PROCEEDINGS OF SCIENCE

Study of tau-neutrino production at CERN SPS

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Lepton universality in tau-neutrino (ν_τ) scattering has been poorly tested. More precise measurement of the ν_τ cross section would enable a search for new physics effects in ν_τ–nucleon CC interactions. Such measurement also has practical importance for next-generation neutrino oscillation experiments and astrophysical ν_τ observations. The DsTau project has been proposed at CERN SPS to study tau-neutrino production with the aim of providing important data for future ν_τ measurements. For ν_τ cross section measurements, the practical method of producing an artificial ν_τ beam employs the sequential decay of D_s mesons produced in high-energy proton interactions. However, there has been no experimental measurement of the D_s differential production cross section in fixed-target experiments using proton beams, which leads to a large systematic uncertainty on the ν_τ flux estimation. The DsTau project aims to reduce this uncertainty in the current cross section measurement from about 50% to 10% by measuring the D_s differential production cross section. For this purpose, emulsion detectors with a 50-nm spatial resolution will allow the detection of $D_s \to \tau \to X$ double kinks in a few mm range. Results from the beam tests conducted in 2016–2017 are presented together with a prospect for the pilot run in 2018 and the physics run in 2021.

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1. Physics motivations

To date, lepton universality in tau-neutrino (ν_τ) scattering has been poorly tested. More precise measurement of the ν_τ cross section would enable a search for new physics effects in ν_τ–nucleon CC interactions. Such measurement also has practical importance and value for future neutrino-oscillation experiments and astrophysical ν_τ observations. DsTau is a new project, which has been proposed at CERN SPS, to study tau-neutrino production [1] aiming at providing important data for future studies of ν_τ interaction.

For a ν_τ cross section measurement, the practical method of producing an artificial ν_τ beam employs the sequential decay of D_s mesons produced in high-energy proton interactions (Fig. 1). However, there has yet to be an experimental measurement of the D_s differential production cross section in fixed-target experiments using proton beams, which has led to a large systematic uncertainty on the ν_τ flux estimation. Therefore the D_s differential production cross section must be measured as a first step towards a more precise ν_τ cross section measurement. This was the primary source of the >50% error in the cross section measurement by DONUT [2]. The statistical uncertainty, 33% in DONUT, is expected to be reduced to about 2% in future ν_τ programs such as the proposed SHiP project [3].

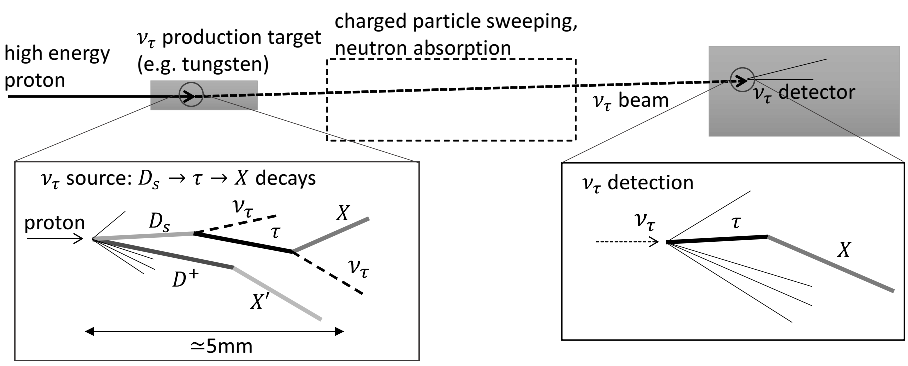

Figure 1: Concept of ν_τ cross section measurement.

In addition to the primary objective of measuring D_s production, analyzing 10^8 proton interactions combined with the high yield of 10^5 charmed decays produced as by-products will enable the extraction of additional physical quantities, including the intrinsic charm content of a proton, the interaction length of charmed hadrons, the Λ_c production rates, and the search for super nuclei.

2. Principle of the experiment

The objective of the DsTau project is to reduce the systematic uncertainty in the cross section measurement from about 50% to 10%. This will be achieved by detecting 1000 $D_s \to \tau \to X$ events and thereby measuring the D_s differential production cross section in 400-GeV proton interactions. This double decay occurs at a distance of ∼5 mm. The challenge of this measurement is the detection of the tiny kink angle of the $D_s \to \tau$ decay, which has a mean value of 7 mrad. To accomplish this, emulsion detectors with nanometric precision readout will be used. The emulsion detector has a position resolution of 50 nm [4], which translates to an intrinsic angular resolution

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of 0.35 mrad with a 200-μm-thick plastic base layer (Fig. 2 (left)). As shown in Fig. 2 (right), each detector unit comprises a 500 μm-thick tungsten target, which is followed by 10 emulsion films interleaved with 200-μm-thick plastic sheets acting as high-precision particle trackers and decay volumes for short-lived particles. A module comprises ten such units followed by an ECC to measure the momenta of the daughter particles. A total of 370 modules will be exposed to a 400-GeV proton beam from SPS at a uniform density of 10^5 protons/cm^2 on the module surface. An estimated 4.6×10^9 protons on target will be collected, yielding 2.3×10^8 proton interactions in the tungsten plates, and 1000 detected $D_s \to \tau$ decays.

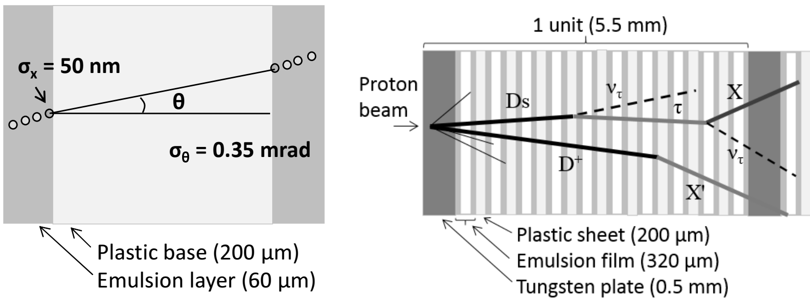

Figure 2: Left: Schematic of the angular measurement in an emulsion film. An angular precision of 0.35 mrad can be achieved by a single emulsion film. Right: A schematic of the topology of $D_s \to \tau \to X$ double-kink events in the detector.

3. Readout and data analysis scheme

The data analysis will require the full-area scanning of the 1000-m^2 emulsion surface by the world's fastest readout system, the Hyper Track Selector (HTS) [5]. After detecting τ-decay topologies, events will be analyzed by dedicated high-precision systems using a piezo-based high-precision Z-axis, allowing emulsion hits to be measured with a nanometric resolution.

To study the differential production cross section of D_s mesons, the momentum of the D_s meson (P_{D_s}) must be measured. Because D_s mesons decay quickly and the invisible ν_τ's escape measurement, the direct measurement of P_{D_s} is not possible. However, the peculiar event topology gives us indications of P_{D_s}. Since the $D_s \to \tau \to X$ decay topology has two kink angles ($\theta_{D_s \to \tau}$, $\theta_{\tau \to X}$) and two flight lengths (FL_{D_s}, FL_τ), the combination of these four variables effectively provides an estimate of P_{D_s}. A machine learning algorithm was trained with a simulated sample ($\tau \to$ 1 prong) using the four variables to estimate P_{D_s}. The momentum resolution is estimated to be 18%.

4. Beam tests and prospect of future runs

Two test beam campaigns were performed in November 2016 and May 2017 at CERN SPS. Figure 3 (left) shows the detector setup at the H4 beamline. To analyze the data, a new tracking algorithm was developed to reconstruct tracks in the extremely high track density of O(10^5–10^6) protons/cm^2, which is 1000 times higher than that of OPERA. An example of the reconstructed

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data from the detector is shown in Figure 3 (center), proving that analyses of short-lived particles are possible (Figure 3 (right)).

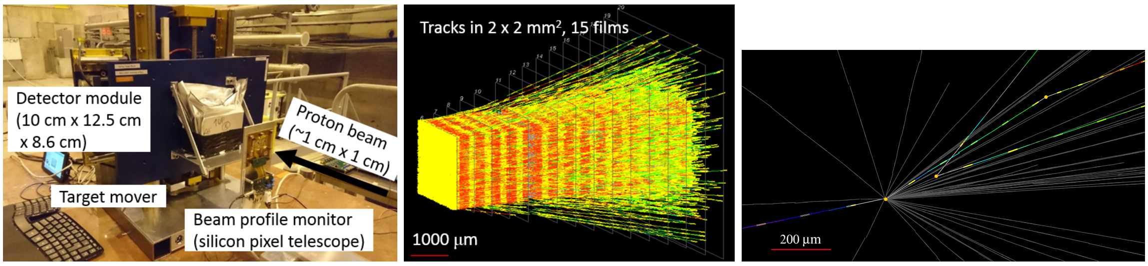

Figure 3: Left: Photo of the detector setup for the test beam campaign at the CERN SPS H4 beamline. The detector module was driven by a target stage such that it was uniformly exposed to the proton beam at a density of 10^5 protons/cm^2. Center: An example of the track data reconstructed in 2×2 mm^2 and 15 films. About 15,000 tracks are reconstructed in this volume. Right: An event with a neutral 2-prong (vee) and a charged 1-prong (kink) topology (tilted view).

The production of emulsion films for 30 detector modules is in progress for the pilot run in August 2018. This is to test large-scale data taking and provide an estimation of the background; however, it also already allows us to re-evaluate the ν_τ cross section measured by DONUT by significantly reducing the overall systematic uncertainty. With the outcome of the physics run in 2021 (Figure 4), DsTau will provide essential inputs for future ν_τ experiments and pave a way for the search of new physics effects in ν_τ–nucleon CC interactions.

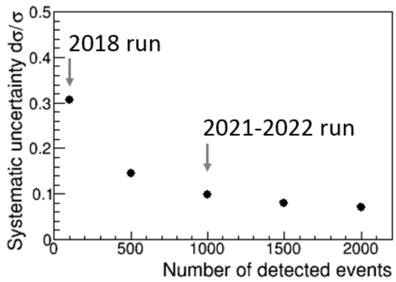

Figure 4: Expected performance of the experiment to reduce systematic uncertainty for ν_τ cross section measurement.

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