Performances of the reconstruction of the primary proton vertices along the beam axis in the NA65(DsTau) experiment

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The NA65 (DsTau) experiment studies the tau neutrino production in accelerator beams, following the sequential D_s decays. For registering short lived particles, produced in high energy proton-nuclear interactions, the experiment uses a set-up based on nuclear tracking emulsion detectors.

The present report shows the capabilities of the reconstruction of the primary proton interactions in the detector, in a pile-up of $10^5 - 10^6$ particles/cm^2.

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Introduction

The DsTau experiment is studying the tau-neutrino production, aiming to reduce the uncertainties in the estimations of the tau neutrino flux to 10% [1]. In accelerator beams, the principal source of tau-neutrino ($> 90\%$) is the leptonic decay of D_s meson [2], produced in proton-nucleus interactions, $D_s \to \tau + \nu_\tau$, followed by $\tau \to X + \nu_\tau$. DsTau will measure the D_s double-differential production cross-section (inclusively decaying to τ and ν_τ) in proton-nuclei interaction.

With a total flux of 4.6×10^9 protons on tungsten and molybdenum targets, about 1000 Ds-tau events are expected to be registered. Paired charm events will be analysed as well, in an mount of an order of 10^5.

The experiment was performed at CERN-SPS with a 400 GeV proton beam. The data taking campaign was finished in September 2023. Event reconstruction and analysis are ongoing.

In this paper procedures precursory to the charm and D_s-τ identification are discussed. The ability to reconstruct the primary proton interactions in a high particle pile-up is reported, by using a data sample from the experiment's pilot run, that used tungsten targets.

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Experimental Technique

The D_s to τ decay is a double kink topology, occurring within millimeters and at small angles, and it can be recognized by using tracking emulsions detectors [1]. In the case of 400 GeV protons colliding with stationary tungsten, the expected mean kink between D_s to τ is 10 mrad, the expected mean decay length for D_s is 2.38 mm, and the mean tau decay length is expected to be 1.38 mm [3]. The emulsions used in the DsTau experiment have angular resolution of 0.35 mrad and spatial resolution of 0.4 μm and are able to register events in a high track density environment, of around $10^5 - 10^6 \text{tracks/cm}^2$.

Around 530 m^2 of emulsion films, packed in several modules, were used in the experiment. A module, as presented in Figure 1, consist of 10 target plates (tungsten or molybdenum), each followed by 10 double sided emulsion layers on plastic bases, separated by plastic films. The nominal thickness of the tungsten target is 500 μm, 200 μm for the separator plastic films and 210 μm for the plastic base and 60 μm for the emulsion layers. The emulsion plates used in the pilot run were created manually.

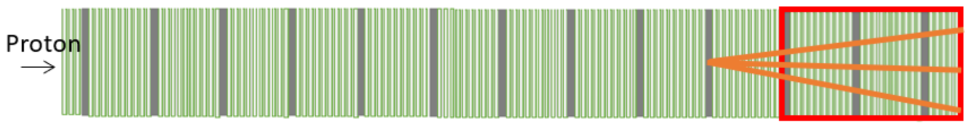


Fig. 1: Detector module (not in scale). The part in red frame will be used for momentum estimations only, by Multiple Coulomb Scattering. The grey layers represent the targets. The tracking units, consisting of emulsion and plastic layers, are represented in green and light blue. Before the first target 5 emulsion plates (with 4 separators) are attached, for characterization of the incoming proton beam. The orange lines represent an example of tracks of 3 charged particles emerging a vertex occurring in the 10th target

Each module was exposed individually, with the beam perpendicular to the surface. In order to achieve an uniform exposure to 3×10^5 protons/cm^2 (corresponding to $\sim 500/\text{cm}^2$ interactions in each tungsten target) the modules are swept in front of the beam, according to its intensity, by a Target Mover [4], connected to real-time beam monitors. During the exposure, no magnetic field is applied to modules.

The exposure was immediately followed by the chemical development of the emulsion plates, which make the particle tracks visible for the microscopes. The emulsion read-out is performed by Hyper Track Selector (HTS) [5], an automatic microscope that is able to scan with a speed of $0.5\text{m}^2/\text{hour}/\text{layer}$. After scanning, the information about the charged particle track in each emulsion film (the base-tracks), become available in digital format. Base-tracks are formed when 2 traces, in opposite emulsion layers of the same film, are connected.

With the use of offline algorithms, the tracking procedures in which the base-tracks are united in tracks, are performed. Several alignment procedures are applied. The so-called vertexing algorithm combines the tracks converging into a point, which is the vertex. A vertex is reconstructed from at lest 4 tracks, each having tan$\theta \leq 0.4$ (the angle of the first base-track on Z-axis, deduced after scanning with HTS). The position of the vertex is calculated by the tracks that have the first segment in a particular emulsion plate, in a square of 725 × 725 μm^2. The vertices that can be attached to a track, having an inclination corresponding to a beam proton in the local area of the vertex, are called the primary interactions. After the reconstruction of them, the primary proton track has to be confirmed in the very fists 5 emulsion plates in the module. The events with a topology corresponding to a charm decay are selected and the D_s to tau topology is searched for.

Reconstruction of proton primary interactions

Compared to the preliminary results presented in [3] and [6], corrections were applied to the algorithms used for reconstructing the primary proton interactions. Figure 2 shows the position of the primary interactions along the beam axis, per unit of reconstruction (an area of 1.7 × 1.7 cm^2). The position of the first 9 tungsten targets is clearly distinguishable by the biggest amount of interactions. The interactions in the soft materials, emulsion and plastic, can be noticed as well. The reconstruction resolution is good enough to observe the fine structure of the detector, including the 60 μm layers of emulsion gel, which, compared to the plastic ones, have a bigger density, and in which more interactions occurred. The descending trend of the interactions is visible by going in the depth of the module, and is caused by the attenuation of the primary beam in the upstream part. Even if the track density increases from the beginning of the module to the end by one order of magnitude, the algorithms are good enough to distinguish the primary interactions from the secondary (and higher order) ones.

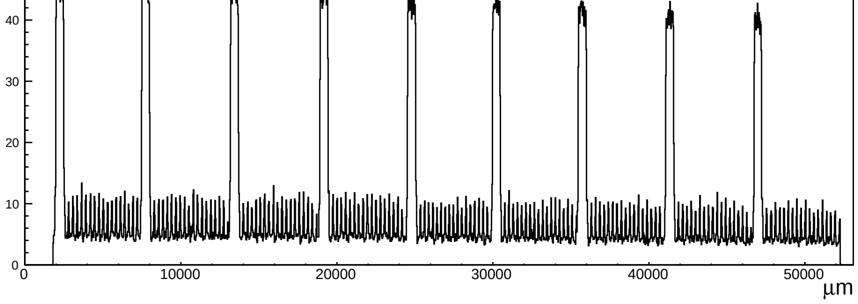


Fig. 2: Interactions along the beam axis, in the upstream part of one module

The resolution of reconstruction along the beam axis and the thickness of the tungsten targets can be extracted by fitting each tungsten peak by a convoluted function. A box function with wings, covering the tungsten peak and the neighbouring emulsion layers, is convoluted with Gauss. In the fit, the limits between which the box function is defined (corresponding to the position of the tungsten peak), the heights of the box (the mean amounts of interactions per bin in tungsten and emulsion layers respectively), as well as the sigma of the Gaussian function (the resolution) are free parameters. Figure 3 shows the fit applied to the first tungsten peak.

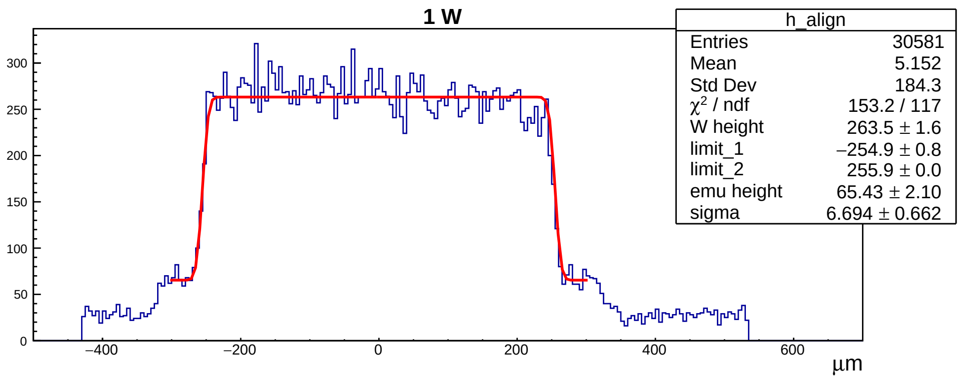
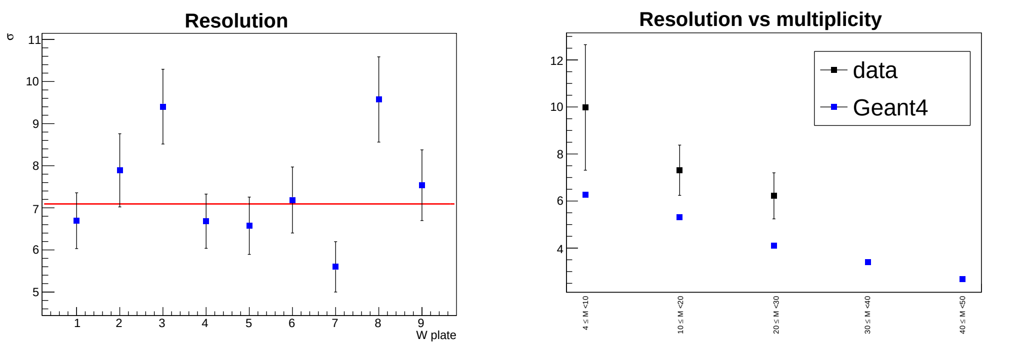


Fig. 3: First tungsten peak fitted by a convolution between a box function with wings and a Gaussian. The extracted value for the thickness, the difference between 'limit_2' and 'limit_1", is 510.87 ± 0.78 μm



(a) Extracted resolutions for each tungsten target from the data sample.

(b) Dependence of the extracted resolution with the multiplicity of event

Fig. 4: Extracted resolution of the reconstruction along the beam axis

The resolution of the reconstruction is around 7 μm. It depends on the quality of the emulsion films used as well as on the flatness of the tungsten target (the fit considers the target as a perfect rectangle). Due to the reconstruction technique the resolution improves from the upstream side of the target to the downstream part: the closest is the vertex to recorded traces, the more precise is reconstructed (daughters scatter inside the tungsten target). Events with a higher multiplicity are reconstructed more precisely as well, as shown in Figure 4b, where Monte Carlo data is compared with data. In the case of Geant4 data, the targets and the emulsion plates have perfect surfaces, therefore, the extracted resolution is smaller. By applying the same methods as for the real data, the reconstructed resolution in MC is $\sim 5\ \mu$m.

The extracted target thicknesses have different values from the nominal value of 500 μm and can vary between 472 μm and 532 μm. The plates were chosen with a flatness variation of under 10%.

Final remarks

The purpose of the DsTau experiment is to evaluate the number of events where a D_s decaying via τ is produced in proton - nuclear interactions. The goal of the present stage of the analysis is to demonstrate the capabilities of the algorithms to reconstruct the primary vertices, despite the track densities up to 10^6 tracks/cm^2. The reconstruction of the interactions of the primary proton vertices, along the beam axis, is shown and is performed with a resolution of 7 μm.

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