SND@LHC neutrino results

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11th Large Hadron Collider Physics Conference
Belgrade, 22-26 May 2023
Neutrino experiments at the LHC

Potential of observing neutrinos at the LHC recognized in the early 90s

- Large neutrino fluxes in forward region from pp collisions
- High $\nu$ energy: $E_{\nu} \left[10^2 - 10^3\right]$ GeV, $\sigma_\nu \propto E_{\nu}$
- A small-scale LHC experiment can observe neutrinos of all three types
- Probe $pp \rightarrow \nu X$ in an unexplored energy domain

- Two experiments presently operating
  - FASER$\nu$ on-axis ($\eta>9$) [T. Boeckh talk]
  - SND@LHC slightly off-axis ($7.2 < \eta < 8.4$)

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LHCP 2023
SND@LHC neutrino results

SND@LHC physics programme
SND@LHC TP: LHCC-P-016

- Measure charm production at high $\eta$
  - Neutrinos in the detector acceptance are mostly coming from charmed hadrons decay
    

- $\nu_e$ as a probe of forward charm quark production
  - constrain gluon PDF at very low momentum fraction ($x \approx 10^{-6}$)

- Lepton universality test: $\nu_\tau/\nu_e$ and $\nu_\mu/\nu_e$
  - The detector is designed to distinguish all neutrino flavours

- Measurement of the NC/CC ratio

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

### Run3: 250fb$^{-1}$

<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>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>130</td>
<td>$3.0 \times 10^{12}$</td>
<td>452</td>
<td>910</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>133</td>
<td>$2.6 \times 10^{12}$</td>
<td>485</td>
<td>360</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>339</td>
<td>$3.4 \times 10^{11}$</td>
<td>760</td>
<td>250</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>363</td>
<td>$3.8 \times 10^{11}$</td>
<td>680</td>
<td>140</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>415</td>
<td>$2.4 \times 10^{10}$</td>
<td>740</td>
<td>20</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau$</td>
<td>380</td>
<td>$2.7 \times 10^{10}$</td>
<td>740</td>
<td>10</td>
</tr>
<tr>
<td>TOT</td>
<td>$4.0 \times 10^{12}$</td>
<td>1690</td>
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</tr>
</tbody>
</table>
In the TI18 tunnel
  - former SPS to LEP transfer line
  - ~480m away from ATLAS interaction point (IP1)

Shielded by:
  - ~100m rock
  - LHC magnets deflecting charged particles

Angular acceptance $7.2 < \eta < 8.4$
Detector concept

- Hybrid detector design
- Optimized for the identification of three $\nu$ flavours and feebly interacting particles.

- **Veto system**
  - 2 planes of stacked scintillator bars
  - tag charged particles entering the detector volume

- **Vertex detector + EM CAL**
  - Emulsion cloud chambers (emulsion/W)
    - neutrino target mass $\sim$830kg
  - Scintillating fiber planes

- **HAD CAL + MUON ID SYSTEM**
  - 5+3 plastic scintillator planes interchanged with iron walls

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`arXiv:2210.02784`
Using data from SciFi and DS detectors, the muon flux is

- **SciFi**: \(2.06 \times 10^4\) cm\(^{-2}\)/fb\(^{-1}\) area: 31x31cm\(^2\)
- **DS**: \(2.35 \times 10^4\) cm\(^{-2}\)/fb\(^{-1}\) area: 52x52cm\(^2\)
  - Vertical flux gradient
  - 2\% deviation of SciFi and DS fluxes in the same acceptance range (31x31cm\(^2\))
  - while systematic error is 3\%(SciFi) and 5\%(DS) on muon flux per detector
- data/MC simulation agreement level 20-25\%
  - MC sim.: **SciFi**: \(1.60 \times 10^4\) cm\(^{-2}\)/fb\(^{-1}\) area: 31x31cm\(^2\)
  - MC sim.: **DS**: \(1.79 \times 10^4\) cm\(^{-2}\)/fb\(^{-1}\) area: 52x52cm\(^2\)
- Providing feedback to CERN SY-STI team for the FLUKA simulation
  - In return, SND@LHC collaboration is provided with updated simulation samples
Observation of $\nu_{\mu}$ using electronic detectors

- **Goal**: high-purity sample of $\nu_{\mu}$ charged current interaction (CC) events

- **Analysis strategy**:
  - Maximise signal/background ratio
    - Background: $\sim 10^9 \mu$ events
    - Strong rejection power needed

- **Dataset**: full 2022 run, 36.8 fb$^{-1}$

- **Signal selection**:
  - **Fiducial volume cut**: reject charged particles entering from the front and sides of the detector
    - Detector activity starts in the 3rd or 4th target wall
      - consistent with a neutral particle interaction
      - probing the $\nu_{\mu}$-induced shower already in SciFi
    - Detector activity is constrained in an inner XY detector region, size $25 \times 26 \text{ cm}^2$
    - Efficiency of this cut on simulated neutrino interactions in the target is 7.5%
  - **Neutrino interaction ID**
    - Large hadronic activity in the calorimetric system (SciFi and HCAL)
    - Isolated outgoing muon track reconstructed in the Muon Identification system
    - Hit time consistent with an event originating from the IP1 direction
Background assesment

Muons reaching the detector location

- Not vetoed, generate showers (bremsstrahlung, DIS in the detector) \((a, b)\) – using the data
- Interact in the surrounding material to produce neutral particles which can then mimic neutrino interactions in the target \((c)\) – rely on simulations

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

\[ N_{\text{neut}} = N_{\text{neut}} \times P_{\text{inel}} \times \epsilon_{\text{sel}} = (7.6 \pm 3.1) \times 10^{-2} \]

Rec. tracks in SciFi

- Total number of muons in target acceptance
- Veto inefficiency
- SciFi plane inefficiency
deemed negligible

\(\sim 5.0 \times 10^{8}\)
\(\sim 5.3 \times 10^{-12}\)

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arXiv:2305.09383
- Observed 8 $\nu_\mu$ CC candidates
- Observation significance 7$\sigma$

Side note: hit multiplicity in SciFi discriminates against neutral-hadron background

Display of a $\nu_\mu$ CC candidate event

SND@LHC neutrino results
LHCP 2023

arXiv:2305.09383
SND@LHC detector is operating since the start of the LHC Run 3
  - has collected 36.8 fb\(^{-1}\) (95% efficiency)

Completed a measurement of the muon flux in the detector

Reporting the observation of incoming \(\nu_\mu\) in the electronics detectors

Observed 8 \(\nu_\mu\) CC candidates against an expected background of \((7.6 \pm 3.1) \times 10^{-2}\)

Observation significance 7\(\sigma\)

Reached the first analysis cornerstone

Started to unveil the physics capacity of the experiment

**Exciting studies ahead!**
Thank you!
Additional slides
CERN approves new LHC experiment

SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility’s ninth experiment.

**Experiment timeline**

- **Letter of Intent**
  - August 2020

- **SND@LHC**
  - January 2021

- **CERN approves new LHC experiment**
  - March 2021

- **Muon from 13.6 TeV pp collision**
  - 6th July 2022

- **Side view**

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**Scattering and Neutrino Detector at the LHC**

**TECHNICAL PROPOSAL**

- **Letter of Intent**
  - August 2020

- **SND@LHC**
  - January 2021

- **CERN approves new LHC experiment**
  - March 2021

- **Muon from 13.6 TeV pp collision**
  - 6th July 2022

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**SND@LHC neutrino results**

LHCP 2023
## Neutrino events timeline

![Graph showing neutrino events timeline](image)

### 2022

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<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
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<th>Nov</th>
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<tbody>
<tr>
<td><strong>EMULSION RUN0</strong></td>
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<tr>
<td><strong>EMULSION RUN3</strong></td>
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</table>

### Instrumented Target Mass
- EMULSION RUN0: 39 kg
- EMULSION RUN1: 807 kg
- EMULSION RUN2: 784 kg
- EMULSION RUN3: 792 kg

### Integrated Luminosity
- EMULSION RUN0: 0.46 fb⁻¹
- EMULSION RUN1: 9.5 fb⁻¹
- EMULSION RUN2: 20.0 fb⁻¹
- EMULSION RUN3: 8.6 fb⁻¹
**Emulsion Cloud Chambers**
- Goal: tracking and vertex ID
- Sub-micrometric resolution
- Geometry
  - 5 walls of 2x2 bricks
- Shielding (protect from neutrons, stabilise T and humidity)
- Brick layout
  - 60 layers of 300 μm-thick emulsions
  - Interleaved by 1 mm tungsten plates
- Target mass ~830 kg

**SciFi**
- Goals:
  - Precise timing information (~350 ps time resolution)
  - EM energy measurement
  - Spatial information (<100 μm spatial resolution)
- Geometry
  - 5 planes of scintillating fibres mat pairs (x-y)
  - Mats built of 6 layers of staggered fibres

**Hadronic calorimeter**
- Goals:
  - Timing information
  - Hadronic energy measurement
  - Spatial information
- Geometry
  - 5 stations of horizontal scintillation bar layers
  - Readout on both ends of a bar

**Muon ID system**
- Goals:
  - Timing information
  - Muon tracking and isolation
- Geometry
  - 3 stations of orthogonal scintillation bar layer pairs
  - Horizontal bars read out on both ends
  - Vertical bars read out on one end (one additional layer in last station)
Using data from SciFi and DS, the muon flux is

- **SciFi**: $2.06 \times 10^4$ cm$^{-2}$/fb$^{-1}$
- **DS**: $2.35 \times 10^4$ cm$^{-2}$/fb$^{-1}$

2% deviation of SciFi and DS fluxes in the same acceptance range

- while systematic error is 3%(SciFi) and 5%(DS) on muon flux per detector

- data/MC simulation agreement level 20-25%

Comparison of Emulsions/SciFi distributions with early data in good agreement, preliminary flux measurement agree within 10%

- Input to target replacement strategy definition