Neutrino Scattering Physics with the SHiP Experiment

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**Introduction**

- Standard Model provided consistent description of Nature’s constituents and their interactions
- No significant deviation from SM found
- With a mass of the Higgs boson of 125 GeV, the Standard Model may be a self-consistent weakly coupled effective field theory up to very high scales (possibly up to the Planck scale) without adding new particles

- SM is not a complete theory: explanation of experimental observations “Beyond the Standard Model” still missing
  - Neutrino masses and oscillations
  - Baryon asymmetry of the Universe (BAU)
  - Dark Matter
Unknown particles or interactions needed to explain these puzzles. Where to search for them?
Hidden Sector and Neutrinos

- Hidden Sector accessible to intensity frontier experiments via sufficiently light particles, coupled to the Standard Model sectors via renormalizable “portals”

- SHiP: new fixed target facility at the intensity frontier to explore Hidden Sector
- Neutrino physics

- Large variety of models investigated: scalar portal, vector portal, neutrino portal, axion portal …
**ONE EXAMPLE: νMSM**

- **νMSM:** ν-Minimal Standard Model
  - 3 additional Heavy Neutral Leptons: right-handed Majorana neutrinos

- **N₁:** Dark Matter candidate
  - Mass ~10 keV

- **N₂,₃:** give mass to neutrinos via see-saw mechanism, produce baryon asymmetry
  - Mass ~few GeV
  - Lifetime>10 µs

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**PRODUCTION**

- Mixing with active neutrino
- Semi-leptonic decay

**DECAY**

- Br(N →μ / e π) ~ 0.1 - 50%
- Br(N →μ / e ρ) ~ 0.5 - 20%
- Br(N →νμe) ~ 1 - 10%

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A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

Prepared for submission to JHEP

The SHiP Collaboration

Abstract

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. Hidden...
REQUIREMENTS

- Proposal: fixed target experiment at the CERN SPS
- SPS: $4 \times 10^{13}$ protons per spill @ 400 GeV $\rightarrow$ $2 \times 10^{20}$ pot in 5 years (same as CNGS)

1) BACKGROUND REDUCTION
- Combinatorial background
- Neutrino flux
- Muon flux
- Neutrino interactions

1) SIGNAL ENHANCEMENT
- Geometrical acceptance
- Reconstruction of decays
- High sensitivity

![Diagram of experiment setup]

- Proposal: fixed target experiment at the CERN SPS
- SPS: $4 \times 10^{13}$ protons per spill @ 400 GeV $\rightarrow$ $2 \times 10^{20}$ pot in 5 years (same as CNGS)
Detector Layout
SENSITIVITIES

VECTOR PORTAL

Based on 2x10^{20} pot @400 GeV in 5 years

SCALAR PORTAL

NEUTRINO PORTAL

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AXION PORTAL
Neutrino Physics @SHiP

- High neutrino flux expected
- Unique possibility of performing studies of $\nu_\mu$, $\nu_e$, $\nu_\tau$

Energy spectrum of different neutrino flavors @beam dump
τ̅: the less known particle in the Standard Model

**DONUT**: 9 observed ντ candidate events (leptonic number not measured)

**OPERA**: first observation of νμ→ντ oscillations in appearance mode

\[ \bar{\nu}_\tau \text{ not detected yet!} \]

One of the four OPERA ντ candidates
Neutrino Detector

Requirements:

- High spatial resolution to observe the \( \tau \) decay (~1 mm)
  - \textit{EMULSION FILMS}
- Electronic detectors to give “time” resolution to emulsions
  - \textit{TARGET TRACKER PLANES}
- Magnetized target to measure the charge of \( \tau \) products
  - \textit{DIPOLAR MAGNET}
- Magnetic spectrometer to perform muon identification and measure its charge and momentum
  - \textit{MUON SPECTROMETER}
Neutrino Target

- 1155 ECC bricks to be replaced 10 times
- Total emulsion surface: 8700 m² (8% of OPERA emulsion production)
- Scanning with modern automated microscopes

Emulsion Cloud Chamber (ECC) Brick
- Passive material (Lead) - 56 layers -
- High resolution tracker (Nuclear emulsions) - 57 films -
- 10 $X_0$

Performances
- Primary and secondary vertex definition with $\mu$m resolution
- Momentum measurement by Multiple Coulomb Scattering - largely exploited in the OPERA experiment -
- Electron identification: shower ID through calorimetric technique
- Sign of the electric charge can be determined with better than 3 sigma level up to 12 GeV
Energy spectrum of different neutrino flavors interacting in the target

CC DIS neutrino interactions in 5 years run (2\times10^{20} \text{ pot})
\( \nu_\tau \) Physics

- \( \nu_\tau \) and \( \bar{\nu}_\tau \) produced in the leptonic decay of a \( D_s^- \) meson into \( \tau^- \) and \( \bar{\nu}_\tau \), and the subsequent decay of the \( \tau^- \) into a \( \nu_\tau \)
- Number of \( \nu_\tau \) and \( \bar{\nu}_\tau \) produced in the beam dump

\[
N_{\nu_\tau + \bar{\nu}_\tau} = 4N_p \frac{\sigma_{CC}}{\sigma_{pN}} f_{D_s} Br(D_s \rightarrow \tau) = 2.85 \cdot 10^{-5} N_p
\]

- Main background source: charm production in \( \nu_\mu^{CC} (\bar{\nu}_\mu^{CC}) \) and \( \nu_e^{CC} (\bar{\nu}_e^{CC}) \) interactions, when the primary lepton is not identified

- Geometrical, location and decay search efficiencies considered
- Expectations in 5 years run (2\( \times \)10\(^{20}\)pot)

<table>
<thead>
<tr>
<th>decay channel</th>
<th>( N_{\nu_\tau}^{exp} )</th>
<th>( N_{\bar{\nu}_\tau}^{exp} )</th>
<th>( N_{bg}^{exp} )</th>
<th>( N_{bg}^{bg} )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \rightarrow \mu )</td>
<td>570</td>
<td>290</td>
<td>19</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>( \tau \rightarrow h )</td>
<td>990</td>
<td>500</td>
<td>12</td>
<td>1.3</td>
<td>80</td>
</tr>
<tr>
<td>( \tau \rightarrow 3h )</td>
<td>210</td>
<td>110</td>
<td>7</td>
<td>0.8</td>
<td>30</td>
</tr>
<tr>
<td>total</td>
<td>1770</td>
<td>900</td>
<td>13</td>
<td>1.4</td>
<td>140</td>
</tr>
</tbody>
</table>
Deep-inelastic charged current neutrino cross section

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

Structure functions

- **F_1**: Same precision as other experiments
- **F_2**: Opposite sign for ν and \(\bar{\nu}\)
- **F_3**: Dependent on the lepton mass. Suppressed in case of ν_μ interactions, becomes relevant for ν_τ interactions
- **F_4**: Evaluation of F_3
- **F_5**: First evaluation of F_4 and F_5, not accessible with lighter neutrinos

- At LO F_4=0, 2xF_5=F_2 (Albright-Jarlskog relations)
- At NLO F_4 \sim 1% of F_5
**Sensitivity to $F_4$ and $F_5$**

The SHiP experiment has the unique capability of being sensitive to $F_4$ and $F_5$.

$F_4 = F_5 = 0$ hypothesis → increase of the $\nu_\tau$ and $\bar{\nu}_\tau$ CC DIS cross sections

→ increase of the number of expected $\nu_\tau$ and anti-$\nu_\tau$ interactions

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**$F_4 = F_5 = 0$**

$\nu_\tau$ CC DIS cross-section

$\bar{\nu}_\tau$ CC DIS cross-section

**SM prediction**

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Sensitivity to $F_4$ and $F_5$

$r = \text{ratio between the cross sections in the two hypotheses}$

$E(\bar{\nu}_\tau) < 38 \text{ GeV}$

($\sim 300 \text{ events expected}$)

$r > 1.6$

$\rightarrow \text{evidence for non-zero values of } F_4 \text{ and } F_5$

$E(\nu_\tau + \overline{\nu}_\tau) < 20 \text{ GeV}$

($\sim 420 \text{ events expected}$)
Large charm production in $\nu_\mu^{CC}$ and $\nu_e^{CC}$ interactions

Process sensitive to strange quark content of the nucleon

- Charm production with electronic detectors tagged by di-muon events (high energy cut to reduce background)
- Nuclear emulsion technique: charmed hadron identification through the observation of its decay
- Loose kinematical cuts $\rightarrow$ good sensitivity to the slow-rescaling threshold behavior and to the charm quark mass
Fraction of neutrino-induced charm events:

Convolution of CHORUS data with SHiP spectrum

\[
\frac{f(\text{charm})}{\Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} \left( \frac{\sigma_{\text{charm}}}{\sigma_{\nu_\mu}^{CC}} \right) dE} = \frac{\int \Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} \left( \frac{\sigma_{\text{charm}}}{\sigma_{\nu_\mu}^{CC}} \right) dE}{\int \Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} dE}
\]

\[
\frac{f(\text{charm})}{\Phi_{\nu_e} \sigma_{\nu_e}^{CC} \left( \frac{\sigma_{\text{charm}}}{\sigma_{\nu_e}^{CC}} \right) dE} = \frac{\int \Phi_{\nu_e} \sigma_{\nu_e}^{CC} \left( \frac{\sigma_{\text{charm}}}{\sigma_{\nu_e}^{CC}} \right) dE}{\int \Phi_{\nu_e} \sigma_{\nu_e}^{CC} dE}
\]

Charmed fractions (%):

\[
\begin{align*}
\frac{\sigma_{\text{charm}}}{\sigma_{\nu_\mu}^{CC}} &= 4.1 \\
\frac{\sigma_{\text{charm}}}{\sigma_{\bar{\nu}_\mu}^{CC}} &= 4.1 \\
\frac{\sigma_{\text{charm}}}{\sigma_{\nu_e}^{CC}} &= 6.0 \\
\frac{\sigma_{\text{charm}}}{\sigma_{\bar{\nu}_e}^{CC}} &= 6.0
\end{align*}
\]

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

No charm candidate from $\nu_e$ and $\nu_\tau$ interactions ever reported!
Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon.

Improvement achieved on $s^+/s^-$ versus $x$

Significant gain with SHIP data (factor 2) obtained in the $x$ range between 0.03 and 0.35.

$Observed \text{ anti-} \nu \text{ in CHORUS} \sim 32$

$\text{in NuTeV} \sim 1400$
CONCLUSIONS

- Search for new physics beyond Standard Model: explore the intensity frontier

- Rich Standard Model physics program:
  - first observation of anti-$\nu_\tau$
  - $\nu_\tau$ and anti-$\nu_\tau$ cross section measurement
  - structure functions study
  - charm physics with neutrinos and anti-neutrinos
  - strange quark nucleon content
Back-up Slides
**Timescale**

- **Form SHiP Collaboration**: December 2014 ✔
- **Technical Proposal**: April 2015 ✔
- **Technical Design Report**: 2018
- **Construction and Installation**: 2018-2022
- **Commissioning**: 2022
- **Data taking and analysis**: 2023-2027
SHIP LOCATION

- Proposed location by CERN beams and support departments
Table 6.2: Overall cost of the SHiP facility and the detectors.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (MCHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Facility</strong></td>
<td></td>
</tr>
<tr>
<td>Civil engineering</td>
<td>57.4</td>
</tr>
<tr>
<td>Infrastructure and services</td>
<td>22.0</td>
</tr>
<tr>
<td>Extraction and beamline</td>
<td>21.0</td>
</tr>
<tr>
<td>Target and target complex</td>
<td>24.0</td>
</tr>
<tr>
<td>Muon shield</td>
<td>11.4</td>
</tr>
<tr>
<td><strong>Grand total</strong></td>
<td><strong>194.5</strong></td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td></td>
</tr>
<tr>
<td>Tau neutrino detector</td>
<td>11.1</td>
</tr>
<tr>
<td>Hidden Sector detector</td>
<td>46.8</td>
</tr>
<tr>
<td>Computing and online system</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Total cost: 135.8 + 58.7 = 194.5 MCHF**
New Physics in the Hidden Sector

Standard Model portals

- **D=2  Vector Portal**
  Kinetic mixing with massive dark/secluded/para-photon $V$
  ➔ Interaction with ‘mirror world’ constituting dark matter

- **D=2  Higgs Portal**
  Mass mixing with dark singlet scalar $\chi$
  ➔ Mass to Higgs boson and right-handed neutrino, and
    function as inflaton in accordance with Planck measurements

- **D=5/2  Neutrino Portal**
  Mixing with right-handed neutrino $N$ (Heavy Neutral Lepton)
  ➔ Neutrino oscillation, baryon asymmetry, dark matter

- **D=4  Axion Portal**
  Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors
  ➔ Solve strong CP problem, Inflaton

- And possibly higher dimensional operators portals and **SUper-SYmmetric portals**
  (light neutralino, light sgoldstino, …)
  ➔ SUSY parameter space explored by LHC
NEUTRINO FLAVOR IDENTIFICATION

REQUIREMENTS

- Electric charge measurement of $\tau$ lepton decay products
- Key role for $\nu_\tau/\bar{\nu}_\tau$ separation in the $\tau \rightarrow h$ decay channel
- Momentum measurement

LAYOUT

- 3 OPERA-like emulsion films
- 2 Rohacell spacers (low density material)
- 1 Tesla magnetic field

PERFORMANCES

- Sign of the electric charge can be determined with better than 3 standard deviation level up to 12 GeV
- The momentum of the track can be estimated from the sagitta
- $Dp/p < 20\%$ up to 12 GeV/$c$

Charge measured from the curvature of the track with the sagitta method.
Neutrino Physics

\[ N_{\nu_\tau + \bar{\nu}_\tau} = N_p \frac{2 \sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \rightarrow \tau) 2 = 2.85 \times 10^{-5} N_p \]

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<td>( \tau \rightarrow e )</td>
<td>17.8</td>
</tr>
<tr>
<td>( \tau \rightarrow h )</td>
<td>49.5</td>
</tr>
<tr>
<td>( \tau \rightarrow 3h )</td>
<td>15.0</td>
</tr>
</tbody>
</table>
TARGET CONFIGURATION

Design considerations with $4 \times 10^{13}$ p / 7s $\rightarrow$ 400 kW

- High temperature
- Compressive stresses
- Atomic displacement
- Erosion/corrosion
- Material properties as a function of irradiation
- Remote handling (Initial dose rate of 50 Sv/h...)

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Muon Shield
Tracking System
**Sistema Traccianti**

Under study:
1. Double wall vessel with liquid scintillator: Cylinder Background Tagger
2. Front window with liquid scintillator/plastic scintillator: Front Background Tagger
3. Downstream high-resolution timing detector
4. (Upstream VETO chamber)
5. Muon system of neutrino detector

⇒ Note: Concept of VETO ⇒ deadtime = rate * time resolution/1s
Ricerca Diretta di Materia Oscura

Production of the Dark Matter beam

Hadron decays

Direct production

Detection via scattering - anomalous neutral currents

$\chi - e^-$ elastic  $\chi -$ nucleon elastic  deep inelastic