TAU NEUTRINO PHYSICS IN SHiP

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On behalf of the SHiP Collaboration
45 Institutes from 14 Countries
Motivation For $\nu_\tau$ Studies

- Less known particle in the Standard Model
- 9 events (with an estimated background of 1.5) 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
  arXiv:1507.01417 [hep-ex]
- Tau anti-neutrino never observed
SHiP At CERN
Search for Hidden Particles


2 x 10^{20} \text{ pot at the SPS (400 GeV)}
Facility Ideal To Study $\nu_\tau$ Physics

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

$$\sigma_{c\bar{c}} = 18.1 \pm 1.7 \, \mu\text{barn}$$

Physics Reports 433 (2006) 127

$$Br(D_s \to \tau) = (5.54 \pm 0.24)\%$$

PDG 2014

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

JHEP 1309 (2013) 058

$$\sigma_{c\bar{c}} \propto A$$

$$\sigma_{pN} \propto A^{0.71}$$

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
**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 (2\times10^{20}pot)

\[ \varepsilon_{\text{geom}} \sim 5\% \]
\( \nu_\tau \) Interactions In The Target

Expected number of interactions*

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

target mass \(\sim 9.6 \text{ ton (Pb)}\)

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

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

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


Uncertainty \((\lesssim 10\%)\) from:

• Scale choices
• Pdf
• Target mass correction

G. De Lellis, HEP 2015 Neutrino
$\nu_\tau$ IDENTIFICATION A LA OPERA

THE FIRST OPERA $\nu_\tau$ CANDIDATE

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

*Physics Letters B691 (2010) 138*
THE NEUTRINO DETECTOR

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\( \nu_\tau / \text{ANTI-} \nu_\tau \) \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

G. De Lellis, HEP 2015 Neutrino
**SIGNAL AND BACKGROUND YIELDS**

**Detection efficiency, charge measurement, muon identification included**

$\tau \rightarrow e$ decay channel not included

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 a likelihood approach
**F₄ AND F₅ STRUCTURE FUNCTIONS**

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

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

\[
F_4 = F_5 = 0
\]

- At LO $F_4 = 0$, $2x F_5 = F_2$
- At NLO $F_4 \sim 1\%$ at 10 GeV

**SM prediction**

\[
E(\bar{\nu}_\tau) < 38 \text{ GeV}
\]
**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
**CHARM PHYSICS @SHiP**

- Neutrino induced charm production
  *Physics Reports 399 (2004) 277*
- Advantage of the emulsion technology: topological, very loose kinematical cuts

\[
\begin{align*}
\nu_\mu^{CC} & \quad f(\text{charm}) = \frac{\int \Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} \left( \frac{\sigma_{\text{charm}}}{\sigma_{\nu_\mu}^{CC}} \right) dE}{\int \Phi_{\nu_\mu} \sigma_{\nu_\mu}^{CC} dE} \approx 4\% \\
\nu_e^{CC} & \quad f(\text{charm}) = \frac{\int \Phi_{\nu_e} \sigma_{\nu_e}^{CC} \left( \frac{\sigma_{\text{charm}}}{\sigma_{\nu_e}^{CC}} \right) dE}{\int \Phi_{\nu_e} \sigma_{\nu_e}^{CC} dE} \approx 6\%
\end{align*}
\]

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

<table>
<thead>
<tr>
<th>Expected events</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>$6.8 \cdot 10^4$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$1.5 \cdot 10^4$</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>$2.7 \cdot 10^4$</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$5.4 \cdot 10^3$</td>
</tr>
<tr>
<td>total</td>
<td>$1.1 \cdot 10^5$</td>
</tr>
</tbody>
</table>

*In NuTeV*  
$\sim 5100 \nu_\mu$  
$\sim 1460 \text{ anti-} \nu_\mu$

*In CHORUS*  
$\sim 2000 \nu_\mu$  
$32 \text{ anti-} \nu_\mu$

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.

Strangeness important for precision SM tests and for BSM searches.

W boson production at 14 TeV: 80% via $ud$ and 20% via $cs$.

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

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

\[ s^- = s(x) - \bar{s}(x) \quad \text{and} \quad s^+ = s(x) + \bar{s}(x) \]

Added to NNPDF3.0 NNLO fit, Nucl.Phys. B849 (2011) 112–143, at $Q^2 = 2 \text{ GeV}^2$
# Dark Matter Search

\( \chi \) produced by a dark photon decay

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

**SIGNAL SELECTION**

\[
\begin{align*}
0.01 < \theta < 0.02 \\
E < 20 \text{ GeV}
\end{align*}
\]

**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>178</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resonant scattering</td>
<td>13</td>
<td>27</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep inelastic scattering</td>
<td>3</td>
<td>7</td>
<td>10</td>
<td></td>
<td></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

\[ P. \text{ deNiverville, D. McKeen, and A. Ritz, } \]

**Phys.Rev. D86 (2012) 035022**

\[ \alpha' = \text{dark photon coupling with } \chi \]

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

\[ m_A = 200 \text{ MeV} \]

\[ \alpha' = 0.1 \]

\[ \text{POT} = 2 \times 10^{20} \]
CONCLUSIONS

• SHiP experiment proposed at CERN
• Unique tau neutrino and anti-neutrino physics
• Rich neutrino physics program
• Strange quark content
• Dark matter search
• Other topics: charmed pentaquark search, tau neutrino magnetic moment