UPC 2023: First International Workshop on the Physics of Ultra Peripheral Collisions

Axion Physics in UPC and LbyL Scattering

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Ultra-Peripheral Collisions of Heavy Ions

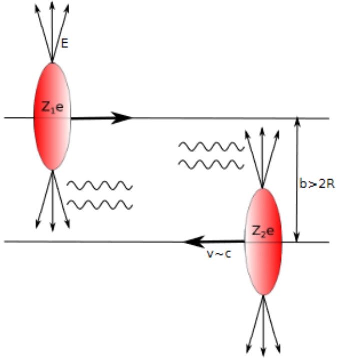

Figure 1: Schematic view of an ultraperipheral collision of heavy ions.

- Accelerated particles surrounded by photons.
- Equivalent Photon Approximation (EPA).
- Photon-photon ($\gamma\gamma$) and photonuclear interactions.
- Cross-section scales with Z^4.
- Cleanner events (compared to pp).

[1] E. Fermi. Electromagnetic Probes of Fundamental Physics, 2003.
[2] E. J. Williams. Phys. Rev. 45, 1934.
[3] C. von Weizsacker. Z. Phys. 88, 1934.

The Light-by-Light Scattering (LbyL), $\gamma\gamma \to \gamma\gamma$, is a rare Standard Model (SM) process that occurs via one loop interactions, with virtual charged particles in QED.

In the Feynman - 't Hooft gauge the diagrams are:

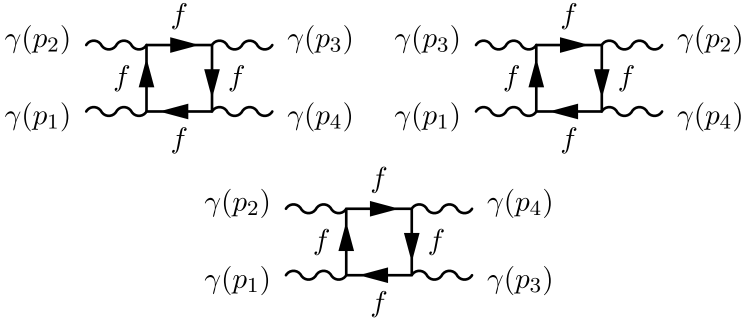

Figure 2: Virtual box Feynman diagrams for LbyL using fermions loop.

[4] D. d'Enterria & G. G. Silveira. Phys. Rev. Lett. 111, 2013.

Light-by-Light Scattering

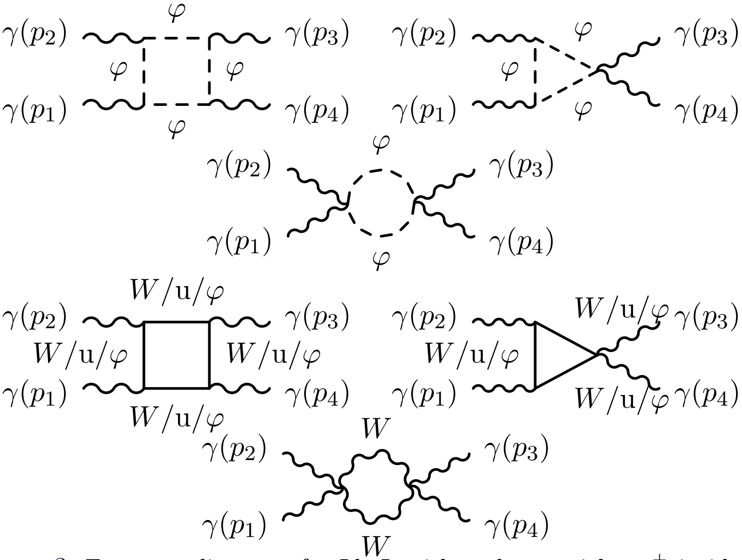

Figure 3: Feynman diagrams for LbyL with scalar particles $\varphi^{\pm}$ inside the loop and combinations between bosons $W^{\pm}$, ghosts $\mathrm{u}^{\pm}$ and scalars $\varphi^{\pm}$.

LbyL measurement at the LHC

The first experimental evidence was established by the ATLAS experiment in 2017 with data obtained from Run 2 at UPC from PbPb at $\sqrt{s_{NN}} = 5.02$ TeV. Later, with data from the same run, the CMS experiment confirmed the process.

The interest of the final state is the exclusive production of two photons, in:

$$\mathrm{Pb} + \mathrm{Pb}\,(\gamma\gamma) \rightarrow \mathrm{Pb}^* + \mathrm{Pb}^*\,\gamma\gamma.$$

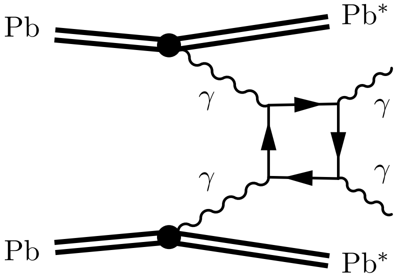

Figure 4: Light-by-light scattering diagram in UPC of PbPb.

[6] ATLAS Collaboration. Nature Phys. 13, 2017.

[7] CMS Collaboration. Physics Letters B, 797, 2019.

[8] ATLAS Collaboration. Phys. Rev. Lett., 123, 2019.

Light-by-Light Scattering

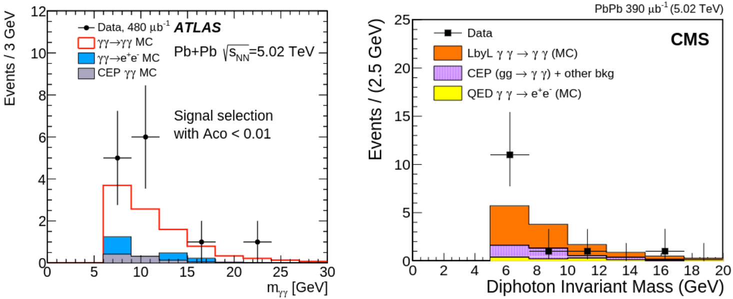

Figure 5: LbyL events observed in ATLAS (left) and CMS (right).

		ATLAS	CMS
$\sqrt{s_{NN}}$	Year ($\mathcal{L}$ [nb^{-1}])	σ_{fid} [nb] (candidate events)	σ_{fid} [nb] (candidate events)
5.02 TeV	2015 (0.48, 0.39)	70 ± 29 (13 events)	120 ± 46 (14 events)
	2018 (1.73)	78 ± 13 (59 events)	-

- Axions were proposed by Pecci-Quinn in 1977 to solve a strong problem involving CP violation in QCD.

Axion-Like Particles (ALP) are pseudoscalar neutral bosons with masses up to the TeV scale that couple to photons through:

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

where a is the ALP pseudoscalar, M_a their mass, $\frac{k}{\Lambda}$ the coupling constant, $F^{\mu\nu}$ the electromagnetic field tensor y $\tilde{F}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$.

- ALP can be considered a background in the reaction $\gamma\gamma \to \gamma\gamma$.

[9] R. Peccei & H. R. Quinn. Phys. Rev. Lett. 38, 1977.

[10] S. Knapen, T. Lin, H. Keong & T. Melia. Phys. Rev. Lett. 118, 2017.

ATLAS and CMS have conducted searches to establish ALP boundaries in the di-photon invariant mass regions between 5 GeV and 100 GeV.

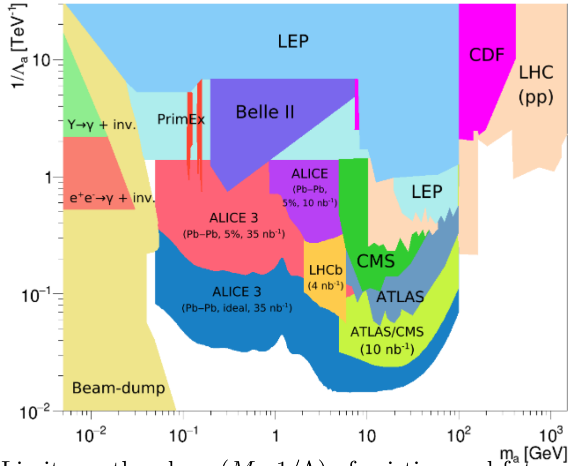

Figure 6: Limits on the plane $(M_a, 1/\Lambda)$ of existing and future ALP searches.

The decay width of the ALP to photons is given by:

$$\Gamma\left(a \to \gamma\gamma\right) = \frac{1}{64\pi}\frac{k^2 M_a^3}{\Lambda^2}.$$

The Feynman diagrams for this process are:

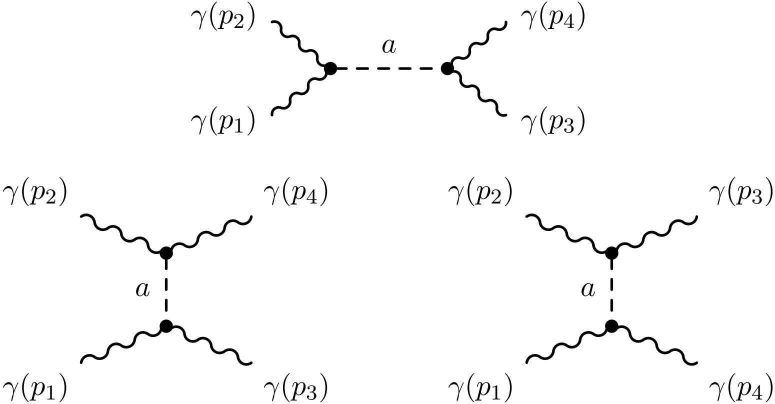

Figure 7: ALP-$\gamma\gamma$ Feynman diagrams for channels s (up), t and u (down) respectively.

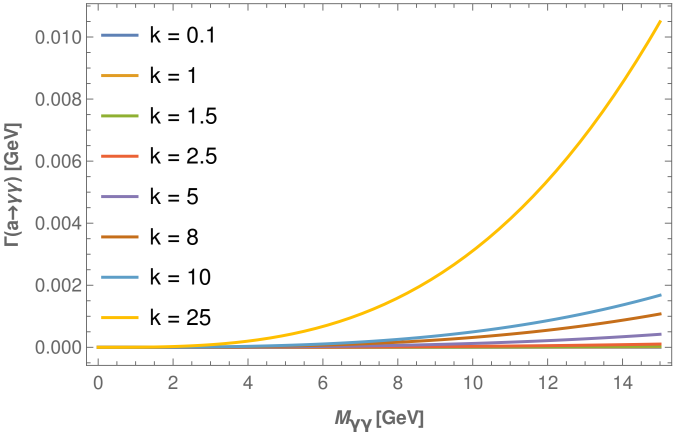

Figure 8: Decay width with respect to the mass of the ALP for different values of k with $\Lambda = 1000$ GeV.

In particular, an analytical study for $M_a = 7$ GeV with $k = 1.5$ and $\Lambda = 1000$ GeV.

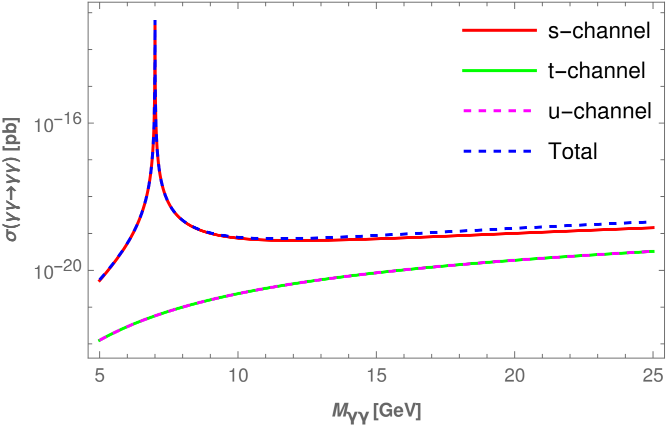

Figure 9: ALP-$\gamma\gamma$ cross section dependence with invariant mass, for channels s, t and u.

ALICE Expectations

ALICE 3 is the ALICE experiment upgrade for Run 5 and Run 6 of the LHC. It will provide the opportunity to extend photon-mediated studies to low p_T and will have a wide region of pseudorapidity η in the detector, which provides an advantage for the selection of exclusive end states in UPCs.

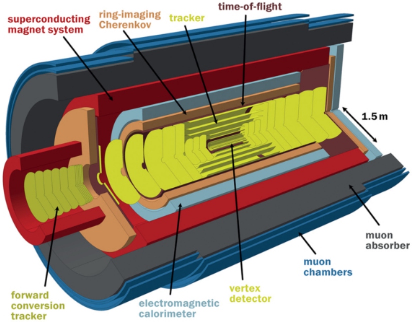

Figure 10: ALICE 3 Experiment Proposal.

[11] ALICE collaboration. CERN-LHCC-2022-009, 2022.

We used MadGraph5_aMC@NLO+gamma-UPC MC generator to produce exclusive final states in photon fusion for PbPb UPCs, at partonic level with $\sqrt{s_{NN}} = 5.02$ TeV.

The following simulations were carried out:

- LbyL scattering with a loop of fermions, boson $W^{\pm}$ and the total SM.
- ALP production through ALP-$\gamma\gamma$ coupling.

In both cases, considering the following experimental cuts proposed for ALICE 3:

$$p_T^{\gamma} > 50 \text{ MeV} \quad \text{and} \quad |\eta^{\gamma\gamma}| < 4.$$

In addition, an analytical study was carried out for the ALP-$\gamma\gamma$ coupling model to compare with MonteCarlo.

[12] H. Shao & D. d'Enterria. JEHP. 9, 2022.

Light-by-Light Scattering

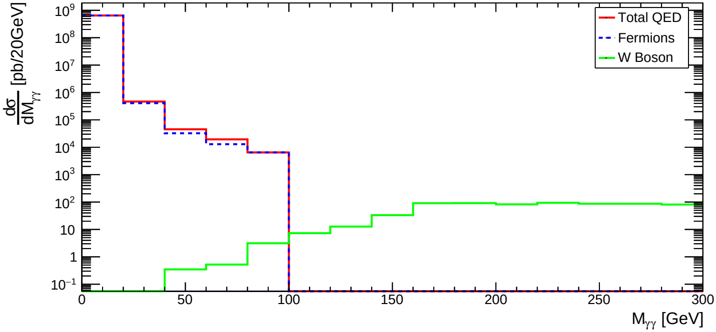

Figure 11: Differential cross section with respect to the invariant mass of di-photons in PbPb UPC at 5.02 TeV.

- LbyL with fermions loop: $0 < M_{\gamma\gamma} < 100$ GeV.
- LbyL with loop of $W^{\pm}$: maximum at $M_{\gamma\gamma} \geq 2M_W$.

Light-by-Light Scattering (only Fermions)

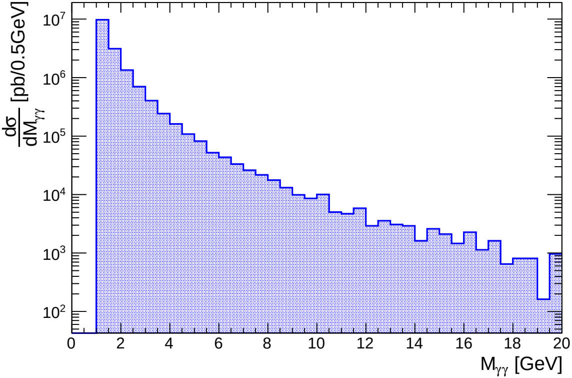

Figure 12: Differential cross section with respect to invariant di-photon mass.

- Decreasing signal distribution
- Maximums for low values of $M_{\gamma\gamma}$.

Light-by-Light Scattering and ALP-$\gamma\gamma$ model

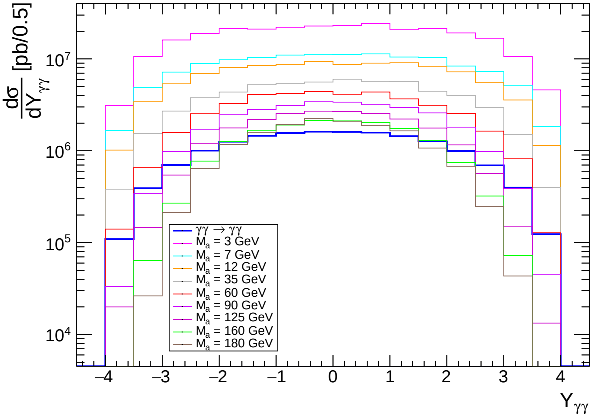

Figure 13: Differential cross section with respect to di-photon rapidity in PbPb UPC at 5.02 TeV.

- The signal has a similar behavior.

Light-by-Light Scattering and ALP-$\gamma\gamma$ model

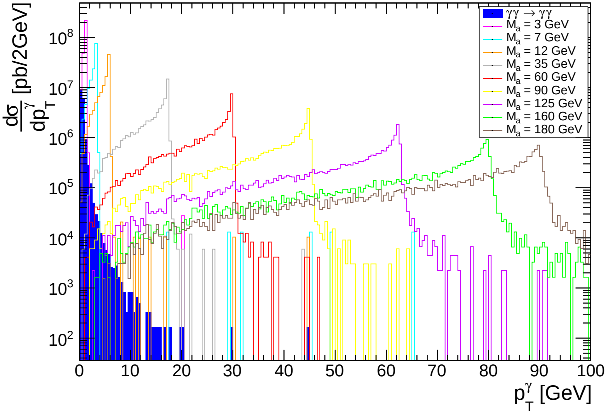

Figure 14: Differential cross section with respect to the transverse moment of a photon in PbPb UPC at 5.02 TeV.

- The p_T distribution for ALP exhibit a different behavior with respect to LbyL.

Analysis and Results

Setting $\Lambda = 1000$ GeV and varying k the analytical results are compared with MC simulations.

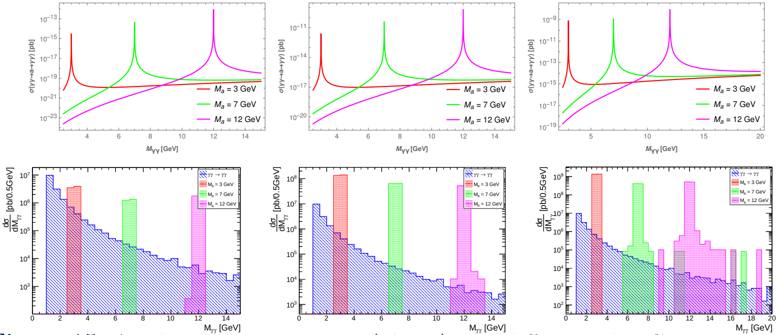

Figure 15: Analytical cross section (above) and differential MC cross section (below) with respect to the invariant mass of diphotons for $k = 1.5$ (left), $k = 8$ (middle) and $k = 25$ (right).

- For $k > 1.5$ ALP is dominant over LbyL.
- With large k, ALP presents tails in the resonance.

Analysis and Results

$W^{\pm}$ contribution in the LbyL loop (higger invariant mass):

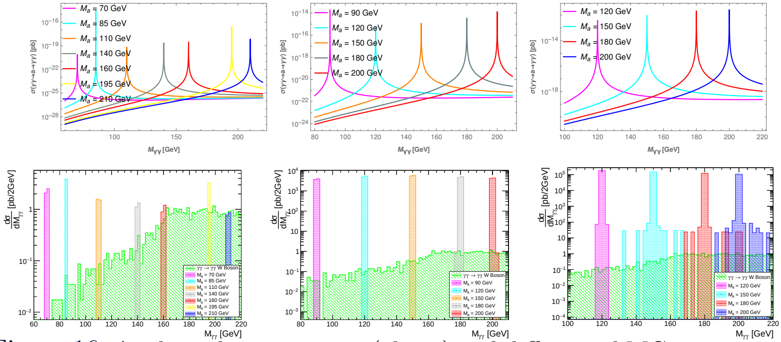

Figure 16: Analytical cross section (above) and differential MC cross section (below) with respect to the invariant mass of di-photons for $k = 0.01$ (left), $k = 0.1$ (middle) y $k = 0.5$ (right)

- Increasing the invariant mass and getting larger values for k, the spectra dominate LbyL contribution.

Background

The production of dileptons is considered dominant background $\gamma\gamma \to \ell^+\ell^-$, specifically dielectrons and the exclusive central production of diphotons (CEP) $gg \to \gamma\gamma$.

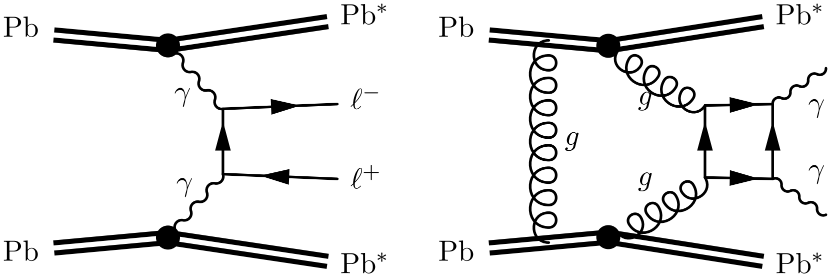

Figure 17: Schematic diagrams of the dominant background in interactions $\gamma\gamma$ in UPC of PbPb. Left: dilepton production. Right: exclusive central diphoton production.

[10] S. Knapen, T. Lin, H. Keong & T. Melia. Phys. Rev. Lett. 118, 2017.

Analysis and Results

Dilepton Production

For the dominant background in the SM, MC events were simulated for $\gamma\gamma \to \ell^+\ell^-$, $\ell = \mu, \tau$ including the magnetic and electric dipole moments.

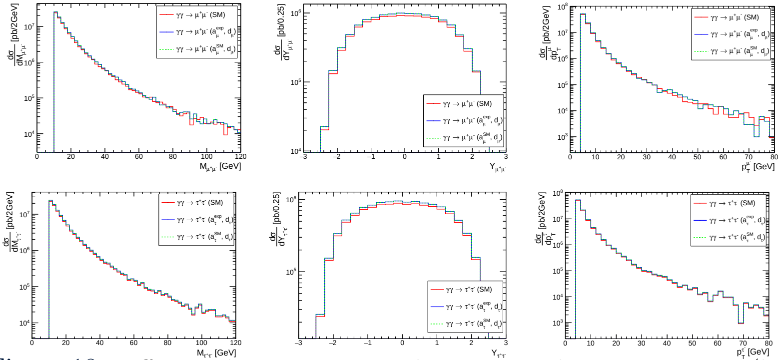

Figure 18: Differential cross section with respect to the invariant mass (left) and rapidity (middle) of dimuons (above) and dielectrons (below) and with respect to the transverse moment (right)

Summary

- We review the LbyL scattering in the Standard Model, including the contributions of the magnetic and electric dipole moments in the dilepton production background.
- A study was carried out, in both, analytically and with MonteCarlo simulations under the context of the ALICE experiment, also using different spaces parameters of the ALP-$\gamma\gamma$ coupling.
- In particular, it was found that the p_T distribution with and without ALP, shows a totally different behavior in the reaction $\gamma\gamma \to \gamma\gamma$, so the signal from the ALP is distinguishable from the one produced by the Standard Model.

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