Heavy Axion at DUNE

Zhen Liu
University of Minnesota
May.24th, 2021
Axion needs no intro

\[ L \supset \frac{\alpha_s}{8\pi} \theta \tilde{G} G + y_u \bar{Q}_L \tilde{H} u_R + y_d \bar{Q}_L H d_R \]

\[ \bar{\theta} \equiv \theta + \text{ArgDet}[Y_u Y_d] \leq 10^{-10} \]

While \text{ArgDet}[Y_u Y_d] anticipated around \( \delta_{CKM} \sim O(1) \)

Strong CP puzzle of QCD

Dynamical solution:
QCD Axion \( a \) as a pseudo Nambu-Goldstone boson

\[ \frac{\alpha_s}{8\pi} \left( \theta - \frac{a}{f_a} \right) \tilde{G} G \]

\[ V(a) \]

\[ a/f_a \]

Zhen Liu             HighQ Axion DUNE                      Pheno 2021

5/24/2021
But a quality problem

The axion fakes a dynamical angle. How good of an imposter is it?

$$V \approx -(100 \text{ MeV})^4 \cos \left( \frac{\theta}{f_a} - \frac{a}{f_a} \right) + \Lambda_{\text{contamination}}^4 \cos \left( \theta' - \frac{a}{f_a} \right)$$

$$\Lambda_{\text{contamination}} < 0.1 \text{ MeV}$$

There are also many other scales: GUT, Planck, Dark matter

$$V = e^{i \frac{a}{f_a}} \frac{\Phi^{14}}{M_{pl}^{10}}$$

Dynamical solution: QCD Axion $a$ as a pseudo Nambu-Goldstone boson

$$\frac{\alpha_s}{8\pi} \left( \theta - \frac{a}{f_a} \right) G G$$

Leading order gravity suppressed operators must be suppressed by $10$ powers of the Planck scale! (for $10^{12}$ GeV Axion decay constant)
The Quality Problem and reinforced Axion potential

Copying Mirror Gauge QCD + Weak and Chiral Matter fields, relates the Lagrangian parameters with a $Z_2$ symmetry. One axion couples to both and solve both strong CP puzzles dynamically.

$SU(2) \leftrightarrow SU(2)'$
$SU(3) \leftrightarrow SU(3)'$
$U(1) \leftrightarrow U(1)'$ or $U(1) \leftrightarrow U(1)'

$\Psi \leftrightarrow \Psi'$

$\leftrightarrow$ represents the $Z_2$ transformation
$X'$ represents the mirror sector

Softly broken by
$\mu^2 H^\dagger H + \mu'^2 H'^\dagger H'$
with $\mu'^2 \gg \mu^2$

Rubakov '97, Berezhiani et al '01, Hook '15, Fukuda et al '15...
The Quality Problem and reinforced Axion potential

\[ m_a^2 \approx \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi f_\pi}{f_a^2} \]

\[ m_a^2 \approx \frac{\Lambda_{QCD}^4}{f_a^2} \]

**Soft Z2 breaking by giving**
- Mirror Higgs large VEV
- \( \Box \) massive fermions decouples earlier
- \( \Box \) mirror QCD run fast and confines

Reinforced Axion Potential

\[ \langle H' \rangle = 10^{14} \text{ GeV} \]
The Quality Problem and reinforced Axion potential

Makes the Quality problem better

\[ V \approx -(100 \text{ MeV})^4 \cos \left( \bar{\theta} - \frac{a}{f_a} \right) - (10^8 \text{ MeV})^4 \cos \left( \bar{\theta} - \frac{a}{f_a} \right) + \Lambda_{\text{contamination}}^4 \cos \left( \theta' - \frac{a}{f_a} \right) \]

\[ \Lambda_{\text{contamination}} < 10^5 \text{ MeV} \]

If the Higgs mass were the only thing different between the two copies, the neutron angles are still the same!

Flavor structure of the SM ensures that any change occurs at 4-loops and beyond

Not true for a generic theory!
The Quality Problem and reinforced Axion potential

Makes the Quality problem better

\[ V \approx -(100 \text{ MeV})^4 \cos \left( \bar{\theta} - \frac{a}{f_a} \right) - (10^8 \text{ MeV})^4 \cos \left( \bar{\theta} - \frac{a}{f_a} \right) \]

\[ + \Lambda_{\text{contamination}}^4 \cos \left( \theta' - \frac{a}{f_a} \right) \]

\[ \Lambda_{\text{contamination}} < 10^5 \text{ MeV} \]

But generates a new quality problem:

\[ \frac{g^2}{32\pi^2} \left( \frac{H H^\dagger}{M_{\text{pl}}^2} G \tilde{G} + \frac{H' H'^\dagger}{M_{\text{pl}}^2} G' \tilde{G}' \right) \]

\[ H' \lesssim 10^{14} \text{ GeV} \]
Theory parameter space

\[
m^2_a \approx \frac{\Lambda_{QCD}^4}{f_a^2}
\]

\[
\frac{\alpha_3}{8\pi} \left( \frac{H^\dagger H}{M_p^2} G G + \frac{H'^\dagger H'}{M_p^2} G' G' \right)
\]

\[
\Rightarrow \langle H' \rangle = \mu' < 10^{14}\text{GeV}
\]
Theory parameter space

\[ m_a^2 \approx \frac{\Lambda_{QCD}^4}{f_a^2} \]

\[ \Phi^6 \]

\[ \frac{M_{pl}^2}{M_{pl}} \]

\[ V(a) \]

\[ \frac{a}{8\pi f_a} \left( c_3 \alpha_3 G \tilde{G} + c_2 \alpha_2 W \tilde{W} + c_1 \alpha_1 B \tilde{B} \right) \]
Theory parameter space

\[ m_a^2 \simeq \frac{\Lambda_{QCD}^4}{f_a^2} \]

no axion EFT control

\[ m_a > f_a \]

\[ \frac{a}{8\pi f_a} \left( c_3 \alpha_3 G G + c_2 \alpha_2 W \tilde{W} + c_1 \alpha_1 B \tilde{B} \right) \]
Theory parameter space

\[ m_a^2 \approx \frac{\Lambda_{QCD}^4}{f_a^2} \]

lighter than QCD axion

Theory Land of Opportunity

\[ \frac{a}{8\pi f_a} \left( c_3 \alpha_3 G G + c_2 \alpha_2 W W + c_1 \alpha_1 B B \right) \]
Existing constraints

\[
\frac{a}{8\pi f_a} \left( c_3 \alpha_3 G \tilde{G} + c_2 \alpha_2 W \tilde{W} + c_1 \alpha_1 B \tilde{B} \right)
\]

\[
c_1 = c_2 = c_3 = 1
\]
DUNE: excellent for heavy Axions

Axion Production
(meson mixing, gluon-gluon fusion)

Axion Decay
(into photon pairs, hadrons)

$p$ 120 GeV

Target

\[\pi^0 \rightarrow a\]

\[\eta/\eta' \rightarrow a\]

DUNE

LArTPC
(67 t)

DUNE

MPD
(1 t)

Sanford Underground Research Facility

Fermilab

800 miles (1300 kilometers)

574 m 579 m 584 m

Distance from Target (not to scale)
DUNE setup

large flux

1.47 \times 10^{21} \text{ POT/yr.}

\pi = \pi_{\text{phys}} + \theta_{a\pi} a_{\text{phys}} + \cdots \approx \pi_{\text{phys}} + \frac{1}{6} f_{\pi} \frac{m_{\pi}^2}{m_a^2 - m_{\pi}^2} a_{\text{phys}} + \cdots,

\eta = \eta_{\text{phys}} + \theta_{a\eta} a_{\text{phys}} + \cdots \approx \eta_{\text{phys}} + \frac{1}{\sqrt{6}} f_{\eta} \left( \frac{m_{\eta}^2}{m_a^2} - \frac{4}{9} \frac{m_{\pi}^2}{m_a^2} \right) a_{\text{phys}} + \cdots,

\eta' = \eta'_{\text{phys}} + \theta_{a\eta'} a_{\text{phys}} + \cdots \approx \eta'_{\text{phys}} + \frac{1}{2\sqrt{3}} f_{\eta'} \left( \frac{m_{\eta'}^2}{m_a^2} - \frac{16}{9} \frac{m_{\pi}^2}{m_a^2} \right) a_{\text{phys}} + \cdots

N_{\text{axions}} = N_{\text{POT}} \times \left[ 2.89 |\theta_{a\pi}|^2 f(m_{\pi}, m_a) + 0.33 |\theta_{a\eta}|^2 f(m_{\eta}, m_a) + 0.03 |\theta_{a\eta'}|^2 f(m_{\eta'}, m_a) \right]

f(m_{\text{meson}}, m_a) = \begin{cases} 
\left( \frac{m_a}{m_{\text{meson}}} \right)^{-1.6} & \text{if } m_a > m_{\text{meson}} \\
1 & \text{if } m_a \leq m_{\text{meson}}.
\end{cases}

Zhen Liu             HighQ Axion DUNE

Kelly, Kumar, ZL, 2011.05995
Decay via $\gamma\gamma$ and hadronic states

- DUNE can detect both $\gamma\gamma$ and hadronic final states

$C_{\gamma\gamma}^{\text{eff}}(m_\alpha \lesssim \text{GeV})$

\[ \approx c_2 + \frac{5}{3} c_1 - 1.92 c_3 - c_3 \frac{m_\alpha^2}{m_\pi^2 - m_\alpha^2} \frac{m_d - m_u}{m_d + m_u} + \ldots \]

\[ \frac{a}{8\pi f_\alpha} (c_3 \alpha_3 G G + c_2 \alpha_2 W W + c_1 \alpha_1 B B) \]
Signal and BG considerations for $a \rightarrow \gamma \gamma$

Backgrounds from neutral current $\pi$ are low energy ($\lesssim 5\text{GeV}$) and isotropic

<table>
<thead>
<tr>
<th>Signature</th>
<th>Liquid Argon</th>
<th>ArgonCube</th>
<th>Gaseous Argon MPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a \rightarrow \gamma \gamma$</td>
<td>Invariant Mass</td>
<td>$N \gamma^0$</td>
<td>Invariant Mass</td>
</tr>
<tr>
<td>$\gamma \gamma$ Direction</td>
<td>Nearly-Isotropic</td>
<td>High-Energy</td>
<td>$\gamma \gamma$ Direction</td>
</tr>
<tr>
<td>High-Energy</td>
<td>Low-Energy</td>
<td>High-Energy</td>
<td>Low-Energy</td>
</tr>
<tr>
<td>$a \rightarrow \text{hadrons}$</td>
<td>Invariant Mass</td>
<td>CC1$\mu2\pi$</td>
<td>Invariant Mass</td>
</tr>
<tr>
<td>Opening angle</td>
<td>DIS</td>
<td>Opening angle</td>
<td>DIS</td>
</tr>
<tr>
<td>High-energy</td>
<td>Low-energy</td>
<td>High-Energy</td>
<td>Low-Energy</td>
</tr>
<tr>
<td>$gg$ Direction</td>
<td>Nearly-Isotropic</td>
<td>$gg$ Direction</td>
<td>Nearly-isotropic</td>
</tr>
<tr>
<td>Low-energy recoils</td>
<td></td>
<td></td>
<td>Low-energy recoils</td>
</tr>
</tbody>
</table>
High-quality axion (or generic Axion-like-particles) shows an exciting opportunity for particle physics.
Axion is an elegant solution to the Strong CP puzzle via its IR robustness.

Quality problem demands new thoughts, and a heavy axion would help.

A mirror hidden sector with shared axion solve both problems.

DUNE will cover a large and unique parameter spaces of such motivated scenarios, high energy and intense source, and multi-purpose near detector

Lots of new opportunities: new search strategies and other facilities (LHC, displaced tracks, etc.)

Thanks you!
Axion EFT

• Axion EFT:

\[ \frac{a}{8\pi f_a} \left( c_3 \alpha_3 \tilde{G} \tilde{G} + c_2 \alpha_2 \tilde{W} \tilde{W} + c_1 \alpha_1 \tilde{B} \tilde{B} \right) \]

• \( aGG \) coupling induces photon coupling via anomaly

• For \( m_a > 3m_\pi \) hadronic decay modes dominate \( \rightarrow \) significant change in phenomenology compared to \( c_3 = 0 \).

\[ c_{\gamma\gamma}^{\text{eff}}(m_a \lesssim \text{GeV}) \approx c_2 + \frac{5}{3} c_1 - 1.92 c_3 - c_3 \frac{m_a^2}{m_\pi^2 - m_a^2} \frac{m_d - m_u}{m_d + m_u} + \ldots \]
DUNE coverage — complementarity
See Brdar, Dutta, Jang, Kim, Shoemaker, Tabrizi, Thompson, Yu 2011.07054 for photon dominance case.