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

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on behalf of SHiP collaboration

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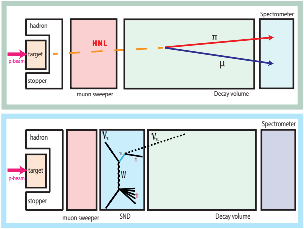
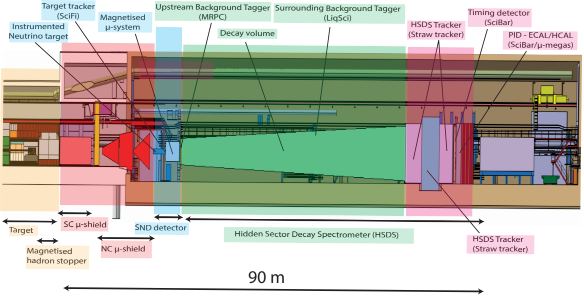
Search for Hidden Particles (SHiP)

- **SHiP** is a recently approved intensity-frontier experiment aiming to search for hidden particles with mass up to $O(10)$ GeV and extremely weak couplings, down to 10^{-10}.
- FIP decay search in background-free environment and LDM scattering
- Rich program at the Scattering & Neutrino Detector (SND): search for Light Dark Matter (LDM) & neutrino interaction physics with unique access to τ neutrino
  - Original Proposal (2013): Developed for new cavern ECN4
  - Refined Proposal (2023): Adaptation to existing ECN3 facility





SHiP experimental techniques: Decay & Scattering

Sensitivity is determined by three key factors:

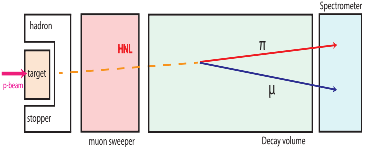
- **Yields** (protons on target)
- **Acceptance** (including lifetime and angular acceptance)
- **Background level**

An exhaustive search require "model-independent" detector configuration, which should enable:

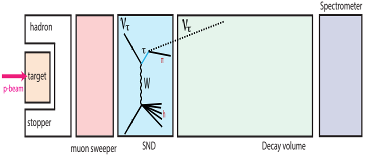
- Comprehensive reconstruction and identification of both fully and partially reconstructible modes
- Sensitivity to partially reconstructed modes
  - Distinguish between different models.
  - Assess the compatibility of the observed signal with theoretical predictions.

	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
	$\nu_\tau,\ \bar{\nu}_\tau$ measurements	$\tau^\pm$
	Neutrino-induced charm production $(\nu_e, \nu_\mu, \nu_\tau)$	$D_s^\pm,\ D^\pm,\ D^0,\ \overline{D^0},\ \Lambda_c^+,\ \overline{\Lambda_c}^-$

Visible decay to SM particles

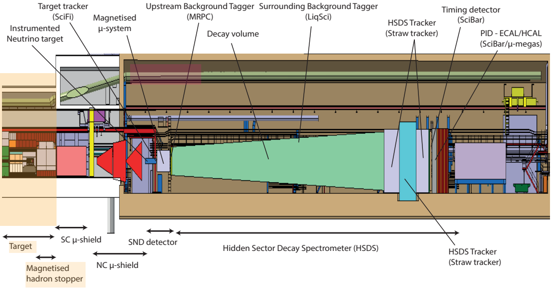


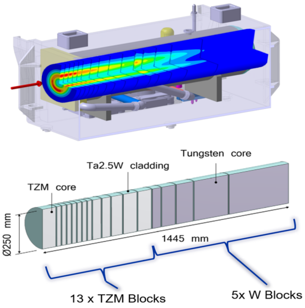
Scattering off atomic electrons and nuclei



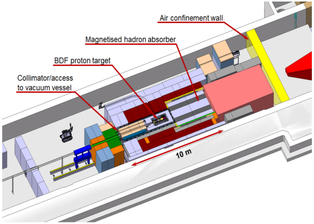
Target & Hadron Stopper

- **Very thick**: use full beam and secondary interactions (12λ)
- **High-A & Z**: maximize production cross-sections (Mo/W)
- **Short λ (high density)**: stop pions/kaons before decay
- 4×10^{19} protons on target per year currently available in the SPS
  - $\sim 2 \times 10^{17}$ charmed hadrons ($>$ 10 times the yield at HL-LHC)
  - $\sim 2 \times 10^{12}$ beauty hadrons
  - $\sim 2 \times 10^{15}$ tau leptons
  - $\mathcal{O}(10^{20})$ photons above 100 MeV
  - $3500\ \nu_\tau + \bar{\nu}_\tau$ per year, and $2 \times 10^5\ \nu_e + \bar{\nu}_e / 7 \times 10^5\ \nu_\mu + \bar{\nu}_\mu$ regardless of target design



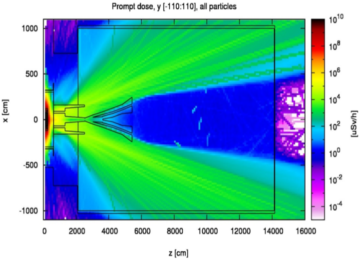


BDF baseline target design

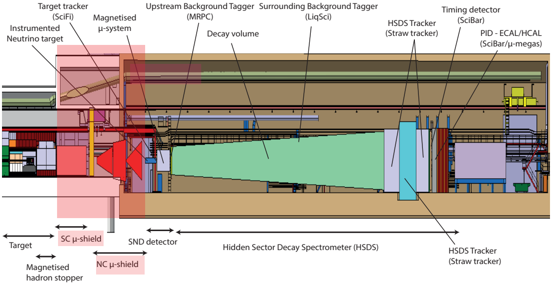


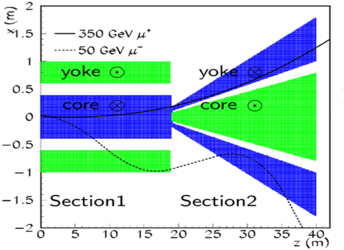
Magnetic Muon Shield

- The muon shield utilizes **an alternate-polarity scheme** to sweep out positive & negative μ to left & right of decay volume
- Active deflection of μ with E $>$ 10GeV
- **ECN3 optimisation (hybrid SC / NC)**: 5.1T Shortened, preserving experiment sensitivity
- **Initial design (NC): 1.7T**



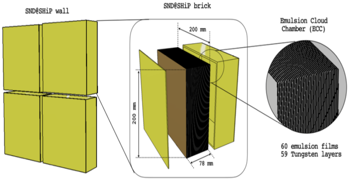
Reduction of μ rate: $2 \times 10^{10}\,\mu \rightarrow < 10^{5}\,\mu$ per spill

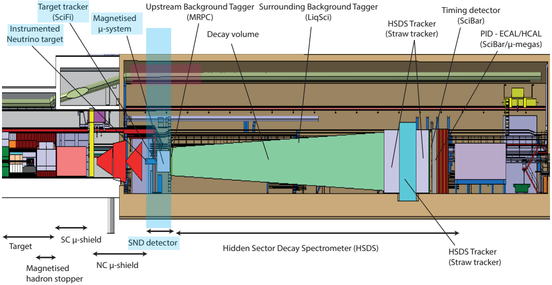


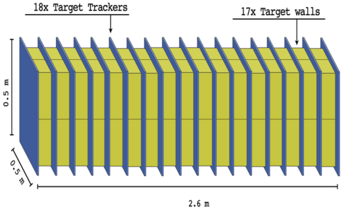


Scattering & Neutrino Detector (SND)

- Original design based on **nuclear emulsions**: DONuT / OPERA / **SND@LHC**
- Emulsion Cloud Chamber (ECC) bricks
- Target Tracker (TT): 18 layers of SciFi
- μ spectrometer: Drift tubes (4 stations)
  - Air core dipole magnet: 1 T
- **Optimisation study in process**

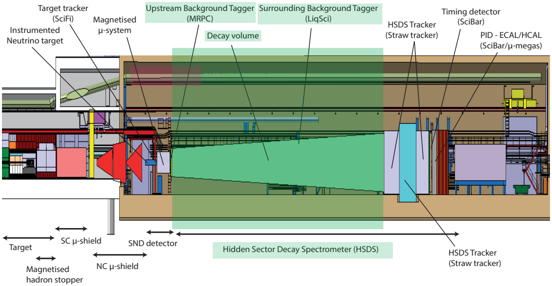


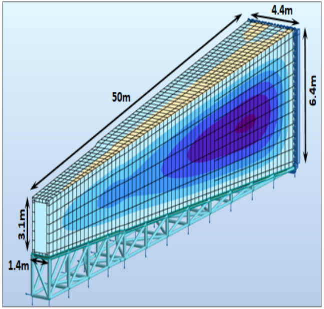




Hidden Sector (HS) Decay Volume

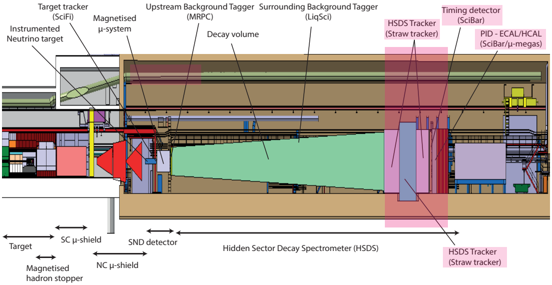
- The fiducial **decay volume** is a pyramidal frustum with a length of **50 meters**
  - $1.0 \times 2.7\,\mathrm{m}^2$ at the upstream end
  - $4 \times 6\,\mathrm{m}^2$ at the downstream end
- **He** at atmospheric pressure
- Lightweight structure (Al / stainless steel)
- **Support** for Liquid Scintillator-Surrounding Background Tagger **LS-SBT** integration
  - Good time resolution: O (1 ns)
  - High efficiency: $>$ 99.0% for m.i.p.

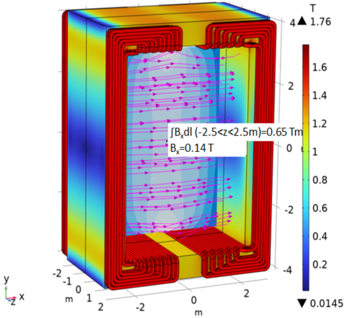




Hidden Sector (HS) Decay Spectrometer

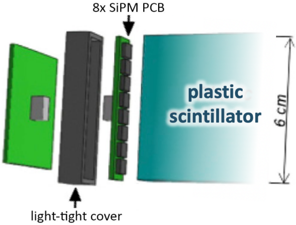
- **Large aperture:** 4.0m × 6.0m
- **Precise track reconstruction:** $< 120\ \mu m$
- **High hit efficiency:** > 99.0 %
- Cu/Au-coated Mylar drift tubes (NA62 design)
- $2\times$ 2 stations of 4 double layers at 10° stereo angle, 10 000 channels altogether
- **Magnet** (NC baseline): 0.65Tm / 0.15T

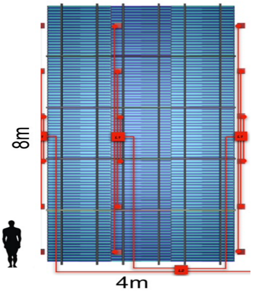


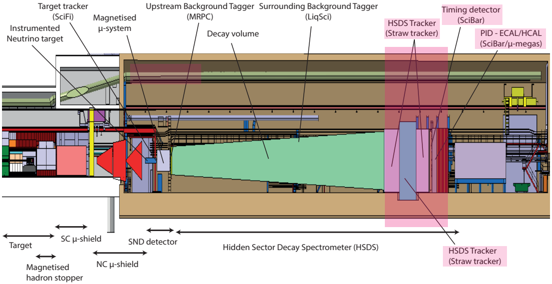


Hidden Sector (HS) Decay Spectrometer: Timing Detector

- **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**



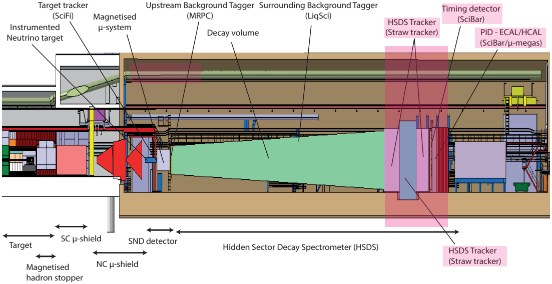




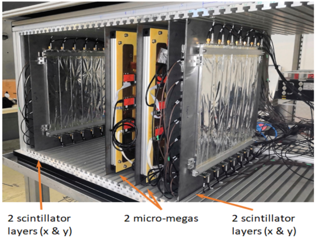
Hidden Sector (HS) Decay Spectrometer: PID

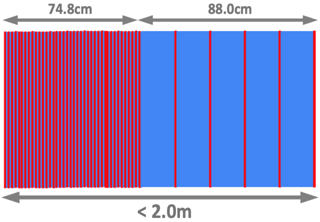
Particle Identification (PID) & Calorimeter (ECal / HCal)

- Reliable pID & μ/π separation
- Electromagnetic shower reconstruction: $<$ 5mrad 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 λ each) & plastic scintillators
- Total nuclear interaction length: 7 λ
  - $+ 1 - 3$ MicroMeGaS high-precision layers



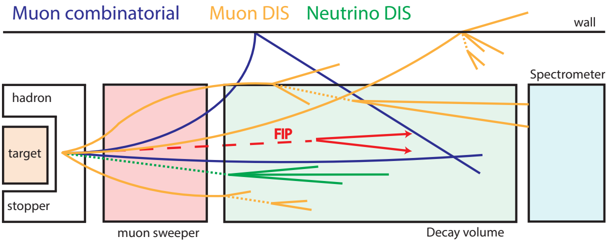
Detector planes without absorber layers





HSDS: Background evaluation for FIP decay search

- Very simple and common selection for both fully and partially reconstructed events — model independence
- Possibility to measure background with data, relaxing veto and selection cuts, muon shield, decay volume



Selection

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)	$< 250\,\mathrm{cm}$

Time coincidence + UBT/SBT

Background source	Expected events
Neutrino DIS	< 0.1 (fully)/< 0.3(partially)
Muon DIS (factorisation)	$< 5 \times 10^{-3}$ (fully) / < 0.2(partially)
Muon combinatorial	$(1.3 \pm 2.1) \times 10^{-4}$

HSDS: Heavy Neutral Leptons (HNL) production

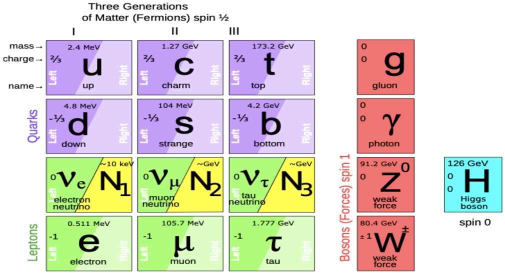
Production processes:

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

Detection:

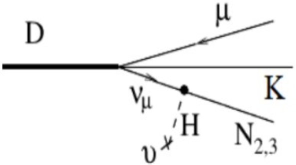
- decays into charged leptons, hadrons

Neutrino Minimal Standard Model νMSM
extension of the SM by adding a 3 right-handed (Majorana) HNL

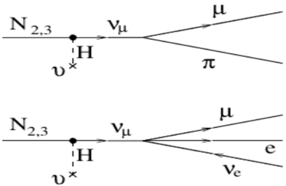


- N_1 ($\sim$ **10 keV) Dark Matter** candidate
- $N_{2,3}$ **(**$\sim$ **GeV)** origin of **neutrino masses** and **Leptogenesis & baryon asymmetry** of the Universe

production

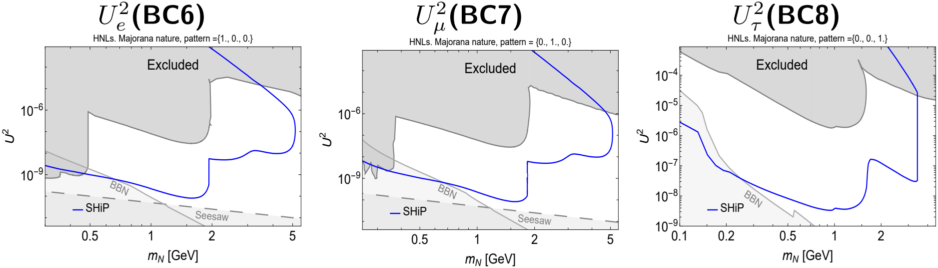


detection



HSDS: Sensitivity to Heavy Neutral Leptons (HNL)

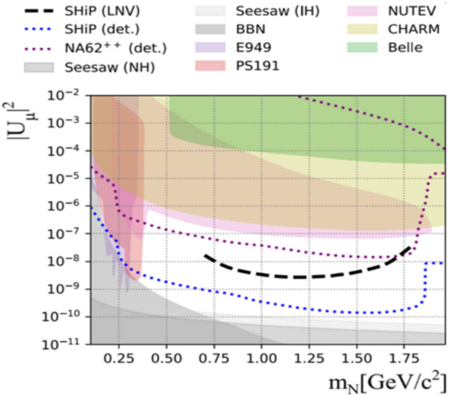
- $$\frac{d\mathrm{Br}(H^+ \to l_\alpha^+ N)}{dE_N} = \tau_H \frac{G_F^2 f_H^2 M_H M_N^2}{8\pi} |V_H|^2 |U_\alpha|^2 \times \left(1 - \frac{M_N^2}{M_H^2} + 2\frac{M_l^2}{M_H^2} + \frac{M_l^2}{M_N^2}\left(1 - \frac{M_l^2}{M_H^2}\right)\right) \times \sqrt{\left(1 + \frac{M_N^2}{M_H^2} - \frac{M_l^2}{M_H^2}\right)^2 - 4\frac{M_N^2}{M_H^2}} \times \delta\left(E_N - \frac{M_H^2 - M_l^2 + M_N^2}{2M_H}\right)$$
- $$\Gamma(N \to \pi^+ l_\alpha^-) = \frac{|U_\alpha|^2}{16\pi} G_F^2 |V_{ud}|^2 f_\pi^2 M_N^3 \left[\left(1 - \frac{M_l^2}{M_N^2}\right)^2 - \frac{M_\pi^2}{M_N^2}\left(1 + \frac{M_l^2}{M_N^2}\right)\right] \times \sqrt{\left(1 - \frac{(M_\pi - M_l)^2}{M_N^2}\right)\left(1 - \frac{(M_\pi + M_l)^2}{M_N^2}\right)}$$
- 90% CL, assuming 6×10^{20} p.o.t. per 15 years

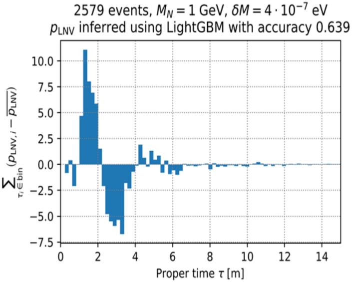


HSDS: HNL & Lepton Number Violation

- Distinguish between **Majorana-** and **Dirac-type** HNL in significant fraction of parameter space

HNL & Lepton Number Violation (LNV):



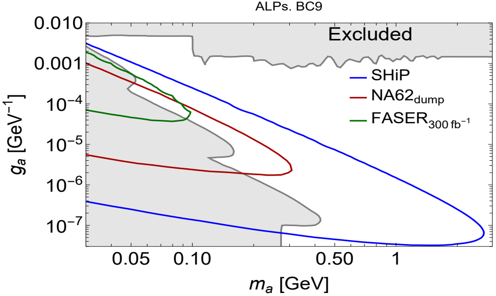


HSDS: Sensitivity to Axion-Like Particles (ALPs)

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

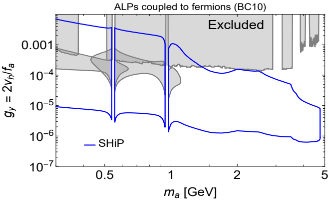
g_a (BC9): Exclusive photon coupling

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



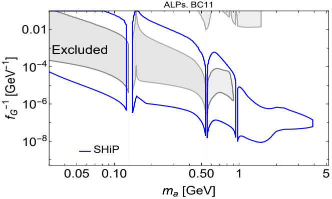
g_γ (BC10): Exclusive fermion coupling

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



f_G (BC11): Exclusive gluon coupling

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

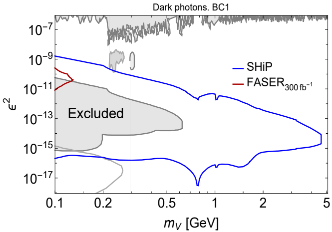


HSDS: Dark photons & Dark scalars

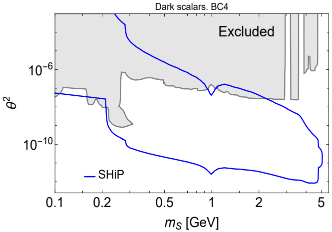
90% CL, assuming 6×10^{20} p.o.t. per 15 years

- **Dark Photons:**
  - Mediate interactions between the dark sector and the Standard Model (SM)
  - **Production Mechanisms:**
    - from neutral meson decays such as π^0, η, and η'
    - 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: ε^2 (BC1)



Sensitivity to dark scalars: θ^2 (BC4)



SND: Light Dark Matter production

- New gauge boson A' associated with an abelian gauge symmetry U(1)$'$, **kinematically mixed** with the photon (portal):

$$\mathcal{L}_{A'} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2}A'_{\mu}A'^{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$$

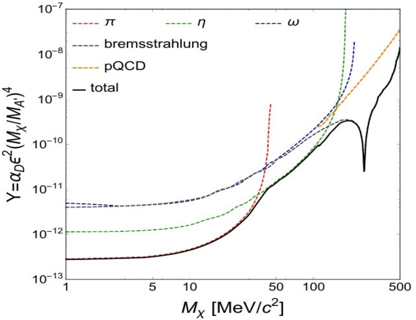
- A' can decay into a couple of **Dark Matter particles** (χ)

$$\Gamma_{A'} = \sum_{l}\Gamma_{A'\to l^+l^-} + \sum_{\text{hadrons}}\Gamma_{A'\to \text{hadrons}} +$$

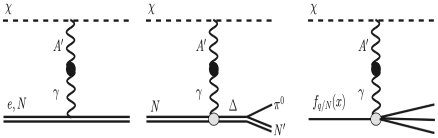
$$+\sum_{\chi}\Gamma_{A'\to\chi\bar{\chi}}$$

- The relevant parameters for the phenomenology of the DP model are $(M_{A'}, \epsilon)$
- **Benchmark model**

$$\alpha_D = 0.1 \quad \left(\frac{M_\chi}{M_{A'}}\right) = \frac{1}{3}$$

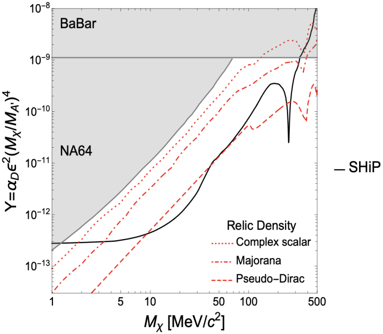


Scattering channels: from left to right, elastic scattering on electrons or nucleons, quasielastic (incoherent) single pion production, and deep inelastic scattering.

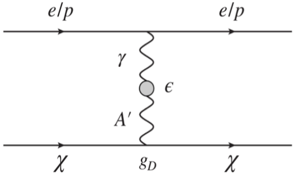


SND: Sensitivity to Light Dark Matter

- 90% CL, assuming 6×10^{20} p.o.t. per 15 years
- Direct search through scattering
- A' decaying into $\chi\bar{\chi}$ pairs for the benchmark point $\alpha_D = 0.1$ and $m_{A'} = 3m_\chi$



LDM scattering off atomic electrons (and nuclei):
a shower produced by the electron scattered by LDM



Background:

ν elastic & QE scattering

	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	**Total**
elastic (e)	156	81	192	126	**555**
QE	-	27	-	-	**27**
RES	-	-	-	-	-
DIS	-	-	-	-	-
Total	156	108	192	126	**582**

SND: Neutrino interaction physics

- First **direct measurement** of $\bar{\nu}_\tau$
- **LFU test** in neutrino interaction
- ν_τ cross section
- ν_τ magnetic moment

Expected observed ν_τ ($\bar{\nu}_\tau$) signal events:

Decay channel	ν_τ	$\bar{\nu}_\tau$
$\tau \to e$	8 000	
$\tau \to \mu$	4 000	3 000
$\tau \to h$	27 000	
$\tau \to 3h$	11 000	
Total	53 000	

	<E>, GeV	CC DIS interaction	CC DIS charm production
N ν_e	63	2.8×10^6	1.7×10^5
N ν_μ	40	8.0×10^6	3.5×10^5
N ν_τ	54	8.8×10^4	
N $\bar{\nu}_e$	49	5.9×10^5	0.3×10^5
N $\bar{\nu}_\mu$	33	1.8×10^6	0.7×10^5
N $\bar{\nu}_\tau$	74	6.1×10^4	

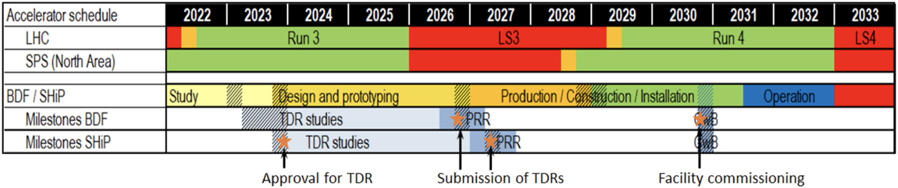
DIS structure functions:

Measurement of F_4 and F_5 in ν_τ/ν_τ interactions

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left(\left(y^2 x + \frac{m_\tau^2 y}{2E_\nu M}\right)F_1 + \left[\left(1-\frac{m_\tau^2}{4E_\nu^2}\right) - \left(1+\frac{Mx}{2E_\nu}\right)\right]F_2 \pm \left[xy\left(1-\frac{y}{2}\right) - \frac{m_\tau^2 y}{4E_\nu M}\right]F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4 - \frac{m_\tau^2}{E_\nu M}F_5 \right)$$

BDF/SHiP preliminary schedule

- Availability of test beams challenging
- Important to start data taking >1 year before **LS4**



Thank you!

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