Feebly-interacting particles at the SHiP experiment

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CPPS seminar

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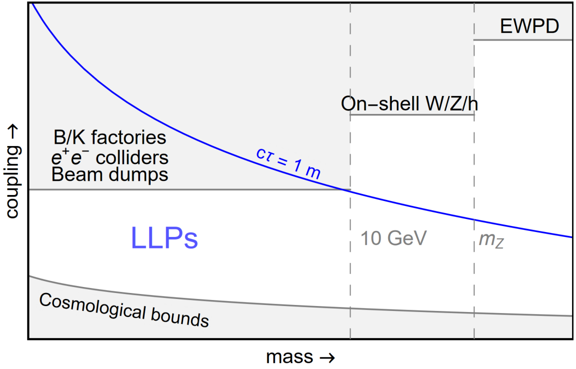
Outline

Topic of the seminar:

- FIPs/LLPs: brief introduction
- Searches for LLPs at SHiP
- Challenges and complexities in LLP phenomenology

Introduction

- LLPs: particles with lifetimes τ large enough to escape prompt collider searches
- In terms of mass m and coupling g, $\tau = m^{-\alpha} g^{-2}$, and $\alpha > 0$
- GeV mass LLPs: **cosmological** and **laboratory** probes work in synergy



LLPs: examples I

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	$c_1 H^\dagger H S^2 + c_2 H^\dagger H S$	A light Higgs boson with interaction suppressed by $\theta \sim \frac{c_2 v_h}{m_h} \ll 1$
Vector mediator V	$-\frac{\epsilon}{2} B_{\mu\nu} V^{\mu\nu} + g V^\mu J_{\mu,B}$	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 $\frac{f_\pi}{f_a} \ll 1$
...	...	...

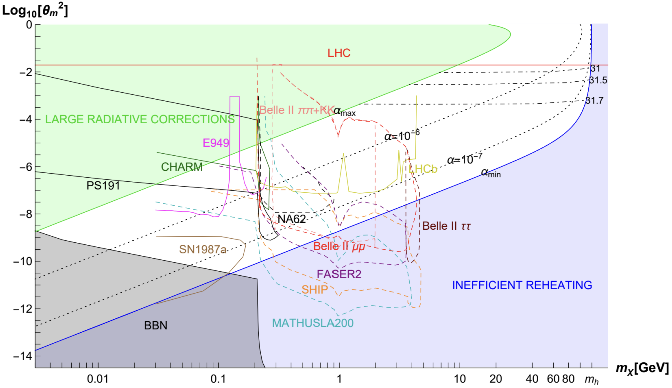
LLPs: examples II

Model	*(Effective) Lagrangian*	*What it looks like*
MCPs χ	$\kappa e\bar{\psi}\gamma^{\mu}\psi A_{\mu}$	Millicharged particle
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
...	...	...

LLPs and BSM problems I

GeV-mass LLPs may be involved in the resolution of various BSM problems

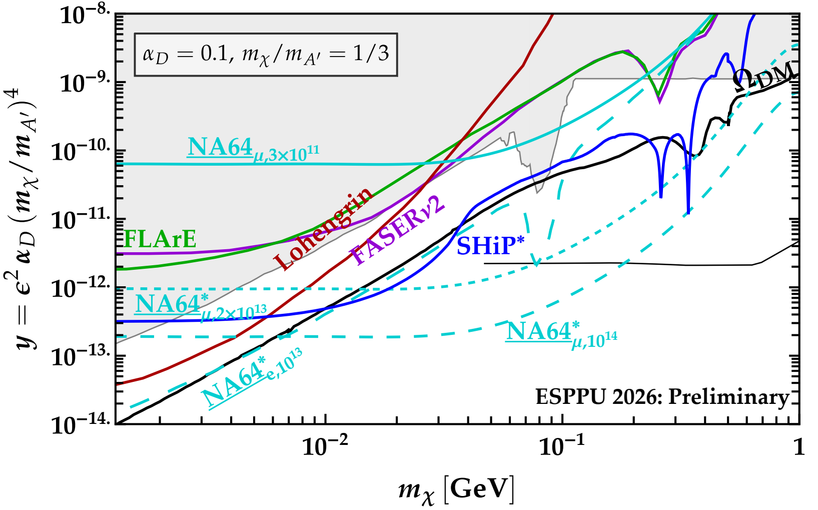
– Higgs-like scalar: light inflaton [0912.0390] [1910.09663]



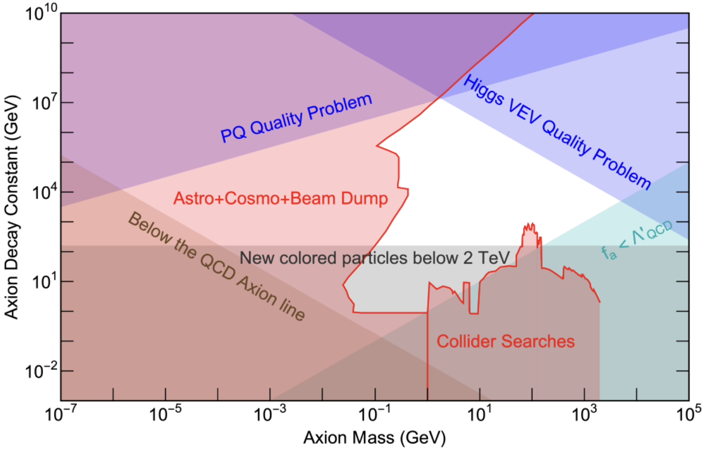
(a) $\beta = 10^{-9}$

LLPs and BSM problems II

- ALPs, Higgs-like scalars, dark photons as mediators: dark matter [1810.01879], [1901.09966]

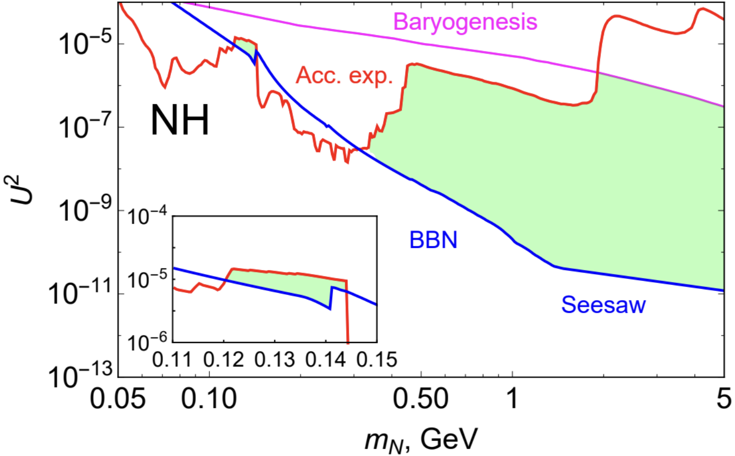


LLPs and BSM problems III



– ALPs: strong CP problem [1911.12364] (aka high-quality axion)

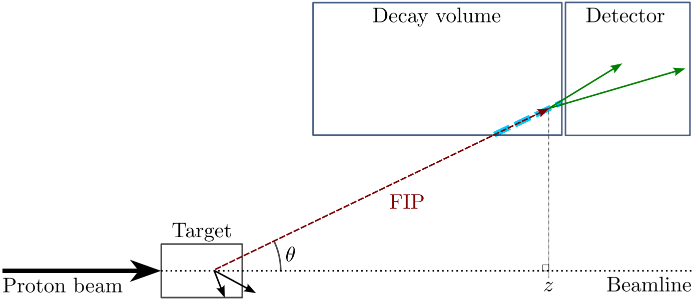
LLPs and BSM problems IV



– HNLs: neutrino masses, baryon asymmetry of the Universe [0503065], [2101.09255]

Intensity frontier experiments I

– Detectors outside the main collider experiments to minimize backgrounds

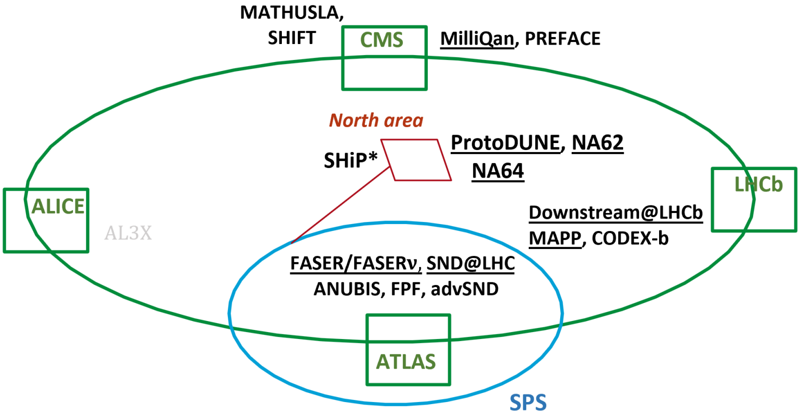


Classification

1. **Collision type:**
   - Collider-based (e.g., *FASER*)
   - Beam dump (e.g., *ProtoDUNE*)
2. **Signature:**
   - Scatterings (SND@LHC,. . .)
   - Decays (CODEX-b)
   - Missing energy (NA64,. . .)

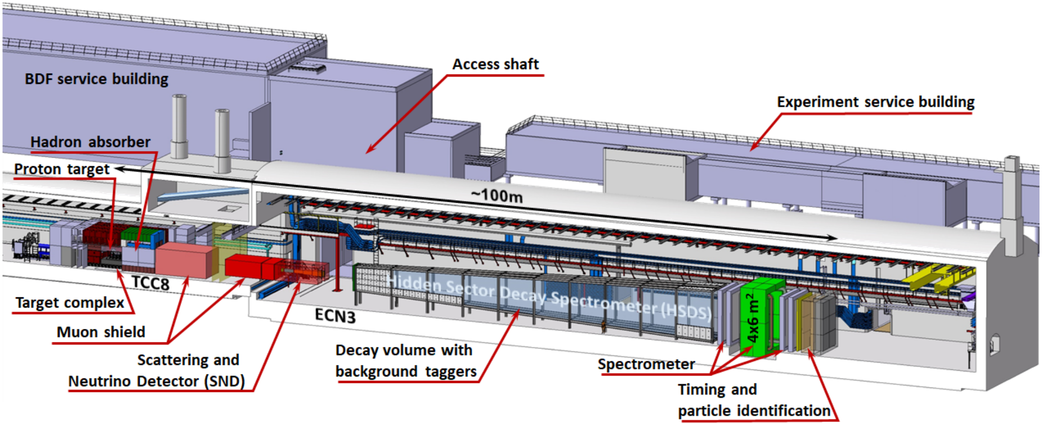
Intensity frontier experiments II

3. **Beam type:**
   - $\boldsymbol{l = e, \mu}$ (NA64,LUXE,...)
   - $\boldsymbol{h = p, Pb}, \ldots$ (NA62,...)
4. **Location:**
   - CERN (MAPP,...)
   - Fermilab (DUNE,...)
   - DESY (LUXE)
   - ...



5. **Timeline:**
   - Associated with **existing** colliders/facilities ($<$ **20** years) (SHiP, ...)
   - Associated with **future** colliders/facilities (@FCC-hh, ILC-BD,...)

SHiP I



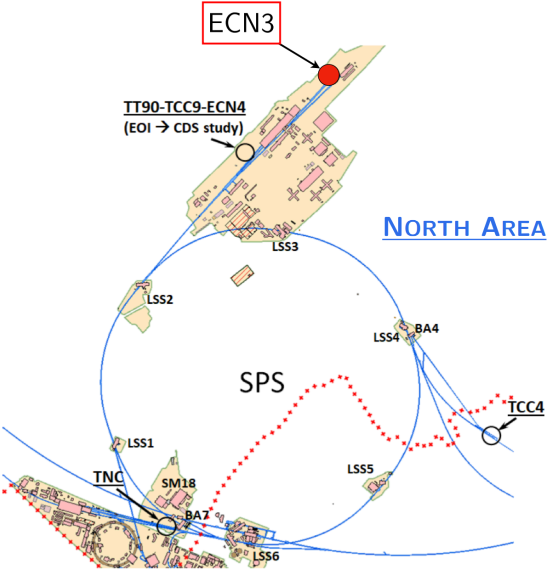
SHiP: beam dump experiment to explore GeV-mass LLPs

SHiP II

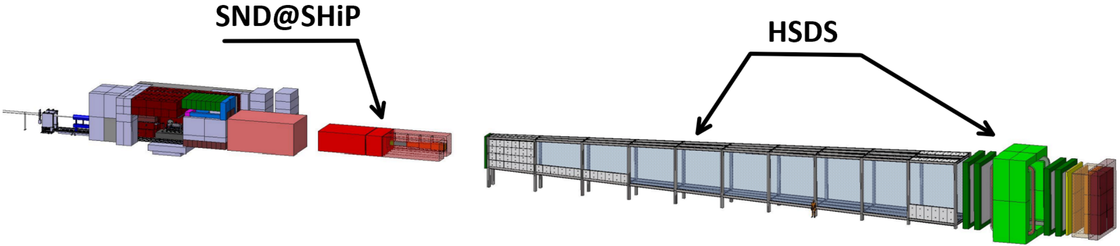
- **Location: CERN SPS**. Proton beam $\boldsymbol{E_p = 400}$ **GeV**
  - North Area →
  - TCC8 target hall →
  - ECN3 cavern
- $\boldsymbol{N_{\text{PoT}}} \simeq 4 \times 10^{19}$/year, 15-year running time

Enormous yields of heavy flavor production

- $\boldsymbol{N_{c\bar{c}} \sim 10^{18}}$: ~ 2 orders of magnitude larger than at HL-LHC
- $\boldsymbol{N_{b\bar{b}} \sim 10^{14}}$: comparable to LHCb@HL-LHC



SHiP III



- **SND@SHiP**: neutrinos and scattering detectors
- **HSDS**: hidden sector decay spectrometer

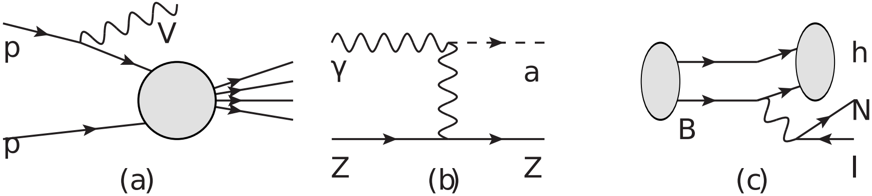
LLP phenomenology at SHiP

Challenges I

Opportunities and challenges

- SHiP may produce enormous amounts of LLPs with mass $m \lesssim 10\,\text{GeV}$
- But their phenomenology is quite complicated

Challenges II



Production modes are driven by the interaction operators and may be very different:

- Deep inelastic processes (proton bremsstrahlung, Drell-Yan, dark showerings)
- Scatterings of secondary particles (e.g., Primakov process)
- Decays of secondary particles (heavy/light mesons, τ leptons)

Decays/post-production interactions: depend on the interaction vertex, in the way that matters for SHiP: leptons/hadrons, multiplicity, etc.

Challenge 1 – mixing with mesons I

- Interaction Lagrangian of a LLP $\boldsymbol{X}$:

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

- Expansion of $\mathcal{O}_a[\psi_{\text{SM}}]$ in terms of bound states $\mathcal{Y}$:

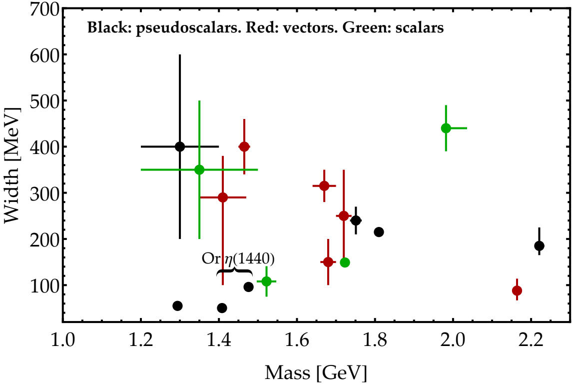
$$\mathcal{O}_a = \overbrace{c_1(\mathcal{Y}, \partial\mathcal{Y}, \partial^2\mathcal{Y})_a}^{\text{1-particle}} + \overbrace{c_2(\mathcal{Y}^2, (\partial\mathcal{Y})^2, \mathcal{Y}\partial\mathcal{Y})_a}^{\text{2-particle}} + \dots \tag{2}$$

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

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

Challenge 1 – mixing with mesons II

- Understanding of spectroscopy of excitations is far from perfect [pdg], [2407.18348]
- This may result in hardly quantified uncertainties in the LLP phenomenology
- May be reflected in both production and decays, depending on the signature



Problem is generic for new particles mixing with hadrons

[2409.11096], [2501.04525], [2504.06828], [2510.05257]

Challenge 1 – mixing with mesons III

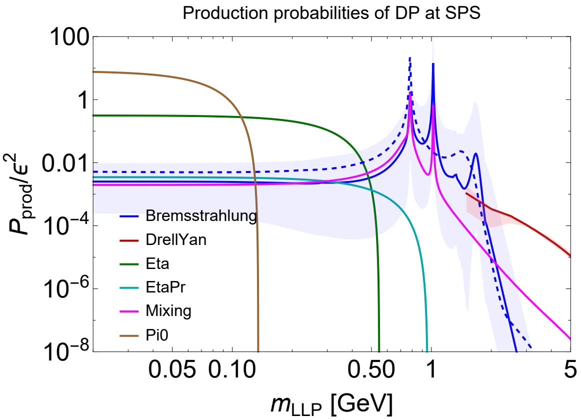
LLP	**Mixing with $\mathcal{Y}$**
Dark photon/dark ρ	ρ^0, ω, ϕ and their excitations
V coupled to J_B^μ	ω, ϕ and their excitations
Higgs-like scalar	f_0 and its excitations
ALP/dark π	π^0, η, η' and their excitations
HNL	No mixing

- Most of the “simplest” LLPs have mixing
- To understand their interaction, it is necessary to carefully know the meson spectroscopy in the mass range $M \lesssim 2$ GeV, which is far from being true

Challenge 1 – mixing with mesons IV

Example 1 – dark photons:

- Decay rates: may be extracted from $e^+e^- \to$ **hadrons**
- Production modes: no such opportunity/currently very limited *See also [1603.08926]*
- Heavy uncertainties come from the proton bremsstrahlung (to which the mixing contributes)



[2409.11096]

Challenge 1 – mixing with mesons V

Example 2 – ALPs coupled to quarks/gluons:

- No data available for direct extraction of production and decay rates
- It is relatively simple to estimate the impact of the mixing with π^0, η, η' on phenomenology, but for $m_a \gtrsim 1\,\text{GeV}$, heavier excitations are essential
- The approach is
  1. To build an effective theory of interaction of excitations $P_h = \pi^0(1300), \eta(1295), \ldots$ (e.g., extended linear sigma model [2407.18348]),

$$\mathcal{L}_{P_h} = \sum_i c_i O_i(\mathbb{P}_{P_h}, \mathbb{P}_P, \ldots), \quad \mathbb{P}_{P_h} = -\sum_{P_h} t_i P_{h,i} \tag{4}$$

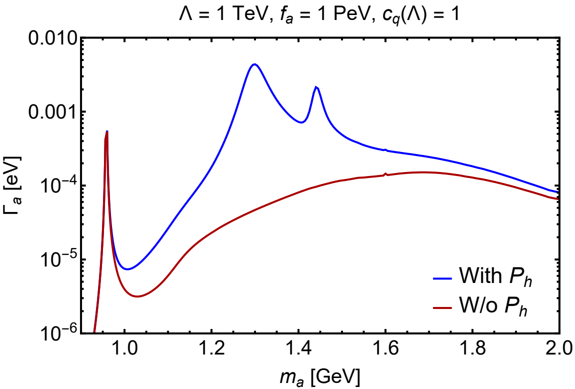
     where c_i are fixed to reproduce the observed properties of P_h
  2. To introduce the ALPs a in a covariant fashion:

$$\mathcal{L}_{P_h,a} = \mathcal{L}_{P_h,a}[\mathbb{P}_h \to \mathbb{P}_h + c_a a,\ \partial\mathbb{P}_h \to \partial\mathbb{P}_h + c_b \partial a] \tag{5}$$

[2501.04525]

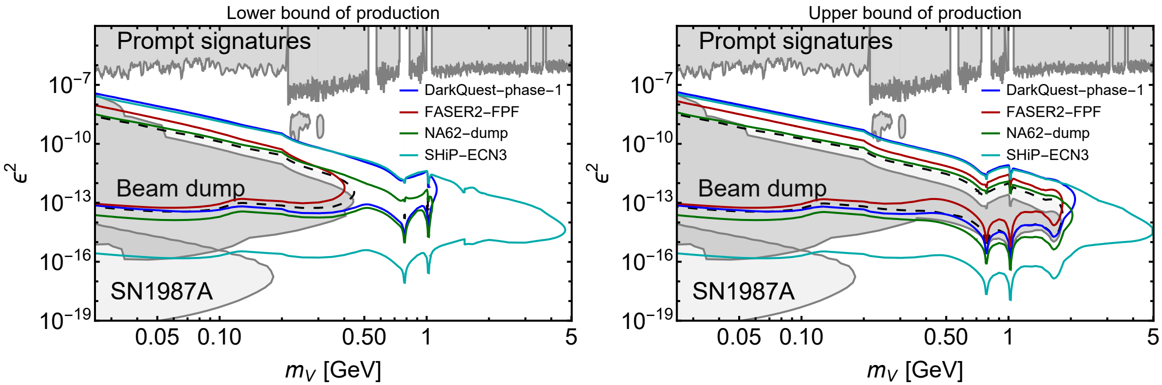
Challenge 1 – mixing with mesons VI

- Initial step – including $\boldsymbol{P_h = \pi^0(1300), \eta(1295), \eta(1440)}$
- The mixing blows up the decay width by two orders of magnitude, enhancing the decay modes $\boldsymbol{a \to 3\pi, KK\pi}, \ldots$



[2501.04525] + in preparation

Challenge 1 – mixing with mesons VII



– Uncertainties heavily change the parameter space of dark photons – both in terms of production and decay!

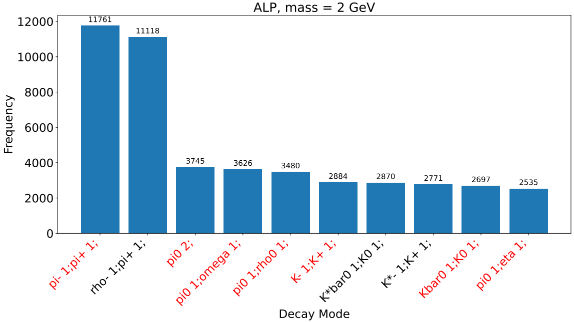
Computed using SensCalc *[2409.11096]*

Challenge 2 – hadronization in PYTHIA8 I

- At some LLP mass $m_X \gtrsim 4\pi\Lambda_{\text{QCD}}$, description of its hadronic decays in terms of exclusive states should match the perturbative calculations
- Decays are then commonly described using tools like PYTHIA8/HERWIG
- One starts with partonic decay $X \to q\bar{q}$, and then hadronizes $q\bar{q} \to \textbf{hadrons}$
- Issue: these hadronization models do not conserve quantum numbers: isospin, G-parity, etc.

Challenge 2 – hadronization in PYTHIA8 II

- Example: ALPs universally coupled to quarks
- Decay modes $a \to \pi\pi, \pi\omega, \pi\rho, KK, \pi\eta$ are forbidden
- But for the mass range $m_a \lesssim 3\,\mathrm{GeV}$, these are the dominant modes according to PYTHIA8



[2504.06828] + In progress

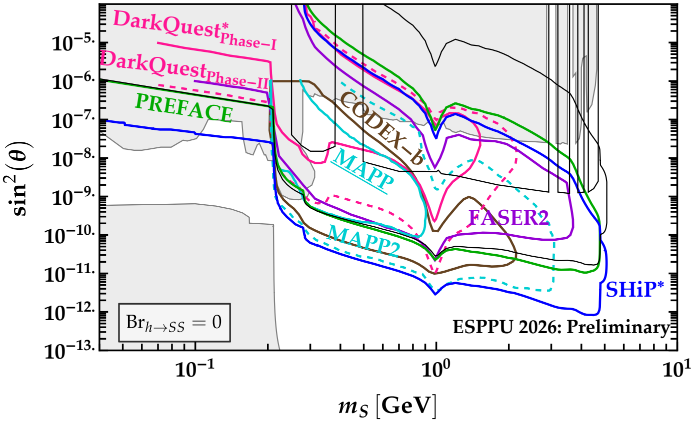
SHiP: exclusion potential

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

Higgs-like scalar

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

- Most efficiently probed at B factories
- SHiP is such a B factory



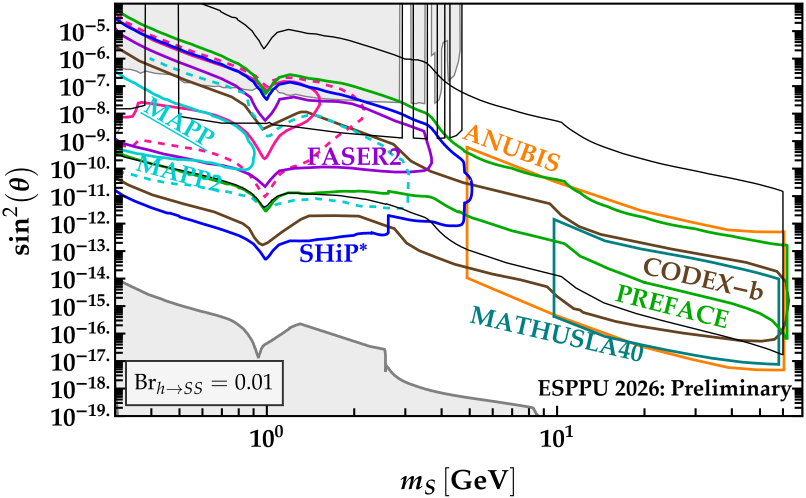
Meaning of the legend. **exp**: proposal. **exp**: currently running. **exp***: approved/in construction. **exp***: currently running, but the luminosity is to be approved

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

Higgs-like scalar

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

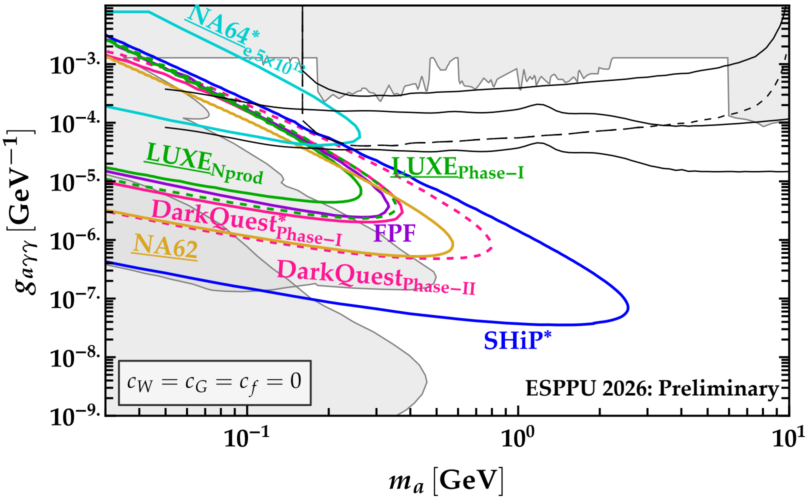
– Most efficiently probed at h and B factories



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

ALP (γ dominance)

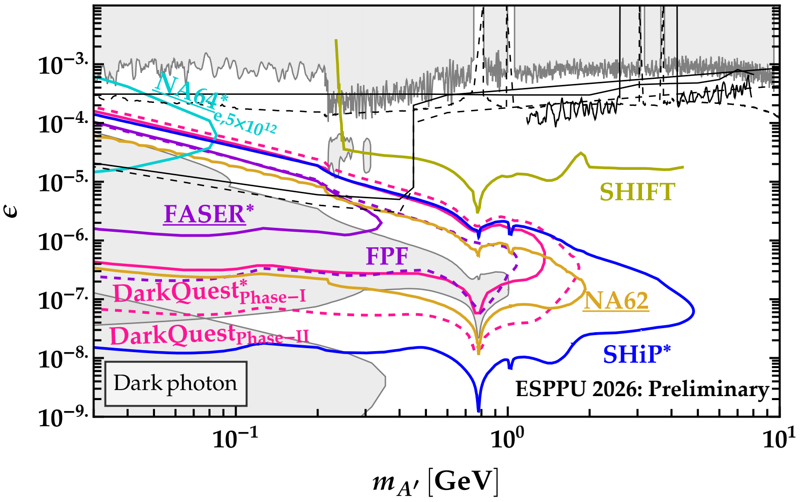
- Sensitivity is dominated by on-axis beam dump experiments or prompt collider searches (decays/missing energy)



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

Dark photons

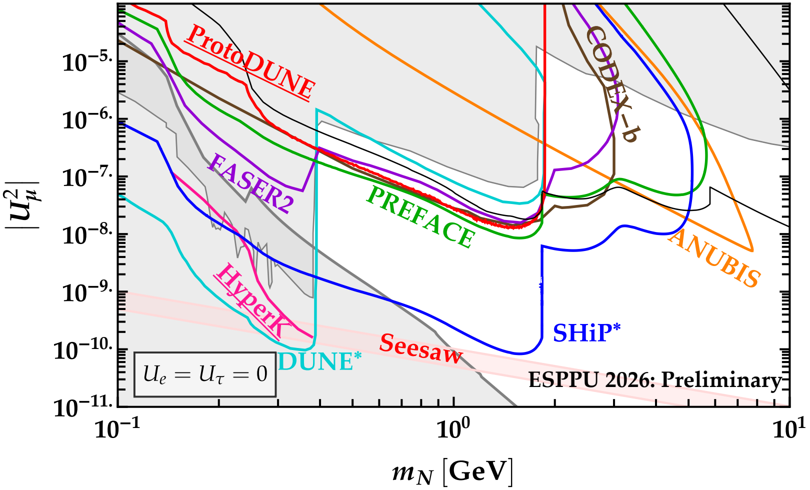
- Dark photons are produced in the forward direction
- Most efficient at far-forward experiments with very high collision intensity



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

HNL

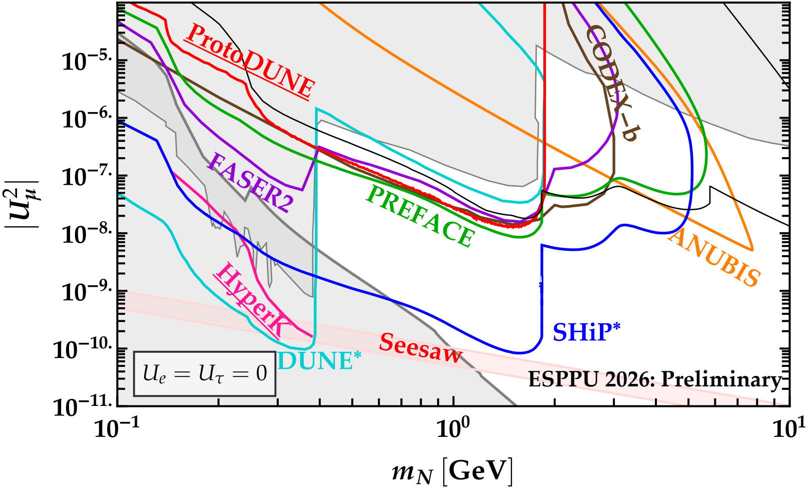
- Sensitivity comes from $\boldsymbol{K, D, B, W, Z}$ factories
- SHiP is a $\boldsymbol{D, B}$ factory



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

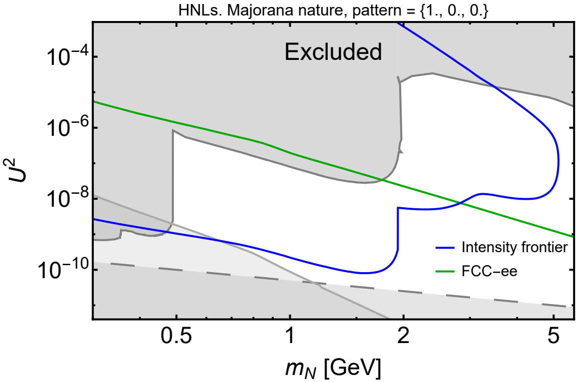


- **FCC-hh-based experiments**: significantly extend the SHiP reach for $m_D < m_N < m_B$

SHiP: Discovery potential

Opportunities: not exclude but discover I

- Intensity frontier experiments may explore orders of magnitude in LLP couplings
- Potentially, may observe thousands of LLPs



What can we extract in case of discovery?

Opportunities: not exclude but discover II

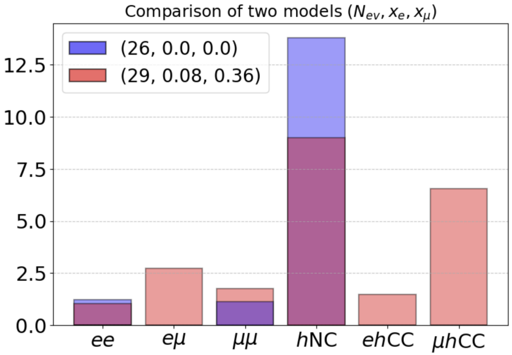
Two topologies with detectable interactions

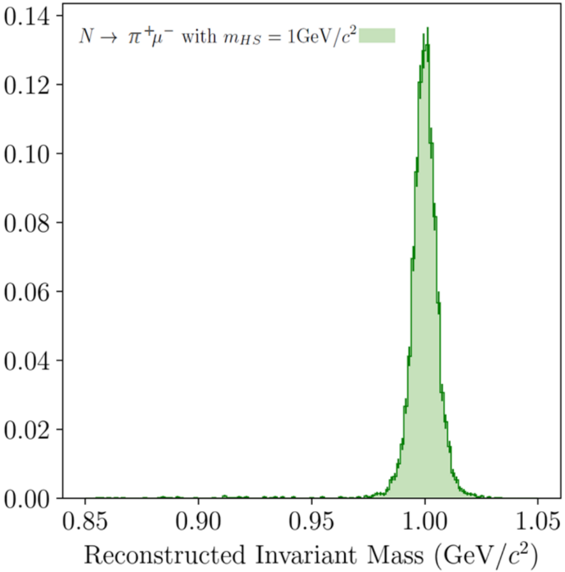
- "**Mono-events**": one detectable interaction (decay/scattering/missing energy)
- "**Multi-bang**": two or more detectable interactions

- Unless a large background for mono-events, they dominate the exclusion reach

Opportunities: not exclude but discover III

- Reconstruct the invariant mass and measure coupling patterns
- Allows to test if LLPs are related to the BSM problems





[2312.05163]

Opportunities: not exclude but discover IV

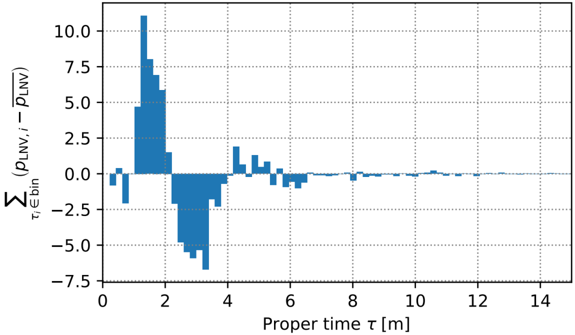
A closer look on HNLs

- 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 $\boldsymbol{\omega_{\text{osc}} = \Delta m^{-1}}$
- 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]

Opportunities: not exclude but discover V

- Resolve oscillations $N_1 \leftrightarrow N_2$ and measure Δm by distinguishing lepton number violating and lepton number conserving events
- This information is encoded in the angular distribution of the decay products (due to helicity conservation)



[1912.05520]

Opportunities: not exclude but discover VI

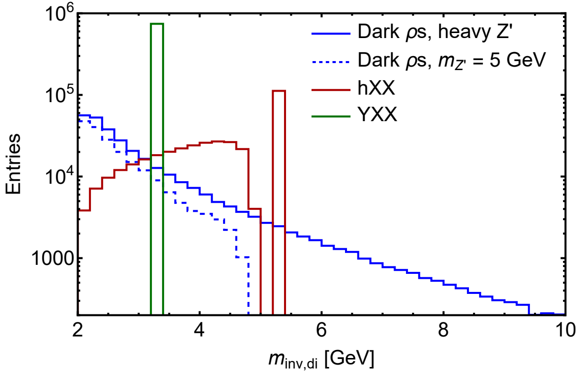
- Intensity Frontier experiments will not have access to the production vertex
- Decay phenomenology of entirely different LLPs may be identical
  - Dark ρs vs dark photons
  - Dark pions vs ALPs
  - LLPs with/without the di-production vertex
    Scalars, HNLs, etc.
  - Inelastic DM χ', χ with/without $\chi'\chi' V$ coupling

Observing only single decays, we may not distinguish between entirely different LLPs

Can we distinguish between them in another way?

Opportunities: not exclude but discover VII

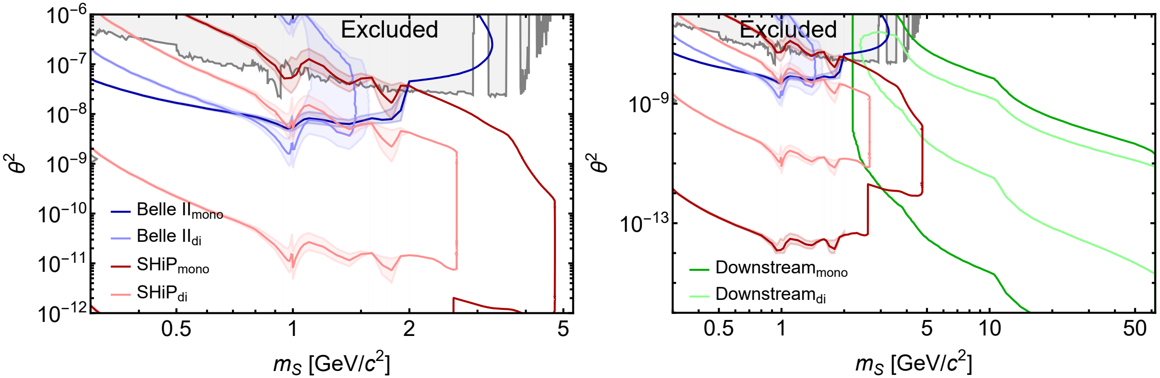
- Often, the models may be distinguished by the presence of the production of multiple LLPs per event
- The multiple LLPs may have a chance of decaying inside the decay volume (**di-decays**)
- This gives access to the combined distributions of the pair



$m_{\rm inv,di}$: identifying the production mode without seeing the vertex

[2503.01760]

Opportunities: not exclude but discover VIII



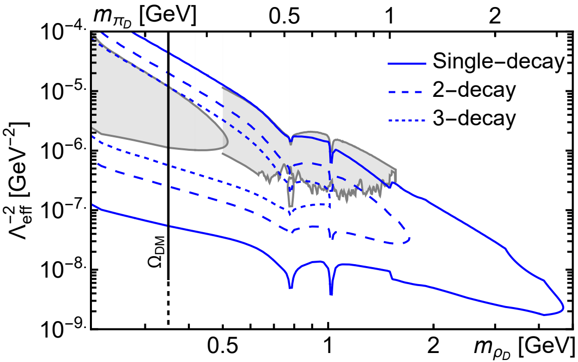
Higgs-like scalars with hSS coupling:

- Mono-decays: dark lines. Di-decays: light lines
- Experiments at various facilities may have sensitivities to di-decays; di-decays may even be the dominant sensitivity

Computed using EventCalc *[2503.01760]*

Opportunities: not exclude but discover IX

- Consider dark QCD coupled via $U(1)_Y$ field A' [2203.08824]
- The colored lines show the SHiP sensitivity to mono- and multi-bang events
- Limit of heavy A' and $m_{\rho_d} < 2m_{\pi_d}$: ρ_d decays visibly
- Typically, produced with large multiplicity $\Rightarrow$ gives rise to multi-particle decays

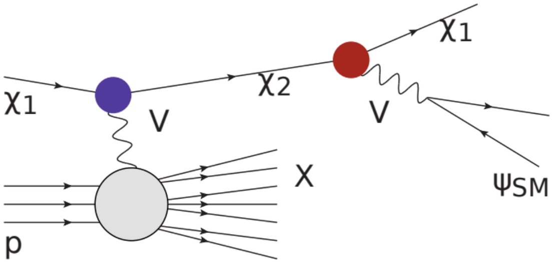


[2510.23696]

Opportunities: not exclude but discover X

Inelastic dark matter models add χ, χ', h_d, A'. Various signatures:

- Displaced decay $\chi' \to \chi + \mathbf{SM}$
- Double bang 1: inelastic scattering of χ followed by subsequent decay of χ'
- Double bang 2: production of $\chi'\chi'/\chi' h_d$ followed by di-decay



[2312.14868]+With GDV Garcia, F. Kalrhoefer, T. Schwetz, in preparation

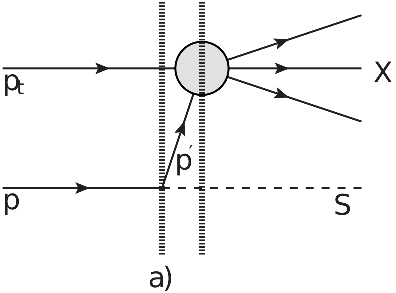
Conclusions

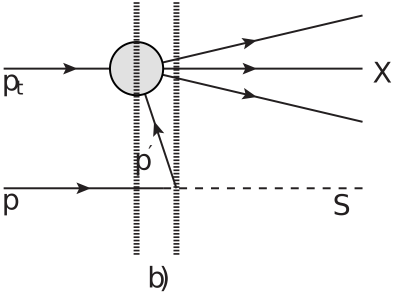
- GeV-mass LLPs: attractive target for searches at the lab
- SHiP: a powerful machine to explore various LLPs in the GeV mass range – not only in terms of exclusion, but also discovery
- Opportunities meet challenges – uncertainties in phenomenology of hadronic interactions of GeV-mass particles

Thank you for attention!

Backup slides

Proton bremsstrahlung [2409.09123], [2409.11096]





- Quasi-real approximation: $\boldsymbol{\sigma_{pp\to V+X} \approx \int d\Phi P_{p\to p'V} \times \sigma_{pp\to X}}$
- Parametrized by the virtuality of $\boldsymbol{p'}$
- Additional source of uncertainty: proton EM form-factor in the timelike region
- Uncertainties may be two orders of magnitude or larger

More on hadronically coupled ALPs I

ALP Lagrangian:

$$\mathcal{L}_a = c_G \frac{\alpha_s}{4\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{\partial_\mu a}{f_a}\sum_q c_q \bar{q}\gamma^\mu\gamma_5 q + \textbf{flavor-changing} \quad (6)$$

1. Perform the chiral rotation

$$q \to e^{-i\gamma_5 c_G \kappa_q a/f_a} q, \quad q = u, d, s \quad (7)$$

with $\mathbf{tr}[\kappa_q] = 1$
It converts the gluonic coupling into the second term of Eq. (**??**)

2. Make a correspondence between the resulting theory and ChPT Lagrangian $\mathcal{L}_{\mathbf{ChPT+a}}[\kappa_q]$ [2012.12272]

– Supplement the interactions with phenomenological Lagrangians describing interactions with other mesons (ρ, K_0, f_2, etc.)

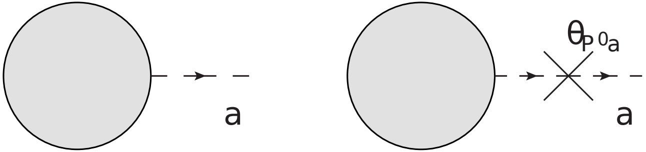
More on hadronically coupled ALPs II

– The ALP-ChPT Lagrangian implies **mixing** of ALPs with pseudoscalar mesons $P^0 = \pi^0, \eta, \eta'$:

$$P^0 \to P^0 + \theta_{P^0 a} a, \quad \theta_{P^0 a} = \frac{f(m_{P^0}, m_a)}{m_{P^0}^2 - m_a^2 - i m_{P^0} \Gamma_{P^0}} + g(\kappa_q) + \ldots \qquad (8)$$

Phenomenologically, a light ALP is an admixture of P^0s

More on hadronically coupled ALPs III



- Resulting Lagrangian must predict κ_q-independent observables [2102.13112] and include all pseudoscalar excitations
- In practice: cancellation of κ_q contribution from the ALP-meson mixing (right) and many-field interactions (left)
- Widely adopted descriptions [1811.03474], [2201.05170], [2305.01715]: many-field κ_q-terms were missing in production and decay rates

ELSM I

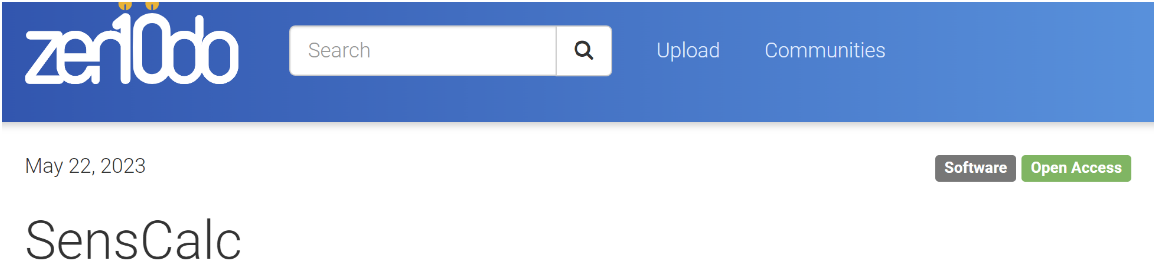
- Extended linear sigma model (ELSM) [2407.18348], [1612.09218]
- ELSM adds a heavy pseudoscalar octet and identifies the “flavorless” excitations with $\boldsymbol{\pi^0(1300), \eta(1295), \eta(1440)}$
- ALPs may be added to ELSM Lagrangian completely similarly to the ChPT case

ELSM II

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 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

SensCalc I



- `SensCalc` – a `Mathematica`-based sensitivity evaluator
- **Input**: experimental setup (geometry, selection cuts), LLP model (branching ratios, matrix elements, lifetimes), tabulated distributions of mother particles
- **Output**: tabulated number of events $\boldsymbol{N_{\mathrm{ev}}(m_{\mathrm{LLP}}, g_{\mathrm{LLP}})}$ that may be converted into exclusion/discovery limits

Based on 2305.13383

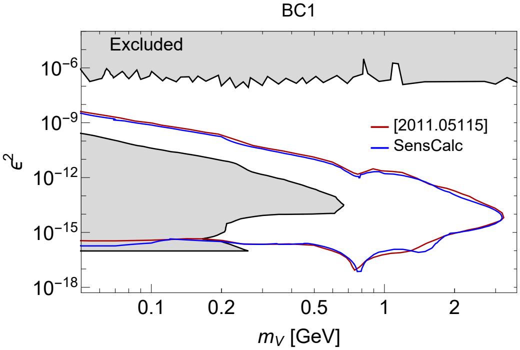
SensCalc II

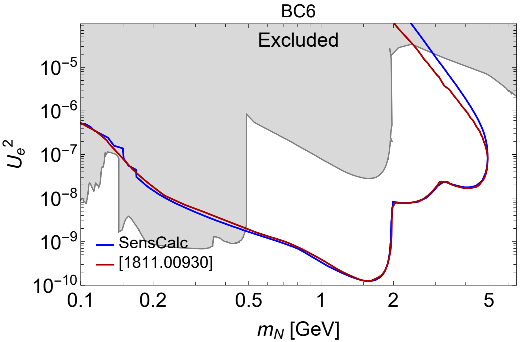
– Semi-analytic approach to compute the number of events

$$\boldsymbol{N}_{\text{ev}} = \sum_i \boldsymbol{N}^{(i)}_{\textbf{prod}} \int dE d\theta dz \, f^{(i)}(\theta, E) \cdot \epsilon_{\textbf{az}}(\theta, z) \cdot \frac{dP_{\textbf{dec}}}{dz} \cdot \epsilon_{\text{dec}}(m, \theta, E, z) \cdot \epsilon_{\text{rec}} \quad (9)$$

- $N^{(i)}_{\textbf{prod}}, f^{(i)}(\theta, E)$: total number of produced LLPs, $\theta - E$ LLP distribution
- $\epsilon_{\textbf{az}}$ is the azimuthal acceptance for the LLP to decay inside the decay volume
- $\frac{dP_{\textbf{dec}}}{dz} = \frac{\exp[-z/(\cos(\theta)c\tau\sqrt{\gamma^2-1})]}{\cos(\theta)c\tau\sqrt{\gamma^2-1}}$ is the differential decay probability for the LLP to decay
- $\epsilon_{\textbf{dec}}$ is the decay products acceptance
- $\epsilon_{\textbf{rec}}$ (must be computed externally) is the reconstruction efficiency

SensCalc III





– `SensCalc` has been cross-checked with independent MC codes for experiments at SPS and LHC: `FairShip`, `SensMC`, `FORESEE`, `ALPINIST`, LHCb simulation framework *(see details in backup slides and in the accompanying preprint)*

SensCalc IV

Implemented experiments:

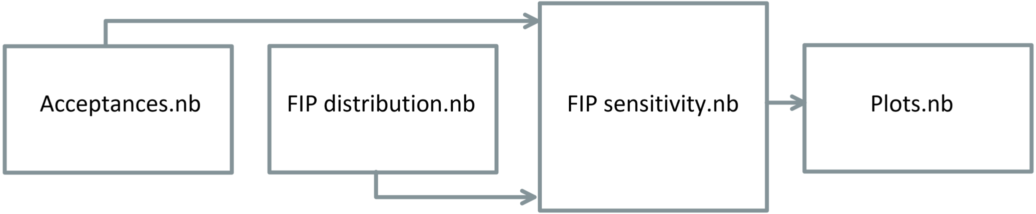
- **SPS**
  - $NA62_{dump}$, SHiP
  - CHARM, BEBC
  - Some dead experiments
- **Fermilab BD**
  - DUNE/DUNE-PRISM, DarkQuest
- **LHC**
  - FASER/FASER2/FASERν, SND@LHC/advSND,
  - FACET, MATHUSLA, CODEX-b
  - Downsream@LHCb, muon chambers@LHCb
- **FCC-hh**
  - Analogs of the LHC-based experiments
- **(semi)Leptonic experiments**
  - Belle II
  - E137

Implemented LLPs:

- **Dark photons**
- **Dark scalars** (with mixing and quartic couplings)
- **HNLs** (with arbitrary mixing pattern)
- **ALPs** coupled to
  - gluons
  - photons
  - fermions
- **Anomaly-free mediators** ($B-L$, $B-3L_\mu$,…)
- **MCPs**
- **Inelastic dipole dark matter**

Other LLPs (including DM) exist in private implementations

Launching SensCalc I



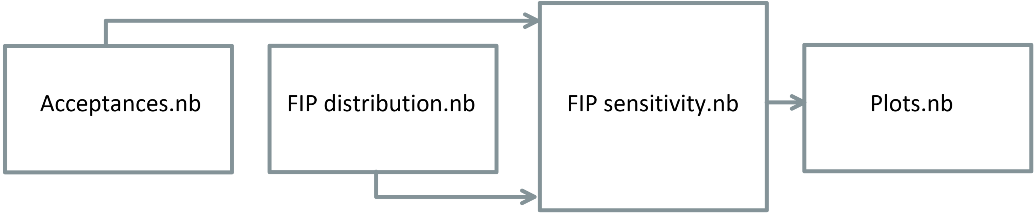
$$N_{\text{ev}} = \sum_i N^{(i)}_{\text{prod}} \int dE d\theta dz\ f^{(i)}(\theta, E) \cdot \epsilon_{\text{az}}(\theta, z) \cdot \frac{dP_{\text{dec}}}{dz} \cdot \epsilon_{\text{dec}}(m, \theta, E, z) \cdot \epsilon_{\text{rec}} \quad (10)$$

Modular structure:

– In `1. Acceptances.nb`, specify the geometry of the experiment and selection criteria for the decay products to produce the tabulated $\epsilon_{\text{az}}, \epsilon_{\text{dec}}$

– In `2. LLP distribution.nb`, specify the facility and the LLP to generate the distributions of LLPs produced by decays or scatterings

Launching SensCalc II



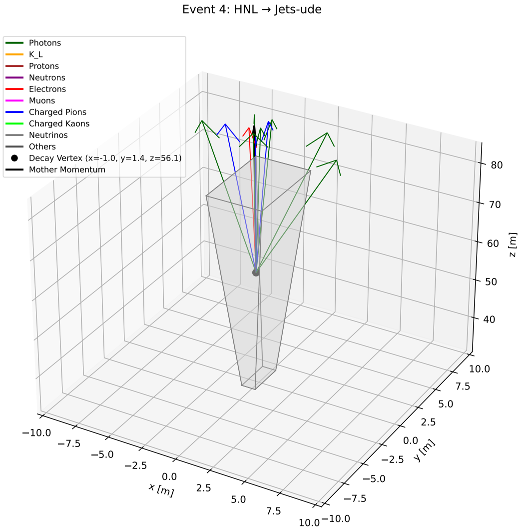
$$N_{\rm ev} = \sum_i N^{(i)}_{\rm prod} \int dE d\theta dz \; f^{(i)}(\theta, E) \cdot \epsilon_{\rm az}(\theta, z) \cdot \frac{dP_{\rm dec}}{dz} \cdot \epsilon_{\rm dec}(m, \theta, E, z) \cdot \epsilon_{\rm rec} \quad (11)$$

Modular structure:

- In `3. LLP sensitivity.nb`, compute the tabulated number of events and sensitivity
- `4. Plots.nb` produces sensitivity plots

Launching SensCalc III

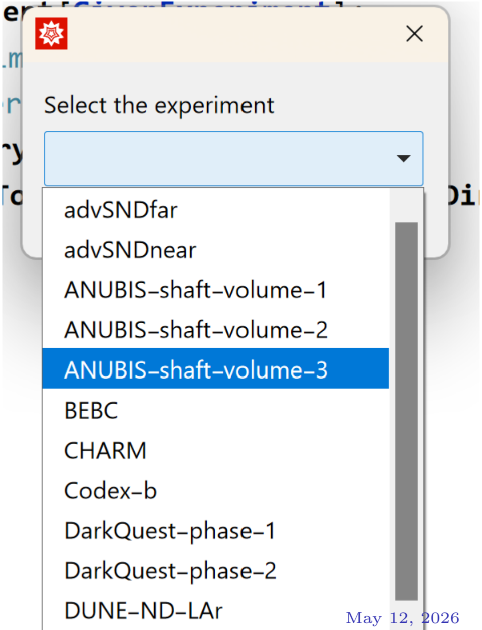
- SensCalc itself does not produce event record – only calculates the event rate and produces some differential distributions
- Monte Carlo event generator based on SensCalc – EventCalc
  1. Mathematica-based: distributed together with SensCalc [2409.11096]
  2. python-based: made for SHiP and is integrated into SHiP software framework



Launching SensCalc IV

- **If the experiment and LLP have already been implemented**: just launch the notebook and pass through dialog windows
- **If something is not implemented**: add by analogy or compute from scratch

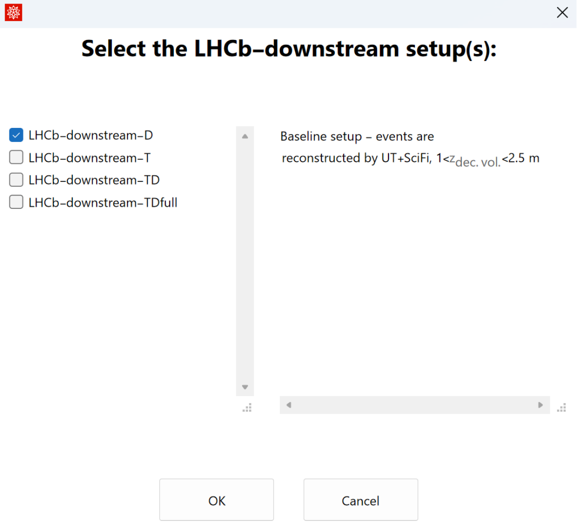
Running time (from scratch):
<1 **hour**



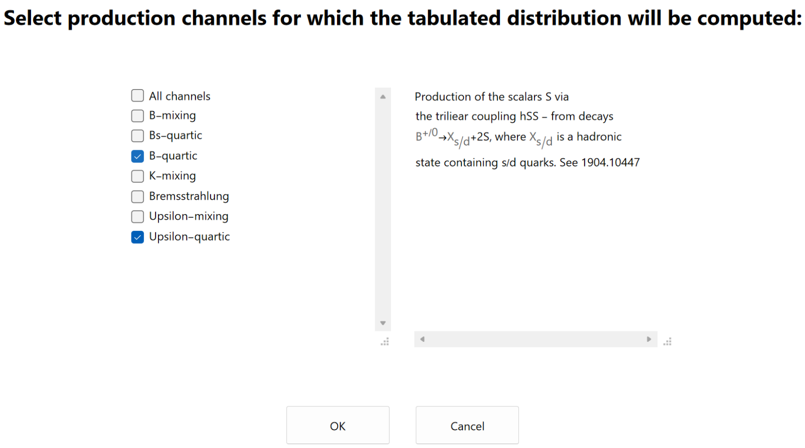
Launching SensCalc V

Users may:

1. **Specify the setup of the experiment**
   Either use already implemented setups or add your



Launching SensCalc VI



2. **Select LLP production and decay modes, and detectable particles**

   Important when considering specific experiments/analyzing details of the sensitivity

Launching SensCalc VII

3. Specify selection criteria and select the detection signature

ALP–fermion

Enter the name of the experiment for exporting the decay acceptance:

SHiP–ECN3

Default decay channels:

$\{2e,\ 2\mu,\ 2\tau,\ 2\gamma,\ \pi^+\pi^-\pi^0,\ \gamma\pi^+\pi^-,\ \pi^+\pi^-2\pi^0,\ 2\pi^+2\pi^-,\ \eta 2\pi^0,\ \eta\pi^+\pi^-,\ K^{*+}K^{*-},\ K^{*0}\overline{K}^{*0},\ K^0\overline{K}^0\pi^0,\ K^-K^0\pi^+,\ K^+K^-\pi^0,\ K^+\overline{K}^0\pi^-,\ \omega\pi^+\pi^-,\ 3$

Keep them or select particular channels?

Keep

How many decay products that in principle may be detected must pass all the criteria?

- (selected) >=2
- All detectable
- Mono–particle
- >=n

At least two detectable particles point to the detector (if decay volume itself is not a detector) and satisfy other cuts (such as the energy cuts, impact parameter cuts, etc.)

Heavy LLPs decay into partons. Use hadronized decay products, or just partons?

Hadronized products

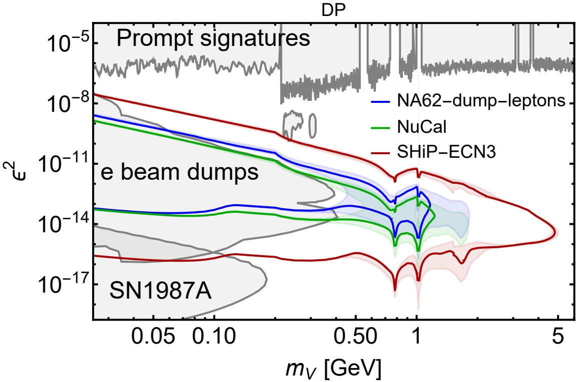
Select one or more descriptions of the ALP–fermion decay used for calculating the decay acceptance:

- Default
- PBC description

Description of hadronic width of ALPs following 2310.03524

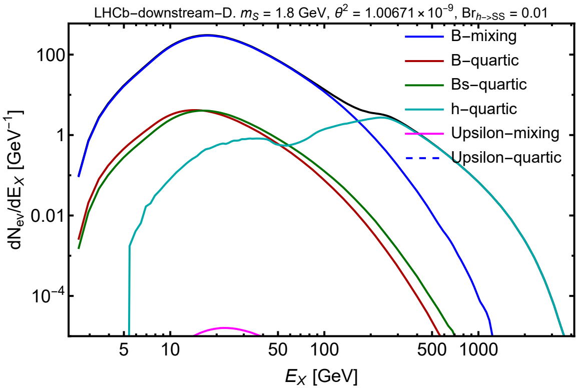
Launching SensCalc VIII

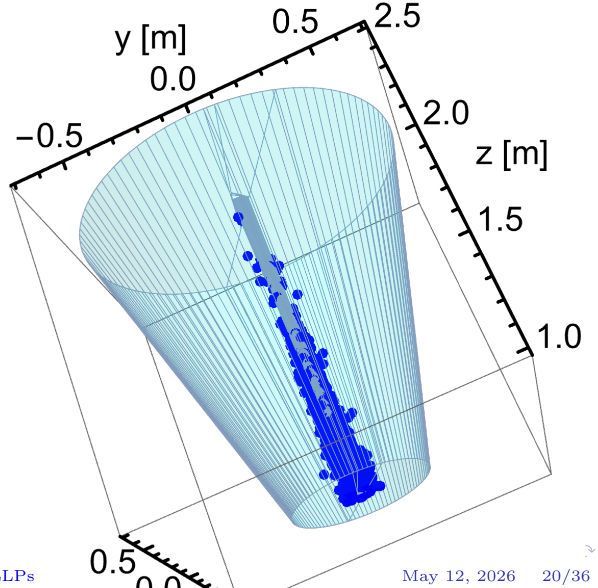
4. **Compute the effects of theoretical uncertainty in LLP phenomenology on sensitivity**



Example: how the uncertainties in the production of dark photon influence the domains constrained by NuCal and NA62 searched for leptons, and the sensitivity of SHiP

5. **Generate events record and have access to various event distributions**





HNL-anti-HNL oscillations I

- 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]

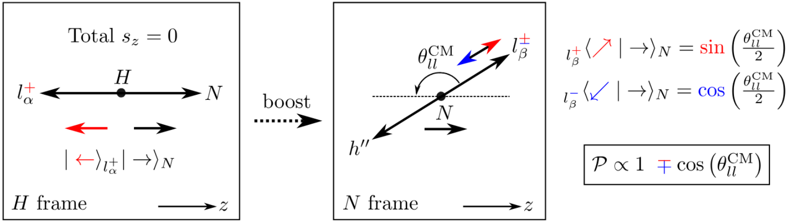
HNL-anti-HNL oscillations II

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

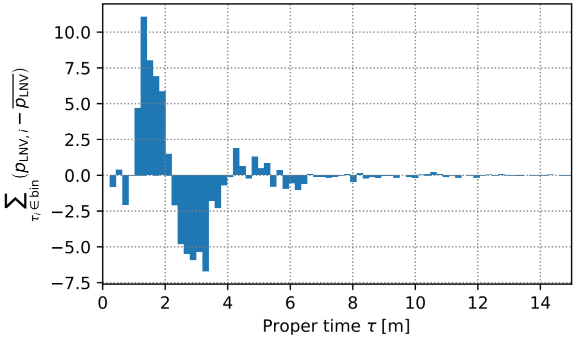
HNL-anti-HNL oscillations III



- 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

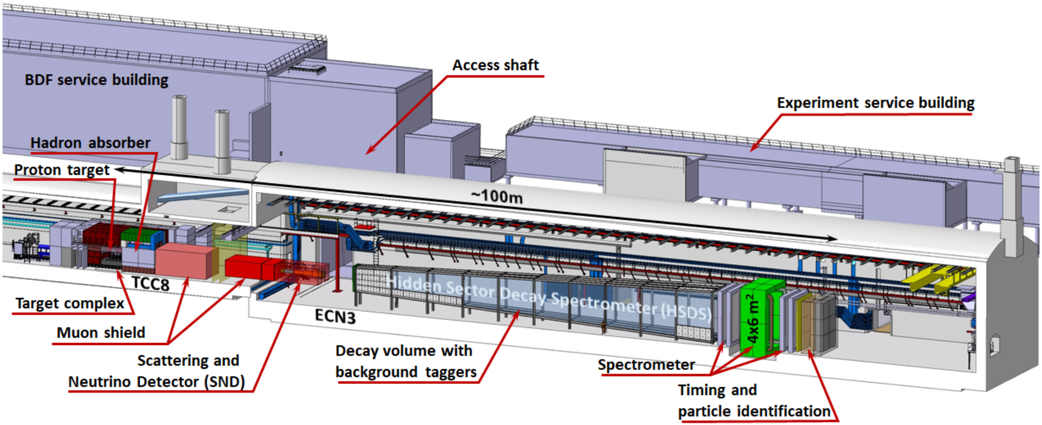
HNL-anti-HNL oscillations IV

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

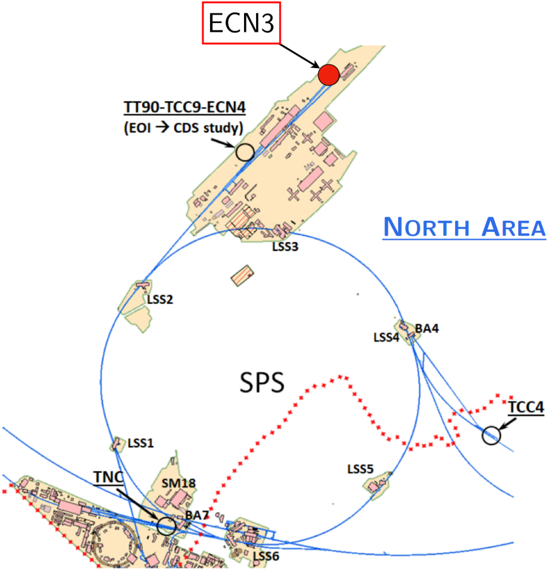
SHiP I



SHiP: beam dump experiment to explore GeV-mass LLPs

SHiP II

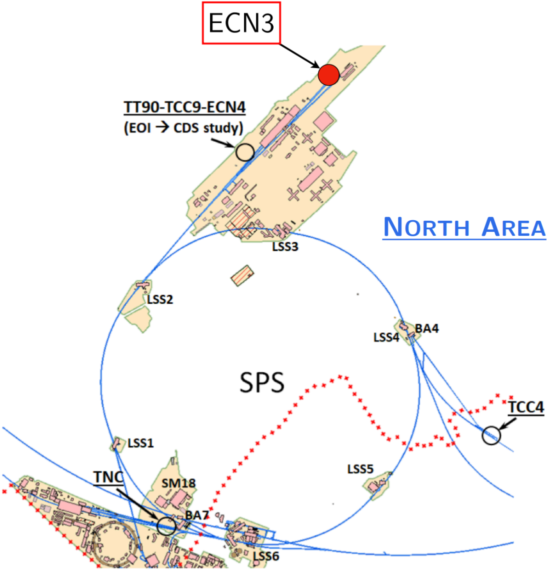
– **Location: CERN SPS**. Proton beam $\boldsymbol{E_p = 400}$ **GeV**
  - North Area →
  - TCC8 target hall →
  - ECN3 cavern



SHiP III

HI-ECN3:

- Beam intensity T4 wobbling-magnet upgrade, dilution sweep magnets, P42 temporary dump, and three in-vacuum stoppers are all engineered and reviewed, with drawings/ECRs issued or imminent
- No show-stoppers identified for delivering the $\mathbf{4 \times 10^{13} PoT/spill}$ beam to TCC8 after LS3
- $N_{\rm PoT,year} = 4\cdot 10^{19} \Rightarrow$ **15-year running time:** $N_{\rm PoT,year} = 6\cdot 10^{20}$



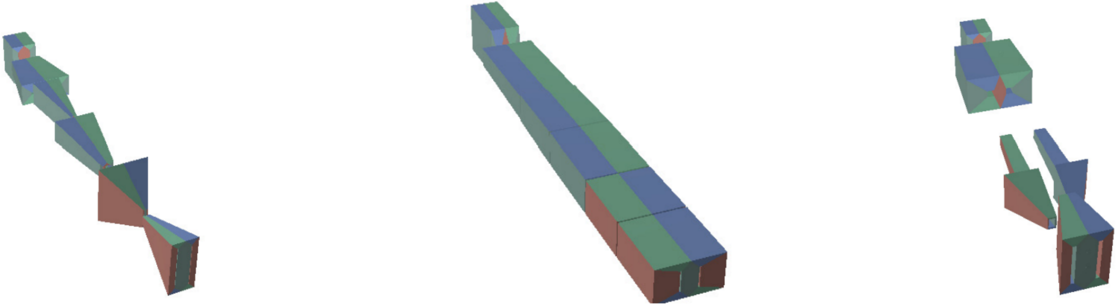
SHiP IV

- **Thick target**
  - **12λ**
  - **Ti-Zr-Mo** alloy followed by pure **W**
  - $\mathcal{O}(2)$ cascade enhancement of the heavy flavor production

Enormous yields of heavy flavor production

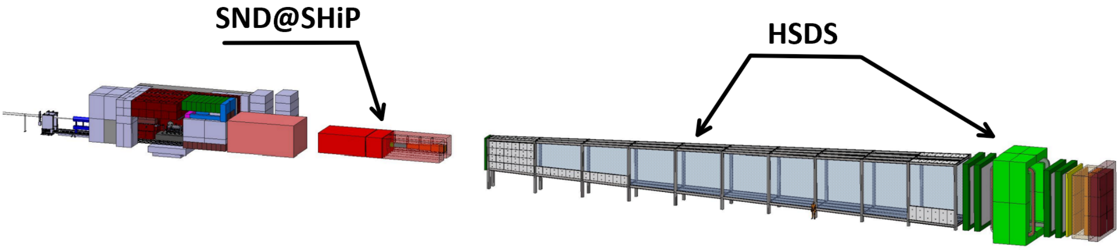
- $N_{c\bar{c}} \sim 10^{18}$: ~ 2 orders of magnitude larger than at HL-LHC
- $N_{b\bar{b}} \sim 10^{14}$: comparable to LHCb@HL-LHC

SHiP V



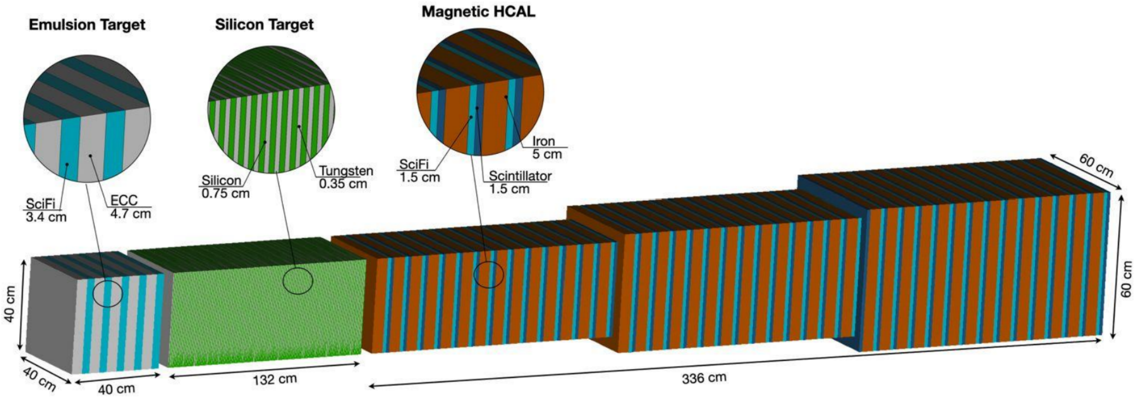
– System of magnets to reduce muon flux with $\boldsymbol{E > 10}$ **GeV** from $\mathbf{2 \cdot 10^{10}}$**/spill** by more than 6 orders of magnitude
– Subject of re-optimization because of moving to ECN3
– A few setups are considered: minimal iron yoke; + diluted with non-magnetic shielding; hybrid warm+SC; decide on option by Fall

Ingredients. 2. Detectors I



- **SND@SHiP**: neutrinos and scattering detectors
- **HSDS**: hidden sector decay spectrometer

Ingredients. 2. Detectors II

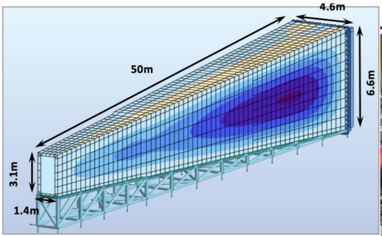


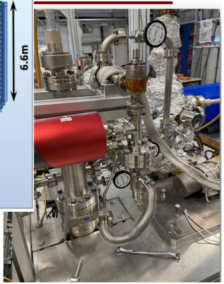
- **SND@SHiP**: Hybrid target with emulsion (experience from SND@LHC) and silicon layers, in the central yoke of the muon shield (*re-optimization in progress*)
  Previously: emulsion outside muon shield
- $\boldsymbol{\nu}$ scattering events: $\sim \mathbf{10^6(\nu_e + \bar{\nu}_e), 10^7(\nu_\mu + \bar{\nu}_\mu), 10^5(\nu_\tau + \bar{\nu}_\tau)}$. **Rich ν physics!**

Ingredients. 2. Detectors III

HSDS: decay vessel

- Pyramidal frustum with dimensions:
  $$\boldsymbol{\Delta x \times \Delta y \times \Delta z =}$$
  $$\mathbf{(1.4-4.6)\ m \times (3.1-6.6)\ m \times 50\ m}$$
- Placed 32 m downstream of the target, 1 atm He filled, with Al frame
  Previously: vacuum, steel





- Geometry and placement: maximize signal yield while not overproducing background [2304.02511]
- Diffusion rates measurements: Hardware installed; sample holders in fabrication; awaiting material coupons

Build and commission a scaled prototype during 2026

Ingredients. 2. Detectors IV

HSDS: magnet

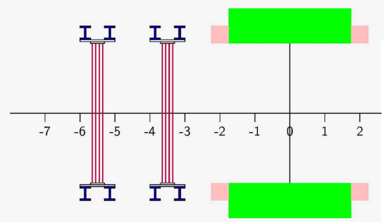
– Power of $\mathbf{0.65\ T \cdot m}$ over tracking stations

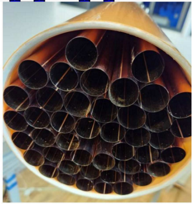
HSDS: straw tracker

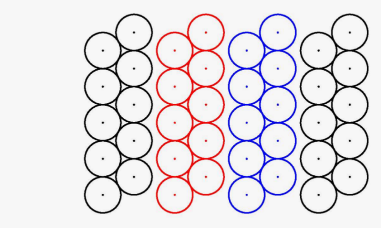
– Ultra-light horizontal gas-filled straws with 2 cm diameter

– 4 straw-stations, separated by a magnetized region

50 prototype straws successfully leak-tested at 3 bar; tubes awaiting shipment to CERN







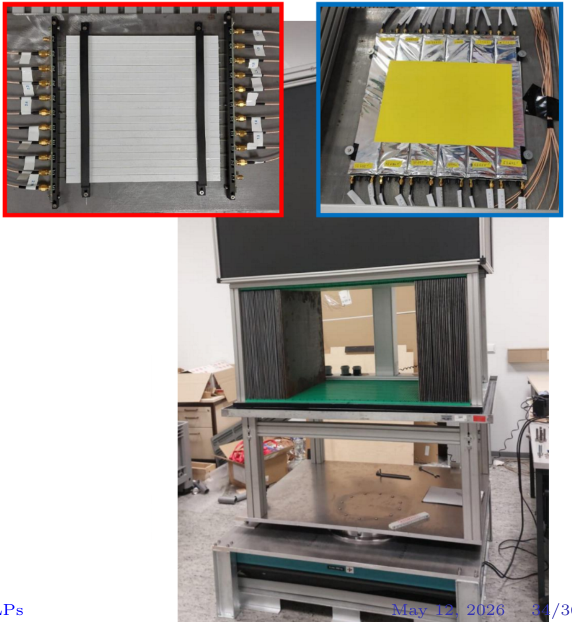
Ingredients. 2. Detectors V

- **HSDS: PID. $20X_0$** hybrid-strip ECAL+ 5λ HCAL (SplitCal)
- Pointing and full-depth PID performance match simulation

Closing the conceptual-prototype phase

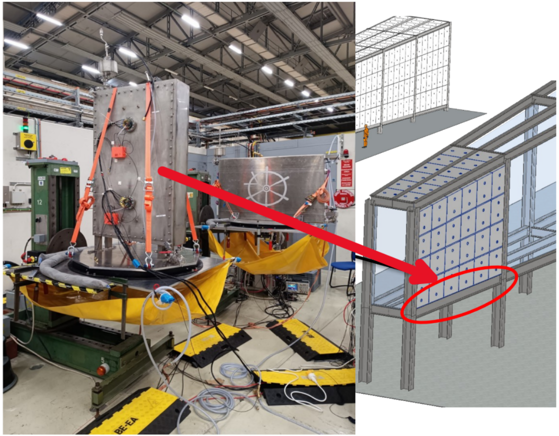
- **HSDS: TOF.** 546 scintillator bars with SiPM-array read-out, providing timing $\boldsymbol{\delta t < 100\text{ps}}$
- Power, cabling, and CAEN supply scheme are defined

Frozen mechanical design



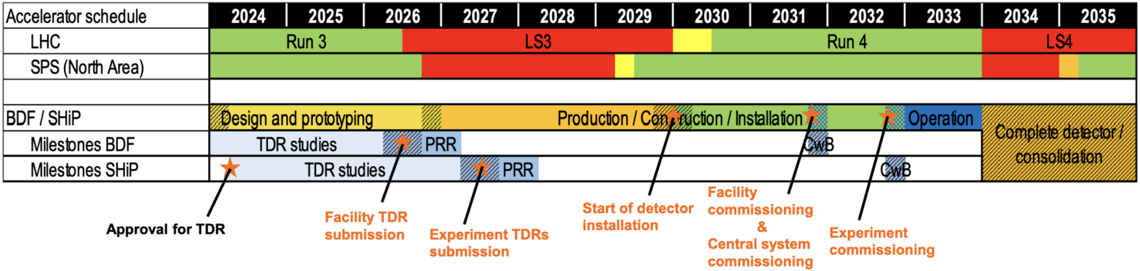
Ingredients. 3. Background taggers

- **HSDS: SBT.** liquid scintillator surrounding cells surrounding decay vessel
  - May: performance analysis of two single-cell prototypes
  - Currently: minimizing the level of deformation with the Al-vessel equipped with SBT; optimizing the structure to reduce self-induced backgrounds
- **HSDS. UBT**: background tagger in front of the decay vessel



SBT+UBT+simple selection: reduce number of bg events to $< \mathcal{O}(1)$ per full running time!

Timeline and costs



- **2024**: SHiP is approved and goes onto the TDR phase
- CERN as host covers HI-ECN3 and civil engineering
- The detector construction amount is $\simeq$ **50 MCHF**
  A significant part has been already secured
- Construction should start in $\sim$ **2029** and collecting data in **2033**