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Letter of intent

Study of ν_τ production by measuring $D_s \to \tau$ events in 400 GeV proton interactions:

Test of lepton universality in neutrino charged-current interactions

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Abstract

The muon-neutrino charged-current (CC) cross section has been measured by many experiments. However, there has been only one measurement of the tau-neutrino CC cross section by the DONuT experiment with a systematic uncertainty larger than 50%, mainly due to uncertainties in the D_s differential production cross section in high energy proton interaction. The evaluation of tau-neutrino cross section would provide a test of lepton universality in neutrino CC interactions, which has never been well tested for tau-neutrinos. In this new program, we propose to study ν_τ production (D_s production fraction $\times$ decay branching ratio of $D_s \to \tau\nu_\tau$) and the energy distribution by analyzing $D_s \to \tau$ events in 400 GeV proton interactions. By employing the state-of-the-art emulsion particle detector technologies, we will analyze 10^8 proton interactions and detect the double kink topology of $D_s \to \tau \to X$ decays. Accomplishing this new measurement, we will re-evaluate the tau-neutrino cross section with the data from DONuT. The expected outcome will significantly reduce the total systematic uncertainty to the 10% level, which is well below the statistical uncertainty of DONuT. In 2016, we will perform a prototype test experiment with 20 m^2 emulsion surface, corresponding to a scale of about 1:20 of the final setup. This test will provide a proof of principle and the results will be used to optimize the module structure. We plan to carry out the first run of the real experiment in 2018.

1 Introduction

Neutrino physics is entering a high precision era where a deeper knowledge of interaction cross sections will be required. Many experiments have been performed or are being conducted for the ν_μ charged-current (CC) cross section measurement [1]. However, there has been only one measurement of the ν_τ CC cross section by the DONuT experiment [2]. In DONuT, ν_τ interactions were directly observed for the first time [3] and the ν_τ cross section was measured with a systematic uncertainty larger than 50% as summarized in the following section.

In this new program we propose to study ν_τ production (D_s production fraction $\times$ decay branching ratio of $D_s \to \tau\nu_\tau$) and the energy distribution by analyzing $D_s \to \tau$ events in 400 GeV proton interactions. By employing the new measurement, we will re-evaluate the ν_τ cross section with the data from DONuT. The new measurement will reduce the total systematic uncertainty to the 10% level that is well below the statistical uncertainty of 33%.

The evaluation of the ν_τ cross section would provide a test of lepton universality in neutrino CC interactions which has never been well tested for ν_τ. There are theoretical calculations [4] to test lepton universality in ν_τ scattering, predicting possible new physics effects in ν_τ cross section. Improvement of the ν_τ CC cross section measurement would possibly provide constraints on the theoretical models. It will be also useful for future possible experiments which are aiming to detect ν_τ such as IceCube. In addition, there would be some by-products, e.g. D_s and Λ_c production rates and topological branching ratios, for which we could improve the current knowledge.

We will conduct the measurement of $D_s \to \tau$ events produced by the 400 GeV proton beam using emulsion particle detectors, which have a unique capability to detect topologies of short-lived particles such as charmed hadrons and τ leptons. Recent advances in emulsion particle detector technologies make possible to analyze some orders of magnitude larger detector surface than the past experiments such as Fermilab experiment E653 that was the previous emulsion fixed-target experiment using high energy hadron beams. In E653, only 10^5 proton interactions were analyzed in emulsions [5]. By now we have the ability to analyze 10^8 proton interactions that will yield 10^5 charmed-particles.

2 Results from the DONuT experiment

DONuT collected data in 1997 and published the final results in 2008, based on 3.6×10^{17} protons on target (pot) using the 800 GeV Tevatron beam at Fermilab. The neutrino beam line is shown in Fig. 1. The 800 GeV protons were stopped in a beam dump in the form of a solid block of tungsten alloy. Following the beam dump, there were two dipole magnets and an additional 18 m of passive steel shielding. Neutrinos and muons were emerging at the end of this shield, 36 m from the beam dump. Neutrinos originated from decays of particles created by primary proton interactions. About 97% of the neutrino flux was composed of ν_e and ν_μ, the rest being ν_τ. ν_τ are produced by the subsequent decay of the produced D_s mesons. The calculated energy spectra of neutrino interacting in the DONuT emulsion target is shown in Fig. 2.

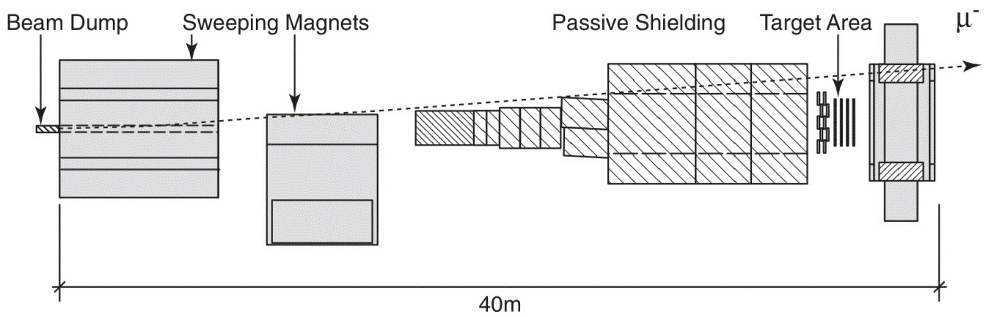

Figure 1: Schematic view of the neutrino beam line [2]. The 800 GeV protons are incident on the beam dump from the left. The emulsion modules are located within the target area, 36 m from the beam dump.

The neutrino target was a hybrid detector of emulsion and scintillating fiber tracker (SFT). The emulsion target, called emulsion cloud chambers (ECC), had repeated structure of 1 mm thick steel sheets interleaved with emulsion plates. Integrated into the emulsion-target station were 44 planes of the SFT built using 0.5-mm-diam scintillating

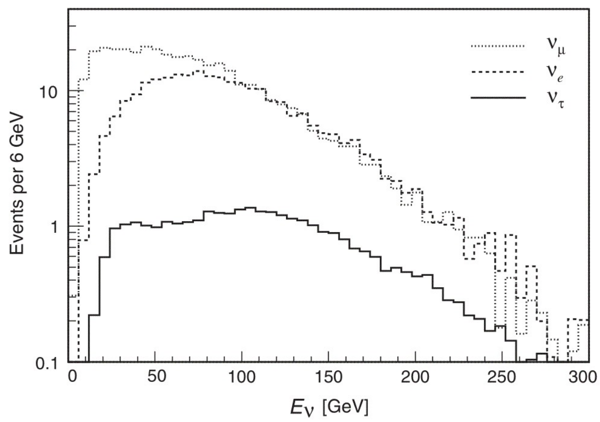

Figure 2: Calculated energy spectra of neutrinos interacting in the DONuT emulsion target [2].

fibers to provide medium-resolution tracking and a time stamp for each event. Muon identification was performed using the muon ID system and electron identification using the emulsion, the SFT and the electromagnetic calorimeter.

Nine ν_τ CC events were detected from a total of 578 observed neutrino interactions and were used to estimate ν_τ CC cross section for the first time [2]. The largest uncertainty in the cross section measurement was the differential cross section of D_s produced in the 800 GeV p-N interactions, which was used to calculate the ν_τ flux. Charmed particles produced by 800 GeV protons in the beam dump were described using the phenomenological formula,

$$\frac{d^2\sigma}{dx_F dp_T^2} \propto (1-|x_F|)^n exp(-bp_T^2)$$

where x_F is Feynman x and p_T is transverse momentum. There is no published data giving n for D_s. So, the energy-independent part of the total CC cross section was parameterized as

$$\sigma_{\nu\tau}^{const} = 7.5(0.335n^{1.52})(1 \pm 0.33(stat.) \pm 0.33(syst.)) \times 10^{-40}\ cm^2 GeV^{-1}$$

This parameter-dependent cross section result is shown graphically in Fig. 3.

To date this remains the only measurement of the ν_τ CC cross section. In our new program, we will study D_s production and the energy distribution in 400 GeV proton-tungsten interactions. With the data, we will estimate the differential cross section of D_s in 800 GeV proton-tungsten interactions and will re-evaluate the ν_τ cross section using the above equation.

3 The experiment: $D_s \to \tau$ precision measurement in 400 GeV proton interactions

We propose to measure ν_τ production (D_s production fraction $\times$ decay branching ratio of $D_s \to \tau\nu_\tau$) and the energy distribution by analyzing $D_s \to \tau$ events and their angular distribution. We are aiming to detect 1000 $D_s \to \tau$ events to reduce the systematic uncertainty in the cross section evaluation to the 10% level.

D_s, produced in 400 GeV proton interactions, decays to τ with a mean flight length of 3.3 mm and τ decays with a mean flight length of 2.0 mm. The kink angle of $D_s \to \tau$

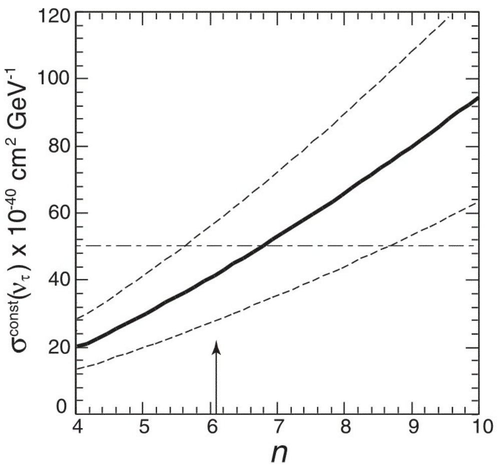

Figure 3: The energy-independent ν_τ cross section as a function of the parameter n is represented by the thick solid curve. The 1-σ statistical error is shown by the dashed curves and the average of the standard model neutrino and antineutrino cross sections is shown by the dot-dashed horizontal line. The arrow shows the expected value of n based on PYTHIA calculations.

decay is very small as shown in Fig. 4. The emulsion detector has an intrinsic spatial resolution of 0.05 μm (Fig. 5), corresponding to an angular resolution of 0.35 mrad. It is therefore capable of detecting the decays of $D_s \to \tau \to X$ by performing a high precision readout. The τ decay has instead a mean kink angle of 100 mrad and can be detected by standard readout. The analysis chain will be: 1) tag a kink of tau decay ($\tau \to X$) and 2) perform high precision measurement to detect an additional small kink ($D_s \to \tau$) for the selected events by 1).

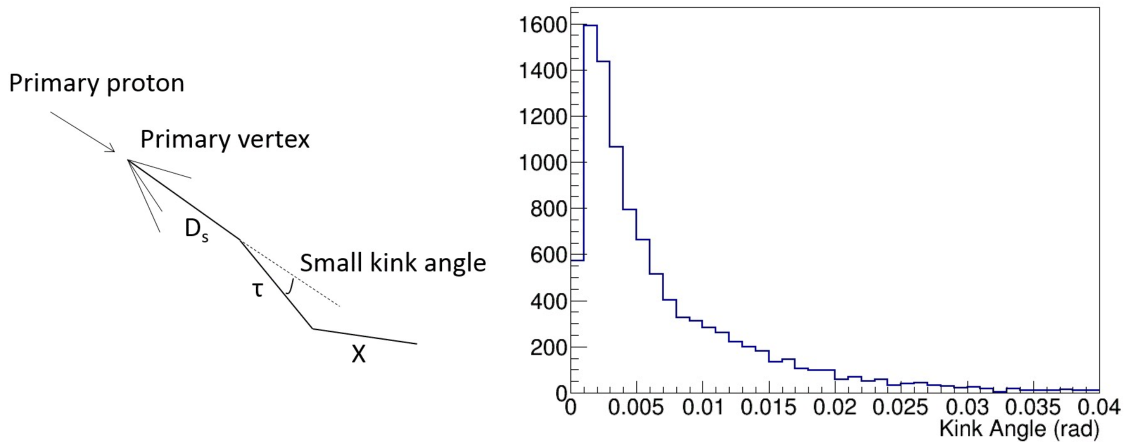

Figure 4: Left: Topology of $D_s \to \tau \to X$ events. Right: Kink angle distribution of $D_s \to \tau$. The mean is 7.0 mrad.

The detection efficiency is estimated to be 22% using PYTHIA simulation by requiring the following criteria: (i) the parent track passes through at least one emulsion film and the flight length is < 5 mm, (ii) the 1st kink angle is > 2 mrad, (iii) the flight length of the 1st kink daughter is < 5 mm, (iv) the 2nd kink angle is > 15 mrad and (v) detection of partner of the charm pair with the flight length < 5 mm (charged decays with the kink

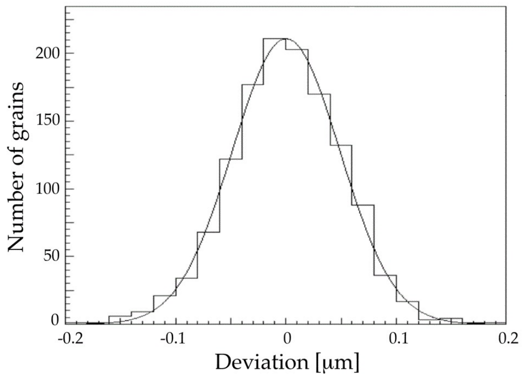

Figure 5: Deviation of grains from a linear-fit line for horizontal tracks [6].

angle > 15 mrad or neutral decays).

The main background source would be hadronic secondary interactions. A preliminary estimate was performed as follows. The mean free path in emulsions for interactions without detectable nuclear fragment is 11 m for 5 GeV pion beam [7] (for plastic, this value is to be measured). Using this value for both emulsions and plastic sheets as a tentative value, the probability to have a double kink with flight length shorter than 5 mm is $(4.5\times10^{-4})^2$ per particle. Assuming the particle multiplicity of 10, the probability of having a double kink which mimic a $D_s \to \tau$ event and a kink which mimic a partner charm event is $10 \times (4.5\times10^{-4})^2 \times 10 \times (4.5\times10^{-4}) = 9\times10^{-9}$. This is sufficiently smaller than the signal probability of 5×10^{-6} per proton interaction. More careful simulation will be needed for a precise estimation of the overall background and to study possible improvement using multivariate techniques. The estimation of hadronic background can be validated using real data of the experiment by analyzing a region outside of the decay volume where no signal event is expected.

In order to detect 1000 $D_s \to \tau$ events, 8.2×10^4 D_s are to be produced since the branching fraction of $D_s^+ \to \tau^+\nu_\tau$ is $(5.55 \pm 0.24)\%$ [8]. As the D_s production cross-section in tungsten target would be about 4×10^{-4} per proton interaction, 2×10^8 proton interactions are to be analyzed.

The module structure for this measurement is shown in Fig. 6. Here we define one unit as one tungsten plate followed by 10 emulsion films interspaced with 200 μm plastic sheets (as decay volume and tracker) and one module consists of 5 units. The emulsion film has 50 μm thick emulsion layers on both sides of a 200 μm plastic base, similar to OPERA film [9]. The thickness of each tungsten plate is 0.5 mm, so that 5 units has 0.025 interaction length. Thus, 8×10^9 pot are needed to achieve the goal. As an option, additional modules made of massive material plates interleaved with emulsion films might be placed downstream for the momentum measurement by multiple Coulomb scattering [10].

The modules will be moved during exposures in order to have uniform irradiation using a target mover. To keep the track density in the emulsion detector at 10^5 tracks/cm^2, we need a detector surface of 8×10^4 cm^2, corresponding to 800 modules (film size of 10 cm $\times$ 10 cm assumed). The total amount of emulsion surface will be 400 m^2. The expected setup of the experiment is shown in Fig. 7. The modules will be placed in the beam line one by one.

In order to distinguish D_s^+ and D_s^-, we are investigating the possibility of installing emulsions in a magnetic field (>5 T). This option might be realized if such a magnet is available.

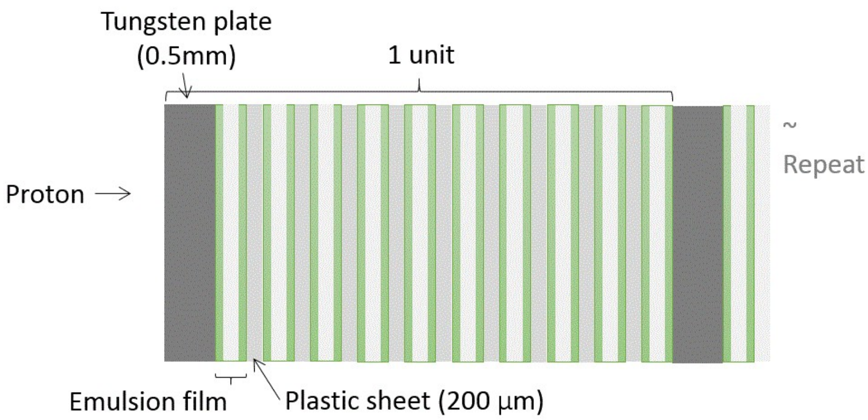

Figure 6: Schematic view of the module structure. One module consists of 5 units.

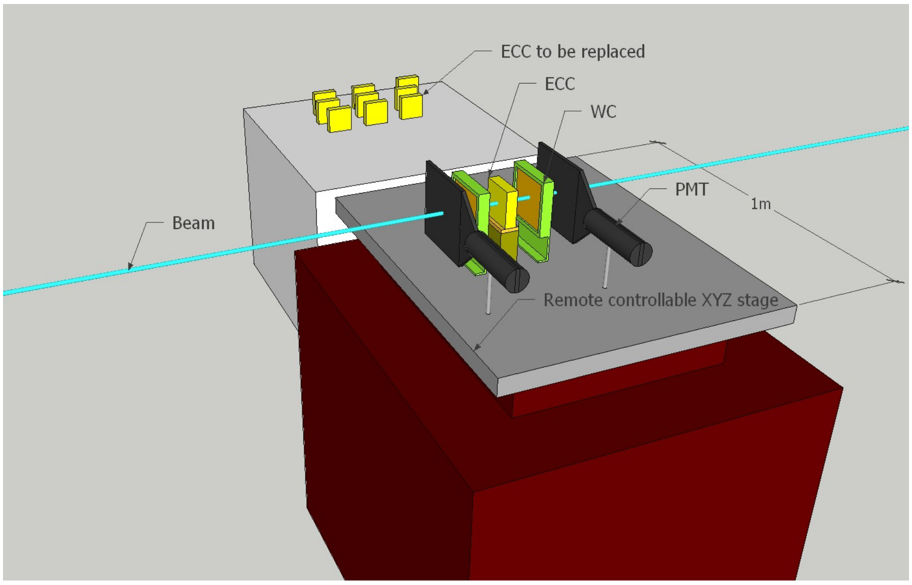

Figure 7: Schematic view of the expected setup of the experiment. An emulsion module is placed on the target mover, inserted between the beam monitors.

4 Readout of emulsion detectors

Over the last decade or so, the readout speed for emulsion detectors has improved remarkably with the evolution of electronics and computing technologies. The progress of readout speed is summarized in Table. 1. In order to deal with the large amount of data in the OPERA experiment, either a FPGA-based electronics [11] or a CPU-based multithread computing [12] have been employed, achieving a surface scanning speed as high as 20-50

cm^2/hour/microscope. In addition, the use of GPGPU (General Purpose Graphic Processing Unit) is recently introduced to speed up image processing and track reconstruction [13].

The bottleneck of scanning speed has been the mechanical movement of the microscope stage, which cannot exceed 5 Hz. A solution can be found in a new readout system called Hyper Track Selector (HTS) [14] which is under development at Nagoya University. The system is designed to maximize the field of view and maintain a low frequency of mechanical movement by using a lens for the photolithography in the inverse direction. About 5000 cm^2/hour has been achieved as of today and 9000 cm^2/hour (21.6 m^2/day) are expected to be reached, 100 times faster than the previous generation. Standard readout of 400 m^2 emulsion surface can be performed in a month.

Experiment	CHORUS	DONuT	OPERA	next generation
Running year	1994-1996	1996-1998	2008-2012	2015-
Scanning speed	0.1 cm^2/h	1 cm^2/h	20-70 cm^2/h	200-10000 cm^2/h

Table 1: Progress of emulsion surface scanning speed by automated readout

5 The collaboration

The collaboration is currently composed of groups from Aichi, Bern, Kobe and Nagoya. Nagoya and Bern have emulsion scanning stations, which are the two largest emulsion scanning laboratories in the world. The foreseen contributions from the groups are shown in Table. 2. The standard readout of the whole emulsion volume will be performed by HTS. After selecting τ decay candidate events, the high-precision readout will be carried out by a dedicated system to be developed in Bern. All groups will participate in the analysis of the data.

	Institutions
Emulsion detector	Bern, Kobe and Nagoya
High-speed readout of the whole volume	Nagoya
High-precision readout for the selected events	Bern
Analysis of the data	Aichi, Bern, Kobe and Nagoya

Table 2: Expected contributions to the experiment

6 Cost of the experiment

The emulsion detector cost has been evaluated in CHF by applying the current exchange rate between Yen and CHF. The results of cost evaluation are summarized in Table. 3.

As written in the previous section, we will use emulsion readout systems in Nagoya and Bern. The systems are being developed in the framework of other research activities and the overall costs are covered by existing funding sources.

	Cost (kCHF)
Emulsion gel	350
Film production	150
Support structure	50
Total	550

Table 3: Cost of the experiment

7 Beam requirements and schedule

Assuming the beam spot size of about 1 cm $\times$ 1 cm, we request 400 GeV protons with slow extraction of about 10^5 per spill to keep the track density in the emulsion detector at 10^5 tracks/cm^2. A total of 8×10^9 pot is to be recorded in the detector.

In 2016, we will perform a prototype test experiment with 20 m^2 emulsion surface, corresponding to a scale of about 1:20 of the final setup. This test will provide a proof of principle and the results will be used to optimize the module structure. We plan to carry out the real experiment with 400 m^2 emulsion surface in total. We plan to have two runs, the first run in 2018 and the second run after the shutdown of SPS, so that we can give feedback from the first run. Total 6 weeks of beam time would be needed to accumulate 8×10^9 pot.

References

[1] K.A. Olive et al. (Particle Data Group), Chin. Phys. C 38 (2014) 090001.

[2] K. Kodama et al., Final tau-neutrino results from the DONuT experiment, Phys. Rev. D 78 (2008) 052002.

[3] K. Kodama et al., Observation of tau neutrino interactions, Phys. Lett. B 504 (2001) 218-224.

[4] H. Liu, A. Rashed, and A. Datta, Probing lepton nonuniversality in tau neutrino scattering, Phys. Rev. D 92 (2015) 073016.

[5] K. Kodama et al., New techniques for emulsion analysis in a hybrid experiment, Nucl. Instr. and Meth. B 93 (1994) 340-354.

[6] C. Amsler et al., A new application of emulsions to measure the gravitational force on antihydrogen, JINST 8 (2013) P02015.

[7] A. Bulte et al., The CHARON detector: An emulsion / counter hybrid set-up to measure the mean free path of near-elastic pion scattering in nuclear emulsion (white kink) at 2-GeV/c, 3-GeV/c and 5-GeV/c, Nucl. Instrum. Meth. A 485 (2002) 426-438.

[8] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38 (2014) 090001 and 2015 update.

[9] T. Nakamura et al., The OPERA film: New nuclear emulsion for large-scale, high-precision experiments, Nucl. Instrum. Meth. A 556 (2006) 80-86.

[10] K. Kodama et al., Momentum measurement of secondary particle by multiple Coulomb scattering with emulsion cloud chamber in DONuT experiment, Nucl. Instrum. Meth. A574 (2007) 192-198.

[11] K. Morishima and T. Nakano, Development of a new automatic nuclear emulsion scanning system, S-UTS, with continuous 3D tomographic image read-out, JINST 5 (2010) P04011.

[12] N. Armenise et al., High-speed particle tracking in nuclear emulsion by last-generation automatic microscopes, Nucl. Instrum. Meth. A 551 (2005) 261.

[13] A. Ariga and T. Ariga, Fast 4π track reconstruction in nuclear emulsion detectors based on GPU technology, JINST 9 (2014) P04002.

[14] M. Yoshimoto, T. Nakano et al., Super Fast Automated Emulsion Scanning System: HTS, talk at the Workshop on Nuclear Track Emulsion and its Future, Predeal, Romania, 14-18 October 2013. http://www.spacescience.ro/wnte2013/.