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

axion-like-particles (ALPs)

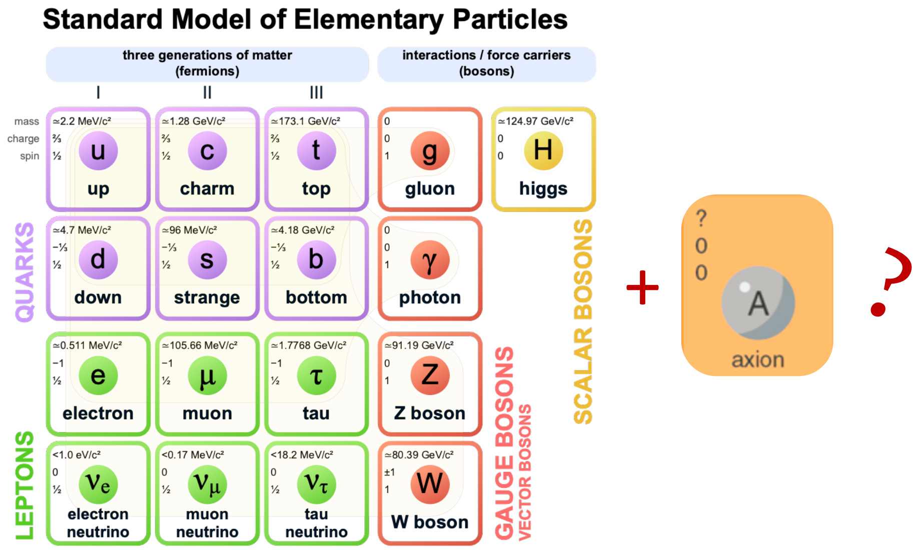
one of the best motivated Standard Model (SM) extensions

⇒ 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

couple only to charged leptons and photons at tree-level

→ Majoron

dynamical generation of right-handed neutrino masses ⇒ majorona active neutrino masses via see-saw

Theoretical Framework · Leptophilic ALPs

- Interaction between ℓALPs and charged leptons

axion

vector

axial

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

breaking scale

flavor fields

$$\ell \equiv (e \;\; \mu \;\; \tau)^T$$

- Coupling to photons

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

EM field strength

we fix

$E_\gamma = 1$

- We neglect couplings to quarks since they are suppressed

Theoretical Framework · Majorons

- Tree-level coupling to neutrinos

Majoron

$$\mathcal{L}_{J\nu\nu} = \frac{1}{2}\lambda_{\alpha\beta} J \nu_\alpha \nu_\beta + h.c.$$

$$\sim m_\nu / f$$

very suppressed!!

- Couplings at 1-loop order

  ↳ charged leptons

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

↳ matrix K given by $K \equiv M_D M_D^\dagger/(vf)$

Dirac neutrino mass matrix

  ↳ quarks ⇒ 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

$$\boxed{\begin{aligned} C_A^{ii} &= C_A^d \\ C_A^{ij} = C_A^o &= C_V^o \\ C_V^d &= 0 \end{aligned}} \quad \rightarrow \quad R_a \equiv \frac{|C_A^d|}{|C_A^o|}$$

free-parameters: m, R_a, f

Majoron

$$\boxed{\begin{aligned} K_{ij} &= K^o \\ K_{ii} &= K^d \end{aligned}} \quad \rightarrow \quad R_J \equiv \frac{|K^d|}{|K^o|}$$

free-parameters: m, R_J, K^o

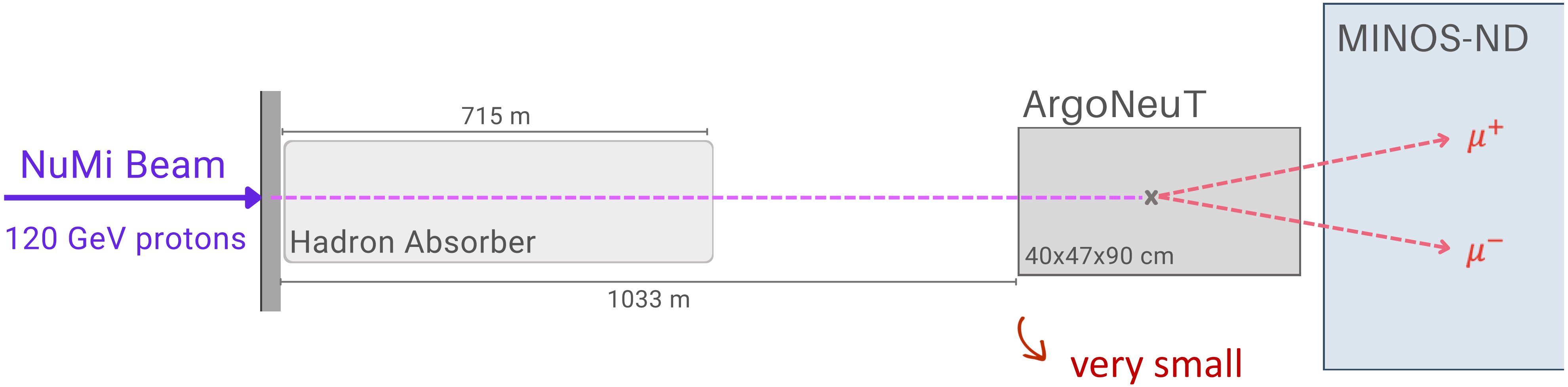
ℓALP – Majoron Dictionary

$$R_a = \frac{1}{2} R_J \qquad K^o = \frac{8\pi^2 v}{f}$$

The ArgoNeuT detector

- Purpose: Test LArTPC (Liquid Argon Time Projection Chamber) technology and measure νAr 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

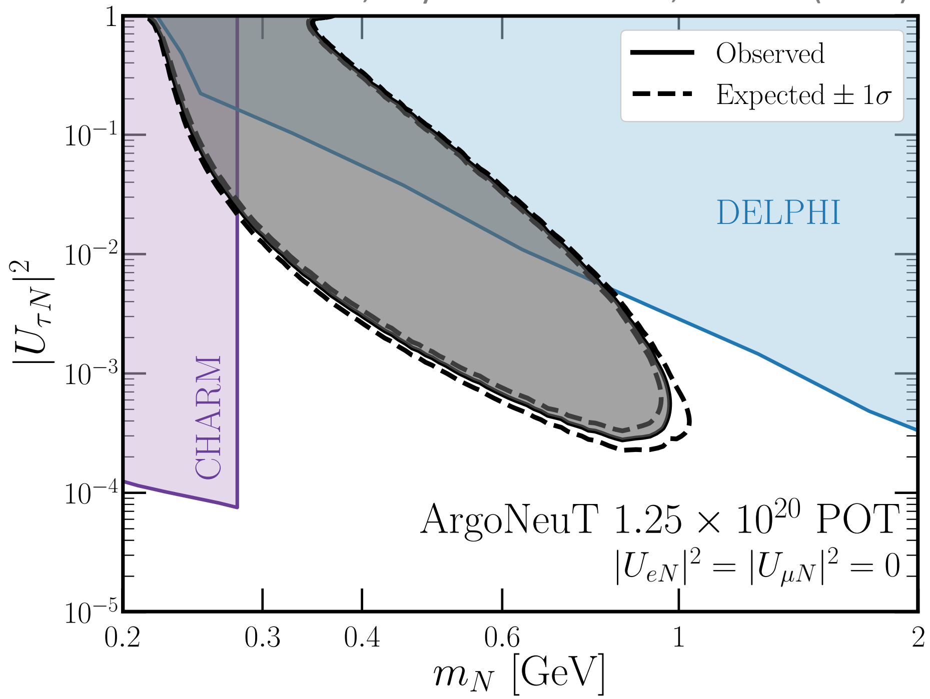


very small volume!!

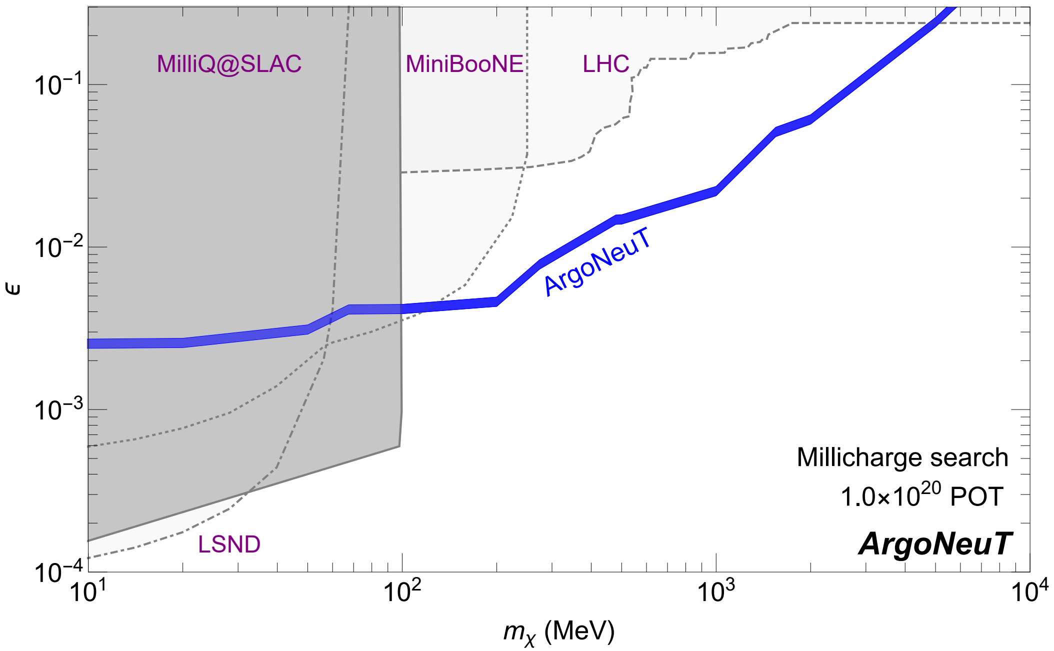
The ArgoNeuT detector

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

R. Acciarri et al., Phys. Rev. Lett. 127, 121801 (2021)



R. Acciarri et al., Phys. Rev. Lett. 124, 131801 (2020)



Heavy Neutral Lepton search { production: τ decays; signal: muon pair } $\Rightarrow$ zero observed events

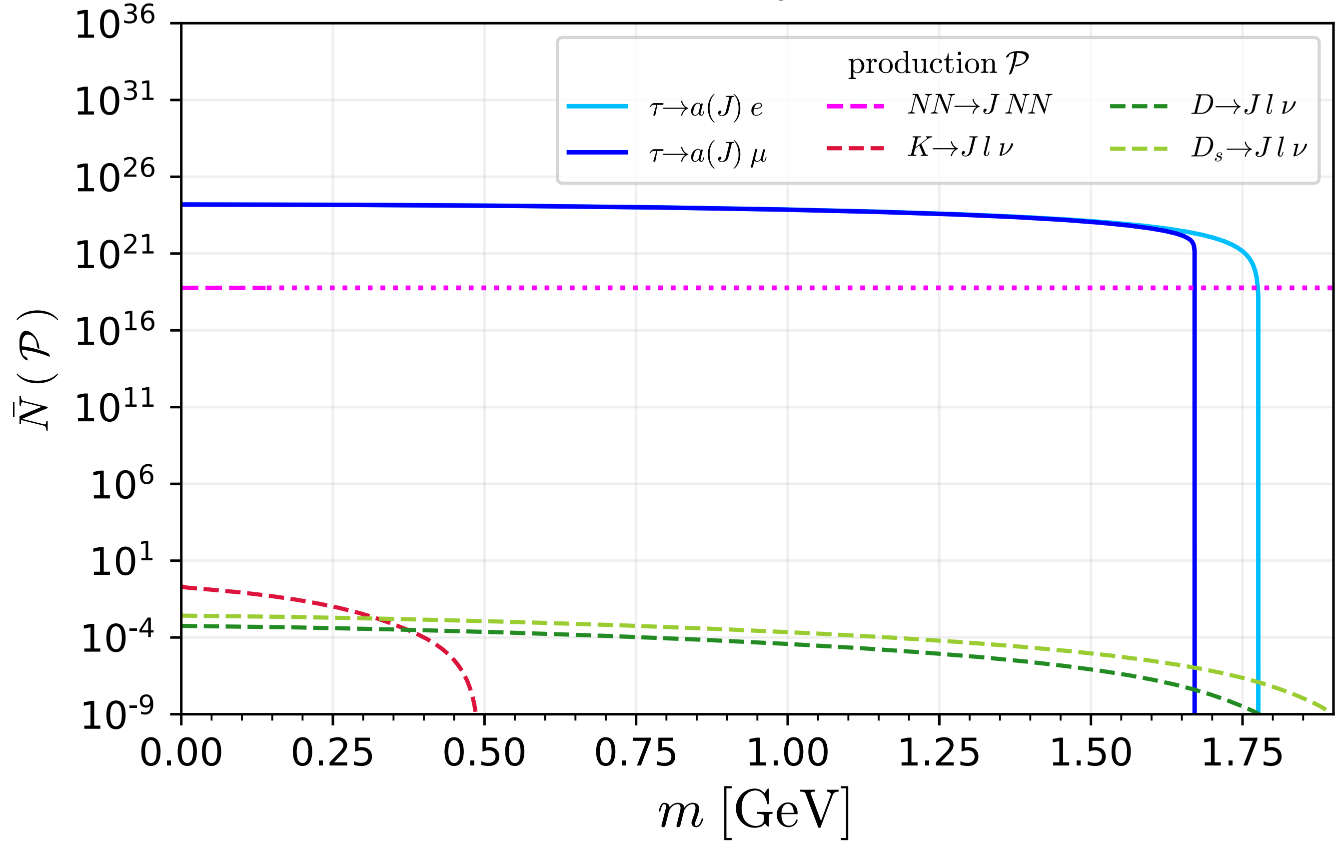
- Idea: due to their f suppressed couplings, the ALPs are typically long-lived, and hence can propagate and decay into a muon pair inside the detector

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

Signal Simulation

- Production $$D^{\pm}_{(s)} \to \nu_\tau + \tau^{\pm}(\to \ell^{\pm} + \text{ALP})$$

Total number of produced ALPs



solid → ℓALP and Majoron
dashed → only Majorons

- we normalized the plot to

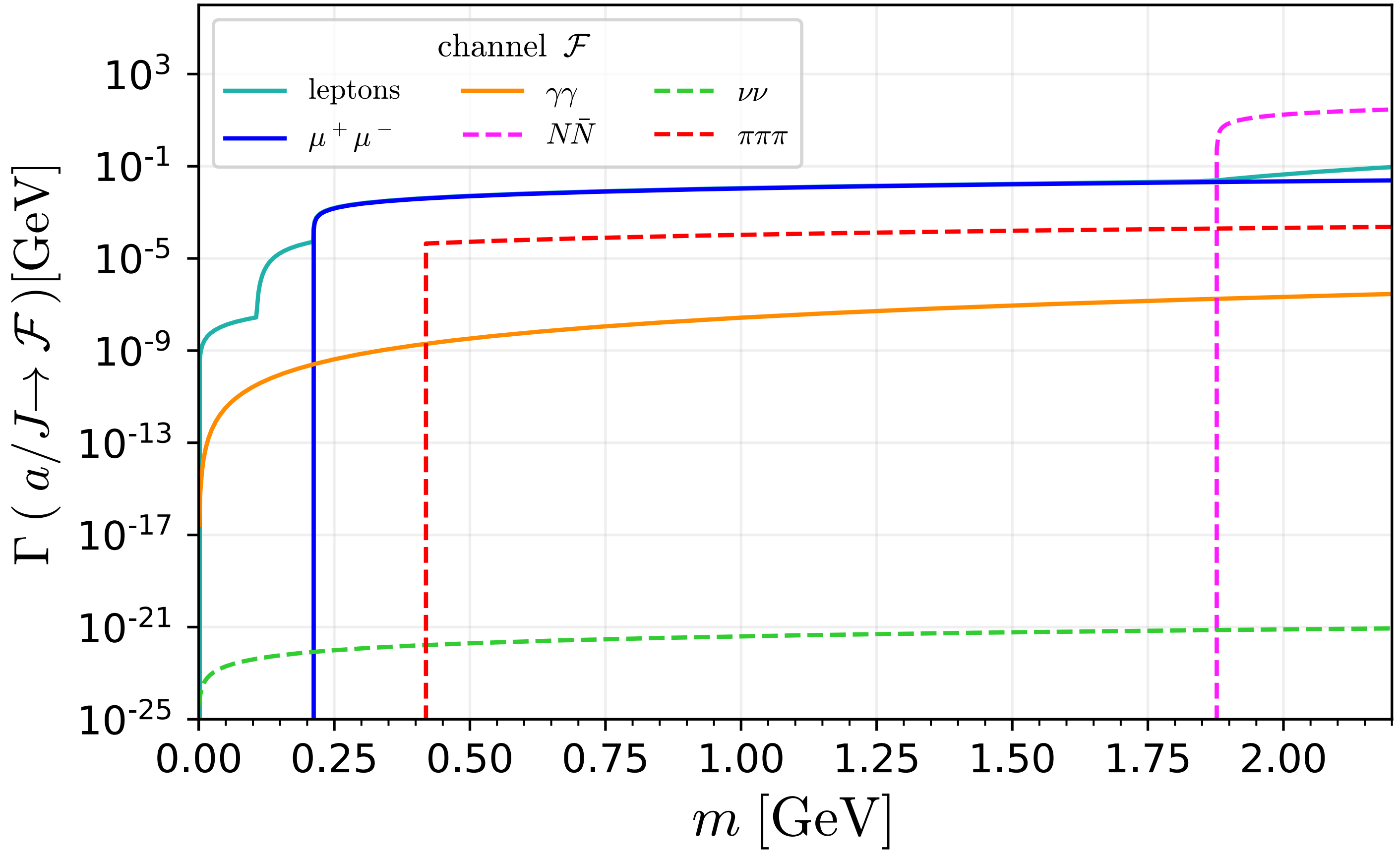
$$f = 1 \text{ GeV}$$
$$C_A^o = 1$$

Signal Simulation

- Decay

$$\mathrm{ALP} \to \mu^- \mu^+$$

ALP Decay Widths



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

- we normalized the plot to

$$f = 1 \ \mathrm{GeV}$$

$$C_A^o = 1 \quad R_a = 5$$

$$E_\gamma = 1$$

Signal Simulation

- The number of ALPs events inside ArgoNeuT is given by

produced ALPs

$$N_{\text{evts}} = \sum_i f_i \, N_a^i P_{\text{dec}}^i \quad \text{where} \quad \begin{cases} i = \{\text{target}, \text{absorber}\} \\ f_i = \text{probability that is produced at target/absorber} \end{cases}$$

decay probability

and the decay probability is

detection efficiency (~0.6)

branching ratio

$$P_{\text{dec}}^i = f_{\text{geom}}^i \underbrace{\left(e^{-d_i/\lambda} - e^{-l_i/\lambda}\right)}_{\text{probability that the ALP decays inside the detector volume}} \mathrm{BR}(a/J \to \mu^+\mu^-)\,\epsilon$$

detector geometrical acceptance

decay length $\lambda = c\beta\gamma\tau$

Signal Simulation

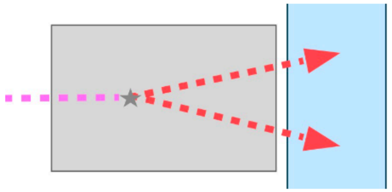
PYTHIA8 → MadGraph + MadDump → N_{evt}

Meson Production

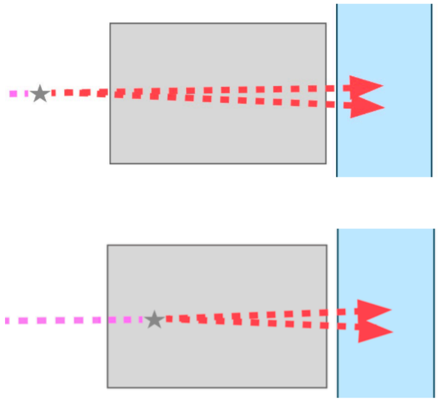
Calculation of decay probability and geometrical acceptance

MadDump source code

- 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.



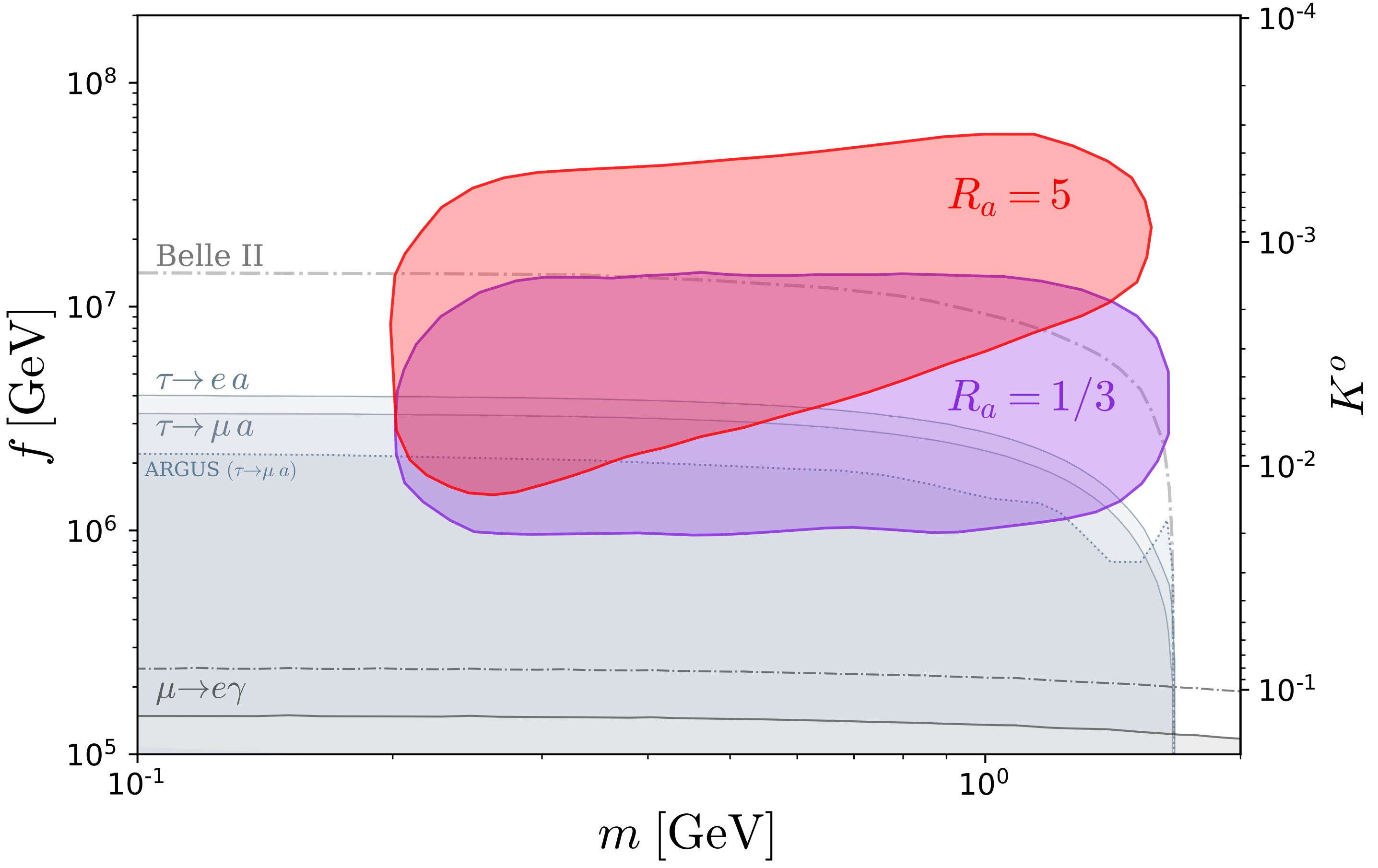
$(\theta_{\mu\mu} \gtrsim 3^\circ)$



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

Results

Region excluded by the ArgoNeut data



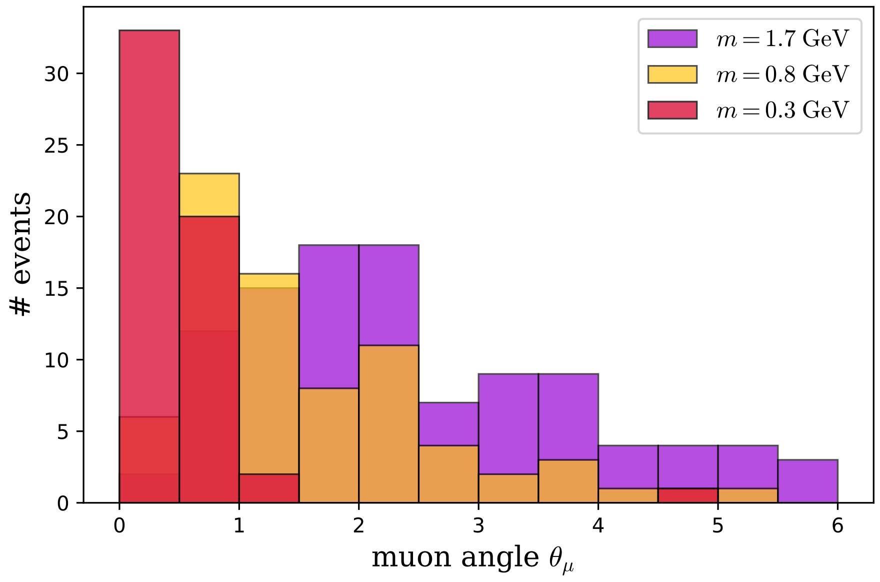
- Exclusion at 95% confidence level

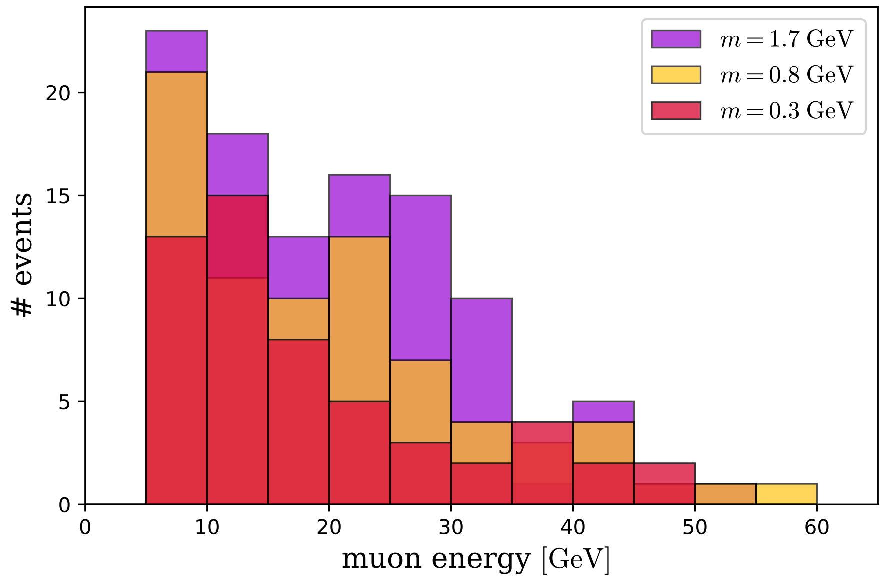
Most stringent bounds on the $2\,m_\mu \lesssim m \lesssim m_\tau$ mass region!

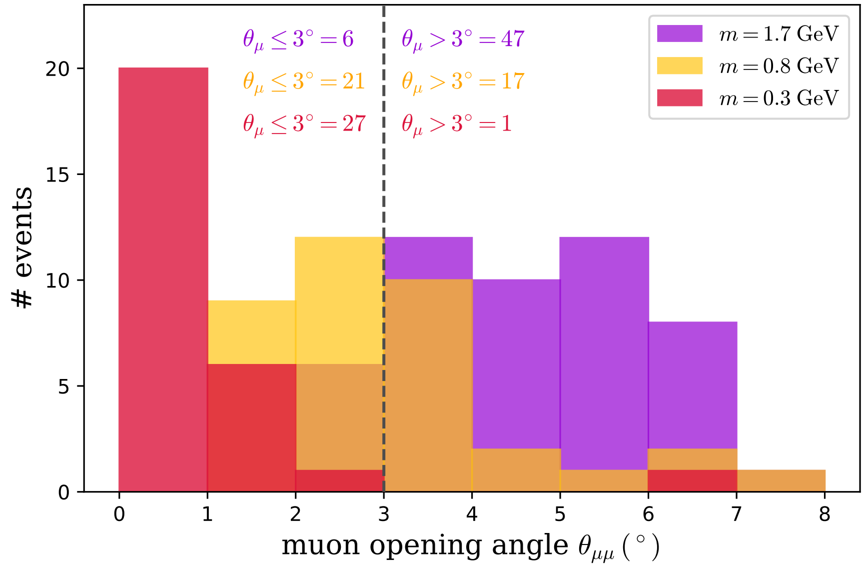
Thank you for your kind attention!

BACKUP

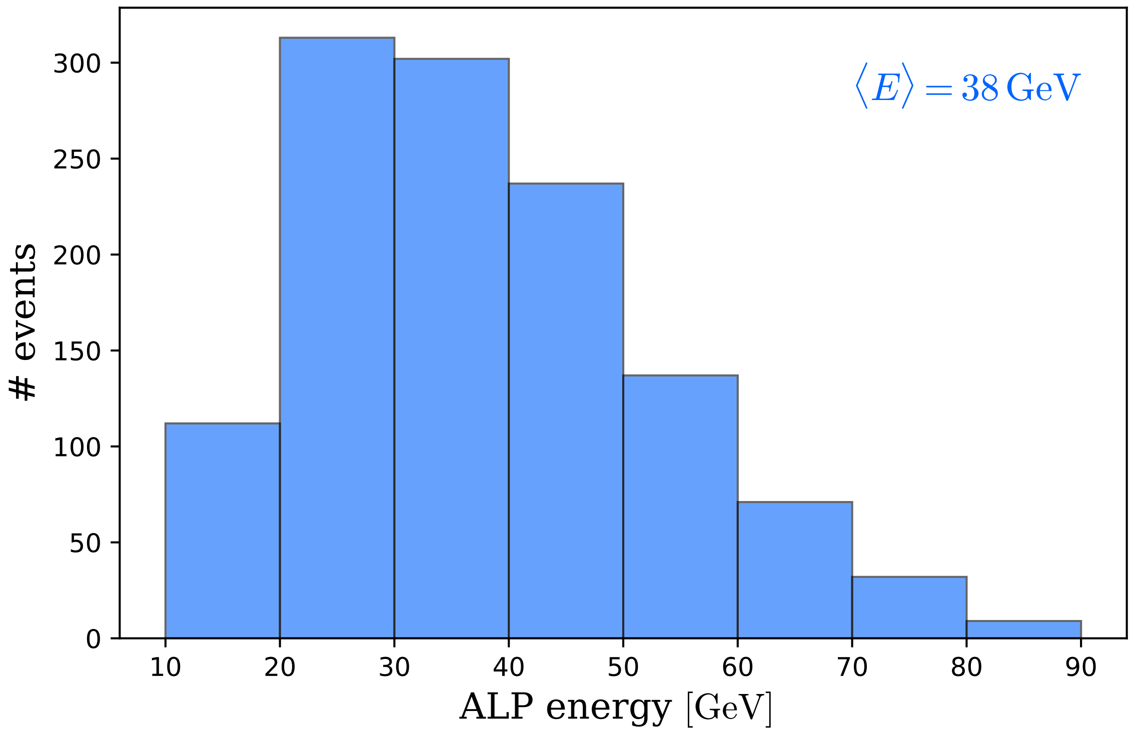
Kinematics · Muons

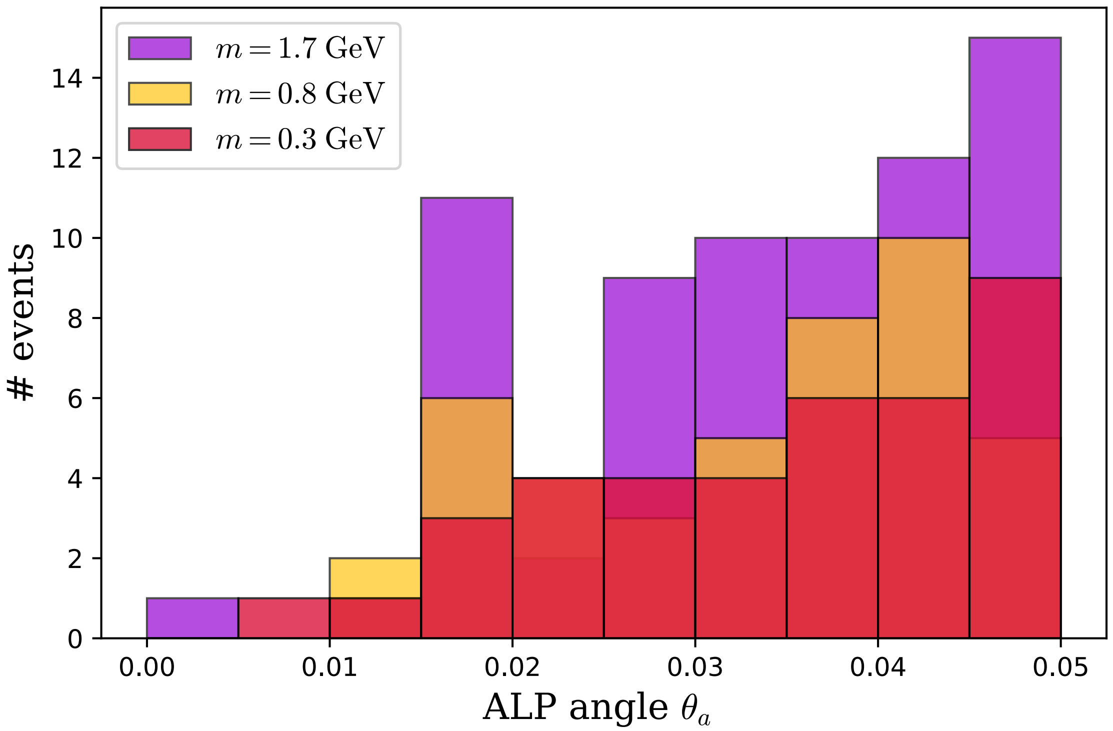






Kinematics · ALPs





Efficiency

Heavy Neutral Lepton search

R. Acciarri et al., Phys. Rev. Lett. 127, 121801 (2021)

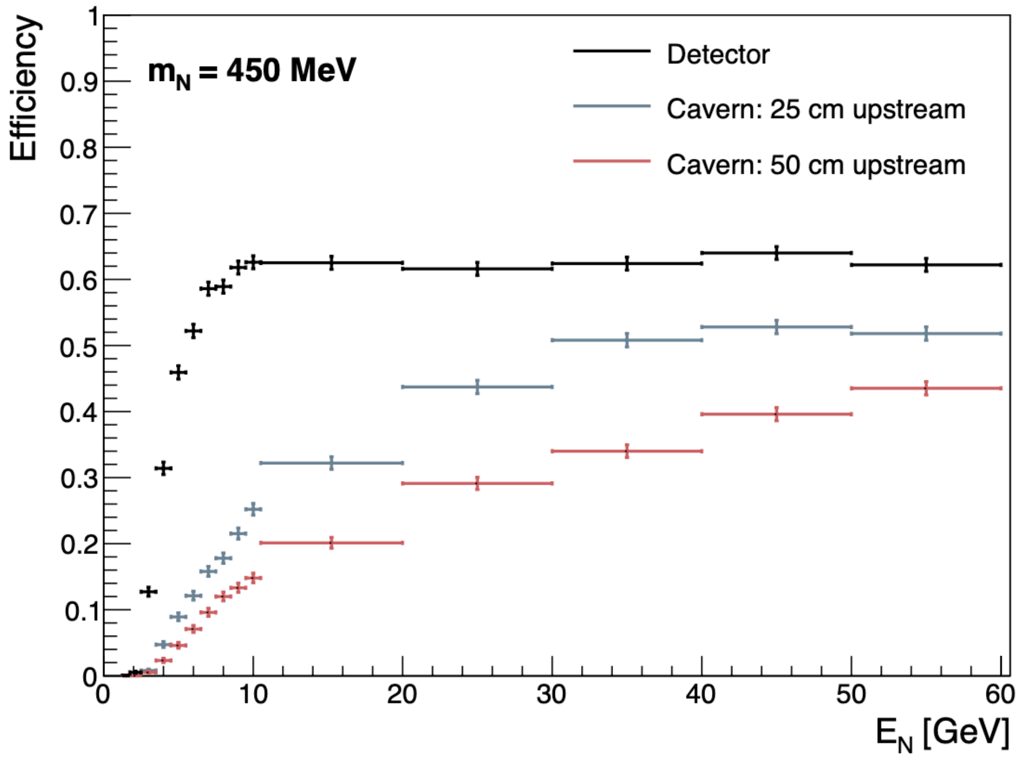


FIG. 4. Selection efficiency as a function of E_N for $m_N =$ 450 MeV HNL decays occurring inside the ArgoNeuT detector (black) and at 25cm (blue) and 50cm (red) into the cavern upstream of ArgoNeuT along the beam direction.

Majoron

[PHYSICAL REVIEW D 100, 095015 (2019)]

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

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

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

Dirac $M_D = yv/\sqrt{2}.$

mass matrix

$$\mathcal{L} = -\frac{1}{2}\bar{n}_R^c V^T \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} V n_R + \mathrm{H.c.}$$
$$\equiv -\frac{1}{2}\bar{n}_R^c M_n n_R + \mathrm{H.c.},$$

where $$(\nu_L^c, N_R) = V n_R$$

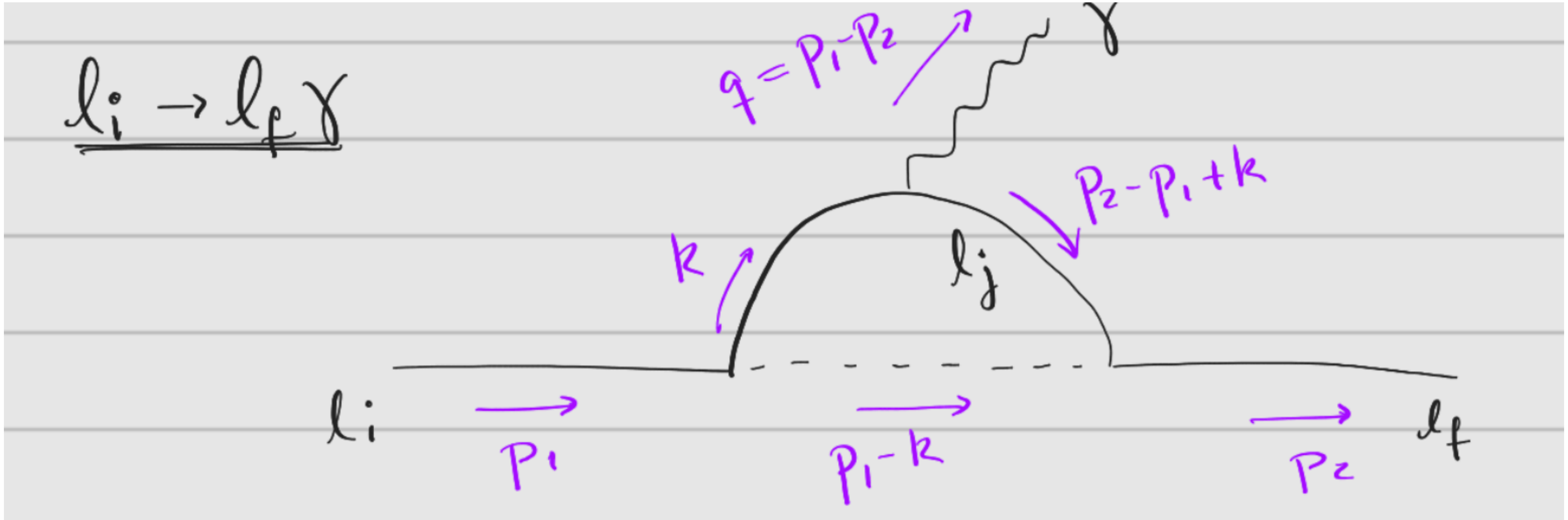
Decay into pions

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

where (with $0 \le r \le 1/9$)

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

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



$l_i \to l_f \gamma$
$q = p_1 - p_2$
γ
$p_2 - p_1 + k$
k
l_j
l_i
p_1
$p_1 - k$
p_2
l_f