Searching for axion-like particles in light-by-light scattering at the Large Hadron Collider

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Introduction

- One of the main goals of Particle Physics is the search for New Physics;
- Photon-physics above the electroweak scale opens new paths for novel searches for New Physics complementary to the standard efforts at the LHC;
- Of particular interest are pseudoscalars weakly coupled to SM particles, known as axion-like particles (ALPs).
- ALPs appear in many extensions of the SM:
  - Pseudo Nambu-Goldstone bosons after spontaneous breaking of a global symmetry;
  - Mediators between hidden sectors and the SM;
- **In this presentation** we show projections for the search of ALPs in exclusive diphoton production in $pp \to p(\gamma\gamma \to a \to \gamma\gamma)p$ at the LHC, based on:
  - **Searching for axion-like particles with proton tagging at the LHC**, CB, S. Fichet, G. von Gersdorff, C. Royon, JHEP06(2018)131
  - **Extending the constraint for axion-like particles as resonances at the LHC and laser beam experiments**, CB, S. Hassani, L. Schoeffel and C. Royon, Phys. Lett. B, PLB 34704 (2019).

Axion-like particles (ALPs)

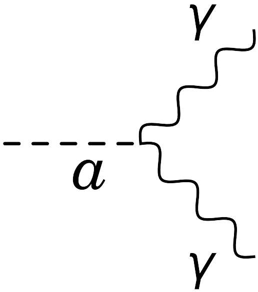
- We focus solely on the coupling of ALP to photons;
- No further assumptions on the ALP–SM particles couplings are necessary!
- Model ALP–photon coupling via conventional dimension-five operator,

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{1}{f}aF\tilde{F}$$

  where a is the ALP field, $\frac{1}{f}$ is the ALP–photon coupling;

- Partial decay width,

$$\Gamma(a \to \gamma\gamma) = \frac{1}{4\pi}\frac{m_a^3}{f^2}$$



ALP–photon interaction

Constraining axion-like particles

- Landscape of ALP–photon coupling versus ALP mass;
- ALPs are strongly constrained at low masses ($m_a = 10^{-15} - 10^{-1}$ GeV), mainly by axion helioscopes.
- ALPs constraints at multi-GeV masses are collider-based:
  - Very hard to constrain ALPs relying **only** on its coupling to photons!
  - Bounds are based on multi-photon measurements at LEP, Tevatron and LHC;
- Constraints are especially difficult for ALPs masses probed in p-p collision at the LHC (circled in red)

Existing constraints

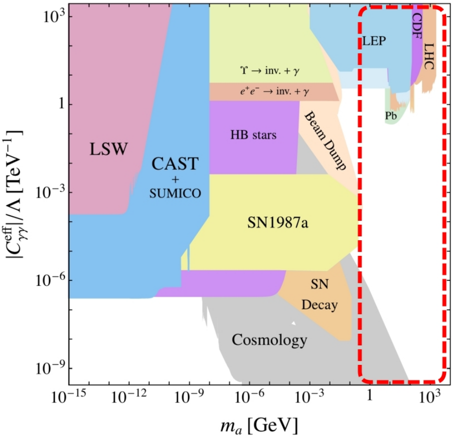
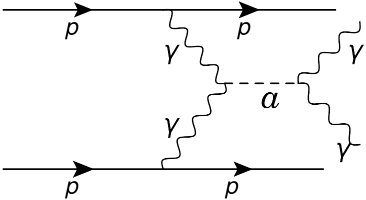


Fig. from Bauer, Neubert, Thamm, **JHEP12(2017)044**

Updated collider-bounds computed by Knapen, Lin, Lou, Melia, **PhysRevLett.118.171801**

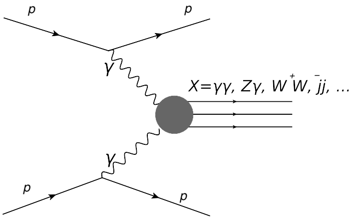
Searching for ALPs in light-by-light scattering

- ALPs coupled to photons induce anomalous light-by-light scattering (LbL);
- Search in ultraperipheral heavy-ion collisions (Knapen, Lin, Lou, Melia, **PhysRevLett.118.171801**);
  - Strong exclusion power (Z^4 enhancement of photon-flux);
  - ALP mass range is limited in UPCs (1 GeV to 100 GeV);
  - Search relies on bump-search over SM-LbL lineshape.
- **This presentation:** exclusive diphoton production in p-p collisions with proton tagging:
  - Access larger invariant diphoton mass (600 GeV to 2 TeV)
    $\hookrightarrow$ Sensitivity is enhanced since ALP production rate increases with $m_{\gamma\gamma}$;
  - Production rates are small ($\sim$ 1 fb);
  - Search does not rely on bump-search strategy, since SM LbL is highly suppressed in p-p collisions.



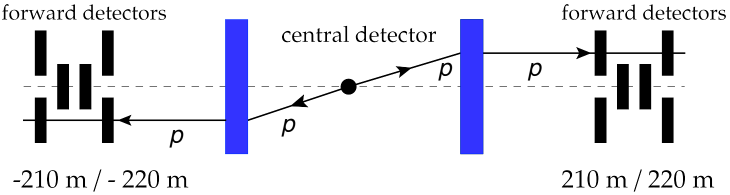
Photon-exchange in p-p collisions

- Central exclusive reactions $pp \to p + X + p$ can be studied by measuring X in a central detector and the intact protons pp with forward proton detectors at $\sim$ 210 m w.r.t. the interaction point.
- Proton fractional momentum loss $\xi = \Delta p/p$ is reconstructed with the forward proton detectors.
- Can select central exclusive processes by comparing $m_{\gamma\gamma}$ with $m_{pp} = \sqrt{\xi_1 \xi_2 s}$ and $y_{\gamma\gamma}$ with $y_{pp} = \frac{1}{2}\ln(\xi_1/\xi_2)$.
- Acceptance in mass of about $300 \leq m_{\gamma\gamma} \leq 2000$ GeV for proton taggers installed at the LHC with ATLAS and CMS experiments



Protons remain intact after interaction
$\rightarrow$ Full reco. of final state!

Forward proton detectors at the LHC



- Diphoton detected in central detector and the intact protons are tagged with forward proton detectors; final state is completely reconstructed;
- LHC magnetic lattice (**blue** rectangles) used as a precise proton longitudinal momentum spectrometer;
- ATLAS Forward Physics (**AFP**) and CMS-TOTEM Precision Proton Spectrometer (**CT-PPS**) are able to operate (and have collected data) with forward proton spectrometers at high instantaneous luminosities;
- Photon-physics above electroweak scale is a reality!

Signal simulation framework

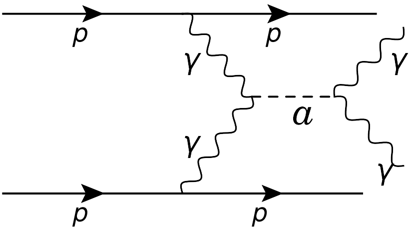
- Light-by-light scattering production rates are computed in the Equivalent Photon Approximation:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}^{pp\to p\gamma\gamma p} = \int \frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\hat{s}}^{\gamma\gamma} \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\Omega}^{\gamma\gamma\to\gamma\gamma} \mathrm{d}\hat{s}$$

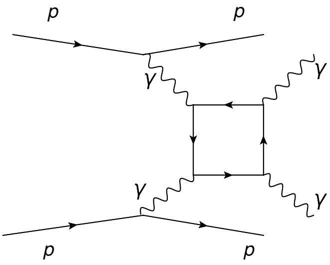
  where $\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\hat{s}}^{\gamma\gamma}$ is the two-photon effective luminosity spectrum;

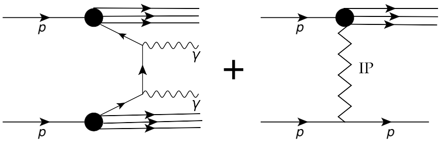
- $\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\Omega}^{\gamma\gamma\to\gamma\gamma}$ is derived from the ALP–photon interaction;

- Exclusive $pp \to p(\gamma\gamma \to a \to \gamma\gamma)p$ production was implemented in the Forward Physics Monte Carlo (**FPMC**) event generator.



Background





Exclusive background (irreducible)

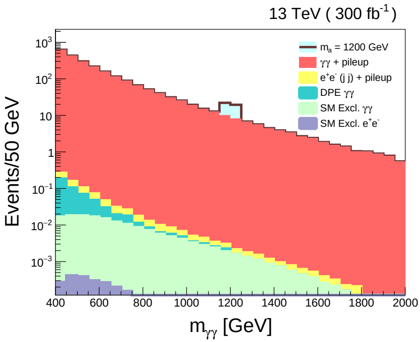
- SM light-by-light scattering;
- Includes contributions from quarks, charged leptons, and W boson boxes
- Small cross section ($\sim 10^{-1}$ fb) for mass range accessible w/ proton taggers;
- Simulated in **FPMC**.

Non-exclusive background (reducible)

- Non-exclusive diphoton production overlapped with diffractive protons from secondary interactions (pileup) is the dominant background.
- Jets and electrons misidentified as prompt-photons overlapped with uncorrelated protons from diffractive reactions in pileup interactions.
- Largely reducible by matching forward-central kinematics!
- Simulated with **PYTHIA8**.

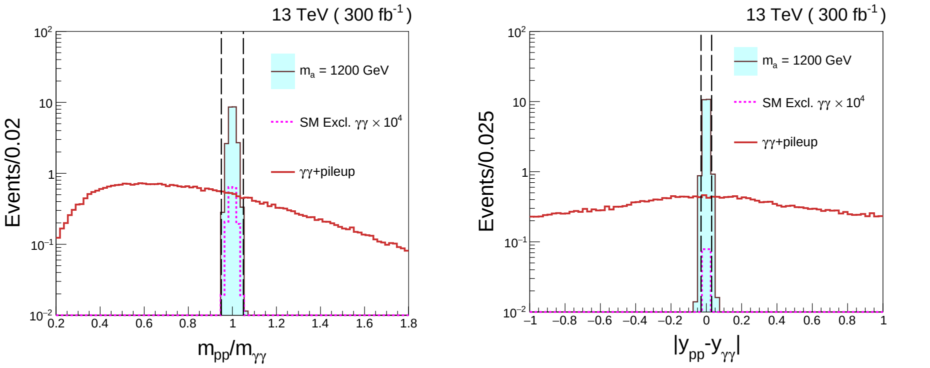
Event selection

- Two photons with minimum $p_T^{\gamma} > 100$ GeV and $|\eta^{\gamma}| < 2.5$;
- Protons reconstructed on each side with $0.015 \leq \xi \leq 0.15$, where the proton taggers are efficient;
- Exclusive processes topology selection:
  - $|\Delta\phi_{\gamma\gamma} - \pi| < 0.01$ rad
  - $p_{T,2}^{\gamma}/p_{T,1}^{\gamma} > 0.95$
- Minimum diphoton invariant mass of $m_{\gamma\gamma} > 600$ GeV; suppresses background with rate steeply falling $m_{\gamma\gamma}$ rate.
- Forward-central system matching: strong rejection of non-exclusive processes!



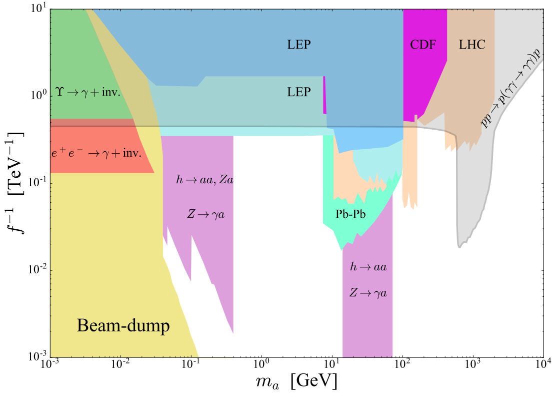
- Assume 300 fb^{-1} of data for our projections in p-p collisions at 13 TeV w/ pileup of 50 interactions;
- Background dominated by inelastic diphoton production overlapped with diffractive protons (in red);
- Signal instance in cyan at $m_a = 1.2$ TeV for $f^{-1} = 0.1$ TeV^{-1};

Exclusive selection



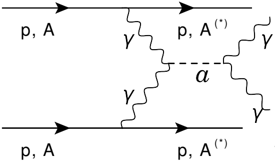
- Non-exclusive events can be rejected by comparing the kinematics of forward and central systems, leading to a robust background suppression;
- Ratio of $m_{\gamma\gamma}$ with diphoton mass reconstructed with forward protons $m_{pp} = \sqrt{s\xi_1\xi_2}$, exclusive processes peak at 1;
- Compare rapidity reconstructed centrally $y_{\gamma\gamma}$ with diphoton rapidity reconstructed with forward protons $y_{pp} = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$, exclusive processes peak at 0;

Results [JHEP06(2018)131, CB, S. Fichet, G. von Gersdorff, C. Royon]



95% CL projections in central exclusive production assuming $\mathcal{B}(a \to \gamma\gamma) = 1$.
Strong exclusion power for resonant ALP production in the collider-bounds region (down to $1/f = 0.02$ TeV^{-1})!

Further constraints using light-nuclei collisions



Where $A =$ Pb, Ar, Xe, O

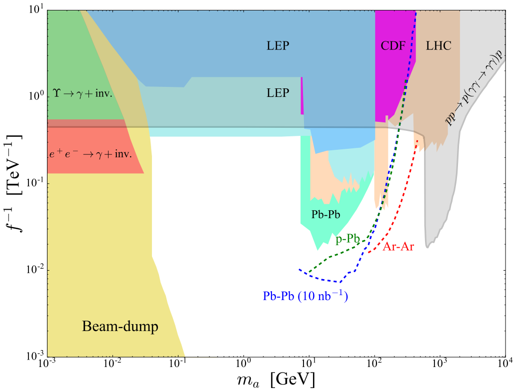
Constraining axion-like particles in:

- **UPCs in Pb-Pb:** Large production rate due to Z^4 enhancement, but upperbound in diphoton invariant mass $m_{\gamma\gamma} < 100$ GeV due to minimum impact parameter between colliding ions.
- **In p-p collisions:** Wide range in diphoton invariant masses, but very small production rates.

Is it possible to cover an intermediate region in mass in light-nuclei collisions?

- **proton-lead collisions at $\sqrt{s_{NN}} = 8$ TeV:** Z^2 enhancement from Pb ion, access to slightly larger invariant diphoton masses due to smaller minimum impact parameter for UPCs.
- **argon-argon collisions at $\sqrt{s_{NN}} = 7$ TeV:** Similar reach in invariant masses as proton-lead, and can profit from $Z^4 \approx 10^5$ photon-luminosity enhancement. In addition, machine may deliver 3-8.8 pb^{-1} of luminosity.
- **oxygen-oxygen, xenon-xenon collisions:** Production rates are too small, and cannot be compensated with the integrated luminosities under discussion.

Results [Phys. Lett. B, PLB 34704 (2019), CB, S. Hassani, L. Schoeffel, C. Royon]



- Ar-Ar collisions ($\mathcal{L}_{\text{int}} = 3$ pb^{-1} at $\sqrt{s_{NN}} = 7$ TeV)
- p-Pb collisions ($\mathcal{L}_{\text{int}} = 5$ pb^{-1} at $\sqrt{s_{NN}} = 8$ TeV)
- Light-nuclei collisions provide complementary bounds to the ones found in Pb-Pb or p-p!

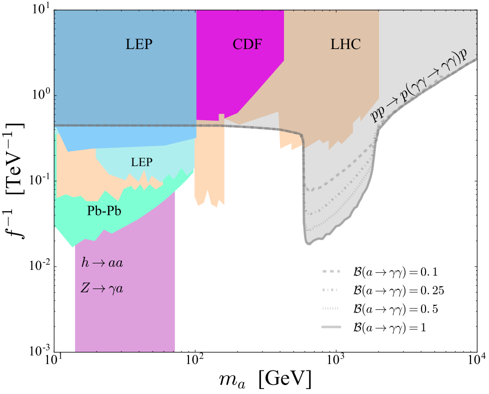
Summary

- We examined the possibility of searching for ALPs in central exclusive production of photon pairs in p-p collisions at 13 TeV for an integrated luminosity of 300 fb^{-1} with proton tagging;
- To assess sensitivities, we implemented the helicity amplitudes for light-by-light scattering induced by effective dimension-five operators couplings to pseudo-scalars to photons in the FPMC generator;
- We found that the discovery potential is competitive with the standard multi-photon searches at the LHC for ALP masses between 600 GeV to 2 TeV;
- Projections based on light-nuclei collisions (Ar-Ar or p-Pb) complementary to the ones found in Pb-Pb and p-p collisions.
- Various compromises between effective photon-luminosities, minimum impact parameter for UPCs, and machine performance $\rightarrow$ complementarity between various approaches.

Thank you!

Back-up slides

Results across branching ratios



Projections for various branching ratio assumptions.

Statistical framework

We calculate our projections for the total signal rate over the whole mass range (0.6 to 2 TeV). We assume a set of observed data. Assume there are no statistical fluctuations in these imaginary data, dubbed as "Asimov data". The observed events follow a Poisson distribution. We have the likelihood function,

$$\mathcal{L}(\sigma) = Pr(n'|b + \sigma L)$$

$$Pr(\hat{n}|n) = \frac{n^{\hat{n}} e^{-n}}{\hat{n}!}$$

w/ $L = 300$ fb^{-1}. For this analysis, the expected number of events from background b is very small.

The posterior probability is $\mathcal{L}(\sigma)\pi(\sigma)$ with flat prior $\pi(\sigma)$. We assume no event is observed $n' = 0$. The non-observation sets an upperbound on the signal event rate.

The higher posterior density region at $1 - \alpha$ is solved analytically in this case, and is given by,

$$1 - \alpha = 1 - e^{-\sigma_\alpha L} \quad (1)$$

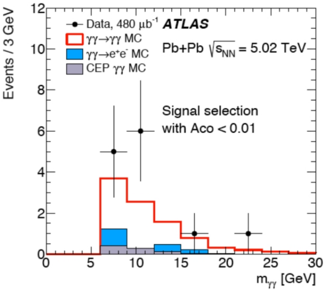
where $\alpha = 0.05$ for 95% CL.

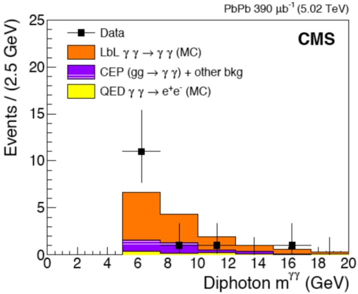
Sequential cut flow

Sequential selection	ALP	Excl. SM	DPE $\gamma\gamma$	e^+e^- / dijet +pileup	$\gamma\gamma$ + pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{T1,(2)} > 200, (100)$ GeV$]$	23.1	0.1	0.1	1.2	1246
$m_{\gamma\gamma} > 600$ GeV	23.1	0.06	0	0.1	440
$[p_{T2}/p_{T1} > 0.95$, $\lvert\Delta\phi^{\gamma\gamma} - \pi\rvert < 0.01]$	23.1	0.06	0	0	35
$\lvert m_{pp}/m_{\gamma\gamma} - 1\rvert < 0.03$	21.8	0.06	0	0	1.2
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	21	0.06	0	0	0.2

Table 1. Signal and background yields after applying the event sequential selections. For illustrative purposes, we choose an ALP with mass $m_a = 1200$ GeV and a coupling value of $f^{-1} = 0.1$ TeV^{-1}. We assume an integrated luminosity of 300 fb^{-1} an average of 50 additional interactions per bunch crossing at $\sqrt{s} = 13$ TeV. Excl. stands for the exclusive backgrounds and DPE for double pomeron exchange background. Non-exclusive diphoton overlapped with soft diffractive protons (rightmost column) constitute the dominating background. The first two rows correspond to the diphoton offline preselection. The third row corresponds to the elastic selection. The last two rows correspond to the exclusive selection, with $m_{pp} = \sqrt{\xi_1\xi_2 s}$ and $y_{pp} = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$.

Light-by-light scattering in Pb-Pb collisions





- Both ATLAS (Nature Physics 13 (2017) 852, ATLAS 2019 results arXiv:1904.03536) and CMS (Subm. to Phys. Lett. B., CERN-EP-2018-271) observed events consistent with light-by-light scattering in ultraperipheral heavy-ion collisions at $\sqrt{s_{NN}} = 5.02$ TeV in Pb-Pb collisions;
- Cross section is enhanced by Z^4, but is bounded at high mass due to the minimum impact parameter in UPCs
- Pb-Pb and p-p cover complementary kinematic regimes;