SHiP project as a new facility at intensity frontier

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on behalf of the SHiP collaboration

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Triumph of the Standard Model: Higgs boson, flavour physics, rare decays and nothing beyond.

Present status
We know however (not from LHC) that there is physics beyond the SM:

- Neutrino masses and oscillations
- Dark matter
- Baryon asymmetry of the Universe
- ...

Besides that, there are many «why» and «how» in the SM:

- How is EW scale so smaller than UV scale?
- Why hierarchy between SM scales?
- Why are lefts doublets and rights singlets?
- Why 3 generations? Why CKM hierarchy & CP?
- ...

Observable Higgs mass corresponds to metastability of the SM vacuum

(from arXiv:1307.3536)


Strong hint to NO New Physics up to the Planck scale.
Standard Model Criticality Prediction:
Top mass $173 \pm 5$ GeV and
Higgs mass $135 \pm 9$ GeV.

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Abstract

Imposing the constraint that the Standard Model effective Higgs potential should have two degenerate minima (vacua), one of which should be -order of magnitudewise- at the Planck scale, leads to the top mass being $173 \pm 5$ GeV and the Higgs mass $135 \pm 9$ GeV. This requirement of the degeneracy of different phases is a special case of what we call the multiple point criticality principle. In the present work we use the Standard Model all the way to the Planck scale, and do not introduce supersymmetry or any extension of the Standard Model gauge group. A possible model to explain the multiple point criticality principle is lack of locality fundamentally.
Perhaps it is more useful to think not about New Physics that could solve theoretical problems of the SM, but about NP that could explain observed effects beyond SM.

*In hope that theory will settle things anyway.*

What could the new degrees of freedom be?

<table>
<thead>
<tr>
<th></th>
<th>SM singlets</th>
<th>SM non-singlets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why not but what for?</td>
<td>Energy Frontier</td>
<td></td>
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<tr>
<td>Energy Frontier</td>
<td>Excluded</td>
<td></td>
</tr>
<tr>
<td>SM scale</td>
<td>Intensity Frontier</td>
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</table>
The diagram illustrates the relationship between energy scale and interaction strength, categorizing physics into known and unknown domains.

**Known Physics**
- Energy Frontier: LHC, FCC

**Unknown Physics**
- Intensity Frontier:
  - Proton decay, n-n oscillations
  - Neutrino physics (not covered in this talk)
  - Flavour physics
  - Lepton Flavour Violation
  - Electric Dipole Moments
  - Hidden Sector

The effect is given by: \[ \text{effect} \sim \frac{g^2}{M^2} \]
Intensity frontier physics reach

- proton decay
- neutrino
- lepton flavor
- quark flavor
- dark matter
- LHC
- Tevatron

Experimental reach [GeV] (with significant simplifying assumptions)

(picture of Z. Ligeti)
Light Hidden Particles $\rightarrow$ **SM**–singlets $\rightarrow$ couple to different singlet composite **SM** operators (Portals)

$$L = L_{SM} + L_{HS} + L_{portal}$$

Visible (SM) matter $\leftrightarrow$ Hidden Sector (HS) contains Dark Matter and can have very complicated structure

Most work is on these 3 renormalizable portals in the **SM**:

- \( L_{\text{Vector portal}} = \epsilon F'_{\mu
u} F^{\mu
u}_Y \)

- \( L_{\text{Scalar portal}} = (\lambda_i S_i^2 + g_i S_i)(\Phi^\dagger \Phi) \)

- \( L_{\text{Neutrino portal}} = F_{\alpha I}(\bar{L}_\alpha \cdot \tilde{\Phi}) N_I \)
\( \nu \text{MSM} \) (T. Asaka, M. Shaposhnikov, 2005)

Most general renormalizable type I see-saw Lagrangian with 3 HNLs:

\[
L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \Phi \bar{N}_I L_\alpha - \frac{M_I}{2} \bar{N}^c_I N_I + h.c.
\]

- \( N_1 \) with mass \( \mathcal{O}(\text{keV}) \) – dark matter
- \( N_2, N_3 \) with mass \( \mathcal{O}(\text{GeV}) \) – neutrino masses and BAU
How to discover?

(see D.Gorbunov, M.Shaposhnikov hep-ph/0705.1729)

<table>
<thead>
<tr>
<th>Models</th>
<th>Final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino portal, SUSY neutralino</td>
<td>$\ell^\pm \pi^\mp, \ell^\pm K^\mp, \ell^\pm \rho^\mp$, $\rho^\pm \rightarrow \pi^\pm \pi^0$</td>
</tr>
<tr>
<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>$\ell^+ \ell^-$</td>
</tr>
<tr>
<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>$\pi^+\pi^-, K^+K^-$</td>
</tr>
<tr>
<td>Neutrino portal ,SUSY neutralino, axino</td>
<td>$\ell^+ \ell^- \nu$</td>
</tr>
<tr>
<td>Axion portal, SUSY sgoldstino</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>SUSY sgoldstino</td>
<td>$\pi^0\pi^0$</td>
</tr>
</tbody>
</table>

$U^2_{e\tau}: U^2_{\mu\tau}: U^2_{\tau\tau} \sim 52:1:1$
**Inverted hierarchy**

$U^2_{e\tau}: U^2_{\mu\tau}: U^2_{\tau\tau} \sim 1:16:3.8$
**Normal hierarchy**

$U^2_{e\tau}: U^2_{\mu\tau}: U^2_{\tau\tau} \sim 0.061:1:4.3$
**Normal hierarchy**
General requirements
to fixed-target (beam dump like) experiment

- Maximize number of particles on target

SPS@CERN: $4 \times 10^{13}$ protons @ 400 GeV

- Preference to slow beam extraction

SPS@CERN: a few seconds, to reduce detector occupancy

- Active muon shield

To deflect muons at short distances in order to put detector as close as possible to target (hidden particles may have large $p_T$)

- Evacuated (or helium) and large detector volume

To reduce neutrino interactions and to give hidden particles space to fly
A bit of history

Proposal to Search for Heavy Neutral Leptons at the SPS
(Submitted on 7 Oct 2013)

EoI (16 auth.)
October 2013

Task force report for Beam Dump Facility
July 2014

SHiP Technical Proposal (250 auth.)
SHiP Physics Paper (85 auth.)
April 2015
Principle layout of the experiment

$p$-beam  Target  $\mu$-shield  HNL decay vessel  spectrometer

\[ \frac{N(HNL) @ SHiP}{N(HNL) @ CHARM} \approx 10000 \]
Current layout (optimized with respect to TP)

Magnetic shield
~ 35 m long
1.8 T magnets

Vacuum decay vessel surrounded by liquid or plastic scintillator veto system

Target
13 TZM+5 W blocks

400 GeV p-beam from SPS, $2 \times 10^{20}$ pot in 5 years
Peak power – 2.6 MW, $10^{11}$ muons/sec

Emulsion detector
LDM scatters on e/nuclei
tau-neutrino physics

Spectrometer
Tracker
Magnet
Calorimeter
Muon detector
• $4 \times 10^{13}$ p / 7 sec → **355 kW** average, **2.56 MW** during 1 sec spill – water cooled to dissipate
• Initial dose ~ **50 Sv/h**
• $10 \lambda_{\text{int}}$ long segmented target; high-Z hybrid solution composed of Mo alloy (TZM, $4 \lambda_{\text{int}}$) & pure W ($6 \lambda_{\text{int}}$)
Tau-neutrino is the least known particle in the SM, first observation by DONUT in 2001.

- 10 $\nu_\tau$ candidates in total recently reported by OPERA

- Tau anti-neutrino is the only particle of the SM that has never been observed – and SHiP can see it

- Number of interactions in 5 years run and target mass $\sim$ 9.6 tons Pb:
  
  $$N_{\nu_\tau} \approx 6.7 \times 10^3 \quad \quad N_{\bar{\nu}_\tau} \approx 3.4 \times 10^3$$
$\nu_\tau$ / iSHiP detector subsystem

TARGET REGION

SPECTROMETER

MUON FILTER

Implemented in FairShip by A. Iuliano

(picture by G.DeLellis)
Main $\nu_\tau$ / iSHiP processes

**$\nu_\tau$ interaction**

Emulsion Cloud Chamber (ECC): passive material (lead) - massive target

Main tracking device – nuclear emulsion, high (a few $\mu$m) resolution

Target SciFi tracker planes ~ $2 \times 1$ m$^2$, provide time stamp

**DM scattering**

$$N_{\nu_\tau + \bar{\nu}_\tau} = 4N_{pot} \frac{\sigma_{cc}}{\sigma_{pN}} f_{D_s} \text{Br}(D_s \rightarrow \tau) = 2.85 \times 10^{-5} N_{pot}$$
SHiP sensitivity to HNL

Covers most of parameter space below B-mass. Moving down towards the ultimate see-saw limit.

- $M_{HNL} < M_B$: SHiP will have much better sensitivity than LHCb & Belle-II
- $M_B < M_{HNL} < M_Z$: FCC in ee-mode
- $M_{HNL} < M_Z$: HL-HE LHC
SHiP sensitivity to scalars
SHiP sensitivity to dark photons

\[ \mathcal{L}_{\text{Vector portal}} = \epsilon F'_{\mu\nu} F_Y^{\mu\nu} \]

- **Decay before reaching detector**
  \[ N \sim \exp(-\epsilon^2 m^2/p) \]

- **Kinematic limit**

- **Lifetime too large:** \( N \approx (\epsilon)^4 \)
SHiP sensitivity to light axion

PBC BSM physics group

(* ) NA62++ (dump mode), 1 day
(**) NA62++ (dump mode) 1 month
SHiP Collaboration – 2018

17 countries; 52 institutes; >250 members
Planning is aligned with:

- **Comprehensive Design Study by 2018**
- **Update of European Strategy for Particle Physics 2019/2020**
- **Production Readiness Review 2020**
- **Data taking 2026**
Summary

- Strong hints to «no NP at the energy frontier» motivate studies (both theoretical and experimental) of perspectives at the intensity frontier

- **Search for Hidden Particles (SHiP) experiment** is proposed to search for NP in the largely unexplored domain of new, very weakly interacting particles with masses $\mathcal{O}(10)$ GeV

- Unique opportunities for tau-neutrino studies

- Sensitivity improves previous experiments by $\mathcal{O}(10^4)$ for Hidden Sector and by $\mathcal{O}(10^2)$ for neutrino physics

SHiP is complement to searches for New Physics at energy frontier at CERN
There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.

W. Shakespeare,
Hamlet, Act 1, scene 5
BACKUP
## Proton beam dump experiments: the past

(from W.Bonivento)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Location</th>
<th>approx. Date</th>
<th>Amount of Beam ($10^{20}$ POT)</th>
<th>Beam Energy (GeV)</th>
<th>Target Mat.</th>
<th>Ref.</th>
</tr>
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<tbody>
<tr>
<td>CHARM</td>
<td>CERN</td>
<td>1983</td>
<td>0.024</td>
<td>400</td>
<td>Cu</td>
<td>[16]</td>
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<tr>
<td>PS191</td>
<td>CERN</td>
<td>1984</td>
<td>0.086</td>
<td>19.2</td>
<td>Be</td>
<td>[17, 18]</td>
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<tr>
<td>E605</td>
<td>Fermilab</td>
<td>1986</td>
<td>$4 \times 10^{-7}$</td>
<td>800</td>
<td>Cu</td>
<td>[19]</td>
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<tr>
<td>SINDRUM</td>
<td>SIN, PSI</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ν-Cal I</td>
<td>IHEP Serpukhov</td>
<td>1989</td>
<td>0.0171</td>
<td>70</td>
<td>Fe</td>
<td>[20–22]</td>
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<tr>
<td>LSND</td>
<td>LANSCE</td>
<td>1994-1995</td>
<td>813</td>
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<td>H$_2$O, Cu</td>
<td>[23]</td>
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<td>NOMAD</td>
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<td>882</td>
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<td>W, Cu</td>
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<td>WASA</td>
<td>COSY</td>
<td>2010</td>
<td>0.41</td>
<td>450</td>
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<td>[18, 24]</td>
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<td>HADES</td>
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<td>0.32pA*t</td>
<td>0.550</td>
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<td>MiniBooNE</td>
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<td>2003-2008</td>
<td>6.27</td>
<td></td>
<td>Be, Steel</td>
<td>[26, 27]</td>
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<td></td>
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<td>2005-2012</td>
<td>11.3</td>
<td></td>
<td>Be</td>
<td>[28]</td>
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<tr>
<td></td>
<td></td>
<td>2013-2014</td>
<td>1.86</td>
<td></td>
<td>Steel</td>
<td>[29]</td>
</tr>
</tbody>
</table>

+ DONUT   FNAL          3.6x10^{-3}  800  W
**νMSM: closer look at N₁**

N₁ can provide dark matter candidate:
- very weak mixing with other leptons
- hence, stable enough for dark matter
- Seesaw: one $M_{\nu_{active}} \sim 10^{-5}$ eV
- Radiative decay: $\tau > \tau_{universe}$
- $E_{\gamma} = \frac{M_{N_1}}{2}$

- X-ray detection:
  - 17/2/14: arxiv.org/abs/1402.4119: An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster
  - Both papers refer to Astro-H (with Soft X-Ray Spectrometer, 2016 launch) to confirm/rule-out the DM origin of this signal.
Use $N_{2,3}$ to explain:

- $\nu$ masses:
  Seesaw constrains Yukawa coupling and $M_{N_{2,3}}$, i.e. $M_\nu \propto U^2 / M_{N_{2,3}}$

- Baryo(Lepto)genesis: make $N_2$ nearly degenerate with $N_3$, and tune CPV--phases to explain baryon asymmetry of universe (BAU).
  - $1/\tau_{N_{2,3}} \propto M_{N_{2,3}}^3$
  - $\tau_{N_{2,3}} < 0.1 \text{ s}$, otherwise Big Bang Nucleosynthesis (BBN, $\sim 75/25$ % H-1/He-4) would be affected by $N_{2,3}$ decays.

These are the particles SHiP is after!
Signal yield

\[ N(pot) = 2 \times 10^{20} \]

\[ n(HS) = N(pot) \times \chi(pp \rightarrow HS) \times P_{vtx} \times A_{tot}(HS \rightarrow \text{visible}) \]

\[ \chi(pp \rightarrow HNL) = 2 \sum_{q=c,b} \chi(pp \rightarrow q\bar{q}) \times Br(q \rightarrow HNL) \times U^2 \]

where

\[ \chi(pp \rightarrow c\bar{c}) = 1.7 \times 10^{-3} \quad \chi(pp \rightarrow b\bar{b}) = 1.6 \times 10^{-7} \]

for 400 GeV protons on Molybdenum target

\[ P_{vtx} \] is probability that HNL (of a given mass and couplings) decays in the SHiP fiducial volume

\[ U^2 = U_e^2 + U_\mu^2 + U_\tau^2 \]

\[ A_{tot}(HS \rightarrow \text{visible}) = \sum_i Br(HNL \rightarrow i) \times A(i) \]

is detector acceptance for all HNL final (visible) states

Typically

\[ P_{vtx} \times A \times \text{Selection} \sim 10^{-6} \]
Expectations before LHC

- Higgs boson or strong interaction of vector bosons («guaranteed discovery»)
- New physics in TeV ballpark (SUSY particles ?; extra dimensions ?; compositeness ?)