

Light new physics at accelerator experiments

Maksym Ovchynnikov
Invisibles 2025

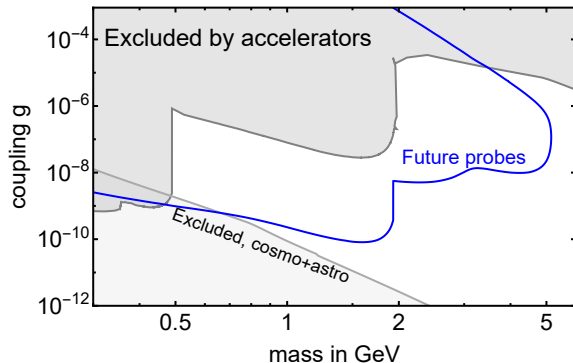
September 4, 2025



What is “light” and why is it special?

“Light” new physics: particles with mass $1 \text{ MeV} \lesssim m \ll \Lambda_{\text{EW}}$

- Large couplings g are excluded $+\tau \propto m^{-\alpha} g^{-2} \Rightarrow$
Long-lived Particles (LLPs)
- LLPs may be copiously produced and efficiently searched for at experiments with large collision intensity
- Many such experiments are currently running/planned



What are the prospects and challenges in searching for LLPs?

LLPs: examples I

Minimal, lowest-dimension, gauge-invariant interactions

Adds one LLP

Model	(Effective) Lagrangian	What it looks like
HNL N	$Y\bar{L}\tilde{H}N + \text{h.c.}$	Heavy neutrino with interaction suppressed by $U \sim \frac{Yv_h}{m_N} \ll 1$
Higgs-like scalar S	$cH^\dagger HS$	A light Higgs boson with interaction suppressed by $\theta \sim \frac{cv_h}{m_h} \ll 1$
Vector mediator V	$-\frac{\epsilon}{2}B_{\mu\nu}V^{\mu\nu} + gV^\mu J_{\mu,B}$	A massive photon/vector meson with interaction suppressed by $\epsilon, g \ll 1$
ALP a	$c_G \frac{\alpha_s}{4\pi} a G^{\mu\nu} \tilde{G}_{\mu\nu} + \dots$	A $\pi^0/\eta/\eta'$ -like particle with interaction suppressed by $\frac{f_\pi}{f_a} \ll 1$
MCPs χ	$\kappa e\bar{\psi}\gamma^\mu\psi A_\mu$	Millicharged particle
...

LLPs: examples II

Non-minimal yet “compact” models

> 1 LLPs, and/or additional quadratic coupling

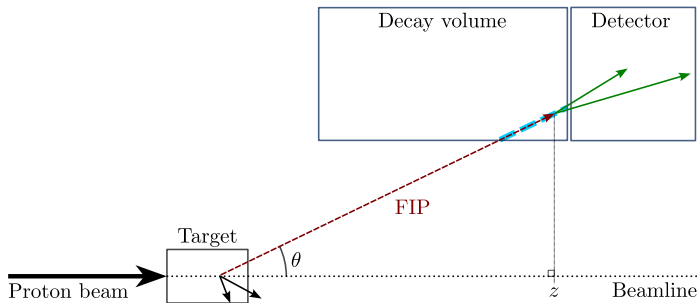
Model	(Effective) Lagrangian	What it looks like
LLPs X with quadratic hXX coupling	$\mathcal{L} = \mathcal{L}_{\min} + \alpha hXX$	Minimal LLP with additional production modes
Quasi-elastic DM χ	$g_d \bar{\chi} \gamma_\mu \chi V^\mu$	Stable particles coupled via dark photons V
Inelastic dark matter χ', χ	$g_d \bar{\chi}' \gamma_\mu \chi V^\mu + \text{h.c.}$	An unstable particle χ' decaying into $\chi + \text{SM}$
Dark QCD ρ_d/π_d	$\bar{q}_d \gamma^\mu q_d Z'_\mu + \dots$	A dark photon/ALP with additional production in showerings
...

How to search for LLPs: Intensity Frontier experiments I

Intensity frontier (IF) experiments

- Accelerator experiments with large collision intensity
- Typically, setups beyond prompt collider detectors

[\[1901.09966\]](#), [\[2505.00947\]](#)



Classification

1. Collision type:

- Collider(-based) (*FASEER*, ...)
- Beam dump (*NA62*, ...)

2. Signature:

- Scatterings (*SND@LHC*, ...)
- Decays (*CODEX-b*, ...)
- Missing energy (*NA64*, ...)

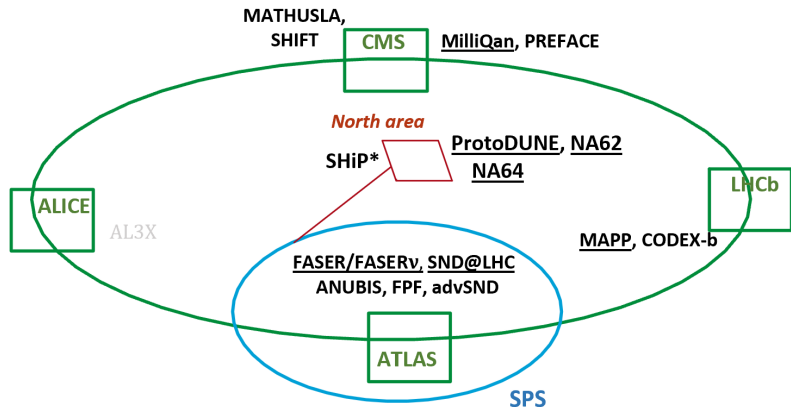
How to search for LLPs: Intensity Frontier experiments II

3. Beam type:

- $l = e, \mu$
(NA64, LUXE, ...)
- $h = p, Pb, \dots$
(NA62, ...)

4. Location:

- CERN (MAPP, ...)
- Fermilab
(DUNE, ...)
- DESY (LUXE)
- ...



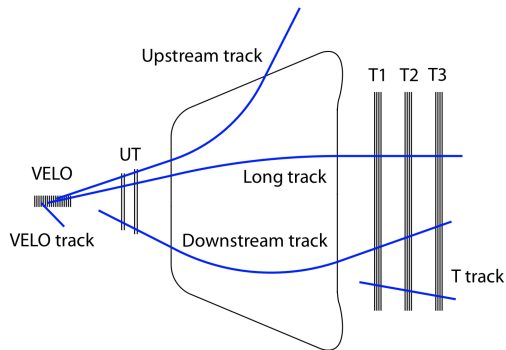
5. Status:

- Currently running (NA62, ProtoDUNE, NA64, FASER, MAPP, Downstream@LHCb...)
- Approved (SHiP, DarkQuest, ...)
- Proposed (FPF, MATHUSLA, FCC-ee, @FCC-hh, ILC-BD, μ collider, ...)

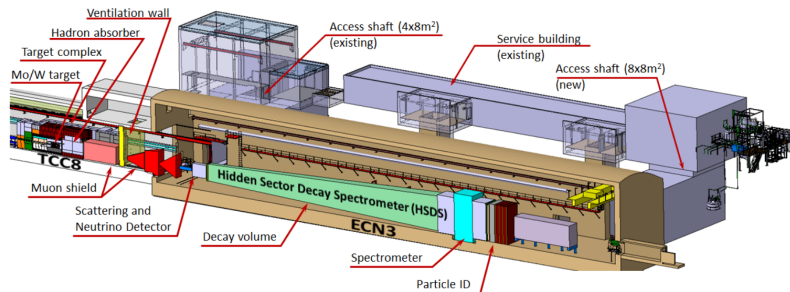
How to search for LLPs: Intensity Frontier experiments III

Downstream@LHCb

- Uses “Downstream tracks”,
 $1 \text{ m} < z < 2.5 \text{ m}$
- Currently running
- Suited for searching for LLPs decaying into charged particles



How to search for LLPs: Intensity Frontier experiments IV



SHiP

- Beam dump experiment@SPS
- Expected to start operating in 2033
- $N_{\text{POT}} = 6 \cdot 10^{20}$ (15 years)
- Will search for both decays and scatterings of LLPs

Potential of IF experiments

Exclusion potential

- Fix a particular LLP model
- How much parameter space may be excluded by future searches if not seeing a signal?
[\[2305.13383\]](#)

VS

Discovery potential

- Assume some events have been observed
- Can we identify the underlying LLP model?
- Can we establish whether it is related to the BSM problems?

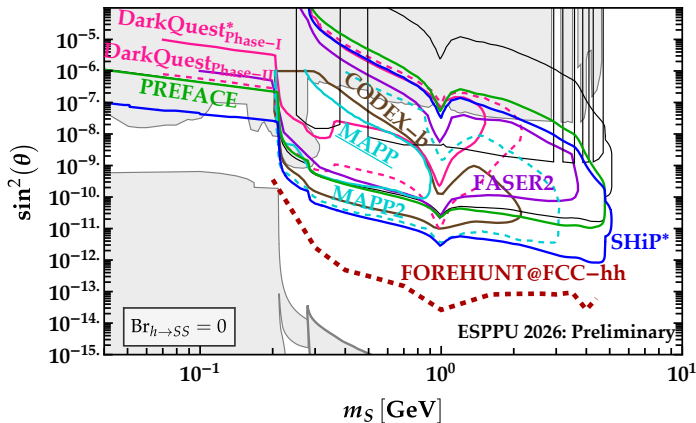
Exclusion potential

Exclusion potential (more: ESPP process) I

Higgs-like scalar

Minimal model (case
 $\text{Br}(h \rightarrow SS) = 0$)

- Most efficiently probed at B factories



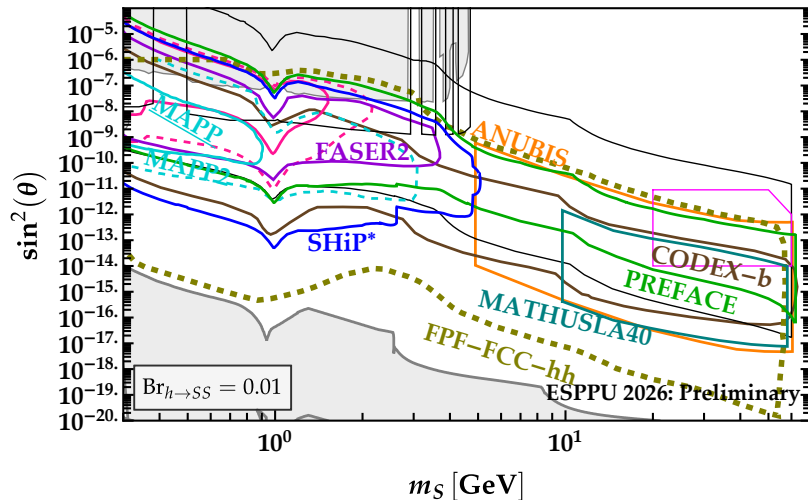
Meaning of the legend. **exp**: proposal. exp: currently running. **exp***: approved/in construction.
exp*: currently running, but the luminosity is to be approved

Exclusion potential (more: ESPP process) II

Higgs-like scalar

Case $\text{Br}(h \rightarrow SS) = 1\%$

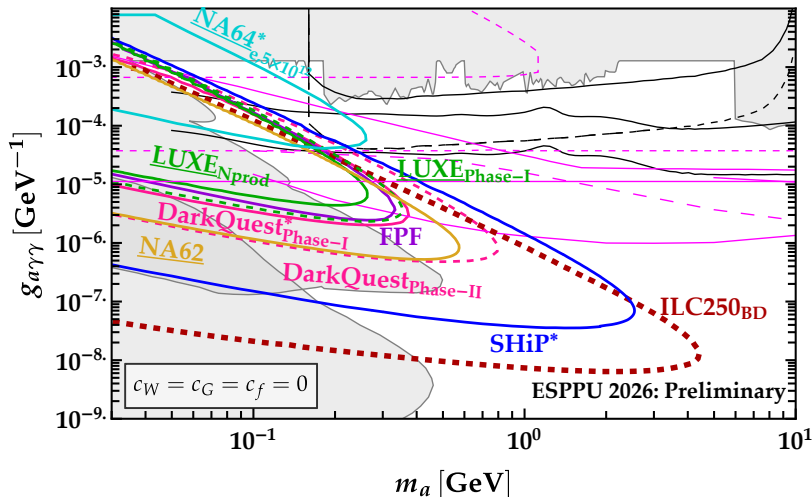
- Most efficiently probed at h and B factories



Exclusion potential (more: ESPP process) III

ALP (γ dominance)

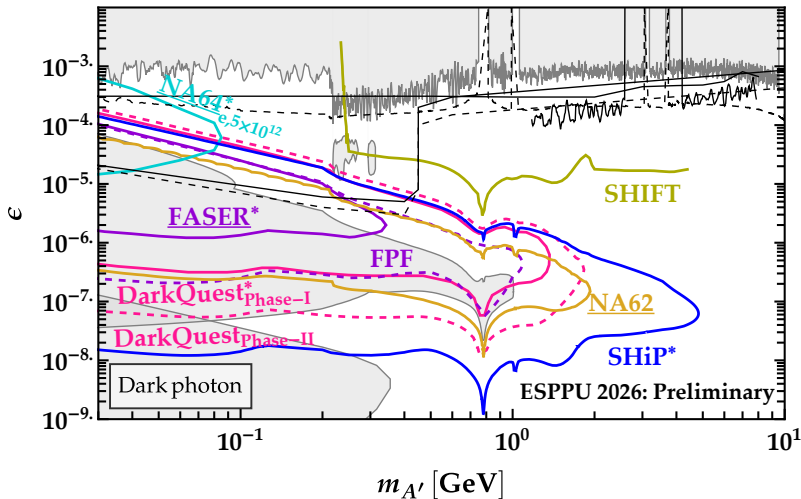
- Sensitivity is dominated by on-axis beam dump experiments or prompt collider searches (decays/missing energy)



Exclusion potential (more: ESPP process) IV

Dark photons

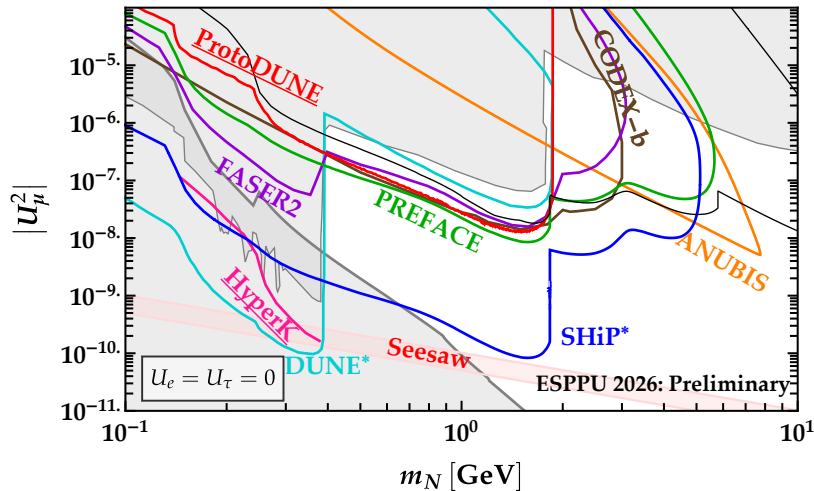
- Dark photons are produced in the forward direction
- Most efficient at far-forward experiments with very high collision intensity



Exclusion potential (more: ESPP process) V

HNL

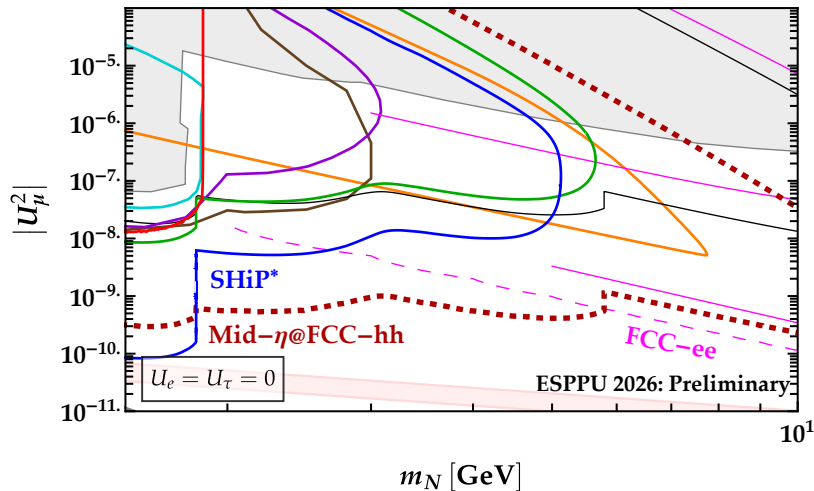
- Sensitivity comes from K, D, B, W, Z factories



Exclusion potential (more: ESPP process) VI

HNL

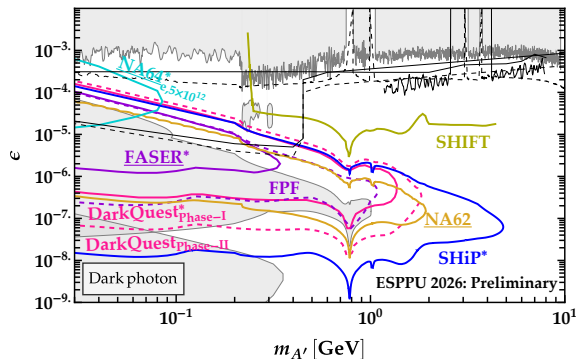
- FCC-ee will complementarily probe the large mass region $m_N \gtrsim m_B$
- But the domain $m_N \lesssim m_B$ will remain underexplored



- **FCC-hh-based experiments**: significantly extend the SHiP reach for $m_D < m_N < m_B$

Issue: uncertainties in phenomenology I

- The plots above assume that we exactly know the LLP phenomenology (how they are produced and decay)
- In reality, this is not true for hadronically coupled LLPs: m_{LLP} is close to Λ_{QCD}
- Hadronic interactions of LLPs cannot be described by either pQCD or ChPT



Issue: uncertainties in phenomenology II

Main challenge – mixing with mesons

- Interaction Lagrangian of a LLP \mathbf{X} :

$$\mathcal{L} = \mathbf{X}^a \cdot \mathcal{O}_a[\psi_{\text{SM}}] + \mathbf{X}^a \mathbf{X}^b \cdot \mathcal{O}_{ab}[\psi_{\text{SM}}] + \dots \quad (1)$$

- $m_{\text{LLP}} \simeq 1 \text{ GeV} \Rightarrow$ expand $\mathcal{O}_a[\psi_{\text{SM}}]$ in terms of bound hadronic states \mathbf{Y} :

$$\mathcal{O}_a = \overbrace{c_1(\mathbf{Y}, \partial\mathbf{Y}, \partial^2\mathbf{Y})_a}^{\text{1-particle}} + \overbrace{c_2(\mathbf{Y}^2, (\partial\mathbf{Y})^2, \mathbf{Y}\partial\mathbf{Y})_a}^{\text{2-particle}} + \dots \quad (2)$$

- $\mathbf{X}^a \mathbf{Y}_a$ – induced resonant mixing. Every process with \mathbf{Y} may involve \mathbf{X} by replacing

$$\psi_{\mathbf{Y}} \rightarrow \theta_{\mathbf{YX}} \psi_{\mathbf{X}}, \quad \theta_{\mathbf{YX}} = \frac{c_1}{m_{\mathbf{X}}^2 - m_{\mathbf{Y}}^2 - im_{\mathbf{Y}}\Gamma_{\mathbf{Y}}} + \dots \quad (3)$$

[2504.06828]

Issue: uncertainties in phenomenology III

Main challenge – mixing with mesons

Particle	Mixing with \mathcal{Y}
Dark photon/dark ρ	ρ^0, ω, ϕ and their excitations
V coupled to J_B^μ	ω, ϕ and their excitations
Higgs-like scalar	f_0 and its excitations
ALP/dark π	π^0, η, η' and their excitations
HNL	No mixing

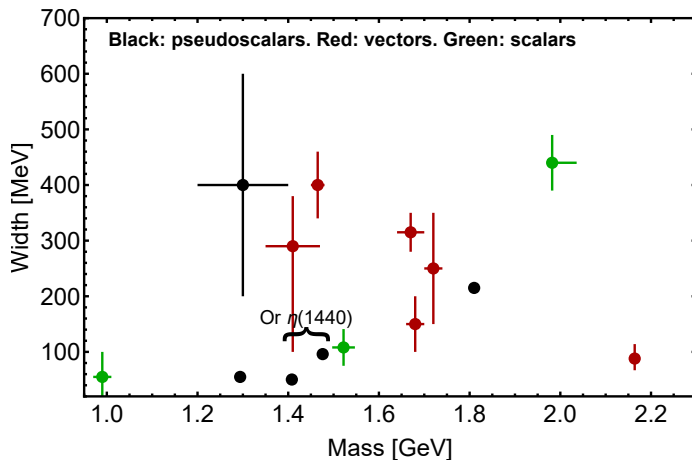
- Most of the “simplest” models introduce mixing
- To understand their interaction, it is necessary to carefully know the meson spectroscopy in the mass range $M \lesssim 2 \text{ GeV}$
- This includes ground states (e.g., ρ^0) and excitations ($\rho^0(1450), \dots$)

[2504.06828]

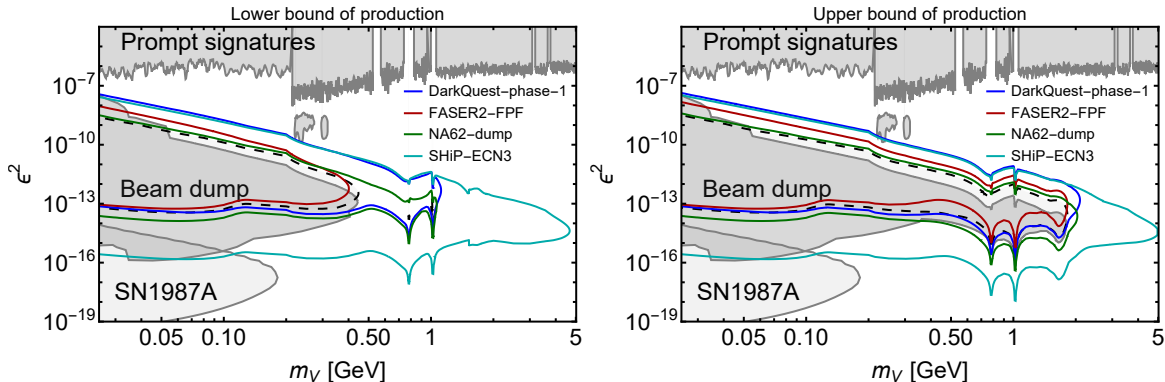
Issue: uncertainties in phenomenology IV

Meson spectroscopy

- Poorly measured masses and widths for some mesons
- Interpretation is ambiguous:
 - One meson or two mesons?
 - 2-quark or 4-quark bound states?
- This is important when embedding them into SU(3) representations



Issue: uncertainties in phenomenology V



Example 1: dark photons

- Uncertainties heavily influence the parameter space of dark photons – both in terms of mass and coupling!

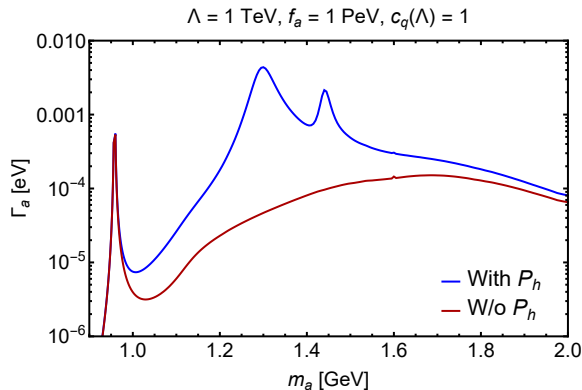
[2409.11096]

Issue: uncertainties in phenomenology VI

Example 2: hadronically coupled ALPs

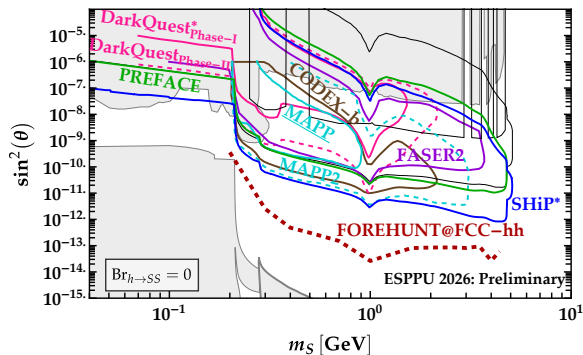
- ALPs mix with π^0, η, η' and excitations $P_h = \pi^0(1300), \eta(1295), \dots$
- To describe the $a - P_h$ -mixing: use ELSM [2407.18348], [1612.09218]
- P_h enhance the ALP decay widths by 1-2 orders of magnitude (depending on the coupling pattern)

- Issue: [1612.09218] dropped various P_h interactions contributing to the mixing
- Their impact on the ALP decays: to be quantified
In progress



[2501.04525]

Exclusion potential: conclusions



- Complementarity between various signatures/experiments in the broad range of masses and couplings
- Upcoming and future searches may explore orders of magnitude in parameter space

What about the discovery potential?

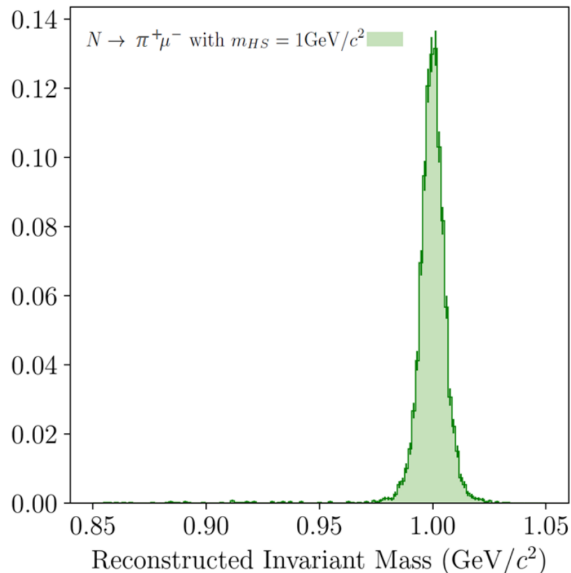
Discovery potential

Reconstructing mass/decays

By observing interactions of LLPs, we may:

- Reconstruct the LLP invariant mass
- Identify decay/scattering modes

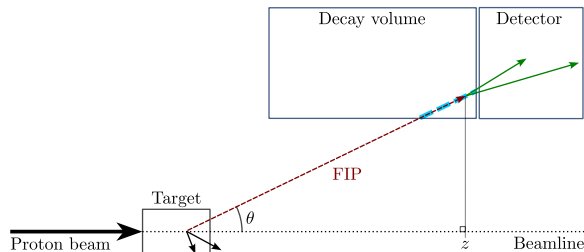
10-1000 events are required, depending on the decay palette (this is why we need large intensity!)



From seeing post-production to identifying the model I

Ambiguity in case of detection

- LLP model identification: seeing LLP production **and** subsequent interaction
- IF experiments: typically, only see post-production interaction
- The typical “exclusion” signature, single vertex, provides little insight about production



[2503.01760]

From seeing post-production to identifying the model II

Ambiguity in case of detection

What we see	What it may be
Dark photon-like decay	Minimal dark photon V Dark photon with hVV coupling Dark ρ meson
ALP-like decay	Minimal ALP ALPs with haa coupling Dark π
Higgs-like particle decay	Minimal scalar S mixing with h Scalars with additional hSS interactions Dark Higgs from DM sector
HNL-like decay	Minimal HNL HNLs with additional $U(1)_Y$ interaction
DM-like scattering	Elastic DM DM with elastic + inelastic couplings

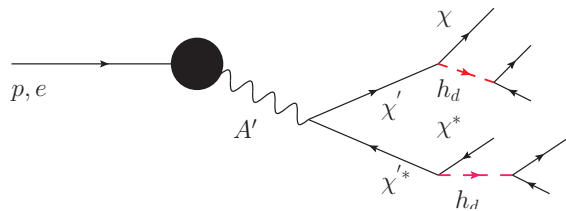
[2503.01760]

From seeing post-production to identifying the model III

Possible solution: going beyond single-vertex signature

≥ 2 decays per event

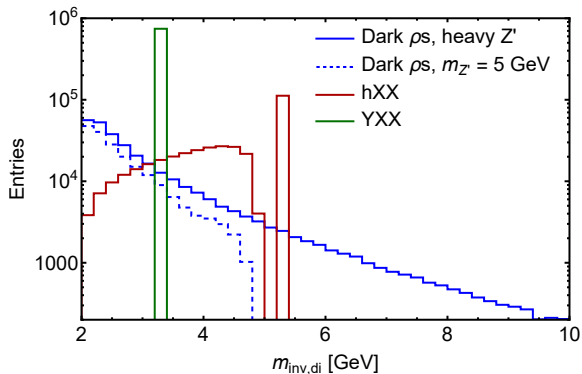
- In many non-minimal models, LLPs may be **produced in pairs**, and may **both decay**
- Seeing such events: rules out the minimal LLP model
- However, ambiguity among different models with pair-decays remains



[2503.01760]

From seeing post-production to identifying the model IV

- Reconstructing decays of the pair \Rightarrow reconstructing their **combined** invariant mass m_{inv}
- Shape of m_{inv} may tell about the LLP pair production without seeing the production
- Allows differentiating between LLPs with different pair-production mechanisms ($\mathcal{O}(100)$ events are needed)

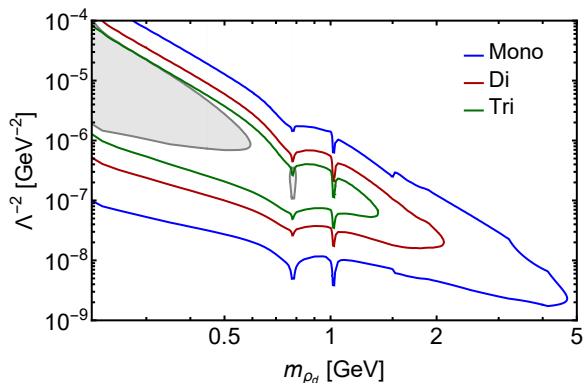


[2503.01760]

From seeing post-production to identifying the model V

Example: dark ρ s

- Compared to dark photons: additional production in showerings
- It may be possible to see events with 1, 2, 3 ρ_d s at SHiP:
 - 1 ρ_d (“mono”): ambiguity with dark photons
 - 2 ρ_d s (“di”): differentiate between ρ_d and dark photon with hVV coupling via m_{inv}
 - 3 ρ_d s (“tri”): smoking-gun signature

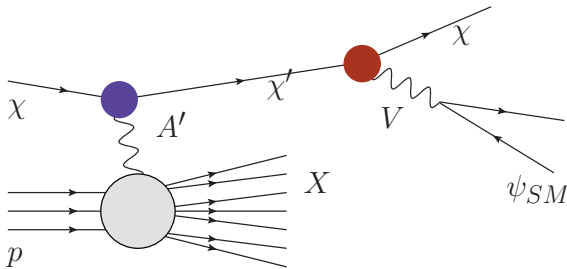
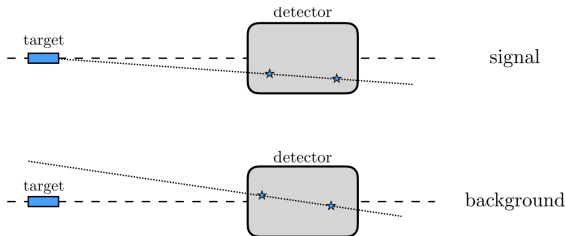


In preparation

From seeing post-production to identifying the model VI

n-scatterings:

- MCPs



Scatterings + decays:

- DM: scatterings $\chi + p/e \rightarrow \chi' + X$ followed by $\chi' \rightarrow \chi + X'$
- Portals: neutrino upscattering + decay

[1707.08573], [1902.03246], [2012.08595], [2312.14868], [2503.01760], [2505.05663],...

From signal to resolution of BSM problems: HNL example I

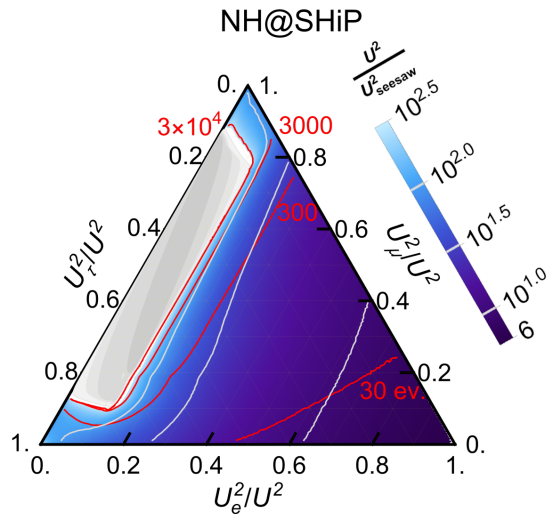
Realistic HNL model as an example (aka ν MSM):

- Two quasi-degenerate HNLs N_1, N_2 with tiny mass splitting Δm
- May simultaneously generate neutrino masses and baryon asymmetry of the Universe
- At accelerator experiments, $N_{1,2}$ typically behave as a quasi-particle N with mass m_N and coupling pattern $U_{e,\mu,\tau}$

Seeing HNL-like decays and reconstructing m_N, U_α , what we may tell?

From signal to resolution of BSM problems: HNL example II

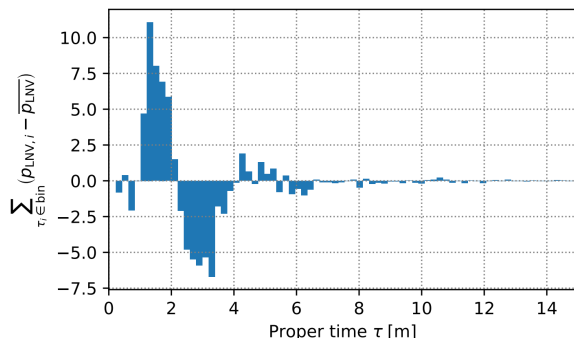
- U_α^2, m_N parametrize neutrino mixing matrix $\theta_{ij}, \delta_{\text{CP}}$
 - Varying $\theta_{ij}, \delta_{\text{CP}}, \Delta m_{ij}^2$ within uncertainty range, obtain the region of possible U_α^2/U^2 for the given ν mass hierarchy
- $$U^2 = \sum_\alpha U_\alpha^2$$
- 100 – 1000 events are required to test the neutrino hierarchy and extract the Majorana phase



[2312.05163]

From signal to resolution of BSM problems: HNL example III

- $N_{1,2}$ oscillate with length
 $l_{\text{osc}} \approx 2\pi\gamma/\Delta m$
- Oscillations violate lepton number
- Resolve oscillations by distinguishing
 LNV and LNC decays \Rightarrow measure Δm
- This information is encoded in the
 angular distribution of the decay
 products (due to helicity conservation)



[1912.05520]

Conclusions

- New physics with mass in the GeV range: underexplored in the past, orders of magnitude exploration in the near future
- Think about future searches not in terms of exclusion but in terms of potential discovery
- Coherent efforts from theoretical and experimental communities will be needed to understand the future results

Backup slides

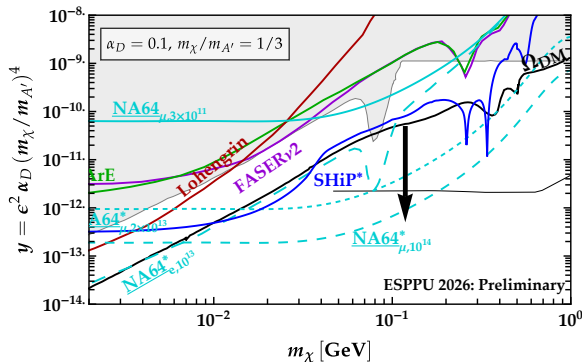
Relic target line

We know a little about

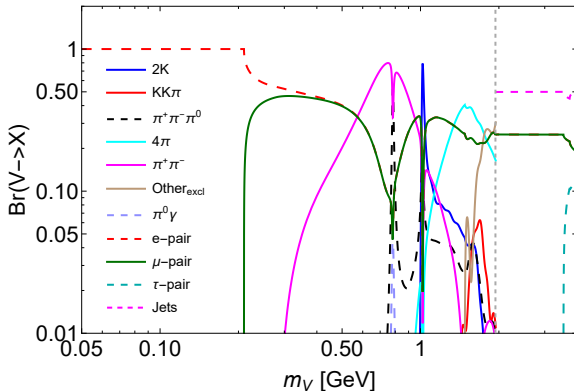
- The Early Universe before neutrino decoupling
- Properties of dark sector – interaction structure, particle content, etc.

DM parameter space may be any

- Entropy dilution, “secret” interactions may heavily affect the abundance
- Do not concentrate on the relic target line



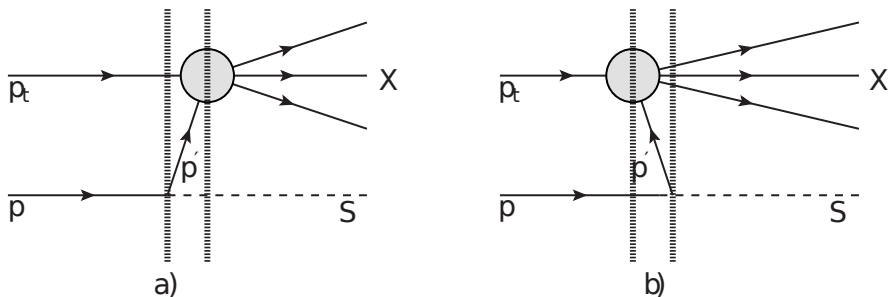
Dark photons: phenomenology I



Dark photons [1801.04847], [2409.09123], [2409.11096]:

- Decays may be extracted from $e^+e^- \rightarrow \mathbf{hadrons}$ the using the VMD+HLS framework

Dark photons: phenomenology II



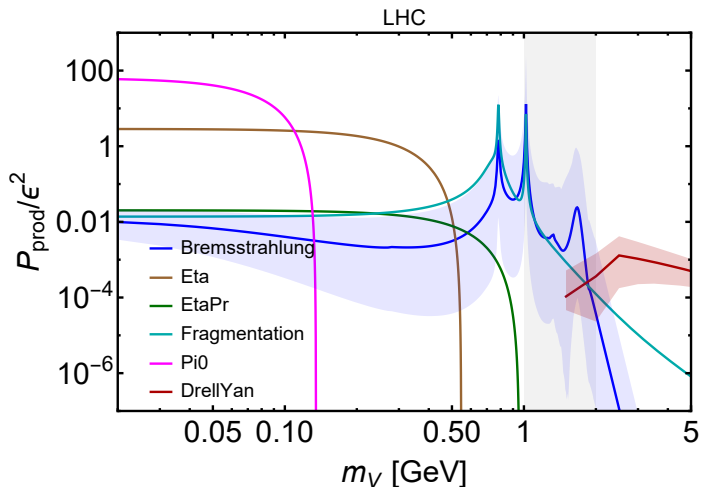
- Production modes: no opportunity to directly use real data. Mixing contributes to proton bremsstrahlung and fragmentation
- Quasi-real approximation: $\sigma_{pp \rightarrow V+X} \approx \int d\Phi P_{p \rightarrow p'V} \times \sigma_{pp \rightarrow X}$ (parametrized by the virtuality of p')
- Proton EM form-factor in the timelike region $F_p^{(1,2)}(q^2 > 0)$: where the mixing enters

Dark photons: phenomenology III

- Unitary analytic model:

$$F_p^{(1,2)}(q) = \sum_i \frac{f_i m_{V_i}^2}{q^2 - m_{V_i}^2 - i\Gamma_{V_i} m_{V_i}}$$

- Varying masses and width of vector mesons V_i heavily changes form-factors and widths – within orders of magnitude
- Results in the plot optimistically fix the widths [2409.09123]



[2504.06828], [2409.11096]

Hadronically coupled ALPs I

$$\mathcal{L}_a = c_G \frac{\alpha_s}{4\pi} \frac{a}{f_a} G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + \frac{\partial_\mu a}{f_a} \sum_q c_q \bar{q} \gamma^\mu \gamma_5 q + \text{flavor-changing} \quad (4)$$

1. Perform the chiral rotation

$$q \rightarrow e^{-i\gamma_5 c_G \kappa_q a / f_a} q, \quad q = u, d, s \quad (5)$$

with $\text{tr}[\kappa_q] = 1$

It converts the gluonic coupling into the second term of Eq. (??)

2. Make a correspondence between the resulting theory and ChPT Lagrangian $\mathcal{L}_{\text{ChPT}+a}[\kappa_q]$ [2012.12272]
3. Supplement the interactions with phenomenological Lagrangians describing interactions with other mesons (ρ , \mathbf{K}_0 , \mathbf{f}_2 , etc.)

Hadronically coupled ALPs II

Unlike dark photons, no data allows direct extraction of ALP decay rates

- Heavy pseudoscalar mesons P_h :

Resonance	$\eta(1295)$	$\pi^0(1300)$	$\eta(1405/1475)^*$	$\pi^0(1800)$
Mass [GeV]	1.294	1.3	1.408/1.476	$1.9 \cdot 10^{-4}$
Width [MeV]	55	200 – 600	50/96	215

*: *may be interpreted as a single $\eta(1440)$*

- Some of P_h s are very narrow and hence cannot be “averaged out”
- Previous studies did not consider the ALP mixing with P_h
[1811.03474], [2110.10691], [2310.03524]

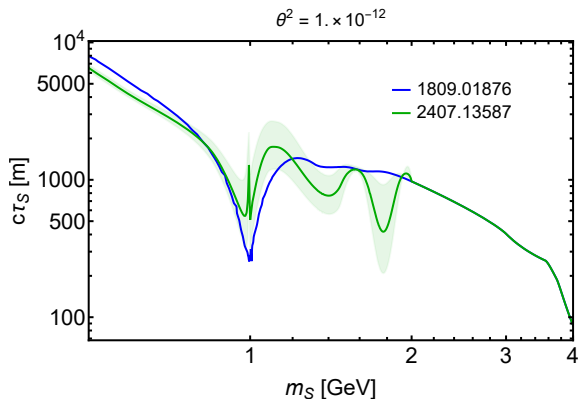
Hadronically coupled ALPs III

- Extended linear sigma model (ELSM) [2407.18348], [1612.09218] – framework of systematic incorporating various mesons
- ELSM adds a heavy pseudoscalar octet and identifies the “flavorless” excitations with $\pi^0(1300)$, $\eta(1295)$, $\eta(1440)$
- ALPs may be added to the ELSM Lagrangian completely similarly to the ChPT case

Incompleteness of ELSM and limited knowledge of properties of heavy excitations [2407.18348]:

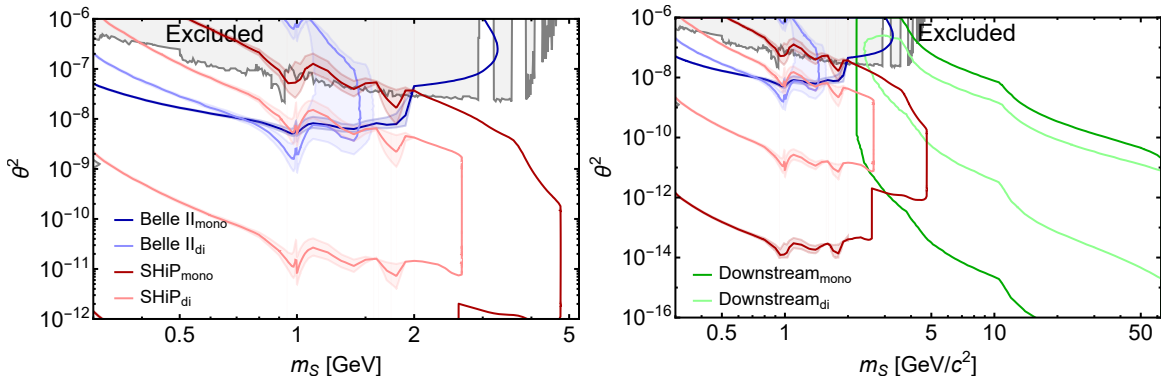
- Ref. [1612.09218] dropped various operators with heavy pseudoscalars that may severely contribute to the c_G terms
 - Including them, however, requires a full re-analysis of the ELSM fit to data
 - A study including these terms: in preparation
- $\pi^0(1300)$ has poorly measured width
- It is not clear whether the $\eta(1295/1440)$ are 2-quark bound states or also include 4-quark admixtures

Higgs-like scalars: decays and their uncertainties



- Decays: no data to extract directly, but the scattering data $\pi\pi \rightarrow \pi\pi$, $\pi\pi \rightarrow \mathbf{K}\mathbf{K}$ may be used to calculate the width using dispersion relation methods
- Issues: systematic uncertainties in the scattering phase shift significantly affect the calculations + only the simplest decay modes ($\mathbf{S} \rightarrow \pi\pi, \mathbf{K}\mathbf{K}$) can be studied this way

Di-decays: Higgs-like scalar I



- Higgs-like scalars S with tri-linear coupling to h at various experiments
- $\text{Br}(h \rightarrow SS)$ is set to the maximally possible $\text{Br}(h \rightarrow SS) = 1\%$, to marginalize over the values of the tri-linear hSS coupling

A closer look on HNLs

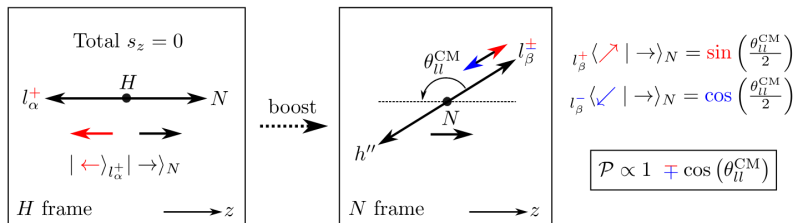
- Two observable ν mass differences \Rightarrow at least two different HNLs $N_{1,2}$ are required.
- HNL mass difference $\Delta m \equiv m_{N_1} - m_{N_2}$ may be arbitrary
- Small $\Delta m \ll m_{N_{1,2}} \approx m_N$ and similar U^2 : $N_{1,2}$ form quasi-particle
- However, there are $N_1 \leftrightarrow N_2$ oscillations with frequency $\omega_{\text{osc}} = \Delta m$
- Small Δm leads to a resonant enhancement of the lepton-violating processes in the Early Universe \Rightarrow HNL-driven BAU becomes possible
- Depending on the mixing pattern $U_e^2 : U_\mu^2 : U_\tau^2$, may also provide masses to active neutrinos [0605047]

A closer look on HNLs

- N_1 effectively behaves as a particle and N_2 as an anti-particle, so oscillations lead to the lepton number violating (LNV) processes
- Three different types of behavior of $N_1 - N_2$ system depending on the scale L of the experiment ($l_{\text{osc}} = 2\pi/\omega_{\text{osc}}c$):
 - $l_{\text{osc}} \ll L$: $N_1 - N_2$ behaves as a single Majorana particle
 - $l_{\text{osc}} \gg L$: $N_1 - N_2$ behaves as a single Dirac particle
 - $l_{\text{osc}} \simeq L$: oscillations may be resolved within the experiment

Resolving HNL oscillations – insights on their relation to BAU

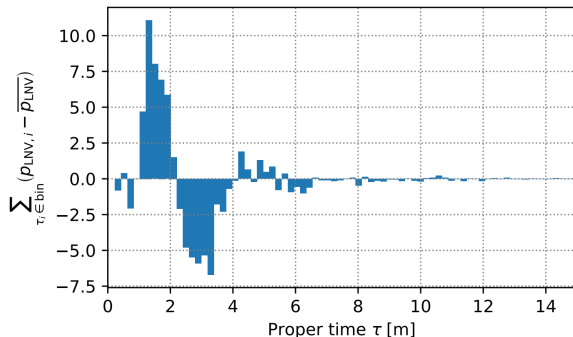
A closer look on HNL discovery III



- Resolving oscillations requires distinguishing LNV and LNC (lepton number conserving) decays
- It would be easily done if one could get access to the production vertex *via, e.g., the leptons sign correlation in the chain $B^\pm \rightarrow l^\pm + N, N \rightarrow l^\pm + \pi^\mp$*
- This is impossible at SHiP. However, the information about the primary vertex is conserved by HNL helicity, which is related to the lepton number
- Helicity, in turn, affects the angular distribution of HNL decay products

A closer look on HNL discovery IV

- So the analysis requires reconstructing the ratio of LNC/LNV events as a function of the decay length
- Given the complexity of HNL production modes, simple analytic arguments are not enough to distinguish the LNC and LNV events
- Multivariate analysis based on boosted decision trees has been performed in [1912.05520](#)



For $l_{\text{osc}} \simeq L$, $\mathcal{O}(1000)$ events are required to extract Δm