A Scattering and Neutrino Detector at the LHC (SND@LHC)

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on behalf of the SND@LHC collaboration
SND@LHC experiment

- The Scattering and Neutrino Detector at the LHC

- Located 480 m downstream of the ATLAS interaction point along the beam collision axis
- Charged particles deflected by LHC magnets. 100 m rock absorbs residual hadrons
- However, neutrinos and (if exist) Feebly Interacting Particles can reach the detector
- The pseudo-rapidity range covered by the detector target $7.2 < \eta < 8.4$ (unexplored before)
SND@LHC experiment

• Installed in TI18 tunnel and Taking Data (Run 3, 250 fb⁻¹)
SND@LHC Detector

- **Upstream Veto Planes**
  Two planes of scintillator bars act as a veto for charged particles

- **TARGET REGION**
  Five walls of Emulsion Cloud Chamber (Emulsion + Tungsten 830 kg), each followed by a Scintillating Fiber plane (timestamp)

- **MUON SYSTEM**
  Eight iron slabs, each followed by one or two planes of scintillating bars

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Neutrino interaction in Emulsion
Event Reconstruction

- Distinguish all three flavors of neutrinos.
- Performed in two phases

  • First Phase (electronic detectors)
    ➢ Tagging incoming charged particles (veto planes)
    ➢ Muon identification (SciFi, muon system)
    ➢ Energy measurement (SciFi, HCAL)

  • Second Phase (nuclear emulsions)
    ➢ Extract and analyze emulsion data (~20 fb⁻¹)
    ➢ Reconstruct ν primary and secondary vertices
    ➢ Match emulsion and electronics reconstruction
Neutrinos at the LHC

- Neutrinos at the LHC can originate from the weak decay of a variety of SM particles of different masses.
Neutrinos in SND@LHC acceptance

• $O(7 \times 10^{12})$ neutrinos produced in the SND@LHC acceptance (250 fb$^{-1}$)
• ~1690 CC neutrino interactions, ~555 NC interactions (tungsten 830 kg)

Ratio of NC/CC events $\sim 0.33$ : A consistency test of SM
Neutrinos at the LHC

- Neutrino energy range $350 \text{ GeV} < E < 10 \text{ TeV}$ is currently unexplored.

- No collider neutrinos had ever been detected so far.

- SND@LHC and FASER now provide the first detection and study of the collider neutrinos in the unexplored energy range.
Physics in SND@LHC

• Measurement of the pp $\rightarrow \nu X$ cross section
• Charmed-hadron production in pp collisions
• Lepton flavor universality in neutrino interactions
• Measurement of the NC/CC ratio
• Search for Feebly Interacting Particles
Charmed-hadron production at LHC

• Electron neutrinos mainly come from the decay of charmed hadrons produced in the LHC pp collisions.

• Measurement of $pp \rightarrow \nu_e X$ cross-section provide insight into the heavy-quark production in an unexplored domain.

- The dominant partonic process for associated charm production at the LHC is gluon-gluon scattering

- Measurement of electron neutrinos can provide valuable constraints on the gluon PDF in small x region

Correlation between $x_1$ and $x_2$
for events with neutrinos in the SND@LHC acceptance
Lepton Flavor Universality

- The capability to identify all three flavors with the SND@LHC offers a unique possibility to test Lepton Flavor Universality in neutrino interactions.
- The $\nu_e/\nu_\tau$ ratio is sensitive to the $\nu$-nucleon interaction cross section ratio of the two neutrino species.

\[ R_{13} = \frac{N_{\nu_e + \bar{\nu}_e}}{N_{\nu_\tau + \bar{\nu}_\tau}} = \frac{\sum_i \bar{f}_{c_i} \text{Br}(c_i \rightarrow \nu_e)}{\bar{f}_{D_s} \text{Br}(D_s \rightarrow \nu_\tau)} , \]

\[ R_{12} = \frac{N_{\nu_e + \bar{\nu}_e}}{N_{\nu_\mu + \bar{\nu}_\mu}} = \frac{1}{1 + \omega_{\pi/k}} . \]

The measurement of the $R_{12}$ ratio can be used as a test of the LFU for $E > 600$ GeV.
Measurement of the NC/CC ratio

• Lepton identification for the three different flavors allow to distinguish CC to NC interaction at SND@LHC.
• If differential neutrino and anti-neutrino flux are equal, the NC/CC ratio can be written as

$$P = \frac{\sum_i \sigma_{NC}^\nu + \sigma_{NC}^\bar\nu}{\sum_i \sigma_{CC}^\nu + \sigma_{CC}^\bar\nu}$$

• In case of DIS, $P$ can be written as

$$P = \frac{1}{2} \left\{ 1 - 2 \sin^2 \theta_W + \frac{20}{9} \sin^4 \theta_W - \lambda (1 - 2 \sin^2 \theta_W) \sin^2 \theta_W \right\}$$

(For a Tungsten target $\lambda=0.04$)

- SND@LHC plans to measure this ratio as a consistency test of the Standard Model
- The systematic uncertainty 10%
  The statistical error 5%
Search for Feebly Interacting Particles

• SND@LHC will also be capable of exploring models with FIPs.
First Physics Results
Observation of Collider Muon Neutrinos

- SND@LHC reported the first observation of muon neutrinos from the LHC collisions, using exclusively data from the electronic detectors.

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Observation of Collider Muon Neutrinos with the SND@LHC Experiment

(Received 17 May 2023; revised 13 June 2023; accepted 20 June 2023; published 19 July 2023)

We report the direct observation of muon neutrino interactions with the SND@LHC detector at the Large Hadron Collider. A dataset of proton-proton collisions at $\sqrt{s} = 13.6$ TeV collected by SND@LHC in 2022 is used, corresponding to an integrated luminosity of 36.8 fb$^{-1}$. The search is based on information from the active electronic components of the SND@LHC detector, which covers the pseudorapidity region of $7.2 < \eta < 8.4$, inaccessible to the other experiments at the collider. Muon neutrino candidates are identified through their charged-current interaction topology, with a track propagating through the entire length of the muon detector. After selection cuts, 8 $\nu_\mu$ interaction candidate events remain with an estimated background of 0.086 events, yielding a significance of about 7 standard deviations for the observed $\nu_\mu$ signal.

DOI: 10.1103/PhysRevLett.131.031802
**Integrated Luminosity**

- A data set of proton-proton collisions at 13.6 TeV collected in 2022 is used for $\nu_\mu$ CC events search corresponding to an integrated luminosity of 36.8 fb$^{-1}$.
Signature of muon neutrino interaction

- In SND@LHC the dominant CC process occurring for muon neutrinos is deep inelastic scattering.
- The signature of these interactions includes an isolated muon track in the muon system, associated with a hadronic shower (SciFi and HCAL).
Analysis strategy

• Expected number of $\nu_\mu$ signal $\sim 157\pm37$ (target mass 792 kg, 36.8 fb$^{-1}$)
• Background : $\sim 10^9$ muons reaching the detector location.

- Muon flux measured using electronic detectors
  $\sim 2.07 \times 10^4$ cm$^{-2}$/fb$^{-1}$
- The expected muon flux in the fiducial area
  $\sim 1.69 \times 10^4$ cm$^{-2}$/fb$^{-1}$

• Need a selection with strong rejection power for very clean events.
Signal Selection

- **Fiducial volume cut**: identify events happening in a fiducial region of the target and reject charged particles entering from the front and sides of the detector.
  - A Neutral vertex event in the 3\textsuperscript{rd} or 4\textsuperscript{th} target walls
  - Detector activity constrained in an inner XY region (25x26 cm\textsuperscript{2})

- **Neutrino ID cut**: select signal-like signature patterns.
  - A Large hadronic activity in the calorimetric system
  - A clean outgoing muon track in the muon system
  - Hit time consistent with an event from the IP1 direction

- **Overall efficiency on signal (MC)** ~ 2.7 %
- **Overall efficiency on data** ~ 10\textsuperscript{-9}
Backgrounds

- **Penetrating Muon background**: enter in the fiducial volume without being vetoed and generate showers via DIS or bremsstrahlung

\[ N_{\mu}^{bkg} = N_{\mu} \times (1 - \epsilon_{Velo}) \times (1 - \epsilon_{SciFi1}) \times (1 - \epsilon_{SciFi2}) \approx 3 \times 10^{-3} \]

- **Muon-induced neutral particles**: Muons can interact in surrounding material, producing neutral particles which mimic neutrino interactions

\[ N_{neutrals}^{bkg} = N_{neutrals} \times P_{inel} \times \epsilon_{sel} = (8.6 \pm 3.8) \times 10^{-2} \]
Observation of muon neutrinos

- After selection cuts, 8 $\nu_\mu$ interaction candidate events remain (4.2 expected)
- An estimated background of 0.086 events
- A significance of 6.8 standard deviations for the observed $\nu_\mu$ signal
Nuclear Emulsion Scanning

- The analysis of the emulsions data is currently ongoing.

Neutral vertex candidate

6 tracks: plate 13 to 31

Muon tracks starting from 1 mm²

Track density per 10 fb⁻¹ → ~10⁵ tracks/cm²
Conclusions

• The SND@LHC is a new experiment designed to perform measurements with neutrinos produced at the LHC.
• Taking data since the start of the LHC Run3.
• Reported the first direct observation of $\nu_\mu$ CC interactions at collider, using electronic detectors, with $36.8 \text{ fb}^{-1}$.
• After selection cuts, 8 signal candidate events was observed with a significance of 6.8$\sigma$.
• Analysis of the emulsion data is currently being processed. Please stay tuned!
Backup slides
SND@LHC Collaboration

180 members, 24 institutes
13 countries & CERN

Bulgaria
Denmark
Germany
Italy
Japan
Korea
Russia
Switzerland
Turkey
United Kingdom
Portugal
Chile
Brazil
CERN
## Summary of SND@LHC performances

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow \nu_e X$ cross-section</td>
<td>5%</td>
</tr>
<tr>
<td>Charmed hadron yield</td>
<td>5%</td>
</tr>
<tr>
<td>$\nu_e/\nu_\tau$ ratio for LFU test</td>
<td>30%</td>
</tr>
<tr>
<td>$\nu_e/\nu_\mu$ ratio for LFU test</td>
<td>10%</td>
</tr>
<tr>
<td>Measurement of NC/CC ratio</td>
<td>5%</td>
</tr>
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</table>
The rate of neutral hadron events with energies above 100 GeV is heavily suppressed by using the veto system to tag the accompanying charged particles (most often the scattered muon).

FIG. 4. Energy spectrum of neutral hadrons produced by muon interactions in the rock and concrete entering the SND@LHC acceptance. The shaded area shows the spectrum after rejecting events with hits in the veto detector.
Distribution of SciFi hits for candidate events

The lower energy of the neutral hadrons compared to the neutrino signal results in fewer hits in SciFi.

FIG. 3. Distribution of SciFi hits for candidate events, along with the expectation from the neutrino signal. The dashed line shows the background-only hypothesis scaled up to a deviation from the nominal expectation at a level of 5 standard deviations. The vertical bars represent 68.3% confidence intervals of the Poisson means.
Future plan - Advanced SND@LHC

- Upgrade of SND@LHC in view of an extended run during Run 4:
  - Extension of the physics case
  - New technologies and detector layout
- Two detectors
  - AdvSND-Far ($7.2 < \eta < 8.4$)
    - Possible locations: TI18, Future Forward Facility
  - AdvSND-Near ($4 < \eta < 5$)
    - Possible locations: existing caverns close to IP

Neutrino interactions in ECC target
(Expectation 3000 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Flavour</th>
<th>$\nu$ in acceptance</th>
<th>CC DIS</th>
<th>AdvSND-Far</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>hardQCD: $c\bar{c}$</td>
<td>hardQCD: $b\bar{b}$</td>
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<tr>
<td>$\nu_e + \bar{\nu}_e$</td>
<td>$6.3 \times 10^{12}$</td>
<td>$1.5 \times 10^{11}$</td>
<td>$1.2 \times 10^4$</td>
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<tr>
<td>$\nu_\mu + \bar{\nu}_\mu$</td>
<td>$6.7 \times 10^{12}$</td>
<td>$1.7 \times 10^{11}$</td>
<td>$1.2 \times 10^4$</td>
</tr>
<tr>
<td>$\nu_\tau + \bar{\nu}_\tau$</td>
<td>$7.1 \times 10^{11}$</td>
<td>$4.7 \times 10^{10}$</td>
<td>$880$</td>
</tr>
<tr>
<td>Tot</td>
<td>$1.4 \times 10^{13}$</td>
<td></td>
<td>$2.5 \times 10^4$</td>
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</table>

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<td>$\nu_\mu + \bar{\nu}_\mu$</td>
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<td></td>
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PYTHIA Monte Carlo Monte Carlo

- c and b decays (5% tau flavour)
- leptonic W decays (33% tau flavour)
- large angle
- To caverns in T118, T112

7.2 < η < 8.4 SND@LHC
η > 8.8 FASERν

Future plan AdvSND-Near


P. Foldenauer, F. Kling and P. Reimitz, [arXiv:2108.05370v1]