New Limits on Leptophilic ALPs and Majorons from ArgoNeuT

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Outline

• Motivations
• Theoretical Framework
  → Leptophilic axion-like-particles (ℓALPs)
  → Majorons
• The ArgoNeuT detector
• Signal Simulation
• Results
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

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

- 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

We fix $E_\gamma = 1$
Theoretical Framework: Majorons

- Tree-level coupling to neutrinos

\[ \mathcal{L}_{J_{\nu\nu}} = \frac{1}{2} \lambda_{\alpha\beta} J^{\alpha} \nu_{\alpha} \nu_{\beta} + h.c. \sim \frac{m_{\nu}}{f} \]

- Couplings at 1-loop order

  \( \mathcal{L}_{J_{\ell\ell}} = \frac{i}{16\pi^2} J^{\ell} \bar{\ell} \left[ m_{\ell} \text{tr}(K) \gamma_5 + 2m_{\ell}K P_L - 2Km_{\ell}P_R \right] \ell \)

  \( K \) given by \( K \equiv \frac{M_D M_D^\dagger}{(v f)} \)

  Dirac neutrino mass matrix

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

\( \leftarrow \) charged leptons

\( \leftarrow \) quarks \( \rightarrow \) induce interactions with mesons and nucleons
Theoretical Framework

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

**Leptophilic ALP**

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

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

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

**Majoron**

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

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

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

**\(\ell\)ALP – Majoron Dictionary**

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

- **Purpose**: Test LArTPC (Liquid Argon Time Projection Chamber) technology and measure $\nu_{\text{Ar}}$ 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

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![Diagram of the ArgoNeuT detector setup]
The ArgoNeuT detector

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

Heavy Neutral Lepton search

\[ |U_{\tau N}| = |U_{\mu N}| = 0 \]

production: $\tau$ decays
signal: muon pair

$\Rightarrow$ zero observed events

- 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

$\Rightarrow$ we can put a bound in the ALP parameter space by reproducing their analysis
Signal Simulation

- Production

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

Total number of produced ALPs

- we normalized the plot to

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

\[ C^o_A = 1 \]
Signal Simulation

- Decay

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

**ALP Decay Widths**

- solid → ℓALP and Majoron
- dashed → only Majorons
- solid orange → ℓALP

- we normalized the plot to

\[
\begin{align*}
    f &= 1 \text{ GeV} \\
    C^0_A &= 1 \\
    R_a &= 5 \\
    E_\gamma &= 1
\end{align*}
\]
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 \( i = \{ \text{target, absorber} \} \)

\[ f_i = \text{probability that is produced at target/absorber} \]

and the decay probability is

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

- Probability that the ALP decays inside the detector volume
- Detection efficiency (~0.6)
- Branching ratio
- Detractor geometrical acceptance
- 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.

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

$\theta_{\mu\mu} \lesssim 3^\circ$
**Results**

Region excluded by the ArgoNeut data

- Exclusion at 95% confidence level

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

- $m = 1.7$ GeV
- $m = 0.8$ GeV
- $m = 0.3$ GeV

- $\theta_\mu \leq 3^\circ$: 6
- $\theta_\mu > 3^\circ$: 47
- $\theta_\theta \leq 3^\circ$: 21
- $\theta_\theta > 3^\circ$: 17
- $\theta_\mu \leq 3^\circ$: 27
- $\theta_\mu > 3^\circ$: 1

- Muon angle $\theta_\mu$
- Muon energy [GeV]
- Muon opening angle $\theta_\mu$ (°)

Number of events

- 0
- 5
- 10
- 15
- 20
- 25
- 30

- 0
- 5
- 10
- 15
- 20
- 25
- 30

- 0
- 5
- 10
- 15
- 20
- 25
- 30
Kinematics · ALPs

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

\begin{itemize}
  \item \textbf{ALP energy [GeV]}
  \item \textbf{ALP angle} \( \theta_a \)
\end{itemize}

- \( m = 1.7 \text{ GeV} \)
- \( m = 0.8 \text{ GeV} \)
- \( m = 0.3 \text{ GeV} \)
**Efficiency**

Heavy Neutral Lepton search

**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 \[M_D = y v/\sqrt{2}\]

mass matrix

\[
\mathcal{L} = -\frac{1}{2} \bar{n}_R^c V^T \begin{pmatrix} 0 & M_D \end{pmatrix} V n_R + \text{H.c.}
\]

where

\[
(\nu_L^c, N_R) = V n_R
\]

\[
\equiv -\frac{1}{2} \bar{n}_R^c M_n n_R + \text{H.c.,}
\]
Decay into pions

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

where (with 0 ≤ r ≤ 1/9)

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

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