New Limits on Leptophilic ALPs and Majorons from ArgoNeuT

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Motivations

one of the best motivated Standard Model (SM) extensions
⇒ are the pseudo Nambu-Goldstone bosons (pNGB) of any theory with a spontaneously broken global symmetry
⇒ rich phenomenology
⇒ masses and SM couplings range over many orders of magnitude
⇒ dark matter/portal

Examples
→ QCD axion (breaking of Peccei-Quinn symmetry)
→ Familons (flavor symmetry)
→ Leptophilic ALPs
→ Majoron couple only to charged leptons and photons at tree-level
dynamical generation of right-handed neutrino masses ⇒ majorona active neutrino masses via see-saw
Theoretical Framework · Leptophilic ALPs

- Interaction between $\ell$ALPs and charged leptons

$$\mathcal{L}_{a\ell\ell} = \frac{\partial_\mu a(x)}{2f} \bar{\ell} \gamma^\mu (C_V + C_A \gamma_5) \ell$$

- Coupling to photons

$$\mathcal{L}_{a\gamma\gamma} = E_\gamma \frac{\alpha_{EM}}{4\pi} \frac{a(x)}{f} F \tilde{F}$$

- We neglect couplings to quarks since they are suppressed
Theoretical Framework · Majorons

- Tree-level coupling to neutrinos
  \[ \mathcal{L}_{J_{\nu\nu}} = \frac{1}{2} \lambda_{\alpha\beta} J_{\nu\alpha} \nu_{\beta} + h.c. \]
  \[ \sim m_{\nu}/f \]

- Couplings at 1-loop order
  \[ \mathcal{L}_{J_{\ell\ell}} = \frac{i}{16\pi^2 \nu} J_{\ell\ell} \left[ m_{\ell} \text{tr}(K) \gamma_5 + 2m_{\ell}K P_L - 2K m_{\ell} P_R \right] \ell \]
  \[ K \equiv M_D M_D^{\dagger} / (v f) \]

- Induce interactions with mesons and nucleons

- Couplings with other SM states emerge at two-loop level
Theoretical Framework

- We assume **degeneracy** among the diagonal and off-diagonal coupling elements.

**Leptophilic ALP**

\[
\begin{align*}
C_A^{ii} &= C_A^d \\
C_A^{ij} &= C_A^o = C_V^o \\
C_V^d &= 0
\end{align*}
\]

\[R_a \equiv \frac{|C_A^d|}{|C_A^o|} \]

**Majoron**

\[
\begin{align*}
K_{ij} &= K^o \\
K_{ii} &= K^d
\end{align*}
\]

\[R_J \equiv \frac{|K^d|}{|K^o|} \]

**\(\ell\)ALP – Majoron Dictionary**

\[
\begin{align*}
R_a &= \frac{1}{2} R_J \\
K^o &= \frac{8\pi^2 v}{f}
\end{align*}
\]

free-parameters: \(m, R_a, f\)

free-parameters: \(m, R_J, K^o\)
The ArgoNeuT detector

- **Purpose**: Test LArTPC (Liquid Argon Time Projection Chamber) technology and measure $\nu$Ar cross-section

- **Location**: 100m underground in the NuMI (Neutrino at the Main Injector) ‘low energy’ beam-line at Fermilab (neutrino energies between 0.5-10 GeV)

- **Data collection**: 2009-2010

![Diagram of ArgoNeuT detector setup](image-url)
The ArgoNeuT detector

- Even with a small size the ArgoNeuT detector was already used to place new constraints in new physics!

[Graph showing exclusion region for HNLs]

- Idea: due to their $f$ suppressed couplings, the ALPs are typically long-lived, and hence can propagate and decay into a muon pair inside the detector.

⇒ we can put a bound in the ALP parameter space by reproducing their analysis

- Heavy Neutral Lepton search

  \[ |U_eN|^2 = |U_{μN}|^2 = 0 \]

⇒ zero observed events
Signal Simulation

• Production

\[ D_{(s)}^{\pm} \rightarrow \nu_\tau + \tau^{\pm}(\rightarrow \ell^{\pm} + \text{ALP}) \]

Total number of produced ALPs

- solid → ΣALP and Majoron
- dashed → only Majorons

• we normalized the plot to

\[ f = 1 \text{ GeV} \]

\[ C_A^o = 1 \]
Signal Simulation

- Decay

\[ \text{ALP} \rightarrow \mu^- \mu^+ \]

ALP Decay Widths

- Solid orange → ℓALP
- Dashed → only Majorons
- Solid → ℓALP and Majoron

\[
\Gamma (a/J \rightarrow \mathcal{F}) \quad [\text{GeV}]
\]

\[
\begin{align*}
\text{channel } \mathcal{F} & \quad \text{leptons} & \quad \gamma \gamma & \quad \nu \nu \\
\mu^+ \mu^- & \quad \mu^- \mu^- & \quad N \bar{N} & \quad \pi \pi
\end{align*}
\]

- We normalized the plot to

\[
f = 1 \quad \text{GeV} \\
C_A^o = 1 \quad R_a = 5 \quad E_\gamma = 1
\]
Signal Simulation

- The number of ALPs events inside ArgoNeuT is given by

\[ N_{\text{evts}} = \sum_i f_i N^i_a P^i_{\text{dec}} \]

where \( i = \{ \text{target, absorber} \} \)

\( f_i \) = probability that is produced at target/absorber

and the decay probability is

\[ P^i_{\text{dec}} = f^i_{\text{geom}} \left( e^{-d_i/\lambda} - e^{-l_i/\lambda} \right) \text{BR}(a/J \rightarrow \mu^+\mu^-) \epsilon \]

branching ratio

detection efficiency (~0.6)

probability that the ALP decays inside the detector volume

decay length \( \lambda = c\beta\gamma T \)
Signal Simulation

PYTHIA8 → MadGraph + MadDump → $N_{\text{evt}}$

Meson Production
Calculation of decay probability and geometrical acceptance

- we include the specific geometry of the ArgoNeuT detector
- we apply the necessary kinematic cuts
- we consider 3 different decay topologies
- we introduced an external python code to compute the ALP decays, including all channels.

$(\theta_{\mu\mu} \gtrsim 3^\circ)$

$(\theta_{\mu\mu} \lesssim 3^\circ)$

MadDump source code
Results

Region excluded by the ArgoNeut data

- Exclusion at 95% confidence level

Most stringent bounds on the $2\, m_\mu \lesssim m \lesssim m_\tau$ mass region!
Thank you for your kind attention!
BACKUP
Kinematics · ALPs

\[ \langle E \rangle = 38 \text{ GeV} \]

Histogram of ALP energy [GeV] and ALP angle \( \theta_a \) for different masses:
- \( m = 1.7 \text{ GeV} \)
- \( m = 0.8 \text{ GeV} \)
- \( m = 0.3 \text{ GeV} \)
FIG. 4. Selection efficiency as a function of $E_N$ for $m_N = 450$ MeV HNL decays occurring inside the ArgoNeuT detector (black) and at 25cm (blue) and 50cm (red) into the cavern upstream of ArgoNeuT along the beam direction.
Majoron

$$\mathcal{L} = - \bar{L} y N_R H - \frac{1}{2} \bar{N}_R^c \lambda N_R \sigma + \text{H.c.} - V(H, \sigma),$$

where $$\sigma = (f + \sigma^0 + iJ)/\sqrt{2}$$

RH Majorana $$M_R = f \lambda / \sqrt{2}$$

Dirac $$M_D = y v / \sqrt{2}$$

$$\mathcal{L} = - \frac{1}{2} \bar{n}_R^c V^T \left( \begin{array}{cc} 0 & M_D \\ M_D^T & M_R \end{array} \right) V n_R + \text{H.c.}$$

where $$\left( \nu_L^c, N_R \right) = V n_R$$
Decay into pions

\[ \Gamma(a \rightarrow \pi^a \pi^b \pi^0) = \frac{\pi}{6} \frac{m_a m_\pi^4}{\Lambda^2 f_\pi^2} \left[ C_{GG} \frac{m_d - m_u}{m_d + m_u} + \frac{c_{uu} - c_{dd}}{32 \pi^2} \right]^2 g_{ab} \left( \frac{m_\pi^2}{m_a^2} \right), \]

where (with \(0 \leq r \leq 1/9\))

\[ g_{00}(r) = \frac{2}{(1 - r)^2} \int_{4r}^{(1 - \sqrt{r})^2} dz \sqrt{1 - \frac{4r}{z}} \lambda^{1/2}(1, z, r), \]

\[ g_{+-}(r) = \frac{12}{(1 - r)^2} \int_{4r}^{(1 - \sqrt{r})^2} dz \sqrt{1 - \frac{4r}{z}} (z - r)^2 \lambda^{1/2}(1, z, r). \]
$l_i \rightarrow l_f$