Study of tau-neutrino production at the CERN SPS

Tomoko Ariga
Kyushu University / University of Bern
for the DsTau collaboration

400 GeV proton interaction
(test beam data)

200 μm
Physics motivations

• Tau neutrinos are among the less studied particles in the SM
• Large systematic uncertainty in the cross section measurement

• Precise measurement of $\nu_\tau$ CC cross section:
  • Search for new physics effect in $\nu_\tau$ – nucleon CC interactions
    • Test of lepton non-universality
  • Important input for future neutrino experiments (Hyper-K, DUNE) and astrophysical $\nu_\tau$ observations (IceCube)
Concept of $\nu_\tau$ cross section measurement

- high energy proton
- $\nu_\tau$ production target (e.g. tungsten)
- charged particle sweeping, neutron absorption
- $\nu_\tau$ beam
- $\nu_\tau$ detector

$\nu_\tau$ source: $D_s \rightarrow \tau \rightarrow X$ decays

$\nu_\tau$ production study: DsTau
- No experimental data on the Ds differential cross section
- Large systematic uncertainty (~50%) in the $\nu_\tau$ flux prediction

$\nu_\tau$ detection: e.g. SHiP
- Statistical uncertainty 33% in DONUT
- Will be reduced to the 2% level in future experiments
The DsTau project at the CERN SPS (SPSC-P-354)

- **Goals**
  - Measurement of $\nu_\tau$ production
    - Measurement of Ds differential production cross section
  - Reduction of systematic uncertainty in the cross section measurement 50% → 10%
    - Re-evaluation of the DONUT result
    - Important input for future $\nu_\tau$ experiment: $\nu_\tau$ program in SHiP

- **Principle of the experiment**
  - Detection of double-kink + another decay topology within a few mm

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**Diagram:**
- Kink angle of $D_s \to \tau$ a few mrad
- Primary proton $\rightarrow D_s, D^+, \nu_\tau, \tau, X, X'$
- $\sim 5$ mm
- $\sigma_x = 50$ nm
- $\sigma_\theta = 0.35$ mrad
Emulsion detectors:
3D tracking device with 50 nm precision

Cross-sectional view

Emulsion layer (44 μm)

Plastic base (200 μm)

Emulsion layer (44 μm)

AgBr crystal
$10^{14}$ crystals in a film

Residual from fitted track
$\sigma = 50$ nm
$\rightarrow$ Angular resolution 0.35 mrad with 200 μm base

10 GeV/c $\pi$ beam
Sensitivity 36 grains/100 μm

2018/7/6
Module structure for $D_s \rightarrow \tau \rightarrow X$ measurement

10 units (total 100 emulsion films)

ECC for momentum measurement (26 emulsion films interleaved with 1 mm thick lead plates)

Proton beam

Profile monitor 2 cm x 2 cm

Detector module 10 cm x 10 cm x 8.6 cm

Target mover

Scintillation counter 10 cm x 10 cm

Real-time feedback

1 m

2018/7/6
Signal and background rates

**Signal**: $D_s \to \tau \to X$ events (double-kink + another decay topology within a few mm)

- **Signal rate**: $2.2 \times 10^{-5}$ /proton int. $\times$ eff. 20%
- To detect 1000 $D_s \to \tau \to X$ events, $2.3 \times 10^8$ proton interactions ($4.6 \times 10^9$ pot) are needed

**Main background**: hadronic interactions without any detectable nuclear fragments

- Test beam data with a 5-GeV $\pi$ beam
  - A kink with FL < 5 mm: $4.5 \times 10^{-4}$ /particle
  - Study with FLUKA is in progress
    - A kink with FL < 5 mm: $2.4 \times 10^{-4}$ /particle

- **BG rate (double kink + another kink)**: $1.4 \times 10^{-9}$ /proton int.
  - Combination with decays is to be studied

- **Validation from real data is planned with the 2018 data**
Analysis scheme for double-kink search

- Full area scanning by the fast scanning system
- Select decays with $\Delta \theta > 20$ mrad

- Precision measurement to detect $Ds \rightarrow \tau$ decay (a few mrad)

Proton beam

$Ds$ → $\nu_\tau$ → $\tau$ → $X$ → $\tau$

Hyper Track Selector (HTS)

Scanning speed 0.5 $m^2/h/layer$
Angular resolution ~2 mrad

Dedicated high-precision systems
Angular resolution ~0.3 mrad
New method for $D_s$ momentum reconstruction by Artificial Neural Network using topological variables

- Difficult to measure $D_s$ momentum directly due to short lifetime

  $\rightarrow$ $D_s$ momentum reconstruction by topological variables

- A Neural Network with 4 variables was trained with MC events

- Momentum resolution for $\tau \rightarrow 1$ prong decays $\Delta p/p = 18\%$

$FL$: flight length

$\Delta p/p = 18\%$
Beam tests

- Nov. 2016 H4 beamline
  - Test of the exposure scheme and the setup
  - Proof of principle

- May 2017 H2 beamline
  - Updated exposure sequence (intensity driven synchronization between beam intensity and target mover)
  - Tests to improve angular resolution

Experimental setup at the H4 beamline

- Target mover (motorized X-Y stage)
- Detector module
- Beam size ~1 cm x 1 cm
- Beam profile monitor (silicon pixel telescope)
- ATLAS IBL modules with FE-I4A chips
Reconstruction of proton interactions in tungsten

- Microscope data taking
  - Pixel size = 0.3 \(\mu\)m x 0.3 \(\mu\)m x 2 \(\mu\)m
- Data size
  - \(~10\) TB image data / film (125 cm\(^2\))
  - (~100 PB will be processed in the 2018 pilot run (50 m\(^2\))
- Track density
  - OPERA: 100 tracks/cm\(^2\) in wide angular space (\(\theta<500\) rad)
  - DsTau: 100,000 tracks/cm\(^2\) in small angular space (\(\theta<10\) mrad)

Reconstructed tracks

- \(~4000\) tracks in 2 x 2 mm\(^2\), 15 films
- 1000 \(\mu\)m

Tracks starting after tungsten

Vertex reconstruction
Measured proton beam density in the analyzed region: $4.36 \times 10^5$ beam tracks/3.61 cm$^2$

**Z distribution of observed vertices**

**Interactions in a tungsten plate**

<table>
<thead>
<tr>
<th>N vertices</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected</td>
<td>1860</td>
</tr>
<tr>
<td>Observed</td>
<td>With parent 1832</td>
</tr>
<tr>
<td></td>
<td>Without parent 130</td>
</tr>
</tbody>
</table>

Consistent with the expectation
Developing a new analysis scheme to analyze over 200 million proton interactions with an automated procedure.
Status of the project

• Letter of Intent, Feb. 2016
  • Beam tests in Nov. 2016, May 2017

• Proposal (SPSC-P-354), Aug. 2017

• Presentation at the 128th Meeting of the SPSC (open session):
  https://indico.cern.ch/event/694185/

• Reviewed during the SPSC meeting, Jan. 2018
  → Positive feedback
    • "The 2018 run has been approved and the Committee recommends that the beam time requested for 2021 will be granted."
The 2018 pilot run

Goal
• Test of large data taking and analysis
• BG estimation with data
• Physics results (~80 Ds → $\tau$ detected)

• Film production in progress (June – August 2018)
  • Needed: 48 m$^2$ (3900 films)
  • Production speed: ~5 m$^2$/week

~50% of the films already produced!
Expected performance

<table>
<thead>
<tr>
<th>Run</th>
<th>Beam time</th>
<th>Emulsion surface</th>
<th>Systematic uncertainty for the cross section measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018 pilot run</td>
<td>1 week</td>
<td>48 m² (30 modules)</td>
<td>30% → Re-evaluation of the DONUT result</td>
</tr>
<tr>
<td>2021 physics run</td>
<td>2 weeks</td>
<td>545 m² (338 modules)</td>
<td>10% → Input for future measurement</td>
</tr>
<tr>
<td>2022 physics run</td>
<td>2 weeks</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Uncertainties in the cross section measurement

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>DONuT</th>
<th>Systematic uncertainty after DsTau outcome</th>
<th>Future ντ measurement with DsTau outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>ντ statistics</td>
<td>0.33</td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Ds differential cross section (xτ dependence)</td>
<td>&gt;0.50</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Charm production cross section</td>
<td>0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decay branching ratio (Ds → τ)</td>
<td>0.23</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>(0.04 at present)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target atomic mass effects</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Aiming at ~10% precision to look for new physics effects in ντ -nucleon CC interactions
Summary

- A new precise measurement of the $\nu_\tau$ cross section is important
  - to test new physics effects in $\nu_\tau$–nucleon CC interactions
  - for neutrino oscillation experiments and astrophysical $\nu_\tau$ observations

- The DsTau project has been proposed at the CERN SPS to study $\nu_\tau$ production (SPSC-P-354)

- This project aims to
  - detect 1000 $D_s \rightarrow \tau$ decays in $2.3 \times 10^8$ proton interactions employing emulsion detectors with a spatial resolution of 50 nm
  - reduce the systematic uncertainty in the $\nu_\tau$ cross section measurement from $>50\%$ to $10\%$

- A pilot run in 2018 has been approved and beam time for a physics run in 2021 recommended by the CERN-SPSC.

- Preparation is in progress for the pilot run in August 2018!
Thank you for your attention
Backup
High precision measurement of track angles

• Intrinsic resolution of each grain = 50 nm
  • Two grains on top and bottom of 200 μm base \(\rightarrow\) 0.35 mrad
  • Discrimination of 2 mrad at 4\(\sigma\) level

• A new system with piezo-based Z axis under development

• Angular measurement reproducibility of 0.15 mrad was achieved

Position reproducibility
~ 8 nm

Angular reproducibility
~ 0.15 mrad

• Angular alignment between films to be done by using dense 400 GeV proton tracks
The DONuT experiment (Fermilab E872)

- First direct observation of $\nu_\tau$ interactions
- 9 $\nu_\tau$ CC events observed with an estimated background of 1.5 events
**Systematic uncertainty in the DONuT measurement**

9 $\nu_\tau$ CC events observed with an estimated background of 1.5 events

\[ \nu_\tau \text{ CC cross section} \quad \sigma_{\nu_\tau}(E) = \sigma_{\nu_\tau}^{\text{const}} \times E_{\nu_\tau} \times K_\tau(E) \]

**The largest uncertainty in DONuT:**

$D_s$ differential cross section (used to calculate the $\nu_\tau$ flux)

Parametrization used in DONUT

\[
\frac{d^2\sigma}{dx_F dp_T^2} \propto (1 - |x_F|)^n \exp(-bp_T^2)
\]

longitudinal dependence  
transverse dependence

No experimental result effectively constraining the $D_s$ differential cross section

The energy-independent part was parameterized as

\[ \sigma_{\nu_\tau}^{\text{const}} = 7.5(0.335 n^{1.52}) \times 10^{-40} \text{ cm}^2 \text{ GeV}^{-1} \]

To reduce the systematic uncertainty in the $\nu_\tau$ CC cross-section lower than 10%, the parameter $n$ has to be determined at a precision of $\sim 0.4$
### Charm production cross section results

\[
\frac{d^2\sigma}{dx_F dp_T^2} \propto (1 - |x_F|)^n \exp(-bp_T^2)
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam type / energy (GeV)</th>
<th>(\sigma(D_s^-)) ((\mu)b/nucl)</th>
<th>(\sigma(D^\pm)) ((\mu)b/nucl)</th>
<th>(\sigma(D^0)) ((\mu)b/nucl)</th>
<th>(\sigma(\Lambda_c)) ((\mu)b/nucl)</th>
<th>(x_F) and (p_T) dependence: (n) and (b) (GeV/c)^2</th>
<th>(n(D_s^-)) (D_s^+) events ((x_F &gt; 0.15))</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERA-B</td>
<td>p / 920</td>
<td>18.5 ± 7.6 (~11 events)</td>
<td>20.2 ± 3.7</td>
<td>48.7 ± 8.1</td>
<td>-</td>
<td>(n(D^0, D^+) = 7.5 \pm 3.2)</td>
<td></td>
</tr>
<tr>
<td>E653</td>
<td>p / 800</td>
<td>-</td>
<td>38 ± 17</td>
<td>38 ± 13</td>
<td></td>
<td>(n(D^0, D^+) = 6.9_{+1.9}^{−1.8}) (b(D^0, D^+) = 0.84_{+0.10}^{−0.08})</td>
<td></td>
</tr>
<tr>
<td>E743 (LEBC-MPS)</td>
<td>p / 800</td>
<td>-</td>
<td>26 ± 8</td>
<td>22 ± 11</td>
<td></td>
<td>(n(D) = 8.6 \pm 2.0) (b(D) = 0.8 \pm 0.2)</td>
<td></td>
</tr>
<tr>
<td>E781 (SELEX)</td>
<td>(\Sigma^-) (sdd) / 600</td>
<td></td>
<td></td>
<td></td>
<td>(\sim 350) (D_s^-) events, (\sim 130) (D_s^+) events (x_F &gt; 0.15) (n(D_s^-) = 4.1 \pm 0.3) (leading effect) (n(D_s^+) = 7.4 \pm 1.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA27</td>
<td>p / 400</td>
<td>12 ± 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA16</td>
<td>p / 360</td>
<td>5 ± 2</td>
<td>10 ± 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WA92</td>
<td>(\pi) / 350</td>
<td>1.3 ± 0.4</td>
<td>8 ± 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E769</td>
<td>p / 250</td>
<td>1.6 ± 0.8</td>
<td>3 ± 1</td>
<td>6 ± 2</td>
<td>320 ± 26 events (D^\pm, D^0, D_s^\pm) (n(D^\pm, D^0, D_s^\pm) = 6.1 \pm 0.7) (b(D^\pm, D^0, D_s^\pm) = 1.08 \pm 0.09)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E769</td>
<td>(\pi^\pm) / 250</td>
<td>2.1 ± 0.4</td>
<td></td>
<td>9 ± 1</td>
<td>1665 ± 54 events (D^\pm, D^0, D_s^\pm) (n(D^\pm, D^0, D_s^\pm) = 4.03 \pm 0.18) (b(D^\pm, D^0, D_s^\pm) = 1.08 \pm 0.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA32</td>
<td>(\pi) / 230</td>
<td>1.5 ± 0.5</td>
<td></td>
<td>7 ± 1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Results from LHCb at \(\sqrt{s} = 7, 8\) or 13 TeV are not included since the energies differ too much)

**No experimental result** effectively constraining the \(D_s\) differential cross section at the desired level or consequently the \(\nu_\tau\) production
<table>
<thead>
<tr>
<th>Structure</th>
<th>DsTau</th>
<th>SHiP charm (SPSC-EOI-017)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin target + decay volume</td>
<td>Thin target + decay volume</td>
<td>Thin target + decay volume</td>
</tr>
<tr>
<td>Target</td>
<td>Tungsten / Molybdenum</td>
<td>Tungsten / Molybdenum</td>
</tr>
<tr>
<td>Emulsion film area</td>
<td>593 m²</td>
<td>20 m² – 60 m²</td>
</tr>
<tr>
<td># of modules (runs)</td>
<td>368</td>
<td>40 – 120</td>
</tr>
<tr>
<td>Pot</td>
<td>4.6 x 10⁹</td>
<td>2 x 10⁷</td>
</tr>
<tr>
<td># of interactions</td>
<td>2.3 x 10⁸</td>
<td>? O(10⁷)</td>
</tr>
<tr>
<td>Charm pair produced</td>
<td>several x 10⁵</td>
<td>10⁴</td>
</tr>
<tr>
<td>Charm pair detection eff</td>
<td>36%</td>
<td>12%</td>
</tr>
<tr>
<td>Charm pair detected</td>
<td>a few 10⁵</td>
<td>10³</td>
</tr>
<tr>
<td>Ds produced</td>
<td>10⁵</td>
<td>10³</td>
</tr>
<tr>
<td>Ds detected</td>
<td>4 x 10⁴</td>
<td>? 100 (no separation from D)</td>
</tr>
<tr>
<td>Ds → τ → X</td>
<td>10³</td>
<td>no sensitivity</td>
</tr>
<tr>
<td>DAQ</td>
<td>100 kHz (not limited by electric detectors, but stage movement)</td>
<td>&lt;10 kHz (limited by DAQ design)</td>
</tr>
</tbody>
</table>
Indication of possible non-universality?

- **W decays** (LEP combination)

\[
\frac{\mathcal{B}(W \rightarrow \tau \nu_\tau)}{\mathcal{B}(W \rightarrow \tau \nu_\tau)} = 1.077 \pm 0.026
\]

\[
\frac{\mathcal{B}(W \rightarrow e \nu_e) + \mathcal{B}(W \rightarrow \mu \nu_\mu)}{2} = 0.994 \pm 0.020
\]

- **B-meson decays**  

\[
\mathcal{B}(B \rightarrow \tau \bar{\nu}_\tau) \quad R_D = \mathcal{B}(B \rightarrow D \tau \bar{\nu}_\tau)/\mathcal{B}(B \rightarrow D \mu \bar{\nu}_\mu)
\]

![Graphs showing B-meson decay rates and R_D values](image)
Efficiency of $D_s \rightarrow \tau \rightarrow X$ detection

<table>
<thead>
<tr>
<th>Selection</th>
<th>Total efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Flight length of $D_s \geq 2$ emulsion layers</td>
<td>77</td>
</tr>
<tr>
<td>(2) Flight length of $\tau \geq 2$ layers &amp; $\Delta \theta(D_s \rightarrow \tau) \geq 2$ mrad</td>
<td>43</td>
</tr>
<tr>
<td>(3) Flight length of $D_s &lt; 5$ mm &amp; flight length of $\tau &lt; 5$ mm</td>
<td>31</td>
</tr>
<tr>
<td>(4) $\Delta \theta(\tau) \geq 15$ mrad</td>
<td>28</td>
</tr>
<tr>
<td>(5) Pair charm: $0.1$ mm $&lt;$ flight length $&lt; 5$ mm (charged decays with $\Delta \theta &gt; 15$ mrad or neutral decays)</td>
<td>20</td>
</tr>
</tbody>
</table>

**Efficiency**

**Yield**
Exposure scheme

- Move detector modules w.r.t. the beam
  - 2016: moved at a constant speed during the spill
  - 2017: intensity driven control by scintillator counter (feedback each 0.2 sec)
- Need ~1 h per module
  - 4 x 11 spills + 20 min to exchange modules

Scanning sequence of the target mover

Beam profile

Time profile in a spill

Beam intensity (kCPS)

Stage speed (mm/sec)