PROCEEDINGS OF SCIENCE

Search for muonic trident production in SND@LHC

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The SND@LHC experiment is designed to study neutrinos produced in proton-proton collisions at the LHC, covering an energy range from 100 GeV to 1 TeV. It explores pseudo-rapidity region of $7.2 < \eta < 8.4$. The compact detector is positioned 480 meters downstream from the ATLAS Interaction Point (IP1) in the TI18 tunnel. Its setup includes a veto system, a tungsten target interleaved with nuclear emulsion layers, scintillating fiber trackers, and a muon detection system. The high muon flux through the SND@LHC detector, originating from the particles produced at IP1, enables the search for rare processes, such as the direct production of a muon pair by a muon interacting with the field of a nucleus. Here, we present the measurement of muonic trident production in the SND@LHC detector.

PoS(EPS-HEP2025)183

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Marseille, France

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[*] Speaker

ISSN 1824-8039. Published by SISSA Medialab.

1. Introduction

The direct production of muon pairs via muon-nucleus interaction is an interesting phenomenon as it plays an important role to test quantum electrodynamics (QED) at short distances and provides verification for Fermi-Dirac statistics. In the past, several experiments have reported the observation of muonic trident production in muon-nucleus interactions. The first observation was made in cosmic ray muon experiment [1] in 1967. Although, it provides experimental verification of the process, their data was not sufficiently accurate to obtain the cross-section of the muonic trident production. In 1971, the production rate of the muonic tridents was measured in Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) [2]. A 10.5-GeV muon beam was designed impinging on a lead target to search for direct production of muon pairs. The process diagram is shown in Figure 1.

$$\mu^{\pm} + Pb \longrightarrow \mu^{\pm} + Pb + \mu^{+} + \mu^{-} \tag{1}$$

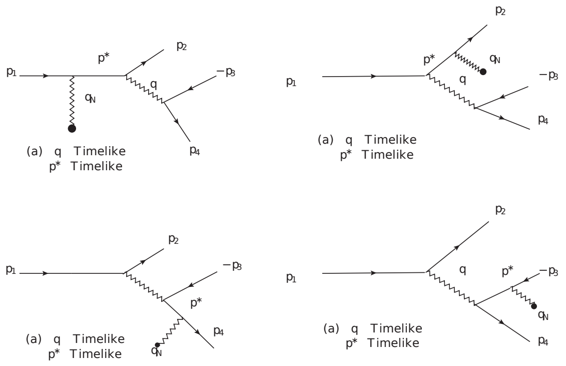

Figure 1: Leading-order Feynman diagrams for muonic trident production [3]: (a,b) radiative topology; (c,d) Bethe-Heitler topology. p^* is the four-momentum of the virtual muon; q is the four-momentum of the virtual photon and q_N is the nuclear recoil four-momentum.

In the experiment, the cross section was measured to be 51 ± 7 nb per Pb nucleus. It was also shown that muons obey Fermi-Dirac statistics. In 2006, CosmoALEPH reported observation of two events from cosmic ray muons [4]. The production rate with the ALEPH detector agrees well with the expectation in both event numbers and particle energies of secondaries, as predicted by the cross-section parametrization in [5]. Although the cross section of the muonic trident process is significantly smaller than that of bremsstrahlung and the production of electron-positron pairs, it becomes a prominent process when high-energy, intense muon beams are used, such as those at SND@LHC.

The SND@LHC detector is designed to detect high-energy neutrinos generated from proton-proton collisions at the LHC, targeting the forward pseudo-rapidity region of $7.2 < \eta < 8.4$. The SND@LHC detector is located 480 meters upstream of the ATLAS interaction point in the TI18 tunnel, where it is shielded from collision debris by approximately 100 meters of rock. Although the primary focus of the experiment includes observation of neutrino interactions and search for dark matter scatterings, the location and the design of the detector naturally provides ideal conditions to study muonic trident production inside the rock.

The SND@LHC detector features a hybrid design [6]. The veto system consists of two horizontal and one vertical planes of stacked scintillating bars, with the vertical plane added in 2024. The primary function of the veto system is to reject charged particles entering the detector volume. The detector's target and the vertex detector consist of five walls of an Emulsion Cloud Chamber (ECC). Each ECC brick is a sequence of tungsten plates and nuclear emulsion films. Five scintillating fiber (SciFi) stations , positioned between the ECC walls, serve as the electromagnetic calorimeter and provide timestamps for the vertices. The hadronic calorimeter and muon system are composed of eight planes of scintillating bars interleaved with 20 cm thick iron blocks. The last three downstream planes with higher granularity are also used as a tracking system for muons. The schematic layout of the detector is shown in Figure 2.

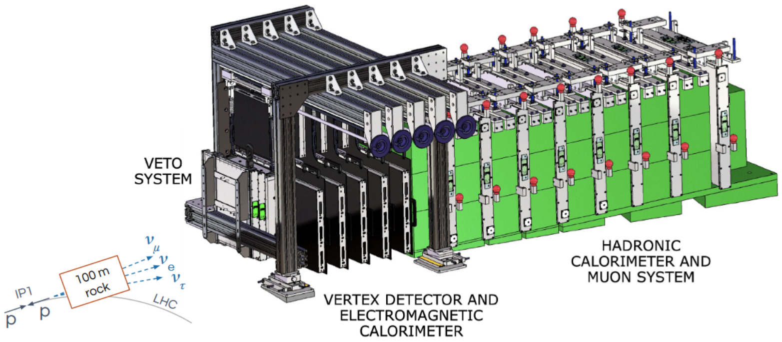

Figure 2: Schematic view of the SND@LHC detector

2. MC Simulation

The Monte Carlo simulation is produced in several stages. The first step is the simulation of primary proton-proton inelastic collisions with DPMJET [7]. Then, the collision debris is transported towards the SND@LHC detector using the LHC FLUKA model [8]. The particle transport was stopped on a virtual plane of 1.8×1.8 m^2, located in the rock about 71.5 m upstream of SND@LHC. The subsequent propagation of muons from the scoring plane to the detector, as well as their interactions, was simulated using the GEANT4 [9] model of SND@LHC and its surrounding environment. The "Molasse Rock" model, which includes 33 elements, was used [10], instead of the default rock model of GEANT4.

3. Analysis

The experimental signature of muonic trident interaction is three nearly collinear tracks. Daughter muons are notably close together, whereas the other track is more separated. This unique characteristic distinguishes tridents from events with uncorrelated three tracks. This is verified by looking at the maximum distance (d_{max}) among three tracks as a function of minimum distance(d_{min}) at the first SciFi station. These parameters are illustrated in Figure 3 in a sample event. Figure 4 shows the distribution of d_{max} in bins of d_{min} for MC and data together with the case when three tracks are uniformly distributed over the detector transverse area.

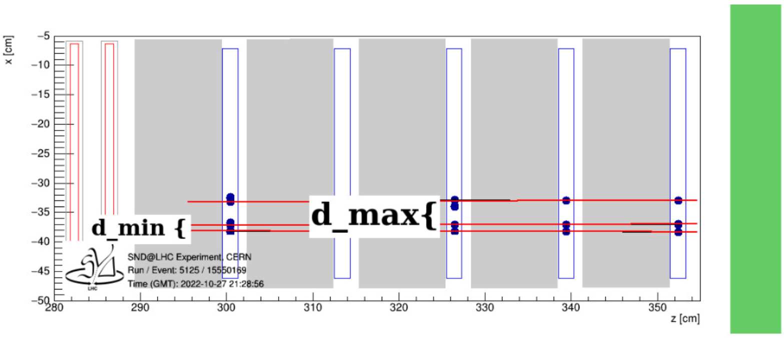

Figure 3: Zoomed horizontal 2D event display illustrating the d_{max} and d_{min} parameters for a candidate event. Reconstructed SciFi hit clusters are shown as blue points, fitted particle trajectories as red lines. Tungsten walls are indicated by grey rectangles, while the first iron wall is shown in green.

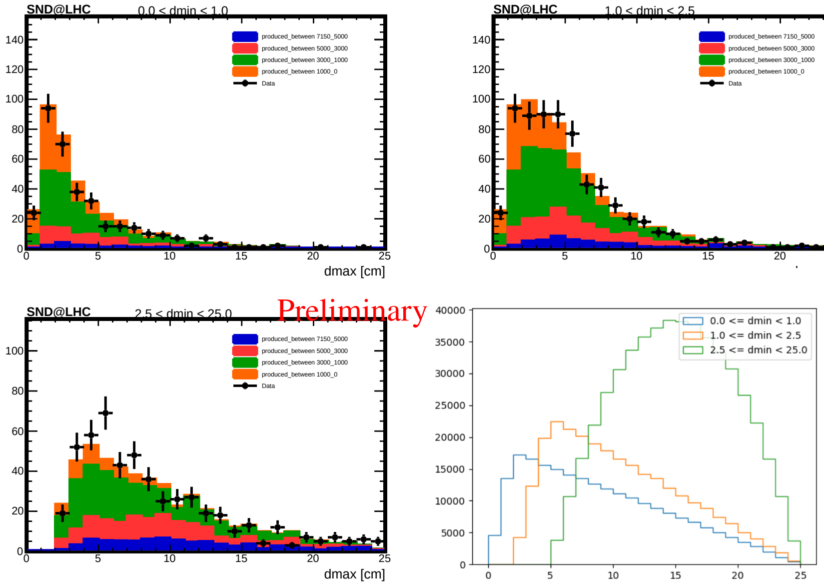

Figure 4: d_{max} distribution in bins of d_{min} showing agreement between MC and data and verifying the trident signature. Stacked histograms are for MC signal events produced in different ranges of depth inside the rock, and black points with error bars represent data normalized to unit integrated luminosity. The bottom right plot shows the same distributions for uncorrelated tracks.

The primary background to muonic trident production arises from bremsstrahlung followed by gamma conversion.

$$\mu^{\pm} + N \longrightarrow \mu^{\pm} + N + \gamma, \quad \gamma + N \longrightarrow N + \mu^{+}\mu^{-} \tag{2}$$

When the incoming muon radiates in the rock, the photon could create a muon pair, resulting in three tracks in the final state. Another process that could generate three muon tracks in the final state is the positron annihilation. In this case, a secondary positron from the primary muon annihilates with the atomic electron, producing a muon pair, yielding three muons in the final state. The overall contribution to the three-track event yield from all possible background sources is expected to be 3.8 %.

3.1 Event Selection

For the analysis, data collected in the 2022 and 2023 campaigns were used. The search for muonic trident events is performed using the SciFi detector. A preliminary selection is performed by requiring a sufficient number of clusters of hits in each SciFi plane. Furthermore, in each event, hits that are outside the -0.5 to +2.0 SND@LHC clock cycle time window are rejected. Doublets of clusters are combined in each subsequent plane, and track candidates are formed. Clone tracks are also eliminated if there is a significant overlap between two track candidates. The one with the better-fit chi-square value is retained, and the others are discarded. Due to the absence of a stereo view in the detector, tracks could be reconstructed in the xz and yz planes, and thus tracks in one projection could not be distinguished in the other. A fiducial cut is also applied to throw events near the detector border. Finally, noisy events are eliminated by applying a cut on the number of hits around the tracks.

3.2 Event Rates

In order to extract event rates in the data, the signal detection efficiency as a function of the depth of the interaction position in the rock is parametrized as shown in Figure 5. The average efficiency over 100 m of rock is (4.3 ± 0.48)%. Using this, the background subtracted and efficiency corrected number of trident events per 1 fb^{-1} becomes 1593 ± 55(stat) while the MC prediction is 1395 events/fb^{-1}.

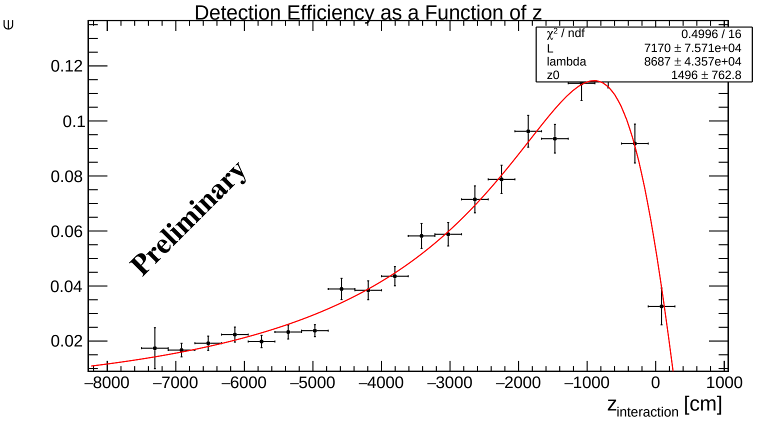

Figure 5: Detection efficiency as a function of z coordinate of the vertex position.

4. Conclusion

The muonic trident production was studied with the SND@LHC detector. The first observation of muonic trident production at the LHC has been reported. The average event rate per 1 fb^{-1} inside the rock is estimated to be 1593 ± 55(stat). The measurement could act as a lighthouse for the existing GEANT4 [9] model of muonic trident production.

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