TAU NEUTRINO PHYSICS IN SHiP

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Motivation for $\nu_\tau$ Studies

- Less known particle in the Standard Model
- 9 events (with an estimated background of 1.5) were reported in 2008 with looser cuts
  \[ \sigma_{\text{const}}(\nu_\tau) = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38} \text{ cm}^2 \text{ GeV}^{-1} \]
- 5 $\nu_\tau$ candidates reported by OPERA for the discovery (5.1$\sigma$ result) of $\nu_\tau$ appearance in the CNGS neutrino beam
- Tau anti-neutrino never observed
SHiP At CERN

~150 m
**FACILITY IDEAL TO STUDY $\nu_\tau$ PHYSICS**

\[ N_{\nu_\tau + \bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} \text{Br}(D_s \rightarrow \tau) = 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15} \]

\[ \sigma_{c\bar{c}} = 18.1 \pm 1.7 \text{ } \mu\text{barn} \]

\[ f_{D_s} = (7.7 \pm 0.6^{+0.5}_{-0.4})% \]  

\[ \text{Br}(D_s \rightarrow \tau) = (5.54 \pm 0.24)% \]  

Physica Reports 433 (2006) 127

\[ \sigma_{c\bar{c}} \propto A \]

\[ \sigma_{pN} \propto A^{0.71} \]

NA27 with 400 GeV protons

Cacciari, Greco, Nason  JHEP 9805 (1998) 007

Cacciari, Frixione, Nason  JHEP 0103 (2001) 006

arXiv: 1504.04855 SHiP Physics Proposal
$\nu_\tau$ FLUXES
\( \nu_\tau \text{ FLUXES} \)

At the beam dump*

\[ N_{\nu_\tau} = N_{\bar{\nu}_\tau} = 2.8 \times 10^{15} \]

At the neutrino detector*

\[ N_{\nu_\tau} = N_{\bar{\nu}_\tau} = 1.4 \times 10^{14} \]

*in 5 years run (2x10^{20}pot)
\( \nu_\tau \) INTERACTIONS IN THE TARGET

Expected number of interactions*

*in 5 years run (2\( \times \)10\(^{20}\) pot)

- target mass \( \sim 9.6 \) ton (Pb)

\[
N_{\nu_\tau} \approx 6.7 \times 10^3
\]

\[
N_{\bar{\nu}_\tau} \approx 3.4 \times 10^3
\]

20% uncertainty mainly from scale variations in ccbar differential cross-section

Uncertainty (\( \lesssim 10\% \)) from:
- Scale choices
- Pdf
- Target mass correction

\( M. \ H. \ Reno, \ Phys. \ Rev. \ D74 \ (2006) \ 033001\)

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ντ DETECTOR

THE UNITARY CELL

Emulsion Cloud Chamber (ECC)

BRICK
- passive material → lead
  (massive target)
- tracking device → nuclear
  (high resolution) 
  emulsions

sensitivity 30 grains/100 μm

PERFORMANCES
• Primary and secondary vertex definition with μm resolution
• Momentum measurement by Multiple Coulomb Scattering
  - largely exploited in the OPERA experiment
• Electron identification: shower ID through calorimetric technique
ντ IDENTIFICATION
THE FIRST OPERA ντ CANDIDATE

ντ \rightarrow \rho^- \nu_\tau
\rho^- \rightarrow \pi^0 \pi^-
\pi^0 \rightarrow \gamma \gamma

1000 um
**MICROMETRIC RESOLUTION**

**A ντ OPERA CANDIDATE (τ→μ)**

*Phys. Rev. D 89 (2014) 051102(R)*
\[ \nu_\tau/\text{ANTI-} \nu_\tau \text{ SEPARATION} \]

**THE COMPACT EMULSION SPECTROMETER**

**TASK**
- Electric charge and momentum measurement of \( \tau \) lepton decay products
- Key role for the \( \tau \rightarrow h \) decay channel
- 3 OPERA-like emulsion films
- 2 Rohacell spacers (low density material)
- 1 Tesla magnetic field

**PERFORMANCES**
- **Electric charge** determined up to 12 GeV
- **Momentum** estimated from the sagitta
- \( \Delta p/p < 20\% \) up to 12 GeV/c
THE NEUTRINO TARGET

FEATURES
• Provide time stamp
• Link muon track information from the target to the magnetic spectrometer

REQUIREMENTS
• Operate in 1T field
• X-Y 100 μm position resolution
• high efficiency (>99%) for angles up to 1 rad

TARGET TRACKER PLANES

• 12 target tracker (TT) planes interleaving the 11 brick walls
• first TT plane used as veto
• Transverse size ~ 2x1 m²

POSSIBLE OPTIONS
• Scintillating fibre trackers
• Micro-pattern gas detectors (GEM, Micromegas)
THE TARGET MAGNETIZATION

GOLIATH MAGNET
CERN H4 beam line

- 1 Tesla vertical magnetic field
- few $m^3$ volume with constant magnetization

Magnetic field behavior in the target region

Within the **blu curves** $B \approx 1.5$ T
Within the **red curves** $B \geq 1$ T
THE NEUTRINO DETECTOR

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AN INTERACTION IN THE NEUTRINO DETECTOR

NOT TO SCALE

\[ \nu_\tau \]

\[ \tau \]

\[ \mu \]

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PERFORMANCES OF THE DETECTOR

\[ \epsilon_{tot} = \epsilon_{geom} \times \epsilon_{loc} \times \epsilon_{ds} \]

Charge measurement performed with
- Compact Emulsion Spectrometer (hadrons and muons)
- magnetic spectrometer (muons only)

Muons come from \( \tau \to \mu \) decays and \( \nu_\mu \) CC interactions
- \( \mu \) identification at primary vertex crucial for charm background rejection

\[ \epsilon_\mu \sim 90\% \]

<table>
<thead>
<tr>
<th></th>
<th>( \tau \to \mu )</th>
<th>( \tau \to h )</th>
<th>( \tau \to 3h )</th>
<th>( \tau \to e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \epsilon_{tot} ) (%)</td>
<td>60</td>
<td>62</td>
<td>63</td>
<td>56</td>
</tr>
<tr>
<td>( \epsilon_{charge} ) (%)</td>
<td>94</td>
<td>70</td>
<td>49</td>
<td>/</td>
</tr>
<tr>
<td>( \eta_{mis} ) (%)</td>
<td>1.5</td>
<td>0.5</td>
<td>1.0</td>
<td>/</td>
</tr>
</tbody>
</table>

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Decay search finding efficiency, charge measurement, muon identification included

$\tau \rightarrow e$ decay channel not exploited

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

The analysis can be improved by exploiting the likelihood approach
**F₄ AND F₅ STRUCTURE FUNCTIONS**

First evaluation of F₄ and F₅, not accessible with other neutrinos

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

**F₄ = F₅ = 0**

- At LO F₄ = 0, 2xF₅=F₂
- At NLO F₄ ~ 1% at 10 GeV

**CC interacting ντ**

![Graph showing the energy and cross-section relationship for CC interacting ντ]

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

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**TAU NEUTRINO MAGNETIC MOMENT**

A massive neutrino may interact e.m. → magnetic moment proportional to its mass

\[
\mu_{\nu} = \frac{3eG_F m_{\nu}}{8\pi^2\sqrt{2}} \approx (3.2 \times 10^{-19}) \left( \frac{m_{\nu}}{1\text{ eV}} \right) \mu_B
\]

Current limits

\[
\cases{\nu_e; \mu_{\nu} < 2.9 \cdot 10^{-11} \mu_B \\
\nu_\mu; \mu_{\nu} < 6.9 \cdot 10^{-10} \mu_B}
\]

\[
\theta_{\nu-e}^2 < 2m_e/E_e
\]

**SIGNAL SELECTION**

\[
\cases{\theta_{\nu-e} < 30 \text{ mrad} \\
E_e > 1 \text{ GeV}}
\]

**BACKGROUND PROCESSES**

\[
\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{NC}
\]

\[
\nu_e(\bar{\nu}_e) + e^- \rightarrow e^- + \nu_e(\bar{\nu}_e) \quad \text{CC}
\]

\[
\nu_e + n \rightarrow e^- + p \quad \text{QE}
\]

\[
\bar{\nu}_e + p \rightarrow e^+ + n \quad \text{QE}
\]

\[
\nu_e(\bar{\nu}_e) + N \rightarrow e^-(e^+) + X \quad \text{DIS}
\]

\[
\sigma(\nu_e,\bar{\nu}_e) \bigg|_{\mu_{\nu}} = \frac{\pi\alpha^2_{em}\mu^2_{\nu}}{m_e^2} \left( \frac{1}{T} - \frac{1}{E_{\nu}} \right)
\]

No interference as it involves a spin flip of the neutrino

**IN SHiP**

\[
n_{\text{evt}} = \frac{\mu^2_{\nu}}{\mu^2_B} \int \Phi_{\nu_\tau} \sigma^\mu N_{\text{nucl}} dE = 4.3 \times 10^{15} \frac{\mu^2_{\nu}}{\mu^2_B}
\]

Assuming 5% systematics from DIS measurements

\[
\mu_{\nu} = 1.5 \times 10^{-7} \mu_B
\]

SHiP can explore a region down to
**Not Only Tau Neutrinos**

- SHiP setup ideally suited to study neutrino and anti-neutrino physics for all three active flavours
- High charmed hadrons production rates ⇒ high neutrino fluxes from their decays, including remnant pion and kaon decays
ELECTRON NEUTRINOS

Excellent $\pi^0/\gamma$ separation thanks to the micrometric accuracy

A close-up of an electron pair
Neutrino-Induced Charm Production @SHiP

- 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
  Physics Reports 399 (2004) 277
- Loose kinematical cuts $\rightarrow$ good sensitivity to the slow-rescaling threshold behaviour and to the charm quark mass
CHARM PHYSICS @ SHiP

- Fraction of neutrino-induced charm events
- Convolution of CHORUS data with SHiP spectrum

\[ \frac{f(\text{charm})}{\int \Phi_{\nu_{\mu}} \sigma_{\nu_{\mu}} dE} \approx 4\% \]

\[ \frac{f(\text{charm})}{\int \Phi_{\nu_{e}} \sigma_{\nu_{e}} dE} \approx 6\% \]

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

<table>
<thead>
<tr>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_{\mu} )</td>
</tr>
<tr>
<td>( \nu_e )</td>
</tr>
<tr>
<td>( \bar{\nu}_{\mu} )</td>
</tr>
<tr>
<td>( \bar{\nu}_e )</td>
</tr>
<tr>
<td>total</td>
</tr>
</tbody>
</table>

In NuTeV ~5100 \( \nu_\mu \)
~ 1460 anti-\( \nu_\mu \)

In CHORUS ~2000 \( \nu_\mu \)
32 anti-\( \nu_\mu \)

No charm candidate from \( \nu_e \) and \( \nu_\tau \) interactions ever reported!

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**Strangeness Nucleon Content**

- Charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon
- Strangeness important for precision SM tests and for BSM searches
- W boson production at 14 TeV: 80% via $\bar{u}\bar{d}$ and 20% via $c\bar{s}$

\[ G_{E2}Q^2 \times 10^{-1} \]

*Phys. Rev. D91 (2015) 113005*

Fractional uncertainty of the individual parton densities $f(x;m^2_W)$ of NNPDF3.0
\textbf{Strange Quark Nucleon Content}

- Improvement achieved on $s^+/s^-$ versus $x$
- Significant improvement (factor two) with SHIP data

\begin{align*}
    s^- &= s(x) - \bar{s}(x) \\
    s^+ &= s(x) + \bar{s}(x)
\end{align*}

EXOTIC PARTICLES: CHARMED PENTAQUARK

• Multi-quark states seen by several experiments
• Search for multi-quark states in neutrino interactions
• Unlike processes as $e^+e^-$ scattering, $\theta^0_c$ production in anti-neutrino interactions is favoured by the presence of three valence quarks
• $c$-bar quarks in anti-neutrinos

Currently limited by the anti-neutrino statistics in CHORUS

$$\frac{\sigma_{\theta^0_c}}{\sigma_{\bar{\nu}_\mu}} < 0.039 \text{ at } 90\% \text{ C.L.}$$

Charm from anti-$\nu_\mu$

CHORUS 32      SHiP   27000
**Dark Matter Search**

χ produced by a dark photon decay
\[ \chi e^- \rightarrow \chi e^- \]

**SIGNAL SELECTION**

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

**BACKGROUND PROCESSES**

<table>
<thead>
<tr>
<th>Process</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></td>
<td></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>

\( \epsilon = \) dark photon coupling with e.m. current
\( m_A = \) dark photon mass

P. de Niverville, D. McKeen, and A. Ritz,
*Phys. Rev. D* 86 (2012) 035022

\( \alpha' = \) dark photon coupling with \( \chi \)

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CONCLUSIONS

• Unique tau neutrino and anti-neutrino physics
• Rich neutrino physics program
• Strange quark content
• Dark matter search