PROCEEDINGS OF SCIENCE

NA65(DsTau): Study of tau neutrino production in p-A interactions

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The DsTau (NA65) experiment at CERN was proposed to measure an inclusive differential cross-section of D_s production, and its decay branching ratios in p-A interactions. The DsTau detector is based on the nuclear emulsion technique providing an excellent spatial resolution for detecting short-lived particles like charmed hadrons. The first results of the analysis of the pilot-run data are presented. The accuracy of the proton interaction vertex reconstruction is reported. A high precision in vertex reconstruction allows one to measure the proton interaction length and charged particle multiplicities accurately in a high-track density environment. The measured data have been compared with several Monte Carlo event generators in terms of multiplicity and angular distribution of charged particles. The proton interaction length in tungsten is measured to be 106.8±0.3 mm. The predictions of KNO-G scaling are tested on the multiplicity distribution in p-A interactions. The results presented in this study can be used to validate event generators of p-A interactions.

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1. Introduction

The DsTau experiment [1] aims to measure the differential production cross-section of D_s mesons in proton-nucleus interactions at 400 GeV, driven by the need to understand better D_s meson decays, which are a primary source of tau neutrino production. A more precise understanding of these decays would reduce uncertainty in tau-neutrino cross-section measurements, aiding in testing the Lepton Universality, a fundamental principle of the Standard Model. The distinctive decay signature of $D_s \rightarrow \tau \rightarrow \nu_\tau$ transitions, characterized by a double kink pattern and the decay topology involving charm particles, requires the use of an emulsion detector with nanometric spatial resolution due to the small angular divergence of approximately seven milliradians. These measurements also provide essential data for future neutrino-based experiments.

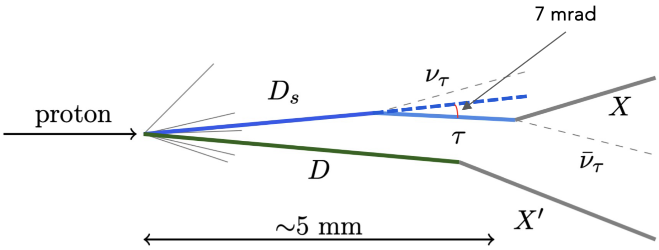

Figure 1: Decay topology of D_s meson decay.

The diagram (Figure 1) illustrating the decay of D_s mesons reveals a double kink topology. The kink angle for the D_s to τ decay is approximately seven milliradians. Detecting such a minimal kink angle necessitates a detector with nanometric spatial resolution. This study analyzes a subset of data from the 2018 pilot run, which involved an expected 4.9×10^9 protons on target and 2.3×10^8 proton interactions with the target.

2. Experimental Setup and Data Taking

Nuclear emulsion films consist of silver halide crystals embedded in a gelatin binder within the emulsion medium. The traces of charged particles are recorded in the silver halide crystals, which are later developed through a series of chemical processes to prepare the emulsion film for scanning. Once developed, the emulsion films are scanned using the Hyper Track Selector (HTS) [2], a computer-aided automatic microscope.

The DsTau detector (Figure 2) is constructed using emulsion films, tungsten plates, and plastic spacers, forming a robust tracking apparatus. Tungsten and molybdenum serve as the proton target materials. Each detector unit consists of one tungsten plate, ten 320-micron-thick emulsion films, and nine 200-micron-thick plastic spacers, repeated ten times, resulting in a total of ten tungsten plates and 100 emulsion films. Additionally, five emulsion films are placed in front of the detector to analyze the characteristics of the incoming particle beam. The tungsten plates, approximately 0.5 mm thick, provide a dense medium for proton beam interaction, while the plastic spacers serve as the decay volume for particle detection [3].

The emulsion scanning process involves two stages. Initially, a rapid full-surface scan is conducted using the HTS, which records all charged particle segments. The HTS operates at a

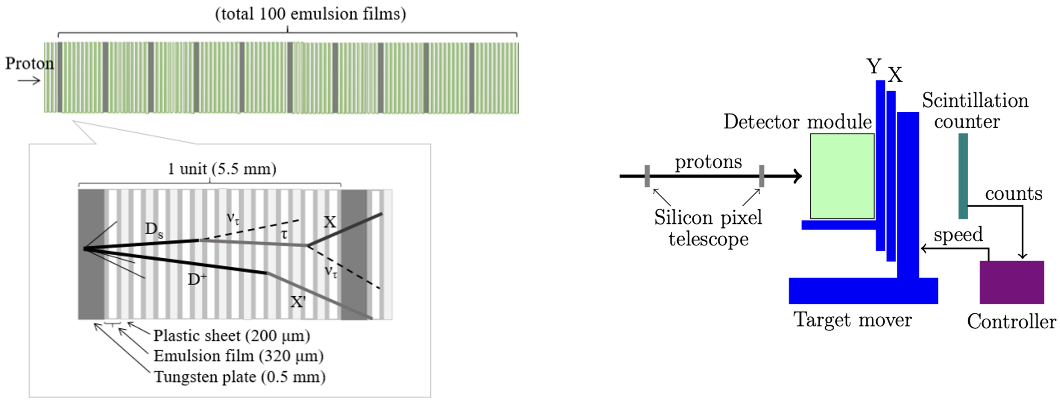

Figure 2: Left: schematics of the DsTau detector.

speed of 5000 cm²/h and is specifically designed to handle the large emulsion films required for the DsTau experiment. During the test run, the emulsion film dimensions were 12.5 cm x 10 cm; however, in subsequent runs, the dimensions were doubled on each axis, resulting in 25 cm x 20 cm emulsion plates. Following the full-surface scan, a detailed scan focuses on detecting $D_s \to \tau$ decays. Although this second scanning process is slower than the HTS, it is essential for accurately capturing the small kink angles characteristic of D_s meson decays.

3. Data Processing

The emulsion data is processed using the DsTau software to reconstruct particle tracks and identify vertices. The process begins with forming base-tracks by linking micro-tracks detected on both sides of the emulsion. A fine alignment procedure is applied to these base-tracks to establish a global reference frame. The base-tracks are then systematically connected, plate by plate, following specific criteria for angular orientation and positional acceptance, creating volume tracks. These tracks include the path the incident beam protons traveled within the module. Finally, a vertexing algorithm is used to reconstruct the locations of proton interactions and charm particle decay points.

In addition to commonly used reconstruction methods, a novel technique called Proton Linking has been developed. This method focuses on selecting beam protons based on their track angles and subsequently tracking these protons as they progress through the entire module. Following this, a decay search algorithm is applied for charm decay candidates. Subsequently, higher-order interactions and their corresponding daughters are identified and linked to the vertex points. This process is currently in progress.

4. Results

This section analyzes proton interaction characteristics and measures interaction lengths in tungsten using data from a subset of the preliminary 2018 pilot run. Proton interactions are simulated with Geant4 [4], EPOS [5], Pythia [6], QGSJET [7], and DPMJET [8] event generators.

The simulated output is processed through Geant4 to simulate measurement effects using data-driven smearing.

Furthermore, a comparative analysis is conducted between experimental data and Monte Carlo (MC) simulations to assess their consistency (Figure 3). This comparison focuses on three parameters: impact parameter, multiplicity of charged tracks, and track angles. The findings demonstrate that the EPOS Monte Carlo simulation closely matches the observed data across all three parameters.

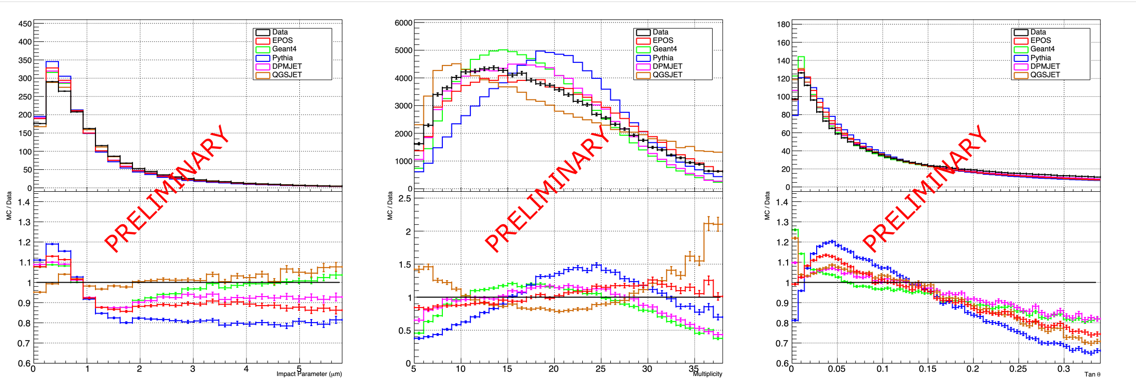

Figure 3: Data/MC comparison. Left: Impact parameter (μm). Middle: Multiplicity. Right: Track angle ($\tan\theta$)

A notable difference becomes evident when the $\tan\theta$ exceeds 0.05. To investigate this issue, an analysis is conducted on track angles across different multiplicities (Figure 3), revealing discrepancies, particularly in cases with multiplicities exceeding 10. Subsequently, slope distributions are examined for two categories: multiplicities below ten and those above 10 (Figure 4). Both analyses indicate that the data and Monte Carlo results are consistent in lower multiplicity regions (values below 10). However, a noticeable discrepancy appears in higher multiplicity regions (values exceeding 10). This can be explained by the constant Pt distribution of hadron interactions simulated in Monte Carlo simulations.

To estimate the reconstruction efficiency, the algorithm compares true vertex positions with reconstructed vertices. The mean vertexing efficiency is 81.0 ± 0.9%, while the mean proton linking efficiency is 92.5 ± 0.1%. The proton purity for proton selection is also measured at 96.0 ± 0.2%.

In addition to compare data with Monte Carlo simulations, the first measurement of proton interaction length in tungsten is conducted using data (Table 1). Measurements were carried out individually for each tungsten sample. The mean value for the data is 92.2 ± 1.0 mm, while the mean value for the Monte Carlo simulations is 97.7 ± 3.0 mm. Notably, the data and Monte Carlo results show consistent distributions, indicating strong agreement.

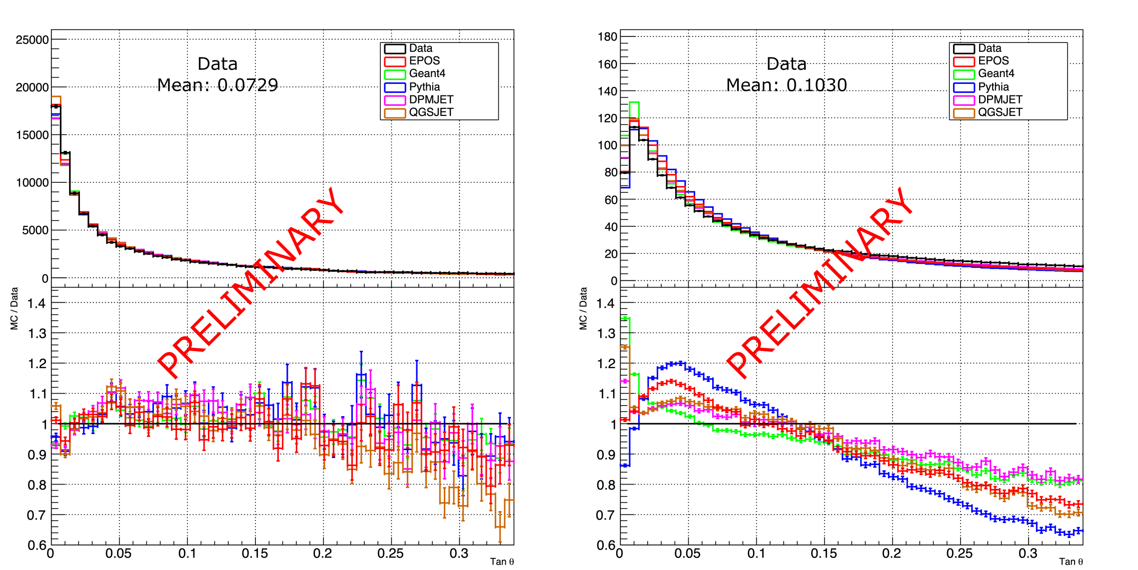

Figure 4: Data/MC comparison for track angle ($\tan\theta$). Left: Events with multiplicity < 10. Right: Events with multiplicity ≥ 10

Table 1: Estimated proton interaction length in tungsten target for Data and Geant4 MC

Sub-volume	Data	Monte Carlo
1	89.0±2.6	94.9±2.7
2	92.5±2.7	95.1±2.7
3	98.2±2.9	96.8±2.8
4	93.6±2.8	95.2±2.8
5	89.9±2.8	95.6±2.8
6	91.2±3.0	95.7±2.8
7	90.1±3.0	97.2±2.9
8	92.7±3.3	97.7±3.0
Mean	92.2±1.0	96.0±1.0

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