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

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Motivating ALPs

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 $\overline{\Theta}$ 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

The ALP Lagrangian

We adopt an effective field theory approach with cutoff scale Λ.

$a \to \gamma\gamma$

$Z \to \gamma a$

$a \to \ell^+\ell^-$

$a \to gg$

$a \to ZZ$

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{c_1}{\Lambda}\partial_\mu a\bar{f}\gamma_\mu\gamma_5 f - \frac{c_2}{\Lambda} aG_{\mu\nu}\tilde{G}^{\mu\nu}$$
$$- \frac{c_3}{\Lambda} aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{c_4}{\Lambda} aF_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{c_5}{\Lambda} aZ_{\mu\nu}\tilde{Z}^{\mu\nu}$$
$$+ \frac{c_6}{\Lambda}(\partial_\mu a)(\partial^\mu a)\phi^\dagger\phi + \frac{c_7}{\Lambda^3}(\partial^\mu a)(\phi^\dagger iD_\mu\phi + h.c.)\phi^\dagger\phi + \dots$$

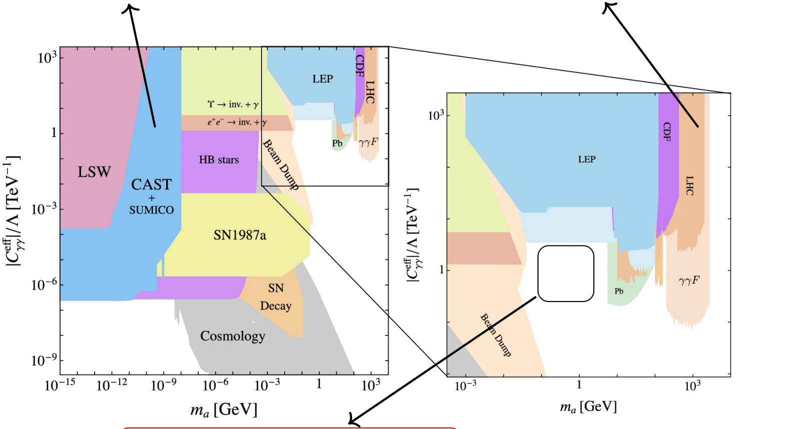
$h \to aa$

$h \to Za$

Introduction to ALP Research

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

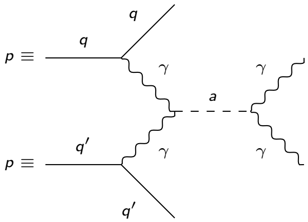
Current LHC constraints ($pp \to Z \to \gamma a$; $pp \to h \to Za, aa$)



Experimentally unconstrained; target region

Bauer et al. (2018)

Achieving Novelty: VBF and Non-Resonant Production



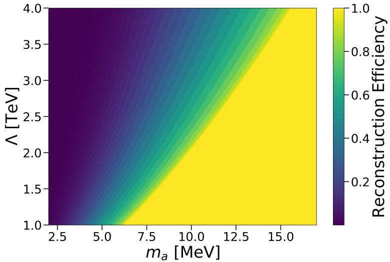
Vector Boson Fusion (VBF)

- 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**

$$L_{a,\perp} = \frac{\sqrt{\gamma_a^2 - 1}}{\Gamma} \sin\theta$$

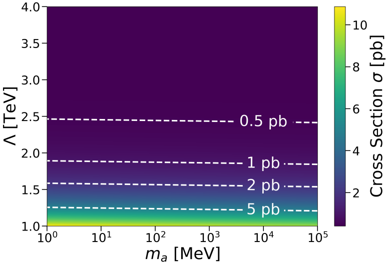


Event Generation

Signal Generation

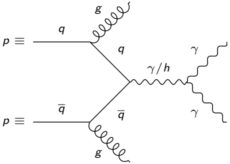
- We generate events using **MadGraph**
- Want sufficient VBF signal statistics for our event selection criteria optimization; to suppress unwanted contributions to $pp \to ajj$ $(a \to \gamma\gamma)$ event generation (e.g., gg fusion, associated ALP production), we impose *MadGraph-level selections* on signal events:

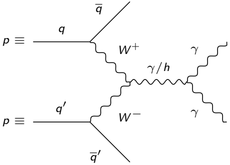
  $|\Delta\eta^{jj}| > 2.4$, $m^{jj} > 120$ GeV



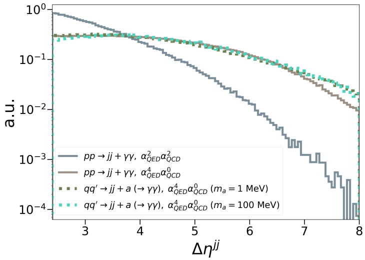
Background Generation

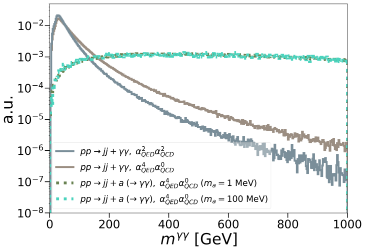
- The dominant Standard Model background processes are a mixed QED-QCD channel $pp \to jj\gamma\gamma$ and a pure electroweak channel $pp \to jj\gamma\gamma$ $(\alpha_{\text{QCD}} = 0)$
- Recognizing our eventual selection of high jet momentum events, we generate BG events in H_T bins to ensure sufficient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

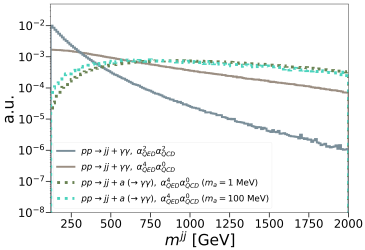


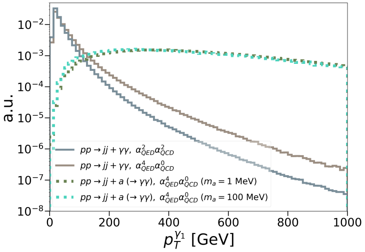


Pre-Selection Kinematics

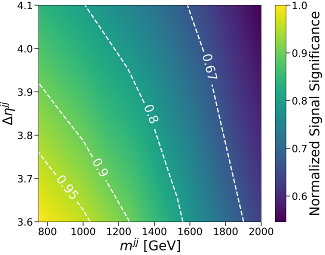








Optimizing Event Selection Criteria

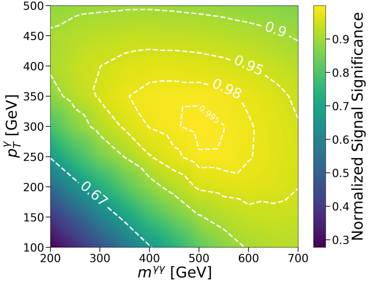


Process

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

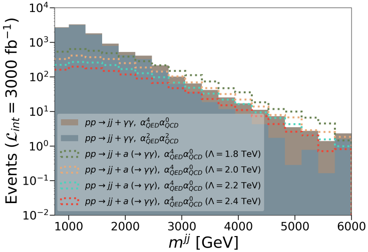
$$\frac{S}{\sqrt{S+B+(0.25\cdot(S+B))^2}}$$

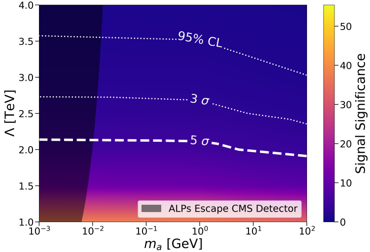
- Using this metric, we optimize event selection criteria on two kinematic variables simultaneously by sampling SS on a grid

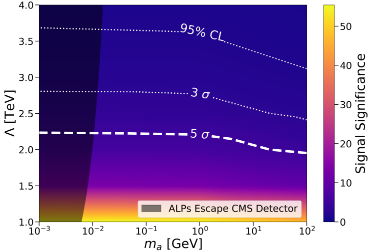


Criterion	$\gamma_1\gamma_2 j_1 j_2$
Central Selections	
$\vert\eta^{\gamma}\vert$	< 2.5
p_T^{γ}	> 30 GeV
$p_T^{\gamma_1}$	> 300 GeV
$m^{\gamma\gamma}$	> 500 GeV
N(ℓ), N(b)	$= 0$
VBF Selections	
p_T^{j}	> 30 GeV
$\vert\eta^{j}\vert$	< 5.0
$\Delta R^{\gamma j}$	> 0.4
$N(j)$	≥ 2
$\eta^{j_1}\cdot\eta^{j_2}$	< 0
$\vert\Delta\eta^{jj}\vert$	> 3.6
m^{jj}	> 750.0 GeV

Results: Signal Significance in the Parameter Space



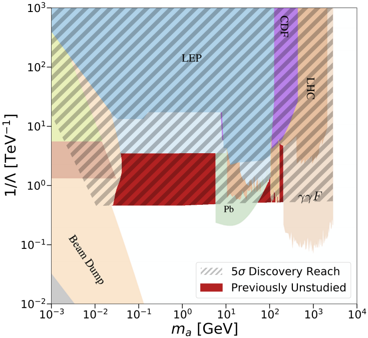




Comments

- On the right we depict the signal significance achieved by our selections as a function of m_a and Λ 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!