# The SHiP experiment at CERN

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on behalf of SHiP Collaboration

Humboldt University of Berlin

Light Dark Matter @ Accelerators (LDMA)
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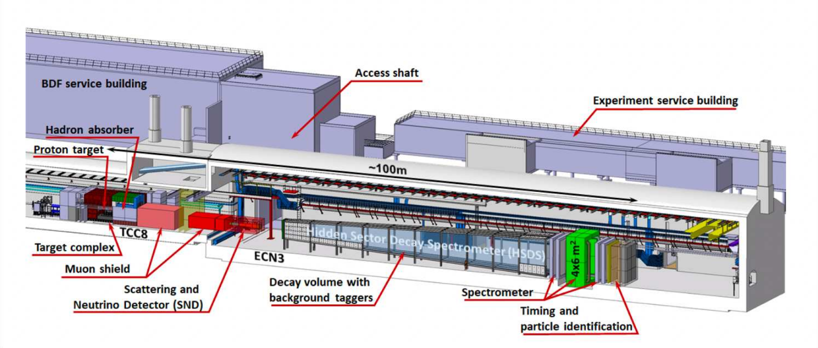
# Search for Hidden Particles (SHiP)

- SHiP is a general-purpose experiment that will be located at the SPS to search for signal of feebly interacting particles (FIPs) predicted by many Beyond Standard Model theories.
- Strong neutrino program focused on tau-neutrino studies.
- Proposed in 2013, **green light** for Technical Design Report preparation in 2024.

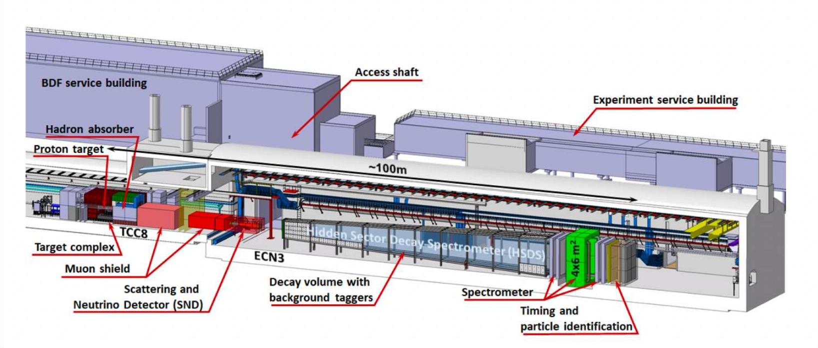


# Search for Hidden Particles (SHiP)

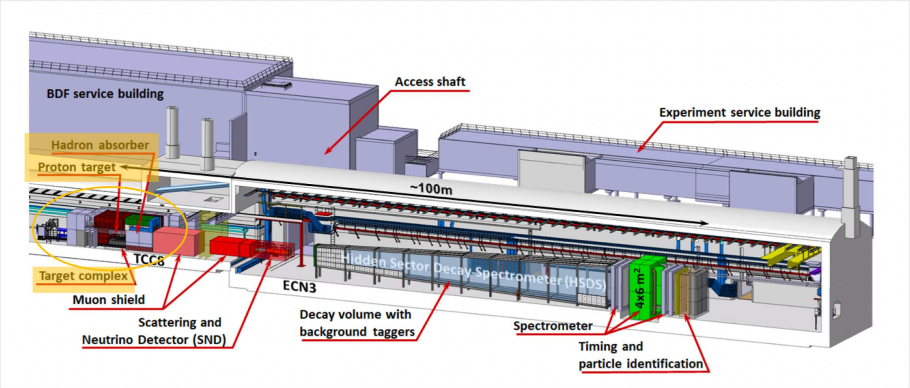
- Beam: SPS 400 GeV protons with $4 \times 10^{19}$ protons-on-target (PoT)/year $\Rightarrow 6 \times 10^{20}$ PoT/15 years
- 2 subdetectors:
  - Hidden Sector Detector (HSD)
  - Scattering and Neutrino Detector (SND)

**Per year:**

- $\simeq 10^{17}$ charmed hadrons.
- $\simeq 10^{13}$ beauty hadrons.
- $\mathcal{O}(10^4)$ $\nu_\tau$ interactions in SND.

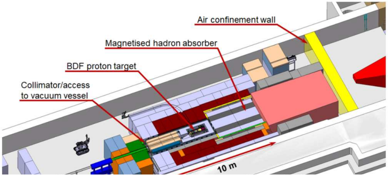


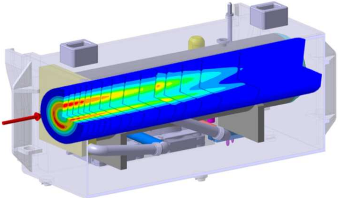
# Target Design

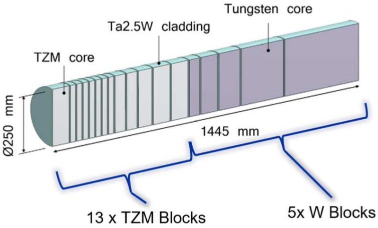


# Target & Hadron Stopper

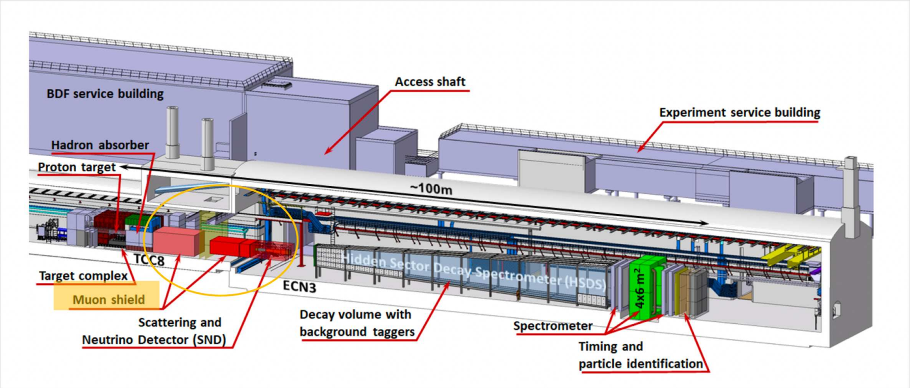
- **Very thick**: use full beam and secondary interactions ($12\lambda$)
- **High-A & Z**: maximize production cross-sections (Mo/W)
- **Short $\lambda$ (high density)**: stop pions/kaons before decay
- $4 \times 10^{19}$ protons on target per year currently available in the SPS
- Beam spot $\sim 1$ cm.



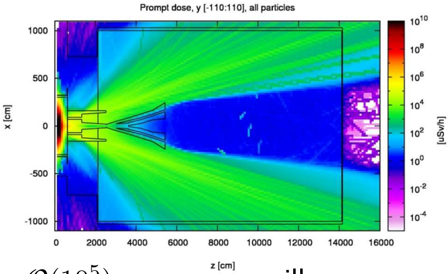


# Magnetic Muon Shield

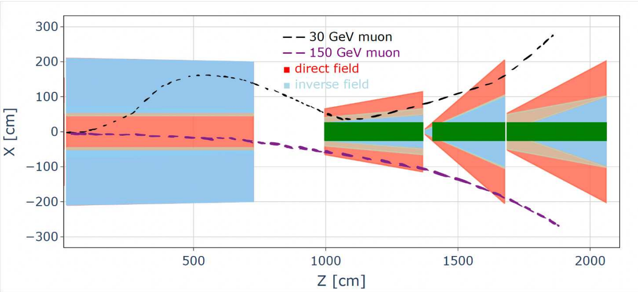


# Magnetic Muon Shield

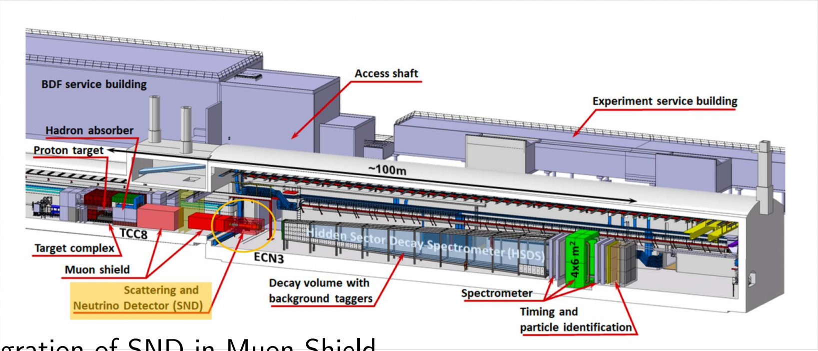
- Active deflection of $\mu$ with E $>$ 10GeV
- Two possible options: fully warm and hybrid with superconducting technology



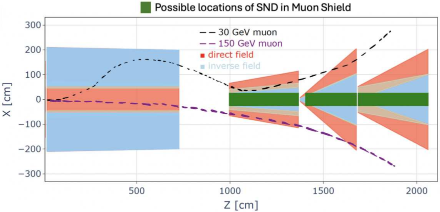

Reduction of $\mu$ rate: $\mathcal{O}(10^{10})$ muons $\Rightarrow$ $\mathcal{O}(10^{5})$ muons per spill (spill $= 1$ sec).



# Scattering & Neutrino Detector (SND)




## Integration of SND in Muon Shield

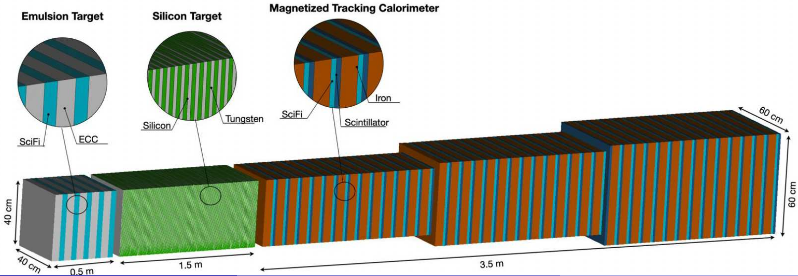


# Scattering & Neutrino Detector (SND)

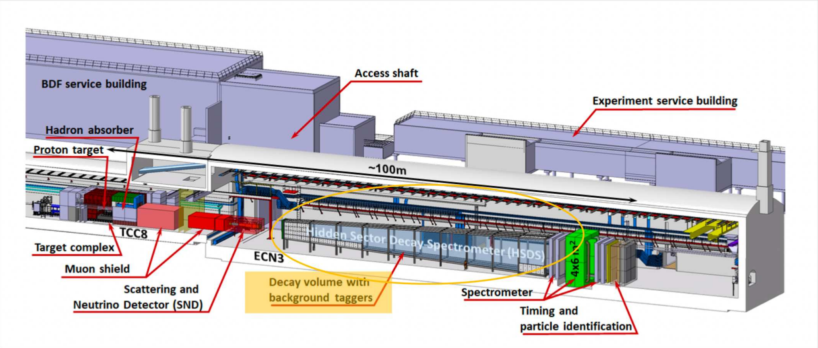
- SND: rich tau-neutrino and light dark matter (LDM) program
- Subsystems:
  - Emulsion & Silicon target: high precision tracking & vertex reconstruction
  - Magnetized Tracking Calorimeter: reconstruction of muon and hadronic showers
- Expected number of neutrino interactions:

$$\simeq 10^6[\nu_e + \bar{\nu}_e] + 10^7[\nu_\mu + \bar{\nu}_\mu] + 10^5[\nu_\tau + \bar{\nu}_\tau]$$

- Optimization to maximize tau-neutrino and LDM physics case.



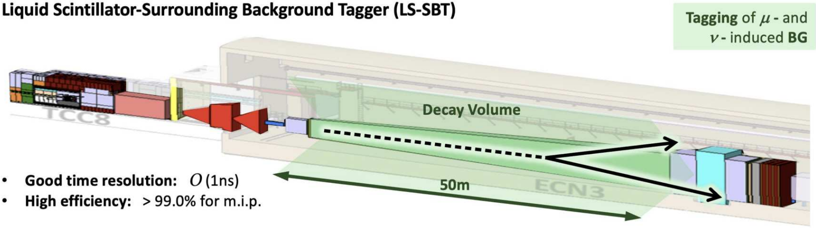
# Hidden Sector (HS) Decay Volume



# Hidden Sector (HS) Decay Volume. SBT

- The fiducial **decay volume** is a pyramidal frustum with a length of **50 meters**
  - $1.0 \times 2.7\,\mathrm{m}^2$ at the upstream end
  - $4 \times 6\,\mathrm{m}^2$ at the downstream end
- **He** at atmospheric pressure
- Lightweight structure (Al / stainless steel)
- **Support** for Liquid Scintillator-Surrounding Background Tagger **LS-SBT** integration

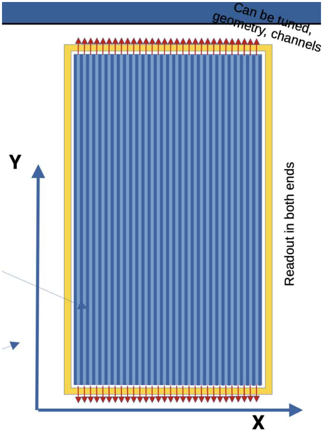
**Liquid Scintillator-Surrounding Background Tagger (LS-SBT)**



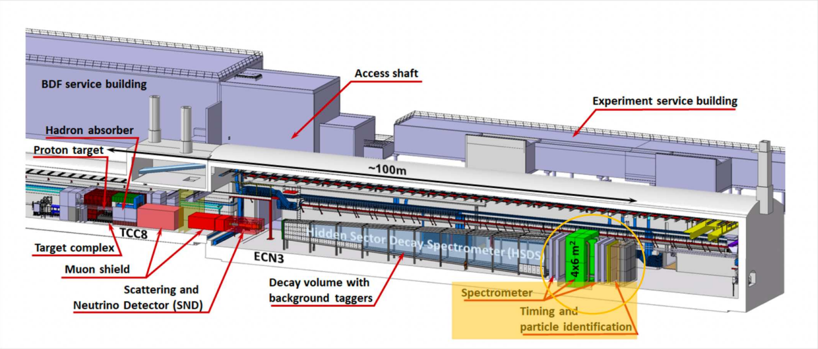

- **Good time resolution:** $O$(1ns)
- **High efficiency:** > 99.0% for m.i.p.

# Hidden Sector (HS) Decay Volume. UBT

- Upstream Background Tagger (UBT) in the beginning of the decay volume: veto muons coming from Muon shield
- Modules composed of two 6 gaps RPCs glass stack.
  - Strips 30 mm width (placed in the middle of two stacks) readout in both sides.
  - Active area of 1500x1200 $\text{mm}^2 = 1.8\ \text{m}^2$
  - Good time precision, $< 50$ ps $\sigma$.
  - Good efficiency, $> 98$ %
  - Easy to build.
  - Low multiplicity, few particles per module.

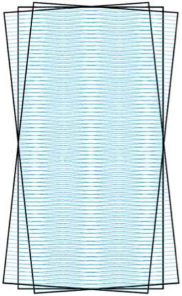


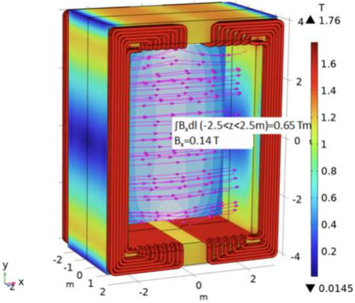
# Hidden Sector (HS) Decay Spectrometer



# Hidden Sector (HS) Decay Spectrometer

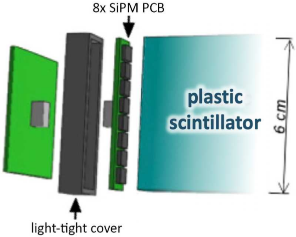
- **Large aperture:** 4.0m $\times$ 6.0m
- **Precise track reconstruction:** $< 120\ \mu m$
- **High hit efficiency:** $> 99.0$ %
- Cu/Au-coated Mylar drift tubes (NA62 design)
- 2$\times$ 2 stations of 4 double layers at $10^\circ$ stereo angle, 10 000 channels altogether
- **Magnet** (NC baseline): 0.65Tm / 0.15T

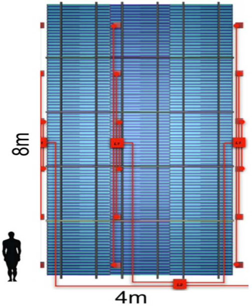


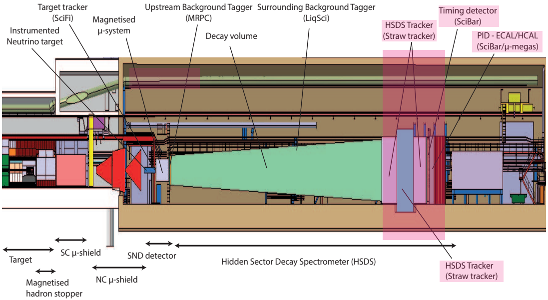


# Hidden Sector (HS) Decay Spectrometer: Timing Detector

- **High time resolution:** $< 100$ ps
- **EJ200 plastic scintillator bars:**
  - Dimensions: 135 cm $\times$ 6 cm $\times$ 1 cm
- Readout at both ends by SiPM arrays
- 3 columns of 111 vertically staggered bars (5 mm overlap), 666 channels altogether
- **ToF (Time of Flight) identification of particle decay products**



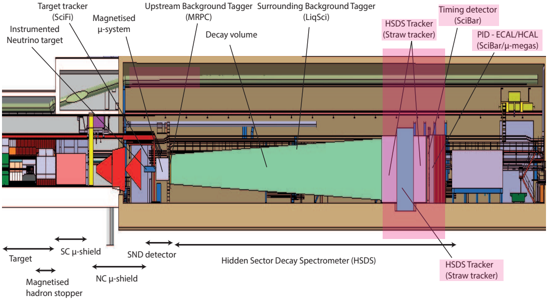



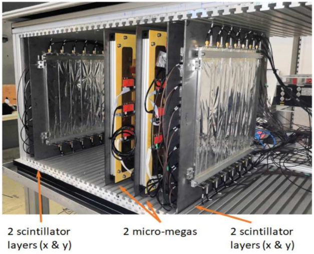
# Hidden Sector (HS) Decay Spectrometer: PID

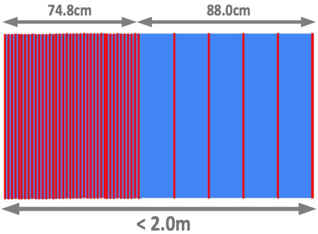
Particle Identification (PID) & Calorimeter (ECal / HCal)

- Reliable pID & $\mu/\pi$ separation
- Electromagnetic shower reconstruction: $< 5$mrad for $\gamma\gamma$ final states
- **Electromagnetic sampling calorimeter (ECal):** 40 layers of Fe absorbers ($1/20\lambda$) & plastic scintillators
- **Compact hadron sampling calorimeter (HCal):** 5 layers of Fe absorbers (1 $\lambda$ each) & plastic scintillators
- Total nuclear interaction length: 7 $\lambda$
  - $+\,1-3$ MicroMeGaS high-precision layers




Detector planes without absorber layers



# Targeted Physics Signatures

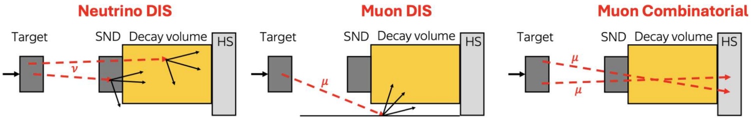
- Sensitivity depends on:
  - PoT
  - Acceptance (lifetime and angular acceptance)
  - Background level

- Signal reconstruction:
  - Tracking to reconstruct decay vertex of charged final state
  - Calorimeters to measure neutral candidates and invariant mass.
  - Particle identification to distinguish models

| | Physics model | Final state |
|---|---|---|
| HSDS | SUSY neutralino | $\ell^{\pm}\pi^{\mp},\ \ell^{\pm}K^{\mp},\ \ell^{\pm}\rho^{\mp}, \ell^{+}\ell^{-}\nu$ |
| | Dark photons | $\ell^{+}\ell^{-}, 2\pi, 3\pi, 4\pi, KK, q\bar{q}, D\bar{D}$ |
| | Dark scalars | $\ell\ell, \pi\pi, KK, q\bar{q}, D\bar{D}, GG$ |
| | ALP (fermion coupling) | $\ell^{+}\ell^{-}, 3\pi, \eta\pi\pi, q\bar{q}$ |
| | ALP (gluon coupling) | $\pi\pi\gamma, 3\pi, \eta\pi\pi, \gamma\gamma$ |
| | HNL | $\ell^{+}\ell'^{-}\nu, \pi l, \rho l, \pi^{0}\nu, q\bar{q}'l$ |
| | Axino | $\ell^{+}\ell^{-}\nu$ |
| | ALP (photon coupling) | $\gamma\gamma$ |
| | SUSY sgoldstino | $\gamma\gamma, \ell^{+}\ell^{-}, 2\pi, 2K$ |
| SND | LDM | electron, proton, hadronic shower |
| | $\nu_{\tau},\ \overline{\nu}_{\tau}$ measurements | $\tau^{\pm}$ |
| | Neutrino-induced charm production $(\nu_e, \nu_\mu, \nu_\tau)$ | $D_s^{\pm},\ D^{\pm},\ D^{0},\ \overline{D^{0}},\ \Lambda_c^{+},\ \overline{\Lambda_c}^{-}$ |

# Background @ SHiP

- SHiP's search for FIP decay signatures is designed to be performed in a **near-zero background** environment
- Use simple criteria to suppress backgrounds whilst keeping high signal efficiency, valid for all signals




| Criterion | Requirement |
|---|---|
| Track momentum | $> 1.0\,\mathrm{GeV}/c$ |
| Track pair distance of closest approach | $< 1\,\mathrm{cm}$ |
| Track pair vertex position in decay volume | $> 5\,\mathrm{cm}$ from inner wall |
| | $> 100\,\mathrm{cm}$ from entrance (partially) |
| Impact parameter w.r.t. target (fully reconstructed) | $< 10\,\mathrm{cm}$ |
| Impact parameter w.r.t. target (partially reconstructed) | $< 250\,\mathrm{cm}$ |

# Signal Studies I. Heavy Neutral Leptons

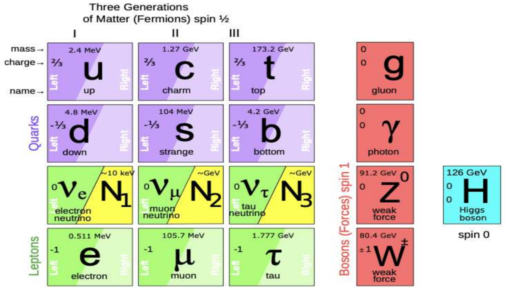
Production processes:

- D (charm) & B (beauty) mesons decays

Detection:

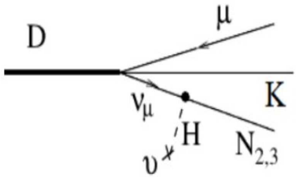
- decays into charged leptons, hadrons

**Neutrino Minimal Standard Model** $\nu MSM$
extension of the SM by adding a 3 right-handed (Majorana) HNL

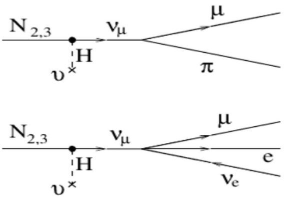



- $N_1$ ( $\sim$ **10 keV) Dark Matter** candidate
- $N_{2,3}$ **($\sim$ GeV)** origin of **neutrino masses** and **Leptogenesis & baryon asymmetry** of the Universe

## production

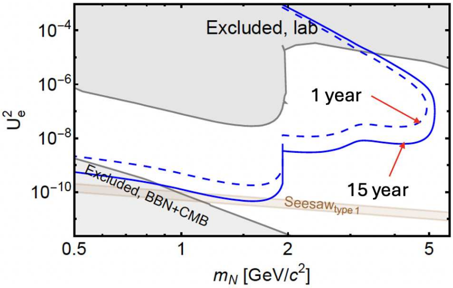



## detection



# Signal Studies I. Heavy Neutral Leptons

- 1y sensitivity covers huge fraction of parameter space
- Reaching the fundamental see-saw theoretical limit needs 15y



# Study the Properties of LLPs

## A Closer Look at HNLs

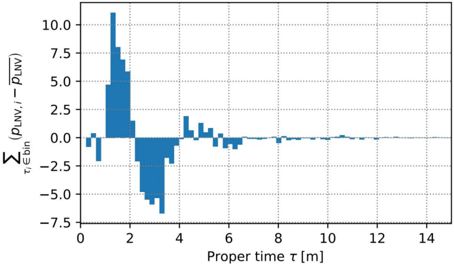
- Two observable $\nu$ mass differences $\Rightarrow$ at least two different HNLs, $N_{1,2}$, are required.
- The HNL mass difference $\Delta m \equiv m_{N_1} - m_{N_2}$ may be arbitrary.
- For small $\Delta m \ll m_{N_{1,2}} \approx m_N$ and similar mixings $U^2$, $N_{1,2}$ form a quasi-degenerate system.
- However, $N_1 \leftrightarrow N_2$ oscillations occur with frequency $\omega_{\text{osc}} = \Delta m^{-1}$.
- A small $\Delta m$ leads to resonant enhancement of lepton-number-violating processes in the Early Universe $\Rightarrow$ HNL-driven BAU becomes possible.
- Depending on the mixing pattern $U_e^2 : U_\mu^2 : U_\tau^2$, HNLs may also explain active neutrino masses.

*[hep-ph/0605047]* + credits to Maksym

# Study the Properties of LLPs

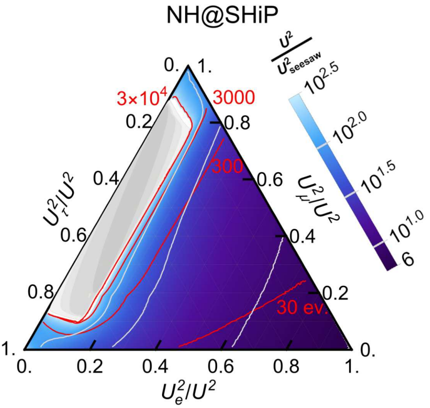
- Oscillations $N_1 \leftrightarrow N_2$ can be resolved and $\Delta m$ measured by distinguishing lepton-number-violating (LNV) from lepton-number-conserving (LNC) events.
- This information is encoded in the angular distributions of the decay products due to helicity conservation.

*[1912.05520]*



# Study the Properties of LLPs

- By reconstructing HNL decay modes, one can extract the mixing ratios $U_\alpha^2/U^2$.
- By varying $\theta_{ij}$, $\delta_{\mathrm{CP}}$, and $\Delta m_{ij}^2$ within their uncertainty ranges, one can derive the allowed regions of $U_\alpha^2/U^2$ for a given neutrino mass hierarchy.
- Around $100$–$1000$ events are required to test the neutrino hierarchy and probe the Majorana phase.



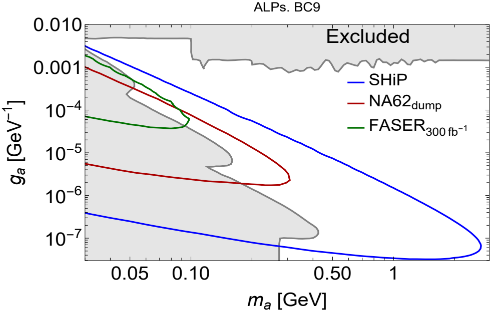

[2312.05163]

# Signal Studies II. Axion-Like Particles (ALPs)

- **Production processes:** B meson decays, pseudoscalar mixing, Primakoff scattering
- 90% CL, assuming $6 \times 10^{20}$ p.o.t. per 15 years

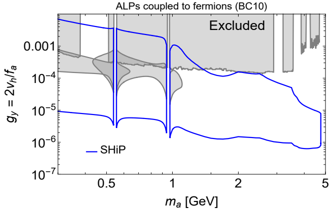
## $g_a$ (BC9): Exclusive photon coupling

$$\mathcal{L}_{\text{int}} = \frac{g_a}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



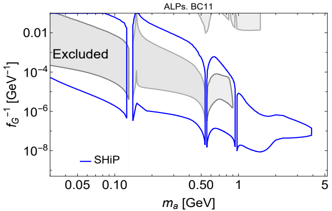

### $g_\gamma$ (BC10): Exclusive fermion coupling

$$\mathcal{L}_{\text{int}} = \frac{g_Y}{2 v_H} (\partial_\mu a) \sum_\alpha \bar{f} \gamma^\mu \gamma_5 f$$




### $f_G$ (BC11): Exclusive gluon coupling

$$\mathcal{L}_{\text{int}} = g_a \frac{\alpha_s}{4\pi} a G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

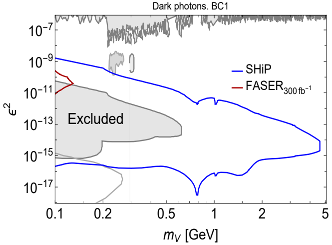


# Signal Studies III: Dark photons & Dark scalars

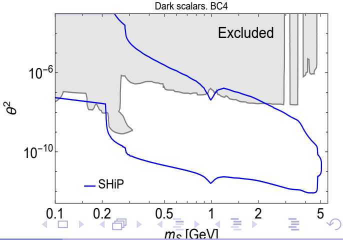
90% CL, assuming $6 \times 10^{20}$ p.o.t. per 15 years

- **Dark Photons:**
  - Mediate interactions between the dark sector and the Standard Model (SM)
  - **Production Mechanisms:**
    - from neutral meson decays such as $\pi^0$, $\eta$, and $\eta'$
    - via bremsstrahlung from high-energy protons
    - through quark-antiquark annihilation
- **Dark Scalars:**
  - Mix with the Higgs boson
  - **Production Mechanisms:**
    - **B Meson Decays**
    - Particularly through exclusive decays involving resonances with $s$ or $d$ quarks.

**Sensitivity to dark photons: $\varepsilon^2$ (BC1)**




**Sensitivity to dark scalars: $\theta^2$ (BC4)**



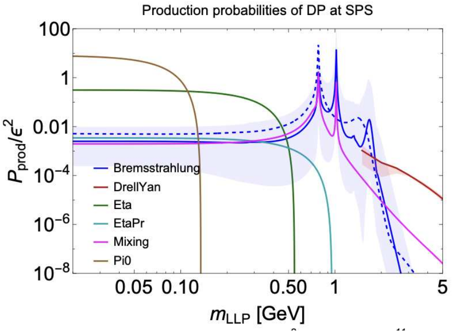
# LDM studies I

- Light dark matter coupled to dark photons:

$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} V^{\mu\nu} + |D_\mu \chi|^2$$

- Production in case of $m_\chi < m_V/2$ is $V \to \chi\bar{\chi}$
- Main signature – scatterings inside SND@SHiP:

$$\chi + e \to \chi + e,\ \chi + p \to \chi + p.$$



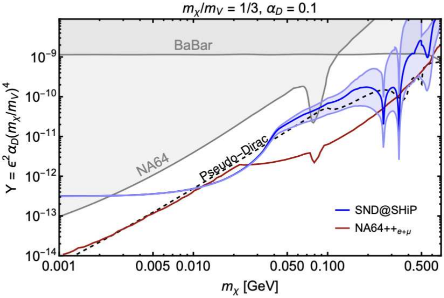

The production probability of the pair $\chi, \bar{\chi}$ as the function of $m_V$

# LDM studies I

- Main signature – scatterings inside SND@SHiP:

$$\chi + e \to \chi + e,\ \chi + p \to \chi + p.$$

- Main background - $\nu$ interactions with the same event topology
- Eliminating $\nu$DIS needs perfect veto for extra tracks




*Pure exclusion potential*

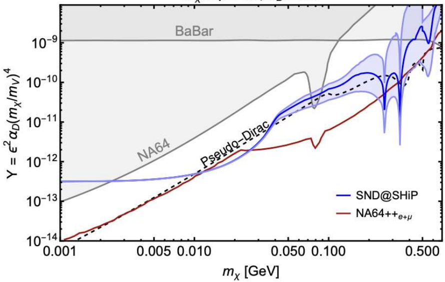
| | $\nu_e$ | $\bar{\nu}_e$ | $\nu_\mu$ | $\bar{\nu}_\mu$ | all |
|---|---|---|---|---|---|
| Elastic scattering on $e^-$ | 260 | 135 | 320 | 210 | 925 |
| Quasi - elastic scattering | - | 45 | | | 45 |
| Resonant scattering | - | - | | | - |
| Deep inelastic scattering | - | - | | | - |
| Total | 260 | 180 | 320 | 210 | 970 |

# LDM studies I

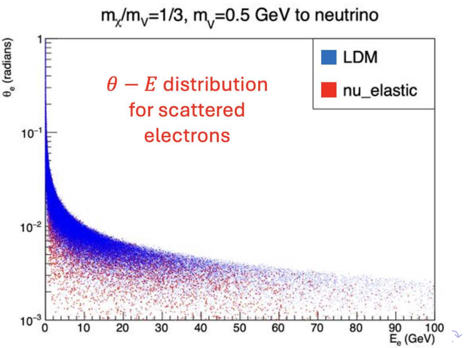
- Main signature – scatterings inside SND@SHiP:

$$\chi + e \to \chi + e,\ \chi + p \to \chi + p.$$

- Main background - $\nu$ interactions with the same event topology
- Eliminating $\nu$DIS needs perfect veto for extra tracks
- Grid-search in $(\theta_e, E_e)$ parameter space. To be improved by multivariate approach.




*Pure exclusion potential*



# LDM Studies II: Inelastic Dark matter

- Inelastic dark matter model coupled via a mediator interacting with the baryon current:

$$\mathcal{L}_{\text{int}} = \bar{\chi}_1 \gamma^\mu \chi_2 A'_\mu$$

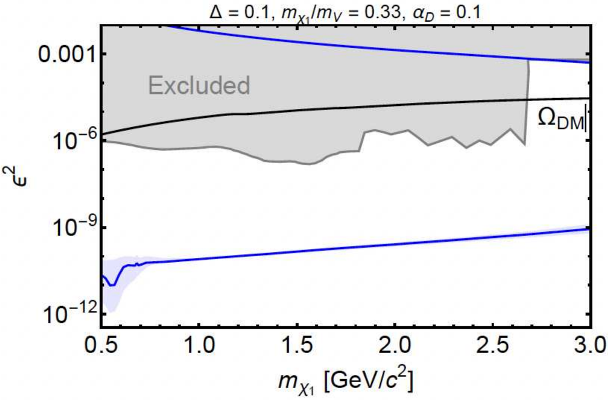
- Signatures to study:

$$\chi_1 \to \chi_2 + e^+e^-$$

$$\chi_1 + p \to \chi_1 + \text{X} \to \chi_2 + e^+e^- + \text{X}$$

$$X = \text{SM products of scattering}$$

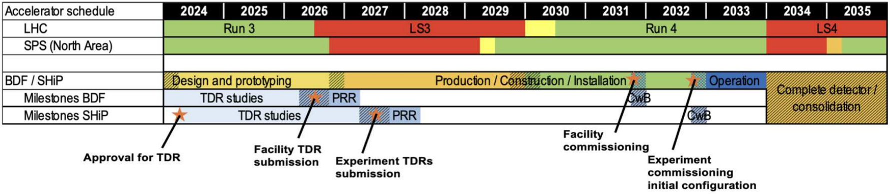
# LDM studies II: Inelastic Dark matter




ESPP 2025

# BDF/SHiP preliminary schedule

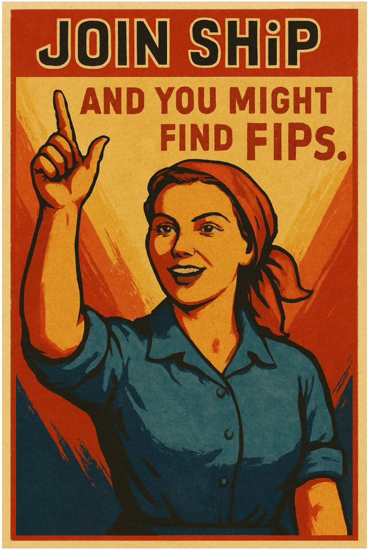
- Aim to commission and operate BDF and experiment before LS4
  - Then have LS4 to complete the detector or make any consolidation required
- Confirmation of delayed LS4 → SHiP now targeting taking commissioning data in 2032
  - TDR — submission in 2027
  - Construction needs to start in 2029
- SHiP will explore large parameter space available for FIPs before committing to the next generation of colliders!



# Outlook

- SHiP is a fixed target experiment at a new beam dump facility at CERN SPS optimised to search for feebly interacting particles
- Covers the area than cannot be covered by colliders (current and future)
- When found, measure properties of the new particles
- Further optimize event selection for higher efficiency. Utilize more modern tools such as machine learning, AI...
- Plenty of room for new ideas and opportunities for new institutes!

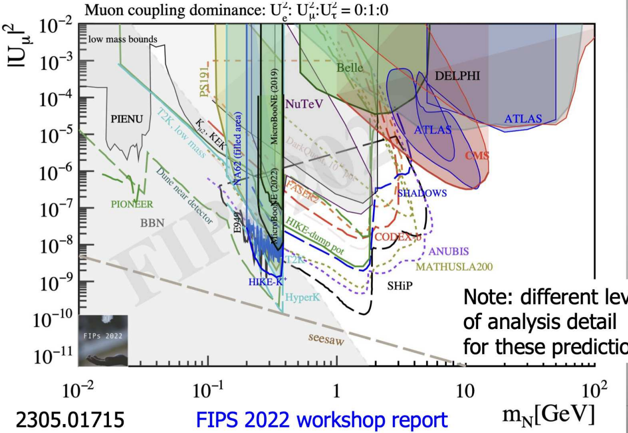
# Thank you for your attention!




(thanks to gpt4o model!)

# Backup slides

# HNL in different experiments




Note: different levels of analysis detail for these predictions

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