Neutrino physics with the SHiP experiment

Alessandra Pastore (INFN Bari)
on behalf of the SHiP Collaboration
Beyond Standard Model...

Experimental hints of BSM physics
- $\nu$ masses and oscillations
- Baryon Asymmetry of the Universe
- Dark Matter

New Physics can be hidden due to **very heavy masses** or **very weak couplings**

- **Energy Frontier**, high energy collisions
- **Intensity Frontier**, beam dump
and beyond Colliders

Search for Hidden Particles (SHiP) @ CERN-based Beam Dump Facility (BDF)

- Slow extraction (1 sec)
- High intensity proton beam
  \[4 \times 10^{13} \text{ p/spill}, 4 \times 10^{19} \text{ pot/year}\]
  \[2 \times 10^{20} \text{ pot/5 years}\]
- \(\ioxid{400} \text{ GeV/c}\) optimal beam momentum

Existing tunnels
Existing buildings
New installations

https://doi.org/10.23731/CYRM-2020-002
Dual detector system
- **Scattering and Neutrino Detector (SND)**
  → neutrino physics and Light Dark Matter searches

- **Hidden Sector detector (HS)**
  → search for new, weakly coupled, long lived particles from the Hidden Sector
The SHiP experiment: general requirements

driven by Hidden Sector phenomenology

5 years of BDF@SPS ($2 \times 10^{20}$ pot):

- $10^{18}$ charm mesons
- $10^{14}$ beauty mesons
- $10^{16}$ tau leptons

target and hadron absorber

High A and Z, and short $\lambda$ target

beam

muon shield

The SHiP experiment: general requirements

driven by Hidden Sector phenomenology

Target and hadron absorber

High A and Z, and short $\lambda$ target

Hadron absorber
Strongly reduce the huge flux of SM particles, in particular pion and kaons before decay
The SHiP experiment: general requirements

Driven by Hidden Sector phenomenology

High A and Z, and short $\lambda$ target

Hadron absorber
Strongly reduce the huge flux of SM particles, in particular pion and kaons before decay

Magnetised muon shield
$\sim 10^{11}$ $\mu$ in 1 spill reduced to $< 10^5$

Muon spectrum validated with dedicated experiment in 2018
The Scattering and Neutrino Detector

High (anti-)ν flux expected @ BDF

→ Unique opportunity to perform studies on ντ, νμ, νe (+ cc) @ SHiP SND

ν Physics potential at SND:

- first ever observation of anti- ντ
- ντ and anti- ντ physics with high statistics
- ν induced charm production studies
- νf cross sections measurements
The Scattering and Neutrino Detector

Magnetized emulsion - tungsten target (ECC) + SciFi trackers (TT)

Magnetized emulsion - tungsten target (ECC) + SciFi trackers (TT)

ECC bricks à la OPERA

$\nu_{\tau} + q \rightarrow \tau^- + X$

Muon ID system: RPCs + iron filters

7.2 m

3.6 m

XIX International Workshop on Neutrino Telescopes 2021
The Scattering and Neutrino Detector

Magnetized target

Magnetized volume of \(\sim 10 \text{ m}^3 (B \approx 1.2 \text{ T})\);
opening / closing mechanism to allow for emulsion film replacement during run

RPC tracking planes hanging from top;
upper trails for insertion / extraction
sensitive area \(\sim 2 \times 4 \text{ m}^2\)
geometrical acceptance \(\sim 60\%\)

Muon ID System
The Hidden Sector Detector

Pyramidal frustum shape, length 50 m
1 mbar, volume 2040 m$^3$

Double-layer steel structure with strengthening ribs

Surrounding background tagger: 480 t of liquid scintillator
• Straw tracker ($\sigma_x < 120 \, \mu m$ per straw) inside the evacuated decay volume

• Timing detector ($\sigma_t < 100$ ps)
  plastic scintillators + SiPM or MRPCs

• ECAL (SpiltCal)
  sampling lead/scintillator + SiPM
  high-precision layers (MicroMegas)

• Muon system
  four active stations equipped with
  scintillating tiles + SiPM +
  iron or concrete
Prototyping SHiP

- Small-scale replica of the SHiP target
- Prototype of the SND muon ID system
- Prototype of a complete cell of the SBT
- Prototype of MRPC (HS timing detector)
- Prototype of a scintillating fibre module of the SND target tracker
- Prototype of the ECAL
Looking for tau neutrino events, so far
9 $\nu_\tau$ events by the DONUT experiment (no separation $\nu_\tau$ - anti $\nu_\tau$)
10 events from $\nu_\mu$ oscillation reported by the OPERA experiment

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$\nu_\tau$</th>
<th>$\bar{\nu}_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>1200</td>
<td>1000</td>
</tr>
<tr>
<td>$\tau \rightarrow h$</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>1000</td>
<td>700</td>
</tr>
<tr>
<td>total</td>
<td>6200</td>
<td>4700</td>
</tr>
</tbody>
</table>

# of expected observed $\nu_\tau$ int.

in SHiP, the expected statistics $\times 10^3$ w.r.t. previous experiments will lead to:

- First observation of anti-$\nu_\tau$
- Measurement of $\nu_\tau$ and anti-$\nu_\tau$ cross-sections
in SHiP, the expected statistics $x 10^3$ w.r.t. previous experiments will also lead to the first evaluation of $F_4$ and $F_5$ not accessible with electron or muon neutrinos

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

$F_4 = F_5 = 0$

anti-$\nu_\tau$ CC DIS cross section

$E(\text{anti-}\nu_\tau) < 38 \text{ GeV}, \approx 300 \text{ events exp.}$
Neutrino physics with the SND

Expected anti-νμ induced charm yield in SHiP ~ 2.5×10⁴
Observed in CHORUS ~32, in NuTeV ~1400

\[
\langle E \rangle \quad \text{CC DIS w. charm prod}
\]
\[
\begin{array}{c|c|c}
N_{\nu_{\mu}} & 55 & 1.3 \times 10^4 \\
N_{\bar{\nu}_{e}} & 66 & 6.0 \times 10^4 \\
N_{\tau_{\mu}} & 49 & 2.5 \times 10^4 \\
N_{\bar{\tau}_{e}} & 57 & 1.3 \times 10^4 \\
\text{Total} & & 2.3 \times 10^5
\end{array}
\]

\(\bar{v}\)-induced charm production sensitive to s-quark content of the nucleon

\[
s^+ = s(x) + \bar{s}(x)
\]

Significant reduction of the uncertainty on s-quark distribution with SHiP data, in the range 0.03 < x < 0.35 for s^+(x)
Search for Heavy Neutral Leptons

Minimal Standard Model (ν MSM): Extension of the SM by 3 right-handed Heavy Neutral Leptons (HNLs)

- **Light N₁**: Mass $O(\text{keV})$
  - Dark Matter candidate
- **Heavy N₂,N₃**: Mass $O(\text{GeV})$
  - Could explain ν masses (through see-saw) and baryon asymmetry

HNL production

HNL decay
Search for Heavy Neutral Leptons


HNL production

HNL decay

XIX International Workshop on Neutrino Telescopes 2021
Conclusion

- The SHiP experiment has been proposed at CERN to search for new Physics at the intensity frontier

- SHiP offers a unique opportunity for neutrino physics, including Heavy Neutral Leptons search and $\nu_\tau$ physics with unprecedented sensitivities

- The detector R&D and prototyping activities are on-going and in a good shape

- The Beam Dump Facility and SHiP Comprehensive Design Studies were already finalized, next step of the Collaboration being the TDR preparation
Light dark matter searches with the SND

Ideal laboratory also for Light Dark Matter scattering signatures

Look for LDM elastic scattering on atomic electrons of the target

\[ \chi e^- \rightarrow \chi e^- \]

signal: single EM shower w/o associated tracks

SIGNAL SELECTION

\[ 0.01 < \theta < 0.02 \]
\[ E < 20 \text{ GeV} \]

background: neutrinos can mimic LDM scattering in case of only one visible track at primary vertex, *f.e.*