

Searching for heavy neutral leptons coupled to axion-like particles at the LHC far detectors and SHiP

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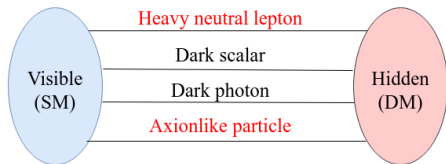
Workshop on Multi-front Exotic phenomena in Particle and
Astrophysics (MEPA 2025)

Nanjing, Jiangsu, China



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Motivation



- “Portal physics” connecting the visible world (SM) and a hidden world (DM): axionlike particle (ALP), heavy neutral leptons (HNLs), dark photon, dark scalar...
- A model with **both ALP and HNL**, **rich phenomenology and strong motivations**: DM, non-zero m_ν , neutrino excesses at short-baseline experiments, strong CP problem, hierarchy problem, ...
- **LHC far detectors** and **SHiP**, a lot of mesons!
- $P \rightarrow P'/V + a, a \rightarrow NN$, sub-GeV ALP and HNL, with the HNL necessarily being long-lived (LLP)
- LLP: produced \Rightarrow travel a macroscopic distance \Rightarrow decay

Model

- Assume **only one generation of HNL** kinematically relevant
- a : ALP, N : HNL

$$\mathcal{L}_a = \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{\partial_\mu a}{\Lambda} \sum_q \sum_{i,j} g_{i,j}^q \bar{q}_i \gamma^\mu q_j$$

$$\mathcal{L}_N = \frac{g}{\sqrt{2}} \sum_\alpha V_{\alpha N} \bar{\ell}_\alpha \gamma^\mu P_L N W_{L\mu}^- + \frac{g}{2 \cos \theta_W} \sum_{\alpha,i} V_{\alpha i}^L V_{\alpha N}^* \bar{N} \gamma^\mu P_L \nu_i Z_\mu$$

$$\mathcal{L}_{a,N} = \frac{\partial_\mu a}{\Lambda} g_N \bar{N} \gamma^\mu \gamma_5 N$$

- Λ : effective cut-off scale
- $g_{i,j}^q$: dimensionless couplings with q going over u_L, u_R, d_L , and d_R
- $V_{\alpha N}$: mixing angle between N and active neutrino ν_α with $\alpha = e, \mu, \tau$
- g_N : dimensionless coupling constant

Quark flavor violation and ALP

- ALP can couple to various fundamental particles in the SM
- Focus on **off-diagonal couplings** in either the up- or down-type quark sector and the ALP with $\mathcal{O}(0.1\text{--}1)\text{-GeV}$ masses, which are strongly constrained from low-energy (meson-scale) processes
- Assume **quark-flavor-diagonal couplings** to be **vanishing**
- Various UV-complete ALP models predict such off-diagonal couplings or **suppressed quark-flavor-diagonal couplings**, including flaxion, astrophobic axion, and models with a Froggatt-Nielsen mechanism
- In this phenomenological study, we remain agnostic about the origin of the particular ALP-quark flavor structure and **treat the ALP-quark couplings as independent parameters**

Benchmark scenarios

- ① **D-scenario:** $q = u$ and $(i, j) = (2, 1)$,

$$\begin{aligned} g_{2,1}^u &= g_{2,1}^{uR} + g_{2,1}^{uL} && \text{for } D^+ \rightarrow \pi^+, D_s^+ \rightarrow K^+, \\ & && \text{and } D^0 \rightarrow \pi^0, D^0 \rightarrow \eta, D^0 \rightarrow \eta', \\ g_{2,1}^u &= g_{2,1}^{uR} - g_{2,1}^{uL} && \text{for } D^+ \rightarrow \rho^+, D_s^+ \rightarrow K^{*+}, \\ & && \text{and } D^0 \rightarrow \rho^0, D^0 \rightarrow \omega. \end{aligned}$$

- ② **B-scenario:** $q = d$ and $(i, j) = (3, 2)$,

$$\begin{aligned} g_{3,2}^d &= g_{3,2}^{dR} + g_{3,2}^{dL} && \text{for } B^+ \rightarrow K^+, \\ & && \text{and } B^0 \rightarrow K^0, B_s^0 \rightarrow \eta, B_s^0 \rightarrow \eta', \\ g_{3,2}^d &= g_{3,2}^{dR} - g_{3,2}^{dL} && \text{for } B^+ \rightarrow K^{*+}, \text{ and } B^0 \rightarrow K^{*0}, B_s^0 \rightarrow \phi. \end{aligned}$$

- Assume either $g_{i,j}^{qL}$ or $g_{i,j}^{qR}$ is zero \Rightarrow both $P \rightarrow P'$ and $P \rightarrow V$ transitions are mediated by a single coupling
- **charge-conjugated channels** are **included** in the numerical study.
- Additional kaon resonances included; cf. [2310.03524](#)

Bounds on $g_{2,1}^u/\Lambda$ and $g_{3,2}^d/\Lambda$

- The ALP decays exclusively to a pair of *long-lived* HNLs
- Consider $D^0 \rightarrow \pi^0 \nu \bar{\nu}$ and $B \rightarrow K \nu \bar{\nu}$ measurements
- $D^0 \rightarrow \pi^0 \nu \bar{\nu}$ from BESIII (2112.14236)
↓
- Fix $g_{2,1}^u/\Lambda = 2 \times 10^{-4} \text{ TeV}^{-1}$ for $m_a = 0.5, 1.0,$ and 1.5 GeV
- $B^+ \rightarrow K^+ \nu \bar{\nu}$ from Belle II (2311.14647)
 $B^{+ / 0} \rightarrow K^{*+ / 0} \nu \bar{\nu}$ from Belle (1303.3719, 1702.03224, PDG2024)
- For the Belle II anomaly, we aim not to *explain* it, but only focus on parameter regions that are *allowed* by the measurement
↓
- Fix $g_{3,2}^d/\Lambda = 4 \times 10^{-6} \text{ TeV}^{-1}$ for $m_a = 1.0$ and 2.5 GeV
 $g_{3,2}^d/\Lambda = 1 \times 10^{-6} \text{ TeV}^{-1}$ for $m_a \geq 4.0 \text{ GeV}$

Production rates of the ALP

$$\Gamma(P \rightarrow P' a) = f \frac{|g_{i,j}^g|^2}{64\pi\Lambda^2} \left| F_0^{P \rightarrow P'}(m_a^2) \right|^2 m_P^3 \left(1 - \frac{m_{P'}^2}{m_P^2} \right)^2 \lambda^{1/2} \left(\frac{m_{P'}^2}{m_P^2}, \frac{m_a^2}{m_P^2} \right)$$

$$\Gamma(P \rightarrow Va) = h \frac{|g_{i,j}^g|^2}{64\pi\Lambda^2} \left| A_0^{P \rightarrow V}(m_a^2) \right|^2 m_P^3 \lambda^{3/2} \left(\frac{m_V^2}{m_P^2}, \frac{m_a^2}{m_P^2} \right)$$

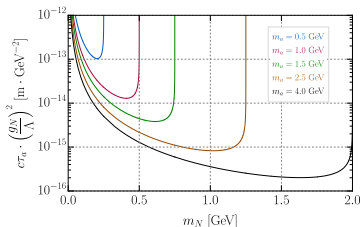
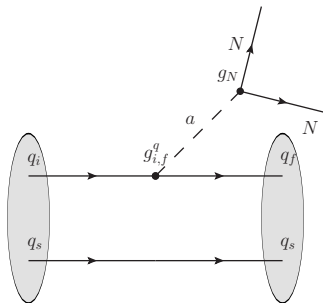
- $\lambda(x, y) \equiv 1 + x^2 + y^2 - 2x - 2y - 2xy$
- $m_{P/P'/V}$: mass of the $P/P'/V$ meson.
- $F_0^{P \rightarrow P'}$ and $A_0^{P \rightarrow V}$: transition form factors
- $f = h = 1$ except in the following neutral-meson transitions:

$$f = 1/2 \text{ for } D^0 \rightarrow \pi^0, \quad f = 2/3 \text{ for } D^0/B_s^0 \rightarrow \eta,$$
$$f = 1/3 \text{ for } D^0/B_s^0 \rightarrow \eta', \quad h = 1/2 \text{ for } D^0 \rightarrow \rho^0/\omega$$

Decay of the ALP

- ALP decay **dominated** by g_N : $\text{Br}(a \rightarrow NN) \simeq 100\%$
- ALP decay width:

$$\Gamma(a \rightarrow NN) = \frac{1}{2\pi} \left(\frac{g_N}{\Lambda} \right)^2 m_N^2 m_a \sqrt{1 - \frac{4m_N^2}{m_a^2}}$$



- Perturbativity:** $\frac{g_N}{\Lambda} m_N < 1$
- ALP can be promptly decaying or long-lived

Decay of the HNL

- HNLs decay via **mixing with the active neutrinos**, mediated by an off-shell W -boson or Z -boson
- Assume that the HNL **mixes with ν_e only**
- Leptonic decays: $\ell\ell^{(\prime)}\nu$ and 3ν
- Semi-leptonic decays: $\nu uu^{(\prime)}$, $\nu dd^{(\prime)}$, and ℓud at parton level
- High mass: decay to multiple hadrons (open-quark approximation)
Low mass: decay to a lepton and a meson

$$\begin{aligned}\Gamma_N &= \theta(1 \text{ GeV} - m_N)\Gamma_{N \rightarrow \text{single meson}} \\ &\quad + \theta(m_N - 1 \text{ GeV}) [1 + \Delta_{\text{QCD}}(m_N)] \Gamma_{N \rightarrow \bar{q}q} \\ &\quad + \Gamma_{N \rightarrow \text{leptons}}\end{aligned}$$

- See [2010.07305](#), [1805.08567](#), or [0901.3589](#), for more detail including decay-width formulas

LHC far detectors and SHiP at CERN

- LHC far detectors

- With proton-proton collisions at $\sqrt{s} = 13\text{--}14\text{ TeV}$
- ATLAS and CMS usually hard to test meson decay products; LHCb can do, but other limitations (int. lumi.)
- “Far detectors” specifically for LLP searches, macroscopic distances from various IPs allowing for shielding and veto; DV reconstruction inside fiducial volume
- ANUBIS, CODEX-b, FACET, FASER and FASER2, MoEDAL-MAPP1 and MAPP2, and MATHUSLA
- Little background, if not background-free

- SHiP

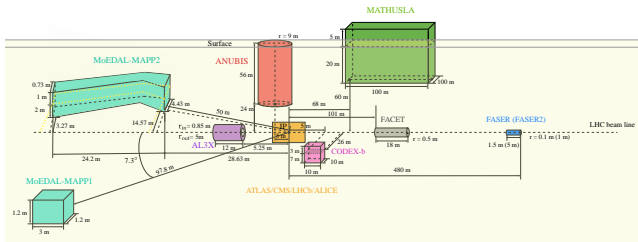
- A proton beam-dump experiment approved in March 2024
- Operation to start in 2031
- Proton beam energy 400 GeV from the CERN SPS accelerator hits a high-density target
- Downstream HSDS 33 m from the target, decay volume 50 m long, front (rear) face with $1.0\text{ m} \times 2.7\text{ m}$ ($4.0\text{ m} \times 6.0\text{ m}$)

Meson numbers

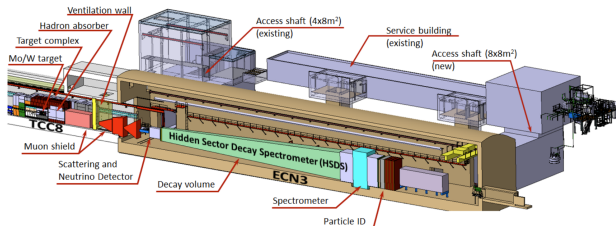
$N_{D^0(-)}$		N_{D^\pm}		$N_{D_s^\pm}$	
HL-LHC	SHiP	HL-LHC	SHiP	HL-LHC	SHiP
3.89×10^{16}	1.29×10^{18}	2.04×10^{16}	4.2×10^{17}	6.62×10^{15}	1.8×10^{17}
$N_{B^0(-)}$		N_{B^\pm}		$N_{B_s^0(-)}$	
HL-LHC	SHiP	HL-LHC	SHiP	HL-LHC	SHiP
1.46×10^{15}	8.1×10^{13}	1.46×10^{15}	8.1×10^{13}	2.53×10^{14}	2.16×10^{13}

- Total numbers of the relevant B - and D -mesons estimated to be produced at the HL-LHC [2010.07305] and SHiP [1805.08567]
- HL-LHC: 3 ab^{-1} and SHiP: 15 years with 6×10^{20} POTs
- $\mathcal{O}(10^{16})$ ($\mathcal{O}(10^{15})$) D -mesons (B -mesons) at the HL-LHC
- $\mathcal{O}(10^{18})$ ($\mathcal{O}(10^{14})$) D -mesons (B -mesons) at SHiP
- 4π solid-angle coverage and summing up both charge-conjugated mesons

Experimental setups



reproduced from [2410.19561] (C.-T. Lu, X. Wang, X. Wei, Y. Wu)



reproduced from [CERN-SPSC-2023-033]

Signal-event-number calculation

$$N_S = \sum_P N_P \cdot \text{Br}(P \rightarrow P' / Va) \cdot \text{Br}(a \rightarrow NN) \cdot 2 \cdot \epsilon_N \cdot \text{Br}(N \rightarrow \text{vis.})$$

- Assume 100% detector efficiency

$$\epsilon_N = \frac{1}{2 N_{\text{MC}}} \sum_{i=1}^{2 N_{\text{MC}}} \epsilon_i$$

$$\epsilon_i = \exp \left[- \frac{L_{T,i}}{\beta_i \gamma_i c \tau_N} \right] \left(1 - \exp \left[- \frac{L_{I,i}}{\beta_i \gamma_i c \tau_N} \right] \right), \text{ if inside detector window}$$

- 0 background, 3 signal events, 95% CL exclusion bounds

- Pythia8 for heavy-meson simulation

- Promptly decaying ALP:

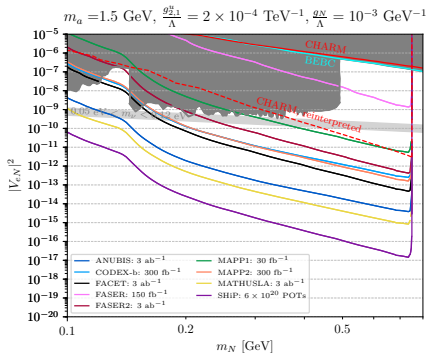
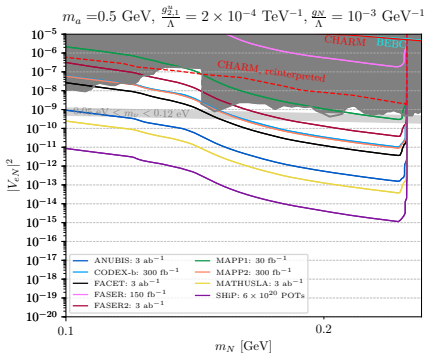
- LHC far detectors: **Displaced Decay Counter (DDC)** [[2308.07371](#)]
- SHiP: **Corner-point method** [[2008.07539](#)]

- Long-lived ALP: **consider the displaced-decay position of the simulated ALP** and the moving direction of the HNL [[2310.12392](#)]

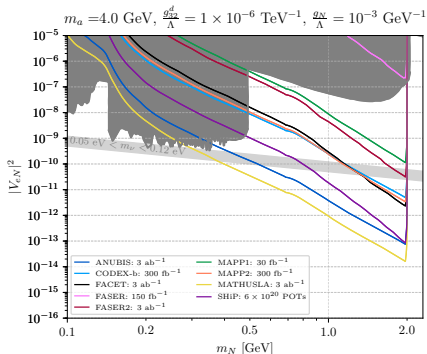
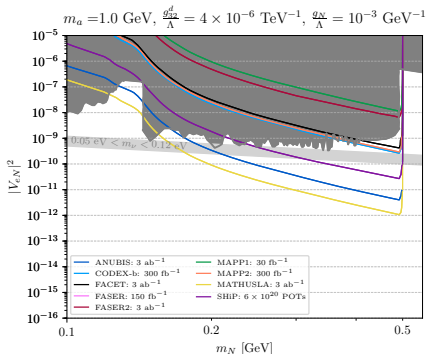
Existing bounds on HNL

- **Direct bounds (on the minimal scenario):** PIENU, super-allowed β decays, CHARM, NA62, T2K, BEBC
- **Reinterpreted bounds:** HNLs from D -meson decays at CHARM and BEBC
 - CHARM and BEBC results are similar so we reinterpret the CHARM results only, following the “overall re-scaling” method of reinterpretation proposed in [2302.03216]

LHC results – prompt ALP – D -scenario

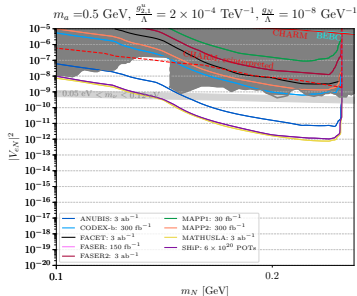
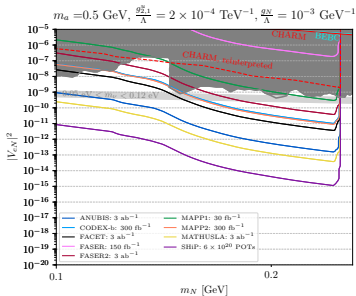


LHC results – prompt ALP – B -scenario

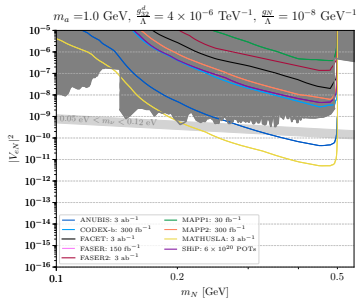
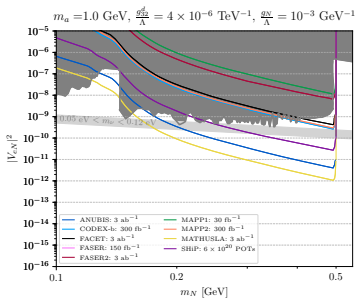


LHC results – compare prompt and long-lived ALP

D-scenario
 $m_a = 0.5 \text{ GeV}$



B-scenario
 $m_a = 1.0 \text{ GeV}$



Summary

- ALP and HNLs are well motivated BSM candidates
- Studied an ALP-HNL model: meson decays at the LHC and SHiP
- Signal processes: $P \rightarrow P' / Va, a \rightarrow NN$ with D - & B -meson scenarios
- ALP is promptly decaying or long-lived, and HNL is long-lived
- Sensitive to active-sterile-neutrino mixing parameters up to 6–7 orders of magnitude beyond the present bounds; if ALP is long-lived, sensitivities are weakened
- See also a follow-up study for Belle II:
[arXiv:2410.00491](#) ([PRD 111 \(2025\) 3, 035010](#))

Thank You!

谢谢!

Back-up slides

QCD loop corrections for HNL decays into multi-meson final states

The loop corrections are taken from a comparison to hadronic τ decays

$$1 + \Delta_{QCD}(m_\tau) \equiv \frac{\Gamma(\tau \rightarrow \nu_e + \text{hadrons})}{\Gamma_{\text{tree}}(\tau \rightarrow \nu_\tau + \bar{u} + D)},$$

where D denotes a d or s quark and

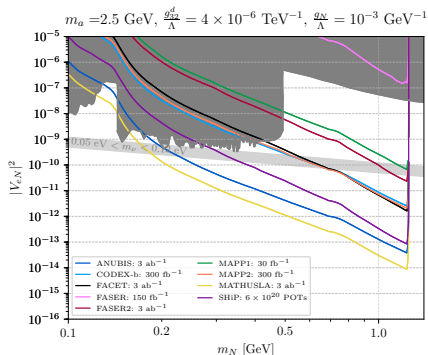
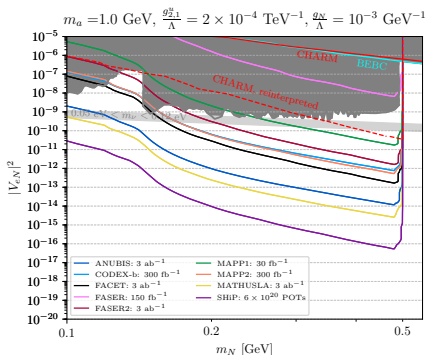
$$\Delta_{QCD} = \frac{\alpha_s}{\pi} + 5.2 \frac{\alpha_s^2}{\pi^2} + \dots,$$

where dots denote higher-order corrections. This gives a good description of the inclusive hadronic τ decay rate and we assume this to hold for sterile neutrino decays in the minimal scenario as well. That is, we use

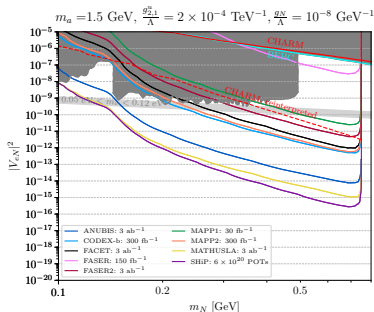
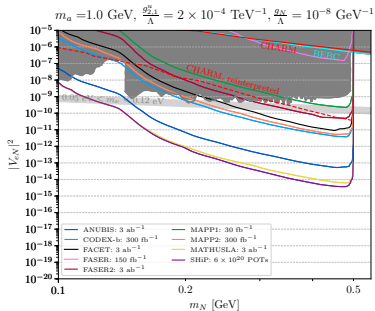
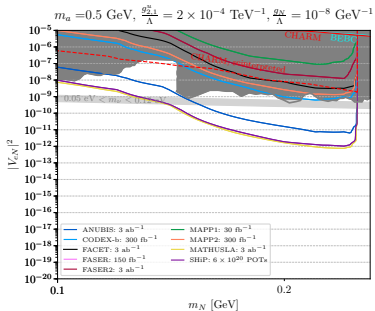
$$1 + \Delta_{QCD}(m_N) \equiv \frac{\Gamma(N \rightarrow e^-/\nu_e + \text{hadrons})}{\Gamma_{\text{tree}}(N \rightarrow e^-/\nu_e + \bar{q}q)},$$

to calculate the inclusive hadronic sterile neutrino decay rate through both charged and neutral weak currents.

Extra sensitivity plots for a promptly decaying ALP



LHC results – long-lived ALP – D -scenario



LHC results – long-lived ALP – B -scenario

