New Probes for Axion-like Particles at Hadron Colliders

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Introduction
## Strong CP Problem (Classical)

### Neutron EDM (Quark model)

**EDM:** \[ \vec{d} = \sum_i Q_i \vec{r}_i \]

\[ d_N = 2 \times \frac{1}{3} e \times \frac{1}{m_\pi} \sqrt{1 - \cos(2\theta)} \]

\[ \approx 10^{-13} |\sin \theta| \text{ e.cm} \]

### Current Measurements

[C. A. Baker et al., PRL, 2006, hep-ex/0602020.]

\[ d_N < 2.9 \times 10^{-26} \text{ e.cm (90\%CL)} \]

### Bounds on \( \theta \)

\[ \theta < 10^{-12} \]

**QFT:** \( \theta_{QCD} G \tilde{G} \)

*Why?*
Strong CP Problem (Classical)

**Neutron EDM (Quark model)**

**EDM:**
\[
\vec{d} = \sum_i Q_i \vec{r}_i
\]

\[
d_N = 2 \times \frac{1}{3} e \times \frac{1}{m_\pi} \sqrt{1 - \cos(2\theta)} \approx 10^{-13} |\sin \theta| \text{ e.cm}
\]

**Current Measurements**

[C. A. Baker et al., PRL, 2006, hep-ex/0602020.]
\[
d_N < 2.9 \times 10^{-26} \text{ e.cm (90%CL)}
\]

**QFT: \( \theta_{\text{QCD}} G \bar{G} \)**

*Why \( \theta \) is so small?*
Strong CP Problem (Classical)

Water: H₂O

Electric Dipole Moment (EDM)

\[ = 3.8 \times 10^{-9} \text{ e.cm} \]

Carbon Dioxide: CO₂

Electric Dipole Moment (EDM)

\[ \approx 0 \times 10^{-9} \text{ e.cm} \]

Question: How the EDMs are different?

Answer: Dynamics of the system
Axions and Axion-like Particles
Axion model

- A global $U(1)_{PQ}$ symmetry
- A new complex scalar $\phi$ charged under $U(1)_{PQ}$
  \[
  \phi = \frac{1}{\sqrt{2}} (v_{PQ} + \sigma) e^{ia/f_a}
  \]
- Tangential excitation ($a$): pseudo Nambu-Goldstone boson (axion)

Solving Strong CP

- Global symmetry breaking $\rightarrow$ shift symmetry ($a \rightarrow a + c$)
- Absorb $\theta$ in $a$
- Potential is minimized when $\theta = 0$
The Cleansing Axion

"I named them after a laundry detergent, since they clean up a problem with an axial current.”
(Nobel lecture 2004)
Axion (QCD axion)

- The QCD axion mass due to strong interaction [S. Weinberg, PRL, 1977]

\[ m_a \approx \frac{m_\pi f_\pi}{f_a} \approx 6 \times 10^{-6} \text{eV} \frac{10^{12} \text{GeV}}{f_a} \]

- The mass of axion is a function of its decay constant (1 parameter)

The QCD axion is for solving strong CP, but there are other axion models

Axion-like Particles (ALP)

- Generic prediction of many high energy physics model with spontaneous global symmetry breaking
- Appear in phenomenological models of string theory
- The ALPs can be dark matter candidates [J. Redondo, 2019]
- The ALP can help to solve baryogenesis [hep-ph/1901.02031]
- The mass of ALP is independent of its decay constant (2 parameters)
Effective field theory for ALP(a)

- No new CP violation source
- ALP(a): CP-odd scalar, singlet of SM gauge group
- ALP is a pseudo-Nambu-Goldstone boson of a broken global symmetry

Up to dimension 5 [H. Georgi, et.al, PLB, 1986]

\[
\mathcal{L}_{\text{eff}}^{\leq 5} = \mathcal{L}_\text{SM} + \frac{1}{2}(\partial_\mu a)(\partial_\nu a) - \frac{1}{2}m_a^2a^2
+ c_{a\Phi} \frac{\partial_\mu a}{f_a}(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi) + \frac{\partial_\mu a}{f_a} \sum_F \bar{\Psi}_F C_F \Psi_F
- c_{GG} \frac{a}{f_a} G^A_{\mu\nu} \tilde{G}^{\mu\nu,a} - c_{BB} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu} - c_{WW} \frac{a}{f_a} W^a_{\mu\nu} \tilde{W}^{\mu\nu,a},
\]

- We probe \(c_{GG}, c_{WW}, c_{BB}\) at the LHC
Phenomenology at the LHC
Phenomenology at the LHC

Sensitive couplings at the LHC

- $\frac{c_{GG}}{f_a}$
- $\frac{c_{WW}}{f_a}$
- $\frac{c_{BB}}{f_a}$
- $\frac{c_{\gamma\gamma}}{f_a} = \frac{c_{BB}}{f_a} \cos^2 \theta_W + \frac{c_{WW}}{f_a} \sin^2 \theta_W$

Based on low-energy experiments:

$\frac{c_{BB}}{f_a} = -\tan^2 \theta_W \frac{c_{WW}}{f_a}$

ALP signatures at the LHC

- ALP is produced on-shell and escapes the detector (Mono-X)
- ALP in S-channel (Di-X)
- ALP is produced on-shell and then decays (Tri-X)

Channels at the LHC

- Mono-jet
- Mono-photon
- Mono-W
- Mono-Z
- Mono-Higgs
- Di-jet
- Di-photon
- Tri-jet
- Tri-photon
- Jet + photon + MET
- $t\bar{t}$ + MET
- Single top + MET
Coupling of ALP to gluons \( \frac{c_{GG}}{f_a} \) via mono-jet at the LHC

- jet + ALP (missing energy) \( \Rightarrow \) mono-jet
- S-channel jet production \( \Rightarrow \) di-jet

CMS mono-jet selection

**Trigger**

- \( \not{\mathcal{E}_T} > 120 \text{ GeV} \)

**Vetos**

- More than two jets with \( p_T > 30 \text{ GeV} \) and \( |\eta| < 4.3 \)
- A second jet with \( \Delta \phi(j_1, j_2) > 2.5 \)
- Well reconstructed electrons or muons with \( p_T > 10 \text{ GeV} \)
- Well reconstructed taus with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.3 \)

**Selection**

- Hardest jet with \( p_T > 110 \text{ GeV} \) and \( |\eta| < 2.4 \)
- \( \not{\mathcal{E}_T} \) cut for each signal region

Coupling of ALP to W bosons $\frac{c_{WW}}{f_a}$ at the LHC

ALPs: collider constraints

Current limits

Prospects HL-LHC

ALP channels

jet + photon + $a$

- Massive $a$ can decay to SM
- Light $a$ appears as MET in the detector

single top + $a$

$tt + a$

ALP + jet + photon

- $\sigma(pp \rightarrow j\gamma a) = 30.0 \times \left( \frac{c_{GG}}{f_a} \right)^2 \text{pb}$
- $\sigma(pp \rightarrow j\gamma a) = 13.9 \times \left( \frac{c_{WW}}{f_a} \right)^2 \text{pb}$
- The cross section is independent of the $m_a$
- The $m_a$ is set to 1MeV

Main backgrounds

- $j\gamma$
- $Z(\rightarrow \nu\bar{\nu})j\gamma$
- $W(\rightarrow l\bar{\nu}_l)j\gamma$

<table>
<thead>
<tr>
<th>Cut</th>
<th>$c_{gg}$</th>
<th>$c_{ww}$</th>
<th>$Zj\gamma$</th>
<th>$Wj\gamma$</th>
<th>$j\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon and Jet</td>
<td>0.591</td>
<td>0.728</td>
<td>0.636</td>
<td>0.28</td>
<td>0.7</td>
</tr>
<tr>
<td>$\Delta\phi(\gamma, j) &lt; 2.7$</td>
<td>0.503</td>
<td>0.402</td>
<td>0.464</td>
<td>0.163</td>
<td>0.087</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 50\text{GeV}$</td>
<td>0.462</td>
<td><strong>0.147</strong></td>
<td>0.370</td>
<td>0.084</td>
<td>$3.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 90\text{GeV}$</td>
<td><strong>0.365</strong></td>
<td>0.031</td>
<td>0.216</td>
<td>0.033</td>
<td>$3.7 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
ALP + jet + photon

Histogram of MET at the HL-LHC

- $Z \rightarrow \nu \bar{\nu}$ using $Z \rightarrow \mu^+ \mu^-$

  Interpret pair of muons as a pair of missing neutrinos Correct for acceptance, efficiencies and branching fraction

  $R(Z \rightarrow \nu \bar{\nu})/R(Z \rightarrow \mu^+ \mu^-) = 5.95$

The 95% CL Limits:

\[
\frac{c_{GG}}{f_a} < 0.012 \text{TeV}^{-1} \quad L = 3000 \text{fb}^{-1}, \sqrt{s} = 14 \text{TeV}
\]

\[
\frac{c_{WW}}{f_a} < 0.041 \text{TeV}^{-1} \quad L = 3000 \text{fb}^{-1}, \sqrt{s} = 14 \text{TeV}
\]
ALP + ttbar

- $\sigma(pp \to t\bar{t}a) = 3.9 \times \left(\frac{c_{GG}}{f_a}\right)^2 \text{pb}$
- Dark Matter + $t\bar{t}$ (2.2fb$^{-1}$)
  [CMS-EXO-16-005]
- Semi-leptonic decay of $t\bar{t}$
- 95% Limits:

  \[
  \frac{c_{GG}}{f_a} < 0.44\text{TeV}^{-1} \quad L = 2.2\text{fb}^{-1}, \sqrt{s} = 13\text{TeV}
  \]

  \[
  \frac{c_{GG}}{f_a} < 0.15\text{TeV}^{-1} \quad L = 100\text{fb}^{-1}, \sqrt{s} = 13\text{TeV}
  \]

  \[
  \frac{c_{GG}}{f_a} < 0.11\text{TeV}^{-1} \quad L = 3000\text{fb}^{-1}, \sqrt{s} = 13\text{TeV}
  \]

  \[
  \frac{c_{GG}}{f_a} < 0.063\text{TeV}^{-1} \quad L = 3000\text{fb}^{-1}, \sqrt{s} = 14\text{TeV}
  \]

<table>
<thead>
<tr>
<th>Channel</th>
<th># @2.2fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>24.6 ± 2.2</td>
</tr>
<tr>
<td>$W + \text{jets}$</td>
<td>6.4 ± 1.6</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>0.10 ± 0.04</td>
</tr>
<tr>
<td>Single $t$</td>
<td>7.0 ± 2.0</td>
</tr>
<tr>
<td>Diboson</td>
<td>1.7 ± 0.4</td>
</tr>
<tr>
<td>Background</td>
<td>39.8 ± 3.4</td>
</tr>
</tbody>
</table>

**Signal regions**

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Jets</th>
<th>$b$ jets</th>
<th>$p_T^{\text{miss}}$</th>
<th>Other selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell + \text{jets} \quad t\bar{t} + p_T^{\text{miss}}$</td>
<td>e or $\mu$</td>
<td>$\geq 3$</td>
<td>$\geq 1$</td>
<td>$\geq 160\text{GeV}$</td>
</tr>
</tbody>
</table>
Bound on gluon-ALP coupling \( (c_{gg}/f_a) \)

Prospect of bounds for low mass ALP at the LHC

\[
f_a/c_{GG}: \text{dashed-lines} \quad \text{LHC14, 3ab}^{-1}
\]

\[
f_a/c_{WW}: \text{solid-lines} \quad \text{LHC8, 19.6 fb}^{-1}
\]

\[
\text{LHC14, 3ab}^{-1}
\]

\[
\text{LHC14, 3ab}^{-1}
\]

\[
\text{LHC14, 3ab}^{-1}
\]

\[
\text{LHC13, 3ab}^{-1}
\]

\[
\text{LHC13, 3ab}^{-1}
\]

\[
\text{LHC13, 3ab}^{-1}
\]

\[
\text{LHC14, 3 ab}^{-1}
\]

\[
f_a/c_{xx} \text{ [TeV]}
\]
**Decay rate of ALP and Bounds on gluon-ALP coupling \((c_{gg}/f_a)\)**

**ALP decay rate**

- pQCD \((m_a > 2\,\text{GeV})\) and ChPT \((m_a < 0.5\,\text{GeV})\)
- \(\frac{\Gamma_{a\rightarrow gg}(m_a=2\,\text{GeV})}{\Gamma_{a\rightarrow 3\pi}(m_a=0.5\,\text{GeV})} \approx \mathcal{O}(10^5)\)
  
Summary and Conclusions
Axions and ALPs are well motivated particles.

Searching for ALPs in colliders is a complementary for low energy searches.

Light ALPs at the LHC would appear as a missing energy in detectors.

We found bounds and expected bounds for ALP using $t\bar{t} + a$ and single top + $a$ channel.

The jet + photon + $a$ is a promising channel to constrain $c_{GG}$ and $c_{WW}$ couplings.
Thank you for your attention
Backup
The QCD Lagrangian (with one flavor of massless quarks):

\[ \mathcal{L} = \int d^4x \left[ -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{\psi} (i \gamma^\mu D_\mu - m_j) \psi - \frac{g^2 \theta_{\text{QCD}}}{32 \pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} \right] \]

\[ G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} \equiv \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} G^a_{\mu\nu} G^{\alpha\beta}_a \]

Neutron EDM (QCD, Chiral Perturbation Theory):

\[ d_N = 3.2 \times 10^{-26} \theta_{\text{QCD}} \text{e.cm} \]

Neutron EDM (QCD + EW):

\[ d_N = 3.2 \times 10^{-26} (\theta_{\text{QCD}} + \det[M_u M_d]) \text{e.cm} \]

If CP is a symmetry of the Nature: \( \theta_{\text{QCD}} + \det[M_u M_d] = 0 \) but, CP is not a symmetry of the Nature.

The Strong CP problem

\[ \theta = \theta_{\text{QCD}} + \det[M_u M_d] < 10^{-10} \]
\[ \Gamma_a = \sum \Gamma_i \iff \Gamma_a = \Gamma_{a \to gg} \text{ (dashed)} \]