Observation of Collider Neutrinos without Final State Muons with the SND@LHC Experiment

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We report the observation of neutrino interactions without final state muons at the LHC, with a significance of 6.4σ. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 and 2023 is used, corresponding to an integrated luminosity of 68.6 fb^{-1}. Neutrino interactions without a reconstructed muon are selected, resulting in an event sample consisting mainly of neutral-current and electron neutrino charged-current interactions in the detector. After selection cuts, 9 neutrino interaction candidate events are observed with an estimated background of 0.32 events.

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Introduction—The SND@LHC experiment consists of a detector placed in the TI18 tunnel at a distance of 480 m, in the forward region, from the ATLAS detector located in the Interaction Point 1 (IP1) of the CERN Large Hadron Collider (LHC). The detector is designed to detect and measure interactions of neutrinos produced in decays of particles produced in proton-proton collisions at IP1. The neutrinos produced in the forward direction stem from high-energy hadrons and have energies of a few hundred GeV to several TeV [1–3], leading to deep inelastic scattering (DIS) in the experiment.

Data taking at the LHC started in 2022, and in Ref. [4] a direct observation of muon neutrino charged current (CC) interactions was reported based on a data sample of 36.8 fb^{-1}. A similar observation was reported in Ref. [5] and a measurement of electron and muon neutrino cross sections using an emulsion detector was reported in Ref. [6].

In this Letter, we search for neutrino interactions with no muons in the final state, referred to as $\nu 0\mu$ events. This measurement is sensitive to CC interactions of either ν_e or ν_τ flavor, and neutral current (NC) neutrino interactions. The observation of a clear signal above background is a sign of other than ν_μ CC neutrino interactions at the LHC. Hence this analysis is the first step towards flavor classification with SND@LHC, and a precursor to the detection of NC interactions at the LHC as well as the observation of collider ν_e CC events with electronic detectors. The detection of collider neutrinos with electronic detectors is of particular interest for the upcoming high-luminosity phase of the LHC [7–9]. The strategy is to select muonless showerlike events. While the analysis is not optimized to distinguish between ν_e, ν_τ, and NC events, it has moderate sensitivity to the observation of ν_e CC interactions, which we also report. The data sample used, collected in 2022 and 2023, corresponds to a total recorded integrated luminosity of 68.6 fb^{-1}.

The SND@LHC detector—SND@LHC is a hybrid detector consisting of emulsion and electronic detectors [10]. It is optimized for the detection of interactions of all neutrino flavors. The electronic detectors provide the time

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stamp of the neutrino interaction and preselect the interaction region while the neutrino-interaction vertex is reconstructed using tracks in the tracking detectors and the emulsion target. The Veto system is used to tag muons and other charged particles entering the detector from the IP1 direction.

The Veto system consists of two parallel planes of scintillating bars. Each plane is made of seven $1 \times 6 \times 42\ \mathrm{cm}^3$ stacked horizontal bars of plastic scintillator. The target section contains five walls. Each wall consists of four units ("bricks") of emulsion cloud chambers (ECC) with tungsten as target material, and is followed by a scintillating fiber (SciFi) station for tracking. Each SciFi station consists of one horizontal and one vertical $39 \times 39\ \mathrm{cm}^2$ plane. Each plane comprises six staggered layers of 250 μm diameter polystyrene-based scintillating fibers. The single particle spatial resolution in one plane is roughly 100 μm and the time resolution for a particle crossing both x and y planes is about 250 ps.

The muon system consists of two parts: the first five stations [upstream (US)], and the last three stations [downstream (DS)]. The eight stations are interleaved with 20 cm-thick iron blocks. Each US station consists of 10 stacked horizontal scintillator bars of $82.5 \times 6 \times 1\ \mathrm{cm}^3$, resulting in a coarse y view and together they act mainly as a hadronic calorimeter. A DS station consists of two layers of thinner bars measuring $82.5 \times 1 \times 1\ \mathrm{cm}^3$, arranged in alternating x and y planes, leading to a spatial resolution in each coordinate of less than 1 cm for muon reconstruction and a time resolution of about 150 ps. Hits in the DS detector and the SciFi tracker are used to identify events with muons. All signals exceeding preset thresholds are read out by the front-end electronics and clustered in time to form events. An efficient software noise filter is applied online to the events, resulting in negligible detector dead time and negligible loss in signal efficiency. Events satisfying certain topological criteria, such as the presence of hits in several detector planes, are written to disk. In the absence of beam, the noise filtering logic reduces the event rate by 5 orders of magnitude to around 4 Hz. At the highest instantaneous luminosity in 2022 and 2023 ($2.5 \times 10^{34}\ \mathrm{cm}^{-1}\ \mathrm{s}^{-1}$), this setup generated a rate of around 5.4 kHz.

This analysis does not use the information from the emulsion detector but is based on the hits and track reconstruction in the scintillating fiber detectors and on the absence of an identified muon in the muon system.

Data and simulation—The data used for the analysis described in this Letter was taken between July 2022 and October 2023, comprising the first two years of the LHC Run 3. An integrated luminosity of $68.6\ \mathrm{fb}^{-1}$ was recorded by the experiment's electronic detectors during this period. A data collection efficiency of 97.2% was achieved relative to the luminosity delivered at IP1 as reported by the ATLAS experiment [11,12]. We highlight the exceptional performance of the detector in 2023, with $31.8\ \mathrm{fb}^{-1}$ collected and an uptime of 99.7%. There were six exchanges of the emulsion-instrumented target during the data taking period, which did not significantly impact the performance and uptime of the electronic detectors. The mass of tungsten installed in the target during this period was 792 kg.

For two periods comprising about half of the collected luminosity, the event builder was not aligned with the timing of bunch crossings at the interaction point. This results in occasional splitting of events and as a consequence the efficiency of the veto detector is worse in these periods. The impact of the lower veto efficiency on this analysis is negligible, as downstream components of the detector are also used to reject the dominant penetrating background due to muons.

Data taken in a hadron test beam in 2023 in the CERN North Area are used to validate the analysis methods. The test-beam detector consisted of four SciFi stations smaller in size than those of SND@LHC, an exact replica of the US hadron calorimeter, and a single DS station. Iron blocks were inserted between the SciFi stations with a thickness equivalent in interaction lengths to the target walls in the SND@LHC detector. The test-beam detector was exposed to hadron beams of mostly pions with momenta ranging from 100 to 300 GeV/c.

Proton-proton collision events are simulated with the DPMJET-III generator [13,14], which is interfaced with a FLUKA [15,16] model of the LHC [17]. Particles are propagated to a virtual plane around 60 m upstream of the SND@LHC detector and recorded for further processing. Neutrino interactions in the detector are simulated with the GENIE generator [18]. Muon DIS interactions in the tunnel material are simulated with PYTHIA6 [19]. The particles resulting from these interactions are propagated through a Geant4 [20] model of the tunnel and the detector geometry implemented in the FairRoot framework [21]. The same setup is used for the test-beam simulation.

The sample of simulated neutrino interactions comprises 3×10^5 events, corresponding to an integrated luminosity of $40\ \mathrm{ab}^{-1}$. The computational expense of simulating muon DIS interactions and propagating the large number of produced particles through the tunnel and detector models, compounded with the very low probability of these interactions being selected into the analysis samples, results in a significant computing challenge. Out of 3×10^8 simulated muon DIS interactions, corresponding to an integrated luminosity of $20\ \mathrm{fb}^{-1}$, none survive the event selection described in the following section. This sample is sufficient to set a stringent upper limit on the number of events expected from this source of background, but it does not allow for probing the detector's response to this type of event. For this purpose, we generate additional samples of 2.6×10^7 neutrons and neutral kaons impinging on the upstream face of the target, with energy spectra extracted from simulated muon DIS events without hits in the Veto system, which result from muon interactions outside of the target. We conservatively distribute the neutral hadrons uniformly in the upstream face of the target. We note that according to the muon DIS simulation, no neutral hadrons above 100 GeV are expected to interact in the target in the absence of Veto system hits due to charged particles accompanying the neutral hadrons. These assumptions have no significant impact on the results reported in this Letter, since the neutral hadron background is constrained by data in a control region and extrapolated to the signal region with large systematic uncertainty, as described in the following section.

Event selection and data analysis methods—The search for the $\nu 0\mu$ signal proceeds in two stages. The first stage consists of a set of selection criteria to isolate events that are consistent with neutral particles interacting in the tungsten target that do not produce reconstructible muons. In the second stage, a discriminating variable is used to define regions enriched in either signal or neutral hadron background. The background-rich region is used to constrain the background expectation, and the signal-rich region is optimized by maximizing the expected significance for excluding the background-only hypothesis.

The analysed events are required to have occurred during LHC stable beam conditions and in coincidence with a proton bunch pair colliding at IP1. In order to avoid complications arising from Veto detector dead time, events are further required to occur at least 625 ns after the previous recorded event. After applying this set of quality criteria the data set comprises 1.1×10^{10} events, with a signal efficiency greater than 99.75%.

Events consistent with a neutral particle interacting in the target are then selected by requiring that the average position in the transverse xy plane of the SciFi hits lies in a tight fiducial area (roughly 25×25 cm^2). As an additional criterion to remove events due to particles entering the top and bottom parts of the detector, it is required that there are no hits in the uppermost and lowermost two bars of the first two layers of the hadron calorimeter. In order to remove events resulting from particles entering the detector from the IP1 direction we require no hits in the veto system. These requirements discard the most common events in the data, associated with charged particles entering the detector from the sides and from the upstream end. The fiducial cuts result in a signal acceptance of 20% and reduce the dataset to 7.9×10^6 events.

To ensure adequate sampling of the electromagnetic and hadronic shower components, events are further required to span at least two SciFi stations and to produce hits in the two most upstream layers of the hadron calorimeter. A minimum of 35 SciFi hits is required, as well as large activity in the hadron calorimeter, with an energy deposition roughly equivalent to at least 10 GeV. These cuts further reduce the data to 2.3×10^4 events, while keeping 58% of the remaining signal.

In order to exclude reconstructible muons, events with hits in the two most downstream planes of the DS detector are also discarded. This ensures that fewer than three DS planes have hits, and no muon tracks can be reconstructed. The background due to ν_μ CC interactions is reduced by a factor of 14. The residual ν_μ CC background is dominated by events where the muon exits the detector through the sides.

The second step of the event selection makes use of a variable developed to identify events with a high density of hits in one SciFi station, as would be expected for events with large electromagnetic or hadron showers. A weight w_i is assigned to each SciFi hit i which is calculated by counting the number of other hits in the same detector plane within 1 cm:

$$w_i = \sum_{j \neq i}^{N} H(x_j - x_i + 1\ \text{cm}) \times [1 - H(x_j - x_i - 1\ \text{cm})],$$

where N is the number of hits in a SciFi plane, x_i are the positions of the hits in cm, and $H(x)$ is the Heavyside step function. The hit weights can vary from zero, when no neighboring hits are present, to 80 when all adjacent channels are activated.

The weights of all hits are added up separately for each SciFi station. The sum of hit-density weights is used to reject a large number of events in the data resulting from the debris of muon interactions in the detector surroundings, which consist of small hit clusters scattered in the detector. To discard events with sparse hit patterns, it is required that the sum of hit-density weights is larger than 20 in at least two stations, and larger than 2×10^3 in at least one station. This reduces the dataset to 25 events, with 18.7 neutrino interactions expected.

The highest sum of hit-density weights among the five SciFi stations is then used as a discriminating variable to select $\nu 0\mu$ events. This variable is sensitive to the energy and profile of showers in the target and it was shown to outperform simpler metrics, such as the number of SciFi hits, in separating NC and ν_e CC interactions from lower energy neutral hadron events. The neutral hadron background rejection performance of this variable, which is a key element of this analysis, was validated using hadron test-beam data. The distribution of the sum of hit-density weights for single 100 GeV$/c$ hadrons interacting in the test-beam detector target is shown in Fig. 1, where it can be seen that most neutral hadrons of this energy produce SciFi hit-density weight sums smaller than 11×10^3. The discrepancy between the test-beam data and simulation in the highest sum of hit-density weight bins is used to derive a conservative uncertainty of 100% on the efficiency for selecting hadrons up to 100 GeV/c into the signal-rich region.

A control region comprising events with summed SciFi hit-density weights smaller than 5×10^3 is used to estimate

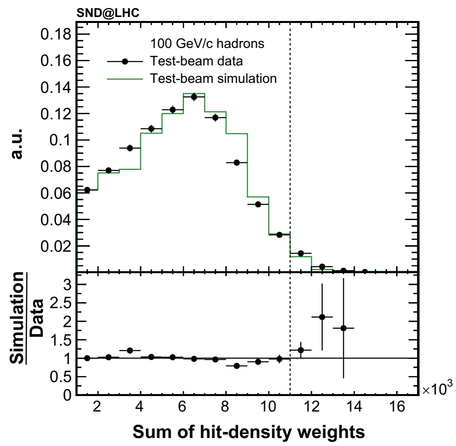

FIG. 1. Distribution of the sum of SciFi hit-density weights for 100 GeV$/c$ test-beam hadrons.

the background due to neutral hadrons resulting from muon DIS interactions in the tunnel walls. Ten events are observed in the control region, with 3.1 neutrino interactions expected. This is consistent with the 90% CL upper limit of 8.2 events obtained from the muon DIS simulation. We use the high-statistics neutral-hadron simulation to extrapolate this constraint to higher SciFi hit-density sum regions.

The signal region is defined by estimating the sensitivity to observe $\nu 0\mu$ events for different thresholds of the hit-density weight sum, ranging from 5×10^3 to 20×10^3, and choosing the threshold that maximizes this metric. The sensitivity is quantified in terms of the exclusion of the null hypothesis, defined by setting the $\nu 0\mu$ signal strength, α, to zero. The one-sided profile likelihood ratio test $\lambda(\alpha)$ is used as the test statistic. The sensitivity is calculated by comparing the test statistic evaluated at the nominal expectation from the simulation, $\lambda_{\mathrm{MC}}(\alpha = 0)$, with the sampling distribution of $\lambda(\alpha = 0)$. The likelihood, which includes a Gaussian factor to account for the background uncertainty, is

$$\mathcal{L} = \mathrm{Poisson}(n|\alpha \cdot s + \beta) \times \mathrm{Gauss}(\beta|b, \sigma_\beta),$$

where n is the number of events in the signal region, s is the expected number of signal events and β is the number of background events given by the Gaussian model, having a mean value b and a standard deviation σ_β. We use the RooStats [22] implementation of this method.

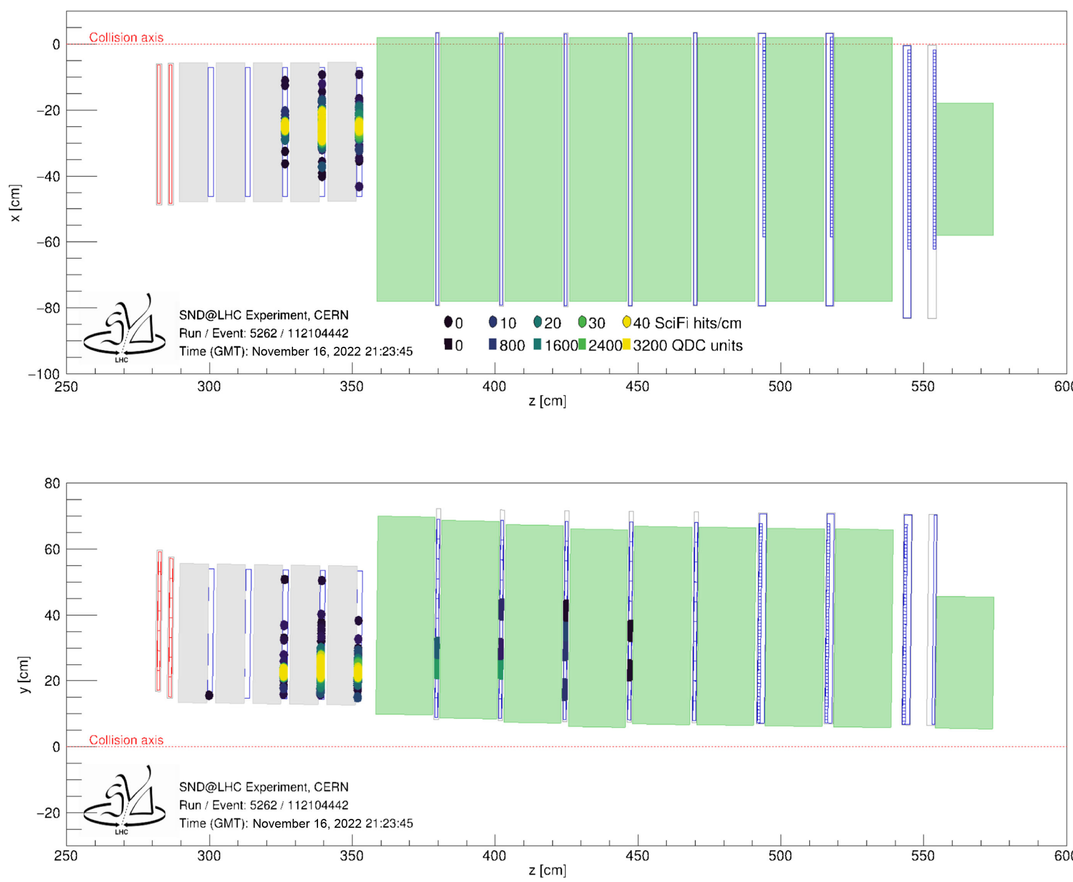

FIG. 2. Representative example of a signal-like event. The top panel shows a top-down view of the detector and the bottom panel shows the view from the side. The colored circles represent the local density of hits in the SciFi detector, corresponding to the number of hits within 1 cm of each hit. The colored rectangles represent the amplitude, in arbitrary units, of hits in the US hadron calorimeter. Lighter shades correspond to higher values.

TABLE I. Number of events passing the selection cuts in the data, and in neutrino signal ($\nu 0\mu$) and background ($\nu 1\mu$) simulation.

	Data	$\nu 0\mu$ simulation	$\nu 1\mu$ simulation
All events	1.11×10^{10}	307.7	495.8
Fiducial volume	7.91×10^{6}	63.6	111.7
Hits in 2 SciFi and 2 US stations	5.95×10^{5}	38.0	83.4
Large SciFi activity	6.34×10^{4}	37.1	74.5
Large hadron calorimeter activity	2.28×10^{4}	35.8	68.3
No hits in last 2 DS stations	1.47×10^{4}	27.7	4.9
Sparse-shower removal	25	16.7	2.0
Signal region	9	7.2	0.30

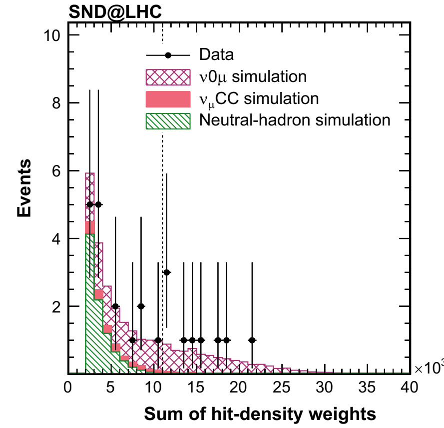

FIG. 3. Distribution of the sum of SciFi hit-density weights for events selected into the analysis sample. The events from the data are shown alongside the expected signal and background.

A systematic uncertainty of 100% is assigned to the neutral hadron background to account for the extrapolation of the control region constraint to the signal region, based on the level of agreement between test-beam data and simulation. The systematic uncertainty on the background due to ν_μ CC interactions is 18.2%. This uncertainty is given by the statistical uncertainty on the number of events observed in the dedicated analysis [4,23], added in quadrature with the DS tracking systematic uncertainty estimated with muon tracks tagged in the SciFi detector [24]. An uncertainty of 100% is assigned to the background due to ν_τ CC interactions with a τ-decay muon in the final state, broadly reflecting the range of model predictions for ν_τ event rates in SND@LHC reported in Ref. [3]. We note that given the dominance of the ν_μ CC component of the background, changing the uncertainties on the neutral hadron and ν_τ CC components from 100% to 200% has no impact on the results reported in this Letter.

The threshold of summed hit-density weights that maximises the sensitivity to observe the $\nu 0\mu$ signal is 11×10^3. In this signal region, the total systematic uncertainty on the number of expected background events is 17.9%. A representative example of a signal-like event is shown in Fig. 2 and a summary of the number of events passing each selection cut is given in Table I.

Results—The expected significance of the $\nu 0\mu$ observation is 5.5σ, with 7.2 signal events expected over a background of 0.30 ν_μ CC events, 1.5×10^{-2} neutral hadron events resulting from muon DIS interactions in the tunnel walls, and 1.7×10^{-3} ν_τ CC interactions with a muon in the final state. The signal expectation is composed of 4.9 ν_e CC events, 2.2 NC events, and 0.1 ν_τ CC events with no muons in the final state.

Nine events are observed in the signal region, resulting in an observation significance of 6.4σ. An example of a signal-like event is shown in Fig. 2. The distribution of the sum of SciFi hit-density weights for events observed in the data is shown in Fig. 3, along with signal and background expectations.

We also consider the significance to observe ν_e CC interactions with this analysis. The NC component of the $\nu 0\mu$ signal originates primarily from the flux of ν_μ. Therefore, assuming the NC to CC cross-section ratio is well modeled in the simulation, we can constrain the NC component of the $\nu 0\mu$ signal using the measurement of ν_μ CC interactions in Ref. [4]. We conservatively scale the NC component by a factor of 1.7, to account for the full difference between the ν_μ CC yield predicted by the simulation and the data reported in Ref. [23]. With this constraint, we extract evidence for the observation of ν_e CC events at the level of 3.7σ, with an expected significance of 2.2σ. The uncertainties on the ν_μ CC and NC components are conservatively taken to be fully correlated. Assuming instead uncorrelated uncertainties on these backgrounds has no significant impact on the signal significance.

Conclusions—We report the observation of neutrino interactions without final state muons at the LHC, with a significance of 6.4σ (5.5σ expected), and evidence for ν_e CC interactions with a significance of 3.7σ (2.2σ expected). This result is the first observation of collider neutrino interactions without final state muons using electronic detectors and a milestone towards neutrino detection in the high-luminosity run of the Large Hadron Collider.

The selected event sample consists mostly of NC and ν_e CC interactions. We expect that minor modifications of the method used for this analysis, when applied to the large amount of data collected by the experiment during 2024, will be sensitive to the direct observation of ν_e CC events using the electronic detectors of SND@LHC. A parallel effort is underway to select these events in the emulsion detector data.

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