Searching for axion-like particles in light-by-light scattering with proton tagging at the LHC

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1. 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;
  - String theory landscape;
  - Mediators between hidden sectors and the SM;

2. Axion-like particles (ALPs)

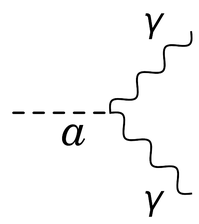
- We focus solely on the coupling of ALP to photons;
- No further assumptions on the ALP–SM particles couplings are necessary!
- Model ALP–photon coupling via conventional dimension-five operator,

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

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

- Partial decay width,

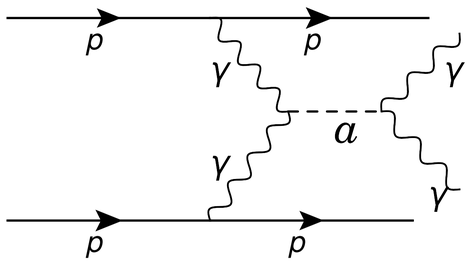
$$\Gamma(a \to \gamma\gamma) = \frac{1}{4\pi}\frac{m_a^3}{f^2} \qquad (2)$$



ALP–photon interaction

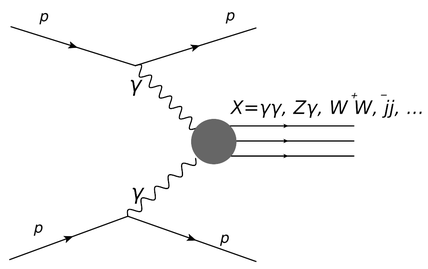
3. Searching for ALPs in light-by-light scattering

- 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 work:** exclusive diphoton production in p-p collisions with proton tagging:
  - Access larger invariant diphoton mass (600 GeV to 2 TeV)
    ↪ 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.



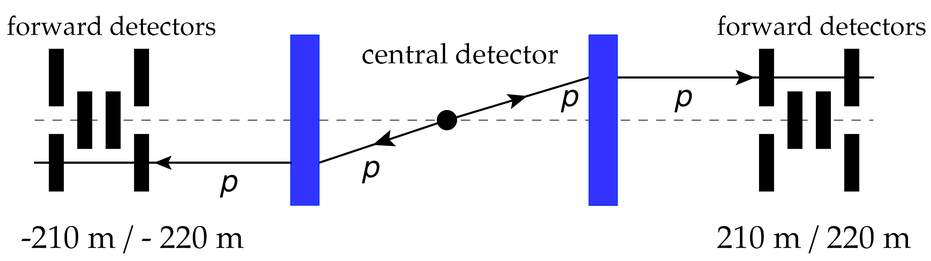
4. Photon-exchange in p-p collisions

- 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



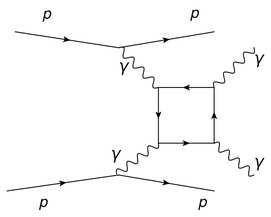
Protons remain intact after interaction
→ Full reco. of final state!

5. Forward proton detectors at the LHC



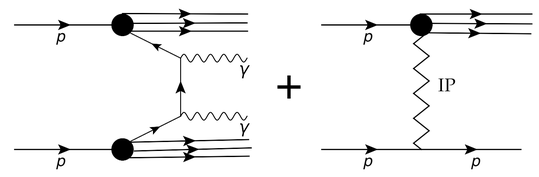
- Diphoton detected in central detector and the intact protons are tagged with forward proton detectors; final state is completely reconstructed;
- LHC magnetic lattice (**blue** rectangles) used as a precise proton longitudinal momentum spectrometer;
- ATLAS Forward Physics (**AFP**) and CMS-TOTEM Precision 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!

6. Background



Exclusive background (irreducible)

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



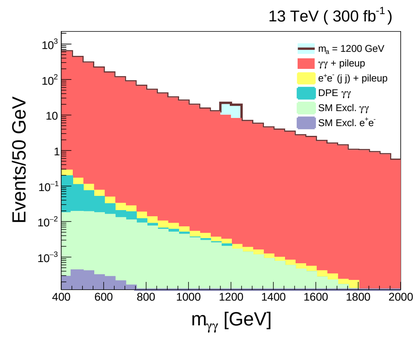
Non-exclusive background (reducible)

- Non-exclusive diphoton production overlapped with diffractive protons from secondary interactions (pileup) is the dominant background.
- Fakes from jets and electrons (positrons) overlapped with diffractive protons.
- Reducible by matching forward-central kinematics.
- Simulated with **PYTHIA8**.

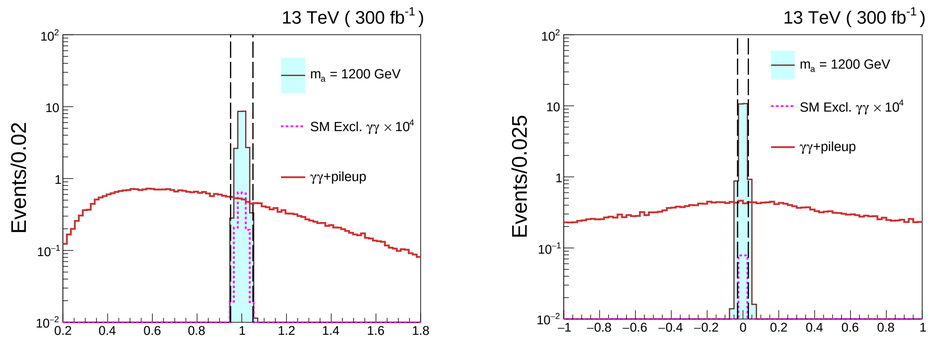
7. Event selection

- 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};

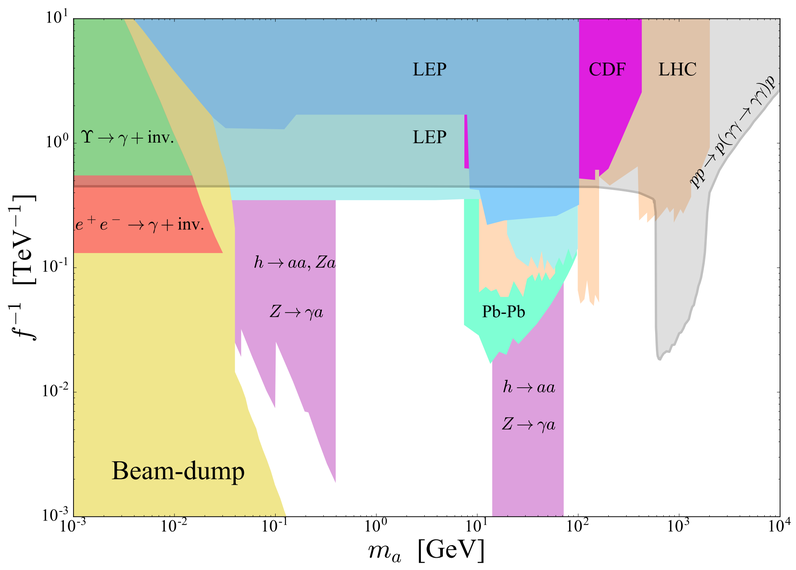


8. Exclusive selection



- 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;

9. Results



Expected 95% CL exclusion limit 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})!

10. Conclusions and outlook

- 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;
- 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;