Probing axion-like particles with $\gamma\gamma$ final states from vector boson fusion processes at the LHC

Andrés Flórez$^2$, Alfredo Gurrola$^1$, Will Johns$^1$, Paul Sheldon$^1$, Elijah Sheridan$^1$, Kuver Sinha$^3$, Brandon Soubasis$^1$

Vanderbilt University$^1$, Universidad de los Andes$^2$, University of Oklahoma$^3$

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Theoretical Origins

- The quantum chromodynamics (QCD) Lagrangian admits a CP (charge conjugation-parity) symmetry violating term, but experiments place stringent constraints on its magnitude; the cause of this suppression is unknown (the strong CP problem).
- In 1977, Roberto Peccei and Helen Quinn proposed a solution involving the promotion of the CP violation phase $\Theta$ to a scalar field which spontaneously broke a new global symmetry.
- The quanta of this new scalar field is the axion.

Axion Properties and Modern Status

- The axion is a neutral spin-0 boson with negative parity (i.e., a pseudoscalar).
- Strict mass-coupling relationships must hold for the axion to solve the strong CP problem; axions satisfying these are denoted QCD axions while unconstrained neutral pseudoscalars are axion-like particles (ALPs).
- Light ALPs are compatible with current dark matter relic density calculations, making them dark matter candidates.
- String theory (ST) has more recently predicted the axiverse, a collection of ALPs, incentivizing ALP study and linking ST with ALP phenomenology.
We adopt an effective field theory approach with cutoff scale $\Lambda$. 

$$\mathcal{L} \supset \frac{1}{2} (\partial_\mu a)^2 - \frac{1}{2} m_a^2 a^2 + \frac{c_1}{\Lambda} \partial_\mu a \bar{f} \gamma_\mu \gamma_5 f - \frac{c_2}{\Lambda} a G_{\mu\nu} \tilde{G}^{\mu\nu} - \frac{c_3}{\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{c_4}{\Lambda} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{c_5}{\Lambda} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{c_6}{\Lambda} (\partial_\mu a)(\partial_\nu a) \phi^\dagger \phi + \frac{c_7}{\Lambda^3} (\partial_\mu a)(\phi^\dagger i D_\mu \phi) + \text{h.c.}) \phi^\dagger \phi + \ldots$$

- $a \rightarrow \gamma\gamma$
- $a \rightarrow \ell^+\ell^-$
- $a \rightarrow g g$
- $a \rightarrow g g$
- $Z \rightarrow \gamma a$
- $a \rightarrow \ell^+\ell^-$
- $a \rightarrow Z a$
- $h \rightarrow a a$
- $h \rightarrow Z a$
Introduction to ALP Research

Astrophysics (solar axions, magnetar ALP production, etc.)

Current LHC constraints
$(pp \rightarrow Z \rightarrow \gamma a; pp \rightarrow h \rightarrow Za, aa)$

Experimentally unconstrained; target region

Bauer et al. (2018)
Achieving Novelty: VBF and Non-Resonant Production

Vector Boson Fusion (VBF)
- The vector boson fusion topology derives merit from its distinct LHC signature
- The matrix element magnitude goes as $|\mathcal{M}|^2 \propto m_{ jj} / p_T^j$ for outgoing quarks or “tagged jets” $j$; maximization occurs for energetic jets with low transverse momenta (high pseudorapidity differences)

Non-Resonant Production of ALPs
- The ALP resonant production cross section scales as $\sigma_{\text{res}} \propto m_a^2 / \Lambda^2$ and is suppressed for $m_a \ll \Lambda$; thus non-resonant ALP production dominates, enabling sensitivity to MeV-scale ALPs
- With no resonant contribution, diphoton kinematics are driven only by energetic jet pair, yielding further discriminating power
- Lighter ALPs are faster and more stable; requiring ALP decay within the detector constrains the perpendicular decay length $L_{a, \perp} = \sqrt{\gamma_a^2 - 1} \sin \theta$

Elijah Sheridan
Probing ALPs with VBF at the LHC
May 24, 2021
Event Generation

Signal Generation

- We generate events using MadGraph
- Want sufficient VBF signal statistics for our event selection criteria optimization; to suppress unwanted contributions to $pp \rightarrow ajj$ ($a \rightarrow \gamma\gamma$) event generation (e.g., $gg$ fusion, associated ALP production), we impose MadGraph-level selections on signal events:
  
  \[ |\Delta \eta^{jj}| > 2.4, \ m^{jj} > 120 \text{ GeV} \]

Background Generation

- The dominant Standard Model background processes are a mixed QED-QCD channel $pp \rightarrow jj\gamma\gamma$ and a pure electroweak channel $pp \rightarrow jj\gamma\gamma$ ($\alpha_{QCD} = 0$)
- Recognizing our eventual selection of high jet momentum events, we generate BG events in $H_T$ bins to ensure sufficient high-energy statistics
Pre-Selection Kinematics

![Graphs showing distributions in various kinematic variables such as $\Delta \eta^{ij}$, $m_{\gamma\gamma}$, $m_{ij}$, and $p_T^{\gamma_i}$ for different processes involving ALPs at the LHC.](image1)

- $pp \rightarrow jj + \gamma\gamma$, $a_{\phi_8}a_{\phi_{10}}$
- $pp \rightarrow jj + \gamma\gamma$, $a_{\phi_8}a_{\phi_{10}}$ ($m_a = 1$ MeV)
- $pp \rightarrow jj + \gamma\gamma$, $a_{\phi_8}a_{\phi_{10}}$ ($m_a = 100$ MeV)
- $qq \rightarrow jj + a \rightarrow \gamma\gamma$, $a_{\phi_8}a_{\phi_{10}}$ ($m_a = 1$ MeV)
- $qq \rightarrow jj + a \rightarrow \gamma\gamma$, $a_{\phi_8}a_{\phi_{10}}$ ($m_a = 100$ MeV)
Optimizing Event Selection Criteria

**Process**

- We adopt the following signal significance (SS) metric; note our conservative estimation of systematic error

\[ S \sqrt{S + B + (0.25 \cdot (S + B))^2} \]

- Using this metric, we optimize event selection criteria on two kinematic variables simultaneously by sampling SS on a grid

<table>
<thead>
<tr>
<th>Criterion</th>
<th>$\gamma_1 \gamma_2 j_1 j_2$</th>
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<tbody>
<tr>
<td><strong>Central Selections</strong></td>
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<tr>
<td>$</td>
<td>\eta_\gamma</td>
</tr>
<tr>
<td>$p_T^{\gamma}$</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>$p_T^{j_1}$</td>
<td>$&gt; 300$ GeV</td>
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<tr>
<td>$m_{\gamma\gamma}$</td>
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<td>$N(\ell), N(b)$</td>
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<tr>
<td><strong>VBF Selections</strong></td>
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<tr>
<td>$p_T^{j}$</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta_j</td>
</tr>
<tr>
<td>$\Delta R_{\gamma j}$</td>
<td>$&gt; 0.4$</td>
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<tr>
<td>$N(j)$</td>
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</tr>
<tr>
<td>$\eta_j^1 \cdot \eta_j^2$</td>
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<tr>
<td>$</td>
<td>\Delta \eta_{jj}</td>
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<tr>
<td>$m_{jj}$</td>
<td>$&gt; 750.0$ GeV</td>
</tr>
</tbody>
</table>
Results: Signal Significance in the Parameter Space

Comments

- On the right we depict the signal significance achieved by our selections as a function of $m_a$ and $\Lambda$ for two integrated luminosities: 150 fb$^{-1}$ (LHC run II, top) and 3000 fb$^{-1}$ (high luminosity LHC, bottom).

- We have discovery potential for a significant range of ALP masses ($\sim$MeV scale to TeV scale) in the region $\Lambda \lesssim 2.25$ TeV.
Discussion and Summary

Discussion

- We overlay our discovery region on the plot of existing ALP constraints shown at the beginning of this talk.
- In particular, we see that our methodology constrains a significant portion of the parameter space and broadens the LHC constraint region, including unprecedented lower mass/weak coupling scenarios.

Summary

- We pursue a phenomenological study of ALPs, a class of particles well motivated by modern problems in the Standard Model as well as by string theory.
- While ALPs are probed in a variety of settings, we take interest in the high mass, strong coupling scenario and employ a collider approach.
- The unique detector signature of the VBF topology and the domination of non-resonant ALP production together provides several kinematic variables with distinct discrimination power.
- Consequently, an optimization of event selection criteria yields discovery potential in a substantial region of the ALP parameter space.
- In particular, our approach makes novel contributions to the extent of LHC constraints on the ALP parameter space, including the incorporation of previously unstudied regions.

Thank you!