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

Zeren Simon Wang 王泽人 (HFUT)

arXiv:2409.18424 (*JHEP 01 (2025) 070*)

in collaboration with Yu Zhang 张宇 and Wei Liu 刘威

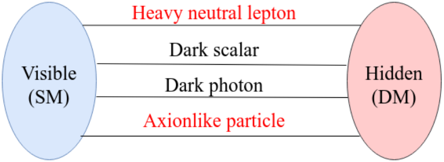
March 30$^{\text{th}}$, 2025
2025 粒子物理标准模型及新物理精细计算研讨会
中国河北保定

合肥工業大學
HEFEI UNIVERSITY OF TECHNOLOGY

Personal

- **PhD**: Bonn University in Germany, 2019 with Herbert Dreiner
- **Postdocs**: Asia Pacific Center for Theoretical Physics (APCTP) in South Korea and Taiwan Tsing Hua University in Taiwan, China
- **Research directions**: BSM physics phenomenology: major contributions to pheno studies on searches for **long-lived particles**
- **Now**: recently joined Hefei University of Technology (合肥工业大学) as an associate researcher
- **INSPIRE-HEP**: *personal page*

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!
- $P \to P'/V + a$, $a \to NN$, 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

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

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

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

- Λ: effective cut-off scale
- $g^q_{i,j}$: 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 $\mathcal{O}(0.1\text{–}1)$-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 $(i,j) = (2,1)$,

$$g^{u}_{2,1} = g^{u_R}_{2,1} + g^{u_L}_{2,1} \quad \text{for} \quad D^+ \to \pi^+,\ D_s^+ \to K^+,$$
$$\text{and} \quad D^0 \to \pi^0,\ D^0 \to \eta,\ D^0 \to \eta',$$
$$g^{u}_{2,1} = g^{u_R}_{2,1} - g^{u_L}_{2,1} \quad \text{for} \quad D^+ \to \rho^+,\ D_s^+ \to K^{*+},$$
$$\text{and} \quad D^0 \to \rho^0,\ D^0 \to \omega\,.$$

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

$$g^{d}_{3,2} = g^{d_R}_{3,2} + g^{d_L}_{3,2} \quad \text{for} \quad B^+ \to K^+,$$
$$\text{and} \quad B^0 \to K^0,\ B_s^0 \to \eta,\ B_s^0 \to \eta',$$
$$g^{d}_{3,2} = g^{d_R}_{3,2} - g^{d_L}_{3,2} \quad \text{for} \quad B^+ \to K^{*+},\ \text{and}\ B^0 \to K^{*0},\ B_s^0 \to \phi\,.$$

- Assume either $g^{q_L}_{i,j}$ or $g^{q_R}_{i,j}$ is zero $\Rightarrow$ both $P \to P'$ and $P \to V$ 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 $g^u_{2,1}/\Lambda$ and $g^d_{3,2}/\Lambda$

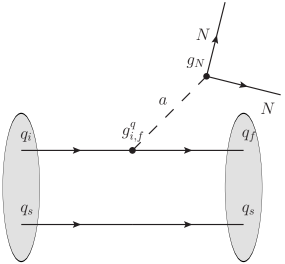
- The ALP decays exclusively to a pair of *long-lived* HNLs
- Consider $D^0 \to \pi^0 \nu\bar{\nu}$ and $B \to K\nu\bar{\nu}$ measurements

- $D^0 \to \pi^0 \nu\bar{\nu}$ from BESIII (*2112.14236*)
  $\Downarrow$
- Fix $g^u_{2,1}/\Lambda = 2 \times 10^{-4}$ TeV^{-1} for $m_a = 0.5, 1.0,$ and 1.5 GeV

- $B^+ \to K^+\nu\bar{\nu}$ from Belle II (*2311.14647*)
  $B^{+/0} \to K^{*+/0}\nu\bar{\nu}$ 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
  $\Downarrow$
- Fix $g^d_{3,2}/\Lambda = 4 \times 10^{-6}$ TeV^{-1} for $m_a = 1.0$ and 2.5 GeV
  $g^d_{3,2}/\Lambda = 1 \times 10^{-6}$ TeV^{-1} for $m_a \geq 4.0$ GeV

Decays of the ALP and the HNL

- ALP decay is dominated by g_N: $\text{Br}(a \to NN) \simeq 100\%$
- ALP decay width $\propto \left(\frac{g_N}{\Lambda}\right)^2$

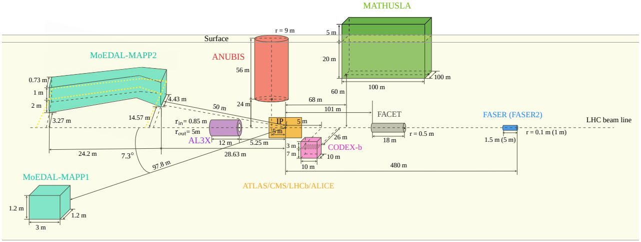


- Perturbativity: $\frac{g_N}{\Lambda} m_N < 1$
- ALP can be promptly decaying or long-lived
- HNLs decay via mixing with the active neutrinos
- Assume that the HNL mixes with ν_e only
- See *2010.07305*, *1805.08567*, or *0901.3589*, for more detail including decay-width formulas

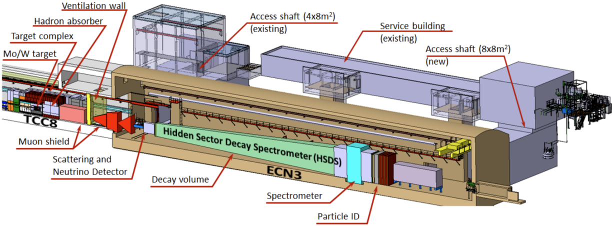
LHC far detectors and SHiP

- LHC far detectors
  - With proton-proton collisions at $\sqrt{s} = 13$–14 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
  - $\mathcal{O}(10^{16})$ ($\mathcal{O}(10^{15})$) D-mesons (B-mesons) with 3 ab^{-1}
- 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; expecting 15 years with 6×10^{20} POTs
  - Downstream HSDS 33 m from the target, decay volume 50 m long, front (rear) face with 1.0 m $\times$ 2.7 m (4.0 m $\times$ 6.0 m)
  - $\mathcal{O}(10^{18})$ ($\mathcal{O}(10^{14})$) D-mesons (B-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

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

- Assume 100% detector efficiency

  - $$\epsilon_N = \frac{1}{2\, N_{\mathrm{MC}}} \sum_{i=1}^{2\, N_{\mathrm{MC}}} \epsilon_i$$

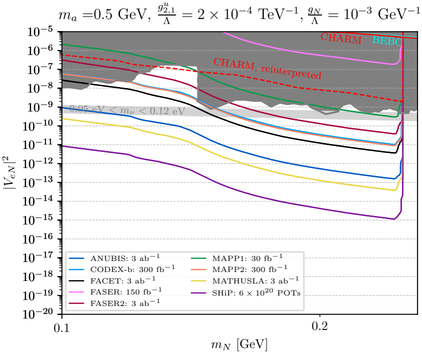
$$\epsilon_i = \exp\left[-\frac{L_{T,i}}{\beta_i \gamma_i c\tau_N} \right] \left(1 - \exp\left[-\frac{L_{I,i}}{\beta_i \gamma_i c\tau_N} \right] \right), \text{ if inside detector window}$$

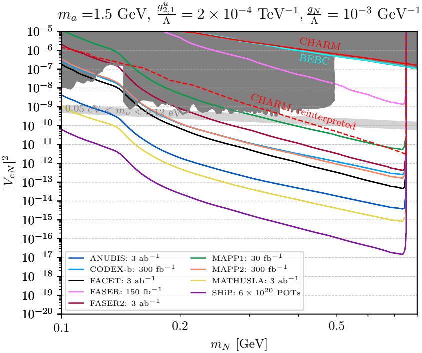
- 0 background, 3 signal events, 95% CL exclusion bounds
  - Pythia8 for heavy-meson simulation
  - Promptly decaying ALP:
    - LHC far detectors: Displaced Decay Counter (DDC) [*2308.07371*]
    - SHiP: Corner-point method [*2008.07539*]
  - Long-lived ALP: consider the displaced-decay position of the simulated ALP and the moving direction of the HNL [*2310.12392*]

Existing bounds on HNL

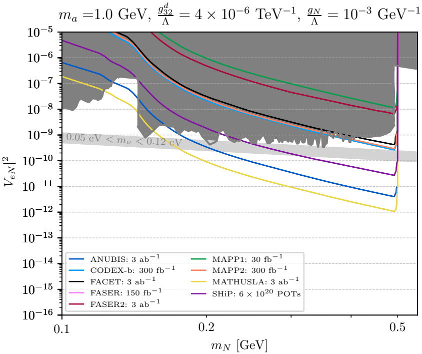
- Direct bounds (on the minimal scenario): PIENU, super-allowed β decays, CHARM, NA62, T2K, BEBC
- Reinterpreted bounds: HNLs from D-meson decays at *CHARM* and *BEBC*
  - CHARM and BEBC results are similar so we reinterpret the CHARM results only, following the "overall re-scaling" method of reinterpretation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

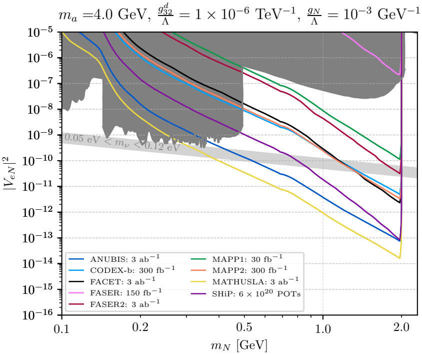
LHC results – prompt ALP – *D*-scenario





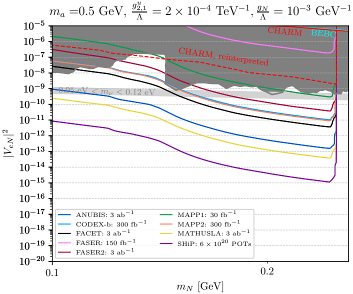
LHC results – prompt ALP – B-scenario

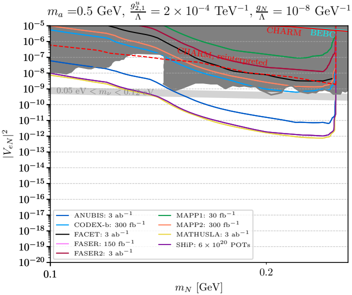




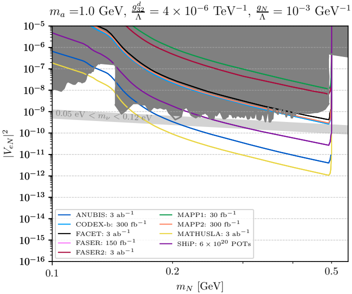
LHC results – compare prompt and long-lived ALP

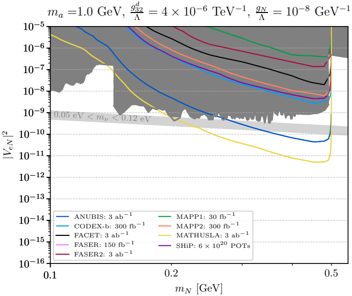
D-scenario
$m_a = 0.5$ GeV





B-scenario
$m_a = 1.0$ GeV





Summary

- ALP and HNLs are well motivated BSM candidates
- Studied an ALP-HNL model: meson decays at the LHC and SHiP
- Signal processes: $P \to P'/Va, a \to NN$ 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 10 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

Production rates of the ALP

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

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

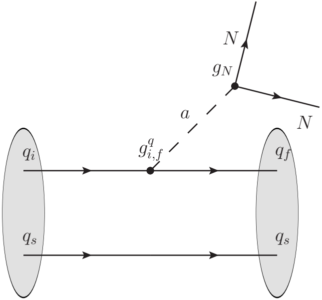
- $\lambda(x, y) \equiv 1 + x^2 + y^2 - 2\,x - 2\,y - 2x\,y$
- $m_{P/P'/V}$: mass of the $P/P'/V$ meson.
- $F_0^{P\to P'}$ and $A_0^{P\to V}$: transition form factors
- $f = h = 1$ except in the following neutral-meson transitions:

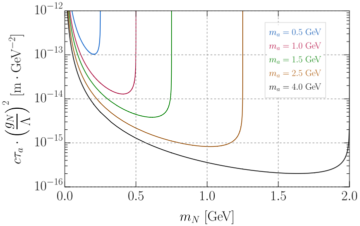
$$f = 1/2 \text{ for } D^0 \to \pi^0, \quad f = 2/3 \text{ for } D^0/B_s^0 \to \eta,$$
$$f = 1/3 \text{ for } D^0/B_s^0 \to \eta', \quad h = 1/2 \text{ for } D^0 \to \rho^0/\omega$$

Decay of the ALP

- ALP decay is dominated by g_N: $\mathrm{Br}(a \to NN) \simeq 100\%$
- ALP decay width:

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





- 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

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

- See *2010.07305* for more detail including decay-width formulas

Meson numbers

$N_{\overset{(-)}{D^0}}$		$N_{D^\pm}$		$N_{D_s^\pm}$	
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}
$N_{\overset{(-)}{B^0}}$		$N_{B^\pm}$		$N_{\overset{(-)}{B_s^0}}$	
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
- 4π solid-angle coverage and summing up both charge-conjugated mesons

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

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

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

where D denotes a d or s quark and

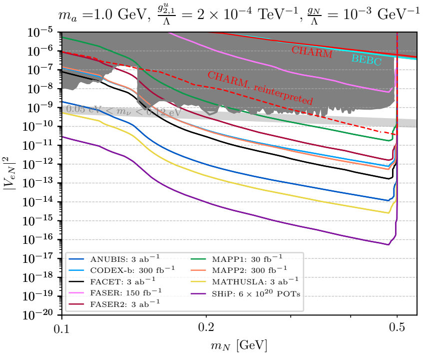
$$\Delta_{QCD} = \frac{\alpha_s}{\pi} + 5.2\frac{\alpha_s^2}{\pi^2} + \dots ,$$

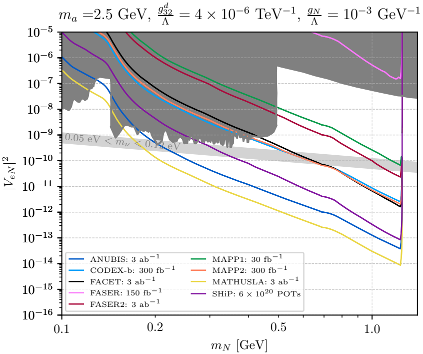
where dots denote higher-order corrections. This gives a good description of the inclusive hadronic τ decay rate and we assume this to hold for sterile neutrino decays in the minimal scenario as well. That is, we use

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

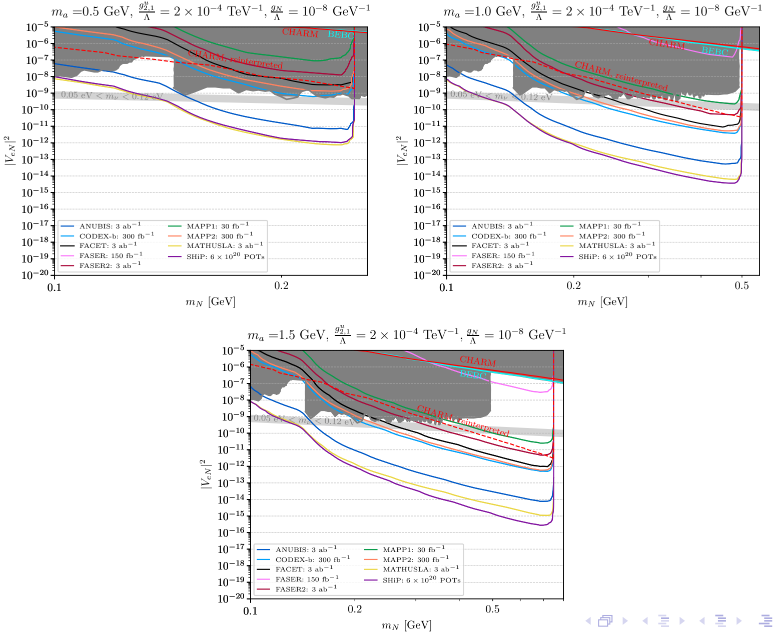
to calculate the inclusive hadronic sterile neutrino decay rate through both charged and neutral weak currents.

Extra sensitivity plots for a promptly decaying ALP





LHC results – long-lived ALP – *D*-scenario



LHC results – long-lived ALP – *B*-scenario