The Scattering and Neutrino Detector at the LHC

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Outline

➢ Overview and Motivation
➢ The SND@LHC detector
➢ Physics concepts
➢ Current status
Compact experiment observing forward-going neutrinos emerging from LHC interactions

- Off-axis detector located 480m downstream of the ATLAS interaction point (IP1) in the T118 tunnel
- Experiment approved by CERN Research Board in March 2021
  https://snd-lhc.web.cern.ch/
- Collaboration of 180 members from 24 institutes in 13 countries and CERN
Motivation

- Unlocking the potential of LHC neutrinos:
  - E range is few hundred GeV to a few TeV
  - 150 fb\(^{-1}\) luminosity for the LHC Run 3 and 1-tonne detector mass located in TI18 result in 2000 high-energy neutrino interactions
    - all three neutrino flavours
    - pseudorapidity range \(7.2 < \eta < 8.6\)
- Large neutrino flux in forward direction covering a wide energy range

- High neutrino energies → relatively large neutrino interaction xsec
- Measure charmed-hadron production indirectly through \(\nu_e\) and \(\nu_\tau\) in an unexplored domain
- \(\nu_\mu\) originate mainly from charmed-hadron decays, low-energy \(\nu_\mu\) also from π and K decays
Physics goals

**Neutrino physics at LHC energies**

- $\sigma_{pp \rightarrow \nu X}$ in $7.2 < \eta < 8.6$ range
- $\nu_e$ as a probe of charm quark production
- Lepton universality test: $\nu_\tau/\nu_e$ and $\nu_\mu/\nu_e$
- Measurement of the NC/CC ratio

**Search for new physics**

- Direct search for feebly interacting particles (FIP) through their scattering

\[ \chi + p/e \rightarrow \chi + p/e \]
\[ \chi + p/n \rightarrow \chi + X \]
Overview of the detector

**Upstream veto plane**
- Single plane of scintillating bars: tag incoming muons

**Target region**
- Emulsion cloud chambers: tungsten target plates interleaved with emulsion: neutrino interaction detection (vertexing)
  - Target mass 830kg
  - Scintillating fiber planes: timestamp, position measurement
  - Together: EM shower energy measurement

**Muon system**
- Plastic scintillator planes interchanged with iron walls: time and energy measurement

Vertex detector + ECAL sampling every $10X_0$ to $\sim40X_0$

HCAL + muon ID system sampling every $\lambda$ to $8\lambda$, (with target region $\sim10\lambda$)
SND@LHC detector in T118: installation ongoing

Front view

Side view

SciFi readout electronics

Emulsion Cloud Chamber

Iron walls (part of the muon system)
Data acquisition

➢ Two types of active sub-systems:
  ➢ Scintillator bars read out by SiPMs - veto and muon systems
  ➢ Scintillating fibers read out by SiPMs, - SciFi tracker

➢ 36 identical DAQ boards synchronized with the LHC bunch crossing clock

➢ Trigger-less: all hits are recorded
  ➢ hits with same time stamp grouped into events
  ➢ basic online signal processing for data quality monitoring

➢ Noise reduction: setting of signal threshold (3.5 ph.e.)
  ➢ online: events must produce signals in a minimum number of boards
Data reconstruction

**First phase:** online; using response of electronic detectors
- Identify $\nu$ interaction and FIP scattering event candidates
- Muons (spanning to the DS muon stations)
- EM showers (limited to SciFi)
- $\nu$ energy (SciFi+Muon system)

**Second phase:** nuclear emulsion data
- about 6 months exposure, then 6 months for scanning of films
- EM showers
- $\nu$ vertex reconstruction
- identify $\nu$ for $\tau$
- match with candidates from electronic detectors
Key detector features

Muon Identification

- $\nu_\mu$ CC interactions identified by detection of muons produced in target interactions
- Muon ID at $\nu$ vertex crucial to identify charmed hadron production, latter form background to $\nu_\tau$ detection if primary muon is not identified

<table>
<thead>
<tr>
<th>% evts</th>
<th>% evts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$\mu$</td>
<td>31.1</td>
</tr>
<tr>
<td>1$\mu$</td>
<td>67.6</td>
</tr>
<tr>
<td>2$\mu$</td>
<td>1.13</td>
</tr>
<tr>
<td>3$\mu$</td>
<td>0.1</td>
</tr>
<tr>
<td>&gt; 3$\mu$</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Energy measurement

- Whole detector acts as a non-homogeneous sampling calorimeter
  - combine information from the SciFi tracker of the Target region and the scintillator bars of the Muon system
  - overall fractional resolution is 22%
- Energy reconstruction technique using convolutional neural networks (CNN) is under development
Expected neutrino flux and interactions

Number of neutrinos in the SND@LHC acceptance

<table>
<thead>
<tr>
<th>Flavour</th>
<th>Neutrinos in acceptance (E) [GeV]</th>
<th>Yield</th>
<th>CC neutrino interactions (E) [GeV]</th>
<th>Yield</th>
<th>NC neutrino interactions (E) [GeV]</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>145</td>
<td>$2.1 \times 10^{12}$</td>
<td>450</td>
<td>730</td>
<td>480</td>
<td>220</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>145</td>
<td>$1.8 \times 10^{12}$</td>
<td>485</td>
<td>290</td>
<td>480</td>
<td>110</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>395</td>
<td>$2.6 \times 10^{11}$</td>
<td>760</td>
<td>235</td>
<td>720</td>
<td>70</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau$</td>
<td>405</td>
<td>$2.8 \times 10^{11}$</td>
<td>680</td>
<td>120</td>
<td>720</td>
<td>44</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>415</td>
<td>$1.5 \times 10^{10}$</td>
<td>740</td>
<td>14</td>
<td>740</td>
<td>4</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>380</td>
<td>$1.7 \times 10^{10}$</td>
<td>740</td>
<td>6</td>
<td>740</td>
<td>2</td>
</tr>
<tr>
<td>TOT</td>
<td>$4.5 \times 10^{12}$</td>
<td>1395</td>
<td></td>
<td>450</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Neutrino production in LHC pp collisions performed with **DPMJET3** embedded in **FLUKA**
- Tau neutrino production with **PYTHIA8**
- Particle propagation towards detector with the **FLUKA** model of LHC
- Neutrino interactions inside the detector simulated using **GENIE**
Physics performance: neutrino physics

Charmed-hadron production in pp collisions

Simulation predicts that 90% $\nu_e + \bar{\nu}_e$ come from the decay of charmed hadrons

- Measurement of $\sigma_{pp \rightarrow \nu e X}$
  
  Reconstructed energy spectrum of $\nu_e$ and $\bar{\nu}_e$ in the SND@LHC acceptance

- Derivation of the charmed-hadron yield from the $\nu_e$ flux
  
  based on angular correlation between $\nu_e$ and parent charmed hadron

Simulation predicts that 90% $\nu_e + \bar{\nu}_e$ come from the decay of charmed hadrons

7.2 < $\eta_{\text{hadron}}$ < 8.6
Physics performance: neutrino physics

Charmed-hadron production in pp collisions: QCD measurements

The dominant partonic process for associated charm production at the LHC is gluon-gluon scattering. Charmed-hadron production in pp collisions:

\[ \frac{d\sigma}{d\eta}(13 \text{ TeV}) \]

Extraction of gluon PDF in very small x-region relevant for Future Circular Colliders

Constrain PDF with data:

\[ R = \frac{d\sigma/d\eta(13 \text{ TeV})}{d\sigma/d\eta_{\text{ref}}(7 \text{ TeV})} \]

4 < \eta_{\text{ref}} < 4.5

Correlation between \( x_1 \) and \( x_2 \) momentum fractions for events in the SND@LHC acceptance

Reduction of the scale uncertainty

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Physics performance: neutrino physics

Lepton flavour universality test
Identification of three neutrino flavours in the SND@LHC detector

Energy spectrum of $\nu_e$ and $\bar{\nu}_e$ in the SND@LHC acceptance

- $\nu_\tau$ in SND@LHC acceptance originate from $D_s$ meson decays
- Sensitive to $\nu$ - nucleon cross section ratio for $\nu_\tau$ and $\nu_e$

$$R_{13} = \frac{N_{\nu_e + \bar{\nu}_e}}{N_{\nu_\tau + \bar{\nu}_\tau}} = \frac{\sum_i \tilde{f}_c \tilde{B}(c_i \rightarrow \nu_e X)}{\tilde{f}_{D_s} \tilde{B}(D_s \rightarrow \tau \nu_\tau)},$$

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

$$R_{12} = \frac{N_{\nu_e + \bar{\nu}_e}}{N_{\nu_\mu + \bar{\nu}_\mu}} = \frac{1}{1 + \omega_{\pi/K}}, \quad \omega_{\pi/K} \text{ is the } \nu_\mu \text{ contamination from } \pi/K$$

NC/CC ratio
Lepton flavour identification in the SND@LHC detector

- If differential $\nu$ and anti-$\nu$ energy spectra are equal, NC/CC ratio ($P$) is

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

- Compare measured $P$ with the SM expectation
- NC/CC ratio used as an internal consistency check

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Detector commissioning and tests

➢ Successful tests of the SciFi tracker/ECAL using cosmic ray muons (Aug 2021): first test of DAQ and event building, MC parameter tuning

➢ Test Scifi tracker and also all detectors on muon beam at the CERN SPS H6 beamline - check electronics response

➢ Test with HCAL/Muon system on pion beam at the CERN SPS H8 beamline (Sep-Oct 2021) - calibration of E measurement with HCAL, important for MC tuning

➢ Detector installation on site started on Nov 1 and is currently ongoing
SND@LHC is on schedule and detector installation is ongoing
Plan to start taking data in 2022!
Detector optimized for neutrino searches in a region where they act as a probe of heavy (mostly charm) quark production
Searches for new particles, sensitivity under evaluation
A new era of collider neutrino physics is just starting!
Acknowledgements

This work is supported by the Bulgarian Ministry of Education and Science within the National Roadmap for Research Infrastructures 2020-2027, contract No. D01-374/18.12.2020
TI18 tunnel: former service tunnel connecting SPS to LEP

Symmetric to TI12, where FASER is located
- In situ background measurement performed by the FASER Collaboration

About 480m away from ATLAS IP:
- ~100m of rock serve as a shield
- Charged particles deflected by LHC magnets
• Exists a detailed FLUKA simulation of proton beams transport along the LHC
  • rate in SND@LHC acceptance: $2 \times 10^4$ particles/cm$^2$/fb$^{-1}$
• Measured particle fluxes in TI18 for FASER during Run 2: $1.2-1.9 \times 10^4$ particles/cm$^2$/fb$^{-1}$
• Backgrounds essentially composed of
  • Muons: only those with $E > 30$ GeV reach the detector:
    • veto detector to tag them
    • exchange emulsion every 25 fb$^{-1}$
  • Neutrons and $K_L$s from muon DIS in rock: mimic neutrino NC
  • Thermal neutrons
    • Coming from proton beam interaction with the residual gas inside the LHC vacuum pipe, beam 2 contributes more
      • 50% are thermal neutrons at $\sim 0.025$ eV
    • Total flux is $2.8 \times 10^8$ particles/cm$^2$/year
      • allows using non-radiation-hard electronic devices
      • place neutron shield around the emulsion detector

<table>
<thead>
<tr>
<th>particles/fb$^{-1}$</th>
<th>E&gt;10 GeV</th>
<th>E&gt;100 GeV</th>
<th>E&gt;200 GeV</th>
<th>E&gt;500 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L$</td>
<td>48</td>
<td>11.7</td>
<td>4.4</td>
<td>0.5</td>
</tr>
<tr>
<td>neutron</td>
<td>17</td>
<td>5.4</td>
<td>2.0</td>
<td>0.5</td>
</tr>
<tr>
<td>anti-neutron</td>
<td>12</td>
<td>3.3</td>
<td>1.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Off-axis position

- Detector is off-axis wrt the collision axis: neutrino yields depend on the pp beams crossing angle (±150 mrad)

<table>
<thead>
<tr>
<th>case</th>
<th>Upward beam crossing</th>
<th>Downward beam crossing</th>
<th>0 beam crossing angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>N observed v interactions wrt nominal (0 angle)</td>
<td>18%</td>
<td>-22%</td>
<td>-</td>
</tr>
<tr>
<td>η</td>
<td>7.3 – 9.0</td>
<td>7.1 – 8.3</td>
<td>7.2 – 8.6</td>
</tr>
</tbody>
</table>
Summary of physics results: expected precision

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \to \nu_e X$ 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>NC/CC ratio</td>
<td>5%</td>
</tr>
</tbody>
</table>
Physics performance: new physics searches

Mediator (V) production channels: \( pp \rightarrow V + X \)

\( V \rightarrow \chi \chi \)

Mediator decays to:

- proton bremsstrahlung
- decay of unflavoured mesons
- Drell-Yan process

\( \chi \) scattering off nucleons: number of events scales as \( \alpha_B^3 \)

\( m_\chi = m_V/3, \alpha_\chi = \alpha_B \)

Excluded by CDF, BES, E949 and BNL

\( \alpha_B = g_B^2/4\pi \)

\( J_\mu^B \) baryonic current:

\[ J_\mu^B = \frac{1}{3} \sum \bar{q} \gamma_\mu q \]