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Axion Physics in UPC and LbyL Scattering

C. O. Ramírez-Álvarez[1], A. Fernández-Téllez[1] and A. I. Hernández-Juárez[2]
[1]*Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla. H. Puebla de Zaragoza, Puebla, 72000 México.*
[2]*Facultad de Estudios Superiores Cuautitlán, Universidad Nacional Autónoma de México. Cuautilán Izcalli, Edo. de México, 54740 México.*

In this work, we revisited the light-by-light scattering physics in ultraperipheral collisions. Furthermore, an extension model with axion-like particles is also studied. We used MadGraph5_aMC@NLO+gamma-UPC event generator for our analysis and the proposed kinematic cuts for the ALICE 3 experiment were considered. Different distribution functions for both light-by-light and axion-like particles are analyzed and we find that the transverse momentum is a good channel to observe the production of axions in ultraperipheral collisions.

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1 Introduction

A novel way to study BSM theories is with ultraperipheral collisions (UPC) of PbPb, which relies on EPA (Equivalent Photon Approximation) [1,2,3,4], a method that considers the electromagnetic fields generated by a moving charged particle as a flow of virtual photons with small virtuality, given by $Q^2 < 1/R^2$, and proportional to Z^4. This results is an enormous improvement, which can be used to search for new physics that couples to photons.

Light-by-light (LbyL) scattering $\gamma\gamma \to \gamma\gamma$, is a rare Standard Model (SM) process and it is not allowed by classical electrodynamics, therefore the reaction $\gamma\gamma \to \gamma\gamma$ arise at the one-loop level, where the Feynman diagrams involve fermions and W bosons running into the loop. The LbyL was first discussed in Ref. [5]. Recently, the detection of this interaction through UPC of heavy ions at the LHC has been pointed out [6,7,8,9,10], whereas both ATLAS and CMS experiments measured this process [11,12,13]. The data obtained can be explained with theoretical and simulation studies, considering only box diagrams with fermions in the loop, since the W boson contributions are relevant energies of the order of $M_{\gamma\gamma} > M_W$.

Experimental and theoretical observations indicate that the SM is an incomplete theory, as it not explain the neutrino mass, hierarchy problem, or CP violation. This has motivated multiple physics communities to propose solutions by introducing new particles or sectors that go beyond the SM (BSM), such as the Axion-Like Particles (ALP), which are pseudoscalar bosons with independent couplings and masses and can have masses up to the TeV scale [14].

In this work, we analyze the SM and Axion-Like Particles phenomenological implications under the context of the physics of the ALICE 3 experiment [15]. MonteCarlo studies are presented using MadGraph5_aMC@NLO+gamma-UPC [16,17] generators to model di-photon invariant mass distributions of two different scenarios, LbyL scattering and ALP-$\gamma\gamma$, the latter we consider different couplings and ALP masses.

2 Light by Light Scattering

In the SM, the $\gamma\gamma \to \gamma\gamma$ scattering is induced through one-loop level diagrams with charged particles (fermions and W boson) running into the loop. For this study, the Feynman-'t Hooft gauge is used, hence scalar particles related to the W boson appear in the loop. The corresponding Feynman diagrams are shown in Fig. 1.

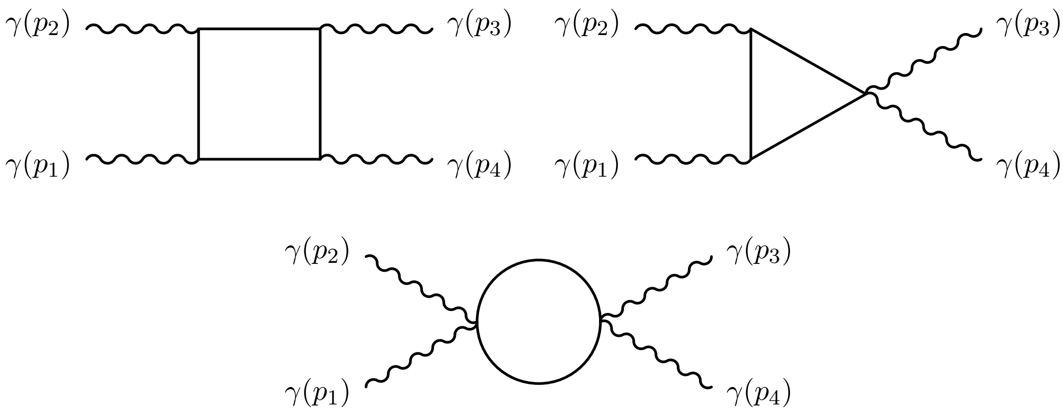


Figure 1: Contributing Feynman diagrams to the LbyL scattering process. The fermions only appear in box diagrams, while the W boson and its associated particles (charged scalars $\varphi^{\pm}$ and ghosts $u^{\pm}$) contribute in the remaining diagrams.

In order to test gamma-UPC library, we reproduce some results obtained for LbyL in [7,9,10]. The MonteCarlo event simulations were performed in MadGraph5_aMC@NLO using the gamma-UPC library that calculates the photon flux for unique $\gamma\gamma$ processes in PbPb UPC, such a formalism is discussed in Ref. [17]. The event selection is according to the proposed ALICE 3 experiment upgrade [15]. We also consider the ECal detector. The kinematic cuts are $p_T > 50$ MeV and $-4 < \eta < 4$. The distribution of the differential cross section with respect to the invariant mass obtained from our simulation is shown in Fig. 2 for 3 cases: only fermions, only W bosons and the total SM. We observe that the fermions contribution dominates at low values in the invariant mass, whereas the W boson contribution becomes relevant at high values $M_{\gamma\gamma}$ and its maximum values are reached at $M_{\gamma\gamma} > 2M_W$. The Fig. 2 is consistent with the reported one in Ref. [18], where proton beams are considered.

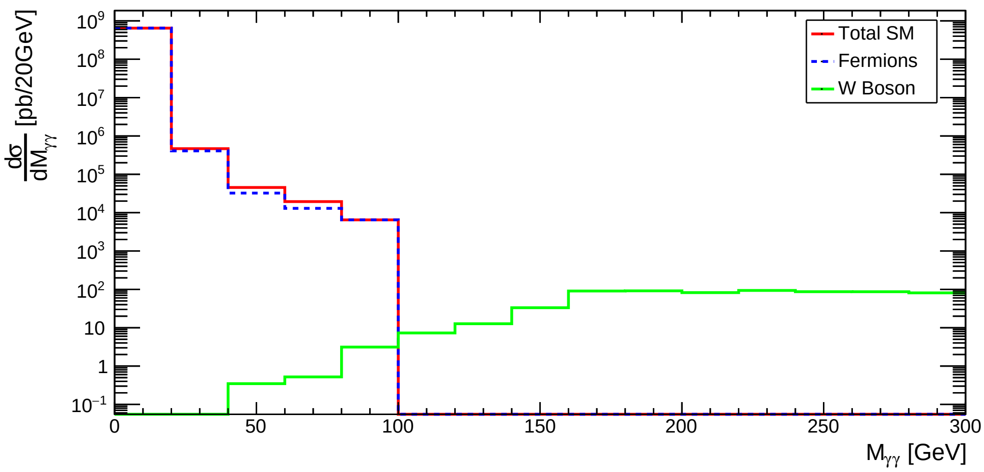
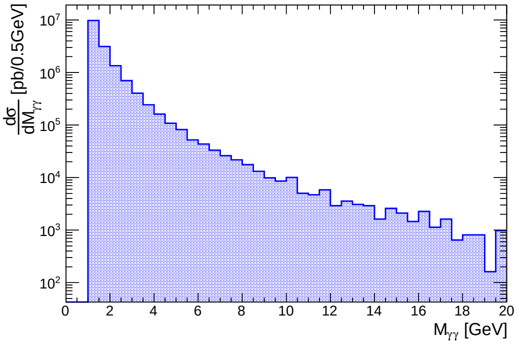
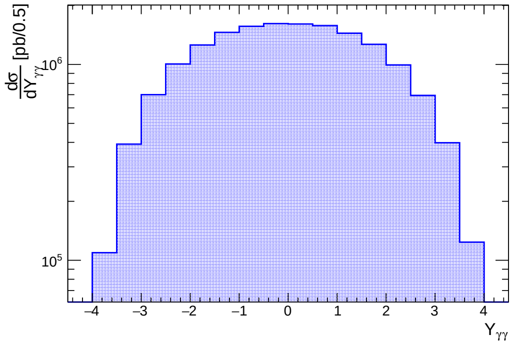


Figure 2: Differential cross section with respect to the invariant mass of di-photons in PbPb UPC at 5.02 TeV. The blue dotted and green line lines corresponds to the diagrams including only fermions and W bosons, respectively, whereas the red line corresponds to the total SM contribution considering all diagrams.

Now, since the experimental measurement obtained by ATLAS and CMS was on a scale of $p_T > 2$ GeV, ALICE 3 will provide the opportunity to perform measurements for low p_T, which implies more precision at low invariant masses. In this sense, it is possible to study LbyL scattering with fermion box and background generated at these scales. In Fig. 3, we show the differential cross section of LbyL scattering with respect to three kinematic variables: invariant mass, rapidity and transverse momentum, where only the contribution with fermions in the loop are considered. Our results agree with those reported in Ref. [9,10].



(a)



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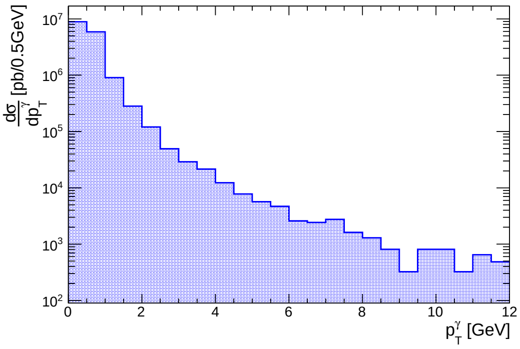


(c)

Figure 3: Differential cross section with respect to: (a) the invariant mass of di-photons, (b) the rapidity of di-photons and (c) the transverse momentum of a photon generated with MadGraph5_aMC@NLO+gamma-UPC in PbPb at 5.02 TeV.

3 Axion-Like Particles

Axions were proposed by Pecci-Quinn in 1977 to solve a strong CP Problem in QCD [19,20]. They are Nambu-Goldstone pseudo-bosons related to the spontaneous breaking of a new global symmetry $U(1)_{\rm PQ}$.

In particular, Axion-Like Particles (ALP) are pseudoscalar bosons with independent couplings and masses, which can be the TeVs [14]. These particles are coupled to the electromagnetic sector via the Lagrangian:

$$\mathscr{L}_{a\gamma\gamma} = \frac{1}{2}\left(\partial a\right)^2 - \frac{1}{2}M_a^2 a^2 - \frac{1}{4}\frac{k}{\Lambda} a F^{\mu\nu}\tilde{F}_{\mu\nu}, \tag{1}$$

where a is the ALP, M_a its mass, $\frac{k}{\Lambda}$ the coupling constant, $F^{\mu\nu}$ the electromagnetic field tensor, and the dual tenso $\tilde{F}_{\mu\nu}$ is defined as $\tilde{F}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$. One can rewrite the ALP-$\gamma\gamma$ coupling in terms of the electric $\mathbf{E}$ and magnetic $\mathbf{B}$ fields as:

$$\mathscr{L}_{\rm int} = \frac{k}{\Lambda} a\mathbf{E}\cdot\mathbf{B}, \tag{2}$$

which implies that photons can mix with ALP in the presence of electromagnetic fields. The LbyL scattering is a clean channel for the search of ALPs as they can be considered as a background to the $\gamma\gamma \to \gamma\gamma$ process. The ALP physics has been revisited in Refs.[14,21,22,23,24,25,26].

The ALPs can be produced in LbyL sacttering through s-channel, as in Fig. 4. For this study, a model with a ALP-$\gamma\gamma$ coupling in the Eq. (1) was generated in the UFO format [27] with the help of the FeynRules package [28]. Then, the model was loaded into MadGraph5_aMC@NLO+gamma-UPC. To observe the ALP resonances, PbPb UPC events at 5.02 TeV were simulated following the same event selection as LbyL, setting $\Lambda = 1$ TeV and varying k. Results are shown for two different ALP masses in Fig. 5 for masses $M_a = 7$ GeV and $M_a = 12$ GeV. We have considered $M_{\gamma\gamma}$ larger than 5 GeV to avoid

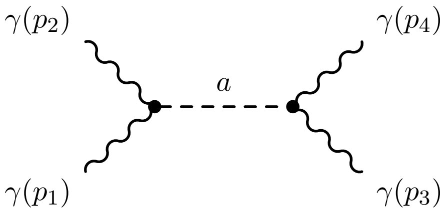
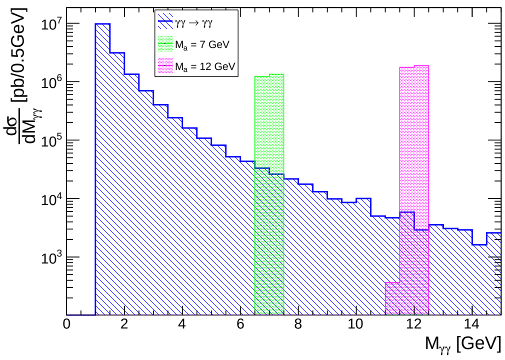
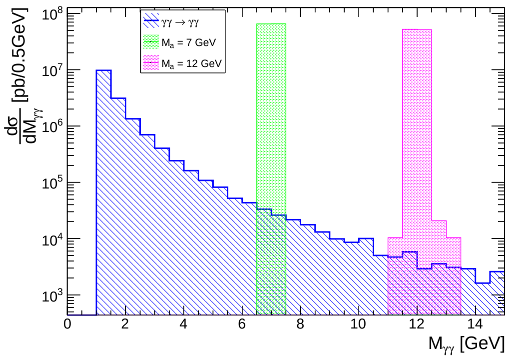


Figure 4: Feynman diagram of the ALP-$\gamma\gamma$ coupling for the s-channel.

the pion background [10] and the light meson resonances [9]. It is observed that the ALP resonances dominate as the value of k increases, whereas for $k < 1.5$ the LbyL signal is the relevant one.



(a)



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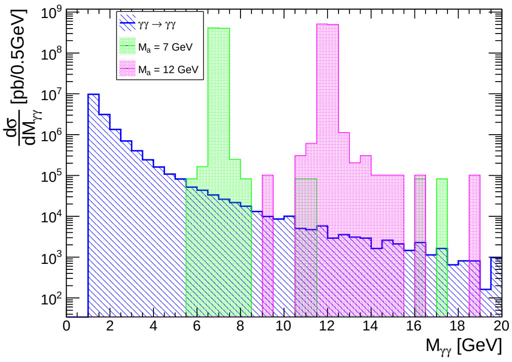

(c)

Figure 5: Differential cross section with respect to the di-photon invariant mass in UPC of PbPb at 5.02 TeV with $\Lambda = 1$ TeV for (a) $k = 1.5$ (b) $k = 8$ and (c) $k = 25$. The green histogram for $M_a = 7$ GeV and the pink histogram for $M_a = 12$ GeV. The histogram for LbyL is included.

Now, to confirm the behavior of the resonances according to the values of k, three other cases are presented with the same ALP masses in Fig. 6 and $k = 0.1, 50, 100$. We note that for $k = 0.1$ the signal dominance correspond to LbyL. On the other hand, for large values of k (50 and 100) the ALP resonances dominate over the LbyL signal. Moreover, an overlap between ALP distributions for the different M_a, which is more visible at $k = 100$.

The differential cross section as function of the rapidity and transverse momentum are shown in Fig. 7 and 8, respectively. We have considered $k = 8$ for different values of ALP masses. In Fig. 7, a similar behavior to the observed in the LbyL case is found. Nevertheless, the differential cross section decreases for large ALP masses.

In contrast, for the distribution functions of the transverse momentum (Fig. 8) the behavior with respect to the LbyL scattering totally different. For the ALP-$\gamma\gamma$ model the signal grows until it reaches its maximum and then it decreases, whereas in the LbyL case the signal is always decreasing until it disappears. This result is interesting as the ALP signal can be distinguished from the LbyL one. Therefore, the transverse momentum is a good channel to observe new physics from ALP. A similar

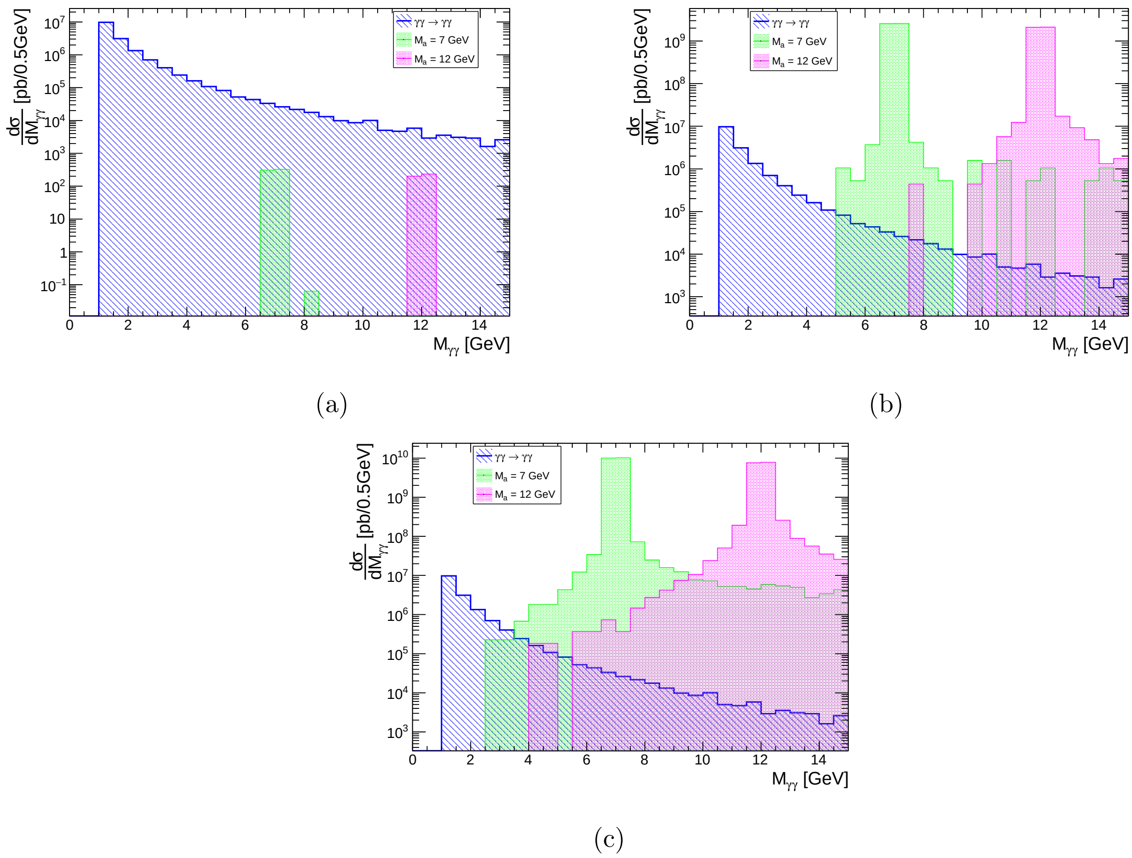

Figure 6: Differential cross section with respect to the di-photon invariant mass in UPC of PbPb at 5.02 TeV with $\Lambda = 1$ TeV for (a) $k = 0.1$ (b) $k = 50$ and (c) $k = 100$. The green histogram for $M_a = 7$ GeV and the pink histogram for $M_a = 12$ GeV. The histogram for LbyL is included.

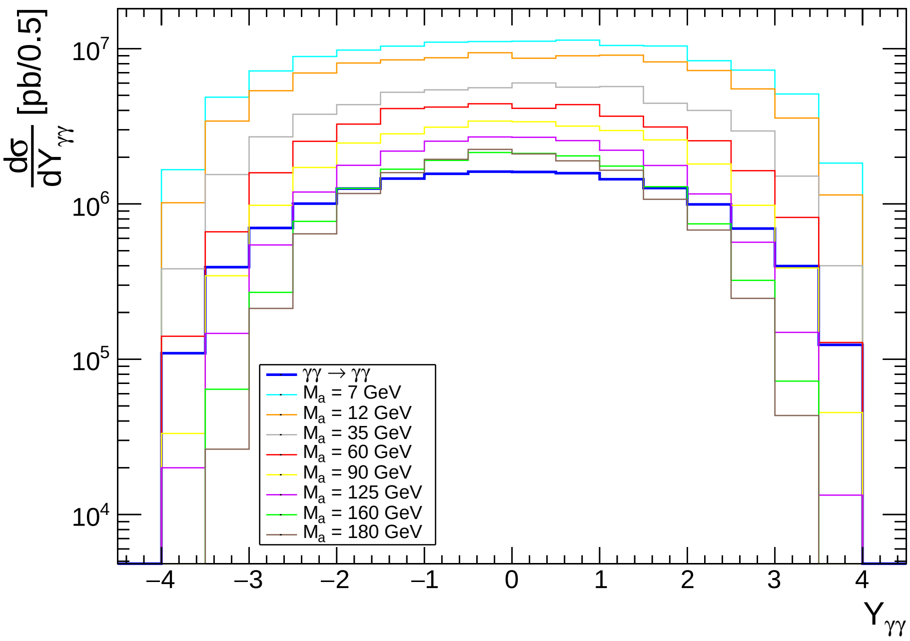

Figure 7: Differential cross section as a function of rapidity with $k = 8$ and different values of M_a setting $\Lambda = 1$ GeV in UPC of PbPb at 5.02 TeV. The LbyL distribution is included.

distribution has been reported in Ref. [25], however, the ALPs arise from $e\gamma$ collisions.

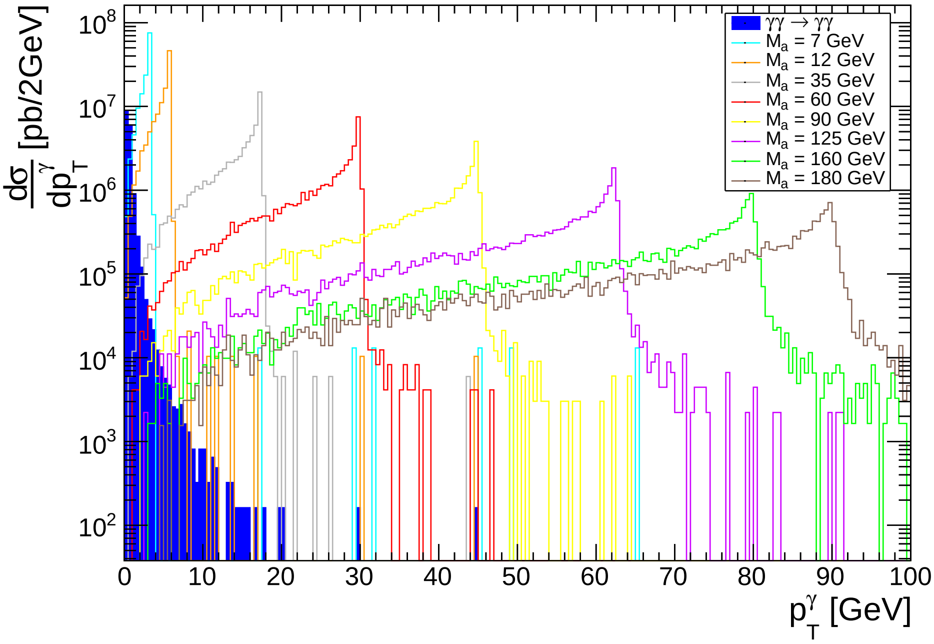

Figure 8: Differential cross section as a function of transverse momentum with $k = 8$ and different values of M_a setting $\Lambda = 1$ GeV in UPC of PbPb at 5.02 TeV. The LbyL distribution is included.

4 Conclusions

In this work, we have presented MonteCarlo simulations, which were performed at the partonic level for the $\gamma\gamma \to \gamma\gamma$ scattering at the one-loop level in the SM. The MadGraph5_aMC@NLO+gamma-UPC MonteCarlo generator was used. Furthermore, the ALP-$\gamma\gamma$ model (BSM) was also implemented. The simulations were carried out in PbPb UPC at 5.02 TeV with a selection of events similar to the proposed for the ALICE 3 experiment.

For LbyL, differential cross section distributions were obtained. They agree with results previously reported in the literature. On the other hand, for the ALP-$\gamma\gamma$ model it was observed that in the inavariant mass distributions functions the ALP resonances dominates for $k > 25$. In the case of rapidity, the ALP distributions are almost indentical to the LbyL signal.

Finally, for the differential cross section with respect to the transverse momentum in the ALP-$\gamma\gamma$ model, we find that the distribution functions are distinguishable from the LbyL case. Thus, this kinematic variable is a good channel for observing ALP production.

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