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Prospects of light-by-light scattering measurements and axion-like particle searches at the LHC

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Abstract. Ultra-peripheral collisions of heavy ions (UPCs) provide a clean environment for studies of two-photon interactions due to large impact parameters between incoming nuclei at which strong interactions are highly suppressed. In particular, UPCs were used by the ATLAS and CMS collaborations at the LHC to establish the evidence of the light-by-light scattering process (LbyL). In addition, there has been a growing interest to studies of physics beyond the Standard Model (BSM) in photon-induced processes, specifically, to studies of production of axion-like particles (ALPs) that appear in a number of extensions of the Standard Model. The ATLAS and CMS managed to measure differential cross sections of LbyL process and improve limits on ALP-γ coupling constant in a range of masses between 5 and 100 GeV, while the region below 5 GeV can be addressed in the future ALICE 3 experiment, the proposed next-generation experiment for LHC Run 5 and beyond. In this work, a review of recent results on LbyL and searches for ALPs at the Large Hadron Collider will be given, and future prospects for the measurements will be discussed.

Keywords: heavy-ion collisions, new physics, two-photon interactions

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Материалы конференции
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Перспективы проведения измерений рассеяния света на свете и поиска аксионоподобных частиц на большом адронном коллайдере

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Аннотация. Ультра-периферические столкновения тяжелых ядер дают возможность для проведения детальных исследований двухфотонных взаимодействий при значительном подавлении адронных процессов, что достигается благодаря значительным прицельным параметрам между налетающими ядрами. В данной работе рассматриваются перспективы для проведения измерений рассеяния света на свете и поиска аксионоподобных частиц с помощью изучения таких столкновений.

Ключевые слова: столкновения тяжелых ионов, новая физика, двухфотонные взаимодействия

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Introduction

Ultra-peripheral collisions of heavy ions (UPCs) provide a unique tool for studies of two-photon interactions [1, 2]. Due to impact parameters being greater than the sum of radii of incoming nuclei, hadronic interactions are strongly suppressed, leading to an increased role of electromagnetic processes. At ultra-relativistic energies electromagnetic field of nuclei is commonly described in terms of the Weizsäcker–Williams formalism and treated as a flux of quasi-real photons with virtualities very close to zero $q^2 < (\hbar c/R)^2$, R being the radius of a nucleus. Photon fluxes depend on the squared nuclear charge Z^2, and consequently cross sections of photon-induced processes scale as Z^4, therefore one can benefit from much higher interaction probability in the processes of interest in comparison to pp or e^+e^- collisions.

Among all the two-photon interactions that can be studied using UPCs, the light-by-light scattering process (LbyL), $\gamma\gamma \to \gamma\gamma$, is particularly interesting. This is a process in the Standard Model (SM) proceeding via virtual box-diagrams involving W± bosons and charged fermions (leptons and quarks). The diagrams may include contributions from new virtual charged particles, therefore the process is considered to be sensitive to a number of Standard Model extensions, such as Born-Infeld Theory [3], anomalous gauge couplings [4], supersymmetry [5], monopoles [6], unparticles [7], low-scale gravity [8] and non-commutative interactions [9].

In addition to light-by-light scattering measurements, there has been an increasing interest in searches for axion-like particles (ALPs) in the process $\gamma\gamma \to a \to \gamma\gamma$. ALPs are introduced as pseudo Nambu-Goldstone bosons of a new spontaneously broken global symmetry in various extensions of the Standard Model, such as supersymmetry, composite dynamics models and Higgs extension models. Light pseudoscalar ALPs are proposed as dark matter candidates or dark-sector mediators [10–12]. Moreover, there are theories suggesting that ALPs found in the low-mass region below 5 GeV could possibly explain the muon $g - 2$ puzzle [10, 13]. In SM extensions, ALPs couple to photons via the effective Lagrangian:

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}, \tag{1}$$

where a is the ALP field, $F^{\mu\nu}$ is the photon field strength tensor, and $g_{a\gamma} = 1/\Lambda_a$ the dimensional ALP-γ coupling constant related to the high-energy scale Λ associated with the broken symmetry. Thus, the production and decay rates of axion-like particles are fully defined in the two-dimensional parameter space of the axion mass ma and the corresponding coupling $g_{a\gamma}$.

In this paper, recent results on measurements of the light-by-light scattering process and searches for axion-like particles at the LHC, as well as future prospects for the measurements are discussed.

Light-by-light scattering measurements

The first evidence of the light-by-light scattering process was established by the ATLAS and CMS collaborations [14, 15]. Since then, more thorough measurements of differential cross sections were carried out in the region of diphoton invariant masses m$\gamma\gamma$ between 5 and 100 GeV. ATLAS has reported the total fiducial cross section, $\sigma = 120 \pm 17$ (stat.) $\pm$ 13 (syst.) $\pm$ 4 (lumi.) nb, which is in a good agreement with the value extracted by CMS, $\sigma = 120 \pm 46$ (stat.) $\pm$ 28 (syst.) $\pm$ 12 (theo.) nb. Both results are in accord with theoretical predictions [16]. Unfortunately, accuracy of the measurements is limited by amount of statistics that can be possibly obtained for invariant masses above 5 GeV, and measurements below the threshold are hardly possible due to trigger restrictions in the ATLAS and CMS detectors.

The low-mass region could be addressed in the ALICE 3, the future next-generation experiment at the Large Hadron Collider [17]. The proposed detector design is aimed at measurements of photons at very low transverse momenta down to $p_T \sim 10$ MeV and below.

Considering wide pseudorapidity coverage $|\eta| < 4$ and high particle tracking capabilities, ALICE 3 gives a unique opportunity for precise light-by-light scattering measurements.

However, diphoton measurements at low invariant masses become very challenging due to the presence of a combinatorial background originating from decays of neutral pions $\gamma\gamma \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ [18]. In order to study possible ways of reducing this source of background events, a dedicated Monte Carlo generator for ultra-peripheral collisions, Upcgen [19], was used. For this study, the light-by-light scattering process and production of π^0 pairs were added to the program. LbyL simulation is based on a dedicated 1-loop calculation that was carried out using FormCalc [20]. Production of neutral pions is based on one of the most complete models of this process that accounts for contribution of intermediate resonance states and QCD mechanisms [21].

We have estimated diphoton invariant mass spectra for LbyL and the π^0 background in Pb–Pb UPCs at $\sqrt{s_{NN}} = 5.02$ TeV for the case of the ALICE 3 fiducial region considering a proposed integrated luminosity $L = 35$ nb^{-1}. As can be seen from Fig. 1, LbyL measurements are hardly possible without a dedicated event selection strategy in the invariant mass range below 3 GeV.

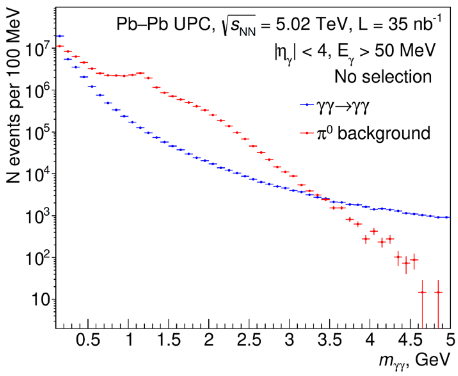

Fig. 1. Diphoton invariant mass spectra of the light-by-light scattering process (blue) and the combinatorial background originating from neutral pion decays (red) for the ALICE 3 acceptance

As proposed in [18], scalar and vector asymmetries of the outgoing photons can be used to reduce background:

$$A_s = \left|\frac{|p_T^1| - |p_T^2|}{|p_T^1| + |p_T^2|}\right|, \quad A_v = \frac{|p_T^1 - p_T^2|}{|p_T^1 + p_T^2|}, \tag{2}$$

where p_T^1 and p_T^2 are the transverse momenta of the outgoing photons. In the light-by-light scattering process, the majority of the photons have back-to-back topology, therefore their asymmetries are very close to zero, while the relative angular distribution of uncorrelated photons coming from decays of different pions is significantly wider. Indeed, a clear difference in asymmetry distributions can be seen in Fig. 2, where the distributions that were obtained using 10^8 Upcgen events are shown. In view of the difference in the topology of outgoing photons for the LbyL signal and the combinatorial background, two options for event selection were considered.

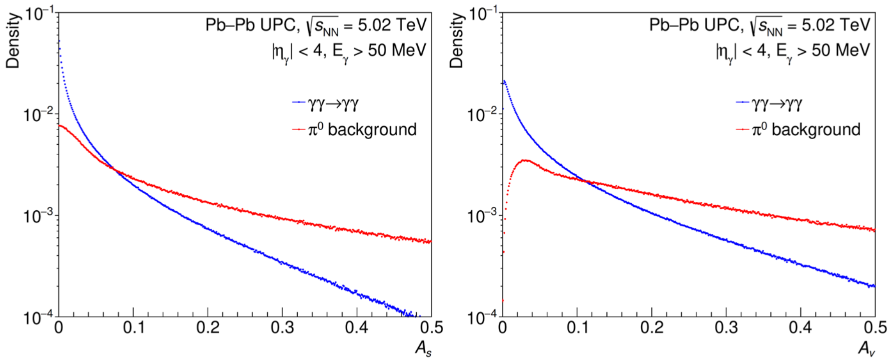

Fig. 2. Normalized scalar (left) and vector (right) asymmetry distributions for LbyL and the combinatorial background

The first approach is based on imposing a simple asymmetry restriction $A_s < 0.02$, as proposed in [18]. Using such criterion, one can effectively suppress background at very low invariant Masses (see Fig. 4, left). However, this rough cut significantly reduces amount of signal events at low invariant masses, which is a major drawback of the approach. In order to improve event selection quality, we applied a machine learning (ML) technique based on the gradient-boosted decision tree algorithm. In this approach, we used a variation of the algorithm implemented by Yandex in their CatBoost library [22]. According to benchmark studies by the CatBoost developers, it provides much faster learning and prediction, up to factors of 30–100, compared to the contemporary gradient boosting libraries, which was verified also in a number of studies in the field of high-energy physics, e.g. [23, 24].

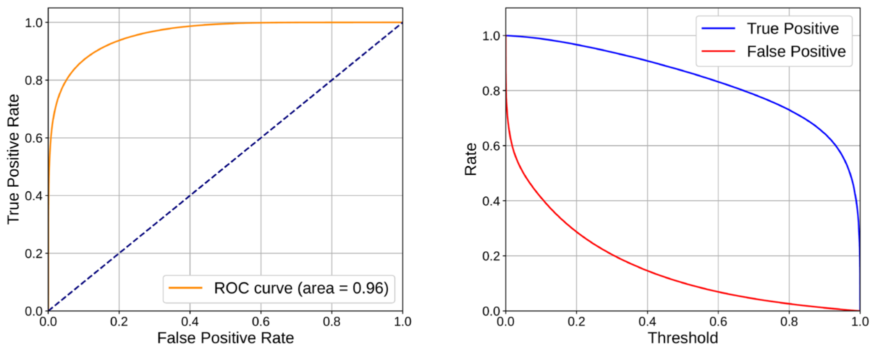

Fig. 3. Characteristic curves for the CatBoost model: ROC-curve (left), true positive and false positive rates as functions of the classification threshold (right)

For model training, all the available kinematic characteristics of the signal and background events were used: four-momenta of the outgoing photons, pair invariant masses and rapidities, as well as scalar and vector asymmetries. The training dataset consisted of 10^8 LbyL events and 10^8 uncorrelated photon pairs from the neutral pion decays. The events were generated in Upcgen, and the final state photons were selected using kinematic cuts for the ALICE 3 acceptance: $|\eta_\gamma| < 4$ and $E_\gamma > 50$ MeV.

For quality assurance purposes we have plotted the following characteristic curves using a separate control dataset with the same properties:

true positive rate as a function of the classification threshold (TPR-curve);

false positive rate as a function of the classification threshold (FPR-curve);

receiver operating characteristic (ROC-curve).

The ML model was applied for event selection in the control dataset to estimate diphoton invariant mass spectra for LbyL and the decay photons from π^0 pair production (see Fig. 4, right). Event selection results were improved drastically in comparison to the simple cut selection: the background was suppressed throughout the mass range, while the majority of signal events were saved.

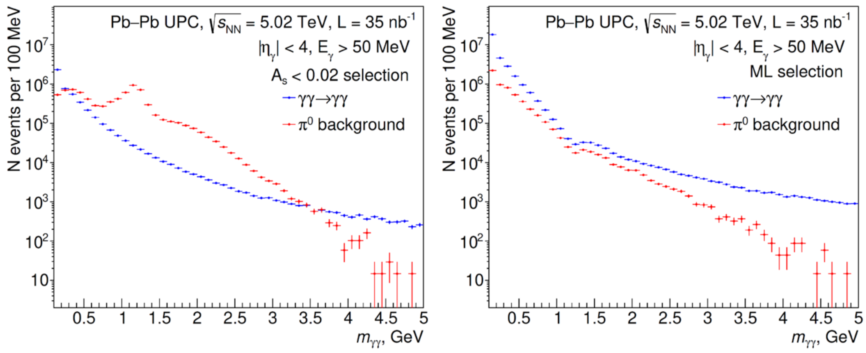

Fig. 4. Diphoton invariant mass spectra for light-by-light scattering process and the combinatorial background with the event selection based on the additional restriction on scalar asymmetry (left) and the machine learning technique (right)

Searches for axion-like particles

The strictest limits on ALPs in the mass range between 5 and 100 GeV have been obtained in light-by-light scattering measurements performed in Pb—Pb UPCs by the CMS [15] and ATLAS [14] collaborations. The ALICE experiment has a possibility to improve the limits using data that will be collected during the future Run 3 and Run 4 stages at the LHC [17, 25]. The future ALICE 3 experiment has an opportunity to extend searches to lower ALP masses below 5 GeV.

From the experimental point of view, two-photon interaction with production of an intermediate axion-like particle, $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$, is very similar to the light-by-light scattering process [26]. ALP production can be detected by a clear peak in the diphoton invariant mass distribution above background processes. In this measurement, LbyL and decay photons originating from the π^0 decays are the main sources of background events. In view of the similarity of kinematic properties of ALP production and LbyL scattering, we attempted to improve limits for ALP-γ coupling for the ALICE 3 experiment provided in [17] using ML model, that was previously trained for suppressing the combinatorial background.

To estimate cross section of ALP production and simulate a signal dataset, we upgraded Upcgen and added ALP production channel to the program, with the simulation process based on the narrow-resonance approximation [27]. Event selection was performed using two methods: using a simple asymmetry cut and a combination of the simple asymmetry restriction and the ML technique. Using cross section estimates, Poisson upper limits at confidence level of 95% [28] on Λ_a in dependence of ALP mass ma for the case of the ALICE 3 fiducial region were extracted. The limits were obtained for 5% and 100% photon reconstruction efficiencies. A comparison between the limits for the two selection methods obtained in an assumption of the ideal photon

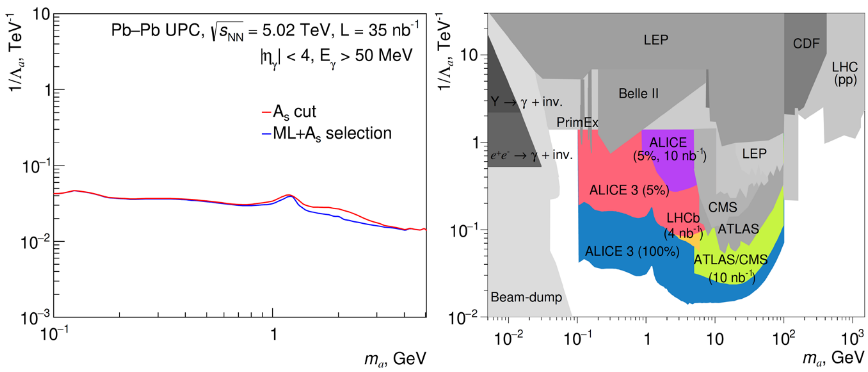

Fig. 5. Left: limits for the ALP-γ coupling obtained using the simple asymmetry cut (red) and using the combination of asymmetry cut with the ML model (blue). Right: limits on ALP-γ coupling constant from existing and future searches for ALPs

reconstruction efficiency is shown in (Fig. 5, left). As can be seen from the figure, only marginal improvement was achieved with ML event selection. Such insignificant change may be due to the fact that in this method only the combinatorial background is suppressed, while LbyL events effectively stay intact.

The results obtained with the combined selection are shown in Fig. 5 (right) in comparison to the existing limits from various experiments (shown in grayscale colors) obtained from [14] and projections for other LHC experiments from [17, 25, 26]. One can see that ALICE 3 has a possibility to reach limits below 1 TeV^{-1} and fill the gap in ALP masses below 5 GeV even with photon reconstruction efficiency of 5% and reach 0.1 TeV^{-1} in the ideal case that can be approached with calorimeter measurements.

Conclusions

In this paper, an overview of the existing results on the light-by-light scattering process and searches for axion-like particles was given. The future prospects for the measurements were discussed and the results of the feasibility studies for the proposed next-generation experiment at the LHC, ALICE 3, were given.

The study results demonstrated that the ML technique can be used to suppress the π0 background dominating in the low invariant mass region much more efficiently in comparison to simple asymmetry cuts, leading to a much higher purity of LbyL signal yield.

The ML technique used for LbyL selection can be also used to select signal events in searches for ALP production due to the similarity of kinematic properties of the two processes. However, the improvement of limits for the ALP-γ turned out to be only marginal. It may be explained by the fact that the ML model filtered out only the combinatorial background, leaving LbyL events almost intact. Nevertheless, the projections on the Λ_a limits for ALICE 3 obtained in this work proved to be competitive even in the case of photon reconstruction efficiency of 5%.

In continuation of this work, a more thorough study using full simulation framework with realistic detector description for the ALICE 3 experiment will be carried out in order to obtain more precise estimates for the ALP limits and diphoton invariant mass spectra for LbyL measurements.

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