Atmospheric axion-like particles at Super-Kamiokande

Zeren Simon Wang (NTHU)

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with Kingman Cheung, Jui-Lin Kuo, Po-Yan Tseng

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Ministry of Science and Technology

Motivation

- Axion-like particles well motivated:
  - *Dark matter* candidates
  - *Wide* possible range of mass
  - Mass and couplings to SM particles *decoupled*
  - Predicted in various BSM models
- Focus on ALP-muon coupling, not directly constrained for $m_a \lesssim 2m_\mu$
- Atmospheric air showers with copious production of light mesons decaying to LLPs
- Light muonphilic ALPs from charged pion decays, decaying into two photons, observable at **Super-Kamiokande**

ALP decay and production, with $m_a \lesssim 2m_\mu$:

- a: ALPs,pseudoscalar bosons

$$\mathcal{L} \supset -i g_{a\mu\mu} a\bar{\mu}\gamma_5\mu$$

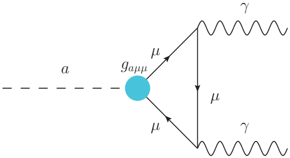
- Loop-induced decay: $a \to 2\gamma$

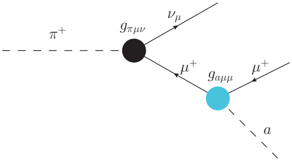
$$\mathcal{L}_{\rm loop} \supset -\frac{1}{4} g^{\rm eff}_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$g^{\rm eff}_{a\gamma\gamma} = \frac{g_{a\mu\mu}\alpha}{m_\mu \pi}\left[1 - \frac{4m_\mu^2}{m_a^2}\arcsin^2\left(\frac{m_a}{2m_\mu}\right)\right] \text{ for } m_a \leq 2m_\mu$$

$$\tau_a = \Gamma^{-1}_{a\to\gamma\gamma} = \frac{64\pi}{(g^{\rm eff}_{a\gamma\gamma})^2 m_a^3} \text{ for } m_a < 2m_\mu$$

- Production: $\pi^\pm \to \mu^\pm \nu a$





Estimating air showers

- Use `MCEq` to solve for the ALP flux at the Earth's surface
- Compute the decay matrix:

$$D^{ij}_{\pi^\pm \to a} = \Delta T^i_{\pi^\pm} \frac{dN_a}{dT_a}(T^i_{\pi^\pm}, T^j_a)$$

  $T_{\pi^\pm}$ and T_a: kinetic energies in the lab frame
  $\Delta T^i_{\pi^\pm}$: kinetic energy bin width
- ALP energy spectrum in the lab frame:

$$\frac{dN_a}{dT_a} = \int \frac{d\Omega}{4\pi} \frac{dN_a}{dE^*_a} \left| \frac{\partial E^*_a}{\partial T_a} \right|$$

  E^*_a is ALP energy in the pion rest frame
- Augment the decay channels of $\pi^\pm$ with $\pi^\pm \to \mu^\pm \nu a$

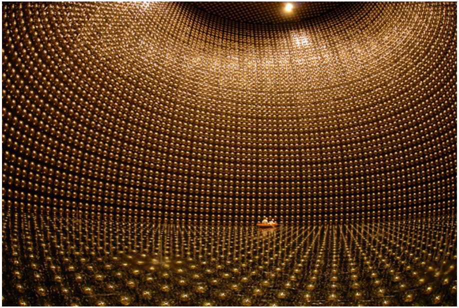
Signal detection

- Cherenkov detector in neutrino experiments can detect such photons from ALP decays; consider Super-Kamiokande
- Signal event distribution:

$$\frac{d^2 N_{\rm event}}{dT_a d\cos\theta} = \epsilon \Delta t A_{\rm eff}(T_a, \cos\theta) \frac{d^2 \Phi_a}{dT_a d\cos\theta}$$

Super-Kamiokande

- Cylinder with radius 20 m and height 40 m
- SK has good energy resolution in the sub- and multi-GeV ranges
- Lifetime: 5326 days with a flat efficiency of 0.75



Background

In 5326 live days, SK best-fit values:

- neutral pion decays into two photons: 1727 events
- neutrino-induced electron-like events that create multiple Cherenkov rings in the electromagnetic showers: 797 events

Computation of constraints

- Perform χ^2-fit to the SK data:

$$\chi_i^2 = 2\left\{N_{\rm sig}^i + N_{\rm bkg}^i - N_{\rm obs}^i\left[1 - \log\left(\frac{N_{\rm obs}^i}{N_{\rm sig}^i + N_{\rm bkg}^i}\right)\right]\right\}$$

  $N_{\rm bkg}^i$ and $N_{\rm obs}^i$ extracted from Phys. Rev. D **97**, 072001 (2018)
- In total 10 bins, derive the 90% C.L. constraint by requiring $\Delta\chi^2 \equiv \chi^2 - \chi_0^2 \leq 4.865$ with $\chi^2 = \sum_i \chi_i^2$ and χ_0^2 being the case without ALP contribution

Sensitivity Results

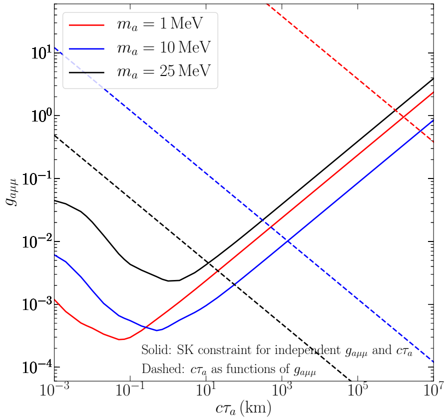


Figure: $c\tau_a$ and $g_{a\mu\mu}$ decoupled

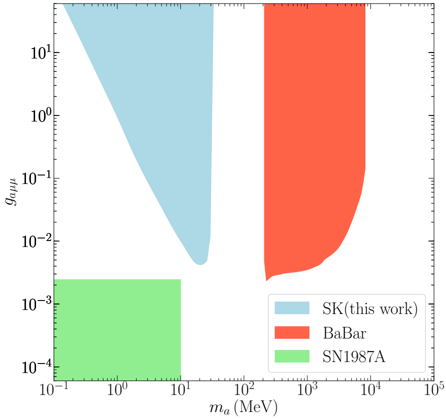


Figure: $c\tau_a \propto 1/g_{a\mu\mu}^2$

Summary

- Focused on $g_{a\mu\mu}$ (muonphilic ALP), leading to ALP production $\pi^{\pm} \to \mu^{\pm}\nu a$ and ALP decay into two photons, with $m_a \leq 2m_\mu$
- The long-lived light ALPs are produced from air showers, travel towards the Earth's surface, and decay into two photons inside Super-Kamiokande
- Estimated the ALP flux and signal event number with `MCEq`
- $N_{\rm bkg}$ and $N_{\rm obs}$ extracted from SK publication
- Sensitivities obtained for independent $c\tau$ and $g_{a\mu\mu}$ and $c\tau \propto 1/g_{a\mu\mu}^2$
- Good sensitivities from SK for m_a between 0.1 and 33 MeV, complementary to collider, beam-dump, and astrophysical probes

Thank You!

Back-up slides

A brief discussion on muon $g-2$

- Theory:
  - Both $g_{a\mu\mu}$ and $g_{a\gamma\gamma}$ contribute to $(g-2)_\mu/2$
  - The one-loop result of $g_{a\mu\mu}$ contribute negatively
  - $g_{a\mu\mu}$ and $g_{a\gamma\gamma}$ together lead to positive contributions at two loop
- Experiment:

$$\Delta a_\mu^{\rm BNL} = a_\mu^{\rm BNL} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}$$

- Large uncertainties in hadronic vacuum polarization
  $\Rightarrow$ not including $(g-2)_\mu$ in our analysis

MCEq

- MCEq numerically solves cascade equations of particles propagating in a dense medium
- H3a parameterization of the cosmic ray flux at the top of the atmosphere
- hadronic interaction model: SIBYLL2.3c
- atmosphere: CORSIKA parameterization of the U.S. Standard Atmosphere

Inverse-Primakoff process

- ALP can interact with atoms in the detector to create mono-γ signal with an energy similar to the energy of ALP
- Cross section:

$$\sigma_{\rm IP} \simeq \left(\frac{g_{a\gamma\gamma}^{\rm eff}}{1\,{\rm GeV}^{-1}} \right)^2 \times 2\,{\rm GeV}^{-2}$$

- $A_{\rm eff}$ for detecting the ALP decay is larger by orders of magnitude than the effective cross section of inverse-Primakoff process $N_T\sigma_{\rm IP}$ with N_T being the total number of target atoms inside the fiducial volume of the detector $\Rightarrow$ the event rate from the ALP decay dominates over that from the inverse-Primakoff process