SHiP:
Search for Hidden Particles
A new experiment proposal at CERN

Walter M. Bonivento
INFN-Cagliari
on behalf of the SHiP collaboration (235 authors, 45 institutions from 14 countries)
The TP: submitted 14 April to CERN/SPS-C

A large (15% in total number of physicists) INFN participation (BA, BO, LNF, CA, NA, FE, RM1) with many leadership roles since the EOI!!
Search for Hidden Particles

After sweat steered their original course west and sailed twelve miles an hour till two hours after midnight, pump ninety miles, which are twenty-two leagues and a half and as the private was the softest color, and kept ahead of the Admiral, she discovered land.

Physics Proposal

Technical Proposal
Addendum to the TP

We are submitting this also this week to SPSc
What is SHIP

SHIP is a proposal for a beam dump experiment at CERN/SPS (400GeV p)

Main goals (so far…):

1) detection of long lived particles, very weakly interacting or sterile: statistical sensitivity with respect to previous experiments of similar type (for HNL) $\times 10000$

$\rightarrow$ Many theories and models on the market (models of DM, SUSY, theories providing explanation for $\nu$ masses and baryogenesis,...) have some sensitivity region to be explored with SHIP!

2) textbook measurements of $\nu_\tau$ interactions with statistical sensitivity with respect to previous experiments of similar type $\times 600$
How?

The high E proton beam of CERN (400GeV)...

...dumped with maximum intensity and followed by the closest, longest and widest possible and technically feasible decay tunnel

signature: a $\geq$ two track decay vertex in the decay tunnel
Shaking hands…

SM was recently fully confirmed by the Higgs-boson discovery!
However: no NP anywhere! Also, naturalness is now severely challenged.

The peculiar Higgs mass suggest that, even in absence of NP, the Universe is metastable.

SM could well be valid up to Planck scale but we have to explain some facts: neutrino oscillations, bariogenesis, dark matter (+inflation, dark energy…)

JHEP 1312 (2013) 089
Where is the new physics?

Energy Frontier
- LHC

Intensity Frontier
- SHiP

EWSB, Hierarchy
WIMP DM ...

RH neutrinos
Dark Matter
Hidden sector
...

Mass of particle (GeV)

Coupling to SM

Intensity Frontier

$\frac{g^2}{M^2} \sim G_F$
The Hidden Sector

Leading SM coupling to Neutral Hidden Sector

\[ \mathcal{O}_s H^\dagger H \quad LHN_R \quad B_{\mu\nu} V^{\mu\nu} \]

renormalizable couplings, i.e. NOT suppressed!

+ other of higher dimensions (e.g. axion-like portal)

(stolen from A. Fradette, New Physics at the Intensity Frontier - Victoria, BC, Sept 2014)
See-saw generation of neutrino masses

Most general renormalisable Lagrangian of SM particles (+3 singlets wrt SM gauge group):

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

Yukawa term: mixing of \( N_I \) with active neutrinos to explain oscillations

Majorana term which carries no gauge charge

The scale of the active neutrino mass is given by the see-saw formula:

\[ m_\nu \sim \frac{m_D^2}{M} \]

where \( m_D \sim Y_{I\alpha} \nu \) - typical value of the Dirac mass term

\[ \nu \sim 246 \text{ GeV} \]

Example:

For \( M \sim 1 \text{ GeV} \) and \( m_\nu \sim 0.05 \text{ eV} \), it results in \( m_D \sim 10 \text{ keV} \) and Yukawa coupling \( \sim 10^{-7} \)
3 Majorana (HNL) partners of ordinary ν, with $M_N < M_W$

In a peculiar parameter space ($N_2$ and $N_3$ almost degenerate in mass and with $m = O$(GeV) and $N_1$ decoupled with $m = O$(keV)), νMSM explains:

- neutrino masses (see-saw), baryogenesis (via lepto-genesis) and DM ($N_1$)! (but most probably DM has to be generated outside the νMSM, by e.g. the decay of an inflaton—>see Higgs portal)

No hierarchy problem (if also the inflaton or the NP yielding $N_1$ has mass below EW scale)

Naturalness of the above parameter space comes from a U(1) lepton symmetry, broken at $10^{-4}$ level.

---

**νMSM:** T.Asaka, M.Shaposhnikov PL B620 (2005) 17  
**N$_{2,3}$ production**

Interaction with the Higgs v.e.v. — mixing with active neutrinos with $U^2$

in the vMSM strong limitations in the parameter space ($U^2,m$)

a lot of HNL searches in the past but, for $m>m_K$, with a sensitivity not of cosmological interest (e.g. LHCb with B decays obtained $U^2 \approx 10^{-4}$, arXiv: 1401.5361)

this proposal: search in D meson decays (produced with high statistics in fixed target $p$ collisions at 400 GeV)
N$_{2,3}$ decays

Very weak HNL-active $\nu$ $\rightarrow$ N$_{2,3}$ have very long life-time

$U^2_\mu = 10^{-7}$, $\tau_N = 1.8 \times 10^{-5}$ s

Various decay modes: the BR's depend on flavor mixing

The probability that N$_{2,3}$ decays within the fiducial volume of the experiment $\propto U^2_\mu$

$\rightarrow$ number of events $\propto U^4_\mu$

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{2,3} \rightarrow \mu/e + \pi$</td>
<td>0.1 - 50 %</td>
</tr>
<tr>
<td>$N_{2,3} \rightarrow \mu/e^- + \rho^+$</td>
<td>0.5 - 20 %</td>
</tr>
<tr>
<td>$N_{2,3} \rightarrow \nu + \mu + e$</td>
<td>1 - 10 %</td>
</tr>
</tbody>
</table>
SHIP sensitivity to HNL

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

Reaching the see-saw limit would require increase of the SPS intensity by an order of magnitude (does not currently seem realistic).

Scenarios for which baryogenesis was numerically proven.
Comparison with others

Interpretation in context of Left-Right symmetric model
Portals to Hidden Physics

- Two nice ways for new hidden physics to couple:
  - Vector Portal: 
    \( \epsilon F_{\mu\nu} F^{\mu\nu} \) 
    \( A' = \text{“hidden photon”} \)
  
  - Higgs Portal: 
    \( \lambda |H'|^2 |H|^2 \) 
    \( H' = \text{“hidden Higgs”} \)

\( (+A |H'| |H|^2) \)
Minimal vector portal

Three photon production modes considered:
1) in pseudo-scalar decays
2) in proton brehmsstrahlung
3) QCD production (Batell et al. 2015)

\[
\begin{array}{|c|c|c|}
\hline
\text{Mass interval (GeV)} & \text{Process} & \text{\( n_{\gamma'/p.o.t} \)} \\
\hline
m_{\gamma'} < 0.135 & \pi^0 \rightarrow \gamma\gamma' & \varepsilon^2 \times 5.41 \\
0.135 < m_{\gamma'} < 0.548 & \eta \rightarrow \gamma\gamma' & \varepsilon^2 \times 0.23 \\
0.548 < m_{\gamma'} < 0.648 & \omega \rightarrow \pi^0\gamma' & \varepsilon^2 \times 0.07 \\
0.648 < m_{\gamma'} < 0.958 & \eta' \rightarrow \gamma\gamma' & \varepsilon^2 \times 10^{-3} \\
\hline
\end{array}
\]

decay to SM particles
Dark photons

hadronic fixed target experiments overcome the kinematic limitation of e- fixed target allowing for $m>1$GeV!
Scalar (Higgs) portal: production/decay

Production via meson decay, D CKM suppressed wrt B (5x10^{-10}) and D cross section only 20k times larger than B cross section at 27GeV

Some uncertainty in the calculation of BR’s

\[ \sin^2 \rho = 1 \]
Scalar and pseudo-scalar portal

PNGBs or generic axions with couplings of order $m_X/F$ to SM matter $X$
Direct SUSY particles detection

RPV neutralinos

SGoldstinos

SUSY breaking scale

SUSY vector portal

Pseudo-Dirac fermions
The experiment
CERN accelerator complex
The beam

Extracted SPS beam 400GeV;

like CNGS $4.5 \times 10^{19}$ pot/year

design figures for the SHIP beam:

slow extraction (1s)

$4 \times 10^{13}$ ppp

$4 \times 10^{19}$ pot/year

fully compatible with NA operation
The SHiP facility is located on the North Area, and shares the TT20 transfer line and slow extraction mode with the fixed target programmes.
Extraction test SHiP
the current 49.2s SPS super-cycle with one single SHiP cycle starting at about 35s (under the text "last update") with a single injection of protons from PS to SPS (beam intensity in yellow), the acceleration to 400 GeV (energy illustrated in white), and the extraction during the flat top of 1s into the TT20 transfer line to the North Area as seen by the smooth drop of intensity with almost all beam extracted! The beam was sent to a beam stopper in the TT20 line. Few times $10^{12}$ per spill every 49.2s for a couple of hours!
Target and muon filter

Longitudinally segmented hybrid target: Mo(58cm)/W(58cm)
the beam is spread on the target to avoid melting

It is followed by a muon filter.

The issue is not trivial since the muon flux is enormous: $10^{11}$/SPS-spill($5 \times 10^{13}$ pot)
The detector

- Reconstruction of HS decays in all possible final states
  Long decay volume protected by various Veto Taggers, Magnetic Spectrometer followed by the Timing Detector, and Calorimeters and Muon systems. All heavy infrastructure is at distance to reduce neutrino/muon interactions in proximity of the detector

Challenges:
- Large vacuum vessel
- 5 m long straw tubes
- Timing detector with ~50 ps resolution
Backgrounds

Main sources of background

✓ Neutrino DIS interactions with material in the vicinity of the HS decay volume (interactions of $\nu$ with air in the decay volume are negligible at $10^{-3}$ mbar)

Origin of neutrino interactions
- Walls of the decay volume (>80%)
- Tau neutrino detector
- HS tracking system

Combination of veto and selection cuts reduces the $\nu$-induced background to zero

Veto efficiency increases with event multiplicity
Background

✓ **Muon combinatorial background**

  Simulation predicts \(O(10^{12})\) muon pairs in the decay volume in 5 years of data taking

  Suppressed by:
  - Basic kinematic and topological cuts \(\sim 10^4\)
  - Timing veto detectors \(\sim 10^7\)
  - Upstream veto and surrounding veto taggers \(\sim 10^4\)

✓ **Muon DIS interactions**

  - \(V^0\)s produced in the walls of the cavern
  - DIS close to the entry of the decay volume \(\rightarrow\) smaller than neutrino induced background

✓ **Cosmics**

✓ **Background summary: no evidence for any irreducible background**

Studies with larger simulated samples of backgrounds are ongoing
Light $\nu$’s detector

Emulsion based detector with the LNGS OPERA brick technology, but with a much smaller mass (750 bricks) very compact (2m), upstream of the HNL decay tunnel $\rightarrow$ with B field and followed by a muon detector (to suppress charm background)
Hybrid detector principle

Nuclear emulsions as μm accuracy trackers: τ production and decay vertices

measure the charge of τ daughters

Electronic trackers to provide the “time stamp” and match emulsion tracks

Passive material as neutrino target

Muon spectrometer

B = 1.5 T

Muon id Momentum charge
Tau neutrino physics

First evaluation of $F_4$ and $F_5$, not accessible with other neutrinos

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

$F_4 = F_5 = 0$

CC interacting $\nu_T$

- At LO $F_4 = 0$, $2xF_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV
Dark photon to dark matter

Use neutrino detector (emulsions) and detect neutral current interaction on atomic e-

$\rightarrow$ not a background-free search (but calculable)

after cuts (angle 10-20mrad, $E<20$GeV), the beam backgrounds:

<table>
<thead>
<tr>
<th>Type</th>
<th>$\nu_e$</th>
<th>$\bar{\nu}_e$</th>
<th>$\nu_\mu$</th>
<th>$\bar{\nu}_\mu$</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic scattering on $e^-$</td>
<td>16</td>
<td>2</td>
<td>20</td>
<td>18</td>
<td>56</td>
</tr>
<tr>
<td>Quasi - elastic scattering</td>
<td>105</td>
<td>73</td>
<td>20</td>
<td>18</td>
<td>178</td>
</tr>
<tr>
<td>Resonant scattering</td>
<td>13</td>
<td>27</td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Deep inelastic scattering</td>
<td>3</td>
<td>7</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>137</td>
<td>109</td>
<td>20</td>
<td>18</td>
<td>284</td>
</tr>
</tbody>
</table>
Time-table

Figure 5.4: Alternative project schedule for the SHiP facility and detector with WP1 in LS3 and adapted to latest accelerator schedule MTP 2016-2020 V1.
We know for sure that there is NP

Yet, we don’t know which one among the NP theories is the right one.

Maybe none of them is right!

We should keep an open mind

Pursuing a diversity of experimental approaches is very important to maximize our likelihoods of finding NP
Backup
About N1

Stability $\rightarrow \tau > \tau (\text{universe})$

Production $\rightarrow ll > vN_1, \, qq \rightarrow vN_1$

Decay $\rightarrow$ the radiative decay $N_1 \rightarrow \gamma v$
provides a line in the X spectrum at $E(\gamma) = m_1/2$

exclusion up to 2013 with single galaxies
The vacuum vessel

- **Estimated need for vacuum:**
  - $\sim 10^{-3}$ mbar

- **Vacuum vessel**
  - $10 \text{ m} \times 5 \text{ m} \times 60 \text{ m}$
  - Walls thickness: 8 mm (Al) / 30 mm (SS)
  - Walls separation: 300 mm
  - Liquid scintillator (LS) volume ($\sim 360 \text{ m}^3$)
  - Readout by WLS optical modules (WOM) and PMTs
  - Vessel weight $\sim 480 \text{ t}$

- **Magnet designed with an emphasis on low power**
  - Power consumption $< 1 \text{ MW}$
  - Field integral: 0.65Tm over 5m
  - Weight $\sim 800 \text{ t}$
  - Aperture $\sim 50 \text{ m}^2$
...some 3 sigma observations in 2014... with stacked spectra of galaxies or clusters, with XMM Newton, Chandra

Also some null observations. More observation time for XMM-Newton on a dedicated object (1.4Msec) —> action going on and hopefully the issue may be clarified
Muon active Filter

- Muon flux limit driven by emulsion based neutrino detector and HS background
- Active muon shield based entirely on magnet sweeper with a total field integral $B_y = 86.4$ Tm
- Realistic design of sweeper magnets in progress
- Challenges: flux leakage, constant field profile, modeling magnet shape
- $< 7k$ muons / spill ($E_\mu > 3$ GeV), well below the emulsion saturation limit
- Negligible flux in terms of detector occupancy

Magnetic sweeper field

Dose rate in the SHiP hall