SHiP: a new facility to search for heavy neutrinos and study $\nu_\tau$ properties

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On behalf of the SHiP Collaboration
The Standard Model provides a consistent description of Nature’s fundamental constituents and their interactions.

Although largely tested and confirmed by several experiments, the SM cannot be regarded as the ultimate theory of Nature, since it cannot account for a number of established experimental facts, such as:

• Neutrino masses and oscillation

• Excess of matter over antimatter in the Universe

• Dark matter
New, yet unknown particles and/or interactions should exist.

*Hidden* particles, not directly interacting with SM particles, could be coupled to the *visible* sector via gauge-singlet operators (portals).
The SHiP experiment

Proposal of a beam dump facility at CERN SPS designed to investigate the *hidden sector* in the GeV mass region and study $\nu_\tau$ physics

Technical Proposal (arXiv:1504.04956) submitted last April, signed by 235 experimentalists from 45 institutes

Physics Proposal (arXiv:1504.04855) signed by 80 theorists
The SHiP physics program

Rich physics program

This talk:
focus on $\nu$ portal and $\nu_\tau$ physics
Oscillation mechanism among active neutrinos well established after several decades of experimental searches, described in terms of two mass splittings and three mixing angles

⇒ Non-zero ν masses ⇒ Beyond SM physics

Neutrinos: current picture
Most general renormalizable Lagrangian (see-saw generation of neutrino masses):

\[ L_{\text{single}} = i \bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha - M_I \bar{N}_I^c N_I + h.c + L_{SM} \]

\( N_I (I = 1, 2, ..., n) \) gauge-singlet fermions

Majorana mass term

Yukawa term: mixing with active neutrinos

If \( n = 3 \) and \( M_I < M_W \): Neutrino Minimal Standard Model (νMSM)
Neutrino portal

νMSM:
3 additional sterile right-handed neutrinos, Majorana partners of active neutrinos with masses < $M_W$ (Heavy Neutral Leptons, HNL)

$N_1$ with mass in the keV region: dark matter candidate

$N_{2-3}$ with mass in the GeV region: allow for the explanation of $\nu$ masses and oscillation and baryon asymmetry

Production: semi-leptonic decay of mesons

T. Asaka e M. Shaposhnikov, PLB620 (2005) 17
**νMSM:**
3 additional sterile right-handed neutrinos, Majorana partners of active neutrinos with masses $< M_W$
*(Heavy Neutral Leptons, HNL)*

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Very small HNL – active $\nu$ coupling: HNL long-lived particles (flight length $O$(km))
Experimental requirements

Search for HNLs produced in charmed hadron decays

Detection of HNL decays to SM particles

Requirements:

- Maximize production of charmed hadrons
- Minimize neutrinos from $\pi$ and K decays
- Effective and compact muon shield
- Hadron and electron/gamma absorber
- Detector *close* to target to maximize geometrical acceptance (large $P_T$)
**The SHiP facility**

**Beam:** $4 \times 10^{13}$ p.o.t. / cycle (7.2s) with slow extraction (1s) to reduce detector occupancy (combinatorial background); $4 \times 10^{19}$ p.o.t. / year

**Target:** titanium-zirconium doped molybdenum + pure tungsten, water cooled

**Active muon filter:** two magnetized regions with opposite field orientation to bend out beam muons

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M. De Serio
• **Hidden particle detector:**
  long, evacuated decay volume with a magnetic spectrometer, calorimeters and $\mu$ detectors

• **Tau neutrino detector:**
  emulsion target equipped with electronic trackers in a magnetic field followed by a $\mu$ spectrometer
HNL discovery potential critically dependent on background rejection:

- 5m x 10m x 50m evacuated elliptical decay volume (pressure \( \sim 10^{-6}\) bar) to suppress \( \nu\) and \( \mu\) interactions, instrumented with surrounding liquid scintillator background tagger + upstream veto tagger

**HNL detector**

- Large aperture dipole magnet instrumented with Straw Tracker planes + timing detector (\( \sim 100\) ps resolution) to suppress combinatorial background
- Electromagnetic / hadronic calorimeter (Shashlik technique, LHCb)
- Muon detector (plastic scintillator bars, MINOS)
HNL: sensitivity

- Significant improvement of present limits
- Largely unexplored region above $m_K$ up to $m_B$

$2 \times 10^{20}$ p.o.t. @ 400 GeV
5 years

$Br(N \rightarrow \mu/e, \pi) \sim 0.1 - 50\%$
$Br(N \rightarrow \mu/e, \rho) \sim 0.5 - 20\%$
$Br(N \rightarrow \nu_{\mu}e) \sim 1 - 10\%$
The SHiP detector

- **Hidden particle detector:**
  long, evacuated decay volume with a magnetic spectrometer, calorimeters and $\mu$ detectors

- **Tau neutrino detector:**
  emulsion target equipped with electronic trackers in a magnetic field followed by a $\mu$ spectrometer
$\nu_\tau$ physics

Abundant production of neutrinos in charmed hadron decays

SHiP ideally suited for studying $\nu$ physics

- First direct observation of anti-$\nu_\tau$
- Measurement of $\nu_\tau$ and anti-$\nu_\tau$ cross section

Only 9 $\nu_\tau$ events (with 1.5 background events) observed in DONUT and 5 $\nu_\tau$ events (from $\nu_\mu$ oscillation) observed so far in OPERA
Requirements:

- Compact high-density magnetized target with sub-micrometric position resolution
- Muon magnetic spectrometer

- Magnetized nuclear emulsion – lead target
- Electronic trackers (time stamp)
ντ detector

- Unique capability of detecting all ν flavors
  - $\nu_\mu$: muon reconstruction in the magnetic spectrometer
  - $\nu_e$: e.m. shower reconstruction in the brick
  - $\nu_\tau$: observation of ν interaction and τ decay vertices in the brick
• \( \nu_\tau \) detector

- \( \nu_\tau / \text{anti-} \nu_\tau \) separation
  - \( \tau \rightarrow \mu \): muon charge measurement in the magnetic spectrometer
  - \( \tau \rightarrow h \): hadron charge measurement in the Compact Emulsion Spectrometer
**ντ** physics performance

**Expected number of signal and background events**

<table>
<thead>
<tr>
<th>decay channel</th>
<th>$N^{\text{exp}}$</th>
<th>$N^{\text{bg}}$</th>
<th>$R$</th>
<th>$N^{\text{exp}}$</th>
<th>$N^{\text{bg}}$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$τ \to \mu$</td>
<td>570</td>
<td>30</td>
<td>19</td>
<td>290</td>
<td>140</td>
<td>2</td>
</tr>
<tr>
<td>$τ \to h$</td>
<td>990</td>
<td>80</td>
<td>12</td>
<td>500</td>
<td>380</td>
<td>1.3</td>
</tr>
<tr>
<td>$τ \to 3h$</td>
<td>210</td>
<td>30</td>
<td>7</td>
<td>110</td>
<td>140</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1770</td>
<td>140</td>
<td>13</td>
<td>900</td>
<td>660</td>
<td>1.4</td>
</tr>
</tbody>
</table>

2x10^{20} p.o.t. @ 400 GeV
5 years
Target mass: 9.6 t

Main background source: charm production in ν CC interactions with unidentified primary lepton
Structure functions $F_4$ and $F_5$, neglected in $\nu_\mu / \nu_e$ interactions, contribute to $\nu_\tau$ cross section (higher $\tau$ lepton mass).

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

$F_4 = F_5 = 0$ for SM prediction.

Expected $\bar{\nu}_\tau$ interactions: ~ 300

$E(\bar{\nu}_\tau) < 38 \text{GeV}$
SHiP ideally suited to study $\nu$ and anti-$\nu$ physics for all three active flavours.

**Expected $\nu$-induced charm production**

<table>
<thead>
<tr>
<th>Expected events</th>
<th>$\nu_\mu$</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_\mu$</th>
<th>$\bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$6.8 \cdot 10^4$</td>
<td>$1.5 \cdot 10^4$</td>
<td>$2.7 \cdot 10^4$</td>
<td>$5.4 \cdot 10^3$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$1.1 \cdot 10^5$</td>
<td></td>
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</tbody>
</table>

Charm production in anti-$\nu$ interactions selects the anti-strange quark in the nucleon.

Significant improvement in the knowledge of nucleon s-quark content with SHiP data in the range $0.03 < x < 0.35$.

Expected charm yield exceeds available statistics from previous experiments by more than one order of magnitude.

NuTeV: ~5100 ($\nu_\mu$) and ~1460 (anti-$\nu_\mu$)

CHORUS: ~2000 ($\nu_\mu$) and 32 (anti-$\nu_\mu$)

$$s^+ = s(x) + \bar{s}(x)$$
Conclusions

- SHiP designed to complement searches for New Physics at LHC by probing a largely unexplored domain at the intensity frontier: search for new, very weakly interacting particles with masses $O$(GeV)
- Technical and Physics proposals submitted to the SPSC in April 2015
- Rich physics program including Heavy Neutral Leptons and $\nu_\tau$ physics with unprecedented sensitivities
• TDRs by end of 2018
• Detector construction (4 years) + installation (2 years)
• Commissioning in 2023 (beam line, target, muon shield)
• Data-taking in 2026
Scalar and vector portals: sensitivity

Exclusion limit at 90 % C.L. for a light hidden scalar particle of mass $m_S$ coupling to the Higgs with $\sin^2\theta$ mixing parameter and decaying in $ee$, $\mu\mu$, $\pi\pi$, $kk$