Tau-neutrino production study in 400 GeV proton interactions

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On behalf of the DsTau Collaboration
Physics motivation

- **Tau-neutrino**: less studied particle in the standard model
  - DONuT: First direct observation of $\nu_\tau$ interactions (9 $\nu_\tau$ candidate events observed)
  - OPERA: Discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode (5 $\nu_\tau$ candidate events)

- Precise measurement of $\nu_\tau$ CC cross section would be a test of lepton universality in neutrino CC interactions
Status of neutrino CC cross section measurements

$\nu_\mu$: measured by many experiments

Average over 30 - 200 GeV

$$\sigma_{\nu_\mu}^{\text{const}} = (0.51 \pm 0.01) \times 10^{-38} \text{ cm}^2 \text{ GeV}^{-1}$$

$\sim 2\%$ error

$\nu_\tau$: only the DONuT experiment

$\nu_\tau$ source is $D_s$ produced in proton interactions:

$D_s^+ \rightarrow \tau^+ \nu_\tau \rightarrow X \bar{\nu}_\tau \nu_\tau$

$D_s^- \rightarrow \tau^- \bar{\nu}_\tau \rightarrow X \nu_\tau \bar{\nu}_\tau$

No experimental data on the $D_s$ differential production cross section ($d\sigma/dx_F$) in high energy proton interaction

$>50\%$ systematic uncertainty in the cross section measurement
Neutrino beam line in DONuT (Fermilab E872)

Target (Tungsten 1m, $10\lambda_{int}$)

Sweeping magnets (pT kick 6GeV/c, 3GeV/c)

Passive shielding (Iron, lead, concrete)

Emulsion + SFT hybrid detector

800 GeV protons

Primary proton

$D_s$, $\tau$, $\nu_\tau$

Main source

| $\nu_e$ | $D^0$, $D^\pm$, $D_s$, $\Lambda_c$ |
| $\nu_\mu$ | $D^0$, $D^\pm$, $D_s$, $\Lambda_c$, $\pi$, $K$ |
| $\nu_\tau$ | $D_s$ |

Energy spectra of neutrinos interacting in the emulsion target
Cross section measurement in DONuT

using 9 ντ CC events observed with an estimated background of 1.5 events

ντ CC cross section

$$\sigma_{\nu \tau}(E) = \sigma_{\nu \tau}^{const} \times E_{\nu \tau} \times K_\tau(E)$$

The largest uncertainty in DONuT:
differential cross section of D_s produced in proton interactions
(used to calculate the ντ flux)

Phenomenological formula used to describe charmed particles

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

longitudinal dependence
transverse dependence

No experimental data giving n for D_s produced by 800 GeV proton interactions

The energy-independent part was parameterized as

$$\sigma_{\nu \tau}^{const} = 7.5 \times 0.335^n \times 15.2 \times 10^{-40} cm^2 GeV^{-1}$$
Parameter-dependent cross section result by DONuT


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

1-σ statistical error

Main systematic uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(_s) differential cross section (x(_f) dependence)</td>
<td>\sim 0.50!?</td>
</tr>
<tr>
<td>Charm production cross section</td>
<td>0.17</td>
</tr>
<tr>
<td>Decay branching ratio</td>
<td>0.23</td>
</tr>
<tr>
<td>Target atomic mass effects (A dependence)</td>
<td>0.14</td>
</tr>
</tbody>
</table>

By measuring the longitudinal part of D\(_s\) production, we can re-evaluate the cross section

No published data giving n for D\(_s\) produced by 800 GeV proton interactions
The DsTau project: Tau-neutrino production study at the CERN SPS

- **Aim**: Improve knowledge of tau-neutrino production
  - Re-evaluate existing $\nu_\tau$ cross section (DONUT result): systematic uncertainty $>50\% \rightarrow \sim 10\%$
  - Provide essential data for future $\nu_\tau$ experiments, e.g. SHiP

- **Method**: Direct measurement of tau-neutrino production in 400 GeV proton interactions
  - Dominant source ($>95\%$): $D_s \rightarrow \tau \nu_\tau \rightarrow X \nu_\tau \nu_\tau$
  - Detect the double-kink topology within a few mm by emulsion detector
  - Measure $x_F$ distribution ($D_s$ momentum estimation using topological variables)

- **Status**
  - LoI submitted to the CERN-SPSC in Feb 2016 $\rightarrow$ positive feedback
  - Prototype test experiment in Nov. 2016
The collaboration

Japan:
Aichi
Kobe
Nagoya

Romania:
Bucharest

Russia:
Dubna

Switzerland:
Bern

Turkey:
Ankara
Signal and background

- **Signal:** a double kink + a charmed particle decay

- **Main background:** hadron interactions

\[ \text{Ds} \rightarrow \tau \rightarrow X + \text{kink \~100 mrad} \]

\[ \text{D}^+ \rightarrow X + \text{kink \~100 mrad} \]

\[ \text{Ds} \rightarrow \tau \rightarrow X + \text{Small kink \~7 mrad} \]

\[ \pi \rightarrow \pi + \text{Nuclear fragments} \]

\[ \pi \rightarrow n + \text{Nuclear fragments} \]
Towards detection of a few mrad kink topology

Emulsion detectors: highest position resolution

Emulsion film

Cross-sectional view

- Emulsion layer (44 μm)
- Plastic base (200 μm)
- Emulsion layer (44 μm)

AgBr crystal

$10^{14}$ crystals in a film

10GeV/c $\pi$ beam

Sensitivity 36 grains/100 μm

3D tracking device

Intrinsic resolution 50 nm
Emulsion research facility in Bern

Detector production and R&D

- Dedicated emulsion facility
  - 30 m deep underground lab
  - Detector production chain and photographic development chain
  - Dedicated R&D program for several kinds of special emulsions, collaborating with Nagoya University in Japan

- High speed readout system
  - Fast $4\pi$ track recognition based on GPU technology (A. Ariga and T. Ariga, Journal of Instrumentation 9 P04002 (2014))
  - Upgrade ongoing

Automated emulsion scanning microscopes
Intrinsic resolution of emulsion detectors

Emulsion detector produced in Bern using high sensitivity emulsion gel produced in Nagoya University

AEgIS 2012 run with antiprotons

Measured intrinsic resolution

Intrinsic resolution $58 \text{ nm}$

Angular resolution $0.05 \mu\text{m} \cdot \sqrt{2}/200 \mu\text{m} = 0.35 \text{ mrad}$
Detection of $D_s \rightarrow \tau \rightarrow X$ events (double-kink topology)

The analysis chain:
1) Tag $\tau \rightarrow X$ decay
2) Perform high precision measurement to detect $D_s \rightarrow \tau$ decay

$\tau$ decay can be easily detected by standard readout (mean kink angle $\sim$100 mrad)

Need high precision readout!

Flight length of $D_s$
Mean 3.3 mm

Kink angle of $D_s \rightarrow \tau$
Mean 7 mrad
Module structure for $D_s \rightarrow \tau \rightarrow X$ measurement

Proton beam (Z) $\rightarrow 10^5$ protons/cm$^2$ (uniform irradiation)

1 module

- Y 10 cm
- Z 5.9~8.6 cm
- X 12.5 cm

5~10 units (total 50~100 emulsion films)

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

Proton beam interacts with the modules:

- Tungsten plate (0.5mm)
- Emulsion film (50 \(\mu\)m thick emulsion layers on both sides of a 200 \(\mu\)m thick plastic base)
- Plastic sheet (200 \(\mu\)m)
Signal efficiency

**Selection**
(FL: Flight Length, Δθ: kink angle)

<table>
<thead>
<tr>
<th>Total efficiency</th>
<th>$D_s^+$</th>
<th>$D_s^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL($D_s$) &gt; 2 emulsion layers</td>
<td>78%</td>
<td>77%</td>
</tr>
<tr>
<td>(FL(τ) &gt; 2 layers &amp; Δθ($D_s$→τ) &gt; 2mrad) or (FL(τ) &gt; 1 layer &amp; Δθ($D_s$→τ) &gt; 15mrad)</td>
<td>44%</td>
<td>43%</td>
</tr>
<tr>
<td>FL($D_s$) &lt; 5mm &amp; FL(τ) &lt; 5mm</td>
<td>32%</td>
<td>31%</td>
</tr>
<tr>
<td>Δθ(τ) &gt; 15mrad</td>
<td>30%</td>
<td>28%</td>
</tr>
<tr>
<td>Pair charm: 0.1mm &lt; FL &lt; 5mm &amp; Δθ &gt; 15mrad</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>
For $x_F$ measurement:

$D_s$ momentum reconstruction from topological variables

- $x_F$ is a longitudinal profile of $D_s$: $x_F = 2p_z^{CM}/\sqrt{s} = 2\gamma(p_{D_s}^{Lab}\cos\theta_{D_s} - \beta E_{D_s}^{Lab})/ \sqrt{s}$
- $D_s$ decays quickly, unable to measure $P$ directly
- Need a method to estimate $P_{D_s}$ from topological variables
Topological variables: correlation with $P_{D_s}$

Sample: tau single prong decay
Ds momentum reconstruction by Artificial Neural Network (ANN) using 4 variables
Expected precision for the cross section measurement

<table>
<thead>
<tr>
<th>Systematic uncertainties</th>
<th>DONuT</th>
<th>With DsTau</th>
</tr>
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<td>$D_s$ differential cross section ($x_F$ dependence)</td>
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$\nu_T$ CC cross section measured by DONUT as a function of the parameter $n$

To reach $\sim10\%$ precision on the cross section, the parameter $n$ is to be measured with a precision of $\sim0.3$
Expected precision for the measurement of $x_F$ distribution

$x_F$ distribution (100000 events)

Fit of the yields to $(1-|x_F|)^n$
$n = 5.8$

$x_F$ distribution (1000 events) $\rightarrow$ parameter $n$
Repeat 100 experiments

Using reconstructed $x_F$

Precision of ~0.3 could be achieved with 1000 events
$x_F$ distributions of $D_s^{\pm}$: energy dependence

800 GeV beam

400 GeV beam

Fit of the yields to $(1-|x_F|)^n$

$n = 6.9$

$n = 5.8$

To re-evaluate DONUT result, need to extrapolate 400 GeV data to 800 GeV

The uncertainty is to be estimated
How many interactions to be analyzed?

• To detect 1000 $D_s \rightarrow \tau \rightarrow X$ events
  – Efficiency $\sim 20\%$, $BR(D_s \rightarrow \tau) = 5.55\%$
  – $8.2 \times 10^4$ $D_s$ to be produced

• $D_s$ production cross section in Tungsten target
  – $\sim 4 \times 10^{-4}$ @400GeV

• $\rightarrow 2 \times 10^8$ proton interactions to be analyzed!

↔ only $10^5$ proton interactions were analyzed in emulsions in E653 (previous emulsion hybrid experiment using high energy hadron beams)

$D_s \rightarrow \tau \rightarrow \mu$ candidate found in Fermilab E653
Target and detector

- In case of 10 units $\rightarrow 0.05 \lambda_{\text{int}}$ in tungsten $\rightarrow 4 \times 10^9$ pot needed to get $2 \times 10^8$ proton int.
- Track density in emulsion: keep $<10^5$ tracks/cm$^2$ at the upstream side
- To expose $4 \times 10^9$ pot $\rightarrow$ detector surface $4 \times 10^4$ cm$^2$ (400 modules)

5~10 units
(total 50~100 emulsion films)

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

Proton beam (Z) $\rightarrow$ 1 module
$10^5$ protons/cm$^2$
(uniform irradiation)

• In case of 10 units $\rightarrow 0.05 \lambda_{\text{int}}$ in tungsten $\rightarrow 4 \times 10^9$ pot needed to get $2 \times 10^8$ proton int.
• Track density in emulsion: keep $<10^5$ tracks/cm$^2$ at the upstream side
• To expose $4 \times 10^9$ pot $\rightarrow$ detector surface $4 \times 10^4$ cm$^2$ (400 modules)
The expected setup of the experiment

Needed beam time
- Assuming $10^5$ protons/spill and the beam spot 1 cm$^2$, detector surface $4 \times 10^4$ (cm$^2$) x 30 (sec/cm$^2$) = ~2 weeks.
- Module exchange time: 10 min x 400 modules = ~ half week.
Readout of emulsion data

New scanning system being developed in Nagoya, aiming at the speed of 9000 cm²/h (22 m²/day)

Another system dedicated to high precision measurements to be developed in Bern

<table>
<thead>
<tr>
<th>New experiment</th>
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<tbody>
<tr>
<td>Emulsion surface</td>
</tr>
<tr>
<td>Readout time</td>
</tr>
</tbody>
</table>
High precision measurement system

- Intrinsic resolution of each grain = 50 nm
  - Two grains on top and bottom of 200 μm base → 0.35 mrad
- Conventional systems spoil it due to mechanical vibration of Z axis (about 0.2μm, corresponding to 1.5 mrad)
- → Need high precision Z-axis
- Piezo objective scanner under testing → Z axis systematics to be kept below 60 μrad (0.06 mrad)
- By fitting a series of grains, the angular resolution would reach 0.2 mrad

- Angular alignment between films to be done by using dense 400 GeV proton tracks
  - 400 GeV proton scatters 2 μrad between emulsion trackers
  - $10^5$ tracks/cm$^2$ = 100 tracks in each microscope view
Prototype test experiment in 2016

• Proton beam test in Nov. 2016
  • 5 days of beam time at the H4 beam line
  • 20 m² emulsion surface (1:20 of the final setup)

• Aim
  • Test of tuning the beam size
  • Optimization of the setup
  • Proof of principle of the experiment
  • $x_F$ evaluation by $\sim30$ detected $D_s \rightarrow \tau$ events

Several conditions
• Track density study
  • $10^4$ / cm² x a few bricks
  • $10^5$ / cm² x $\sim10$ bricks
  • $10^6$ / cm² x a few bricks

• Longitudinal thickness
  • 5, 10, 20 units (50, 100, 200 films)
Preparation in progress

• Emulsion film production in Bern using the gel from Japan

• Target mover: XY stage and control

• Beam profile monitor with silicon pixel sensors (~4cmx4cm)
Film production in Bern

Total 20 m² double-side coated films (1600 small-size films)
Plan: 0.15 m² / table x 9 pouring tables x 4 production batches / day

Pour emulsion gel on plastic sheet
(60 cm x 25 cm = 1500 cm² per table)

8 more tables are being installed

Maximum speed of 10 m² per week will be achieved with this system
Target mover: XY stage and control

Move the modules w.r.t. the beam for uniform irradiation with a density of $10^5$/cm$^2$

Timing chart

<table>
<thead>
<tr>
<th>SPS WVE</th>
<th>1 sec before FT, TTL positive, 2μs width</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS WE</td>
<td>1 msec before FT</td>
</tr>
<tr>
<td>SPS EE</td>
<td>after FT</td>
</tr>
<tr>
<td>Beam (Flat Top)</td>
<td>$t_{FT} = 4.8s$</td>
</tr>
<tr>
<td>Motor control</td>
<td>$t_{delay}$ $\rightarrow$ Start move $\rightarrow$ Stop stage</td>
</tr>
<tr>
<td>Motor speed</td>
<td>$v = \frac{dx}{t_{FT}}$</td>
</tr>
<tr>
<td>Motor pos</td>
<td>$dx = 1cm$</td>
</tr>
</tbody>
</table>

Moving test
Timetable of the whole project

- 2016
  - Lol to the SPSC
  - Proposal
  - Detector production
  - Beam test
  - R&D of high precision readout

- 2017
  - Readout of emulsion data and analysis

- 2018
  - Proton run1

- 2019
  - (SPS shutdown)

- 2020
  - Feedback
  - Proton run2

- 2021
  -Publication of the results

- 2022
Summary and prospects

• $\nu_\tau$ CC cross section measurement could be a test of lepton universality
  • $\nu_\tau$ cross section measurement have been reported only by DONUT
  • The DONUT results suffer from large systematic error (>50%), not only statistical error (30%)
  • The main systematic error is how $D_s$ were produced at beam source

DsTau project

• $D_s \rightarrow \tau \rightarrow X$ precision measurement in high energy proton interactions is essential input toward precise evaluation of $\nu_\tau$ cross section
• $2 \times 10^8$ proton interactions are to be obtained to analyze $1000 D_s \rightarrow \tau \rightarrow X$ events

• Prototype test experiment in Nov. 2016
• Aiming to realize the experiment hopefully in 2018 before the SPS shutdown