The BDF/SHiP experiment at the ECN3 high-intensity beam facility at the CERN SPS

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On behalf of the SHiP collaboration

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SHiP
Search for Hidden Particles

Positioning SHiP on a landscape of new physics searches I

Three Frontiers to explore new physics at accelerators

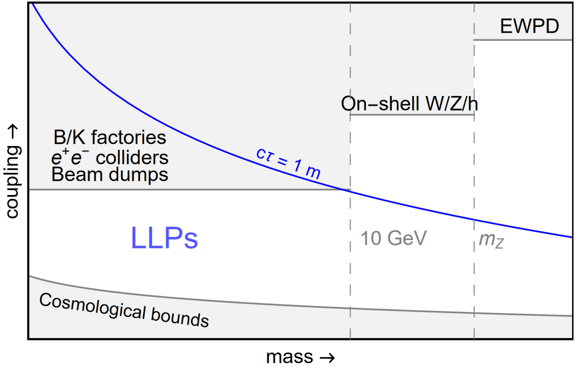
1. Energy	2. Intensity (operators)	3. Intensity (particles)
New physics is heavy but may be produced by increasing $\sqrt{s}$	New physics is too heavy to be produced but induces detectable effective interactions	New physics is light and feebly-coupled but may be detected if increasing intensity

Positioning SHiP on a landscape of new physics searches II

Frontier 3

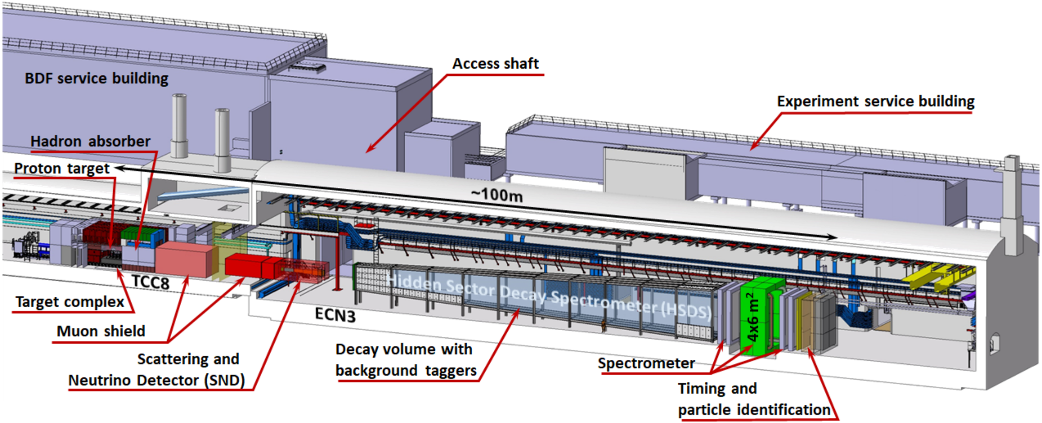
- Particle X with mass m and coupling $g \ll 1$
- $c\tau_X\gamma_X \propto g^{-2}m^{-\alpha}$: light Particles are Long-Lived (LLPs)
- Probing LLPs – maximize $N_{\text{ev}}/\sqrt{N_{\text{bg}}}$, with

$$N_{\text{ev}} \simeq N_{\text{prod}} \times \epsilon_{\text{geom}} \times \times \Delta z/(c\tau_X\gamma_X) \times \epsilon_{\text{det}} \quad (1)$$



- Complicated to probe with LHC: large N_{bg} and/or small $\epsilon_{\text{geom}} \cdot \epsilon_{\text{det}}, \Delta z$
- Complicated to probe with FCC-ee: small N_{prod}

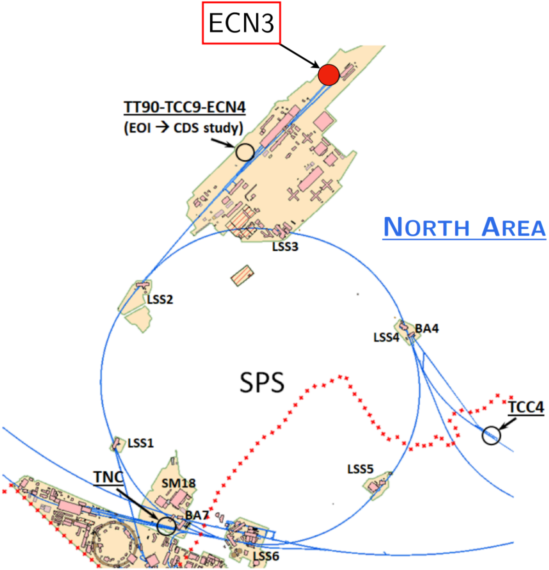
Positioning SHiP on a landscape of new physics searches III



SHiP: beam dump experiment to explore GeV-mass LLPs

Ingredients. 1. Facility, beam, and target I

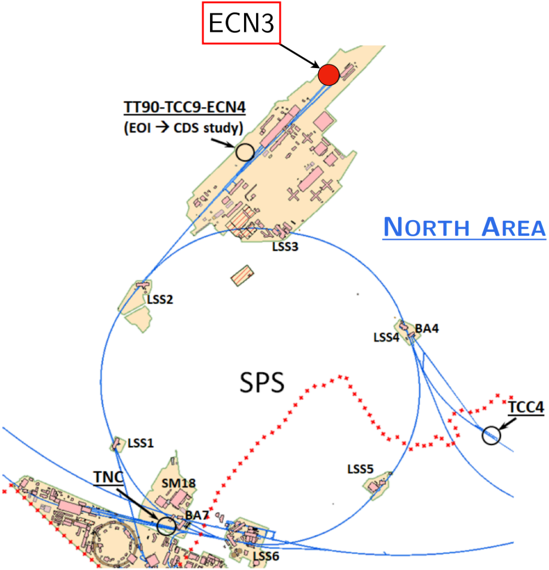
- **Location: CERN SPS**. Proton beam $\boldsymbol{E_p = 400}$ **GeV**
  - North Area →
  - TCC8 target hall →
  - ECN3 cavern



Ingredients. 1. Facility, beam, and target II

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
- $N_{\text{PoT,year}} = 4 \cdot 10^{19} \Rightarrow$ **15-year running time:** $N_{\text{PoT,year}} = 6 \cdot 10^{20}$



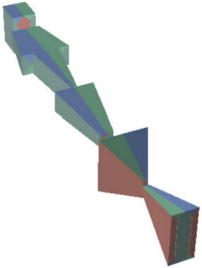
Ingredients. 1. Facility, beam, and target III

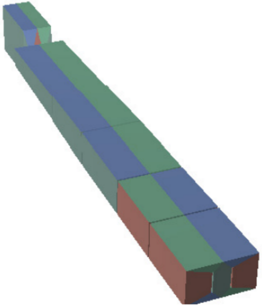
– **Thick target**
  - **12λ**
  - **Ti-Zr-Mo** alloy followed by pure **W**
  - $\mathcal{O}(2)$ cascade enhancement of the heavy flavor production

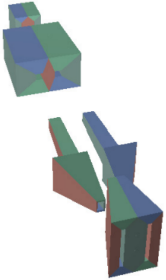
Enormous yields of heavy flavor production

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

Ingredients. 2. Muon shield

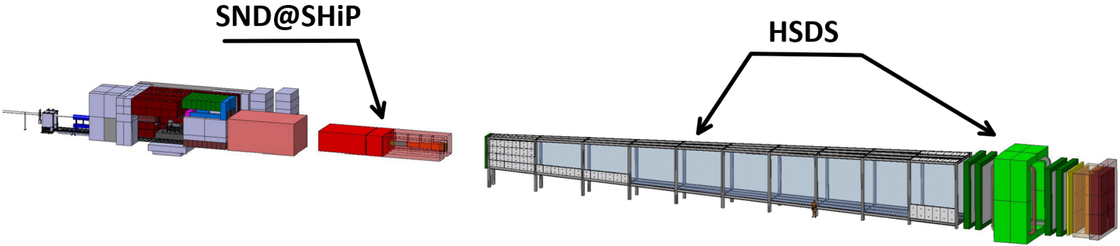






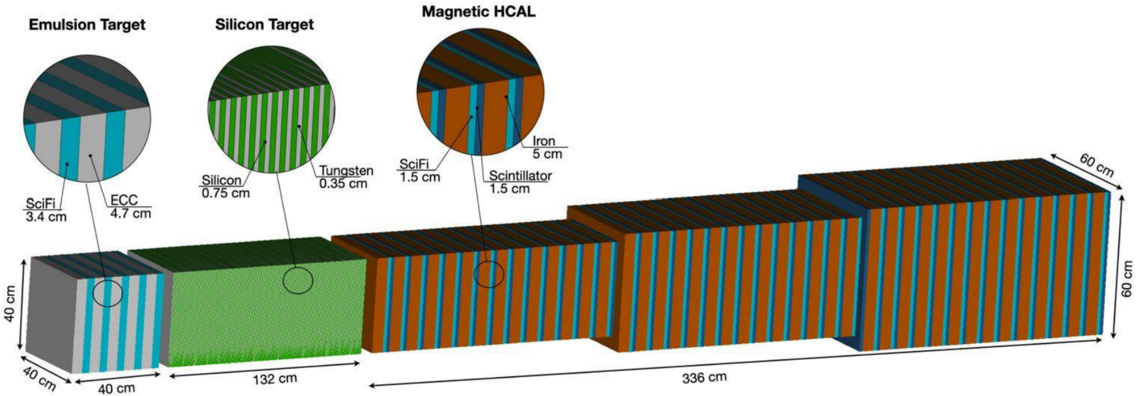
- System of magnets to reduce muon flux with $\boldsymbol{E > 10}$ **GeV** from $\mathbf{2 \cdot 10^{10}}$**/spill** by more than 6 orders of magnitude
- Subject of re-optimization because of moving to ECN3
- A few setups are considered: minimal iron yoke; + diluted with non-magnetic shielding; hybrid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

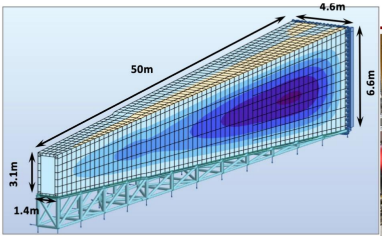


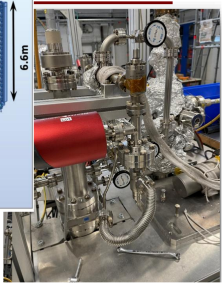
- **SND@SHiP**: Hybrid target with emulsion (experience from SND@LHC) and silicon layers, in the central yoke of the muon shield (*re-optimization in progress*)
  Previously: emulsion outside muon shield
- $\boldsymbol{\nu}$ scattering events: $\sim \mathbf{10^6}(\boldsymbol{\nu_e + \bar{\nu}_e}), \mathbf{10^7}(\boldsymbol{\nu_\mu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

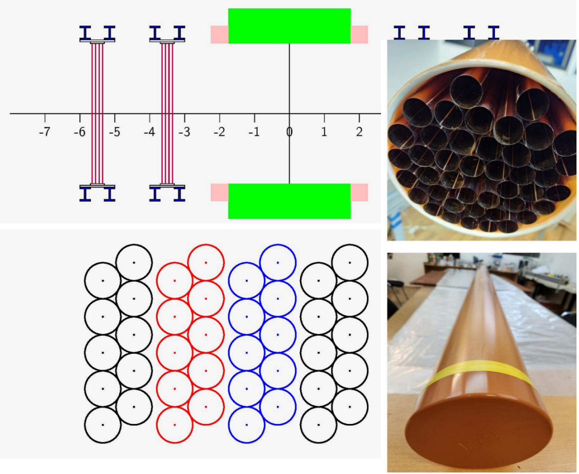
HSDS: magnet

- Power of **0.65 T · 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



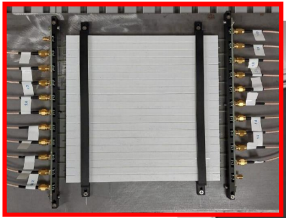
Ingredients. 2. Detectors V

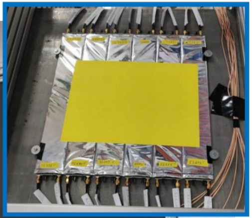
- **HSDS: PID. 20X_0** hybrid-strip ECAL+ 5λ HCAL (SplitCal)
- Pointing and full-depth PID performance match simulation

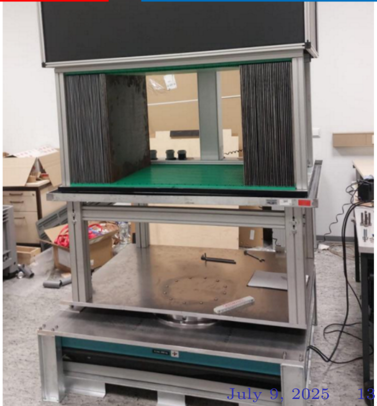
Closing the conceptual-prototype phase

- **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



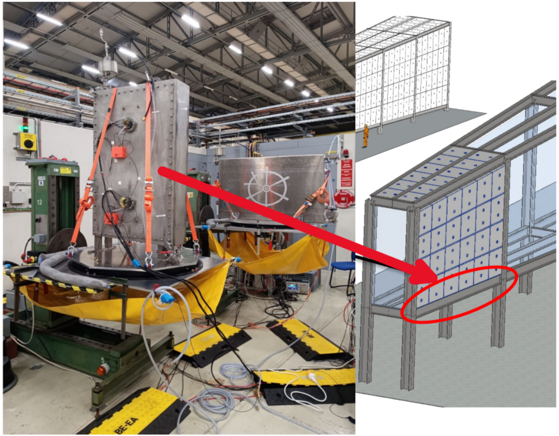




Ingredients. 3. Background taggers

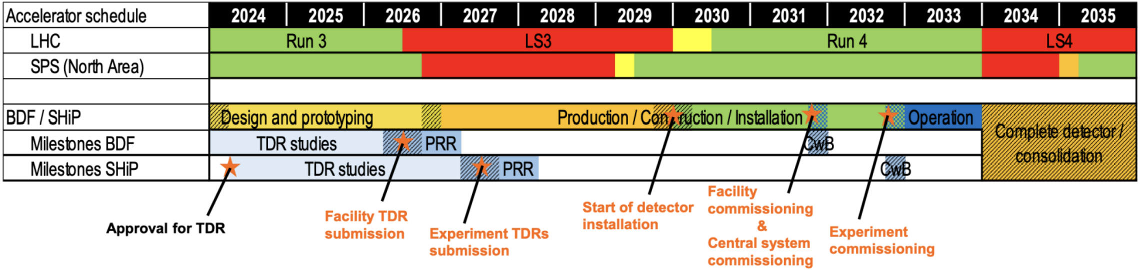
– **HSDS: SBT.** liquid scintillator surrounding cells surrounding decay vessel
  - May: performance analysis of two single-cell prototypes
  - Currently: minimizing the level of deformation with the Al-vessel equipped with SBT; optimizing the structure to reduce self-induced backgrounds

– **HSDS. UBT**: background tagger in front of the decay vessel



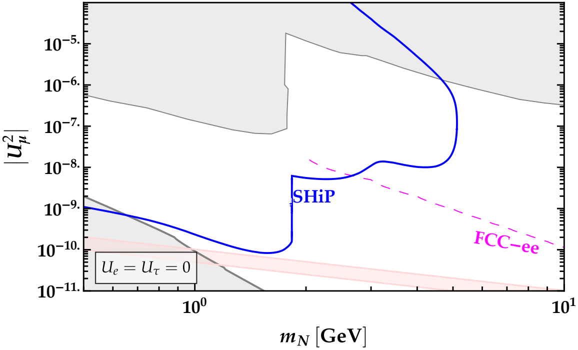
SBT+UBT+simple selection: reduce number of bg events to $< \mathcal{O}(1)$ per full running time!

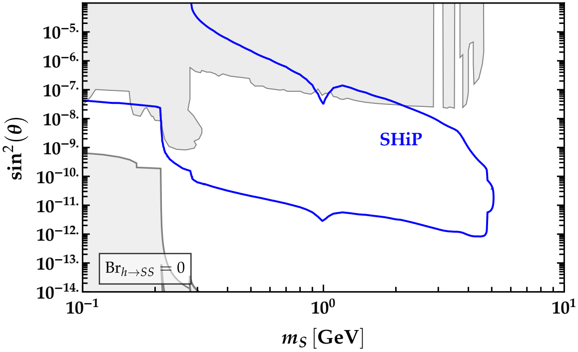
Timeline and costs



- **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**

Exploring new physics with SHiP I



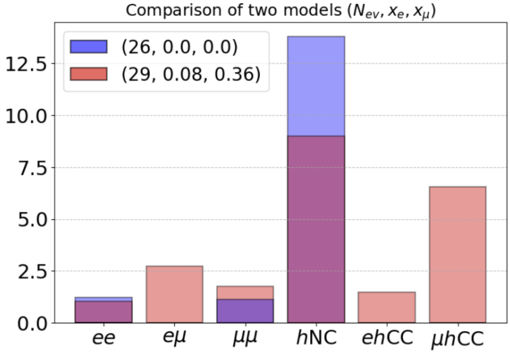


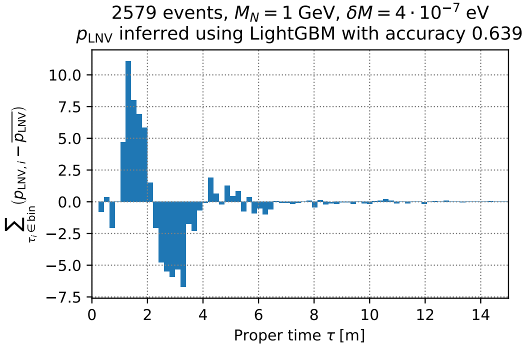
From exclusion potential...

– Probing orders of magnitude in the parameter space of various models: ALPs, dark photons, HNLs, Higgs-like scalars, inelastic DM, $\boldsymbol{B-L}$, dark QCD, neutralinos, ...

Comparison with currently running and proposed experiments: ESPP talk

Exploring new physics with SHiP II





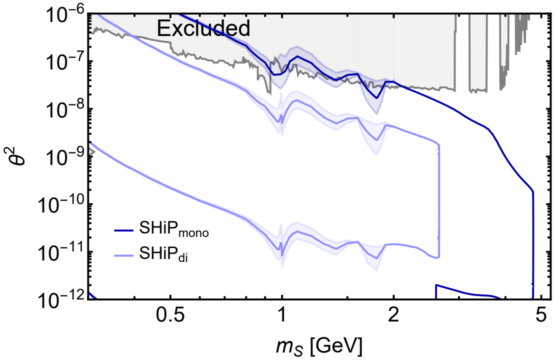
To revealing LLP properties in case of discovery

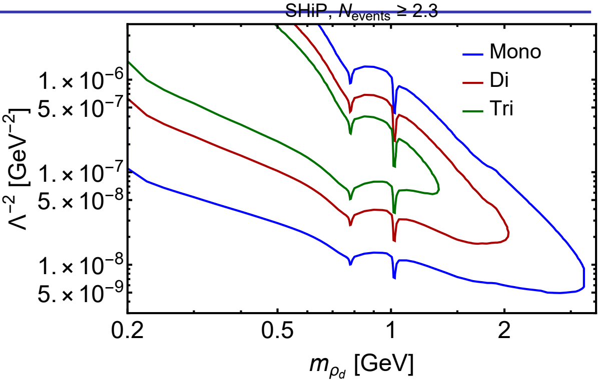
Searching for events with 1 decay/scattering:

- Reconstructing invariant mass, spin, decay properties
- "Hidden properties" (LNV, quasi-particle mass splitting) ⇒ Relation to BSM problems

[1912.05520], [2312.05163]

Exploring new physics with SHiP III





To revealing LLP properties in case of discovery

Searching for events with two or more decays/scatterings:

- Revealing production mode
- Discriminating between LLPs with identical decay phenomenology

[2312.14868], [2503.01760], to appear

Conclusions

- SHiP: unique combination of large intensity, optimal geometry, background rejection
- Ultimate new physics exclusion and discovery potential
- Current status: transitioned from design to early hardware realization, with key prototypes (muon-shield magnets, straw tracker, calorimeter modules, tungsten target) already in fabrication or test
- A lot of underexplored directions:
  - New physics models
  - Non-trivial signatures
  - Exploring QCD
- Neutrino physics performance

You are very welcome to join!

Collaboration

36 institutes from 18 countries + CERN

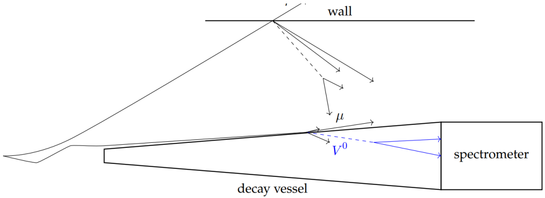
Backup slides

Backgrounds at SHiP

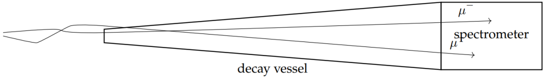
- Background studies: full GEANT4 simulation, with the muon flux generation generated on test beam flux
- Background reduction:
  - Pre-selection (DOCA$<$ **10 cm**+IP$<$ **2.5 m**+good-quality tracks)
  - SBT+UBT

Background rates per 15-year time:

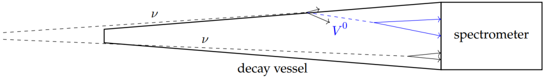
Muon comb	$< \mathbf{10^{-4}}$
$\boldsymbol{\mu}$ DIS	$< \mathbf{0.2}$
$\boldsymbol{\nu}$ DIS	$< \mathbf{0.3}$



(a) Muon Deep Inelastic Scattering (DIS)

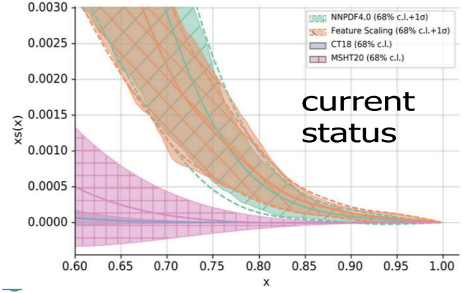


(b) Muon combinatorial

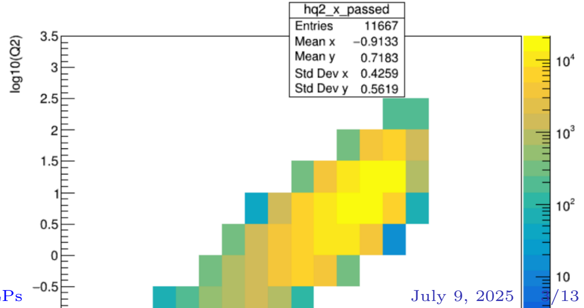


(c) Neutrino inelastic scattering

Neutrino physics at SHiP



- ν_τ cross-section measurements
- Measurement of F_4, F_5 parametrizing ν DIS reactions
- Measurements of PDFs
- Checking lepton flavor universality
- Measurements of V_{cd}



Exploring new physics with SHiP I

"Portals" – lowest-dimensional gauge-invariant operators with LLPs:

Model	**(Effective) Lagrangian**	**What it looks like**
HNL N	$Y\bar{L}\tilde{H}N + \text{h.c.}$	Heavy neutrino with interaction suppressed by $U \sim \frac{Y v_h}{m_N} \ll 1$
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 $\frac{f_\pi}{f_a} \ll 1$
...	...	...

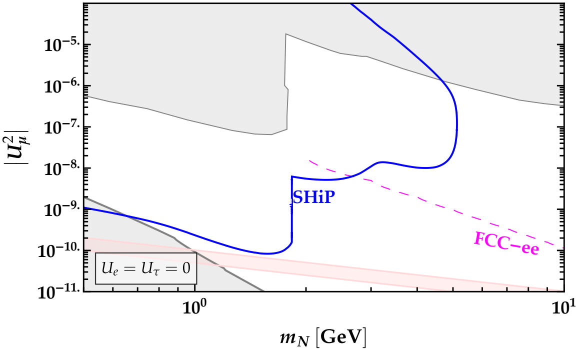
Exploring new physics with SHiP II

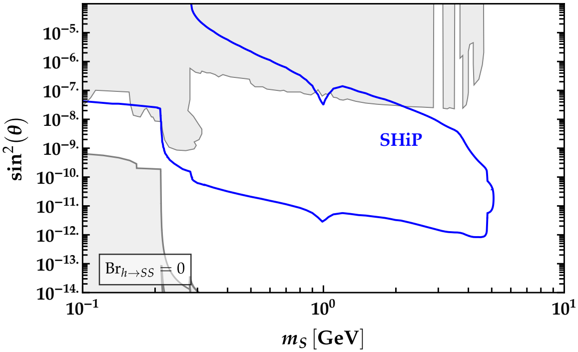
Model	(Effective) Lagrangian	What it looks like
MCPs χ	$\kappa e\bar{\psi}\gamma^{\mu}\psi A_{\mu}$	Millicharged particle
Quasi-elastic DM χ	$g_d\bar{\chi}\gamma_{\mu}\chi V^{\mu}$	Stable particles coupled via dark photons V
Inelastic dark matter χ', χ	$g_d\bar{\chi}'\gamma_{\mu}\chi V^{\mu} + \text{h.c.}$	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
...	...	...

Simulation tools:

- SensCalc
- EventCalc@SHiP

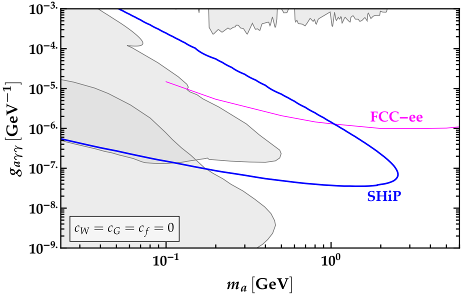
Exclusion potential: examples I

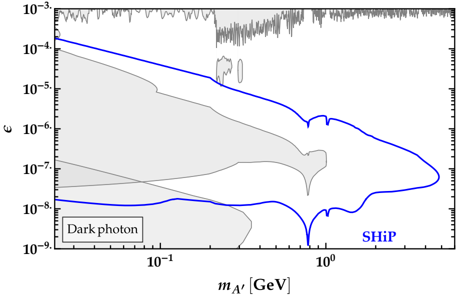




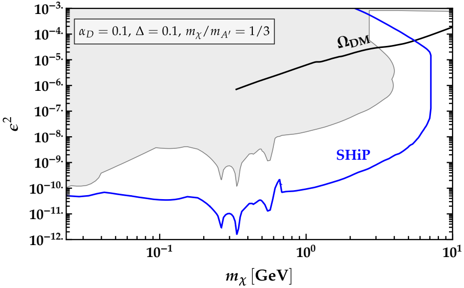
– **Heavy flavor machine**: efficient production of HNLs, Higgs-like scalars, ALPs coupled to fermions,. . .

Exclusion potential: examples II



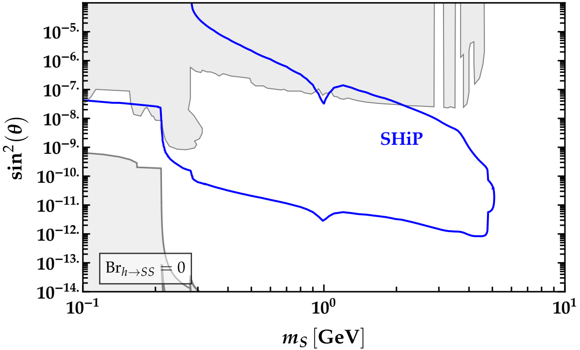


– **On-axis placement**: excellent sensitivity to
- Photonic ALPs
- Dark photons
- Inelastic DM,. . .



Discovery potential I

– SHiP may probe orders of magnitude of unexplored parameter space
– $\mathcal{O}(1000)$ events may be observed in case of **discovery**



What is discovery potential?

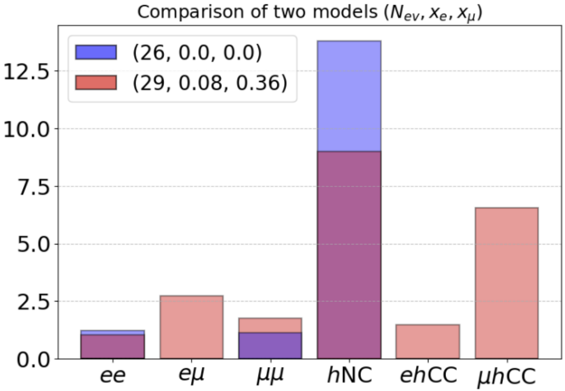
Discovery potential II

Simple signatures – “mono”-events

– Reconstructing decay modes and kinematics ⇒ identifying particle’s spin and decay operators
ECAL+PID+magnetic field

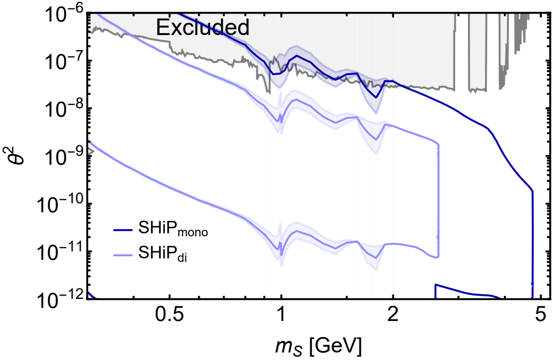
– **HNL case as an example:**

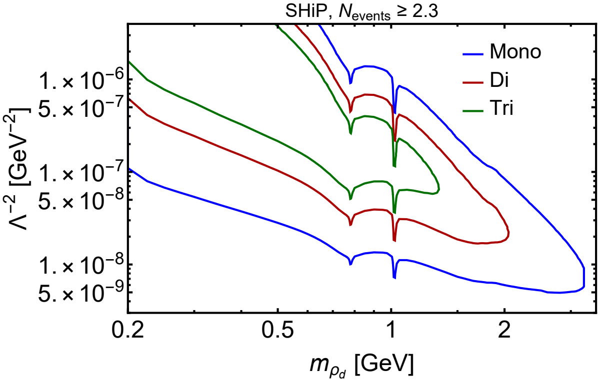
- Extracting mixing pattern
- Checking consistency with neutrino oscillations
- Resolving HNL-anti-HNL oscillations and measuring mass splitting



[1912.05520], [2312.05163]

Discovery potential III





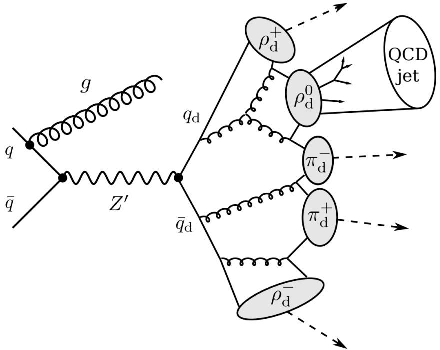
– Less trivial signatures: **n-bangs** (scattering+decay, 2/3/n decays per events)
– Essential for differentiating between the models

[2312.05163], [2503.01760], in preparation

What if simple signatures are not enough? I

Different models may have the same "mono"-events

- **Inelastic DM:**
  - Add $\boldsymbol{A'\chi'\chi'}$ vertex
    (vs models with $\boldsymbol{A'\chi'\chi}$ *only)*
  - Make $\boldsymbol{h_d}$ visible
    (vs Higgs-like scalars)
- **Portals:**
  - Dark QCD vs portals
    Dark pions vs ALPs, dark $\boldsymbol{\rho}$*s vs dark photons*
  - Mediators with/without quadratic coupling to SM
    LLPs $\boldsymbol{X}$ *with vs without* $\boldsymbol{hXX}$ *coupling*

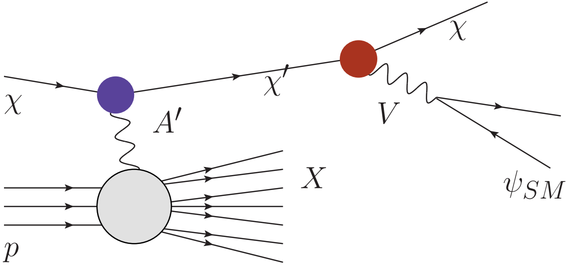


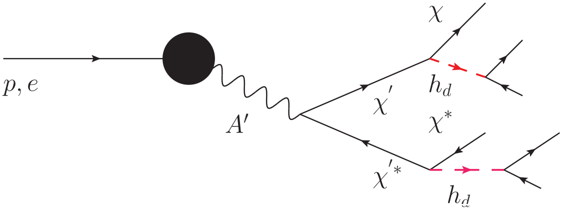
May be distinguished by production, but accelerator-based experiments (typically) do not see it!

Solution: "multi-bang" events I

n-decays:

- DM: decays $\chi^*\chi^*, \chi^* h_d, h_d h_d$
- Portals: $SS, NN, n\rho_d/n\pi_d$





Scatterings + decays:

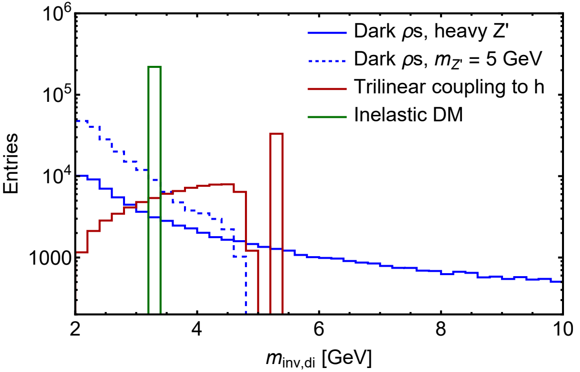
- DM: scatterings $\chi + p/e \to \chi' + X$ followed by $\chi' \to \chi + \mathbf{X'}$
- Portals: neutrino upscattering + decay

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

Solution: “multi-bang” events II

n-decays as an example:

- Access to correlated distributions of the decaying particles: $\boldsymbol{c\tau, m_{\rm inv}}$
- $\boldsymbol{m_{\rm inv,di}}$: may allow identifying the production without seeing it



n-decays may be observed at experiments with large intensity

[2503.01760]+backup