Status of DsTau data taking and analysis

On behalf of the DsTau Collaboration

400 GeV proton

500 µm

kink

neutral decay

primary vertex

On behalf of the DsTau Collaboration
DsTau: Physics motivations

- **Tau neutrino** is the least known particle of the Standard Model.
  - $\nu_\tau$ beam: DONuT
  - Oscillated $\nu_\tau$: OPERA, Super-K, IceCube
  - $\nu_\tau$ cross section error $>50\%$ (DIS) due to systematic uncertainty in $\nu_\tau$ production (DONuT)

- **Measurement of $\nu_\tau$ production**
  - Reduce uncertainty of $\nu_\tau$ flux from $>50\%$ to $10\%<$
  - Fundamental input for future $\nu_\tau$ experiments: SHiP, DUNE, Hyper-K

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- $\nu_\tau$ averaged energy independent cross section

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

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

- No experimental data giving $n$ for $D_s$
DsTau: Physics motivations

- First Measurement of Ds differential cross section
- Forward charm physics
  - Large theoretical uncertainty for forward charm production.
  - *Intrinsic charm* content of proton can effect $\nu_\tau$ flux drastically, by enhancing charm production in forward direction, $\nu_\tau$ flux may change by a factor of 10
  - Neutrino experiments need data on the forward charm production

SHiP case (400 GeV p-N) interaction

![Graph showing differential cross section for Ds production](image1)

FASER case (7-7 TeV)

![Graph showing interacting neutrinos](image2)

JHEP02(2019)077

arXiv:2105.08270
DsTau: Unique signature

- Double charm hadron production
- Double kink topology

400 GeV proton

4.6 \times 10^9 \text{ protons}, 2.3 \times 10^8 \text{ proton interactions in target (tungsten & molybdenum),}

\sim 10^5 \text{ charm pairs} & \sim 10^3 \, D_s \rightarrow \tau \rightarrow X \text{ decays can be detected.}
Emulsion detectors

3D tracking device with highest position resolution

Emulsion film

Cross-sectional view

AgBr crystal

$10^{14}$ crystals in a film

Plastic base 210 $\mu$m

Emulsion layer 70 $\mu$m

Emulsion layer 70 $\mu$m

200 $\mu$m

Residual from fitted track $\sigma = 50$ nm

Angular resolution 0.35 mrad

10 GeV/c $\pi$ beam

Sensitivity 36 grains/100 $\mu$m

20 $\mu$m

Graph showing residuals vs. grains/20 nm
Concept of $D_s \to \tau \to X$ detection

10 units (total 100 emulsion films)

Momentum measured by MCS. (26 emulsion films interleaved with 1 mm thick lead plates)

Tungsten / molybdenum

(0.5mm) 1 unit

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

Emulsion film Plastic sheet (200 μm)

Proton beam

Real-time feedback

Target mover

1 m
Change of structure for momentum measurement

-2018
10 units
(total 100 emulsion films)
ECC for momentum measurement
(26 emulsion films interleaved with
1 mm thick lead plates)

Proton

2021-
10 units
(total 100 emulsion films)

Momentum analyzer for events at
downmost tungsten plates:
3 tungsten plates and 25 emulsion plates

- Original structure had more material → too high track density in ECC
  - Dedicated scanning is required
- Reduce material, but sufficient performance
- Making data taking procedure simple

<table>
<thead>
<tr>
<th></th>
<th>Original: lead emulsion ECC</th>
<th>New: additional tungsten units</th>
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</thead>
<tbody>
<tr>
<td>Structure</td>
<td>25 1mm lead, 26 emulsion plates</td>
<td>3 0.5mm tungsten, 25 emulsion plates</td>
</tr>
<tr>
<td>Momentum resolution</td>
<td>20 - 40% (upstream ev.)</td>
<td>15 - 40% (upstream ev.)</td>
</tr>
<tr>
<td></td>
<td>20 - 40% (downstream ev.)</td>
<td>35 - 45% (downstream ev.)</td>
</tr>
<tr>
<td>Weight</td>
<td>15.0 kg</td>
<td>2.4 kg</td>
</tr>
</tbody>
</table>
1. High speed scanning of full area to select $\tau \rightarrow X + \text{partner-charm}$ decays ($\Delta \theta \sim 100$ mrad)

**Angular resolution $\sim 2$ mrad**

2. Precision measurement to detect $D_s \rightarrow \tau$ decay (a few mrad)

**Angular resolution $\sim 0.3$ mrad**

Scanning speed of 9000 cm$^2$/h (22 m$^2$/day)
Data reconstruction

- The automatic scanning systems read out the track information accumulated in the emulsion film during the exposure, digitize it and transfer to the computers for the pattern recognition and tracking/vertexing.

Processing in subvolumes 1.5 cm x 1.5 cm x 30 plates

- Alignment with proton beam tracks, 100 tracks/mm².
- Residual of track segments to fitted line (RMS) ≃ 0.4 μm

- Fluka, \( N_p \geq 11, P \geq 0.3 \text{ GeV/c} \)
- Data, \( N_p \geq 11 \)

Track finding efficiency in a single film 94%-98%
Data processing

- Film to film alignment and track reconstruction procedures require powerful processing servers with CPU/GPU and high memory (~128-256~GB of RAM) and disk space (~10~TB for each data module) resources.
- Distributed data processing is being done gradually. Up to now, 25 out of 30 modules in 2018 run have been fully processed (track reconstruction).

Japan (Nagoya/Kyushu):
- 2 processing servers
- CPU, GPU, 256 GB of RAM
- Storage capacity: ~150 TB (+2 in Chiba in near future)

Russia (JINR):
- 2 processing servers
- CPU, GPU, 256 GB of RAM
- Storage capacity: ~150 TB

Romania (ISS):
- 1 processing server
- CPU, GPU, 128 GB of RAM
- Storage capacity: ~40 TB

Turkey (METU):
- TRUBA computing center resources
- CPU, GPU, 128 GB of RAM
- Storage capacity: 100+ TB

- Batch system of the CERN computing center is also going to be used to process the 2021 physics run data.
Reconstructed double vertex

- **Kink**
  - IP of daughter 291.6 \( \mu m \)
  - FL 2536.6 \( \mu m \)
  - Kink angle 118 mrad

- **Vee**
  - IP of daughters 20.9, 109.7 \( \mu m \)
  - FL 554.5 \( \mu m \)
  - Opening angle 242 mrad

~4000 tracks in 2 x 2 mm\(^2\), 15 films

1000 \( \mu m \)

200 \( \mu m \)
Study of Proton interaction with tungsten

- Proton interaction vertices location by fine alignment on the material boundaries.
- Secondary tracks multiplicity distribution by each detector components.
- The results will be summarized into a paper soon.
Study of Proton interaction with tungsten

- 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.
Originally, it was planned to use >200 m² of emulsion but due to Covid19, the emulsion production is slowed down in Japan. The number of detector modules is reduced to 110 m² (≈2200 films).

Updates
- Films size was changed from 12.5 cm x 10 cm → 25 cm x 20 cm
DsTau 2021 run

- New target mover

- XDWC for beam profile monitor
- Scintillator(s) to feedback beam intensity in real-time

- Development facility, a full renovation by CERN is underway

@ building 169
DsTau 2021 run

- 17 modules were exposed
  - 12 tungsten and 5 molybdenum targets
    → about 30% of total (including 2018 run)
- All films were developed & scanning started

track density uniformity

\[
\text{mean} \approx 2.4 \times 10^5 \text{ /cm}^2 \\
\sigma \approx 7.97 \times 10^3 \text{ /cm}^2 \\
\frac{\sigma}{\text{mean}} \approx 0.038
\]
Plan for 2022, 2023 runs

- Emulsion film production
  - Limited amount of emulsion, ~100 m²
    - Shortened beam time (1 week) was requested

<table>
<thead>
<tr>
<th></th>
<th>Plan 2021</th>
<th>Updated plan 2022</th>
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<tbody>
<tr>
<td>Pilot run</td>
<td>50 m²</td>
<td>50 m² (1w)</td>
</tr>
<tr>
<td>2021 run</td>
<td>100 m²</td>
<td>110 m² (2w)</td>
</tr>
<tr>
<td>2022 run</td>
<td>450 m²</td>
<td>110 m² (1w)</td>
</tr>
<tr>
<td>2023 run</td>
<td>0 m²</td>
<td>330 m² (3w)</td>
</tr>
</tbody>
</table>

- Need of an additional data taking in 2023 for 3 weeks
- 2022 run is scheduled between 12–19 October @ H4
Summary

- DsTau 2021 data taking campaign was successfully finished
  - 30% of planned exposure was done
- Emulsion data readout, reconstruction and analysis are going on smoothly.
- The first physics results will be published soon.
- 2022 run is rescaled due to COVID19
  - Data taking extended one year.
Momentum reconstruction

- Momentum measurement is important to discriminate charm decays from background.
- Algorithm has been implemented and tested.
- Systematic application still needs a reorganization of data access over different data sets and alignment between them → Work in progress.
High precision measurement of track angles

- Intrinsic resolution of each grain = 50 nm
- Two grains on top and bottom of 200 mm 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
Signal: a double kink + a charmed particle decay

- Signal rate: $2.2 \times 10^{-7}$/proton int

Main background: hadron interactions

$$P_{BG}^{charged} = 1.3 \pm 0.4 \times 10^{-9}/\text{proton}$$

$$P_{BG}^{neutral} = 2.7 \pm 0.8 \times 10^{-9}/\text{proton}$$
$D_s$ momentum reconstruction

- Difficult to measure $D_s$ momentum directly due to short lifetime
- Reconstruct the momentum using Artificial Neural Network (ANN) with 4 variables

MC with 400 GeV beam

$\Delta p/p = 18\%$
# Efficiency of $D_s$ detection

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>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>

![Diagram showing the process of detecting $D_s$ particles](image)
Search for double charm events in pilot data

- Emulsion readout was completed & data reconstruction is going on.
- $3.4253301 \times 10^7$ 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

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Signal</td>
</tr>
<tr>
<td>Double Decay</td>
<td>115</td>
<td>80.1±19.2</td>
</tr>
<tr>
<td>Topology</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$JHEP$ 01 (2020) 033
$\nu_\tau$ cross section measurement by oscillated neutrinos

**SK**

Atmospheric

\[ \nu_\mu \rightarrow \nu_\tau \quad \text{and} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\tau \]

\[ \sigma_{\text{meas}} = (1.47 \pm 0.32) \sigma_{\text{theory}} \]

**OPERA**

CNGB $\nu_\mu$ beam

$\nu_\mu \rightarrow \nu_\tau$

$\sigma$ with a Pb nucleus

\[ \langle \sigma \rangle_{\text{meas}} = (5.1^{+2.4}_{-2.0}) \times 10^{-36} \text{ cm}^2 \]

\[ \langle \sigma \rangle_{\text{meas}} = (1.2^{+0.6}_{-0.5}) \langle \sigma_G \rangle \]

\[ \text{arXiv:1711.09436} \]

Presented 1st day by Guillaume Pronost