Production of $\nu_\tau$ neutrinos and $\bar{\nu}_\tau$ antineutrinos in fixed target experiment SHiP

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5 Summary
$\nu_\tau$ physics and more...

**Tau neutrino** ($\nu_{\tau}$) still the less known particle of the Standard Model

- direct measurements of $\nu_{\tau}$ CC-interaction fairly recent
  - **DONUT**: 9 ± 1.5 events 
    (no distinction between $\nu_{\tau}$ and $\bar{\nu}_{\tau}$)
  - **OPERA**: 10 events 
    (only $\nu_{\tau}$, discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations)
- IceCube (first two candidates for astrophysical $\nu_{\tau}$)
- no $\bar{\nu}_{\tau}$ has ever been detected yet, making it the last missing tile of the SM

**Neutrino factories:**
- much more $\nu_{\tau}/\bar{\nu}_{\tau}$ events
- study the properties and cross section
- first observation of $\bar{\nu}_{\tau}$

**CERN SPS ⇒ Search for Hlidden Particles (SHIP) experiment**

**in a broader perspective:**
- Light Dark Matter search
- extraction of $F_4$ and $F_5$ structure functions
- measure the $s$-content of the nucleon
**SHIP experiment** ⇒ a general purpose fixed target facility at the CERN SPS accelerator using high intensity of the SPS 400 GeV proton beams

- to explore the domain of hidden particles (very weakly interacting non-SM particles with masses in the \( \mathcal{O}(10) \) GeV region)
- to make measurements with tau neutrinos

**abundant source of \( \nu_\tau \) and \( \bar{\nu}_\tau \) \( \implies \) direct and chain decays of \( D_\pm^s \) meson

- production of large amounts of neutrinos (not only \( \nu_\tau \))
- first direct observation of \( \bar{\nu}_\tau \)
- study \( \nu_\tau \) and \( \bar{\nu}_\tau \) properties
- test lepton flavor universality by comparing interactions of \( \nu_\mu \) and \( \nu_\tau \)

400 GeV proton beam (\( \sqrt{s} = 27.4 \) GeV) to enhance charm cross section as much as possible

- a hybrid target made of blocks of molybdenum and tungsten (materials with a short interaction length) to maximize neutrinos from charmed hadrons while minimizing those coming from pions and kaons decays
- neutrino detector with lead (\( \sim 9.6 \) tons)

far-forward production:
\[ \eta \gtrsim 4.6 - 5.6 \]
Mechanisms under consideration

$D_s^\pm$ meson from charm and strange quark fragmentation

**Starting point:**
Differential cross section for $D_s^\pm$ meson production in $p + ^{96}\text{Mo}$ interactions at $\sqrt{s_{NN}} = 27.4$ GeV approximately:

$$\frac{d\sigma_{p + ^{96}\text{Mo}}}{dydp_t} = Z_{\text{Mo}} \frac{d\sigma_{pp}}{dydp_t} + (A_{\text{Mo}} - Z_{\text{Mo}}) \frac{d\sigma_{pn}}{dydp_t}$$

- shadowing (negligible)
- anti-shadowing, EMC-effect (rather small)

**Two different mechanisms:**

**Leading (favored) fragmentation**
$c \to D_s^+$ and $\bar{c} \to D_s^-$
- $c\bar{c}$-pair production cross section
- heavy-to-heavy hadronization

**Subleading (unfavored) fragmentation**
$s \to D_s^-$ and $\bar{s} \to D_s^+$
- $s$-quark and $\bar{s}$-antiquark production cross section
- light-to-heavy hadronization
pQCD charm quark-antiquark pair cross section

- The leading-order (LO) partonic processes for $Q\bar{Q}$ production $\Rightarrow q\bar{q}$-annihilation and gluon-gluon fusion (dominant at high energies)

- Main classes of the next-to-leading order (NLO) diagrams:
  - pair creation with gluon emission
  - flavour excitation
  - gluon splitting

- The NLO/NNLO corrections of a special importance for charm production!

**collinear approach:**
- state of the art for single particle spectra at NLO (FONLL, GM-VFNS)
- MC@NLO+PS for correlations
- NNLO not available for charm/bottom

**$k_T$-factorization:**
- exact kinematics from the very beginning
- correlation observables directly calculable
- some contributions even beyond the NLO available (also differentially)
Leading fragmentation of charm quarks

$c \to D_s$ transition and independent parton fragmentation

**heavy-to-heavy fragmentation:** $c \to D_s^+$ and $\bar{c} \to D_s^-$

independent parton fragmentation picture

- $c \to D_s$: Peterson($z$), $\varepsilon = 0.05$ (rather well known from $e^+e^-$ data)
- fragmentation fraction $P_{c \to D_s} = 5\% - 9\%$ (quite uncertain)

**high energies:**

- $y_H = y_q$, $p_{t,H} = z \cdot p_{t,q}$ with $z \in (0, 1)$
- can be safely used only when both $m_q$ and $m_H$ can be neglected
- problematic at $p_{t,H} \lesssim m_H$
- LHC charm data well described

**low energies:**

- $\eta_H = \eta_q$, $p_{H}^+ = z \cdot p_{q}^+$ with $z \in (0, 1)$
- light-cone scaling: $p^+ = E + p$
- energy conservation conditions:
  $E_H > m_H$ and $E_H \leq E_q$
- $m_q, m_H \to 0 \Rightarrow y_H = y_q$, $p_t$-scaling

Peterson($z$), $\varepsilon = 0.05$ and $P_{c \to D_s} = 8\%$
Subleading fragmentation of $s$-quarks

**pQCD strange quark/antiquark production cross section**

The leading-order (LO) partonic processes for $s$ and/or $\bar{s}$ production $\Rightarrow$

- $sg \rightarrow sg, su \rightarrow su, s\bar{u} \rightarrow s\bar{u}, sd \rightarrow sd, s\bar{d} \rightarrow s\bar{d}, ss \rightarrow ss, s\bar{s} \rightarrow s\bar{s}$
- #7 different channels (+ symmetric counterparts) for quark (+ charge conjugate for antiquark)

- **Collinear factorization approach with on-shell partons**
- Special treatment of minijets at small transverse momenta:
  
  \[ F_{\text{sup}}(p_t) = \frac{p_t^4}{(p_t^0)^2 + p_t^2} \]  
  (suppression factor as adopted in PYTHIA)

- $p_t^0 = 1.5$ GeV (typical value; could be fitted e.g. to low energy charm data)

- **MMHT2014, NNPDF30, JR14 PDFs** $\Rightarrow$ asymmetric strange sea $s(x) \neq \bar{s}(x)$

- Similar cross sections for charm and strange quark production
Subleading fragmentation of $s$-quarks

$s \rightarrow D_s$ fragmentation and $D_s^+/D_s^-$ asymmetry at the LHCb

**light-to-heavy fragmentation:** $\bar{s} \rightarrow D_s^+$ and $s \rightarrow D_s^-$

fragmentation fraction and function completely unknown

- $c \rightarrow D_s$: Peterson$(z)$, $\varepsilon = 0.05$ (rather well known)
- $u \rightarrow D_s$: Peterson$(1-z)$, $\varepsilon = 0.05$ (analogous to $u, d \rightarrow K$)
- $s \rightarrow D_s$: Peterson$(z)$, $\varepsilon = 0.5$ (analogous to $b, c \rightarrow B_C$)
- fragmentation function for $s \rightarrow D_s$ shifted to intermediate $z$-values with respect to the standard $c \rightarrow D_s$ case
- $P_{c \rightarrow D_s} > P_{s \rightarrow D_s}$

**LHCb:** $D_s^+/D_s^-$ production asymmetry data:

- $s \rightarrow D_s$: Peterson$(z)$, $\varepsilon = 0.5$ and $P_{s \rightarrow D_s} = 3\%$

![Graphs showing $D_s^+/D_s^-$ production asymmetry data at the LHCb](image)
Introduction

Production of $D_s^\pm$ meson

Production of $\nu_\tau$ neutrinos

Predictions for SHIP experiment

Summary

**$D_s^\pm$ cross section for $p + ^{96}$Mo at $\sqrt{s_{NN}} = 27.4$ GeV**

**Theoretical computations:** $D_s^\pm$ energy distr.: MMHT2014 (left) vs. NNPDF30 (right)

leading + subleading fragmentation mechanism

A pretty much different results are obtained for the two different PDF sets, especially for large meson energies.

Our model leads to a rather small (MMHT2014 PDF) or a fairly significant (NNPDF30 PDF) contribution to the $D_s$ meson production at large energies which comes from the $s/\bar{s}$-quark fragmentation.

More measurements of $D_s^\pm$ at low energies needed to reduce uncertainties.
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$D_s \rightarrow \nu_\tau$: direct and chain decay modes

**DIRECT decay:** $D_{s}^{+} \rightarrow \tau^{+}\nu_{\tau}$ and $D_{s}^{-} \rightarrow \tau^{-}\overline{\nu}_{\tau}$  
analogue to the standard text book cases of $\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$

- spin zero particle decays isotropically in its rest frame
- $\text{BR}(D_{s}^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}/\overline{\nu}_{\tau}) = 0.0548 \pm 0.0023$
- $\tau$ lepton takes almost whole energy of the $D_s$  
- $\tau$ leptons are polarized in its direction of motion (structure of weak interaction in the SM)

**CHAIN decay:** $D_{s}^{+} \rightarrow \tau^{+} \rightarrow \overline{\nu}_{\tau}$ and $D_{s}^{-} \rightarrow \tau^{-} \rightarrow \nu_{\tau}$

many possible decay channels $\Rightarrow$ all included

- 35% leptonic and 65% semi-leptonic modes
- all confirmed decays lead to production of $\nu_{\tau}$ ($\overline{\nu}_{\tau}$)
- we assume that $\overline{\nu}_{\tau} = \overline{\nu}_{D_s}$ and $\overline{\nu}_{D_s}$
- and polarization of $\tau$ in its rest frame is 100 %.
- we use TAUOLA Monte Carlo code

both, direct and chain decay modes lead to symmetric production of $\nu_{\tau}$ and $\overline{\nu}_{\tau}$

$\nu_{\tau}/\overline{\nu}_{\tau}$ asymmetry might appear only as a result of $D_{s}^{+}/D_{s}^{-}$ asymmetry
The energy dependent **FLUX OF NEUTRINOS** can be written as:

\[
\Phi_{\nu_\tau/\bar{\nu}_\tau}(E) = \frac{N_p}{\sigma_{pA}} d\sigma_{pA \to \nu_\tau}(E)/dE ,
\]

- \( N_p \) is integrated number of beam protons \((N_p = 2 \times 10^{20}\) (current SHiP project)
- \( \sigma_{pA} = A \cdot \sigma_{pN} \) \(\Rightarrow\) crucial quantity, where \( \sigma_{pN} \) is the inelastic hadronic cross section per nucleon on a target with \( A \) nucleons
- \( \sigma_{pN} \) for molybdenum target is rather uncertain (usually 10-20 \( \text{mb} \))

The above formula can be used to **estimate number of \( \nu_\tau \) and \( \bar{\nu}_\tau \) produced at the beam dump** \(\Rightarrow\)

for the decays of \( D_s \) meson produced from charm quark fragmentation it reads:

\[
N_{\nu_\tau} = 2 \frac{N_p}{\sigma_{pA}} \sigma_{pA \to \nu_\tau} \chi = 2 \frac{N_p}{\sigma_{pN}} \sigma_{pp \to c\bar{c}\chi} \text{BR}(D_s \to \tau) \text{P}(c \to D_s)
\]

- the factor of 2 accounts for neutrinos from the direct decay of \( D_s^+ \) and neutrinos from the chain decay of \( D_s^- \)
- \( \text{P}(c \to D_s) = 8\% \), \( \text{BR}(D_s \to \tau) = 0.0548 \), \( \sigma_{pp \to c\bar{c}\chi} = 10 \mu \text{b} \) and \( \sigma_{pN} = 20 \text{ mb} \)
- we get \( N_{\nu_\tau} = 1.32 \times 10^{15} \) (five years run)

... only a part of the \( \nu_\tau/\bar{\nu}_\tau \) produced at beam dump will be then detected (observed)
Detection of the $\nu_\tau$ and $\bar{\nu}_\tau$ produced at the beam dump

**Neutrino detector at SHIP experiment:** a dedicated Pb-target was proposed (ECC brick)

number of neutrinos/antineutrinos observed in the target:

$$N^\text{target}_{\nu_\tau/\bar{\nu}_\tau} = \int dE \Phi_{\nu_\tau/\bar{\nu}_\tau}(E) P^\text{target}_{\nu_\tau/\bar{\nu}_\tau}(E)$$

where $P^\text{target}_{\nu_\tau/\bar{\nu}_\tau}(E) = n_{\text{cen}} \sigma_{\nu_\tau \text{Pb}}(E) d$ is a probability of interacting with the target

$\Rightarrow$ it depends on the $\sigma_{\nu_\tau \text{Pb}}$ and $\sigma_{\bar{\nu}_\tau \text{Pb}}$ cross sections

- at not too small energies ($\sqrt{s_{\text{NN}}} > 5$ GeV) the nuclear cross sections can be obtained from elementary cross sections as: $\sigma_{\nu_\tau \text{Pb}} = Z \sigma_{\nu_\tau \text{p}} + (A - Z) \sigma_{\nu_\tau \text{n}}$
- elementary and nuclear cross sections strongly depend on $\nu_\tau/\bar{\nu}_\tau$ energy
- dominated by charge current DIS (contributions of nucleon resonances negligible)

- we use NuWro Monte Carlo code
- proton-target: the cross sections for $\nu_\tau$ and $\bar{\nu}_\tau$ almost the same
- neutron-target: the cross sections for $\nu_\tau$ and $\bar{\nu}_\tau$ quite different
- marginal difference between exact Pb-target and 82p+(208-82)n combination
**Production of $D_s^\pm$ meson**

**Production of $\nu_\tau$ neutrinos**

**Predictions for SHIP experiment**

**Summary**

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**Introduction**

Introduction

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**Differential cross sections**

**$p + ^{96}\text{Mo}$ interactions at $\sqrt{s_{NN}} = 27.4 \text{ GeV}$**

**Theoretical computations:** MMHT2014 PDFs $\Rightarrow$ direct (solid) vs. chain (dashed)

FONLL leading (left) and LO subleading (right) + SHIP forward cut

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- The direct decay dominates for smaller while the chain mode for larger energies
- The crosspoint is found to be between $20 - 40 \text{ GeV}$ and is slightly different for the leading and for the subleading contributions
- $\nu_\tau/\bar{\nu}_\tau$ production asymmetry in the case of the subleading mechanism

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**SHIP**
Differential cross sections

$p + ^{96}\text{Mo}$ interactions at $\sqrt{s_{NN}} = 27.4\text{ GeV}$

**Theoretical computations:** NNPDF30 PDFs $\Rightarrow$ direct (solid) vs. chain (dashed)

- FONLL leading (left) and LO subleading (right) + SHIP forward cut

- the differences of the neutrino distributions driven by the respective differences of the $D_s$-meson distributions
- NNPDF30 PDF $\Rightarrow$ smaller leading and larger subleading contribution (especially at larger energies $E_{lab} > 150\text{ GeV}$)
- NNPDF30 PDF $\Rightarrow$ larger $\nu_\tau/\bar{\nu}_\tau$ production asymmetry
**Introduction**

**Production of** $D_s^\pm$ **meson**

**Production of** $\nu_\tau$ **neutrinos**

**Predictions for SHiP experiment**

**Summary**

**Differential cross sections**

$p + ^{96}\text{Mo}$ interactions at $\sqrt{s_{NN}} = 27.4 \text{ GeV}$

**Theoretical computations:** collinear PDFs $\Rightarrow$ MMHT2014 (left) vs. NNPDF30 (right)

leading/subleading (FONLL/LO) + direct decay + chain decay + SHiP forward cut

- two different scenarios for the two different PDF sets
- the MMHT2014 PDFs set leads to a negligible subleading contribution in the whole energy range while the NNPDF30 PDFs set provides the subleading contribution to be dominant at larger energies ($E_{lab} > 120 \text{ GeV}$)
- if such distributions could be measured by the SHiP experiment then they could be useful to constrain the PDFs in the purely known kinematical region.
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$p + ^{96}$Mo interactions at $\sqrt{s_{NN}} = 27.4$ GeV

**SHIP**

Theoretical computations: charm cross section $\Rightarrow$ FONLL (left) vs. $k_T$-factorization (right)

leading/subleading + direct decay + chain decay + SHIP forward cut

\[ D_s^+ + D_s \rightarrow \nu_\tau + \bar{\nu}_\tau \]

\[ \sqrt{s} = 27.4 \text{ GeV} \]

- Direct + chain
- SHIP: $\eta_\nu > 5.3$
- MMHT2014 PDF

- Leading (dashed)
- Subleading (dotted)
- Sum (solid)

- Direct + chain
- SHIP: $\eta_\nu > 5.3$
- LO coll. MMHT2014 PDF + $k_T$-fact. KMR-MMHT2014lo uPDF

- Leading (dashed)
- Subleading (dotted)
- Sum (solid)

- Subleading $s \rightarrow D_s$ contribution the same in both figures
- $k_T$-factorization leads to a slightly smaller cross sections for the leading component which makes the subleading contribution even more important
- Shapes of the FONLL and $k_T$-factorization leading distributions very similar
**Number of observed neutrinos**

**Number of observed $\nu_\tau$ per interval of (laboratory) energy**

**Theoretical computations:**

FONLL charm + Peterson FF + direct and chain decay + SHIP forward cut

![Graphs showing theoretical predictions](image)

- number of neutrinos observed in Pb-target: $N_{\nu_\tau/\bar{\nu}_\tau}^{\text{target}} = \int dE \Phi_{\nu_\tau/\bar{\nu}_\tau}(E) P^\text{target}_{\nu_\tau/\bar{\nu}_\tau}(E)$
- direct components are peaked at $E_{\text{lab}} \approx 20$ GeV
- chain components are peaked at $E_{\text{lab}} \approx 50$ GeV (similarly for the subleading mechanism)

after integrating the above integrals ...
## Number of observed $\nu_\tau$ and $\bar{\nu}_\tau$ for the SHiP experiment

... order of $10^3$ of tau neutrino/antineutrino events at SHiP!

<table>
<thead>
<tr>
<th>Framework/mechanism</th>
<th>flavour</th>
<th>Number of observed neutrinos</th>
<th>$\nu_\tau + \bar{\nu}_\tau$</th>
<th>$\frac{\nu_\tau - \bar{\nu}<em>\tau}{\nu</em>\tau + \bar{\nu}_\tau}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FONLL + NNPDF30 NLO PDF</strong></td>
<td>$\nu_\tau$</td>
<td>96</td>
<td>515</td>
<td>818</td>
</tr>
<tr>
<td>$c/\bar{c} \to D^\pm_s \to \nu_\tau/\bar{\nu}_\tau$</td>
<td>$\bar{\nu}_\tau$</td>
<td>27</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td><strong>LO coll. + NNPDF30 LO PDF</strong></td>
<td>$\nu_\tau$</td>
<td>28</td>
<td>336</td>
<td>435</td>
</tr>
<tr>
<td>$s/\bar{s} \to D^\pm_s \to \nu_\tau/\bar{\nu}_\tau$</td>
<td>$\bar{\nu}_\tau$</td>
<td>22</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td><strong>FONLL + MMHT2014nlo PDF</strong></td>
<td>$\nu_\tau$</td>
<td>277</td>
<td>1427</td>
<td>2292</td>
</tr>
<tr>
<td>$c/\bar{c} \to D^\pm_s \to \nu_\tau/\bar{\nu}_\tau$</td>
<td>$\bar{\nu}_\tau$</td>
<td>80</td>
<td>508</td>
<td></td>
</tr>
<tr>
<td><strong>LO coll. + MMHT2014lo PDF</strong></td>
<td>$\nu_\tau$</td>
<td>17</td>
<td>142</td>
<td>203</td>
</tr>
<tr>
<td>$s/\bar{s} \to D^\pm_s \to \nu_\tau/\bar{\nu}_\tau$</td>
<td>$\bar{\nu}_\tau$</td>
<td>7</td>
<td>37</td>
<td></td>
</tr>
</tbody>
</table>

- the chain contribution is significantly larger (by about factor of 7) than the direct one
- MMHT2014 PDF $\Rightarrow$ the leading mechanism much larger than the subleading one (by about factor of 10)
- NNPDF30 PDF $\Rightarrow$ the difference between the leading and the subleading components is much smaller (by about factor of 2).
- the $\nu_\tau/\bar{\nu}_\tau$ production asymmetry increased when the subleading contribution is taken into account.
Conclusions and outlook

- we have discussed the mechanism and cross sections for production of $\nu_\tau$ and $\bar{\nu}_\tau$ in fixed target experiment SHIP for $\sqrt{s_{NN}} = 27.4$ GeV with 400 GeV proton beam and molybdenum target

- we include two different contributions of $D_s$ meson production: the leading fragmentation of $c$ and $\bar{c}$ and the subleading fragmentation of $s$ and $\bar{s}$.

- the cross section for $c/\bar{c}$ production has been obtained either using the FONLL framework or in the $k_T$-factorization approach.

- we have predicted $\sim 800 - 2000$ tau neutrino events from charm quark fragmentation

- the subleading fragmentation may increase the probability of observing $\nu_\tau/\bar{\nu}_\tau$ neutrinos/antineutrinos by the planned SHiP fixed target experiment at CERN $\Rightarrow \sim 200 - 400$ tau neutrino events from strange quark fragmentation

- the SHiP experiment could be useful to test $s/\bar{s}$ content of the proton.

Thank You for attention!