The reconstruction of the primary proton vertices in the DsTau(NA65) experiment

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30 October 2023
1. Physics Motivation

2. DsTau experimental technique

3. Reconstruction of the primary vertices
Physics Motivation of DsTau experiment

1. Evaluation of $\nu_\tau$ flux produced in p-nucleus interactions
   
   • The $\nu_\tau$ interaction cross-section is known with worse accuracy than for other neutrinos, due to low statistics of registered tau neutrinos and large systematic errors in tau neutrino flux estimation for the beams
   
   • $D_s \rightarrow \tau + \nu_\tau$ is the main source of $\nu_\tau$ in the accelerator neutrino beams
   
   • DsTau will measure the Ds double-differential production cross-section (inclusively decaying to $\tau$ and $\nu_\tau$) in proton-nuclei interaction

![Graphs showing averaged energy independent cross section of all neutrino flavors and $\nu_\tau$ cross section in DONuT experiment as a function of the parameter n.]

Left: $\nu, \bar{\nu}$ averaged energy independent cross section of all neutrino flavors. Right: $\nu_\tau$ cross section in DONuT experiment, as a function of the parameter $n$.

2. Study of charm production in proton-nucleus interactions
   
   • expected $10^5$ events having paired charms
DsTau experimental technique

400 GeV protons interacting on W/Mo targets → $D_s$

Double-kink topology of $D_s \rightarrow \tau \rightarrow X$ events

Decay candidates are selected by the peculiar double kink topology of the reaction

- Average kink angle of $D_s - \tau \sim 10$ mrad (G4)
- Average kink angle of $\tau$ decay $\sim 96$ mrad
- $D_s$ decay length (mean lifetime: $5 \times 10^{-13}$ s) $\sim 2.4$ mm (G4, Fluka)
- $\tau$ decay length (mean lifetime: $3 \times 10^{-13}$ s) $\sim 1.4$ mm (G4)

→ very challenging! → high resolution tracking emulsion detectors
Nuclear emulsion detector in DsTau

left: DsTau emulsion plate with 2 emulsion layers on a plastic base; right: electron microscope view of the AgBr crystals (diameter of 200 nm) and traces under the microscope

- intrinsic angular resolution 0.35 mrad, spatial resolution 0.4 \( \mu m \)
- **high density of tracks**
  \( 10^5 - 10^6 \text{ tracks/cm}^2 \)

Hyper Track Selector (HTS)

- automatic procedure
- scanning speed 0.5\( m^2/\text{hour/layer} \)
- angular resolution 2mrad

After scanning, the information about the tracks is in digital format
Films development

→ several chemical processes similar with photographic plate development
Experimental set-up - at SPS (CERN)

Structure of detector modules (not in scale)

530 m² high accuracy emulsion films on plastic bases

beam monitor + target mover → uniform exposure

3 × 10^5 protons/cm²

fluctuations 1.9±0.3%

Data taking - completed
The analysis chain

**Emulsion read-out:**
1. Films development → will finish this week
   - make the particle tracks visible for microscope
2. Automatic scanning with HTS → in progress
   - digital microtracks (the part of the track left in each emulsion layer)
   - microtracks are combined → basetracks

**Offline dedicated software for the reconstruction of events:**
3. Basetracks are combined in tracks (tracks reconstruction)
4. Alignment
5. Vertex reconstruction
   - 2 dedicated software (standard, fast → under development, in JINR)

**Dedicated software for the extraction of events of interest:**
6. Searching events with secondary vertices corresponding to short lived particles
7. Searching for Ds decaying $\tau$

**Under analysis**

4.6 × 10⁹ protons, 2.3 × 10⁸ proton interactions, 10⁵ charm pairs, 1000 $D_s - \tau$
Tracks and vertices reconstruction

Proof of the technique capabilities: reconstruction and recognition of events is a high track density environment

Examples of DsTau 3D reconstructed events

Example of DsTau reconstructed double charm event (neutral and 1 prong decaying particles visible)
Reconstruction of primary proton vertices

Vertices in the depth of one module, in unit of reconstruction

Subsample with interactions in the first tungsten target and soft materials

Fine structure of the detector is visible:
- emulsion - 60um
- plastic - 200 um
- W - 500 um
Extraction of the resolution and targets thicknesses

The resolution of reconstruction along the beam axis is the same in the entire detector, despite the increase of the track density in the depth \(10^5 \rightarrow 10^6 \text{tracks/cm}^2\).

![Graph showing resolution and targets thicknesses](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>30581</td>
</tr>
<tr>
<td>Mean</td>
<td>5.152</td>
</tr>
<tr>
<td>Std Dev</td>
<td>184.3</td>
</tr>
<tr>
<td>(\chi^2 / \text{ndf})</td>
<td>153.2 / 117</td>
</tr>
<tr>
<td>W height</td>
<td>263.5 ± 1.6</td>
</tr>
<tr>
<td>limit_1</td>
<td>-254.9 ± 0.8</td>
</tr>
<tr>
<td>limit_2</td>
<td>255.9 ± 0.0</td>
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<tr>
<td>emu height</td>
<td>65.43 ± 2.10</td>
</tr>
<tr>
<td>sigma</td>
<td>6.694 ± 0.662</td>
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</tbody>
</table>

Fit with a convolution of a box function (with wings) with Gauss: limits defining the box function, the heights of it and sigma are free parameters → resolution along the beam axis and the thickness of the target
The average extracted resolution (along Z) is $\sim 7 \text{ um}$ and depends on:

- quality of emulsion films
- flatness of the target
- multiplicity
- position inside target

Detailed study of the resolution
Resolution dependence on the position inside the target

One tungsten target

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
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<tbody>
<tr>
<td>upstream</td>
<td>6.38 ± 0.02</td>
<td>5.61 ± 0.02</td>
<td>4.74 ± 0.02</td>
<td>4.06 ± 0.01</td>
<td>3.71 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>100 um</td>
<td>100 um</td>
<td>100 um</td>
<td>100 um</td>
<td>100 um</td>
</tr>
<tr>
<td>downstream</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*mean resolution along beam axis in the first 8 plates of the module, generated with G4; In MC, the resolution is ~ 5 um (variation of thicknesses and non-flatness is not included)
MC is transformed in the same format as the real data (basetracks) and, then, tracks and vertices are reconstructed with the same tools as for the real data.

MC models work with 5-10% accuracy
Indicated errors are statistical
Observed multiplicity for data is consistent with expectations
Summary

- data taken completed, scanning and analysis ongoing, faster algorithms under development in JINR group
- the existing algorithms are capable to reconstruct events in a track density of $10^5$-$10^6$ tracks/cm$^2$
- the primary events in the scanned data are reconstructed with a resolution of $\sim 7 \ \mu m$

HAPPINESS IS

...studying physics.
2021 and 2022 data taking at CERN-SPS

Thank you for your attention!
Back-up slides
Status of the experiment

- 2018: 30 modules (with a surface of $12.5 \times 10 \ cm^2$) were exposed, all plates scanned, all reconstructed
- 2021: 17 modules (with a surface of $25 \times 20 \ cm^2$) exposed, scanning started
- 2022: 17 modules exposed
- 2023: 40 modules exposed

DsTau web site:
https://na65.web.cern.ch/

https://link.springer.com/
article/10.1007/JHEP01(2020)033

Experiment proposal:
Reconstruction resolution and efficiency - G4 data

![Reconstruction efficiency graph](image)

Subvolume 1

<table>
<thead>
<tr>
<th>Geant4</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
<th>$\chi^2$ / ndf</th>
<th>Emulsion</th>
<th>Plastic</th>
<th>Sigma</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>82590</td>
<td>-1.512</td>
<td>69.04</td>
<td>73.67 / 45</td>
<td>2299 ± 13.7</td>
<td>1329 ± 6.6</td>
<td>4.861 ± 0.414</td>
</tr>
</tbody>
</table>

Resolution ($\mu$m)

<table>
<thead>
<tr>
<th>Combination</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+E</td>
<td>5.37 ± 0.14</td>
</tr>
<tr>
<td>W+E+P</td>
<td>5.57 ± 0.13</td>
</tr>
<tr>
<td>E+P</td>
<td>4.64 ± 0.15</td>
</tr>
</tbody>
</table>
A clear discrepancy between generators, in p-p interactions (simplest case) - showing the different MC approaches;
The final goal of the experiment is to measure the Ds decaying via tau cross section. For this, not only the number of the events have to be known, but also the efficiencies for recognising these events has to be calculated.

Codes for estimation of detection efficiency are under development: efficiency of Ds reconstructed track recognition (38.09 ± 0.13) % and for τ track 25.3 ± 0.1 % according to Geant4 data.

Codes capable to recognise Ds decaying tau are under development.

Event with double (charged) charm candidates [?]
The DsTau experiment will highlight the $\nu_\tau$ from $D_s$ leptonic decay

$\rightarrow$ In DONuT experiment, 95% of $\nu_\tau$ sources were from $D_s \rightarrow \tau + \nu_\tau$

Measurement of $D_s$ differential production cross section:

$$
\frac{d^2\sigma}{dx_F \cdot dp_T^2} \propto (1 - |x_F|)^n \cdot e^{-b \cdot p_T^2},
$$

(1)

where $x_F$ is the longitudinal momentum $p_L/p_{L\text{max}}$ and $p_T$ is the transverse momentum. $n$ and $b$ are the parameters controlling the longitudinal and transverse dependence of the differential production cross section, respectively.