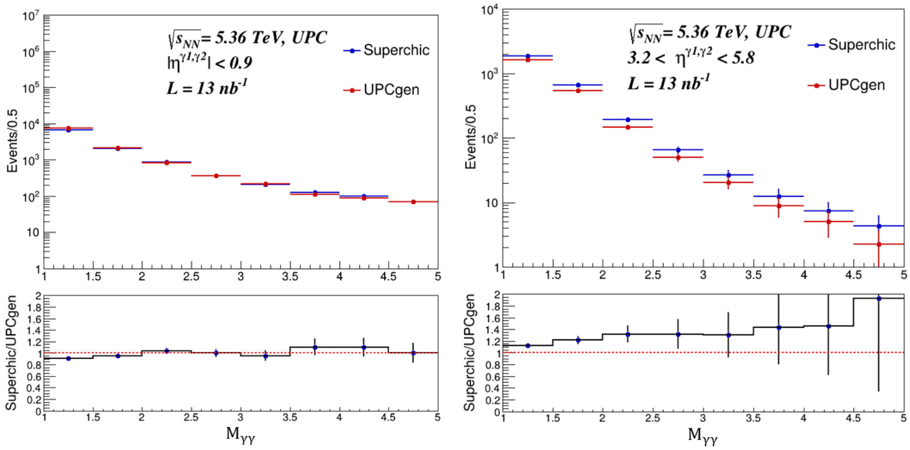

Fig. 3. Top panels: Comparison of the diphoton invariant mass spectra generated by SuperChic 5.4 and UPCgen MC generators for the central region (left-hand side) and forward (right-hand side) region. Bottom panels: The ratio of predicted yield by SuperChic 5.4 to UPCgen MC generators.

While the SuperChic/UPCgen yield ratio remains around unity in the central region, the same does not hold for the forward region. There, significant differences emerge starting from the lowest invariant mass, following an increasing trend. Although the higher bins fall within statistical uncertainties due to the low event yield, the rising trend persists, indicating a systematic effect rather than mere statistical fluctuations. These differences are likely due to the different photon flux models used by the generators.

4. Conclusions

The total expected number of events, summing over both the central and forward rapidity regions that fulfill fiducial requirements, predicted by both generators is 2221 ± 47 for SuperChic 5.4 and 2157 ± 46 for UPCgen. These values represent ideal estimates, assuming 100% efficiency and no additional requirements. Additionally, they correspond to the maximum possible integrated luminosity that could be accumulated over both Run 3 and Run 4.

The actual number of expected events might be lower due to various experimental factors like the detector efficiency, and need to account for background contribution, and the achievable integrated luminosity. However, despite these challenges, the overall event rates remain promising, particularly in the low invariant mass region, where precise measurements can provide valuable insights. While reaching an invariant mass as low as 1 GeV/c^2 may be challenging, the observed trends and differences between the generators highlight the importance of studying these processes in detail.

The authors would like to thank the Ministry of Science and Higher Education, Poland for the supporting grant 2022/WK/01.

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