PROCEEDINGS OF SCIENCE

NA65/DsTau: Study of tau-neutrino production at the CERN SPS

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DsTau is an experiment at the CERN SPS, approved by CERN in June 2019 as NA65, to study ν_τ production aiming at providing important data for future ν_τ studies. A precise measurement of the ν_τ cross section would enable a search for new physics effects in ν_τ CC interactions. It also has practical importance for the next generation experiments for neutrino oscillation studies and astrophysical ν_τ observations. The practical way of producing a ν_τ beam is by the sequential decay of D_s mesons produced in high-energy proton interactions. However, there is 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 experiment aims to reduce the systematic uncertainty in the current ν_τ cross section measurement to 10% or below, by measuring the D_s differential production cross section (especially longitudinal dependence). For this purpose, emulsion detectors with a spatial resolution of 50 nm will be used allowing the detection of $D_s \to \tau \to X$ double kinks in a few mm range. During the physics runs, 2.3×10^8 proton interactions will be collected in the tungsten target, and 1000 $D_s \to \tau$ decays will be detected. In addition to the primary aim, the analysis of $\mathcal{O}(10^5)$ charmed particle pairs can provide valuable by-products such as studies of the forward charm production and the intrinsic charm content in proton. Results from the test runs and the pilot run will be presented together with a prospect for the physics runs in 2021 and 2022.

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1. Study of tau neutrinos

There are only a few measurements for tau neutrinos and their properties are not well studied. In particular, the ν_τ charged-current (CC) cross section is known with much larger statistical and systematical uncertainties compared to the other neutrino flavors, as shown in Figure 1. Moreover, a precise measurement of the ν_τ CC cross section would be interesting to test the lepton universality in neutrino scattering. The measurement of the ν_τ CC cross section has also a practical impact on current and future neutrino oscillation experiments. Mass hierarchy measurements in Super-Kamiokande [1] and accelerator neutrino experiments such as DUNE [2] and Hyper-Kamiokande [3] rely on ν_e flux measurements. The systematic uncertainty from the ν_τ interaction cross section could be a limiting factor in their analyses due to ν_τ interactions with $\tau \to e$ decays.

The ν_τ interaction cross section was only measured in DONuT [4], OPERA [5] and SK [6] but with large statistical and/or systematical uncertainties of 30-50% due to low statistics and experimental uncertainties. In a future experiment SHiP [7] at CERN, it is expected to collect thousands of ν_τ interactions, providing a negligible statistical uncertainty in the cross section measurement. Thus the overall uncertainty of the cross section will be determined by the systematic uncertainties, especially by the ν_τ flux uncertainty, which will be studied by this experiment [8, 9]. The dominant source of ν_τ in the accelerator-based neutrino beam is leptonic decays of $D_s^\pm$ mesons produced in proton-nucleus interactions. It is necessary to know the differential production cross section of D_s to estimate the flux of ν_τ's that pass through the detector. Conventionally, the differential production cross section of charmed particles is approximated by a phenomenological formula $d^2\sigma/dx_F dp_T^2 \propto (1- \mid x_F \mid)^n e^{-bp_T^2}$ (1), where x_F is Feynman x and p_T is transverse momentum. n and b are the parameters controlling the longitudinal and transverse dependence of the differential production cross section, respectively. Although there were several measurements on charm particles as summarized in [10], there is a lack of measurements on the D_s differential production cross section in 400 GeV proton interactions, especially concerning the longitudinal dependence represented by the parameter n. This has been the main source of the uncertainty of the ν_τ cross section measurements. A new measurement of differential production cross section of D_s is necessary for precise ν_τ measurements in future experiments.

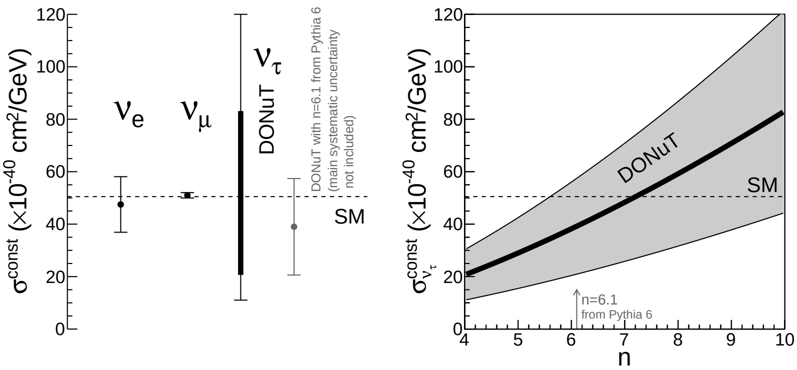

Figure 1: Left: ν, $\overline{\nu}$ averaged cross section of the three neutrino flavors. For the DONuT's result, the value is plotted in the empirical range of the parameter n in formula (1). Right: The cross section result from the DONuT experiment [4].

2. Physics goals

In the DsTau experiment, a direct measurement of ν_τ production will be performed by detecting $D_s \to \tau \to X$ decays following high-energy proton-nucleus interactions. The project aims to detect ~ 1000 $D_s \to \tau \to X$ decays in 2.3×10^8 proton interactions with the tungsten target.

DsTau will provide a differential cross section of D_s production in 400 GeV proton-nucleus interaction, which can be directly implemented in future experiments. It could be fit with the phenomenological formula (1), and the parameter n could be estimated. The expected precision of the parameter n as a function of the number of detected events is shown in Figure 2. With the statistics of 1000 $D_s \to \tau \to X$ detected events, the relative uncertainty of the ν_τ flux will be reduced to below 10%.

In addition to the primary aim of studying ν_τ production, a high yield of $\mathcal{O}(10^5)$ charmed particle pairs is expected. The analysis of those events can provide valuable by-products, such as measurements of the forward charm production, the intrinsic charm content in proton [11], the interaction cross section of charmed hadrons.

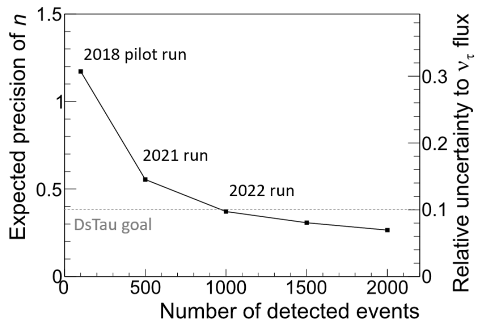

Figure 2: Expected precision for the measurement of parameter n as a function of the number of detected $D_s \to \tau \to X$ events.

3. The DsTau detector

The principle of the experiment is to detect the topology of $D_s \to \tau \to X$ events appears as a double-kink as shown in Figure 3 (left). In addition, another decay of a charged/neutral charmed particle will be observed with a flight length of a few millimetres. Such a double-kink plus decay topology in a short distance is a very peculiar signature of this process.

The basic unit is made of a 500-μm-thick tungsten plate as a target followed by 10 emulsion films interleaved with 200-μm-thick plastic sheets which act as a decay volume for short-lived particles as well as high-precision particle trackers. A module comprises ten such units followed by the so-called Emulsion Cloud Chamber for momentum measurement of the daughter particles. The whole detector module is 12.5 cm wide, 10 cm high and 8.6 cm thick and consists of a total of 131 emulsion films. During the physics runs, a total of 370 modules will be exposed to the 400 GeV proton beam.

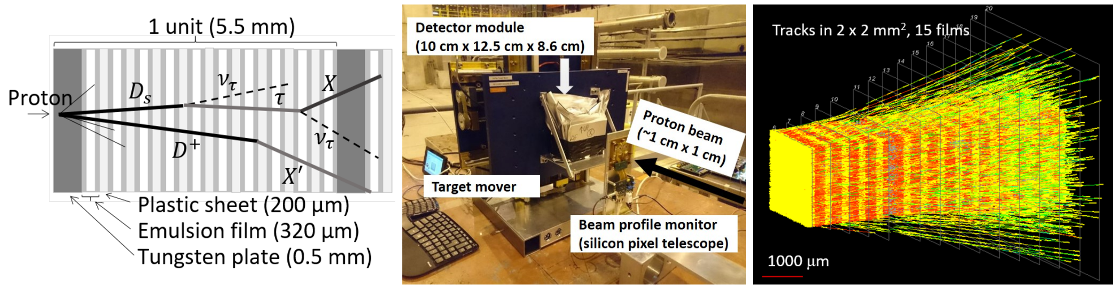

Figure 3: Left: Schematic view of the basic unit. Middle: Detector setup for the test beam at the CERN SPS H4 beamline. The module was driven by a target mover so that it was uniformly exposed to the proton beam. Right: 3D display of the reconstructed tracks.

The detection efficiency for the $D_s \to \tau \to 1$ prong events is estimated by PYTHIA simulation to be 20%. The momentum of D_s will be reconstructed by means of a machine-learning algorithm using topological variables such as flight lengths (FL_{D_S}, FL_τ) and kink angles ($\delta\theta_{D_s\to\tau}$, $\delta\theta_{\tau\to X}$). The combination of these four variables provides an estimate of P_{D_s}. The resolution is estimated to be 20%.

4. Results from the test runs and the pilot run

Two test runs were conducted at the CERN SPS H2 and H4 beam lines in 2016 and 2017 to test and improve the detector structure and exposure scheme. In 2018, a pilot run was conducted, collecting 10% of the full statistics collected. Figure 3 (middle) shows the detector setup at the H4 beamline. To have uniform irradiation of the detector, the beam spot was enlarged to roughly 1 cm$\times$2 cm by tuning the beam optics.

The event analysis is based on readout of the full emulsion detectors by the Hyper Track Selector (HTS) system [12] with the readout speed of 0.45 m^2/hour/layer, which is the fastest system at present. Readout of emulsion films from the pilot run is in progress and about 86% of the total will be finished by the end of 2019. The reconstructed tracks (Figure 3 (right)) are then used to find vertices. A systematic search for the decay topology of short-lived particles is applied to the reconstructed vertices. Events with a charged particle decay and another charged or neutral decay are selected. An example of double charm event candidate found by this analysis scheme is shown in Figure 4. The statistics of the found vertices and events with the double decay topology observed in a sub-sample of the data are shown in Table 1. It is consistent with the prediction. The decay length distribution of the data and the FLUKA simulation is shown in Figure 5. Events with decay topologies will be further analyzed by dedicated high-precision systems [13] to detect $D_s \to \tau$ decays.

5. Summary and prospects

The DsTau experiment will study ν_τ production following high energy proton interactions, 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. The letter of intent and proposal of DsTau were reviewed by CERN-SPSC. DsTau was then approved by CERN in June 2019 as NA65.

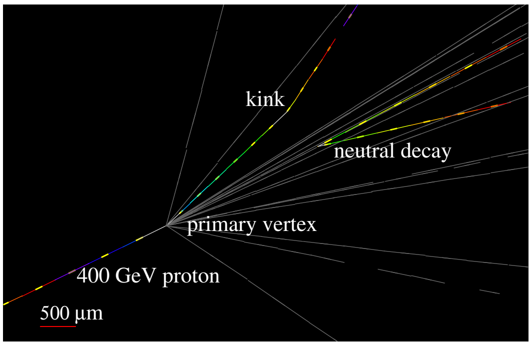

Figure 4: A double charm candidate event with a neutral 2-prong (vee) and a charged 1-prong (kink) topology (tilted view) [10].

	Observed	Expected	
Vertices in tungsten	29 297	28 390 ± 910 (syst)	
		Signal	Background
Double decay topology	19	13.5±3.2	2.4±0.3

Table 1: Statistics found in the sub-sample of data in which 5 629 670 protons are analyzed in one unit (1 tungsten plate) [10].

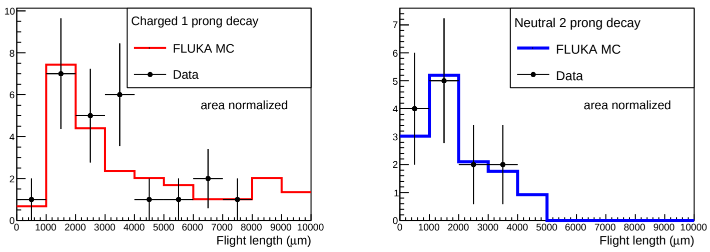

Figure 5: Flight length distributions for charged 1-prong and neutral 2-prong decay candidates in the double-charm event samples [10].

The test runs in 2016-2017 and the pilot run in August 2018 were performed, in which we accumulated over 20 million proton interactions in the detector. The readout and analysis of these samples are in progress. The results provide a proof of the feasibility of the full-scale physics runs in 2021 and 2022. DsTau will provide a ν_τ flux prediction for future experiments with accuracy under 10%. The systematic uncertainty of the ν_τ CC cross section measurement can be sufficiently reduced.

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