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

S. Vasina and on behalf of the DsTau (NA65) Collaboration
Joint Institute for Nuclear Research, Joliot-Curie 6, Dubna, Russia
E-mail: vasina@jinr.ru

Abstract. The tau neutrino interaction cross-section was directly measured in the DONuT experiment but it suffers from a large systematic (∼50%) and statistical (∼30%) errors. The main source of the systematic error was due to poor knowledge of the tau neutrino flux. The DsTau experiment at CERN-SPS has been proposed to measure an inclusive differential cross-section of the D_s production with a consecutive decay to tau lepton in p-A interactions, which is a main source of tau neutrinos in neutrino beams at accelerators. The search for $D_s \to \tau \to X$ decay is challenging due to milimetric range of D_s and τ decay lengths and a small angle between them of the order of few mrad. Nevertheless a precise measurement is possible with the use of nuclear emulsion providing a sub-micron spatial resolution. The experiment is aiming to collect 2.3×10^8 proton interactions in the tungsten target, and to detect ∼1000 $D_s \to \tau \to X$ decays. DsTau successfully performed a pilot run in 2018 collecting ∼10% of the full data and was approved as NA65 in 2019. The results from the pilot run are presented in this paper and the prospect for physics runs in 2021–2022 are given.

1. Introduction

Tau neutrino is one of the least studied particles due to it's poor measurements. Only the DONuT [1] experiment observed 9 tau neutrinos directly in the beam and several experiments measured tau neutrinos from oscillations with a poor statistics [2, 3]. Experimental results were obtained under rather different conditions. Therefore, the direct comparison is rather difficult. In general, the measurements were done with statistical and systematic errors of 30–50% due to poor statistics and experimental uncertainties. The future beam-dump experiments can provide ν_τ cross section measurements with negligible statistical errors [4]. Thus, the accuracy of cross section measurements will be mainly caused by the systematic errors, in particular, due to the ν_τ flux uncertainty, which will be improved in the DsTau (NA65) experiment.

The main source of ν_τ in the accelerator-based neutrino beam is decay of $D_s^\pm$ mesons produced in proton-nucleus interactions: $D_s^- \to \tau^- \bar{\nu}_\tau$ with the further decay $\tau^- \to \nu_\tau X$. The uncertainty in the ν_τ flux will be determined by the production rate as well as the angular divergence of the flux. Thus, the accurate measurement of D_s differential production cross section will provide an evaluation of the ν_τ flux on the detector.

The DsTau experiment will study ν_τ production in 400 GeV/c proton-nuclear interactions at CERN SPS by measuring $D_s \to \tau \to X$ decays. The experiment aims to collect 2.3×10^8 proton interactions in the target, which would allow registering ∼1000 D_s decays. The identification of the decays is possible by using high spacial-resolution nuclear emulsion and sub-micrometer precision readout. DsTau will provide an independent ν_τ flux prediction for the

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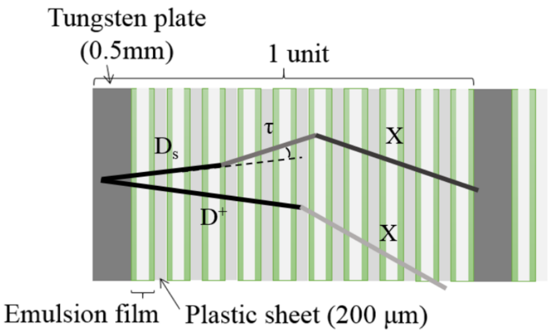
future neutrino beams with an accuracy better than 10%. Then, the ν_τ charged current cross section measurement with sufficiently low systematic uncertainty would allow testing the Lepton Flavour Universality of Standard Model in neutrino interactions.

It is possible also to perform other studies related to charmed particles physics, since $\sim 10^5$ events with charmed particle pairs are expected in the data sample. For example, measurement of intrinsic charm component in proton [5] by measuring the emission angle (pseudorapidity) of the charmed particle pairs, the interaction length of charmed hadrons, the Λ_c production rate and search for super-nuclei [6] will be possible measurements.

2. Experimental setup

Although $D_s \to \tau \to X$ decays have a very peculiar topology, the "double-kink" and a charged or neutral charmed particle pair in the interaction vertex (figure 1), its observation is rather challenging. According to simulation using Pythia 8.1 [7], the mean flight lengths of D_s, τ and pair-charm are 3.6 mm, 2.1 mm and 4.2, respectively. The kink angle between D_s and τ is rather small — 6.2 mrad on average. The measurement of D_s momentum is difficult as well due to presence of two ν_τ, which are not detected. Therefore, only utilization of nuclear emulsion with position resolution of about 50 nm and an angular resolution of 0.34 mrad allows identifying such decay topologies.



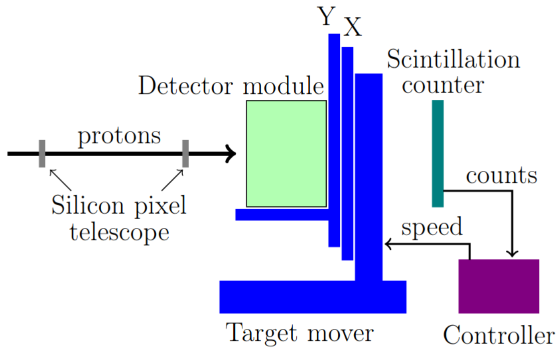


Figure 1. Schematic view of the "double-kink" event in the basic unit of DsTau decay module (left) and scheme of the experimental setup (right) [8].

The background is mainly induced by the interactions of secondary hadrons in the detector. The number of expected background events in the full data sample is about 18 estimated by the Fluka [9] based simulation.

The basic unit of the DsTau detector is shown in figure 1. It is a 0.5-mm-thick tungsten target followed by 10 emulsion plates interleaved with 9 plastic sheets with thickness of 190 μm. Each emulsion plate consists of a 210 μm plastic base with 70 μm emulsion layers on both sides. A decay module is formed by 10 basic units. The front side of module is equipped with proton tagger consisting of 5 emulsion plates interleaved with 4 plastic separators that is used for primary protons identification. The module is followed by Emulsion Cloud Chamber (ECC) module for charged particles momentum measurement. In 2018 pilot run ECC consists of 26 lead plates of 1-mm thick interleaved with emulsion plates. The analysis of the pilot run data demonstrates that it can be replaced by extra basic units, which can provide compatible accuracy in momenta measurements. This strategy was applied in 2021 physics run. The total size of the detector in 2018 pilot run was $12.5 \times 10.0 \times 8.6$ cm and in physics run the size of emulsion and tungsten plates are 4 times larger, the total module thickness is also different due to redesign of ECC part of the detector.

A schematic view of experimental setup is shown in figure 1. The beam profile is measured by a silicon pixel telescope and time profile is measured by a scintillation counter. The detector is driven by a target mover along X and Y axes according to scintillation counter signal intensity to have a uniform distribution of primary protons with about 10^5 tracks/cm^2 in the detector.

3. Reconstruction and analysis

The analysis of the particle tracks accumulated in the emulsion during exposure is done in two steps. First, scanning of the full emulsion area by a fast system, so called Hyper Track Selector (HTS) [10] with a relatively coarse angular resolution ($\sim$ 2.5 mrad). The second step is a high precision measurement around the τ decay candidates preselected by HTS to find $D_s \to \tau$ small kinks. For this step another scanning microscope with a slower readout speed, but having a high angular resolution (0.16 mrad) is used. More details on the scanning systems are given in [8, 11].

The output of the emulsion readout by the scanning system is the information on the track segments at both sides of the emulsion film. These two segments are linked together forming so called basetrack, which is a basic unit of information used in the further track reconstruction. The emulsion readout has been completed for the whole data sample collected in 2018 pilot run.

The track reconstruction is based on linking of basetracks at different films according to their angles and positions. In DsTau this task is quite challenging due to high track density of $10^5 - 10^6$ tracks/cm^2 while in almost all previous emulsion experiments it was of the order of $10^2 - 10^4$ tracks/cm^2 in larger angular space. Nevertheless, the averaged basetrack finding efficiency is measured to be higher than 95%, shown in figure 2. There is a slow decrease in efficiency at the downstream part of the detector due to increase of the track density, but it is still high enough to reconstruct tracks with an efficiency of >99%.

Due to the large amount of data contained in emulsion, the data processing is divided into sub-volumes, 1.9 cm $\times$ 1.9 cm $\times$ 30 emulsion films. An alignment between films (rotation, transverse position shifts and gap) is obtained by means of recorded tracks, 400-GeV proton beam tracks are used as the most straight. The algorithm assures a sub-micron alignment.

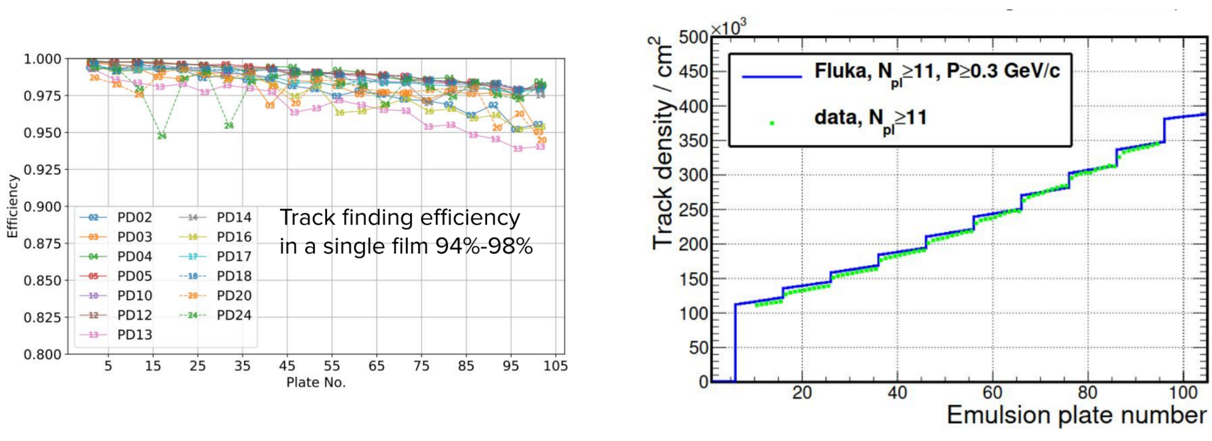


Figure 2. The film-by-film basetrack finding efficiency in different modules exposed in 2018 pilot run (left) and the evolution of track density as a function of depth in a module (right).

The reconstructed tracks are used to reconstruct vertices, the number of vertices is $\sim 500/cm^2/$ tungsten plate. A systematic search for a decay topology of short-lived particles is applied. The statistics of the found vertices and events with the double decay topology in a sub–sample $\sim$2% of the data corresponding to $>34.2 \times 10^6$ protons analyzed are shown in table 1. It is consistent with the expectation based on the simulation for the equivalent data sample. The kinematic variables of found charged 1-prong and neutral 2-prong decay candidates are in agreement with Fluka based simulation, figure 3. This sub-sample was used to tune parameters for the kink search and neutral charms with 2-prong topology search in order to optimise efficiency and background rejection before 2nd step of the scanning for the small angle kink hunting.

Table 1. Statistics found in the sub–sample of 2016, 2018 data related to >34.2 $\times 10^6$ protons analyzed.

	Observed	Expected	
Vertices in tungsten	147,236	155,135	
		Signal	Background
Double decay topology	115	80.1±19.2	12.7±5.0

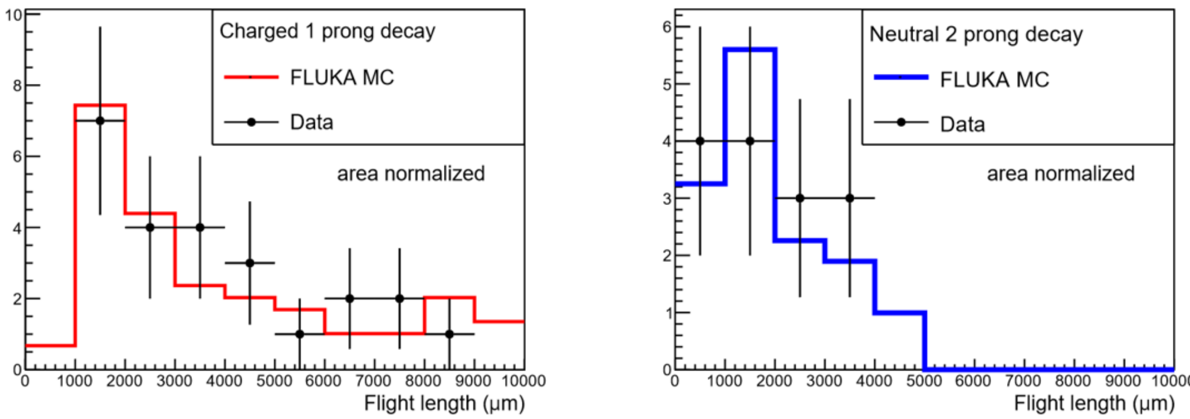


Figure 3. Flight length distributions for charged 1-prong and neutral 2-prong decay candidates in the double-charm event samples. The FLUKA MC histograms are area-normalized to data.

The mass processing with efficiency-improved cuts has been started. More than 20% of the data have been analysed. That corresponds to more than 486×10^6 of protons. About 2.65×10^6 vertices, in tungsten plates have been detected, about 17, 500 of them are double decay topology candidates. The "double-kink" candidate events found in this sample is shown in figure 4. More detailed analysis will be done for double decay topology candidates sample. Some algorithms of detailed analysis still to be tuned while others (fine alignment for local areas, momentum measurement and others) can be applied systematically.

4. Conclusions and prospects

The DsTau experiment studies the tau neutrino production in 400 GeV/c proton interactions with the tungsten target by measuring the differential production cross-section of D_s mesons, which is important for future neutrino experiments. The experiment is aiming to analyse 2.3×10^8 proton interactions in tungsten employing emulsion detector with a spacial resolution of 50 nm. This data sample will contain $\sim10^5$ interaction with charm pairs and would allow to detect $\sim$1000 $D_s \to \tau \to X$ decays.

DsTau performed test runs in 2016 and 2017 and successfully collected about 10% of full statistics during 2018 pilot run. The 2021 physics run has been successfully completed in the beginning of October. The analysis of the data sample collected in the 2018 pilot run is ongoing.

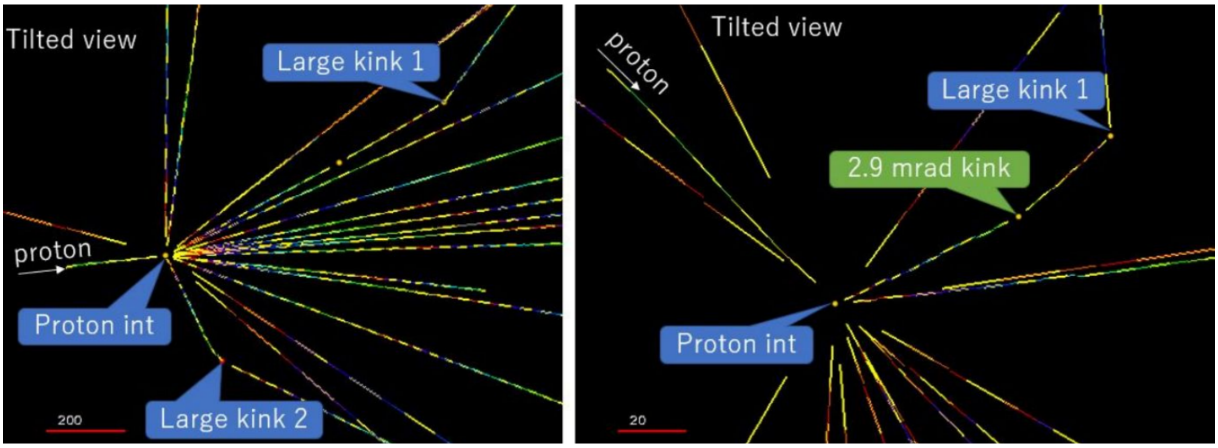


Figure 4. "Double-kink" candidate event found in 2018 sub-sample analysed with tuned parameters: general view of the vertex with 2 large kinks (left) and zoom on the kink parent with a small kink of 2.9 mrad (right).

Acknowledgments

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References

[1] Kodama K et al.(DONuT Collaboration) 2008 *Phys. Rev. D* **78** 052002
[2] Agafonova N et al.(OPERA Collaboration) 2015 *Phys. Rev. Lett.* **115** 121802
[3] Li Z et al. (Super-Kamiokande Collaboration) 2018 *Phys. Rev. D* **98** 052006
[4] Alekhin S et al. (SHiP Collaboration) 2016 *Rep. Prog. Phys.* **79** 124201
[5] Bai W, Reno M H 2019 *JHEP* **02** 077
[6] Lyukov V V 1989 *Nuovo Cim. A* **102** 583-595
[7] Sjostrand T et al. 2008 *omput. Phys. Commun.* **178** 852-867
[8] Aoki S et al. (The DsTau/NA65 Collaboration) 2020 *JHEP* **01** 033
[9] Böhlen. T T, Cerutti F, Chin M P W, Fasso A, Ferrari A, Ortega P G, Mairani A, Sala P R, Smirnov G and Vlachoudis V 2014 *Nucl. Data Sheets* **120** 211
[10] Yoshimoto M, Nakano T, Komatani R, Kawahara W 2017 *PTEP* **10** 103
[11] Aoki S et al. (The DsTau/NA65 Collaboration) 2017 *CERN-SPSC-2017-029, SPSC-P-354*