Study of tau neutrino production in proton-nucleus interactions

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Abstract. Tau neutrino properties are not so well known in comparison to those of muon or electron neutrinos. The tau neutrino interaction cross-section was directly measured by the DONUT experiment in 2008 on a basis of 9 registered tau neutrinos, and with a large systematical error of 50% due to a poor knowledge of the tau neutrino flux in this beam dump experiment. However, more accurate measurement of the cross section is needed for future neutrino experiments. It would also allow testing the Lepton Universality (LU) of Standard Model in neutrino interactions. Recently several results for B-meson decays (LHCb, Babar) demonstrated hints of possible LU violation. The tau neutrinos are produced in the Ds meson decays to tau, $D_s\rightarrow \tau \nu\tau$, and the cascade decay of the tau $\tau \rightarrow \nu \tau X$. DsTau experiment has been proposed to study the tau neutrino production at CERN SPS. It will measure the $D_s$ production differential cross-section in the proton-tungsten interactions. This will allow reducing of the uncertainty due to the tau neutrino flux in the DONUT result from 50% to 10%. The peculiar $D_s$ cascade decay topology (“double kink”) in a few mm range will be detected by nuclear emulsion tracker thanks to its excellent spatial resolution (~50nm).

In 2016 and 2017, we made test beam exposures of nuclear emulsion modules at CERN SPS 400GeV/c proton beam followed by the pilot run in August 2018. A physics run in 2021 is scheduled. The status and prospects of the DsTau project as well as a review of the modern nuclear emulsion technique and the methods of its data analysis are presented.

1. Introduction

Tau neutrino existence was predicted after tau lepton discovery in 1975, but only 25 years after, in 2000, first few tau neutrinos were detected in DONuT experiment [1]. So far only 19 tau neutrinos were registered in the DUNuT and OPERA [2] experiments. Given such poor statistics, the properties of tau neutrino are not well studied. In particular, the cross section of tau neutrinos charged current interaction is known with much larger statistical and systematical uncertainties [1] than for the other types of neutrinos (figure 1). The first is due to a difficulty of tau neutrinos detection, and the later is mainly determined by the uncertainty of the amount of tau neutrinos in the beam.

A dominant source of tau neutrinos in the beams at accelerators is leptonic decay of $D_s$ mesons, produced in protons-nucleus interactions, to tau lepton and tau neutrino: $D_s\rightarrow \tau \nu\tau$, $\tau \rightarrow \nu\tau X$, producing $\nu\tau$ and anti-$\nu\tau$ in every $D_s\rightarrow \tau$ decay.

However, the cross section of $D_s$ mesons production in the interactions of primary protons with nuclear target is not well measured yet. The existing studies of $D$-mesons production have low statistics and doesn’t provide a reliable results for the differential cross-section [3].
Figure 1. The measured cross section of the charge current interactions of all three types of neutrinos.

In the DsTau project [4-8], we propose a new approach to study directly $\nu_\tau$ production by measuring the $D_s \rightarrow \tau$ decays in high-energy proton-nucleus interactions. The project aims to detect ~1000 $D_s \rightarrow \tau$ events in $2.3 \times 10^8$ proton interactions in tungsten target to study the differential production cross section of $D_s$ mesons. With this project, the uncertainty of the $\nu_\tau$ flux prediction will be reduced down to <10%. Then, the systematic uncertainty of the $\nu_\tau$ cross-section measurement will not prevent testing the Lepton Universality in neutrino scattering in future neutrino experiments where high $\nu_\tau$ detection statistics is expected [9]. The measurement of the $\nu_\tau$ cross section has a practical impact on the neutrino oscillation experiments. Mass hierarchy measurements by means of atmospheric neutrinos (for example, by Super-K and Hyper-K) rely on $\nu_e$ measurements that are contaminated by $\nu_\tau$ due to $\tau \rightarrow e$ decays. The systematic uncertainty from the $\nu_\tau$ cross section will be the limiting factor in their analysis [10]. Accelerator-based experiments (DUNE [11], Hyper-K [12]) also suffer from $\nu_\tau$ background to $\nu_e$. Unlike other error sources, the uncertainty of the $\nu_\tau$ cross section cannot be constrained by near detector measurements, and this is relevant for CP-violation and mass hierarchy analyses. Along with the low-energy neutrino study (E$_{\nu} \sim 1$ GeV), DUNE plans to extend its physics program to high-energy neutrino beams and study the $\nu_\tau$ appearance channel (E$_{\nu} > 10$ GeV). In this scenario, a better understanding of the $\nu_\tau$ cross section will be necessary. Results from the DsTau project will also benefit high-energy astrophysical $\nu_\tau$ observations (for example, IceCube [13]).

2. Principle of the experiment

The dominant source of $\nu_\tau$ is a sequential decay of $D_s$ mesons, $D^+_s \rightarrow \tau + \nu_\tau \rightarrow X \nu_\tau$ and $D^-_s \rightarrow \tau^- \nu_\tau \rightarrow X \nu_\tau$, created in high-energy proton interactions with the nuclear target. The topology of such an event is shown in figure 2. $D_s$ decays to $\tau$ with a mean flight length of 3.3 mm and $\tau$ decays with a mean flight length of 2.0 mm. In addition, because charm quarks are created in pairs, another decay of charged/neutral charmed particle will be observed with a flight length of a few millimetres. This «double-kink plus decay topology» is a very peculiar signature for this process, and with a proper selection the background for such a topology is estimated to be less 2% while the detection efficiency is still high (about 20%). Measuring this signature has an advantage over comparing the $D_s$ production cross section and the decay-branching ratio of $D_s \rightarrow \tau$ separately. Our measurement gives an inclusive measurement of both of them; therefore some of the systematic errors are cancelled out. We therefore consider this measurement as a direct measurement of $\nu_\tau$ production. However, the detection of this topology is challenging – one needs precisely measuring small track angles in a small volume of the event.
State-of-the-art emulsion detector with a nanometric spatial resolution will be used to achieve this goal. The technique provides a unique opportunity to detect the peculiar double-kink topology of $D_s \to \tau \to X$ decays. The nuclear emulsion technique went through a technological revolution during last 20 years. The high-speed and high-precision readout of the track information in the emulsions has been improved drastically (almost 4 orders of magnitude) since the time of the DONuT experiment and became readily available. Ultimate spatial resolution of the emulsions allows accumulating up to $10^5$ tracks in a square centimeter with effective reconstructing of the vertexes.

The DsTau setup consists of a beam monitor detector, block of emulsions interspaced by plastic plates and thin (0.5 mm) tungsten target plates (every 10 emulsions). The block of emulsions moves in the directions across the beam with a help of dedicated mechanism and with a speed depending on the beam intensity to have uniform exposure over the emulsions surface (figure 3). In 2017, we had short beam tests at CERN SPS 400 GeV proton beam to prove the basic ideas. In 2018, during the pilot run, we accumulated $1.7 \times 10^7 p\cdot W$ interactions (about 10% of the whole data set to be recorded).

3. Data analysis

The data analysis will be performed in two stages: first, the full-area of 1000 m$^2$ emulsion surface will be scanned by the world’s fastest readout system, the Hyper Track Selector (HTS) [14]. After detecting $\tau$-decay topologies, events will be further analyzed by dedicated high-precision systems using high precision piezo Z-axis stage, which allows the emulsion tracks measuring with a nanometric resolution. The double kink topology will be recognized by a special algorithm. To study the differential production cross section of $D_s$ mesons, the momentum of the $D_s$ meson has to be measured. Because $D_s$ mesons decay quickly and the invisible $\nu_\tau$ escape measurement, the direct measurement of the momentum is not possible. However, the peculiar event topology allows using an indirect method. 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 (of $D_s$ and $\tau$), the combination of these four variables effectively provides an estimate of $D_s$ momentum. A machine learning algorithm was trained with a simulated sample ($\tau \to 1$ prong) using the four variables to prove the technique. The momentum resolution was estimated to be about 18%.
3.1. Expected performance.

The branching ratio of $\tau$ lepton decay to a single charged particle (1-prong) and to 3-prong mode is 85% and 15%, respectively [15]. The following estimation was performed for the case of $\tau \rightarrow 1$-prong. The detection efficiency is estimated to be 20% using a PYTHIA 8.1 [16] simulation, the following selection criteria: (1) the parent particle has to pass through at least one emulsion film (two sensitive layers), (2) the first kink daughter has to pass through at least two sensitive layers and the kink angle is $\geq 2$ mrad, (3) the flight length of the parent and the first kink daughter has to be $< 5$ mm, (4) the second kink angle is $\geq 15$ mrad and (5) the partner charm particle is detected with $0.1 \text{ mm} \leq \text{ flight length} < 5$ mm (they can be charged one with a kink angle $> 15$ mrad or neutral). Figure 4 shows the estimated distribution of the events as a function of the Feynman $x$ ($x_F = 2p^{CM}Z/\sqrt{s}$) and $p_T$ before the selection (a) and the detection efficiency in the $x_F - p_T$ plane (b). A possibility of further improvements of the detection efficiency is under study. Since the track length affects the angular resolution, the better resolution can be achieved when the particles pass through more than two sensitive layers. The efficiency can be improved by applying different thresholds for the first kink angle, depending on the flight length of the parent and daughter.

![Figure 3. The experimental setup.](image)

![Figure 4. Simulated distribution of the D_s events in the $x_F - p_T$ plane before the selection (a) and their expected detection efficiency (b).](image)

The processing of the data samples of 2017 and 2018 is ongoing. In figure 5 the examples of the reconstructed events of proton interactions with the target are presented (a) as well as the distribution of the vertex coordinate along the beam.
Figure 5. Examples of the reconstructed vertexes of the p-W interactions and the distribution of their Z coordinate.

4. Prospects

The dataset accumulated in 2018 will be processed in 2019 to finally confirm the feasibility of D_s detection and of the tau neutrino production study. The vertex detection algorithm will be further developed to make the processing faster. Machine learning approaches to suppress the hadron interaction background and to improve the momentum measurement will be elaborated. In 2021-2022, the main dataset is planned to be registered. Its processing will allow measuring of the D_s production differential cross section and decreasing of the systematic uncertainty in the tau neutrino charge current cross-section down to 10%. A large amount of charmed particles decays is expected to be recorded as well providing possibility of interesting by-product results.

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