Search for new physics with the SHiP experiment at CERN

Oliver Lantwin *on behalf of the SHiP Collaboration.*

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[oliver.lantwin@cern.ch]

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~250 scientific authors
17 member countries: Bulgaria, Chile, Denmark, France, Germany, Italy, Japan, Korea, Portugal, Russia, Sweden, Switzerland, Turkey, United Kingdom, Ukraine, United States of America + CERN, Dubna
49 member institutes: Sofia, Valparaiso, Niels Bohr Institute Copenhagen, LAL Orsay, LPNHE Paris, Berlin, Humboldt University Hamburg, Mainz, Bari, Bologna, Cagliari, Ferrara, Lab. Naz. Gran Sasso, Frascati, Naples, Rome, Aichi, Kobe, Nagoya, Nihon, Toho, Gyeongsang, LIP Coimbra, Dubna, ITEP Moscow, INR Moscow, P.N. Lebedev Physical Institute Moscow, Kurchatov Institute Moscow, IHEP Protvino, Petersburg Nuclear Physics Institute St. Petersburg, Moscow Engineering Physics Institute, Skobeltsyn Institute of Nuclear Physics Moscow, Yandex School of Data Analysis, Belgrade, Stockholm, Uppsala, CERN, Geneva, EPFL Lausanne, Zurich, Middle East Technical University Ankara, Ankara University, Imperial College London, University College London, Rutherford Appleton Laboratory, Bristol, Warwick, Taras Shevchenko National University Kyiv, Florida
5 associated institutes: Jeju, Gwangju, Chonnam, National University of Science and Technology "MISIS" Moscow, St. Petersburg Polytechnic University

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

→ 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

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

-- Fabiola Gianotti

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“... We need to be as broad as possible in our exploratory approach”
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))
  \[H^\dagger \tilde{N} L\]

- 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!
A model with a minimal number of additional particles that can solve all of the experimental problems is the neutrino minimal standard model ($\nu$MSM) [arXiv:hep-ph/0505013]

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

$$D_s^+\left\{\begin{array}{cc} c & \nu_\mu \\ s & \end{array}\right\} W^+ N_{2,3}$$

$$N_{2,3} \times \nu_\mu \rightarrow W^+ d \pi^+$$

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

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
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 $\pi$ 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]
Crucial challenges

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:

<table>
<thead>
<tr>
<th>Particle</th>
<th>Final states</th>
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<tbody>
<tr>
<td>HNL, neutralino</td>
<td>$\ell^\pm \pi^\mp, \ell^\pm K^\mp, \ell^\pm \rho^\mp$</td>
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<tr>
<td>Vector, scalar, axion portals; goldstino</td>
<td>$\ell^\pm \pi^\mp$, $\ell^\pm K^\mp$, $\ell^\pm \rho^\mp$, $\ell^\pm \nu_\ell$</td>
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<tr>
<td>HNL, neutralino, axino</td>
<td>$\gamma\gamma$</td>
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<tr>
<td>Axion portal, sgoldstino</td>
<td>$\pi^0\pi^0$</td>
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\(^{†}\)see poster by Alexander Korzenev

Aim for redundancy to suppress background
Status

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

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The SHiP experiment
Sensitivity: HNL

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

- 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

NB: Before re-optimisation
Sensitivity: Dark Scalars

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 $c\tau \sim \mathcal{O}(m)$, where lifetime is too short for SHiP and too long for $B$-experiments

Figure: Dark scalar sensitivity at SHiP.
Sensitivity: Dark Photons

- 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

Figure: Dark photon sensitivity at SHiP.
Sensitivity: Light Dark Matter

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 $\nu_e$ scattering, but differences in the kinematics can be exploited.
- Preliminary; cascade production not yet implemented $\rightarrow$ already best sensitivity for scattering

LDMX@SLAC:
- missing energy at electron beam

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

NB: Before re-optimisation

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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