Study of tau neutrino production with nuclear emulsion at CERN-SPS

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for the DsTau Collaboration
Tau neutrino cross section measurement - concept -

- **ντ production study: DsTau**
  - No data of Ds differential production cross-section
  - Larger ~50% uncertainty of ντ flux

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**ντ source:** $D_s \rightarrow \tau \rightarrow X$

**ντ production target (tungsten)**

- Proton beam
- Neutron Absorber
- Rejection of Charged tracks

**ντ beam**

- **ντ detector**

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**ντ detection:** SHiP etc.

- 9 ντ detected by DONuT (bam ντ). 33% statistical error
- 10 ντ detected by OPERA (Oscillated ντ)
- SHiP ~ 10000 events a few % statistical error
1. Precise understanding of $\nu_\tau$ production flux

Measurement of differential production cross section of Ds.

Using a specific decay topology :: Ds-$\tau$-X (double kink) decay.

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

$x_F$ : Longitudinal momentum (Pl) / Pl_max
$Pt$ : Transverse momentum

Ds-$\tau$ decay angle is small as average 7mrad in flight length a few mm.
Using Sub micron spatial resolution 3D tracker :: Nuclear emulsion tracker.

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**Small kink decay angle (7mrad)**

Ds $\rightarrow$ $\tau$ kink decay

Proton $\rightarrow$ Ds $\rightarrow$ $\tau$ $\rightarrow$ X

$400\text{GeV/c}$

Decay Angles (2), Flight length (2) $\rightarrow$ Ds momentum

$\Delta p/p = 20\%$
DsTau Experiment (CERN NA65) Physic motivations

1. Precise understanding of $\nu_\tau$ production flux (cont.)

Reduction of $\nu_\tau$ nucleon cross section uncertainty 50% → 10%.
For re-evaluation with updated $\nu_\tau$ flux for DONUT
For input for future experiment SHiP $\nu_\tau$ program etc.

The detected 1000 $\text{Ds} \rightarrow \text{tau} \rightarrow X$ events for the uncertainty reduction
A total of $2 \times 10^8$ proton interactions will be analyzed to hand detected 1000 $\text{Ds} \rightarrow \text{tau} \rightarrow X$.

2. Understanding of charm production

Several $10^5$ events having pair charms among proton interaction products.
The angle ($\theta$, $\phi$) correlation of the pair charm particles for event by event, etc.
$X_F$ distribution for Charged and Neutral charm respectively.
Analysis about Charms produce into Forward direction :: intrinsic charms (valence quark like c) exist etc.
into “Backward direction (soft Charm production region)”

3. Understanding of proton interaction

Plenty of proton interactions.
Interaction with several Materials (Tungsten, Molybdenum, Nuclear Emulsion, Plastic).
Charged track’s angle (rapidity) and momentum distributions.
Nuclear Emulsion detector: 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

10 GeV/c $\pi$ beam

Sensitivity 36 grains/100 μm

Residual from fitted track

$\sigma = 50$ nm

→ Angular resolution 0.35 mrad with 200 μm base

NuFact2021
DsTau loadmap

Test beam 2016
• Test of the detector structure

Test beam 2017
• Improved detector structure
• Refine exposure scheme

Pilot run 2018
• 1/10 of the full-scale experiment with tungsten target.
• $\nu_\tau$ flux ~30% uncertainty
• Revise the DONUT result
• Charm physics

Physics run 2021-2022
• Full scale experiment with tungsten and molybdenum targets
• Aiming detect 1000 $D_s \rightarrow \tau \rightarrow X$ events
• $\nu_\tau$ flux~10%

Pilot run 2018 Aug. @H2
Accumulated $\sim 1.8 \cdot 10^7$ interactions

Film Production
Detector assembling
30 modules exposed.

Approved as NA65
The detector structure (~400 modules)

2.3x10^8 Proton-tungsten interactions (4.6x10^9 POT)

400 GeV/c Proton beam

10 Unit
(A total 100 nuclear emulsion films)

Momentum analyzer ECC
(1mm Lead plate and 26 nuclear emulsion)

400 GeV/c Proton beam

Target Decaying Volume & Tracking detector

Proton beam

Ds ντ
ντ

D^+
X
X'

Plastic sheet (200 μm)
Nuclear emulsion film (320 μm)
Tungsten target (0.5 mm)

Profile monitor
2 cm x 2 cm

Detector module
10 cm x 10 cm x 8.6 cm

Scintillation counter
10 cm x 10 cm

Real-time feedback

Uniform irradiation on detector surface x,y
Tracks readout from Nuclear emulsion & Analysis.

Nuclear emulsion prior treatment for scanning.
Surface cleaning, Thickness control.
400-800 films/month

1. **Full surface scanning**
   - ~300 films/month
   - ~700 films/month (with night shifts)

2. **Ds -> τ search**
   - Precise measurement for Small angle kink (~7 mrad)

**Track readout speed 0.5 m²/h/面**
**Angle resolution ~2 mrad**

**Hyper Track Selector (HTS)**

**Dedicated microscopes**
Angular resolution ~0.3 mrad

![Image of experimental setup](image_url)
Proton-target nucleus interaction

Interaction density per a tungsten plate ~500/cm

Multiplicty distribution of several materials
Angular distributions of proton interaction

- General distribution agrees with the FLUKA prediction.
- A deficit of forward angle (<20 mrad or $\eta > 4.6$) is observed.
- Comparisons between other generators are ongoing.
Example of an event with Charm Pair cand. Kink(Charged one prong) + Vee(Neutral two prongs)

\[ \langle IP^{1\text{ry}} \rangle = 1.6 \, \mu m \]
\[ FL_{\text{kink}} = 3.32 \, \text{mm} \]
\[ IP_{\text{kink daughter}}^{1\text{ry}} = 174 \, \mu m \]
\[ FL_{\text{vee}} = 2.20 \, \text{mm} \]
\[ \theta_{\text{opening}} = 0.132 \, \text{rad} \]

Coplanarity of vee = 15.2 mrad

→ more than two bodies decay
Search for events associating a charm pair

- **3.4253301 x 10^7** injected protons (2% of Pilot run) were analyzed
- **2.72120 x 10^5** proton interactions (1.47236 x 10^5 tungsten int) detected
- 159 (115 tungsten int) events with charm pair
- Currently increasing statistics (next page) with tuning selection parameters.
- About to start to small angle kink search.

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertices in tungsten</td>
<td>147,236</td>
<td>155,135</td>
</tr>
<tr>
<td>Double decay topology</td>
<td>115</td>
<td>80.1±19.2</td>
</tr>
</tbody>
</table>

Flight length of Charged Charm cand.

![Charged 1 prong](image1)

Flight length of Neutral Charm cand.

![Neutral 2 prongs](image2)
Updating the analysis statistics

Currently mass processing for event vertexing, decay search is performing. So far **18 times** sample compared to previous page were processed. Semi-automatically done up to selection of events with double decay vertices.

The **dedicated charm decay validation** will be done.

- **Event Display checks**
  - rejection of secondary interaction by checking additional track existence.
- **Kinematical analysis**
  - Momentum of decay daughters will be measured by angle difference between materials by Multiple Coulomb Scattering.
  - Rejection of single scattering due to low momentum.
  - Cut secondary interactions by decay transverse momentum (<100 MeV/c) to be tuned.

<table>
<thead>
<tr>
<th>Analyzed sample/ 2018 pilot run</th>
<th>22.2%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons on tungsten plates</td>
<td>486,137,516</td>
</tr>
<tr>
<td>Vertices in tungsten plate</td>
<td>2,653,846</td>
</tr>
<tr>
<td>Double decay vertex candidates</td>
<td>17,574</td>
</tr>
</tbody>
</table>

To be **dedicate checked**
Some small angle kink detection

- We started small kink hunting for already observed two decay topology events.
- The parent track making “Large kink” is checked whether small kink is hidden in the series of track segments formed the parent track or not.
- After tuning parameters for cuts, mass checks will be come soon.
Schedule

Physics run (NA65) in 2021 -2022

2016 test beam exposure
• Test for detector structure

2017 test beam exposure
• Improvement of detector structure
• Improvement beam exposure scheme

2018 Pilot run
• 1/10 accumulation events scale
• $\nu_\tau$ flux $\sim$ 30% uncertainty
• DONUT update $\nu_\tau$ cross section

2021-2022 Physics run
• 1000 detected $D_s \rightarrow \tau \rightarrow X \nu_\tau$
• $\nu_\tau$ flux uncertainty $\sim$ 10%

- Two weeks beam per year
- Beam time 2021 Sep22 to Oct06.
- Smaller size than original schedule due to COVID19.

Pilot run 2018
30 (=1) 49

Physics run 2021
150 (x5) 246 $\rightarrow$ 100

Physics run 2022
190 (x6.3) 312 $\rightarrow$ 458

DsTau goal

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

longitudinal dependence
transverse dependence

2021/Sep/08  NuFact2021
The **DsTau** aims to study $\text{Ds} \rightarrow \tau \rightarrow X$ differential production cross section at $400 \text{ GeV/c}$ p-tungsten int.

- Nuclear emulsion tracker for $\text{Ds} \rightarrow \tau$ small kink ($\sim 7\text{ mrad}$) detection in short range ($\sim \text{mm}$).

- A total of $2 \times 10^8$ proton-tungsten interactions will be analyzed.
- Detecting $\sim 1000$ $\text{Ds} \rightarrow \tau \rightarrow \text{decays}$ will reduce uncertainty on $\nu\tau$ flux to 10%.
- During the main analysis $\sim 10^5$ Charm pair associating proton interaction will be collected and Properties of Charm pair production will be studied in detail.
- **Proton interaction with right (CH), medium (Ag,Br), heavy (W, Mo) nucleus**, can be studied in detail.

**The 2018 pilot run analysis**

The mass processing is running and about 22% of fiducial volume were done so far.

$2.65 \times 10^6$ p-tungsten int. collected, dedicated analysis will be done for double decay topology candidates.

Small angle ($\text{Ds} \rightarrow \tau$ decay) hunting is about to start after tuning selection parameters.

**The 2021 physics run**

CERN SPS 400 Gev Proton beam exposure very soon, **beam time Sep22 to Oct06**.
Backup
Facility construction was completed at the end of 2020. Production test is ongoing.
New Scanning system @Nagoya University: HTS2

- Larger working area: 30cm x 40cm
- Larger FOV: 9.33 x 5.25 mm²
- Continuous scanning (not stop & go)

→ Total film area of 2021, 2022 physics run is 11 times that of 2018 Pilot run.
And 2018 Pilot run films scanning was done in 17 months.
So about 1 year to readout for each physics run films using HTS2.
Target mover prepared for Physics run

We changed detector area size 12.5x10cm² → 25x 20cm² to scan emulsion film quickly.

Target mover used for other exp (J-PARC E07) is tuned for DsTau beam exposure.

Shipped from Japan to CERN
Intrinsic (valence quark like) charm ??

Two cases could be considered and both cases can be analyzed in DsTau.

1) Intrinsic Charm in beam proton.
   The Charm became forward going high energy.

2) Intrinsic Charm in target nucleon.
   It would be a soft Charmed hadron.
   Could it be captured in the target nucleus (ie. Charmed Hyper Nucleus) ?
Tau neutrino interaction cross section

The property of $\nu_\tau$ is least known among active neutrinos. Is the lepton flavor universality kept also neutrinos? Large error on $\nu_\tau$ cross section measurement so far. New physics effect could be hidden in the error. Also for input for future neutrino oscillation analysis or cosmic neutrinos.

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

longitudinal dependence\[ \text{transverse dependence} \]

Figure 1: $\nu_\tau$ CC charm production

Figure 2: B meson’s Tau leptonic day

\( \nu_\tau \) Anomaly??

\( B \) Anomaly?
**Signal and background rates**

- **Signal**: $D_s \rightarrow \tau \rightarrow X$ events (double-kink + another decay topology within a few mm)
- **Signal rate**: $2.2 \times 10^{-5} \text{ /proton int. } \times \text{ eff. } 20\%$
- To detect 1000 $D_s \rightarrow \tau \rightarrow X$ 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): $1.4 \times 10^{-9} \text{ /proton int.}$
  - Combination with decays is to be studied

- **Validation from real data is planned with the 2018 data**
## 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

![Efficiency](image1)

### Yield

![Yield](image2)
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>$t_{delay}$</td>
</tr>
<tr>
<td>Motor speed</td>
<td>$v = \frac{dx}{t_{FT}}$</td>
</tr>
<tr>
<td>Motor pos</td>
<td>$dx = 1\text{cm}$</td>
</tr>
</tbody>
</table>

Remote control via network

Stage

Moving test
Realizing Ideal Alignment :: with plenty of 400GeV/c protons

- High beam proton track density \( \sim 10^5 \) /cm²
- 400 GeV/c proton :: \( \sim \text{No MCS scattering} \)!
- Processing in sub-volumes
  - e.g. 1.5 cm x 1.5 cm x 30 films
- Alignment with proton beam tracks
  - Alignment accuracy better than 0.4 \( \mu m \)

Align films with proton tracks, 100 tracks/mm²

Residual of track segments to fitted line (RMS) \( \simeq 0.4 \mu m \)

30 films
(two tungsten plates to reject low momentum daughter candidates)

2021/Sep/08

NuFact2021
Track reconstruction, track density (Data/MC), tracking efficiency

Tracks 1 mm x 1 mm

Track density increase toward downstream due to interaction products. The MC reproduce the behavior.

More than 95% efficiency even high track density, downstream plates
High precision measurement of track angles

- Intrinsic resolution of each grain = 50 nm
  - Two grains on top and bottom of 200 μm base → 0.35 mrad
  - Discrimination of 2 mrad at 4σ 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
Momentum measurement

- Using 5 plates, an angle (AX,AY) was calculated.
  1. Averaged angle by 5 plates.
  2. Angle formed by position connected by first and last segment.
- Then angle difference before i-th tungsten and after j-th tungsten was calculated and take RMS for sample (j-i) cell length.
- For zero cell length conjunction angle not crossing tungsten plate are used.
- Momentum yet estimated but looking RMS vs. Cell length in next slides.
  (Comment the estimated momentum by eye 1GeV/c / (rms(1Cell) / 5mrad))

Cell length=1
Angular difference of continuous two angles at Cell length=0: Accuracy of the measurement

- Angle made by: 3D positions of Pl#(n) and pl#(n+4)
- Lever arm Length dZ~2mm, Corresponds to “base” thickness 2mm

\[ \sigma \sim 0.45\text{mrad} \]

\[ \sigma \sim 0.42\text{mrad} \]

Tail would be made by low momentum
MCS Momentum measurement quality

Momentum by X and Y make linear correlation Up to ~30 GeV/c

Momentum resolution \( \frac{dP}{P} \sim 15\text{-}25\% \) up to 30 GeV/c