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 -

Proton beam

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

$D_\tau$ production

$\nu_\tau$ production study: DsTau

- No data of Ds differential production cross-section
- Larger $\sim 50\%$ uncertainty of $\nu_\tau$ flux

Rejection of Charged tracks

Neutron Absorber

$\nu_\tau$ beam

$\nu_\tau$ detector

$D_\tau$ source: $D_s \rightarrow \tau \rightarrow X$

$\nu_\tau$ detection: SHiP etc.

- 9 $\nu_\tau$ detected by DONuT (bam $\nu_\tau$). 33% statistical error
- 10 $\nu_\tau$ detected by OPERA (Oscillated $\nu_\tau$)
- SHiP $\sim 10000$ events a few % statistical error
DsTau Experiment (CERN NA65) Physic motivations

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.

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

$x_F$: 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.

Decay Angles (2), Flight length (2) -> 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 $50\% \rightarrow 10\%$.
   For re-evaluation with updated $\nu_\tau$ flux for DONUT
   For input for future experiment SHiP $\nu_\tau$ program etc.

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

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 π beam
Sensitivity 36 grains/100 μm

Residual from fitted track
σ = 50 nm
→ Angular resolution 0.35 mrad
with 200 μm base
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 $\sim$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 $\sim$10%

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

Approved as NA65

Film Production
Detector assembling
30 modules exposed.
The detector structure (~400 modules)

$2.3 \times 10^8$ Proton-tungsten interactions (4.6x$10^9$ POT)

400 GeV/c Proton beam

10 Unit (A total 100 nuclear emulsion films)

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

Target

Decaying Volume & Tracking detector

Proton beam

Ds $\nu$ X $\nu$ D$^+$ 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.

Total ~4000 films

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)

Hyper Track Selector (HTS)

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

Dedicated microscopes
Angular resolution ~0.3 mrad

Proton Beam
Ds
D^+
ντ
τ
X
X'

Objective lens
Illuminator
Stage
Camera

Computers
Proton-target nucleus interaction

Interaction density per a tungsten plate
~500/cm

Multiplicity distribution of composed 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)

\[ \begin{align*}
\langle IP^{1\text{ry}} \rangle &= 1.6 \text{ \( \mu \)m} \\
FL_{\text{kink}} &= 3.32 \text{ mm} \\
IP_{kink \text{ daughter}}^{1\text{ry}} &= 174 \text{ \( \mu \)m} \\
FL_{\text{vee}} &= 2.20 \text{ mm} \\
\theta_{\text{opening, vee}} &= 0.132 \text{ rad} \\
\text{Coplanarity of vee} &= 15.2 \text{ mrad} \\
\rightarrow & \quad \text{more than two bodies decay}
\end{align*} \]
Search for events associating a charm pair

- $3.4253301 \times 10^7$ injected protons (2% of Pilot run) were analyzed
- $2.72120 \times 10^5$ proton interactions ($1.47236 \times 10^5$ tungsten int) detected
- 159 (115 tungsten int) events with charm pair
- Increasing statistics now.
- 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>$80.1\pm19.2$ &amp; $12.7\pm5.0$</td>
</tr>
</tbody>
</table>

Flight length of Charged Charm cand.  
Flight length of Neutral Charm cand.
Schedule
Physics run (NA65) in 2021-2022

- Two weeks beam per year
- 2021 Oct. smaller size than original schedule due to COVID19.

<table>
<thead>
<tr>
<th></th>
<th>detector modules</th>
<th>Nuclear emulsion (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot run 2018</td>
<td>30 (≈1)</td>
<td>49</td>
</tr>
<tr>
<td>Physics run 2021</td>
<td>150 (x5)</td>
<td>246 → 100</td>
</tr>
<tr>
<td>Physics run 2022</td>
<td>190 (x6.3)</td>
<td>312 → 458</td>
</tr>
</tbody>
</table>

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 $D_s \rightarrow \tau \rightarrow X$
- $\nu_\tau$ flux
- $\nu_\tau$ flux uncertainty $\sim$ 10%

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

- longitudinal dependence
- transverse dependence

DsTau goal

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- Test for detector structure

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DsTau goal
Summary

- The **DsTau** experiment aims to study $D_s \rightarrow \tau \rightarrow X$ differential production cross section at **400 GeV/c proton**- tungsten interactions. **Pilot run 2018, Physics run 2021,2022**.

- **Nuclear emulsion tracker** provides ideal two track separation in **3D** and alignment accuracy $\sim 0.4\mu m$.

- The **angular resolution** better than $0.5\text{mrad}$ depending on lever arm. **Large angular acceptance**, (standard analysis $\tan \theta < 0.5$, dedicated analysis $\tan \theta < 1$ or more).

- **Charged track's momentum** will be measured by multiple coulomb scattering (tungsten, lead), up to $\sim 30\text{ GeV/c}$ with several 10% accuracy which covering main part of momentum region of the tracks.

- A total of $2 \times 10^8$ proton-tungsten interactions will be analyzed to found $\sim 1000 \text{ Ds->tau->decays}$.

- During the main analysis $\sim 10^5$ Charm pair associating proton interaction will be collected.

- **Properties of Charm pair production** will be studied in detail. Would be feedback to MC generators.
  - **Charm particle correlation** of the pairs.
    - Valence quark like charm particle, **Intrinsic Charm** production in **forward direction** test?

- **Proton interaction with right (CH), medium (Ag,Br), heavy (W, Mo) nucleus, properties**
  - Comparison with MC generators, **understanding** especially tracks produced in **Forward direction**.
Backup
Intrinsic (valence quark like) charm??

Two case 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.

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

\( x_F \) dependence \( \nu_\tau \) CC charm production

\( b \) dependence \( \nu_\tau \) Anomaly??

\( \nu_\tau \) B meson’s Tau leptonic day
Signal and background rates

- **Signal**: $D_s \rightarrow \tau \rightarrow X$ events (double-kink + another decay topology within a few mm)
- **Signal rate**: $2.2 \times 10^{-5}$ /proton int. x 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 π 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**
## Efficiency of Ds $\rightarrow \tau \rightarrow X$ 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</td>
<td>20</td>
</tr>
</tbody>
</table>

*charged decays with $\Delta\theta > 15$ mrad or neutral decays*
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>Component</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS WVE</td>
<td>1 sec before FT, TTL positive, 2μs width</td>
</tr>
<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>$t_{FT} = 4.8 s$</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>$dx = 1 cm$</td>
</tr>
</tbody>
</table>

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

- **High beam proton track density** $\sim 10^5$/cm²
- 400 GeV/c proton :: *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) $\approx 0.4 \mu$m
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.

Tracks from tungsten target

More than 95% efficiency even high track density, downstream plates

2020/09/14
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

![Graphs showing position and angular reproducibility](image)

- 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))
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

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

\[ \sigma \approx 0.42 \text{mrad} \]
MCS Momentum measurement quality

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

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