PROCEEDINGS OF SCIENCE

Recent results from the DsTau(NA65) experiment at the CERN-SPS

A. Murat Güler for the DsTau Collaboration [a,*]

[a] *Middle East Technical University,*
Dumlupınar Bulvarı No:1, Ankara, Türkiye

E-mail: ali.murat.guler@cern.ch

The DsTau (NA65) experiment at CERN aims to measure the inclusive differential cross-section for the production of D_s mesons decaying into a tau lepton and a tau neutrino in proton–nucleus (p-A) interactions. The DsTau detector employs the nuclear emulsion technique, providing exceptional spatial resolution for detecting short-lived particles such as charmed hadrons. In this report, we present the initial results from the analysis of the pilot-run data, focusing on the accuracy of proton interaction vertex reconstruction. Achieving high precision in vertex reconstruction allows for accurate measurements of the proton interaction length and charged particle multiplicities, even in a high-track density environments. The data we collected have been compared with several Monte Carlo event generators. The findings from this study can help validate event generators.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(EPS-HEP2025)145

1. Introduction

The tau neutrino is one of the least understood particles in the Standard Model of particle physics. New data on its interactions offers a valuable opportunity to test models beyond the Standard Model. Specifically, the investigation of lepton flavor universality in weak interactions can be explored within the neutrino sector, providing a complementary approach to measurements carried out by the LHCb and Belle II collaborations. Furthermore, having precise knowledge of the tau neutrino flux in accelerator-based neutrino beams is crucial for current and future experiments, such as FASER, SND@LHC, and SHiP. Historically, only a few experiments have successfully observed tau neutrino interactions, and these observations have been limited due to small sample sizes. The DONuT experiment [3] provided the first estimate of the tau neutrino cross-section; however, this estimate comes with significant uncertainties—approximately 50% systematic uncertainty, primarily due to the poor understanding of D_s-meson production and decay mechanisms. The DsTau(NA65) experiment [1] aims to reduce the systematic uncertainty in tau neutrino production to the 10% level by detecting approximately 10^3 $D_s \to \tau$ decays from 2×10^8 proton interactions on tungsten or molybdenum targets. The experiment also enables high-statistics studies of charmed hadron pair production in p–A interactions. In this talk, we present the first results from the analysis of primary proton interactions based on a subset of data collected during the 2018 run [2]. The high quality of the data enables precise measurements of the multiplicity and angular distributions of charged secondary particles produced in different target materials. The measured distributions are compared with predictions from several widely used Monte Carlo (MC) generators, offering valuable inputs for refining and tuning the interaction models used in these MC generators.

2. Data Taking

Among the available detector technologies, only nuclear emulsion can provide the sub-micron spatial and sub-milliradian three-dimensional angular resolutions required to detect the D_s decay into a τ lepton. The DsTau detector, which is based on the nuclear emulsion technique, is composed of tungsten/molybdenum plates interleaved with nuclear emulsion films and plastic spacers. Tungsten and molybdenum (used only during the 2021–2023 physics runs) were selected as target materials because they are also employed in neutrino beam production at accelerators, as in the DONuT and SHiP experiments. Each emulsion film is composed of two 70 μm-thick emulsion layers coated on both sides of a 210 μm-thick plastic base. The films are interleaved with plastic spacers, which provide a decay volume and serve as a high-precision tracking medium. Each unit consists of a 500 μm-thick tungsten plate followed by ten nuclear emulsion films interleaved with nine plastic spacers. This structure is repeated ten times within a module measuring 12.5 cm in width, 10 cm in height, and 4.8 mm in thickness. Additionally, five emulsion films with plastic spacers are placed upstream to tag the incoming beam protons. Downstream of the module, an Emulsion Cloud Chamber (ECC) composed of 26 emulsion films interleaved with 1 mm-thick lead plates is installed to reconstruct the momentum of secondary particles through measurements of multiple Coulomb scattering.

Developments in emulsion scanning systems by the Nagoya University group [4] have made large-area emulsion experiments feasible and efficient. The most advanced system to date, the Hyper Track Selector (HTS) [5], is capable of reading out track information from both emulsion layers at an average speed of 1000 cm^2/h in the DsTau experiment.

The CERN Super Proton Synchrotron provides a beam of protons with a momentum of 400 GeV/c. In 2018, a pilot run was carried out to demonstrate the detection of proton interactions in a high track density environment and to collect approximately 10% of the total planned dataset. During the pilot run, 30 detector modules were exposed to the proton beam at the H4 beam line. Each emulsion module was mounted on a motorized X–Y stage, referred to as the *target mover* [6], which allowed for synchronized movement of the module with the proton spills. This setup ensured uniform irradiation of the detector surface, achieving a density of 10^5 tracks per cm^2. The emulsion scanning of the 2018 run films has been completed, and analysis of the collected data is in progress. The present results are based on the analysis of a subset of the 2018 dataset [1].

3. Analysis

To reconstruct particle tracks and vertices after emulsion data acquisition, the data are processed using the DsTau software. After the base track reconstruction, film-to-film alignment is performed through base track pattern matching. Once all films are aligned, base-tracks are connected sequentially from film to film according to angular and positional tolerances, forming so-called volume tracks. The track finding and fitting procedures take into account possible inefficiencies in the base-track reconstruction. Further alignment between films (a scale factor, a rotation, transverse position shifts, and a gap) is obtained by using tracks, reconstructed in each sub-volume. In particular, for the transverse position alignment, the 400-GeV proton beam track, supposed to be most straight, is selectively used.

The beam protons in the module are selected based on the track angles, which are determined by fitting baseline tracks in the first five emulsion films to a straight line. Following the linking process, the number of beam protons traversing each tungsten plate is estimated, as shown in Table 1. The beam proton track is subsequently linked to the reconstructed vertices through a method called proton-vertex linking. A vertex is identified as a proton interaction vertex if its parent matches in both angle and position with one of the beam protons selected in proton-linking step. This procedure eliminates contamination from secondary particle interactions, which progressively increases with depth in the module. For the present analysis, a sample of 95,314 events that have a reconstructed beam-proton and its interaction vertex in the tungsten plate is used from a single module of the 2018 run (Table 1). To ensure high efficiency and purity in track and vertex reconstruction, the data related to interactions in the last two tungsten plates are not included. To estimate the reconstruction efficiencies, approximately 2×10^6 proton interactions were simulated using several event generators: EPOS [9], PYTHIA8 [10], QGSJET [11], DPMJET [12], and GEANT4.11. In the latter, a particle gun setup was employed in combination with the hadronic physics lists G4HadronElasticPhysics, G4HadronPhysicsFTFP_BERT, and G4IonPhysics. The simulation incorporated a realistic proton density distribution within the emulsion module. The generated events were then propagated through the detector geometry using GEANT4.11, and the simulated data were processed with the HTS tracking algorithms. The reconstruction efficiencies were modeled as linear functions of the

Table 1: Vertex reconstruction(ϵ_v), Proton-Linking (ϵ_p) and Proton-Vertex linking(ϵ_{pv}) efficiencies calculated using EPOS and realistic track density(ρ) in each tungsten plate of a module.

Tungsten Plate	N	N_0	$\frac{N}{N_0}$ (%)
1	13,586	3,310,658	0.41
2	13,390	3,292,677	0.41
3	12,653	3,256,746	0.39
4	12,256	3,214,141	0.38
5	11,745	3,157,020	0.37
6	11,264	3,082,105	0.36
7	10,645	2,996,099	0.35
8	9,775	2,892,348	0.34
Total	95,314	25,201,794	0.38

Table 2: Vertex reconstruction(ϵ_v), Proton-Linking (ϵ_p) and Proton-Vertex linking(ϵ_{pv}) efficiencies calculated using EPOS and realistic track density(ρ) in each tungsten plate of a module.

Tungsten Plate	ϵ_v (%)	ϵ_p (%)	ϵ_{pv} (%)
1	81.8 ± 2.5	93.7 ± 0.1	100.0 ± 0.1
2	81.4 ± 2.5	93.5 ± 0.1	100.0 ± 0.1
3	81.0 ± 2.5	93.2 ± 0.1	99.2 ± 0.1
4	80.6 ± 2.5	92.9 ± 0.1	98.2 ± 0.1
5	80.1 ± 2.5	92.6 ± 0.1	96.9 ± 0.1
6	79.6 ± 2.5	92.3 ± 0.1	95.7 ± 0.1
7	79.0 ± 2.5	92.0 ± 0.1	94.1 ± 0.1
8	78.4 ± 2.5	91.6 ± 0.1	92.2 ± 0.1
Mean	80.3 ± 2.5	92.7 ± 0.1	97.0 ± 0.1

local track density. The measured densities from the experimental data were used to estimate the efficiency for each tungsten plate, with a summary provided in Table 2. Since vertex reconstruction requires a minimum of five tracks, the choice of hadronization model in the event generator can affect the predicted multiplicity distributions and, consequently, the reconstruction efficiency. The systematic uncertainty due to this effect was evaluated to be 2.5% by comparing the fractions of events with multiplicity exceeding four among the EPOS, DPMJET, and PYTHIA simulations. Figure 1 illustrates the comparison of the measured multiplicity distribution with predictions from various MC event generators. Among the tested generators, EPOS shows the best overall agreement with the measured multiplicity distribution.

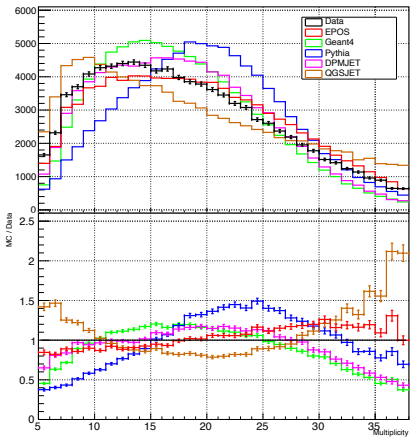

Figure 1: MC/Data comparison of track multiplicity, normalized to the number of events in data.

3.1 Measurement of proton interaction length

Following the characterization of the detector response and reconstruction performance, the proton interaction length in tungsten is measured to quantify the inelastic interaction probability and to compare with model expectations. To determine the interaction length of protons in tungsten, the number of reconstructed beam protons entering the tungsten plate and their interaction vertices in tungsten were used. For each tungsten plate, interaction length is calculated using

$$\lambda = -\frac{L}{ln(1 - \frac{N'}{N'_0})} \tag{1}$$

where L is the measured thickness of the tungsten plate, N' and N'_0 are the number of proton interactions in the tungsten plate, and the number of beam protons entering the tungsten plate which are corrected by efficiencies of Table 2. The value of L is 489±2 μm (464 μm) for Data (MC). The measured mean interaction length in tungsten is 93.7 ± 2.6 mm, which is in good agreement with the EPOS prediction of 95.8 ± 2.8 mm.

4. Conclusion

Using a sub-sample of the 2018 data, we present the first results on key observables, together with comparisons between experimental data and predictions from various event generators. Overall, EPOS predictions show the best agreement with the data across most distributions, except for the slopes of secondary particles. The analysis of the proton interactions demonstrated that precise tracking and vertex reconstruction can be successfully achieved even in high track-density environments. Such performance is crucial for detecting charmed hadrons and accurately determining the τ neutrino flux. We report the first measurement of the proton interaction length in tungsten, determined to be 93.7 ± 2.6 mm.

References

[1] S. Aoki et al. [DsTau/NA65 Collaboration], DsTau: study of tau neutrino production with 400 GeV protons from the CERN-SPS, JHEP 2020 (2020) 33, doi: 10.1007/JHEP01(2020)033.

[2] S. Aoki et al. [DsTau/NA65 Collaboration], Study of proton–nucleus interactions in the DsTau/NA65 experiment at the CERN-SPS Eur.Phys.J.C 85 (2025) 3, 230, https://doi.org/10.1140/epjc/s10052-025-13928-1.

[3] K. Kodama et al. [DONuT Collaboration], Observation of tau neutrino interactions, Phys.Lett.B 504 (2001) 218-224, doi: 10.1016/S0370-2693(01)00307-0.

[4] S. Aoki, et al., Fully automated emulsion analysis system, Nucl. Instrum. Methods B 51 (1990) 466, doi: 10.1016/0168-583X(90)90569-G, T. Nakano, PhD thesis, Nagoya University, Japan, 1997.

[5] M. Yoshimoto, T. Nakano, R. Komatani, H. Kawahara, Hyper-track selector nuclear emulsion readout system aimed at scanning an area of one thousand square meters, PTEP 10 (2017) 103, doi: 10.1093/ptep/ptx131.

[6] S. Aoki et al. [DsTau/NA65 Collaboration], Development of proton beam irradiation system for the NA65/DsTau experiment, JINST 18 (2023) 10, P10008, doi: 10.1088/1748-0221/18/10/P10008.

[7] E. Yuksel, MSc Thesis, Study of proton interactions in the DsTau Experiment at the CERN-SPS, METU Thesis (2024).

[8] S. Agostinelli et.al., [GEANT4 Collaboration] GEANT4–a simulation toolkit, Nucl.Instrum.Meth.A 506 (2003) 250-303, doi: 10.1016/S0168-9002(03)01368-8.

[9] S. Porteboeuf, T. Pierog, K. Werner, Producing Hard Processes Regarding the Complete Event: The EPOS Event Generator, https://doi.org/10.48550/arXiv.1006.2967.

[10] T. Sjöstrand et.al., An Introduction to PYTHIA 8.2, https://doi.org/10.48550/arXiv.1410.3012.

[11] S. Ostapchenko, Status of QGSJET, https://doi.org/10.48550/arXiv.0706.3784.

[12] J. Ranft, New features in DPMJET version II.5, https://doi.org/10.48550/arXiv.hep-ph/9911213.