Imperial College London

SHiP
Search for Hidden Particles

Search for new physics with the SHiP experiment at CERN

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Technical Proposal: [CERN-SPSC-2015-016]
Physics Proposal: [CERN-SPSC-2015-017]

The state of particle physics

"We know there is new physics,..."

- There is experimental evidence for new physics beyond the standard model (SM):
  1. Neutrino masses and their origin
  2. Dark Matter
  3. Baryon asymmetry of the universe

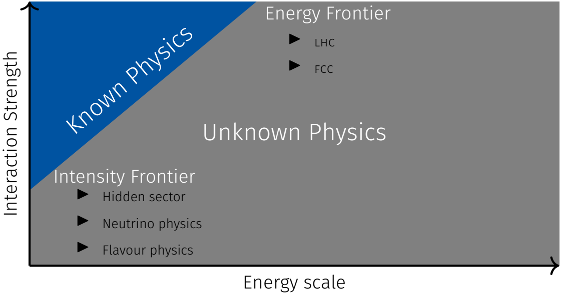
$\rightarrow$ these problems could be solved by new particles that are coupled to the standard model (if very weakly)

- And of course there are plenty of theoretical criticisms of the standard model...

New physics?

"... We don't know where it is..."

- We do not know at which energy new physics will show up.
- New physics could have eluded us so far in two ways:
  - new physics is at a higher energy scale
  - new physics is too weakly coupled to be detected at the current generation of experiments



"... We need to be as broad as possible in our exploratory approach"

— *Fabiola Gianotti*

I will focus on the second option: Super-weakly coupled new physics with $m_{\mathrm{NP}} < \mathcal{O}(10\,\mathrm{GeV})$.

Hidden sectors & portals

If there is super weakly coupled new physics, there generally is a portal that mediates between the standard model and one or more hidden particles, i.e. the hidden sector (HS):

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{portal}} + \mathcal{L}_{\text{HS}}$$

There are four possible types of portal:

- Scalar (e.g. dark scalar, dark Higgs) $(H^\dagger H)\phi$
- Vector (e.g. dark photon) $\epsilon F_{\mu\nu} F'_{\mu\nu}$
- Fermion (e.g. heavy neutral lepton (HNL)) $H^\dagger \overline{N} L$
- Axion-like particle (ALP) $a F^{\mu\nu} \tilde{F}^{\mu\nu}$

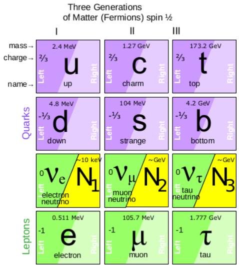
Consider example of the fermion portal here: HNL

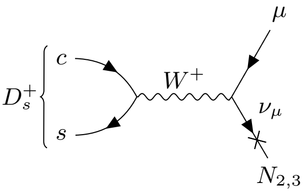
See our physics proposal [CERN-SPSC-2015-017] for an overview of the many other models we can test!

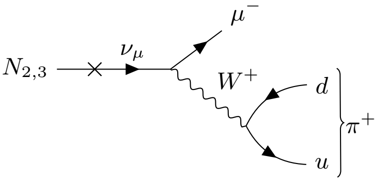
Example: Fermion portal/HNL of the νMSM

A model with a minimal number of additional particles that can solve all of the experimental problems is the neutrino minimal standard model (νMSM) [arχiv:hep-ph/0505013]

- Add three right-handed Majorana neutrinos N_i:
  - Light N_1 with mass $\mathcal{O}(10\,\mathrm{keV})$, essentially decoupled from $N_{2,3}$
    - Dark matter candidate
  - Heavy $N_{2,3}$ with masses $\mathcal{O}(1\,\mathrm{GeV})$, weakly coupled to standard model $\rightarrow$ HNL
    - Set active neutrino masses
    - Create baryon asymmetry of the universe via leptogenesis and sphaelerons
    - Produced in charm decays; detectable via visible decays:

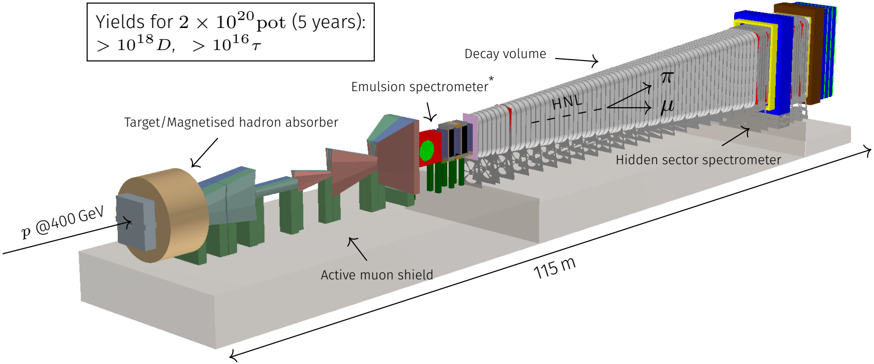






Concept

Yields for 2×10^{20}pot (5 years):
$> 10^{18} D, \quad > 10^{16} \tau$



Two signatures:

1. Via decay to visible particles in hidden sector spectrometer
2. Via scattering in nuclear emulsion

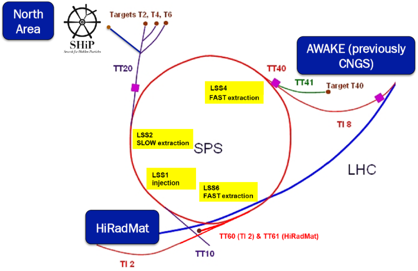
} Generic signatures predicted by many new physics models

*see talk by Marilisa De Serio in the Neutrino Physics track

Crucial challenges

Maximise intensity and mass reach

- Intense proton beam from the SPS @400 GeV at the new beam dump facility (BDF) in the North Area
- Very dense target of $12 \times \lambda_{\text{int}}$
  - abundant production of heavy flavour
  - reduced neutrino production from π and K decays
- Number of protons per cycle similar to CNGS, but slow instead of fast extraction
- Operation in parallel with LHC, other beam-lines at the SPS



Crucial challenges

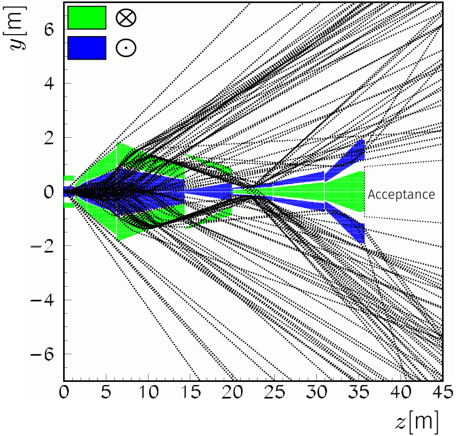
Zero background

- Passive hadron absorber
- Active muon shield that has to reduce muon flux by at least 6 orders of magnitude
- kinematic range of muons up to $p \sim 350$ GeV
- kinematic range of muons up to $p_T \sim 8$ GeV

The muon shield is the critical component to optimise to maximise the experimental acceptance

- A measurement of the muon spectrum for the SHiP target at the H4 test-beam at CERN's SPS is planned for 2018

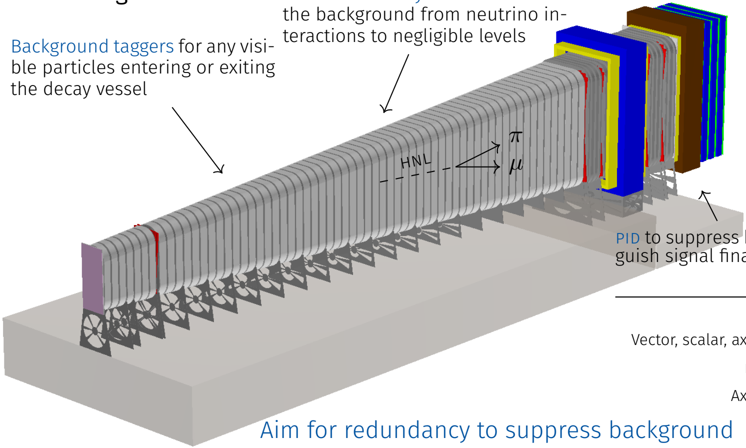
[2017 JINST 12 P05011]



Zero background

Background taggers for any visible particles entering or exiting the decay vessel

Evacuated decay vessel to reduce the background from neutrino interactions to negligible levels



- Timing† to suppress combinatorial background from muons
- Tracking for vertexing and impact parameter measurement

PID to suppress background and distinguish signal final states:

Particle	Final states
HNL, neutralino	$\ell^{\pm}\pi^{\mp}, \ell^{\pm}K^{\mp}, \ell^{\pm}\rho^{\mp}$
Vector, scalar, axion portals; goldstino	$\ell^{\pm}\ell^{\mp}$
HNL, neutralino, axino	$\ell^{\pm}\ell^{\mp}\nu_{\ell}$
Axion portal, sgoldstino	$\gamma\gamma$
Sgoldstino	$\pi^0\pi^0$

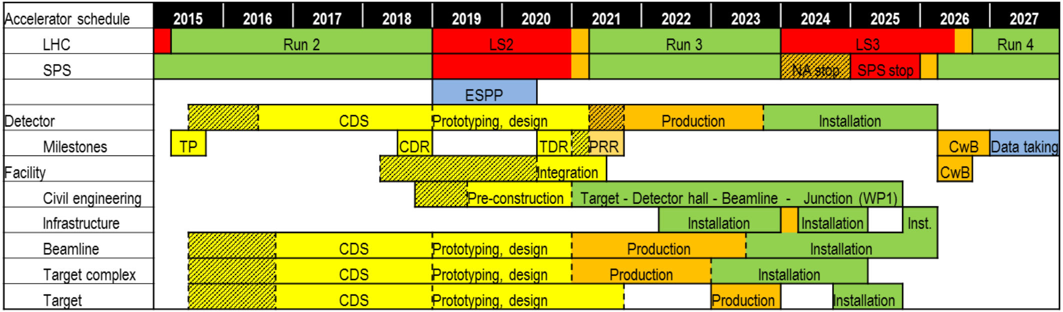
Aim for redundancy to suppress background

† see poster by Alexander Korzenev

Status

SHiP
Search for Hidden Particles

- Expression of interest — 2013
- Technical proposal (TP) & physics proposal (PP) — 2015
- SPSC and CERN research board recommended we continue to a comprehensive design study (CDS) phase → Re-optimisation of the entire experiment — Now!
- Part of the CERN Physics beyond colliders (PBC) working group and will be an input to the European strategy meeting (ESPP) in 2019/2020



Sensitivity: HNL

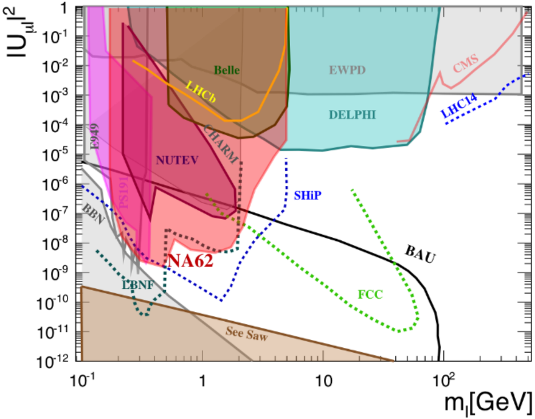


Figure: HNL sensitivity at SHiP for νMSM with $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$ and a normal neutrino mass hierarchy.

NB: Before re-optimisation

- Best sensitivity up to charm kinematic limit
- Significant contribution from B-decays

Theoretical limits from:

- Baryon asymmetry of the universe (BAU)
- Big bang nucleosynthesis (BBN)
- Model-independent limit for any Seesaw model

Sensitivity: Dark Scalars

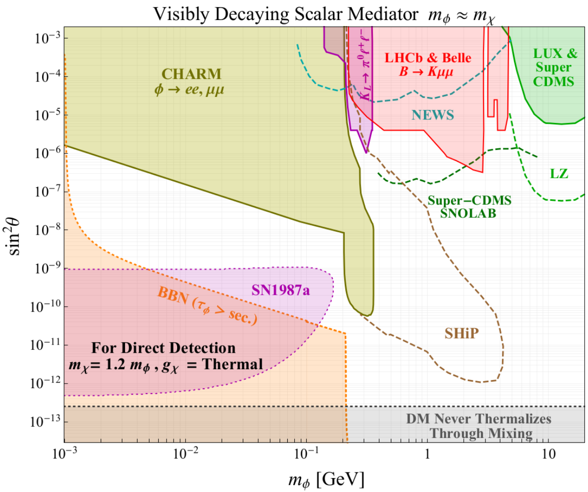


Figure: Dark scalar sensitivity at SHiP.

- For short lifetimes B-factories and LHCb best
- SHiP covers unique parameter space complementing other experiments
- Large contribution from B-decays at SHiP
- "Hole" at $c\tau \sim \mathcal{O}(\mathrm{m})$, where lifetime is too short for SHiP and too long for B-experiments

NB: Before re-optimisation

Sensitivity: Dark Photons

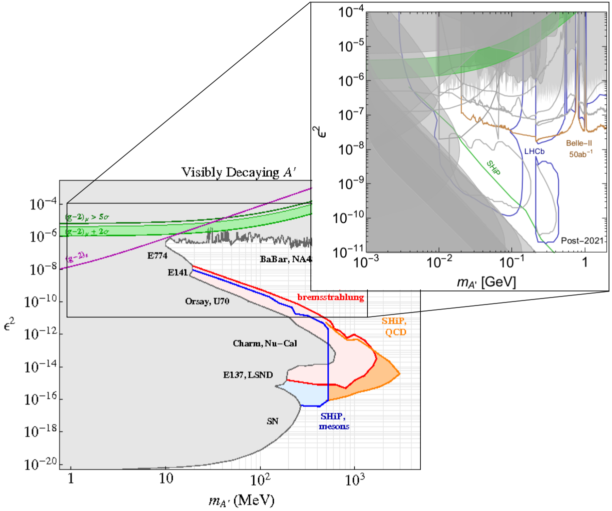


Figure: Dark photon sensitivity at SHiP.

- Based on $> 10^{20}\gamma$ at SHiP over 5 years
- Visible decays of dark photons
- Produced in QCD, bremsstrahlung and meson decays
- No production via EM showers yet → Work in progress
- Complementary to regions studied by other experiments
- Top-right edge of sensitivity determined by short lifetime

NB: Before re-optimisation

Sensitivity: Light Dark Matter

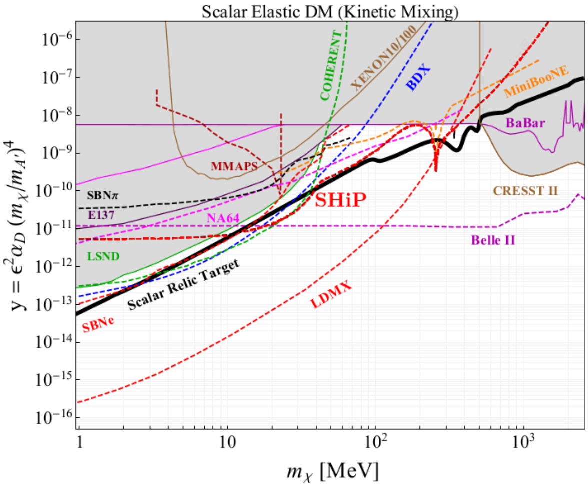


Figure: Light dark matter sensitivity at SHiP for $\frac{m_{A'}}{m_\chi} = 3$.

NB: Before re-optimisation

- For dark matter lighter than WIMPS "direct detection" experiments quickly lose sensitivity.

Two approaches:

- missing mass/energy searches ($\propto U^2$)
- scattering/recoil ($\propto U^4$)

SHiP: Indirect detection via electron and nuclear recoil in nuclear emulsion:

- Main background for electron recoil from ν_e scattering, but differences in the kinematics can be exploited.
- Preliminary; cascade production not yet implemented → already best sensitivity for scattering

LDMX@SLAC:

- missing energy at electron beam

Conclusion

- Plenty of room for new physics to hide in the dark sector!
- SHiP is sensitive to many different final states in decay and scattering
- SHiP is currently undergoing a re-optimisation to improve physics performance while respecting cost constraints
- Sensitivities and backgrounds are being updated for new configurations, additional production and decay channels are being added in collaboration with theorists

> *"We have to leave all this spectrum of possibilities open and just enjoy this extremely fascinating science."*
>
> — *Carlo Rubbia*