Axion-like-particles at ATLAS/CMS, LHCb, and Kaon factory

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Refs.
preliminary work with Stefania Gori, Gilad Perez
**Introduction**

PBC target: Axion and Axion-Like Particles

Axion = Pseudo-Nambu Goldstone Boson associated to Peccei-Quinn symmetry, a global U(1), introduced to address the Strong QCD problem. Vast range of masses and couplings possible, with fixed relation.

Axion-Like Particle (ALP): a generalized version of the axion (at the cost of the original motivation from the strong CP problem). No direct relation between coupling and mass.

Axions and ALPs in the sub-eV mass range (lively and well-established community)

Talk by Albert De Roeck

Interest to explore the MeV-GeV region at accelerator-based experiments

Axion associated to the Peccei-Quinn symmetry
The aim of this letter is to go beyond these common beliefs and to motivate the LHC collaborations to look for resonances with a mass below the sum of the cuts on the SM Higgs boson in the diphoton channel [6, 7]. As a matter of fact, the current LHC search program is mostly tailored to probe new resonances of mass higher than 10 GeV. Theoretical bias towards heavy new physics (NP) and of the common belief that either previous collider experiments (UA1, UA2, LEP and Tevatron) and/or Higgs couplings anomalies of the global symmetry, and is smaller than the associated NP scale which depends on the explicit breaking of the group of some larger global symmetry. When a pNGB (pseudoscalar Nambu-Goldstone boson), often called axion-like particle (ALP). The axial couplings of the pNGB to SM gauge bosons can be written as $\alpha_i c_i G G + \alpha_i c_i W W + \alpha_i c_i B B$.

We derive a new bound on diphoton resonances using inclusive diphoton cross section measurements between the first derive a new bound (of 10-100 pb) on the diphoton cross section measurements at the LHC, up to its high luminosity (HL) phase, and finally estimate the indicative reaches on the diphoton signal strengths that could be attainable by proper searches at the LHC, in the so-far poorly constrained mass range between the smallest possible mass. We ready the strongest existing constraint on axion-like particles that couple to gluons and photons, for masses down to the smallest possible mass. We put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put constraints on lighter resonances that are put 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Theoretical Motivation
- Axion-like-Particles and Heavy Axion

Search at
- ATLAS/CMS for 10GeV-50GeV
- LHCb for O(1)GeV-20GeV
- KOTO for <350MeV

Summary
Theoretical Motivation
Expect light resonance?

Yes. pNGB: pseudo Nambu Goldstone bosons are common among BSM models, mass can be arbitrary light, e.g. $\pi$

Focus: **Axion-like-particles (ALPs)** e.g.

- R-axion from low-scale SUSY
  - E.g. Bellazzini, Mariotti, Redigolo, Sala, Serra (1702.02152)

- pNGB from composite Higgs
  - Barnard, Gherghetta, Ray (’13), Ferretti (’16)...

- New pion from TeV QCD’
  - Kilic, Okui, Sundrum (’09), Nakai, Sato, KT (’16)...

- Heavy Axion/Visible Axion
  - Rubakov (’97), Fukuda, Harigaya, Ibe, Yanagida (’15), P. Agrawal, K. Howe (’17)

Unlike QCD axion case, $m_a \sim m_\pi f_\pi / f_a$, mass and coupling $(1/f_a)$ are independent
Strong CP problem and Axion

\[ \frac{\theta g_s^2}{32\pi^2} G \bar{G} \]

\[ \tilde{\theta} \lesssim 10^{-10} \]

Phase promoted to axion field, and settled at minimum

[peccei, quinn][weinberg; wilczek; kim-shifman-vainshtein-zakharov; dine–fischler–srednicki–zhitnitsky]

Axion window

\[ 4 \times 10^8 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV} \]

Constraints (e.g. Astro, SN1987) push to very high \( f_a \)

*Over DM abundance & problem in inflation with \( f_a > 10^{12} \text{ GeV} \)
Peceei-Quinn symmetry quality problem

Global symmetry explicitly broken by gravity or cutoff
→ PQ symmetry should be extremely robust

\[ \Delta V_{\text{PQ}} = \lambda_\Delta \frac{\Phi^\Delta}{\Lambda_{\text{UV}}^{\Delta - 4}} + \text{h.c.} \]

Even gravity breaking with \( \Delta = 12 \) shifts min. \( (f_a \sim 10^{12}\text{GeV}) \)
\( \delta \theta > 10^{-10} \)

• With \( \Delta < 12 \) operators, strong CP problem is not solved
• Standard scenario requires complex UV

Extended gauge group, discrete symmetry, extra dimension…

[S. M. Barr, D. Seckel ('92); M. Kamionkowski, J. March-Russell ('92)]

[Dine('92); R. Holman et al('92); Randall ('92); E. Chun and A. Lukas('92); HC Cheng, D.E.Kaplan('01), Dias, Pleitez, Tonasse ('12),… K. Harigaya, et al ('13); M. Redi, R. Sato('16), Fukuda, Ibe, Suzuki('17)…]
PQ quality problem motivates Heavy Axion

Axion window

- Severe quality problem
  → UV model building
- DM candidate

Standard Axion

- Non-minimal
- No quality problem
- Testable

Heavy Axion

- Too much DM

\[ \Delta = 6 \left( \Lambda = m_{\text{pl}} \right) \]

\[ \Delta = 6 \left( \Lambda = m_{\text{GUT}} \right) \]

Too much DM

Need ALP-gluon coupling
Effective Lagrangian

\[ L_{\text{int}} = \frac{a}{4\pi f_a} \left[ \alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B} \right] \]

- \( f_a \sim 0.1 - 10 \) TeV and \( c_3 \neq 0 \)
- Loops of gluinos, tops. Necessary to solve strong CP problem
- Benchmark \( c_1 = c_2 = c_3 = 10 \)
- Production@LHC is gluon fusion,
- Prompt decay to dijet or diphoton due to \( m_a < m_Z \)
Effective Lagrangian

$$\mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \left[ \alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B} \right]$$

$$f_a \sim 0.1 - 10 \text{ TeV and } c_3 \neq 0$$

Loops of gluinos, tops. **Necessary to solve strong CP problem**

**benchmark**  \( c_1 = c_2 = c_3 = 10 \)

- production@LHC is gluon fusion,
- prompt decay to dijet or diphoton due to \( m_a < m_Z \)

Many previous ALP studies with \( c_3=0 \) (\( \text{Br}_{a\rightarrow\gamma\gamma} \sim 100\% \))

- Photonphilic ALP: LEP[Jaeckel, Spannowsky(‘15)]
- Heavy-ion[Knapen et al(‘16)], Beamdump with NA62 [B. Dobrich et al (‘16)], Sub 10GeV, ALP-W int. induces FCNC(B->Ka) [Izaguirre, Lin, Shuve(‘16)], etc.
Search at ATLAS/CMS
\[ m_a = 10-50 \text{GeV} \]
### Existing constraints from LEP to LHC

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Process</th>
<th>Lumi</th>
<th>$\sqrt{s}$</th>
<th>low mass reach</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEPI</td>
<td>$e^+e^- \rightarrow Z \rightarrow \gamma a \rightarrow \gamma jj$</td>
<td>12 pb$^{-1}$</td>
<td>Z-pole</td>
<td>10 GeV</td>
<td>[29]</td>
</tr>
<tr>
<td>LEPI</td>
<td>$e^+e^- \rightarrow Z \rightarrow \gamma a \rightarrow \gamma \gamma \gamma$</td>
<td>78 pb$^{-1}$</td>
<td>Z-pole</td>
<td>3 GeV</td>
<td>[30]</td>
</tr>
<tr>
<td>LEPII</td>
<td>$e^+e^- \rightarrow Z^<em>, \gamma^</em> \rightarrow \gamma a \rightarrow \gamma jj$</td>
<td>9.7,10.1,47.7 pb$^{-1}$</td>
<td>161,172,183 GeV</td>
<td>60 GeV</td>
<td>[31]</td>
</tr>
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<td>LEPII</td>
<td>$e^+e^- \rightarrow Z^<em>, \gamma^</em> \rightarrow \gamma a \rightarrow \gamma \gamma \gamma$</td>
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<td>60 GeV</td>
<td>[31, 32]</td>
</tr>
<tr>
<td>D0/CDF</td>
<td>$p\bar{p} \rightarrow a \rightarrow \gamma \gamma$</td>
<td>7/8.2 fb$^{-1}$</td>
<td>1.96 TeV</td>
<td>100 GeV</td>
<td>[33]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$pp \rightarrow a \rightarrow \gamma \gamma$</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
<td>65 GeV</td>
<td>[34]</td>
</tr>
<tr>
<td>CMS</td>
<td>$pp \rightarrow a \rightarrow \gamma \gamma$</td>
<td>19.7 fb$^{-1}$</td>
<td>8 TeV</td>
<td>80 GeV</td>
<td>[35]</td>
</tr>
<tr>
<td>CMS</td>
<td>$pp \rightarrow a \rightarrow \gamma \gamma$</td>
<td>19.7 fb$^{-1}$</td>
<td>8 TeV</td>
<td>150 GeV</td>
<td>[36]</td>
</tr>
<tr>
<td>CMS</td>
<td>$pp \rightarrow a \rightarrow \gamma \gamma$</td>
<td>35.9 fb$^{-1}$</td>
<td>13 TeV</td>
<td>70 GeV</td>
<td>[37]</td>
</tr>
<tr>
<td>CMS</td>
<td>$pp \rightarrow a \rightarrow jj$</td>
<td>18.8 fb$^{-1}$</td>
<td>8 TeV</td>
<td>500 GeV</td>
<td>[38]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$pp \rightarrow a \rightarrow jj$</td>
<td>20.3 fb$^{-1}$</td>
<td>8 TeV</td>
<td>350 GeV</td>
<td>[39]</td>
</tr>
<tr>
<td>CMS</td>
<td>$pp \rightarrow a \rightarrow jj$</td>
<td>12.9 fb$^{-1}$</td>
<td>13 TeV</td>
<td>600 GeV</td>
<td>[40]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$pp \rightarrow a \rightarrow jj$</td>
<td>3.4 fb$^{-1}$</td>
<td>13 TeV</td>
<td>450 GeV</td>
<td>[41]</td>
</tr>
<tr>
<td>CMS</td>
<td>$pp \rightarrow ja \rightarrow jjj$</td>
<td>35.9 fb$^{-1}$</td>
<td>13 TeV</td>
<td>50 GeV</td>
<td>[42]</td>
</tr>
</tbody>
</table>

Below lowest mass, smooth background structure is lost. Sideband not possible.

1. Trigger ISR
2. Jet substructure

CMS Boosted dijet

CMS [arXiv:1710.00159]

Krohn et al ('10); Dasgupta et al ('13); Larkoski et al ('14)
Diphoton x-section measurements

<table>
<thead>
<tr>
<th>Process</th>
<th>Theory / Data</th>
<th>Data + stat. unc.</th>
<th>Total exp. uncertainty</th>
<th>NNLO (NNLO)</th>
<th>SHERPA 2.2.1 (ME+PS at NLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp → a → γγ</td>
<td>4.2 fb⁻¹</td>
<td>5.36 fb⁻¹</td>
<td>4.9 fb⁻¹</td>
<td>20.2 fb⁻¹</td>
<td>5.0 fb⁻¹</td>
</tr>
<tr>
<td>pp → a → γγ</td>
<td>1.96 TeV</td>
<td>1.96 TeV</td>
<td>7 TeV</td>
<td>8 TeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>pp → a → γγ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

They report lower mass!

m_a > 8.2 GeV
m_a > 6.4 GeV
m_a > 9.4 GeV
m_a > 13.9 GeV
m_a > 14.2 GeV
Diphoton x-section measurements

\[ m_{\gamma\gamma} > \Delta R \cdot \sqrt{p_{T1}^{\text{min}} p_{T2}^{\text{min}}} \]

\(~13.8\text{GeV}\)

<table>
<thead>
<tr>
<th>(m_a) in GeV</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\epsilon_S) for (\sigma_{8\text{TeV}}) ATLAS [9]</td>
<td>0</td>
<td>0.0007</td>
<td>0.008</td>
<td>0.014</td>
<td>0.024</td>
<td>0.037</td>
<td>0.071</td>
<td>0.233</td>
<td>0.347</td>
<td>0.419</td>
<td>0.452</td>
<td>0.484</td>
</tr>
</tbody>
</table>

Signal Efficiency
ALP parameter space

A. Mariotti, D. Redigolo, F. Sala, KT ('17)
ATLAS/CMS diphoton trigger requires \( \Delta R_{\gamma\gamma} > 0.4 \) and \( p_T^{\gamma} > 20 \text{GeV} \). Also, \( p_T^{\gamma} \) will increase.

\[
m_a = \Delta R_{\gamma\gamma} \sqrt{p_T^{\gamma_1} p_T^{\gamma_2}} \\
\sim \Delta R_{\gamma\gamma} \frac{p_T^{\text{ISR}}}{2}
\]

**Trigger and Isolation**

Extra jets (ISR)

**Mono-j/Mono-\( \gamma \) trigger,** e.g. \( p_T^j > 500 \text{GeV} \)

& **modify Isolation** to probe \( 0.15 < \Delta R_{\gamma\gamma} < 0.4 \)

Simply diphoton trigger with **lower** \( p_T^{\gamma} \) prescaled trigger or **LHCb**
**Trigger and Isolation**

ATLAS/CMS diphoton trigger requires \( \Delta R_{\gamma\gamma} > 0.4 \) and \( pT_{\gamma} > 20\text{GeV} \). Also, \( pT_{\gamma} \) will increase.

\[
m_a = \Delta R_{\gamma\gamma} \sqrt{pT_{\gamma_1} pT_{\gamma_2}} \\
\sim \Delta R_{\gamma\gamma} \frac{p_{T_{\text{ISR}}}}{2}
\]

Mono-j/Mono-\( \gamma \) trigger, e.g. \( pT_j > 500\text{GeV} \)

& **modify Isolation** to probe \( 0.15 < \Delta R_{\gamma\gamma} < 0.4 \)

\[\Delta R < 0.4\]

\( \gamma \text{test} \)

\( \gamma \text{from jet} \)

\( E_{T_{\text{iso}}}^{\Delta R_{\gamma_i,\gamma_{\text{test}}} < 0.4} \equiv E_{T_i} < 10\text{GeV} \)

**modified**

\( E_{T_{\text{iso}}}^{\gamma_i} - E_{T_{\gamma_1}} < 10\text{GeV} \)

ATLAS h->aa->4\( \gamma \) [arXiv:1509.05051]

almost same rejection rate for fake photon
Study monojet(>500GeV)+Boosted Diphoton w/ mod Iso
one w/ mono photon trigger goes below 10GeV (in progress)
Future Prospect

\[ \frac{f_a}{c_i} \]

1 TeV

100 GeV

10 GeV

10-100 keV 100 MeV

Standard Axion

Chiral Lagrangian

Beam dump

SN1987A

K^+ K^0_L

K^+ K^0_L

Babar

LHCb

ATLAS/CMS

Boosted Diphoton

ATLAS/CMS

Standard Resonance Search

ATLAS/CMS

Diphoton cross section

1 GeV

10 GeV

100 GeV

1 TeV

Perturbative QCD

Theoretical Challenge

f^a/c_i

10-100 keV

100 MeV

1 GeV

10 GeV

100 GeV

1 TeV
Search at LHCb
\[ m_a = O(1)-20 \text{GeV} \]
Diphoton resonance at LHCb

Triggers $B_s^0 \rightarrow \gamma \gamma$ at LHCb

Abstract

The trigger strategy used in the search for the $B_s^0 \rightarrow \gamma \gamma$ decay in Run 2 is described. A sample of data is also provided, corresponding to 80 pb$^{-1}$ of diphoton candidates collected in 2015.

Category: 0CV
2 unconverted

1CV
unconverted &converted

2CV
2 converted

diphoton
electron candidate
displaced vertex

Recast 0CV analysis to ALP

Followup 1906.09058v1
Real-time discrimination of photon pairs using machine learning at the LHC

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T(\gamma)$ [GeV]</td>
<td>&gt; 3.5</td>
</tr>
<tr>
<td>$E_T(\gamma_1) + E_T(\gamma_2)$ [GeV]</td>
<td>&gt; 8</td>
</tr>
<tr>
<td>$M(\gamma_1 \gamma_2)$ [GeV/c$^2$]</td>
<td>[3.5, 6.0]</td>
</tr>
<tr>
<td>$p_T(\gamma_1 \gamma_2)$ [GeV/c]</td>
<td>&gt; 2</td>
</tr>
</tbody>
</table>
Diphoton resonance at LHCb

Assume: constant Acceptance & Efficiency. (of $B_s \rightarrow \gamma \gamma$)

$A(2<\eta<5)=0.13, \quad \varepsilon=0.14$

data($\sim$BG) is also const

Then, require $S<2\sqrt{D}$ (no subtraction of BG)
Also Babar/Belle2 Y(3S)

\[
\begin{align*}
\text{BR} (Y \rightarrow a\gamma) & \sim 8 E^2 \frac{\alpha_{\text{em}}}{4\pi} \left( \frac{m_Y}{4\pi f} \right)^2 \left( 1 - \frac{m_a^2}{m_Y^2} \right)^3 \\
\text{BR} (Y \rightarrow \mu\mu) & \sim \frac{m_Y}{4\pi f}
\end{align*}
\]
Search at KOTO
\[ m_a < 350 \text{MeV} \]
$K_L \rightarrow \pi^0 \alpha \rightarrow 4\gamma$ at KOTO

*K_L decay point is unknown*

<table>
<thead>
<tr>
<th>Main Target</th>
<th>K_L→π^0(γγ)vv</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong></td>
<td>Photon, invisible</td>
</tr>
<tr>
<td><strong>BG</strong></td>
<td>K_L→3π, 2π</td>
</tr>
<tr>
<td><strong>VETO</strong></td>
<td>Charged particle</td>
</tr>
<tr>
<td><strong>Decayed N_K (‘15)</strong></td>
<td>~10^{11}</td>
</tr>
</tbody>
</table>

~2GeV K_L

Future (~2026)

~10^{13}

30GeV p @ J-PARC
Heavy Axion EFT=ALP EFT

\[ \frac{a}{4\pi f_a} \left[ \alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B} \right] \]

Induce \( K_L/K^+ \) decay to axion by \( \pi^{-}a \) mixing or FCNC with \( W \)

\[ K_L \rightarrow \pi^0 a \quad K^+ \rightarrow \pi^+ a \]

\[
\text{BR}(K \rightarrow \pi a) \sim \left( \frac{0.1 f_\pi}{f_a/c_3} \right)^2 \text{BR}(K \rightarrow \pi \pi^0)
\]

Only decay channel is \( a \rightarrow 2\gamma \), \( a \rightarrow 3\pi \) kinematically forbidden

KOTO can search for \( K_L \rightarrow \pi^0 a \) with \( N_{KL} \sim 10^{13} \)

E. Izaguirre, T. Lin, B. Shuve ('16)
ALP hunt at KOTO

Physics target: $K_L \rightarrow \pi^0 a \rightarrow 4\gamma$

Challenges

• decay point unknown (only Ecal, no tracker)
• combinatorics of $\gamma \gamma$ pairs

1. assumption for reconstruction

$$m_{\gamma_1 \gamma_2}^2 \simeq E_1 E_2 (1 - \cos \theta_{12}) \equiv m_{\pi^0}^2$$

2. Require $m_{4\gamma} \simeq m_{K_L}$

to find a correct pair

[G. Perez, S. Gori, KT (Preliminary)]
Expected bound on \( \text{Br}(K_L \rightarrow \pi^0 a) \sim 10^{-8} \)
Translated to \( f_a/c_3 \sim 10\text{GeV} \) or \( f_a/c_2 \sim 100\text{GeV} \)
Theoretical Challenge

Standard Axion

~10GeV

100GeV

Beam dump

SN1987A

1TeV

ATLAS

CMS

Standard Resonance Search

ATLAS/CMS

Boosted Diphoton

Diphoton cross section

LHCb

Belle II

KOTO projection

Perturbative QCD

Chiral Lagrangian

10-100 keV

100MeV

10GeV

KOTO

prompt

KOTO/CMS

Diphoton

cross section

Babar

KOTO

Belle II

ATLAS/CMS

Beam dump

100MeV

10GeV

f_a/C_i

1TeV

100GeV

10GeV

1-100 keV
Summary

- Axion-like-particles with gluon coupling and low $f_a$ is motivated by various models.
- The heavy axion with low $f_a$ is a good guidepost for experiments.
- ATLAS/CMS covers $>$10 GeV mass region with diphoton or mono-triggers.
- LHCb covers $O(1)$-20 GeV with diphoton trigger
- KOTO covers $<$350 MeV with $N_{KL} \sim 10^{13}$
- Long-lived particle searches are relevant for sub-GeV mass and higher $f_a$ region.
Summary

Beam dump

KOTO
Belle II
LHCb

ATLAS/CMS

Boosted Diphotoon

ATLAS/CMS
Standard
Resonance
Search

Beam dump

KOTO
Belle II
LHCb

FASER
NA64µ NA62
CODEX-B MilliQan
SHiP MATHUSLA
MoEDAL

100MeV

1GeV

10GeV

100GeV

1TeV

10-100 keV

100MeV

Standard Axion

Chiral Lagrangian

Theoretical Challenge

Perturbative QCD

m_a

f_a

100GeV

10GeV

10GeV

100MeV

1TeV

SN1987A

Beam dump

KOTO
Belle II
LHCb

ATLAS/CMS

Boosted Diphotoon

NA62