DsTau: study of tau neutrino production with nuclear emulsion in the CERN-SPS

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Abstract

Tau neutrino is one of the least known particle of Standard Model; there are only few measurements with a limited statistics. The DONUT experiment first reported the tau neutrino interaction cross-section but their measurement suffers from large systematic error of more than 50% which is mainly due to uncertainty in the tau neutrino flux prediction. The tau neutrino cross section is an essential ingredient in neutrino experiments and its precise measurement would enable a search for new physics effects such as testing the Lepton Universality in neutrino interactions. The main goal of the DsTau experiment is to measure an inclusive differential cross-section of a D_s production with a consecutive decay to tau lepton in p-A interactions at the CERN-SPS. The measurement of DsTau will reduce the systematic uncertainty in tau neutrino interaction cross-section to 10% level. The results from the pilot run and the prospect for physics runs in 2021-2022 will be discussed.

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1 Introduction

The DsTau collaboration is aiming at studying tau neutrino production in p-A interactions at the CERN-SPS. Although tau neutrino is one of the least known particle of the Standard Model, only a few experiments have reported its interactions with a limited statistics. The DONuT experiment (Beam-Dump experiment) [1] at Fermilab was the first experiment observing the tau neutrino interactions directly. Later, tau neutrino interactions were also observed by OPERA[2], Super-K[3] and IceCube[4] experiments. However, in these experiments tau neutrino come from neutrino oscillations. Using the limited number of tau neutrino interactions, DONuT measured the tau neutrino interaction cross section with a large uncertainty. In their measurement, the systematic uncertainty is more than 50% which is due to uncertainity in the tau neutrino flux. Indeed, DONuT reported tau neutrino cross section measurement as a function of a parameter n, which acts on the longitudinal part of the D_s differential cross section: $\frac{d^2\sigma}{dx_F dp_T^2} \propto (1-|x_F|)^2 e^{-bp_T^2}$ where x_F Feynman x and p_T is transverse momentum. Since the central value of the cross section depends on n value, the tau neutrino cross section can be estimated only if n value derived from PYTHIA. However n value depends on the PYTHIA version. In the recent version of PYTHIA it is significantly different than the value in the version 6.1. In order to reduce the systematic uncertainty of the tau neutrino cross-section to 10%, n has to be determined at a precision of ~ 0.4. The preciece measurement of tau neutrino cross section is very important, it will allow testing of lepton universality in tau neutrino interactions. Furthermore it also has practical implications for neutrino oscillation experiments and high-energy astrophysical observations.

2 Methodology and Experimental Setup

In proton Beam-Dump experiments, tau neutrino mainly come from D_s which has a peculiar double-kink topology; D_s decays into tau lepton and anti-tau neutrino and then tau lepton decays to leptons or hadrons. The mean flight length of both decays is small ($\sim 3mm$). In addition, in proton interactions the charm quarks are produced in pair, therefore another decay of a charmed hadron in the emulsion detector will be observed. Although the signal event topology is quite unique, D_s detection has technical challenges as all decays take place at a scale of millimetres and the kink angle of D_s to tau lepton is anticipated to be very small, only a few mrad. Therefore this measurement requires very precise tracking detector. DsTau uses emulsion particle detector which provides the best spatial resolution among all tracking detectors. Moreover, improvements in emulsion detector and its readout systems made in last decades allow to use emulsion in large scale experiments. The nuclear emulsion consists of a mixture of several nuclei – silver and bromine dispersed in gelatine, which acts as a semiconductor with a band gap energy of about 2.5 eV. The trajectory of a charged particle can be reconstructed through ionization of silver halide molecules which leads to the formation of silver atoms. The recorded silver atoms are then amplified by using a chemical process such that the trajectory of charged particles can be visible under the optic microscope. The position resolution of emulsion detector depends on the size of silver bromide. For example, 200-nm crystals can provide a position resolution of 50 nm and angular resolution of 0.35 $mrad$. Therefore, this angular resolution allows us to set a threshold for the detection of kink angle of 2 $mrad$ at the 4σ confidence level. The DsTau detector consists of 10 units and each of them is made of a tungsten plate followed by emulsion films interleaved with plastic sheets. This structure acts as a decay volume for charmed hadron and tau lepton as well as high-precision tracking detector. Each unit follows an Emulsion Cloud Chamber (ECC), which is made of emulsion films interleaved with lead plates. It is used for momentum measurement of charged daughter particles through Multiple Coulomb Scattering. A schematic view of the experimental setup is shown in Figure 1. In addition to this structure three additional emulsion films act as a trigger for incoming protons will be placed upstream. A single module containing 129 films has a transverse area of 12.5×10 cm^2 and 8.6 cm thick. Based on this structure 4.6×10^9 protons on target are necessary to collect $2.3x10^8$ proton interactions in the tungsten or molybdenum plates. For a uniform irradiation of proton beam on the detector, the detector modules are located on a motorised stage which moves synchronously with the SPS spills.

The recent improvements on the emulsion readout system enables the scanning and analysis at a track density up to about 10^6 particles/cm^2. This limits density of the proton beam at the upstream surface of the detector module to be $\leq 10^5$ cm^{-2}.

The emulsion readout is the essential part of the experiment. It will be performed in two stages. The first stage involves the scanning of emulsion films by the Hyper Track Selector

(HTS) system [6] of Nagoya University. It can reach a scanning speed of $0.5m^2/h$/layer. After detecting a decay topology in the fast scanning, the event will be scanned a second time with a high-precision microscope for a D_s kink search. The measurement resolution of the system is estimated to be 0.15 $mrad$ (RMS) which is sufficient for D_s kink detection.

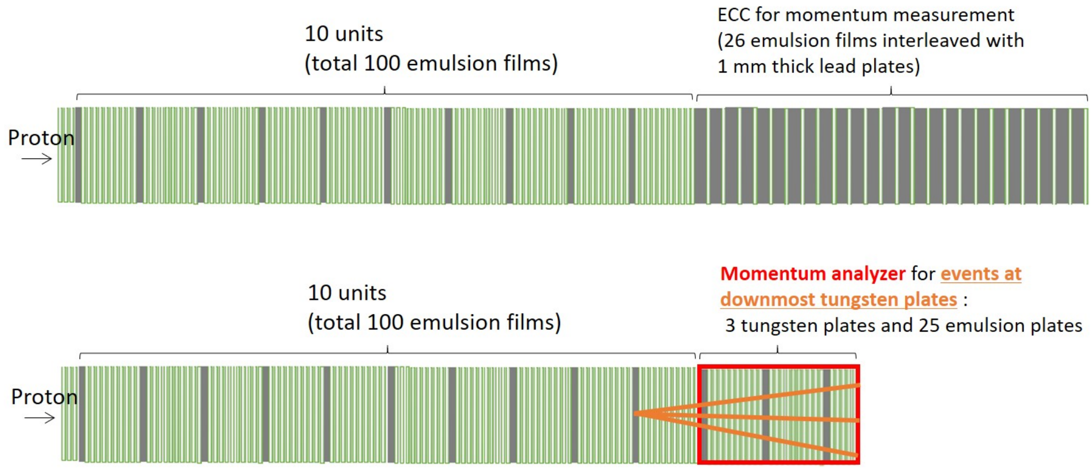

Figure 1: Schematic view of emulsion detector

The D_s signal topologies are very uniques; all decays take place in a very short distance; a few millimeters. The background to D_s decays is mainly from secondary hadron interactions. If the nuclear fragments at the interaction vertex are not detected, they constitute a background. This background can be suppressed applying the transverse momentum cut. The D_s momentum is reconstructed by using a machine-learning approach. The topological variables, two flight lengths and two kink angles which are proportional and inverse proportional to the γ factor of parent particles are used. The algorithm is trained and tested with the simulated sample ($D_s \to \tau \to 1-prong$). By combining these variables effectively, D_s momenta can be obtained with a precision of 20%.

3 Analysis of pilot run data

The pilot run which was carried out in 2018 allows to test each step of the experiment from emulsion production to data analysis. During the pilot run, DsTau collected 10% data of the physics run; about 4000 emulsion film were used to construct 30 emulsion modules. The detector set up is located at the H4 beamline at CERN. Since the proton beam divergence can be tuned to 1 x 2 cm^2 at maximum, the target mover which is synchronized to beam spill was used to have uniform irradiation over the emulsion module surface.

After the exposure, emulsion films are developed and scanned under the optical microscope. The emulsion scanning of the pilot run has completed and analysis of the collected data is going on. Figure 2 shows a double charm event topology found and reconstructed in the pilot run data. The number of located proton interactions and number of double decay topology identified in the sub-sample of the data are shown in Table 1. The number of observed events is consistent with the MC prediction based on FLUKA.

Table 1: Analysis results of a sub-sample of the pilot run

	Observed	Expected	
Located proton Int.	147,236	155,135	
		signal	background
Double decay topology	115	80.1±19.2	12.7±5.0

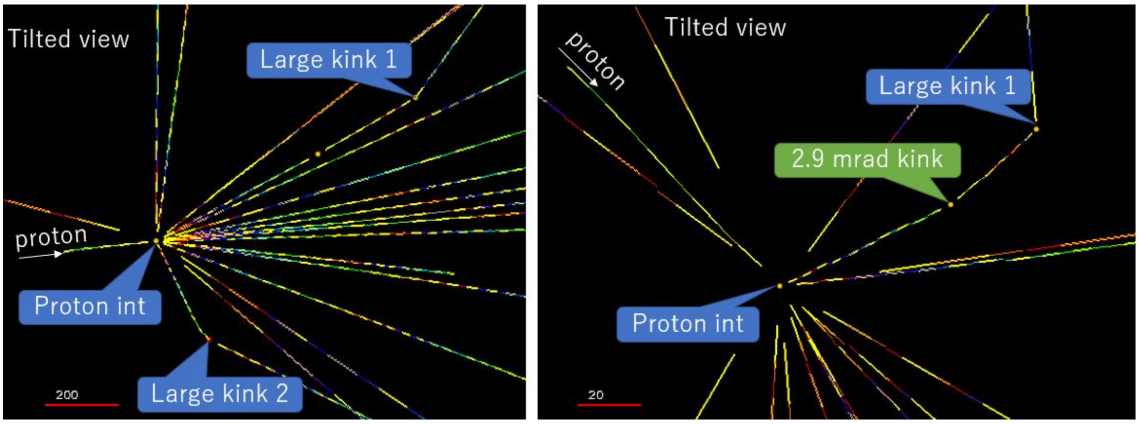

Figure 2: An event with two large kinks detected in the pilot run data. One of the kink parents has a small kink of 2.9 mrad.

4 Conclusion

The DsTau experiment was approved by CERN's research board in 2019 aiming at measuring tau neutrino production in p-A interactions by employing the CERN-SPS proton beam and nuclear emulsion technique. The test beam studies and the pilot run were successfully carried out in 2016-2017 and 2018 respectively. The data processing and analysis of the pilot run are ongoing. Events having a small kink angle are successfully reconstructed in the pilot run data. The collected data in the pilot run would allow the re-estimation of the tau neutrino interaction cross-section. The full-scale physics runs will be performed in 2021 and 2022. In the physics run, 2.3×10^8 proton interactions will be collected in the tungsten target, and about 10^3 D_s decays will be detected. The 2021 run is scheduled in between September and October. The preparation of the physics run is going on smoothly and all the components of the experiment will be ready before the physics run.

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