Overview of FIP searches at fixed-target experiments

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Light dark world 2025

September 17, 2025

Topics of the talk

1. **Fixed-target (FT) experiments: what are they and what FIPs do they search for**

2. **Exclusion power of FT experiments**

3. **Theoretical uncertainties in the FIP phenomenology**

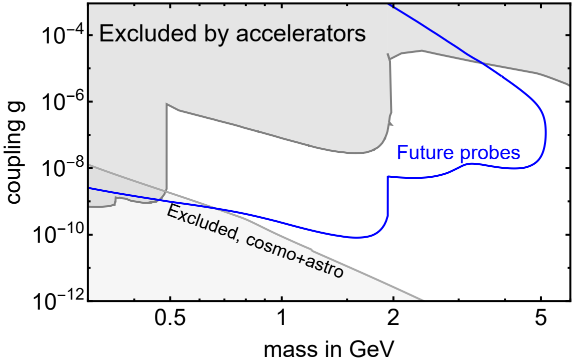
4. **Discovery power: potential and caveats**

1. FT experiments: what are they and what do they search for

Introduction I

FIPs with mass 1 MeV $\lesssim m \ll \Lambda_{\mathrm{EW}}$

- Variety of well-defined models
- Involved in many BSM scenarios
- Target parameter space: between cosmo/astro* and past lab experiments



* *Up to our ignorance of the cosmological setup*

Introduction II

Minimal, lowest-dimension, gauge-invariant interactions

Adds one FIP

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	$c_G\frac{\alpha_s}{4\pi}aG^{\mu\nu}\tilde{G}_{\mu\nu} + \dots$	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
...	...	...

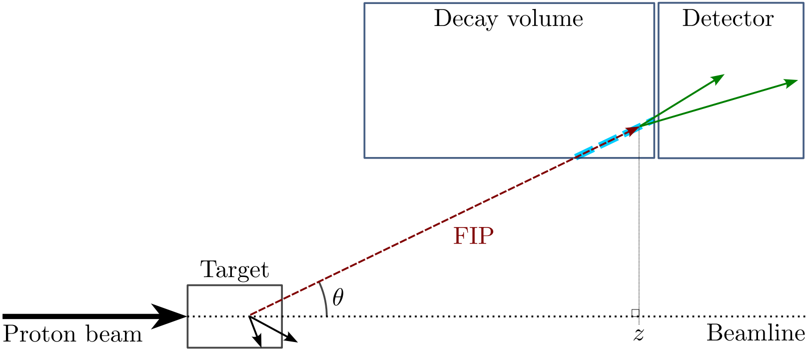
Introduction III

Non-minimal yet "compact" models

>1 FIPs, and/or additional quadratic coupling

Model	(Effective) Lagrangian	What it looks like
FIPs X with quadratic hXX coupling	$\mathcal{L} = \mathcal{L}_{\text{min}} + \alpha hXX$	Minimal FIP 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 DM 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
...	...	...

Beam dump experiments I



Fixed-target experiments – perfect setups to search for FIPs

- Large intensity+background suppression
- Forward placement $\Rightarrow \lesssim \mathcal{O}(1)$ geometric acceptance
- Not too small (good for small $c\tau$), not too large γ_{FIP} (good for large $c\tau_{\text{FIP}}$)

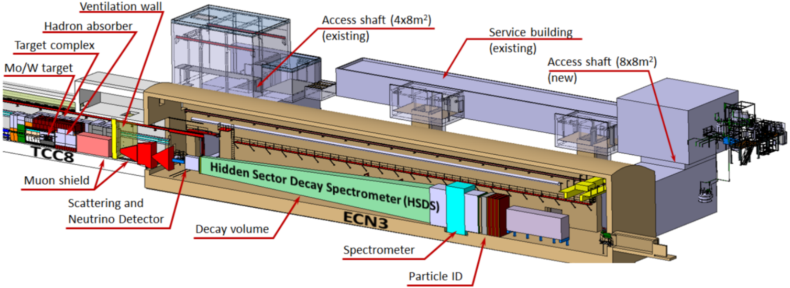
Beam dump experiments II

Classification

1. **Signature:**
   - Scatterings (ICARUS, DUNE, ProtoDUNE, SHiP, ...)
   - Decays (above + NA62, DarkQuest, ...)
   - Missing energy (NA64, NA62, ...)
2. **Beam type:**
   - Electron/photon (NA64, LUXE, ILC-BD)
   - Muon (NA64-μ)
   - Proton (NA62, ...)
3. **Location:**
   - SPS (NA64, NA62, ProtoDUNE, SHiP,...)
   - Fermilab (ICARUS, DUNE, DarkQuest)
   - DESY (LUXE)
   - LHC (SHIFT)
   - JAEA (J-PARC)
4. **Status:**
   - **Currently running** (NA62, NA64,...)
   - **Approved/to be run*** (LUXE, SHiP, DarkQuest)
   - Proposals (SHIFT, ILC-BD, NA64-μ)

See Fixed-target panel + talks by Sara, Josu, Jan, ...

Beam dump experiments III



SHiP

- Beam dump experiment@SPS, operating time starts in 2033 (for 15 years)
- Bg-free searches for decays
- $\boldsymbol{N_{\mathbf{PoT}} = 6 \cdot 10^{20}}$ $(\boldsymbol{10^3 \times \sigma_{pp} \cdot \mathcal{L}_{\mathbf{HL\text{-}LHC}}})$
- $\boldsymbol{N_{b\bar{b}} \sim 10^{14}}$ (comparable to LHCb@HL-LHC)

Potential of FT experiments

Exclusion potential

- Fix a particular FIP model
- How much parameter space may be excluded by future searches if not seeing a signal?
  Framework: [2305.13383]
- Important for selling your experiment

VS

Discovery potential

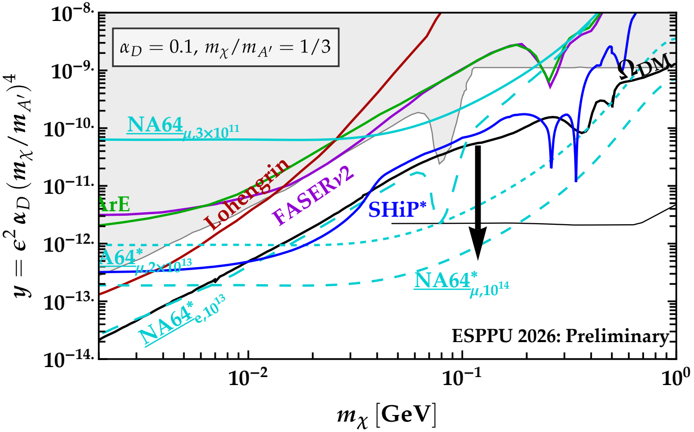
- Assume some events have been observed
- Can we identify the underlying FIP model?
- Can we establish whether it is related to the BSM problems?
- Important for established experiments

1. Exclusion potential

Exclusion potential (**more: ESPP process**) I

Quasi-elastic DM

- Efficiently explored with scattering/missing energy signature
- Thermal relic line: may be practically anywhere, subject to cosmic setup



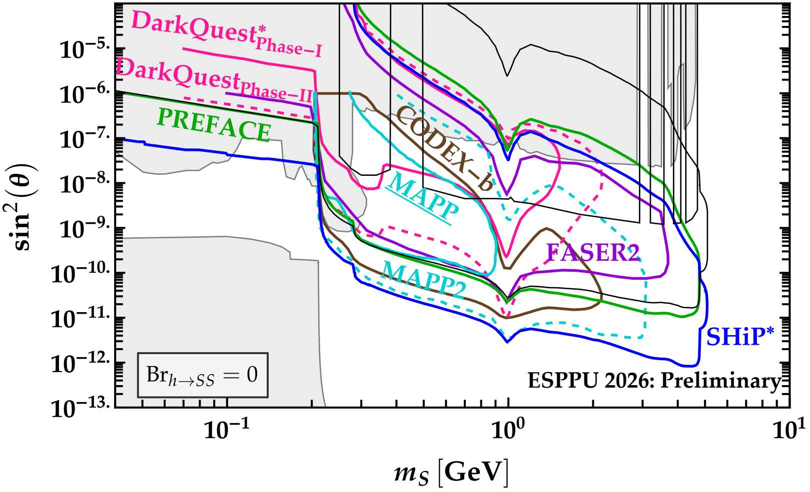
Meaning of the legend. **exp**: proposal. **<u>exp</u>**: currently running. **exp***: approved/in construction. **<u>exp</u>***: currently running, but the luminosity is to be approved

Exclusion potential (**more: ESPP process**) II

Higgs-like scalar

Minimal model (case **Br($h \to SS$) = 0**)

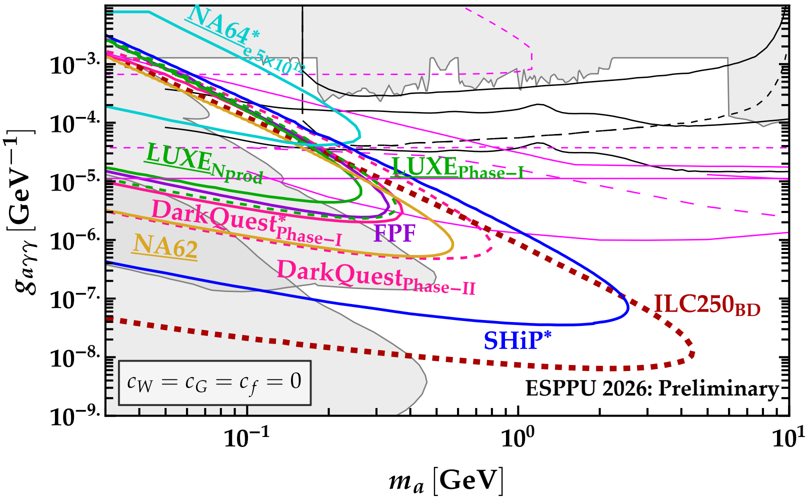
- Scalars may be copiously produced via FCNC currents [1904.10447]
- Most efficiently probed at B factories



Exclusion potential (**more: ESPP process**) III

ALP (γ dominance)

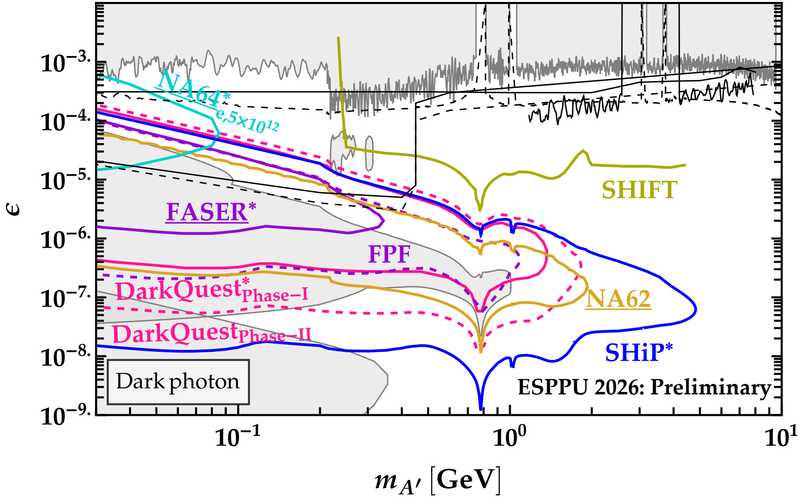
- ALPs are efficiently produced in the Primakov process [1904.02091]
- Very efficient at FT experiments



Exclusion potential (**more: ESPP process**) IV

Dark photons

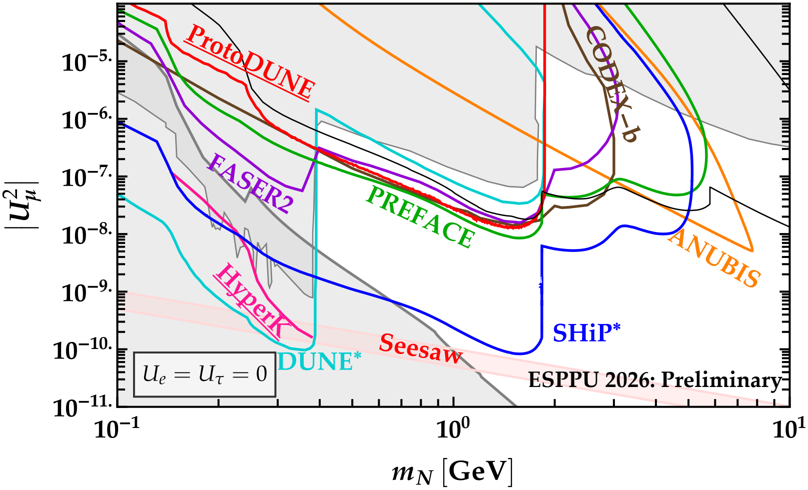
- Dark photons are produced in the forward direction in EM-like processes [2409.11096], [2504.06828]
- Such processes are efficient at fixed-target experiments



Exclusion potential (**more: ESPP process**) V

HNL

- HNLs are produced like massive neutrinos [1805.08567]
- Sensitivity comes from $\boldsymbol{K, D, B}$ factories



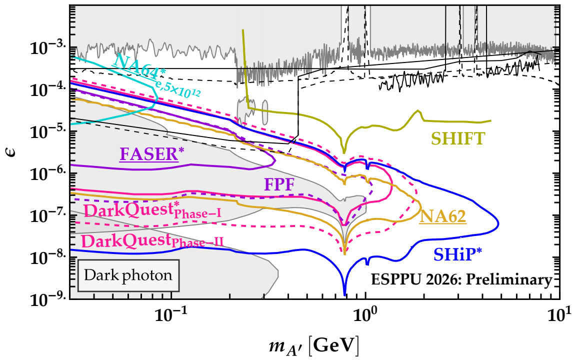
2. Uncertainties in phenomenology

Issue: uncertainties in phenomenology I

Hidden assumption made above:

We exactly know the FIP phenomenology (how they are produced and decay)

- In reality, this is not true for hadronically coupled GeV-mass FIPs
- Their hadronic interactions cannot be described by either pQCD or ChPT



Issue: uncertainties in phenomenology II

Main challenge – mixing with mesons

- Interaction Lagrangian of a FIP X:

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

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

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

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

$$\psi_{\mathcal{Y}} \to \theta_{\mathcal{Y}X}\psi_X, \quad \theta_{\mathcal{Y}X} = \frac{c_1}{m_X^2 - m_{\mathcal{Y}}^2 - i m_{\mathcal{Y}}\Gamma_{\mathcal{Y}}} + \dots \tag{3}$$

[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

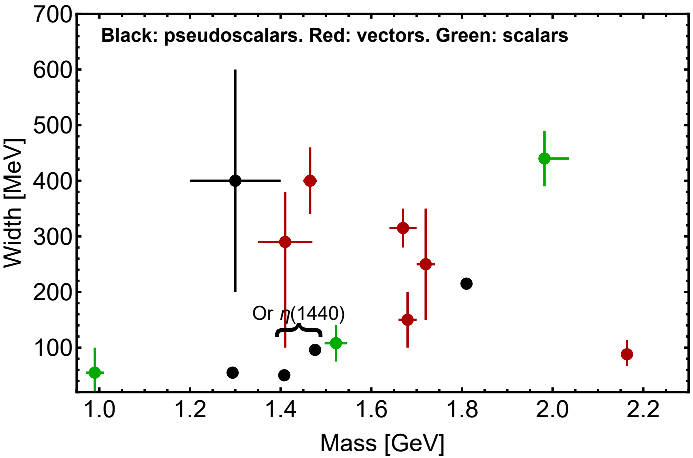
- Most of the "simplest" FIP models introduce mixing
- To understand their interaction, it is necessary to carefully know the meson spectroscopy in the mass range $M \lesssim 2$ GeV
- This includes ground states (e.g., ρ^0) and excitations ($\rho^0(1450), \dots$)

[2504.06828]

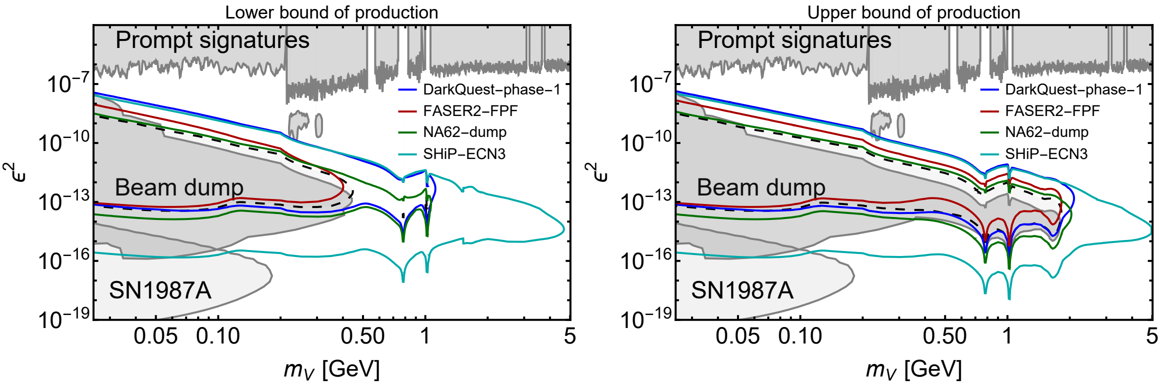
Issue: uncertainties in phenomenology IV

Meson spectroscopy [pdg]

- 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

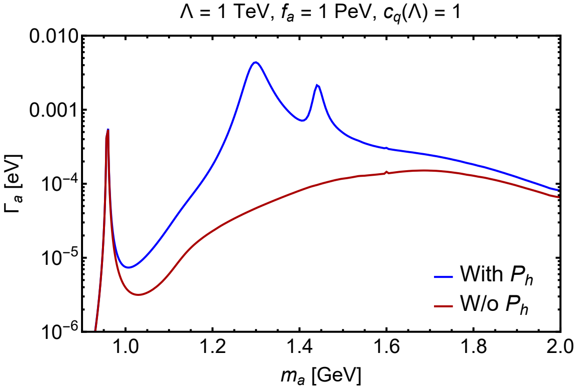
- Uncertainties are mainly in production, and heavily influence the parameter space of dark photons – both in terms of mass and coupling!
- Affect any experiment, vector mediators $\boldsymbol{V}$ coupled to hadrons, and also DM coupled to $\boldsymbol{V}$!

[2409.11096]

Issue: uncertainties in phenomenology VI

Example 2: hadronically coupled ALPs

- ALPs mix with π^0, η, η' and excitations $P_h = \pi^0(1300), \eta(1295), \ldots$
- 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)

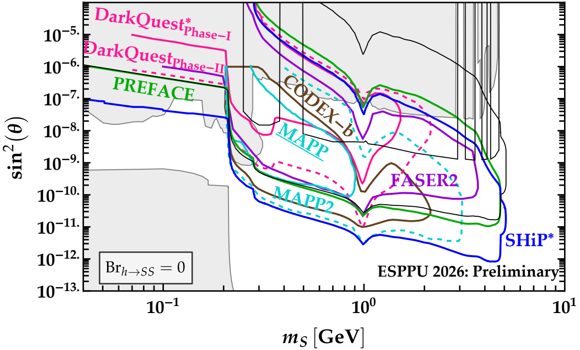


- Issue: [1612.09218] dropped various P_h interactions contributing to the mixing
- Their impact on the ALP decays: to be quantified

  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

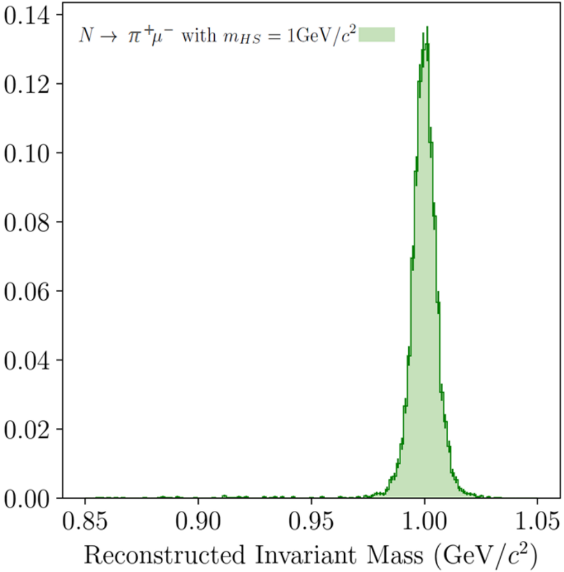
We observed events. What's next?

Reconstructing mass/decays

By observing interactions of FIPs, we may:

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

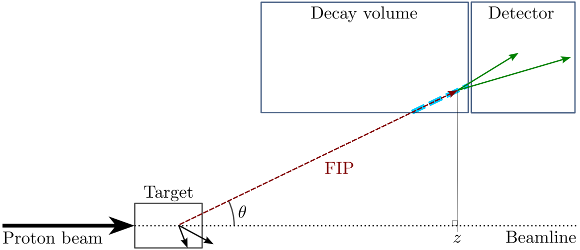
10-1000 events are required, depending on the decay palette (this is why we need large intensity!)



From seeing post-production to identifying the model I

Ambiguity in case of detection

- FIP model identification: seeing FIP production **and** subsequent interaction
- FT 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

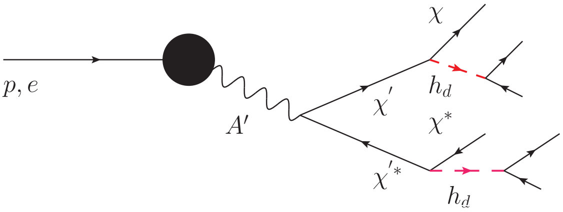
[2503.01760]

From seeing post-production to identifying the model III

Possible solution: going beyond single-vertex signature

$\geq$ 2 decays per event

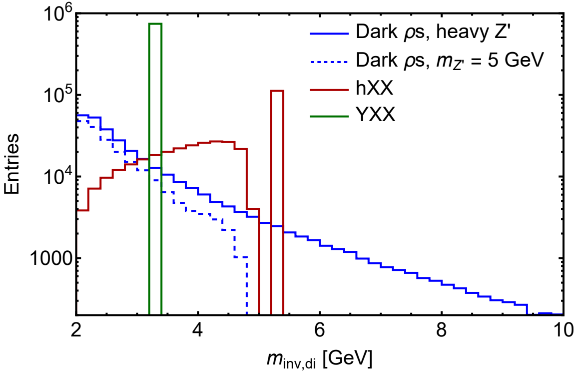
- In many non-minimal models, FIPs may be **produced in pairs**, and may **both decay**
- Seeing such events: rules out the minimal FIP model
- However, ambiguity among different models with pair-decays remains



[2503.01760]

From seeing post-production to identifying the model IV

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



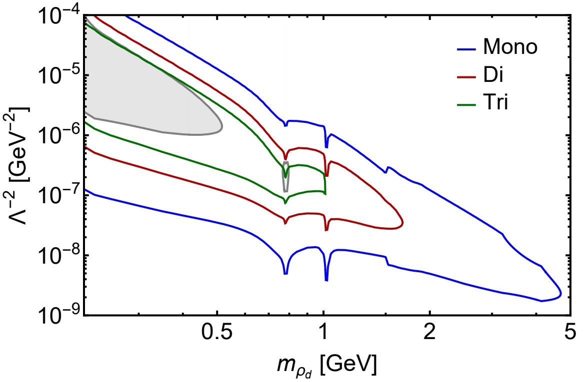
[2503.01760]

From seeing post-production to identifying the model V

Example: dark ρs

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

Sensitivity to Higgs-like scalars: see [2503.01760]

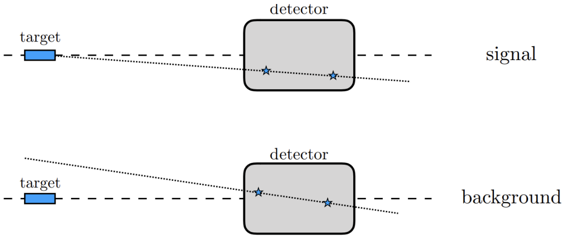


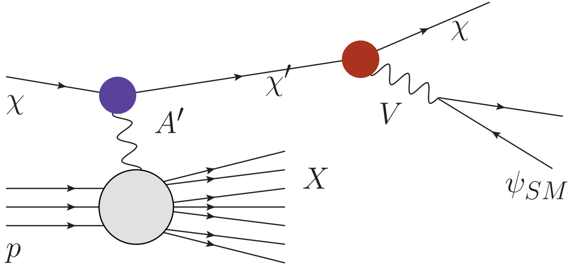
In preparation

From seeing post-production to identifying the model VI

n-scatterings:

- MCPs





Scatterings + decays:

- DM: scatterings $\boldsymbol{\chi + p/e \to \chi' + X}$ followed by $\boldsymbol{\chi' \to \chi + \mathrm{X}}$'
- 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

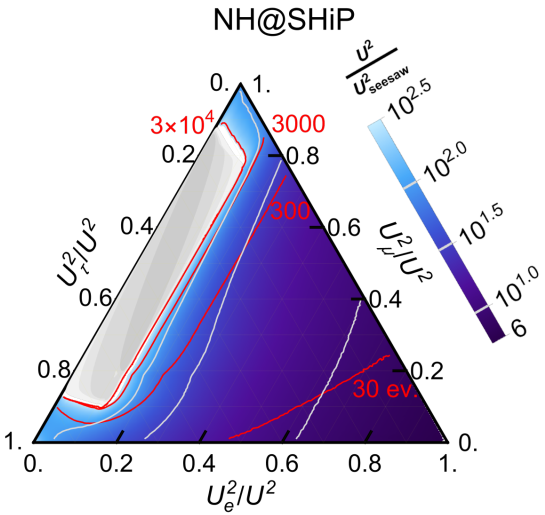
Realistic HNL model as an example (aka νMSM):

- 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

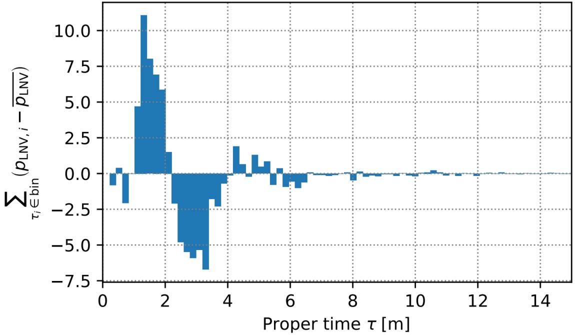
- U_α^2, m_N parametrize neutrino mixing matrix θ_{ij}, δ_{CP}
- Varying θ_{ij}, δ_{CP}, Δm_{ij}^2 within uncertainty range, obtain the region of possible U_α^2/U^2 for the given ν mass hierarchy
  $U^2 = \sum_\alpha U_\alpha^2$
- $100 - 1000$ events are required to test the neutrino hierarchy and extract 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 with fixed-target experiments
- 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

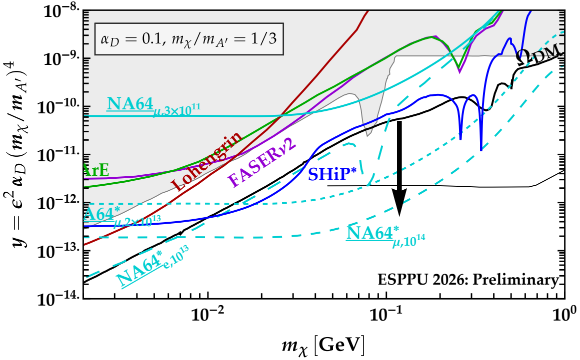
Relic target line

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

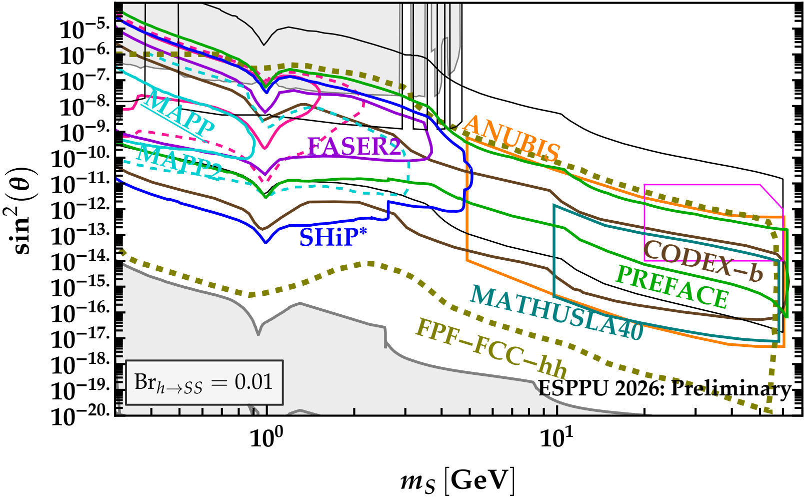


Beam dump experiments vs collider searches I

Higgs-like scalar

Case $\mathbf{Br}(\boldsymbol{h} \to \boldsymbol{SS}) = 1\%$

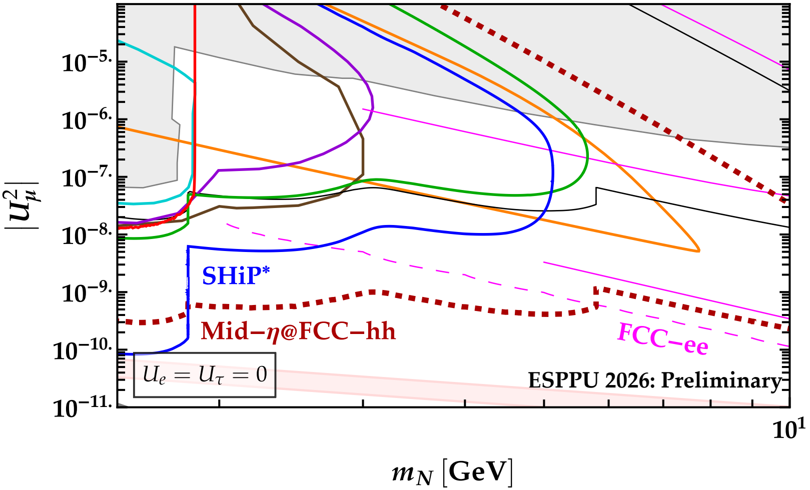
– Most efficiently probed at $\boldsymbol{h}$ and $\boldsymbol{B}$ factories



Beam dump experiments vs collider searches II

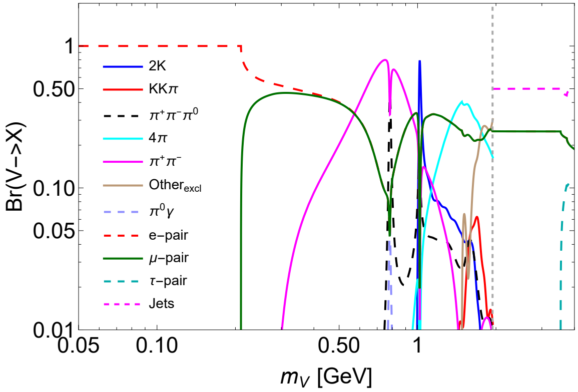
HNL

- 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 $m_D < m_N < m_B$

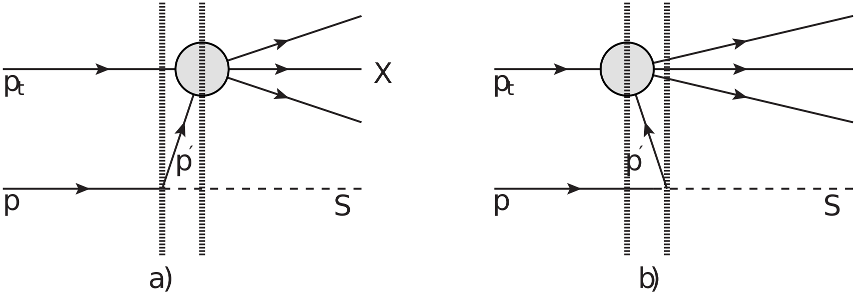
Dark photons: phenomenology I



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

– Decays may be extracted from $e^+e^- \to$ **hadrons** the using the VMD+HLS framework

Dark photons: phenomenology II



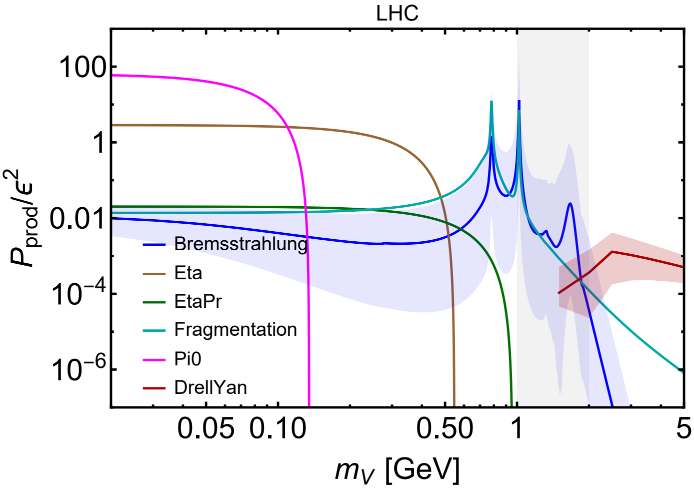
- Production modes: no opportunity to directly use real data. Mixing contributes to proton bremsstrahlung and fragmentation
- Quasi-real approximation: $\sigma_{pp\to V+X} \approx \int d\Phi P_{p\to p'V} \times \sigma_{pp\to X}$ (parametrized by the virtuality of p')
- Proton EM form-factor in the timelike 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

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

1. Perform the chiral rotation

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

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

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

2. Make a correspondence between the resulting theory and ChPT Lagrangian $\mathcal{L}_{\mathrm{ChPT+a}}[\kappa_q]$ [2012.12272]
3. Supplement the interactions with phenomenological Lagrangians describing interactions with other mesons (ρ, K_0, f_2, etc.)

Hadronically coupled ALPs II

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

– Heavy pseudoscalar mesons $\boldsymbol{P_h}$:

Resonance	$\boldsymbol{\eta(1295)}$	$\boldsymbol{\pi^0(1300)}$	$\boldsymbol{\eta(1405/1475)^*}$	$\boldsymbol{\pi^0(1800)}$
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* $\boldsymbol{\eta(1440)}$

– Some of $\boldsymbol{P_h}$s are very narrow and hence cannot be “averaged out”

– Previous studies did not consider the ALP mixing with $\boldsymbol{P_h}$ *[1811.03474]*, *[2110.10691]*, *[2310.03524]*

Hadronically coupled ALPs III

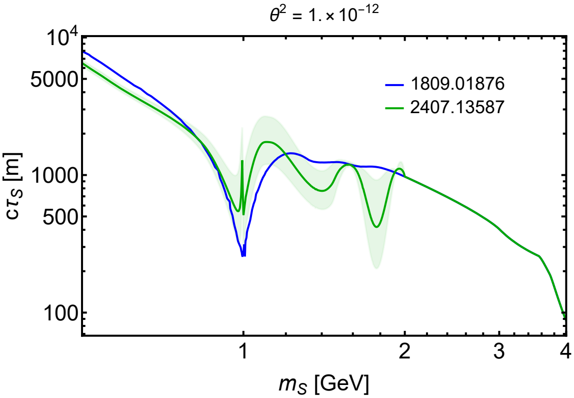
- Extended linear sigma model (ELSM) [2407.18348], [1612.09218] – framework of systematic incorporating various mesons
- ELSM adds a heavy pseudoscalar octet and identifies the “flavorless” excitations with $\boldsymbol{\pi^0(1300), \eta(1295), \eta(1440)}$
- ALPs may be added to the ELSM Lagrangian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

Hadronically coupled ALPs IV

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

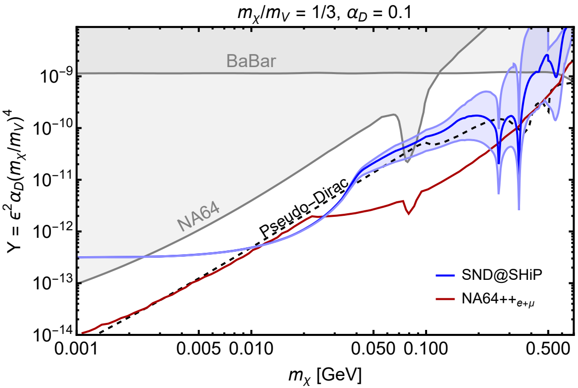


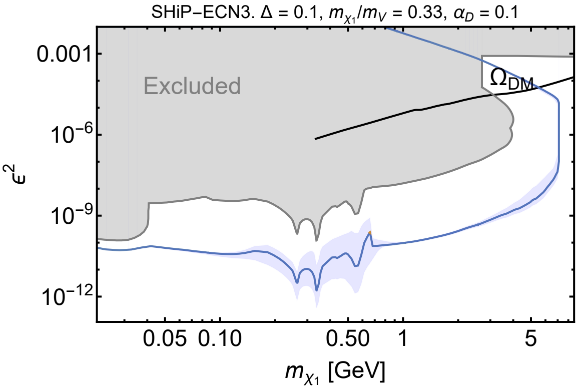
- Decays: no data to extract directly, but the scattering data $\pi\pi \to \pi\pi$, $\pi\pi \to KK$ may be used to calculate the width using dispersion relation methods
- Issues: systematic uncertainties in the scattering phase shift significantly affect the calculations + only the simplest decay modes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

Impact of uncertainties in dark photon phenomenology on sensitivity to DM I

- In a typical DM model to be probed at fixed-target experiments, the main production mode is the decay of the mediator
- Hence, any uncertainty in mediator's phenomenology propagates to the DM phenomenology!

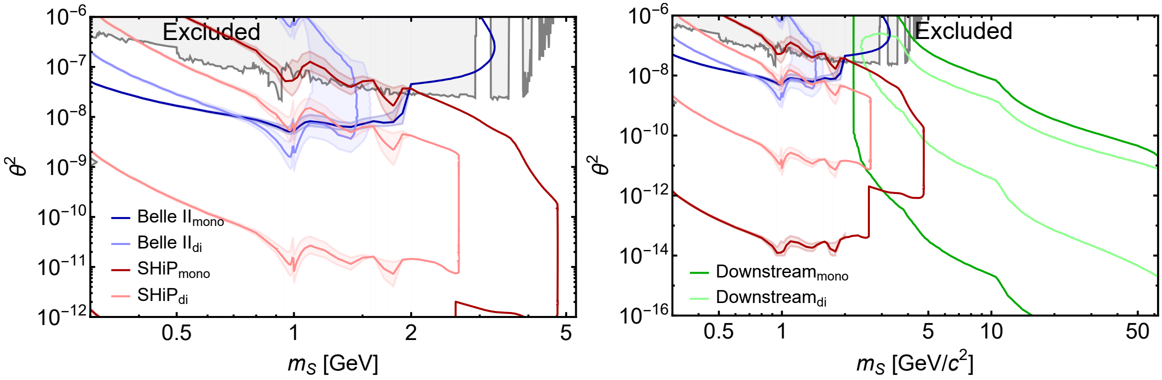
Impact of uncertainties in dark photon phenomenology on sensitivity to DM II





- Examples: quasi-elastic and inelastic DM models coupled to dark photons at SHiP

Di-decays: Higgs-like scalar I



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

A closer look on HNL discovery I

A closer look on HNLs

- Two observable $\boldsymbol{\nu}$ mass differences $\Rightarrow$ at least two different HNLs $\boldsymbol{N_{1,2}}$ are required.
- HNL mass difference $\boldsymbol{\Delta m \equiv m_{N_1} - m_{N_2}}$ may be arbitrary
- Small $\boldsymbol{\Delta m \ll m_{N_{1,2}} \approx m_N}$ and similar $\boldsymbol{U^2}$: $\boldsymbol{N_{1,2}}$ form quasi-particle
- However, there are $\boldsymbol{N_1 \leftrightarrow N_2}$ oscillations with frequency $\boldsymbol{\omega_{\text{osc}} = \Delta m}$
- Small $\boldsymbol{\Delta m}$ 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 $\boldsymbol{U_e^2 : U_\mu^2 : U_\tau^2}$, may also provide masses to active neutrinos [0605047]

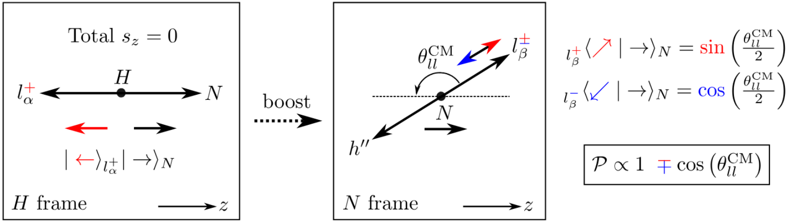
A closer look on HNL discovery II

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

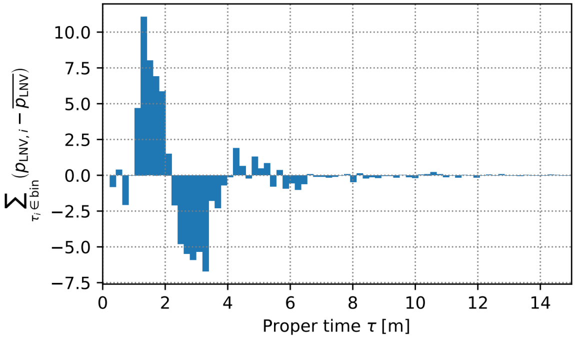
A closer look on HNL discovery III



- 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* $B^\pm \to l^\pm + N$, $N \to l^\pm + \pi^\mp$
- 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