Status and Physics of the SHiP experiment at CERN

TAUP 2017 – Snolab

Daniel Bick

SHiP
Search for Hidden Particles

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

TAUP
Topics in Astroparticle and Underground Physics

July 26, 2017

SM very successful, however. . .

Strong Evidence for BSM Physics

- Neutrino masses and oscillations
- The nature of non-baryonic Dark Matter
- Excess of matter over antimatter in the Universe
- Cosmic inflation of the Universe

Shortcoming of Theory

- Gap between Fermi and Planck scales
- Dark Energy
- Connection to gravity
- . . .

New/extended models needed $\Rightarrow$ **new particles**

Where to Find New Physics

- Why haven't we seen these new particles, yet?
  - Too heavy or too weakly interacting

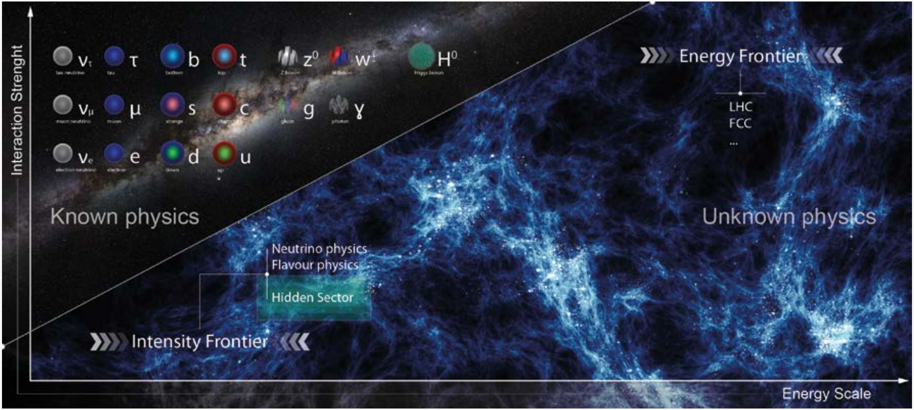


Image: CERN Courier 2/2016

How to Explore Hidden Sector?

- Phenomenologies of hidden sector models share a number of unique and common physics features

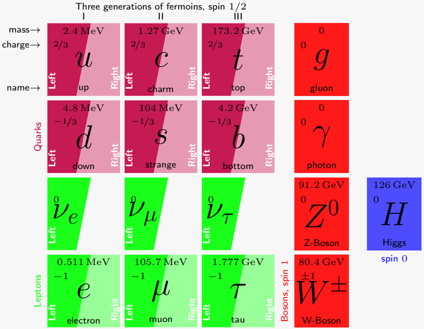
Models	Final States
Neutrino portal, HNL, SUSY neutralino	$\ell^\pm\pi^\mp$, $\ell^\pm K^\mp$, $\ell^\pm\rho^\mp$
Vector, scalar, axion portals, SUSY sgoldstino	e^+e^-, $\mu^+\mu^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+\pi^-$, K^+K^-
Neutrino portal, HNL, SUSY neutralino, axino	$\ell^+\ell^-\nu$

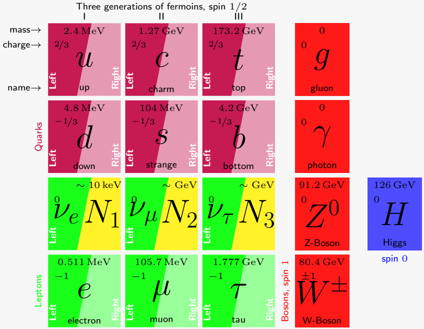
- Production through meson decays (π, K, D, B)
- Production and decay rates are strongly suppressed relative to SM
  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Long-lived objects $\mathcal{O}(\mu s)$
  - Travel unperturbed through ordinary matter

νMSM

Minimal approach, extends SM by three neutral particles

→ T.Asaka, M.Shaposhnikov **PLB 620** (2005) **17**

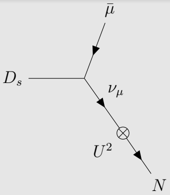


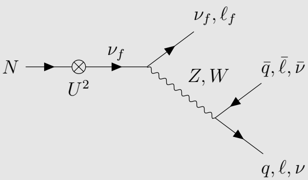


- N_i: 3 Heavy Neutral Leptons (HNL)
- N_1: $\sim 10\,\mathrm{keV}$
  - DM candidate
- N_2, N_3: $\sim$ GeV region
  - Neutrino masses
  - Baryon asymmetry of the Universe

Experimental Concept

Example for HNLs





- Typical lifetimes $> 10\,\mu\text{s}$ for $m_{N_{2,3}} \sim 1\,\text{GeV}$
- Decay distance $\mathcal{O}(\text{km})$

- Detection of hidden particles through their decay in SM particles
- Detector must be sensitive to as many decay modes as possible

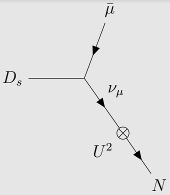
▷ Full reconstruction essential to minimize model dependence

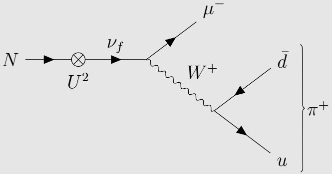
- Branching ratios suppressed compared to SM couplings $\mathcal{O}(10^{-10})$

▷ challenging background suppression → estimated $\mathcal{O}(0.01)$ needed

Experimental Concept

Example for HNLs





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- SHiP is a new proposed intensity-frontier experiment aiming to search for neutral hidden particles with mass up to $\mathcal{O}(10)\,\mathrm{GeV}$ and extremely weak couplings down to 10^{-10}.

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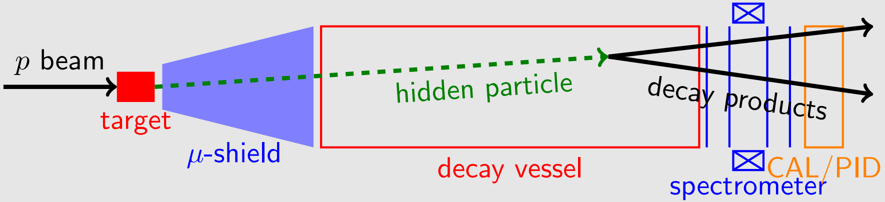
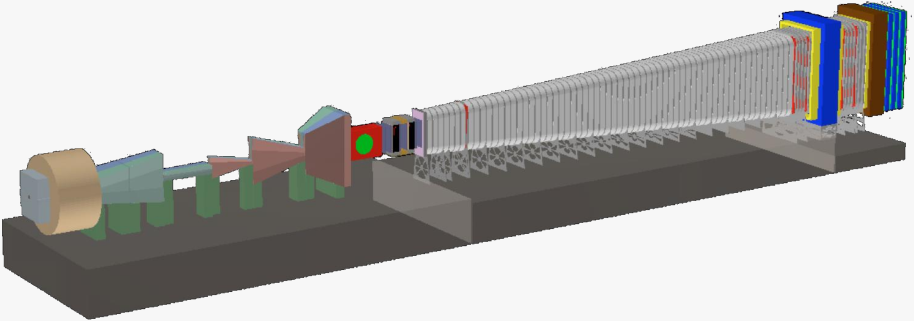
Decay of hidden particles

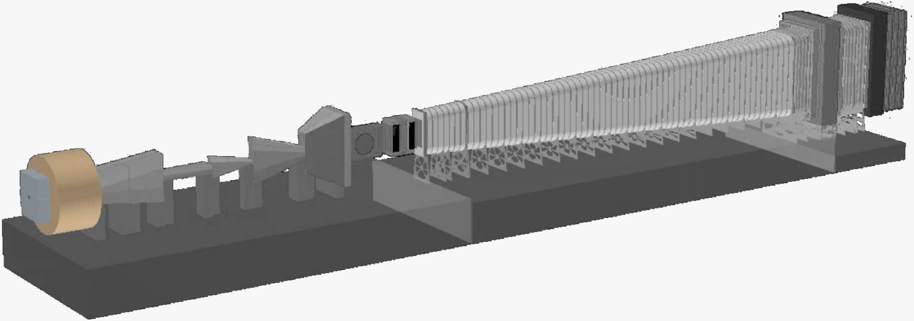


- Large decay volume followed by spectrometer, calorimeter, PID
- Shielding from SM particles: hadron absorber and veto detectors

Experiment Layout



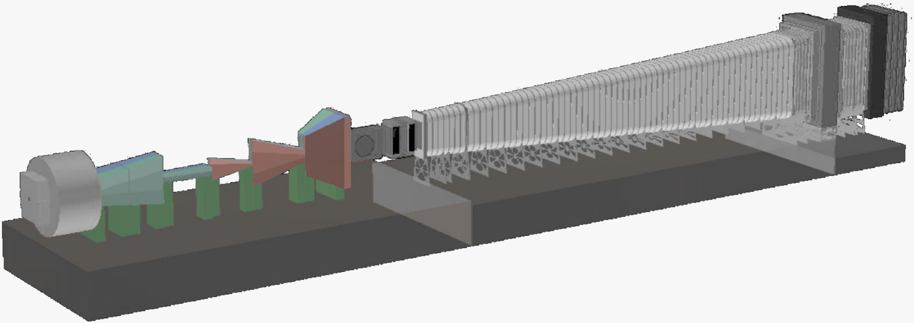
Experiment Layout



Target

- $58\,\text{cm Mo}\ (4\,\lambda)$, $58\,\text{cm W}\ (6\,\lambda)$
  - ▷ Optimized for heavy meson production
- Followed by hadron stopper

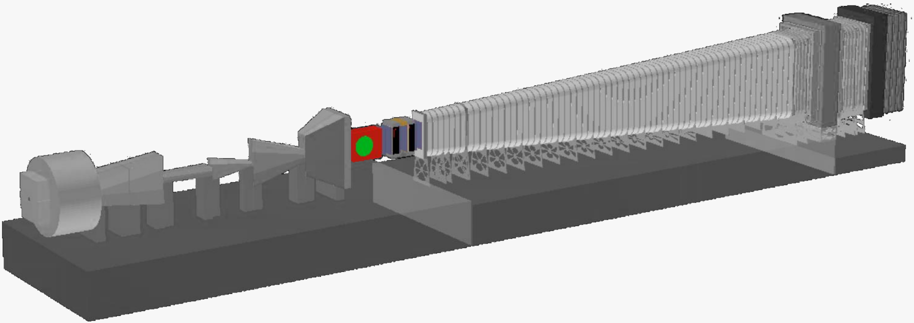
Experiment Layout



Active Muon Shield

- Deal with 10^{10} muons/spill
- Active magnetic muon shield and passive absorber
- Less than 100k μ/spill remaining

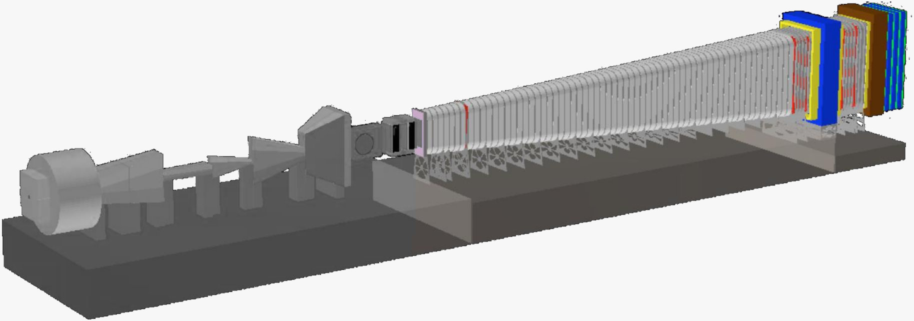
Experiment Layout



Emulsion Spectrometer

- OPERA-like detector
- Magnetized neutrino targed (lead interleaved with photo emulsion)
- Followed by muon spectrometer

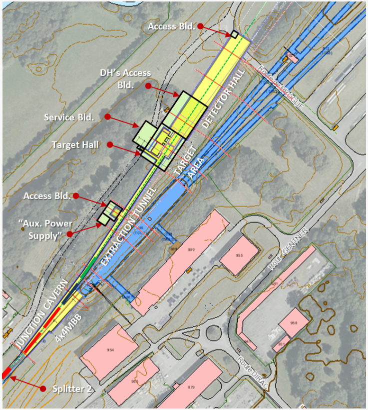
Experiment Layout

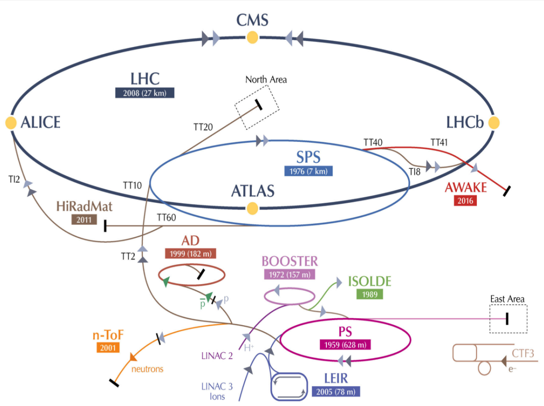


Decay Vessel and Hidden Particle Detector

- $50\,\mathrm{m}$ Long evacuated decay vessel
  - $10^{-6}\,\mathrm{bar}$
  - Surrounded by background taggers
- Straw Tube Spectrometer followed by calorimeters and muon detector

Fixed Target Facility @ SPS North Area





- $400\,\mathrm{GeV}$ protons
- $4 \cdot 10^{13}$ pot/spill (every $7\,\mathrm{s}$)

▷ $2 \cdot 10^{20}$ pot in 5 years

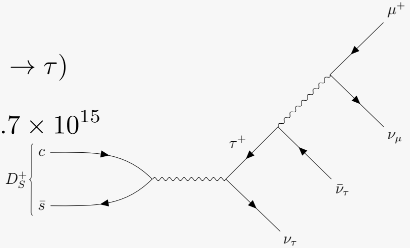
SM Physics

- Production of large amounts of Neutrinos

▷ Study ν_τ and $\bar{\nu}_\tau$ properties

▷ Test lepton flavor universality by comparing interactions of ν_μ and ν_τ

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau)$$
$$= 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15}$$



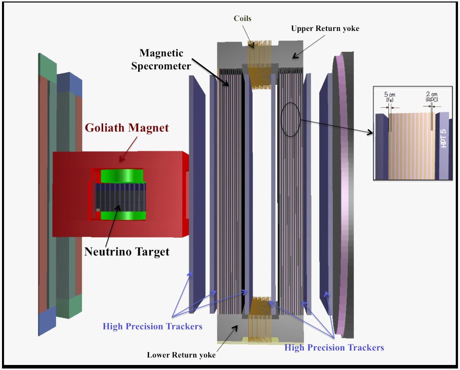
ν-production @ p-target

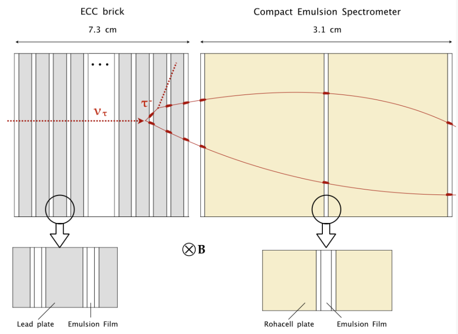
- $5.7 \cdot 10^{15}$ ν_τ and $\bar{\nu}_\tau$
- $5.7 \cdot 10^{18}$ ν_μ and $\bar{\nu}_\mu$
- $3.7 \cdot 10^{17}$ ν_e and $\bar{\nu}_e$

Interactions @ ν-target

	$< E >$ (GeV)	Number of ν
ν_μ	30	$2.3 \cdot 10^6$
ν_e	46	$3.4 \cdot 10^5$
ν_τ	58	$7.1 \cdot 10^3$
$\bar{\nu}_\mu$	27	$9.5 \cdot 10^5$
$\bar{\nu}_e$	46	$1.4 \cdot 10^5$
$\bar{\nu}_\tau$	58	$3.6 \cdot 10^3$

Emulsion Spectrometer





- 9.6 tons emulsion/lead target in magnetic field:
- 11 walls of 14×6 ECC-bricks, replaced every 6 months for scanning
- ▷ Total number of bricks: $924 \to 6930\,\mathrm{m}^2$ emulsion films
- Each brick is followed by a compact emulsion spectrometer
- Resolution of $1\,\mu\mathrm{m}$

ν_τ Physics and more...

Direct measurements of tau neutrino CC-interaction fairly recent

- DONUT: 9 ± 1.5 events
  - no distinction between ν_τ and $\bar{\nu}_\tau$
- OPERA: 5 events
  - only ν_τ

SM Physics opportunity for SHiP

- $\mathcal{O}(4000)$ $\nu_\tau/\bar{\nu}_\tau$ interactions

▷ Study the properties and cross-section

▷ First observation of $\bar{\nu}_\tau$

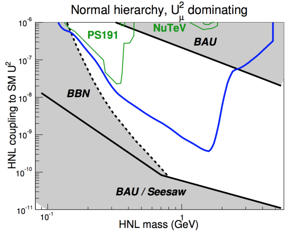
- Light Dark Matter search
- Extraction of F_4 and F_5 structure functions
- Measure the s-content of the nucleon

Sensitivity to HNLs

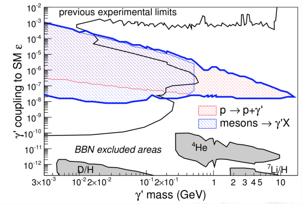
Neutrino Portal

- HNLs: 120 events expected for $m_{N_{2,3}} = 1\,\mathrm{GeV}$
- SHIP will scan most of the cosmologically allowed region below the charm mass

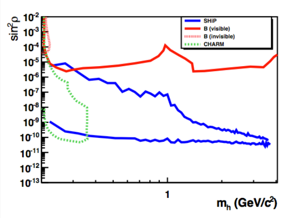
- Sensitive also to many other models



Vector portal (dark photon)

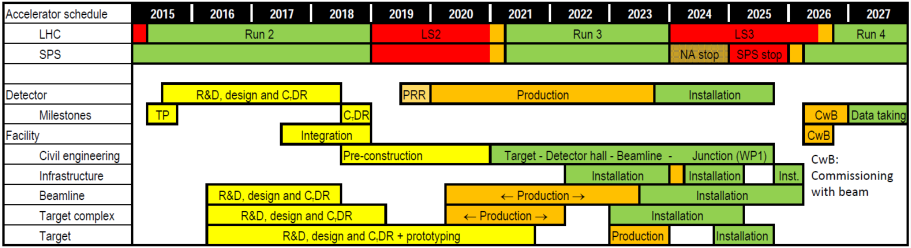


Scalar portal



Summary and Outlook

- SHiP is proposed to complement searches for new physics at CERN in the largely unexplored domain of new, very weakly interacting particles with masses $\mathcal{O}(10)\,\mathrm{GeV}$
- Also great opportunities for SM physics
  - ▷ Improve sensitivity of ν_τ-physics by $\mathcal{O}(1000)$
- Recognized as an experiment by CERN since May 2016



- Next step: Conceptual Design Report in 2018
  - ▷ Input for the European strategy for particle physics
- Begin data taking in 2026

The People behind SHiP

Technical Proposal

arXiv:1504.04956v1 [physics.ins-det] 20 Apr 2015

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHiP
Search for Hidden Particles

CERN-SPSC-2015-016
SPSC-P-350
8 April 2015

Technical Proposal

A Facility to Search for Hidden Particles (SHiP) at the CERN SPS

The SHiP Collaboration[1]

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden particles are predicted by a large number of models beyond the Standard Model. The high intensity of the SPS 400 GeV beam allows probing a wide variety of models containing light long-lived exotic particles with masses below $\mathcal{O}(10)$ GeV/c^2, including very weakly interacting low-energy SUSY states. The experimental programme of the proposed facility is capable of being extended in the future, e.g. to include direct searches for Dark Matter and Lepton Flavour Violation.

[1] Authors are listed on the following pages.

arXiv:1504.04956v1

∼ 250 physicists from 47 institutions and 15 countries

Physics Proposal

arXiv:1504.04855v1 [hep-ph] 19 Apr 2015

CERN-SPSC-2015-017 (SPSC-P-350-ADD-1)

A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

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Abstract: This paper describes the physics case for a new fixed target facility at CERN SPS. The SHiP (*Search for Hidden Particles*) experiment is intended to hunt for new physics in the largely unexplored domain of very weakly interacting particles with masses below the Fermi scale, inaccessible to the LHC experiments, and to study tau neutrino physics. The same proton beam setup can be used later to look for decays of tau-leptons with lepton flavour number non-conservation, $\tau \to 3\mu$ and to search for weakly-interacting sub-GeV dark matter candidates. We discuss the evidence for physics beyond the Standard Model and describe interactions between new particles and four different *portals* — scalars, vectors, fermions or axion-like particles. We discuss motivations for different models, manifesting themselves via these interactions, and how they can be probed with the SHiP experiment and present several case studies. The prospects to search for relatively light SUSY and composite particles at SHiP are also discussed. We demonstrate that the SHiP experiment has a unique potential to discover new physics and can directly probe a number of solutions of beyond the Standard Model puzzles, such as neutrino masses, baryon asymmetry of the Universe, dark matter, and inflation.

⋆Editor of the paper
§Convener of the Chapter

arXiv:1504.04855v1

∼ 85 theorists, more than 250 pages

Backup

Background in Hidden Particle Detector

Background sources and rejection strategies

- ν- and μ-induced backgrounds
  - e.g inelastic ν-interactions in the surroundings of the HP detector
  - ▷ Reconstructed momentum must point back to proton target
  - ▷ Veto upstream the decay volume
  - ▷ Reconstructed vertex must be in decay volume
- Random combination of tracks
  - Rate at spectrometer: $7\,\mathrm{kHz/spill}$
  - ▷ Timing veto with a precision of $\mathcal{O}(100\,\mathrm{ps})$
  - ▷ Surround background tagger and upstream veto detector
- Cosmic muons
  - Scattering/DIS on cavern and vessel walls
  - ▷ Surround background tagger and upstream veto detector
  - ▷ Event topology, pointing of momentum

- Backgrounds have been investigated in extensive MC studies.

▷ Overall expected background: less than 0.1 events in 5 years

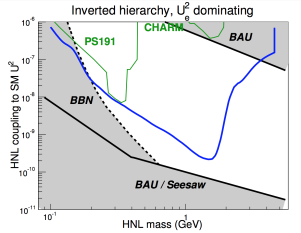
Background

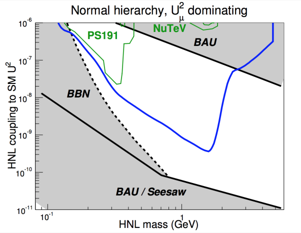
Background source	Statistical factor	Expected background
ν ($p > 10.0$ GeV/c)	35.	< 0.07
ν (4.0 GeV/c$< p < 10.0$ GeV/c)	~ 1	0 (MC)
ν (2.0 GeV/c$< p < 4.0$ GeV/c)	0.07	0 (MC)
μ DIS HS	~ 1	0 (MC)
μ DIS wall	0.001	0 (MC)
μ Combinatorial	10^4	< 0.1
μ Cosmics ($p < 100$ GeV/c)	0.2	0 (MC)
μ Cosmics ($p > 100$ GeV/c)	800.	< 0.1
μ Cosmics DIS ($p > 100$ GeV/c)	10^3	< 0.1
μ Cosmics DIS (10 GeV/c$< p < 100$ GeV/c)	~ 1	0 (MC)

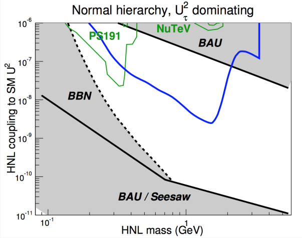
Sensitivity to HNLs

Neutrino Portal

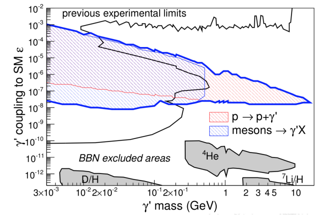
- HNLs: 120 events expected for $m_{N_{2,3}} = 1\,\text{GeV}$
- SHIP will scan most of the cosmologically allowed region below the charm mass
- BAU constraint is model-dependent







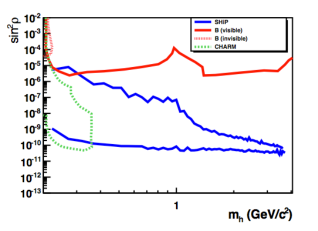
Vector Portal (**Dark Photons**)



- $U(1)$ associated particle γ' in HS that can have non-zero mass and mix with the SM photon with ε
- Produced in QCD processes or in decays of $\pi^0 \to \gamma'\gamma$, $\eta \to \gamma'\gamma$, $\omega \to \gamma'\pi^0$ and $\eta' \to \gamma'\gamma$

Scalar Portal

- Mostly produced in penguin-type B and K decays
- Can mix with the SM Higgs with $\sin^2\theta$

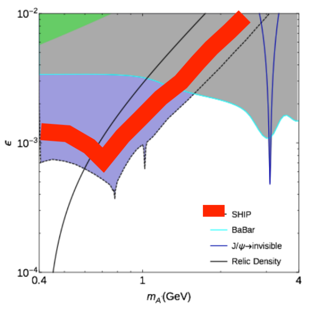


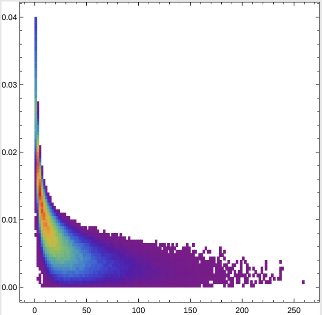
Light Dark Matter production

- Decay of dark photon A created n the beam dum produces DM particle χ

LDM in the emulsion spectrometer

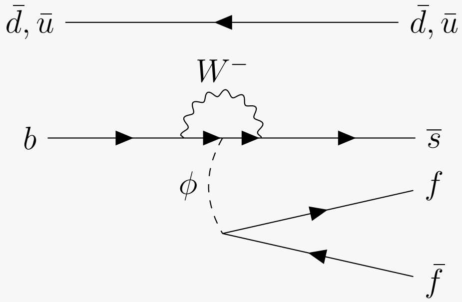
- Detection through elastic scattering on electrons and nuclei
- Background from ν elastic scattering: about 300 events expected

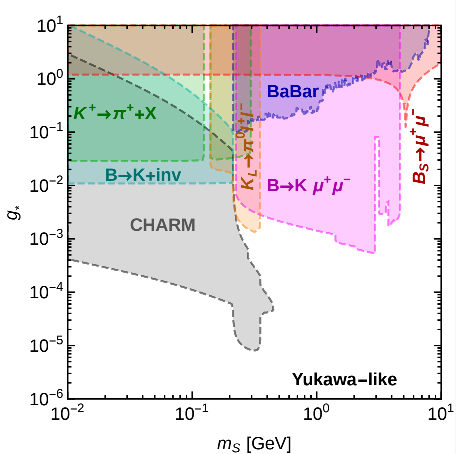




Scalar Portal

- Production through K and B decays





$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx\ dy} =$$

$$\frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left((y^2x + \frac{m_\tau^2 y}{2E_\nu M})F_1 + \left[(1-\frac{m_\tau^2}{4E_\nu^2}) - (1+\frac{Mx}{2E_\nu})y\right] F_2\right.$$

$$\left.\pm \left[xy(1-\frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M}\right] F_3 + \frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5\right)$$