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

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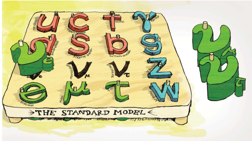
# Outline

# $\nu_\tau$ 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: $9 \pm 1.5$ events**
    (no distinction between $\nu_\tau$ and $\overline{\nu}_\tau$)
  - **OPERA: 10 events**
    (only $\nu_\tau$, discovery of $\nu_\mu \to \nu_\tau$ oscillations)
- IceCube (first two candidates for astrophysical $\nu_\tau$ )
- no $\overline{\nu}_\tau$ has ever been detected yet, making it the last missing tile of the SM




Neutrino factories:

- much more $\nu_\tau/\overline{\nu}_\tau$ events
- study the properties and cross section
- first observation of $\overline{\nu}_\tau$

**CERN SPS** $\Rightarrow$ Search for HIdden Particles (SHIP) experiment

SHiP
*Search for Hidden Particles*

in a broader perspective:

- Light Dark Matter search
- extraction of $F_4$ and $F_5$ structure functions
- measure the $s$-content of the nucleon

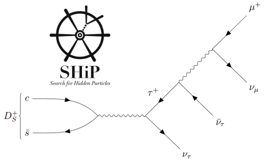
# Tau neutrino factory in fixed-target experiment SHIP

**SHIP experiment** $\Rightarrow$ 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

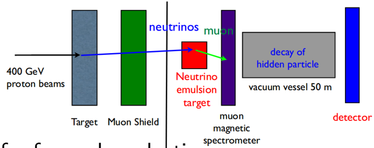
**abundant source of $\nu_\tau$ and $\overline{\nu}_\tau$ $\Longrightarrow$ direct and chain decays of $D_s^{\pm}$ meson**

SHiP
Search for Hidden Particles



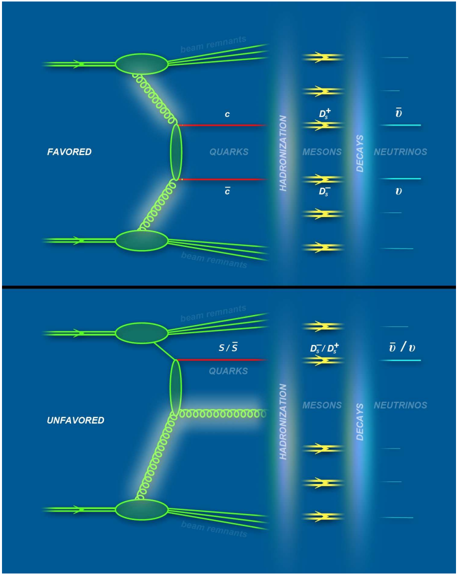

- production of large amounts of neutrinos (not only $\nu_\tau$)
- first direct observation of $\overline{\nu}_\tau$
- study $\nu_\tau$ and $\overline{\nu}_\tau$ properties
- test lepton flavor universality by comparing interactions of $\nu_\mu$ and $\nu_\tau$

- **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:
$\eta \gtrsim 4.6 - 5.6$

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




**Starting point:**

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

approximately:

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

- 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

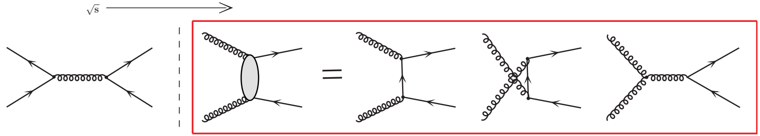
**Subleading (unfavored) fragmentation**

$s \to D_s^-$ and $\bar{s} \to D_s^+$

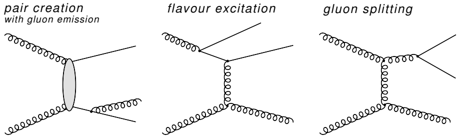
- $s$-quark and $\bar{s}$-antiquark production cross section
- light-to-heavy hadronization

# pQCD charm quark-antiquark pair cross section

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




- Main classes of the next-to-leading order (NLO) diagrams:




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

**collinear approach**:

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

**$k_T$-factorizaton**:

- exact kinematics from the very beginning
- correlation observables directly calculable
- some contributions even beyond the NLO available (also differentially)

# $c \to D_s$ transition and independent parton fragmentation

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

independent parton fragmentation picture

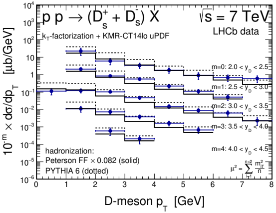
- $c \to D_s$: Peterson$(z)$, $\varepsilon = 0.05$ (rather well known from $e^+e^-$ data)
- fragmentation fraction $P_{c \to D_s} = 5 - 9\%$ (quite uncertain)

high energies:

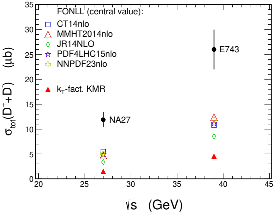
- $y_H = y_q$, $p_{t,H} = z \cdot p_{t,q}$ with $z \in (0,1)$
- can be safely used only when both $m_q$ and $m_H$ can be neglected
- problematic at $p_{t,H} \lesssim m_H$
- LHC charm data well described

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 $P_{c \to D_s} = 8\%$



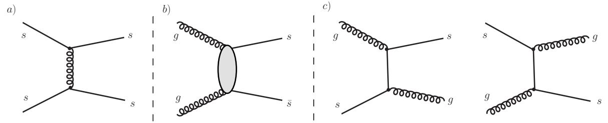

low energy charm data slightly underestimated

# pQCD strange quark/antiquark production cross section

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

$sg \to sg$, $su \to su$, $s\bar{u} \to s\bar{u}$, $sd \to sd$, $s\bar{d} \to s\bar{d}$, $ss \to ss$, $s\bar{s} \to s\bar{s}$

#7 different channels (+ symmetric counterparts) for quark (+ charge conjugate for antiquark)

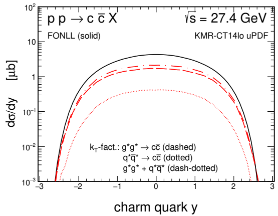


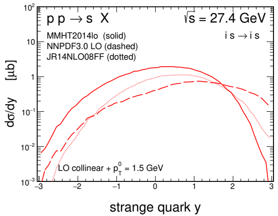

dominant processes:
$gs \to gs$, $g\bar{s} \to g\bar{s}$
$gg \to s\bar{s}$

- collinear factorization approach with on-shell partons
- special treatment of minijets at small transverse momenta:

  $F_{sup}(p_t) = \frac{p_t^4}{((p_t^0)^2 + p_t^2)^2}$ (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 $s(x) \neq \bar{s}(x)$



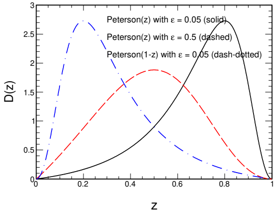

similar cross sections for charm and strange quark production

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

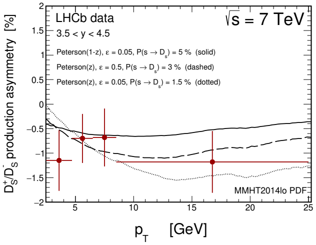
**light-to-heavy fragmentation**: $\bar{s} \to D_s^+$ and $s \to D_s^-$

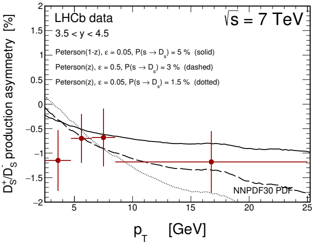
fragmentation fraction and function completely unknown

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




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



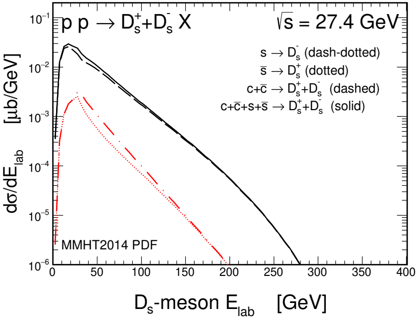



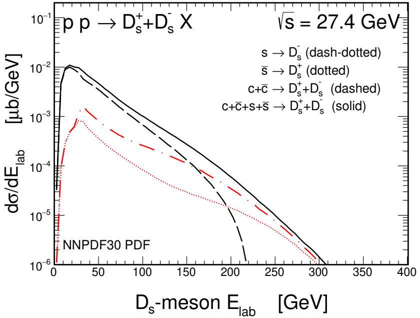

- $s \to D_s$: Peterson$(z)$, $\varepsilon = 0.5$ and $P_{s \to D_s} = 3\%$

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

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

leading + subleading fragmentation mechanism



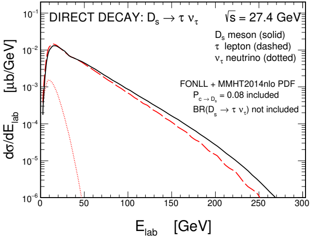



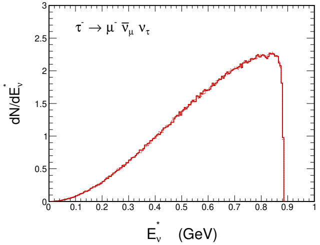

- a pretty much different results are obtained for the two different PDF sets, especially for large meson energies
- our model leads to a rather small (MMHT2014 PDF) or a fairly significant (NNPDF30 PDF) contribution to the $D_s$ meson production at large energies which comes from the $s/\bar{s}$-quark fragmentation
- more measurements of $D_s^\pm$ at low energies needed to reduce uncertainties

# $D_s \to \nu_\tau$: direct and chain decay modes

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

- spin zero particle decays isotropically in its rest frame
- $BR(D_s^{\pm} \to \tau^{\pm} \nu_\tau / \overline{\nu}_\tau) = 0.0548 \pm 0.0023$
- $\tau$ 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**: $D_s^+ \to \tau^+ \to \overline{\nu}_\tau$ and $D_s^- \to \tau^- \to \nu_\tau$
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 $\vec{v}_\tau = \vec{v}_{D_s}$ and $\vec{p}_\tau = \vec{p}_{D_s}$ 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

# $\nu_\tau$ and $\overline{\nu}_\tau$ neutrino yield at the beam dump

The energy dependent **FLUX OF NEUTRINOS** can be written as:

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

- $N_p$ 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 mb)

The above formula can be used to
**estimate number of $\nu_\tau$ and $\overline{\nu}_\tau$ produced at the beam dump $\Longrightarrow$**
for the decays of $D_s$ meson produced from charm quark fragmentation it reads:

$$N_{\nu_\tau} = 2\frac{N_p}{\sigma_{pA}}\sigma_{pA\to\nu_\tau X} = 2\frac{N_p}{\sigma_{pN}}\sigma_{pp\to c\bar{c}X}\, \mathrm{BR}(D_s \to \tau)\, \mathrm{P}(c \to D_s)$$

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

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

# Detection of the $\nu_\tau$ and $\overline{\nu}_\tau$ produced at the beam dump

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

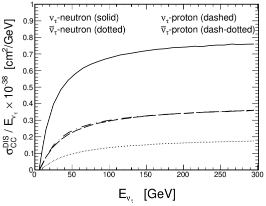
number of neutrinos/antineutrinos observed in the target:

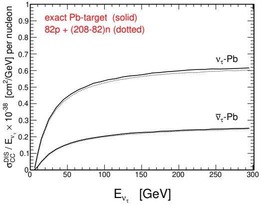
$$N^{\rm target}_{\nu_\tau/\overline{\nu}_\tau} = \int dE \Phi_{\nu_\tau/\overline{\nu}_\tau}(E) P^{\rm target}_{\nu_\tau/\overline{\nu}_\tau}(E)$$

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

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

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



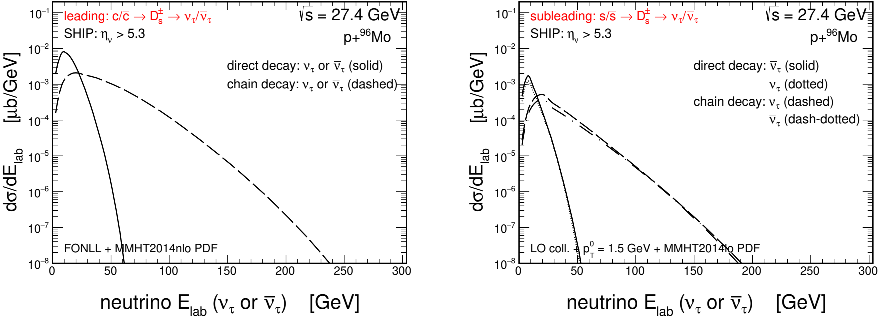




- we use NuWro Monte Carlo code
- proton-target: the cross sections for $\nu_\tau$ and $\overline{\nu}_\tau$ almost the same
- neutron-target: the cross sections for $\nu_\tau$ and $\overline{\nu}_\tau$ quite different
- marginal difference between exact Pb-target and 82p+(208-82)n combination

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

Theoretical computations: MMHT2014 PDFs ⇒ direct (solid) vs. chain (dashed)

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

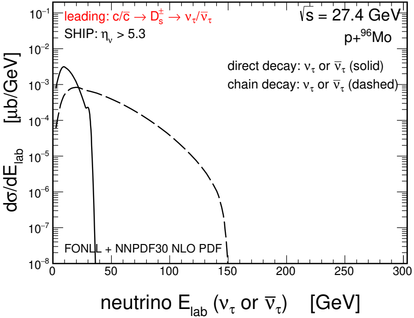


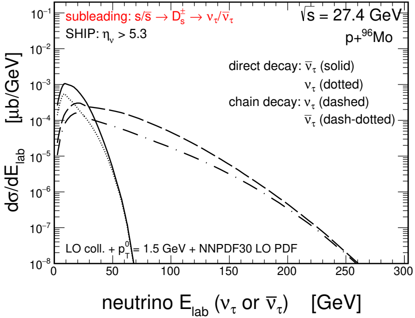

- the direct decay dominates for smaller while the chain mode for larger energies
- the crosspoint is found to be between 20 − 40 GeV and is slightly different for the leading and for the subleading contributions
- $\nu_\tau/\overline{\nu}_\tau$ production asymmetry in the case of the subleading mechanism

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

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

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



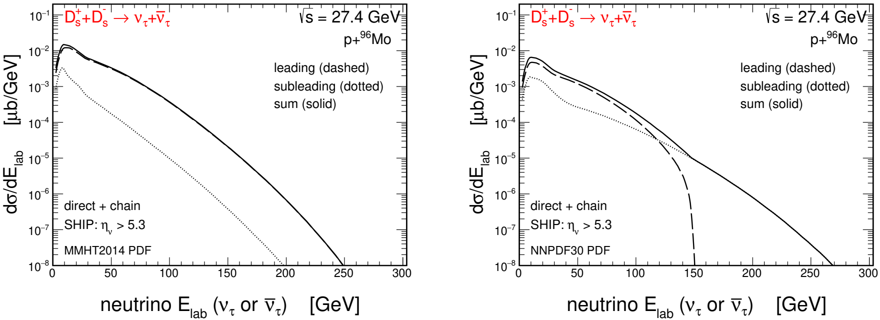




- the differences of the neutrino distributions driven by the respective differences of the $D_s$-meson distributions
- NNPDF30 PDF $\Rightarrow$ smaller leading and larger subleading contribution (especially at larger energies $E_{\mathrm{lab}} > 150$ GeV)
- NNPDF30 PDF $\Rightarrow$ larger $\nu_\tau/\bar{\nu}_\tau$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

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

Theoretical computations: collinear PDFs ⇒ MMHT2014 (left) vs. NNPDF30 (right)

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

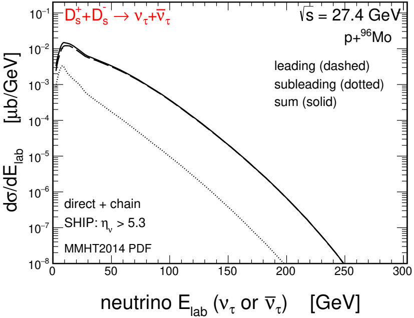


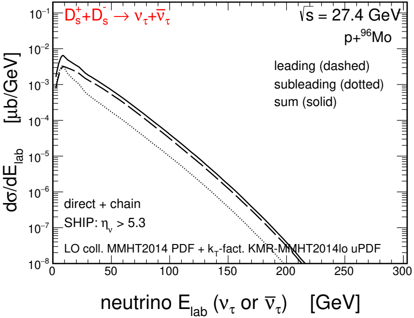

- two different scenarios for the two different PDF sets
- the MMHT2014 PDFs set leads to a negligible subleading contribution in the whole energy range while the NNPDF30 PDFs set provides the subleading contribution to be dominant at larger energies ($E_{\mathrm{lab}} > 120$ GeV)
- if such distributions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

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

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

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



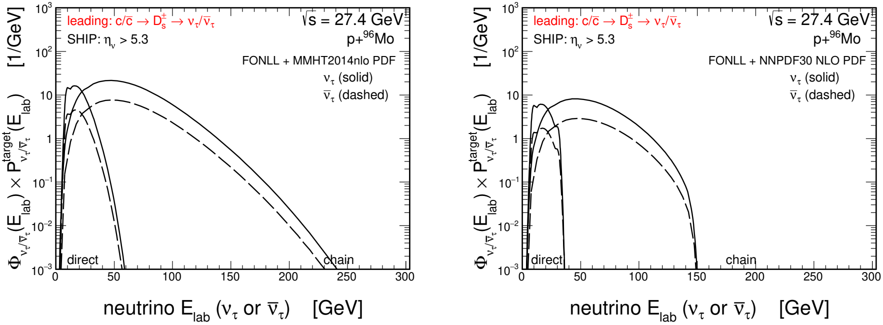




- subleading $s \to D_s$ contribution the same in both figures
- $k_T$-factorizaton leads to a slightly smaller cross sections for the leading component which makes the subleading contribution even more important
- shapes of the FONLL and $k_T$-factorization leading distributions very similar

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

Theoretical computations:

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




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

after integrating the above integrals ...

# Number of observed $\nu_\tau$ and $\overline{\nu}_\tau$ for the SHiP experiment

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

| Framework/mechanism | flavour | Number of observed neutrinos direct | chain | $\nu_\tau + \overline{\nu}_\tau$ | $\frac{\nu_\tau - \overline{\nu}_\tau}{\nu_\tau + \overline{\nu}_\tau}$ |
|---|---|---|---|---|---|
| FONLL + NNPDF30 NLO PDF | $\nu_\tau$ | 96 | 515 | 818 | 0.49 |
| $c/\bar{c} \to D_s^\pm \to \nu_\tau/\overline{\nu}_\tau$ | $\overline{\nu}_\tau$ | 27 | 180 | | |
| LO coll. + NNPDF30 LO PDF | $\nu_\tau$ | 28 | 336 | 435 | 0.67 |
| $s/\bar{s} \to D_s^\pm \to \nu_\tau/\overline{\nu}_\tau$ | $\overline{\nu}_\tau$ | 22 | 49 | | |
| FONLL + MMHT2014nlo PDF | $\nu_\tau$ | 277 | 1427 | 2292 | 0.49 |
| $c/\bar{c} \to D_s^\pm \to \nu_\tau/\overline{\nu}_\tau$ | $\overline{\nu}_\tau$ | 80 | 508 | | |
| LO coll. + MMHT2014lo PDF | $\nu_\tau$ | 17 | 142 | 203 | 0.58 |
| $s/\bar{s} \to D_s^\pm \to \nu_\tau/\overline{\nu}_\tau$ | $\overline{\nu}_\tau$ | 7 | 37 | | |

- 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 $\nu_\tau/\overline{\nu}_\tau$ 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 $\overline{\nu}_\tau$ 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 $\nu_\tau/\overline{\nu}_\tau$ 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!