Constraints on Physics Beyond the Standard Model using the LHC - Axion Like Particles

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Axion Like Particles

Pseudo scalar particles - weakly interacting

Resolve:

- Strong CP problem
- Cold Dark Matter
- Anomalous Magnetic moment of the muon
  - Experimental value differs from the Standard model value
  - \( a^\text{exp}_\mu - a^\text{SM}_\mu = (29.3 \pm 7.6) \times 10^{-10} \)
General ALP model

- Defines the ALP-SM interactions.
- Gives us an equation that solves the magnetic moment of muon discrepancy. Which has been obtained from arXiv:1708.00443.

\[
\delta a_\mu = \frac{m_\mu^2}{\Lambda^2} \left\{ K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2} h_1 \left( \frac{m_a^2}{m_\mu^2} \right) - \frac{2\alpha}{\pi} c_{\mu\mu} C_{\gamma\gamma} \left[ \ln \frac{\mu^2}{m_\mu^2} + \delta_2 + 3 - h_2 \left( \frac{m_a^2}{m_\mu^2} \right) \right] 
- \frac{\alpha}{2\pi} \frac{1 - 4s_w^2}{s_w c_w} c_{\mu\mu} C_{\gamma Z} \left( \ln \frac{\mu^2}{m_Z^2} + \delta_2 + \frac{3}{2} \right) \right\}
\]
Research Framework - CONTUR

UFO
- Takes a Lagrangian and generates matrix elements
- Allows event generator to choose which vertices to work with

HERWIG
- Monte-Carlo event generator
- Simulates proton-proton collision LHC events

RIVET
- Library of routines (contains particle cross-section data)
- Generates histograms
- Compiles the exclusion from the individual histograms into a grid
Couplings

• $g_{Pu}, g_{Pd} (=0)$: universal couplings of ALP to up and down quarks, respectively
• $c_{GG}(=0)$: coupling of ALP to gluons
• $c_{ZA}(=0)$: coupling of ALP to one Z boson and one photon
• $c_{AA}$: coupling of ALP to photons
• $g_{Pl}$: universal coupling of ALP to leptons

• Scenario 1: $c_{ah}=c_{Zh5}=0$
• Scenario 2: $c_{ah}=c_{Zh5}=1$
• Scenario 3: $c_{ah}=1, c_{Zh5}=0$
Scenario 1: $c\text{ah}=c\text{Zh}5=0$ (Low mass)

0.5 GeV

1.5 GeV

3 GeV
Scenario 1: $c_{ah}=c_{Zh5}=0$ (0.5 GeV)

CMS_8_WW
(reference point 0727)

CONTUR heatmap

ATLAS_8_MM_GAMMA
(reference point 0734)
Decay rate mass dependence

\[ \Gamma(a \rightarrow \gamma\gamma) = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} |C_{\gamma\gamma}|^2 \]

and

\[ \Gamma(a \rightarrow \ell^+\ell^-) = \frac{m_a m_\ell^2}{8\pi\Lambda^2} |C_{\ell\ell}|^2 \sqrt{1 - \frac{4m_\ell^2}{m_a^2}} \]

\[ \propto m_a^3 \]

\[ \propto m_a \]

0.5 GeV

ATLAS_8_MM_GAMMA

Consists of cross-sections of Z\(\gamma\) and Z\(\gamma\gamma\)

CMS_8_WW

Consists of cross-sections of W-boson productions via Higgs decays
Anomalous magnetic moment of muon

0.5 GeV

1.5 GeV

3 GeV
Scenario 1: $c_{ah}=c_{Zh5}=0$ (High mass)
Scenario 2: \( c_{ah} = c_{Zh5} = 1 \) (Low mass)

At 0.5 GeV

**Case 2:**
\[
\sigma(H \rightarrow Za) = 0.982802 \\
\sigma(H \rightarrow aa) = 0.00241992
\]

**Case 1:**
\[
\sigma(H \rightarrow Za) = 0.985186 \\
\sigma(H \rightarrow aa) = 0
\]
Scenario 2: $cah=cZh5=1$ (High mass)

- No visible impact as no change to the decay modes as at high mass only the $a \rightarrow \gamma\gamma$ is the dominant decay mode.
Scenario 3: $c_{ah}=1$ and $c_{Zh5}=0$

- Same exclusion as Scenario 2 $c_{ah}=c_{Zh5}=1$

- Same cross-sections for Higgs to ALP decay too

- Hinting at $c_{Zh5}$ coupling turned on in UFO file or some underlying loop process taking place giving this contribution.

3 GeV
Conclusion

• Axion Like Particles cannot be fully ruled out

• Explains various unresolved phenomena

• Using CONTUR we narrowed down parameter space where ALP model explains region anomalous magnetic moment of the muon

• High pressure on the ALP-lepton coupling value and we see that we have excluded most of the ALP-photon coupling space

• Even for high mass cases there is a region which cannot be fully excluded hinting that this model should be probed further and it makes for a viable BSM candidate

• Scans at other CoM energy levels should also be run in order to compare our results with tau – anti tau lepton measurements

• Scans can also be run for more events to see smoother exclusions.
Backup
Scenario 1 3 GeV (bump origin)

ATLAS_8_GAMMA

Consists of cross-sections of $H \rightarrow \gamma \gamma$
Strong CP problem

• Evidence of Charge Parity symmetry violation in Electroweak interactions
• Charge Parity symmetry theoretically allowed to be broken in Strong interactions
• Charge Parity symmetry not observed to be broken in Strong interactions
• New global symmetry introduced which helps explain this situation
• This symmetry when undergoes through Spontaneous symmetry breaking it creates pseudo-scalar particles such the as ALP.
The loop functions read (with $x = m_a^2/m_\mu^2 + i0$)

\[ h_1(x) = 1 + 2x + x(1-x) \ln x - 2x(3-x) \sqrt{\frac{x}{4-x}} \ \text{arccos} \ \frac{\sqrt{x}}{2} \]

\[ h_2(x) = 1 - \frac{x}{3} + \frac{x^2}{6} \ln x + \frac{2 + x}{3} \sqrt{x(4-x)} \ \text{arccos} \ \frac{\sqrt{x}}{2} \]
One-loop diagrams contributing to the anomalous magnetic moment of the muon.
ALP Feynman diagrams

(a)  
(b)  
(c)  
(d)  
(e)  
(f)  
(g)  
(h)  
(i)