Detection of high-energy neutrinos at LHC with SND@LHC

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On behalf of the SND@LHC collaboration
Overview

- The SND@LHC experiment
- Detector overview
- Neutrino physics program
- Commissioning, installation and run status

SND@LHC Technical Proposal
Motivation

• 1990, Klaus Winter point out possibility of tau neutrino detection at LHC neutrino
  • Still number of observed tau neutrino interaction is limited (DONUT and OPERA)

CERN is unique in providing high energy neutrinos in an unexplored energy region from LHC.

Also unique in measuring $pp \rightarrow \nu X$, equivalent with $10^{17}$ eV cosmic ray interaction which produce ultra high energy neutrinos.

LHC neutrino contains all three kinds of high energy neutrino useful to study lepton flavor universality.
• About 480m away from the ATLAS IP
• TI18 tunnel: former service tunnel connected SPS to LEP. Not used anymore.
• Symmetric to TI12 tunnel where FASER is located.
• Charged secondary particles deflected by LHC bending magnets
• Shielded by 100 m of rock
• Located slightly off axis
  • Angular acceptance: 7.2<\eta<8.4
  • FASER is placed on axis covering \eta>8.8
• Aiming to collect 290 fb^{-1} (150 in proposal)
  • More luminosity become available in RUN3
SND@LHC detector

- **Veto System**
  - Tag penetrating muons (Scintillating bars)

- **Vertex Detector and EM Cal**
  - Five target walls followed by SciFi tracker
  - Tungsten ECC (Emulsion Cloud Chamber)
    - 59 1mm thick tungsten plate + 60 emulsion films
    - Neutrino interaction vertex detector
    - Flavor identification for $\nu_e$ and $\nu_\tau$
  - Scintillating fibers for timing and EM calorimetry
    - 17 $X_0$ each 5 target walls

- **Had Cal and Muon System**
  - 8 iron walls (8λ) interleaved with plastic scintillator planes for fast time resolution and hadronic energy measurement
- Angular acceptance: $7.2 < \eta < 8.4$
- Target material: Tungsten
- Target mass: 830 kg
- Surface: 390x390 mm$^2$

Electromagnetic calorimeter
$\sim 40 \times_0$

Hadronic calorimeter
$\sim 10 \lambda$

Off axis location

Target material: Tungsten
Target mass: 830 kg
Surface: 390x390 mm$^2$
ECC target

- Number of bricks: 20
  - walls: 5
  - Bricks per wall: 4

- Brick surface: 192x192 mm²
  - Brick thickness: 78 mm
  - 60 films + 59 W plate

- Passive material: Tungsten
  - Total mass: 830 kg
  - Total emulsion surface: 44 m²

Fine 3D tracking detector composed of 0.2 μm diameter AgBr crystal in gelatin.
High energy interaction in emulsion

600 GeV $\pi^-$

Sulfur 200 GeV/nucleon

100 $\mu$m
EVENT RECONSTRUCTION

**FIRST PHASE: electronic detectors**
- Event reconstruction based on Veto, Target Tracker and Muon system
  - Identify neutrino candidates
  - Identify muons in the final state
  - Reconstruction of electromagnetic showers (SciFi)
  - Measure neutrino energy (SciFi+Muon)

**SECOND PHASE: nuclear emulsions**
- Event reconstruction in the emulsion target
  - Identify e.m. showers
  - Neutrino vertex reconstruction and 2ry search
  - Match with candidates from electronic detectors (time stamp)
  - Complement target tracker for e.m. energy measurement
KEY FEATURES

- **Muon identification**
  - $\nu_\mu$ CC interactions identified thanks to the identification of the muon produced in the interaction
  - Muon ID at the neutrino vertex crucial to identify charmed hadron production, background to $\nu_\tau$ detection

- **Energy measurement**
  - The detector acts as a non-homogeneous sampling calorimeter

- Combing information from SciFi (target region) and Scintillator bars (Muon System)
  - Average resolution on $\nu_e$ energy: 22%

- Performance of SciFi tracker as sampling calorimeter, using a CNN
  - Electron energy resolution

<table>
<thead>
<tr>
<th>% evts</th>
<th>% evts</th>
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<tbody>
<tr>
<td>CC-DIS</td>
<td>NC-DIS</td>
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<tr>
<td>0$\mu$</td>
<td>31.1</td>
</tr>
<tr>
<td>1$\mu$</td>
<td>67.6</td>
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<tr>
<td>2$\mu$</td>
<td>1.1</td>
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NEUTRINO EXPECTATIONS

- Integrated luminosity: **290 fb\(^{-1}\)**
- Upward/downward crossing angle: **0.43/0.57**

- Neutrino production in LHC pp collisions performed with **DPMJET3** embedded in FLUKA
- Particle propagation towards the detector through **FLUKA** model of LHC accelerator

<table>
<thead>
<tr>
<th>Flavour</th>
<th>Neutrinos in acceptance</th>
<th>CC neutrino interactions</th>
<th>NC neutrino interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν(_μ)</td>
<td>120</td>
<td>3.4 \times 10^{12}</td>
<td>450</td>
</tr>
<tr>
<td>ν(\bar{\mu})</td>
<td>125</td>
<td>3.0 \times 10^{12}</td>
<td>480</td>
</tr>
<tr>
<td>ν(_e)</td>
<td>300</td>
<td>4.0 \times 10^{11}</td>
<td>760</td>
</tr>
<tr>
<td>ν(\bar{e})</td>
<td>230</td>
<td>4.4 \times 10^{11}</td>
<td>680</td>
</tr>
<tr>
<td>ν(_τ)</td>
<td>400</td>
<td>2.8 \times 10^{10}</td>
<td>740</td>
</tr>
<tr>
<td>ν(\bar{\tau})</td>
<td>380</td>
<td>3.1 \times 10^{10}</td>
<td>740</td>
</tr>
<tr>
<td>TOT</td>
<td>7.3 \times 10^{12}</td>
<td>1930</td>
<td></td>
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</table>
Neutrino physics program in RUN3

• $pp \rightarrow \nu_e X$ cross section and forward charmed hadron production
  • Neutrino beam simulation predicts that 90% $\nu_e + \bar{\nu}_e$ come from charmed hadron decays
  ▶ Reconstructed spectrum of $\nu_e + \bar{\nu}_e$ flux in SND@LHC acceptance

5% Stat. , 15% Sys. uncertainty

▶ Correlation between pseudo-rapidity of the electron (anti-)neutrino and the parent charmed hadron
▶ Use neutrino as a probe for forward charm production

5% Stat. , 35% Sys. uncertainty

Neutrinos in SND@LHC acceptance

LHCb acceptance
Lepton Flavor Universality (LFU) test

- LHC neutrino beam contain all three neutrino flavors and SND@LHC has flavor identification capability

Sensitive to $\nu$-nucleon interaction cross-section ratio of two neutrino species

$$R_{13} = \frac{N_{\nu_e + \bar{\nu}_e}}{N_{\nu_{\tau} + \bar{\nu}_\tau}} = \frac{\sum_i f_{c_i} B_{\tau}(c_i \rightarrow \nu_e)}{\sum_i f_{D_s} B_{\tau}(D_s \rightarrow \nu_\tau)},$$

30% Stat. , 20% Sys. uncertainty

The measurement of the $\nu_e/\nu_\mu$ ratio can be used as a test of the LFU for $E>600$ GeV

$$R_{12} = \frac{N_{\nu_e + \bar{\nu}_e}}{N_{\nu_\mu + \bar{\nu}_\mu}} = \frac{1}{1 + \omega_{\pi/k}}.$$
Installation, commissioning and run status

- Installation in TI18 started on November 1\textsuperscript{st} 2021
- Electronic detector installation completed on December 3\textsuperscript{rd} 2021
- Installation of the neutron shield completed on March 15\textsuperscript{th} 2022
Installation, commissioning and run status

- View of the machine to the IP (left) and of the detector in TI18 (right)
Installation, commissioning and run status

Cosmic ray
(March 5th 2022)

Muon from pp collisions @13.6 TeV
(July 6th 2022)
Installation, commissioning and run status

Emulsion film from Nagoya (JP) and Slavich (RU) Early July.

Tungsten ECC installed July 26th, 2022
Total mass: 830 kg
Number of emulsion films: 1200

Film production @Nagoya
Conclusions

- SND@LHC is approved on March 2021
  - We successfully prepared whole detector in time.
  - Data taking started in April 2022 with 1/20 emulsion module
  - Full ECC modules installed on July 26th

- Measuring unexplored region of high energy neutrino events
  - Cross section measurement at TeV region
    - Uncertainty 5±15%(ν_e + antu ν_e)
  - Forward region heavy flavor production through neutrino
    - Forward region (7.2<η< 8.4) where even LHCb can not explore
  - LHC neutrino beam contain all three kind of neutrino
    - Lepton Flavor Universality test with 10±10%(e/μ) to 30±20%(e/τ) uncertainty

- Stay tune for the result
  - Real run just started
  - 290 fb^{-1} in RUN3(2022-25) : 1930 events including 34 tau neutrino