Search for New Physics at a Future Beamdump Facility at the CERN SPS: The SHiP Experiment

DPG Frühjahrstagung 2018 – Würzburg

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

SHiP
Search for Hidden Particles

DPG

March 21, 2018

Physics Motivation

Standard Model 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

Mediators (portals) to the Hidden Sector

Visible Sector

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{Mediator}} + \mathcal{L}_{\mathrm{HS}}$$

Mediator/portals to the HS:
vector, scalar, axial, neutrino

Hidden Sector

- Ability to couple to SM gives constraints from theory
  - ▷ Not too many options
- c.f. arXiv:1504.04855v1

- ▷ Dark photons
- ▷ Scalar and pseudoscalar mediators
- ▷ ALPs
- ▷ Heavy Neutral Leptons

All could be dark matter if very light (long-lived) or protected by symmetry

Where to Find New Physics

No new particles observerd, yet ▷ could be too heavy or too weakly interacting

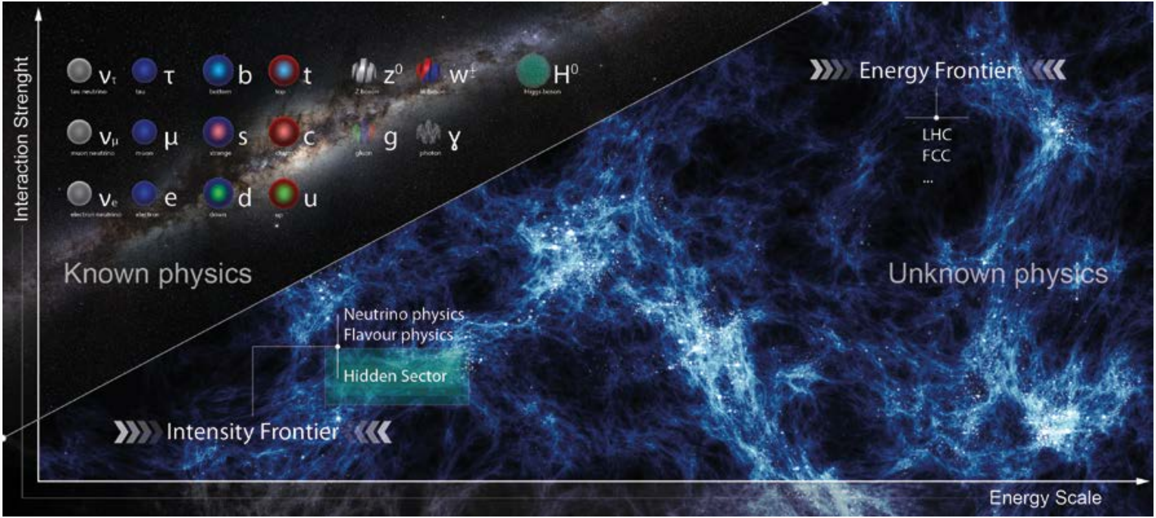


Image: CERN Courier 2/2016

How to the Explore Hidden Sector?

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

▷ Production through meson decays (π, K, D, B)

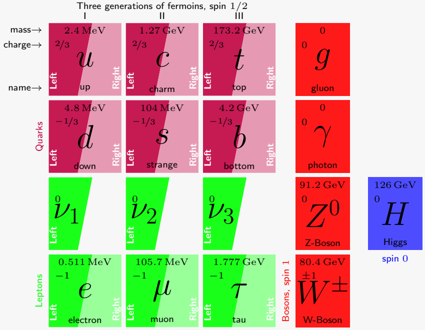
▷ Production and decay rates are strongly suppressed relative to SM

  - Production branching ratios $\mathcal{O}(10^{-10})$
  - Long-lived objects $\mathcal{O}(\mu\mathrm{s})$
  - Travel unperturbed through ordinary matter

▷ Decay into two charged particles

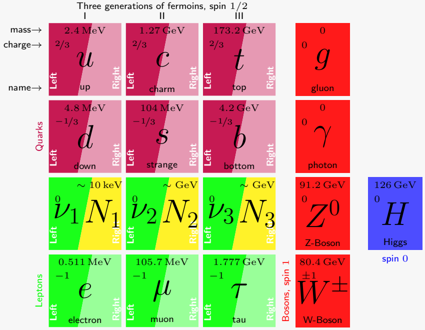
Models	Final States
Neutrino portal, HNL, SUSY neutralino	$\ell^{\pm}\pi^{\mp}$, $\ell^{\pm}K^{\mp}$, $\ell^{\pm}\rho^{\mp}$
Vector, scalar, axion portals, SUSY sgoldstino	$e^{+}e^{-}$, $\mu^{+}\mu^{-}$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^{+}\pi^{-}$, $K^{+}K^{-}$
Neutrino portal, HNL,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

ν Minimal Standard Model



SM: massless and left-handed neutrinos

ν Minimal Standard Model



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

SM: massless and left-handed neutrinos
νMSM: extends SM by three right-handed heavy neutral leptons (HNLs)

N_1: $\sim 10\,\mathrm{keV}$

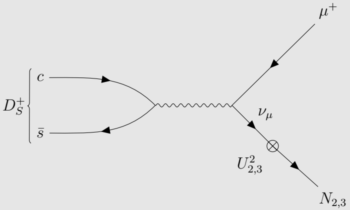
- DM candidate

$N_{2,3}$: $\sim$ GeV region

- Neutrino masses
- Baryon asymmetry of the Universe

HNL Production

- $N_{2,3}$ mix with active ν
- Produced in (semi-)leptonic decays
  e.g.: $K \to \mu\nu$, $D \to \mu\nu X$, $B \to \mu\nu X$, $Z \to \nu\bar{\nu}$



- Production $\propto \sigma_D \times |U|^2$
- $|U_2|^2 = |U_{2,\nu_e}|^2 + |U_{2,\nu_\mu}|^2 + |U_{2,\nu_\tau}|^2$

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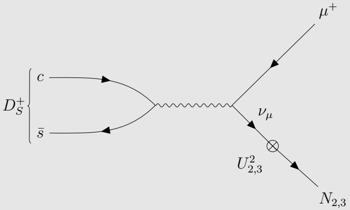

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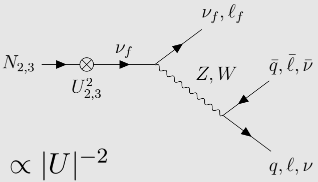
HNL Decay

- Into leptons and light mesons

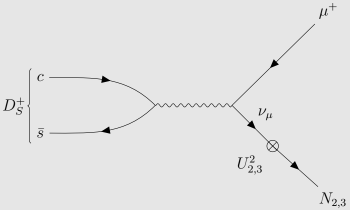


- $\tau_{N_{2,3}} \propto |U|^{-2}$
  - Typically $> 10\,\mu\mathrm{s}$ for $m_{N_{2,3}} \sim 1\,\mathrm{GeV}$
  - $ct = \mathcal{O}(\mathrm{km})$

HNL Interaction with SM Particles

HNL Production

- $N_{2,3}$ mix with active ν
- Produced in (semi-)leptonic decays e.g.: $K \to \mu\nu$, $D \to \mu\nu X$, $B \to \mu\nu X$, $Z \to \nu\bar{\nu}$



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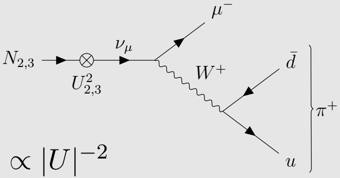
HNL Decay

- Into leptons and light mesons



- $\tau_{N_{2,3}} \propto |U|^{-2}$
  - ▷ Typically $> 10\,\mu\mathrm{s}$ for $m_{N_{2,3}} \sim 1\,\mathrm{GeV}$
  - ▷ $ct = \mathcal{O}(\mathrm{km})$
- $\mathcal{B}(N \to \mu/e + \pi) \simeq 0.1 - 50\%$
- $\mathcal{B}(N \to \mu/e + \rho) \simeq 0.5 - 20\%$
- $\mathcal{B}(N \to \nu + \mu + e) \simeq 1 - 10\%$

Detection Strategy

- Hidden particles mainly produced in decays of (charmed, beauty) hadrons and proton bremsstrahlung

▷ Use of a Beam Dump facility providing e.g. lots of (charmed) mesons

- Detection of hidden particles through their decay in SM particles

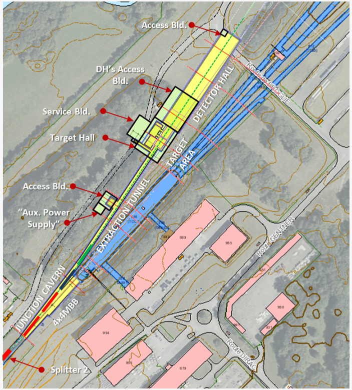
▷ Detector must be sensitive to as many decay modes as possible

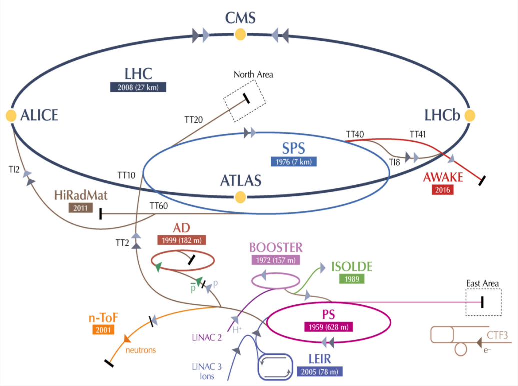
▷ Full reconstruction essential to minimize model dependence

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

▷ Challenging background suppression $\rightarrow$ estimated $\mathcal{O}(0.1)$ needed

New Beam Dump Facility @ SPS North Area





- 2013: Proposal to Search for Heavy Neutral Leptons at the SPS
- ▷ CERN-SPSC-2013-024 arXiv:1310.1762
- Huge R&D effort by CERN for a new BDF

- 400 GeV protons
- 4×10^{13} pot/spill
- 1 s long spill every 7 s
- ▷ 2×10^{20} pot in 5 years

- 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}.

Decay of hidden particles

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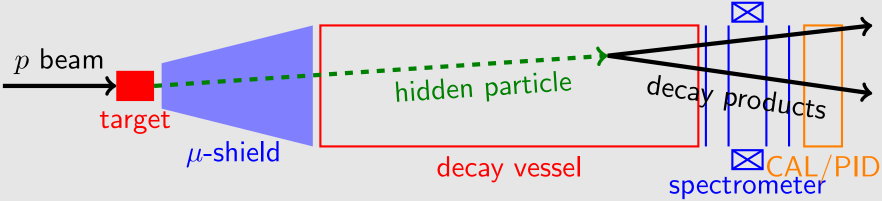
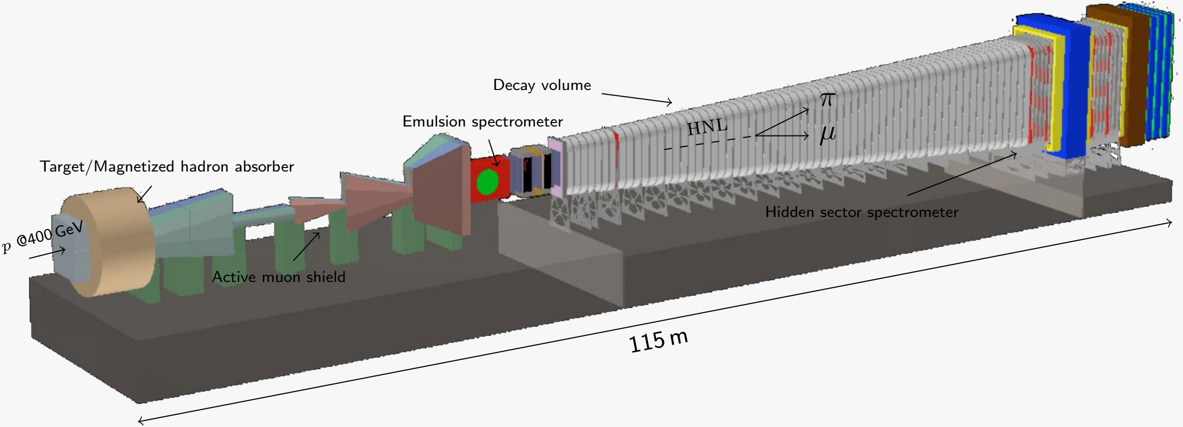
Decay of hidden particles



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

Current Experimental Layout



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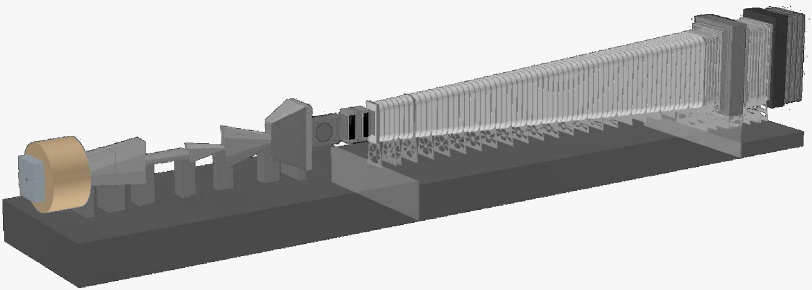
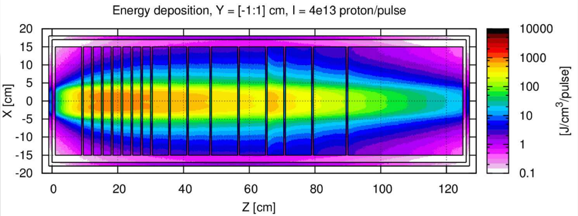


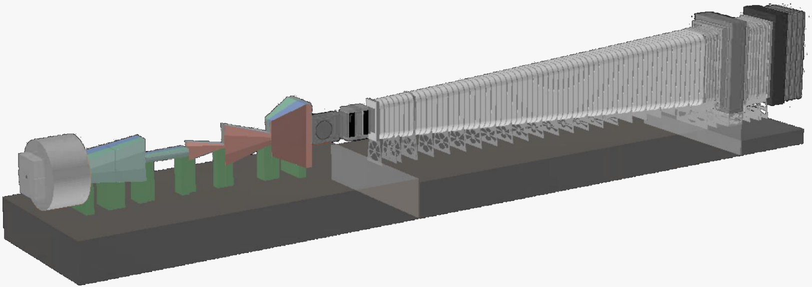


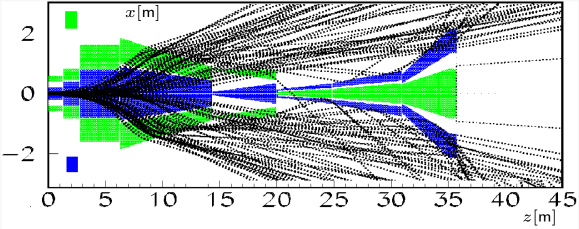
Target

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

- Testbeam with replica this July

Current Experimental Layout

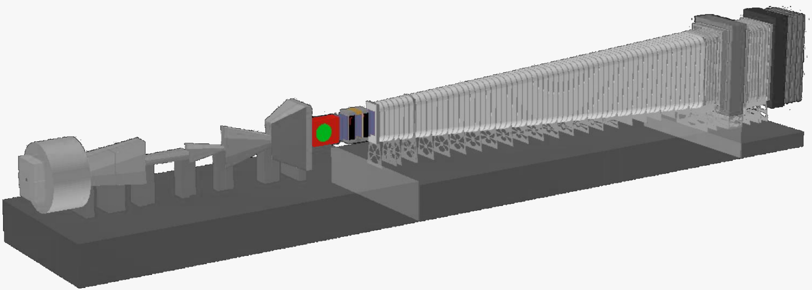




Active Muon Shield

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

Current Experimental Layout

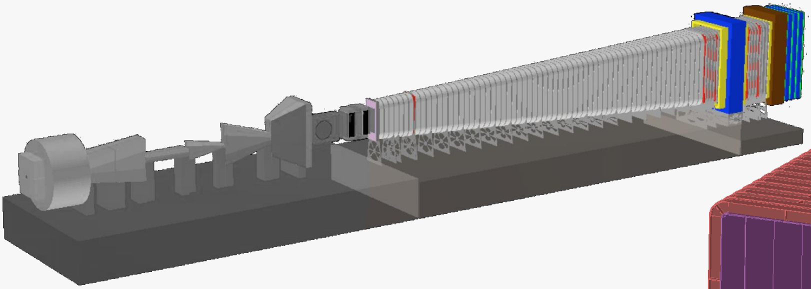


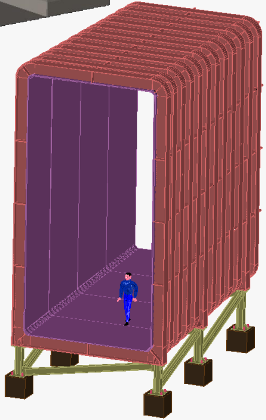
Emulsion Spectrometer

- Magnetized neutrino targed
- OPERA-like detector
  - ▷ lead interleaved with photo emulsion
- Followed by spectrometer

- ▷ νSHiP
  - (SM) neutrino physics
- ▷ iSHiP
  - indirect searches
  - ▷ LDM

Current Experimental Layout

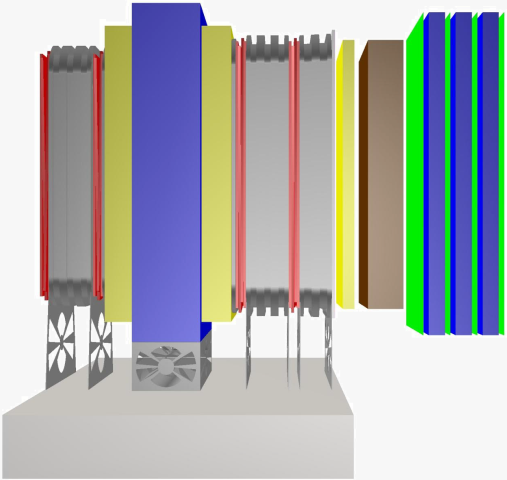




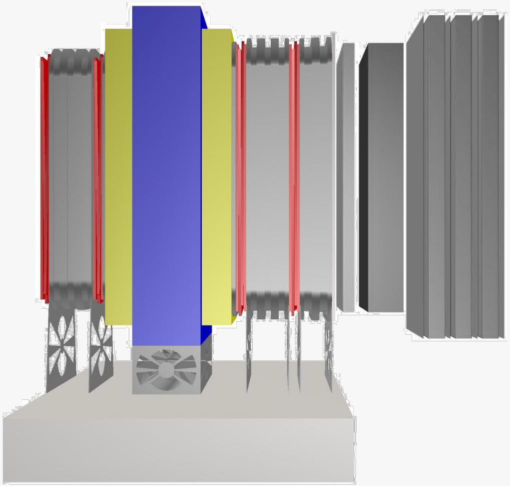
Decay Vessel and Hidden Particle Detector

- $50\,\mathrm{m}$ long evacuated decay vessel ▷ $10^{-3}\,\mathrm{bar}$
- Surrounded by liquid scintillator
  - ▷ background tagger and photon detection
- Straw Tube Spectrometer followed by calorimeters and muon detector

Detectors



Detectors

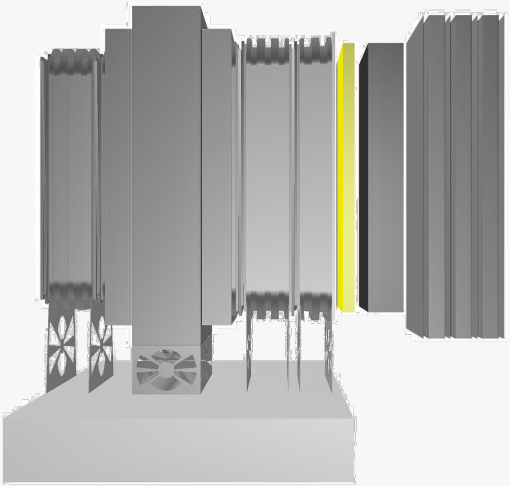


Spectrometer

- Area of 5 m × 10 m
- 5 m long straw-tubes of 2 cm diameter
  - ▷ operated horizontally
  - ▷ 18 000 straws
- 4 stations with 4 × 4 stereo layers (y-u-v-y views)
- Huge magnet (0.15 T)

- 1×10^7 hits/station per spill
- Resolution of 120 µm
- Momentum resolution: better 1% up to 50 GeV

Detectors



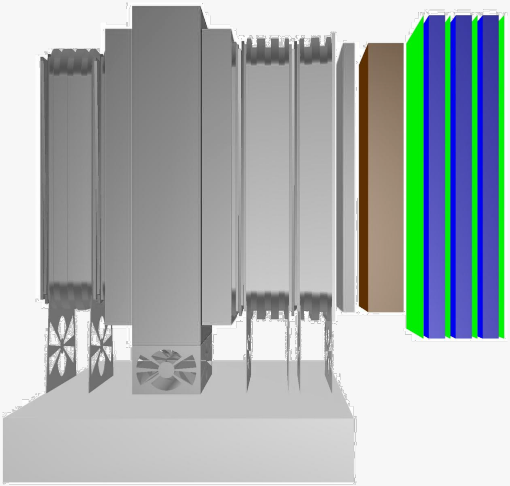
Timing Detector

- Needed to reduce combinatorial di-muon background (random crossing in the detector)
  - ▷ timing resolution of 100 ps or less

Two options:

- Plastic scintillators read-out by SiPMs
- Multigap resistive plate chambers (MRPCs)

Detectors



Calorimeters

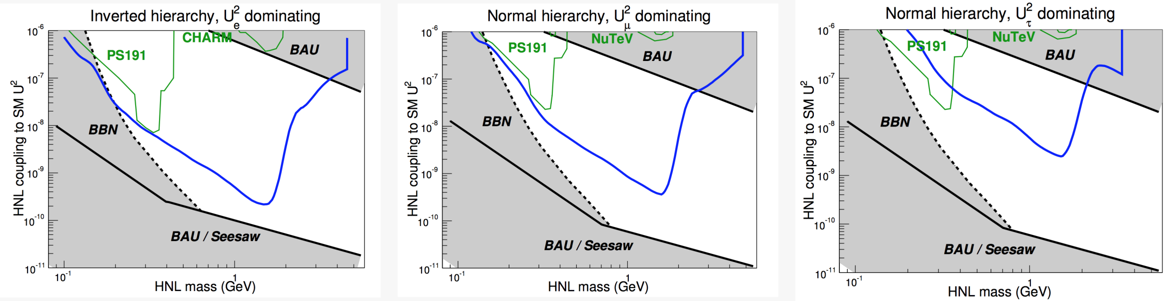
- ECAL: pointing calorimeter based on scintillating fibers read out by SiPMs or MicroMegas
  - Needed to identify γ, e, μ and π^0 and measure their energy
- HCAL: Tag neutral particles (K_L, n) for BG rejection

Muon Filter

- Identify muons in signal channels
- Scintillating bars with WLS fibers and SiPM readout

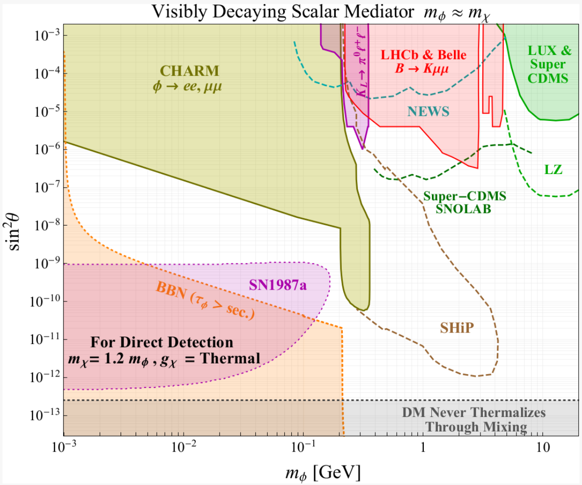
Sensitivity to HNLs

- Sensitivities depend on input parameters for U and hierarchy



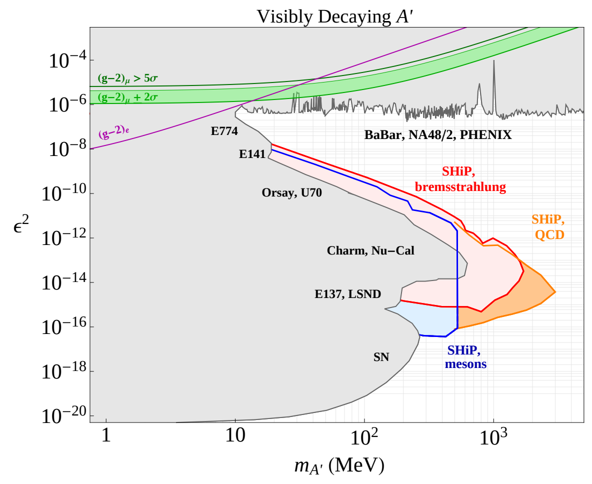
▷ SHIP will scan most of the cosmologically allowed region below the charm mass

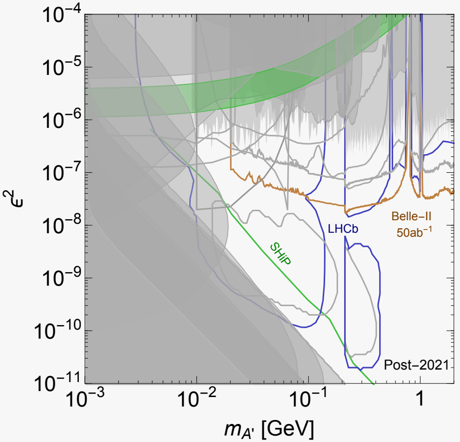
Dark Scalars



- SHiP covers unique parameter space
- $c\tau \simeq 0\,\mathrm{m}$ region: τ too short for SHiP and too long for B-experiments

Dark Photons





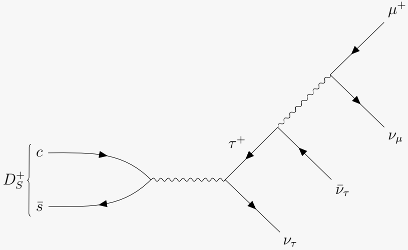
arXiv:1608.08632

- Complementary to regions studied by other experiments

ν_τ Physics

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 $\bar{\nu}_e$



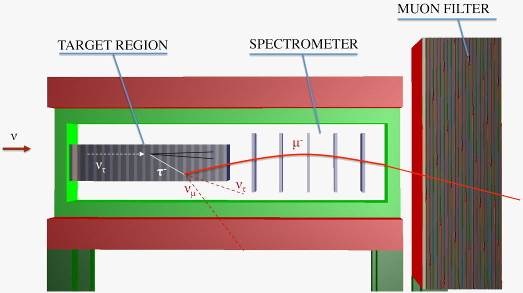
- Production of large amounts of neutrinos
  - ▷ Study ν_τ and $\bar{\nu}_\tau$ properties
  - ▷ Test lepton flavor universality by comparing interactions of ν_μ and ν_τ

- Target for neutrino interactions
  - ▷ $\sim$ 10 tons lead
  - ▷ 40 m behind p-target

Interactions in ν-target

- ▷ $\nu_\mu + \bar{\nu}_\mu$: ~ 2 per spill
- ▷ $\nu_e + \bar{\nu}_e$: ~ 0.2 per spill
- ▷ $\nu_\tau + \bar{\nu}_\tau$: ~ 0.02 per spill

Emulsion Spectrometer



- Magnetized OPERA-like Pb/Emulsion Target
  - ▷ 26 000 m^2 emulsion films
- Followed by spectrometer and muon filter

ν_τ-physics

- $\mathcal{O}(4000)$ $\nu_\tau/\bar{\nu}_\tau$ interactions
  - ▷ DONUT: 9±1.5 events
  - ▷ OPERA: 5 events
- ▷ Study the properties and cross-section
- ▷ First observation of $\bar{\nu}_\tau$

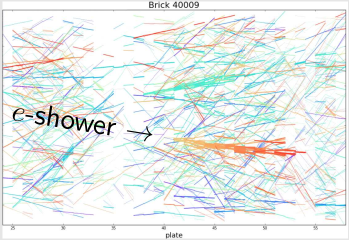
Other SM-physics

- F_4 and F_5 structure functions
- s- and $\bar{s}$-contents of the nucleon
- Test nuTeV anomaly
- Search for charmed penta-quarks

Light Dark Matter production

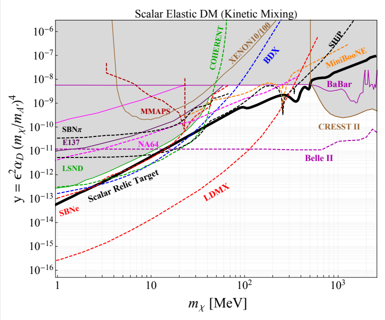
- Decay of dark photon A' in the beam dump produces DM particle χ

Search for Light Dark Matter via elastic scattering



- Machine learning technique to identify isolated e-shower
- Background from ν-scattering
  - ▷ About 300 events ▷ different kinematics

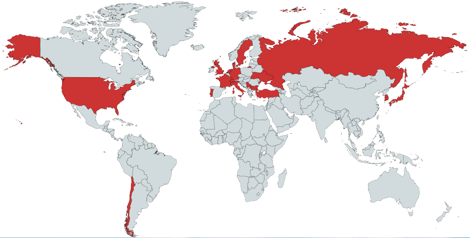
Sensitivity at SHiP for $\frac{m_{A'}}{m_\chi} = 3$



Community Report: New Ideas in Dark Matter
arXiv:1707.04591

SHiP Collaboration

- ~250 physicists
- 57 institutions
- 18 countries
  +CERN +JINR
- Strong support from the theory community



German Contributions to SHiP

HU Berlin
T 4.6, T 4.7, T 40.10, T 65.7, T 65.8, T 65.9

- Liquid Scintillator Surround Background Tagger
  - ▷ Studies of wavelength shifting optical modules

JGU Mainz
T 65.6, T 86.8, T 86.9

- Electromagnetic Calorimeter (ECAL) with directional information
- Liquid Scintillator Studies for the Surround Background Tagger

Universität Bonn
T 89.9

- Testbeam measurements to understand charm production in target
  - ▷ Pixel detectors for tracking

Forschungszentrum Jülich

- Officially became a member last week
  - ▷ Read-out electronics for the central tracker

Universität Hamburg
T 4.5

- Straw-tubes for the main spectrometer
- Drift-tubes for muon-flux and charm cc testbeam

Summary: Status and Outlook of SHiP

2014: Collaboration founded

2015: Technical Proposal arXiv:1504.04956v1

Physics Proposal arXiv:1504.04855v1

2016: Recognized as CERN experiment

2018: Four weeks of testbeam @ H4 (SPS)

- ▷ Investigate muon flux after target
- ▷ Charm production in target

Comprehensive Design Report

- ▷ Optimized detector layout
- ▷ Improved background studies and sensitivities
- • Input for the European Strategy of Particle Physics

2020: Approval!

2021: Start of civil engineering

- ▷ Linked to LHC shutdown phases

2026: Start of Data Taking