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

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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 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 $\Lambda$. 

\[
\mathcal{L} \supset \frac{1}{2} (\partial_{\mu} a)^2 - \frac{1}{2} m_a^2 a^2 + \frac{c_1}{\Lambda} \partial_{\mu} a \bar{f} \gamma_\mu \gamma_5 f - \frac{c_2}{\Lambda} a G_{\mu\nu} \tilde{G}^{\mu\nu} - \frac{c_3}{\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{c_4}{\Lambda} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{c_5}{\Lambda} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{c_6}{\Lambda} \partial_{\mu} a (\partial^{\mu} a) \phi^\dagger \phi + \frac{c_7}{\Lambda^3} (\partial^{\mu} a)(\phi^\dagger iD_\mu \phi + h.c.) \phi^\dagger \phi + \ldots
\]
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)
Vector Boson Fusion (VBF)

- The vector boson fusion topology derives merit from its distinct LHC signature.
- The matrix element magnitude goes as $|\mathcal{M}|^2 \propto m_j^i / p_T^j$ 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 $L_{a,\perp} = \sqrt{\gamma_a^2 - 1} \sin \theta$.

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Probing ALPs with VBF at the LHC
**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 $pp \rightarrow a_{jj} (a \rightarrow \gamma\gamma)$ 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

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**Graphical Notations**
- $p \equiv q$
- $p \equiv \bar{q}$
- $p \equiv q'$
- $\gamma/h$
- $W^+$
- $W^-$
Pre-Selection Kinematics

![Graph 1](pp→jj + γγ, α_{SEQ}α_{DCD}, pp→jj + γγ, α_{SEQ}α_{DCD}, qq→jj + a (→ γγ), α_{SEQ}α_{DCD} (m_a = 1 MeV), qq→jj + a (→ γγ), α_{SEQ}α_{DCD} (m_a = 100 MeV))

![Graph 2](pp→jj + γγ, α_{SEQ}α_{DCD}, pp→jj + γγ, α_{SEQ}α_{DCD}, pp→jj + a (→ γγ), α_{SEQ}α_{DCD} (m_a = 1 MeV), pp→jj + a (→ γγ), α_{SEQ}α_{DCD} (m_a = 100 MeV))

![Graph 3](pp→jj + γγ, α_{SEQ}α_{DCD}, pp→jj + γγ, α_{SEQ}α_{DCD}, pp→jj + a (→ γγ), α_{SEQ}α_{DCD} (m_a = 1 MeV), pp→jj + a (→ γγ), α_{SEQ}α_{DCD} (m_a = 100 MeV))

![Graph 4](pp→jj + γγ, α_{SEQ}α_{DCD}, pp→jj + γγ, α_{SEQ}α_{DCD}, pp→jj + a (→ γγ), α_{SEQ}α_{DCD} (m_a = 1 MeV), pp→jj + a (→ γγ), α_{SEQ}α_{DCD} (m_a = 100 MeV))
Optimizing Event Selection Criteria

Process

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

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

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

| Criterion | $\gamma_1 \gamma_2 j_1 j_2$ |
|-----------|-----------------------------|
| **Central Selections** | |
| $|\eta^\gamma|$ | $< 2.5$ |
| $p_T^\gamma$ | $> 30$ GeV |
| $p_T^{j_1}$ | $> 300$ GeV |
| $m_{\gamma \gamma}$ | $> 500$ GeV |
| $N(\ell), N(b)$ | $= 0$ |
| **VBF Selections** | |
| $p_T^j$ | $> 30$ GeV |
| $|\eta^j|$ | $< 5.0$ |
| $\Delta R_{\gamma j}$ | $> 0.4$ |
| $N(j)$ | $\geq 2$ |
| $\eta^{j_1} \cdot \eta^{j_2}$ | $< 0$ |
| $|\Delta \eta^{jj}|$ | $> 3.6$ |
| $m^{jj}$ | $> 750.0$ GeV |
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.

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**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.

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**Thank you!**