A new Scattering and Neutrino Detector at the LHC

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on behalf of the SND@LHC collaboration
Neutrino Experiments at the LHC

Proposals for **studying high-energy neutrinos at LHC** date back to the early 90’s

- **Measure** \( pp \rightarrow \nu X \) in an **uncovered energy domain**
  - **Achievable** with rather **small-size detectors** [*]
    - Large \( \nu \) fluxes from pp collisions **at high** \( \eta \)
    - \( E_\nu \sim [10^2 \text{ – } 10^3] \text{ GeV}, \sigma_\nu \propto E_\nu \)
- **Two experiments** presently operating
  - **FASER** \( \nu \) on-axis (\( \eta > 9 \)) [*C. Cavanagh talk*]
  - **SND@LHC** slightly off-axis (\( 7.2 < \eta < 8.4 \))

[*] Further studies on the physics potential of an experiment using LHC neutrinos
Measure **charm production** at high **high** $\eta$ ($gg \to c\bar{c}$)
- Due to $\eta$ acceptance, $\nu$s mostly coming from charmed hadrons decay

**Probe gluon PDF** low momentum fraction ($x \sim 10^{-6}$)
- FCC detectors
- Extra-galactic $\nu$ observation (atmospheric $\nu$ background)

**Test lepton flavour universality** using $\nu$s:
- **SND@LHC** is designed to distinguish all $\nu$ flavours

**Direct search of feebly-interacting particles (FIPs)**
- E.g.: Dark scalars, Heavy Neutral Leptons, Dark Photons
SND@LHC: Detector Location

SND@LHC is located in the TI18 service tunnel (SPS to LEP transfer line, then dismissed)

- ~480 m away from ATLAS interaction point (IP1)
- Shielding:
  - ~100 m of rock
  - LHC magnets (deflect charged particles)
- Angular acceptance: $7.2 < \eta < 8.4$
**SND@LHC:** Detector Location

**SND@LHC is located** in the **TI18** service tunnel (SPS to LEP transfer line, then dismissed)

Machine to IP1 (left) – SND@LHC in TI18 (right)
Angular acceptance: $7.2 < \eta < 8.4$

- Veto system
- Target, Vertex detector, EM CAL
- HAD CAL, MUON SYSTEM
VETO
- **Goal**: charged particle identification
- 2 planes of stacked **scintillator bars**

**Goal**: charged particle identification

2 planes of stacked **scintillator bars**
Emulsion Cloud Chambers (ECC)

- **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
SND@LHC: Detector Layout

SciFi

- **Goals:**
  - Precise timing information
  - EM energy measurement
  - Spatial information

- **Geometry**
  - 5 planes of scintillating fibres mat pairs (x-y)
  - Mats built of 6 layers of staggered fibres

\[ \sigma_t \sim 250 \text{ ps} \]

single-station (x and y)
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

[*] interleaved with 20 cm Fe blocks
Muon 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)

[*] interleaved with 20 cm Fe blocks
SND@LHC: Some Cornerstones

- **August 2020**
  - Letter of intent

- **January 2021**
  - Technical Proposal

- **March 2021**
  - Approval by CERN Research Board

- **April 2022**
  - Beams Back in LHC

- **July 2022**
  - Run 3 starts (√s 13.6 TeV)

SND@LHC Event Display (6th of July 2022)

- **September 2021**

- **December 2021**

- **March 2022**
Readout and DAQ

- **Trigger-less acquisition** system
- **Timestamp-based event building** from DAQ
- Multiple levels of noise filtering (FE thresholds, DAQ)

**Two-staged Reconstruction**

**First phase:** electronic detectors (event)
- Tagging of incoming charged particles (Veto, SciFi)
- Muon identification (Muon System)
- Calorimetric energy measurement (SciFi, HCAL)

**Second phase:** nuclear emulsions (~20 fb$^{-1}$)
- Extract, develop, scan, and analyse emulsion data
- Reconstruct $\nu$ primary and secondary vertices
- Match emulsion and electronics reconstruction
  - Timestamp
  - Complement EM energy measurement

Discriminate between $\nu_{\mu,e,\tau}$ flavours
Overview of the 2022 Data-Taking

- **Delivered lumi. (IP1):** 38.7 fb⁻¹
- **Recorded lumi.:** 36.8 fb⁻¹ ← 95%
- **4 emulsion runs**

Emulsions replaced three times over the 2022 run
Performance studies with Run3 data (highlights)

- **Event rates** were mapped to the LHC filling scheme
  - Study non-colliding bunches to assess non-collision background

- **Results**: beam 1 background < 1.0% – beam 2 background < 1.5%

- Can clearly tag events entering from the downstream detector end
Performance studies with Run3 data (highlights)

2022 data also used to study detector performance and measure muon flux

**Emulsion tacks:** 1 cm² x-y section – RUN0 (0.5 fb⁻¹)

Comparison of Emulsions/SciFi distributions with early data in good agreement, preliminary flux measurement agree within 10%
- Input to target replacement strategy definition

**Refined muon flux studies** performed with later 2022 data:
- Using data from SciFi and Muon system
- Accounting for higher order corrections (e.g. efficiency)
  - SciFi: $2.06 \cdot 10^4$ cm⁻² / fb⁻¹
  - Muon system: $2.35 \cdot 10^4$ cm⁻² / fb⁻¹
- Data/MC disagreement ~20 - 25%
Observation of $\nu_\mu$ using electronic detectors

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

**Analysis strategy**
- Look for $\nu_\mu$ **charged current interaction** (CC) events
- Maximise S/B, counting-based approach
- **Challenge**
  - must reach negligible background out of $\sim 10^9 \mu$ events
  - apply cuts with **strong rejection power**

**Signal selection**
- **Fiducial volume cuts**
  - require **neutral vertex** event from the 3rd or 4th target walls
  - select **x-y fiducial area** (25 x 26 cm$^2$) to reject background entering from edges
- **Neutrino ID**
  - require **large hadronic activity in SciFi and HCAL**
  - timing compatible with upstream event from IP1 collision
  - reconstructed and **isolated muon track** (muon system)
Background estimation

Muon-induced background
“undetected” muons

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

~5.3 x 10^{-12}

\[ 5.0 \times 10^8 \]

\[ \approx 2.1 \times 10^4 \text{ cm}^2 \text{ fb} \times 36.8 \text{ fb}^{-1} \times 650 \text{ cm}^2 \]

Muons

Muon-induced neutral interactions
assessment of systematics ongoing

\[ N_{\text{neutrals}}^{bkg} = N_{\text{neutrals}} \times P_{\text{inel}} \times \epsilon_{\text{sel}} \]

\[ = (7.6 \pm 3.1) \times 10^{-2} \]
Observed candidates, analysis result

- Observed 8 $\nu_\mu$ CC candidates
- Observation significance $7.0\sigma$
Summary

- **After approval** by the CERN Research Board in March 2021 the SND@LHC detector was **built** and **installed** in TI18 **over just a one year span**

- **Operating since the start of the LHC Run 3**, has collected 36.8 fb\(^{-1}\) (95% uptime efficiency)

- **Incoming muon flux** was measured using **SciFi, Muon system** and **Emulsions**

- **Attempted the observation of incoming** \(\nu_\mu\) **solely based on electronics detectors**
  - Observed **8 \(\nu_\mu\) CC candidates** against an **expected background** of \((7.6 \pm 3.1) \times 10^{-2}\)
  - **Observation significance 7.0 \(\sigma\)**

**Exciting times have started!**

[SND@LHC Web Page](#)
Thank you!
Backup
### Neutrino Physics Summary - Run3

<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>
</tbody>
</table>
Measure of $pp \rightarrow \nu_e X$ cross-section, then charm production

$pp \rightarrow \nu_e X$ cross section

- Simulation prediction: $\sim 90\%$ of $\nu_e$ come from charm decays
- Unfold detector response to get energy spectrum
- Assume SM $\sigma_e$

charm production

- Apply statistical subtraction of $\pi/K$ component to the above result
- Exploit correlation between neutrino and parent hadron
- Use different generators to assess systematics
Lepton Flavour Universality Test

- $\nu_\tau$ essentially only coming from $D_s$ decays
- $\nu_e$ coming from decay of all charmed hadrons (essentially $D_0, D, D_s, \Lambda_c$)
- $R_{13}$ only depends only on charm hadronisation fractions and $Brs$

\[
R_{13} = \frac{N_{\nu_e + \bar{\nu}_e}}{N_{\nu_\tau + \bar{\nu}_\tau}} = \sum_i \tilde{f}_c \tilde{B}r(c_i \to \nu_e) / \tilde{f}_{D_s} \tilde{B}r(D_s \to \nu_\tau),
\]

- $\nu_\mu$ produced also in decays of $\pi/K$
- Above 600 GeV, ~flat contamination around 35%
- Decay modes are essentially the same
- negligible systematic from $Brs$ and charm hadronisation

\[
R_{12} = \frac{N_{\nu_e + \bar{\nu}_e}}{N_{\nu_\mu + \bar{\nu}_\mu}} = \frac{1}{1 + \omega_{\pi/k}} \text{ contamination from } \pi/k
\]
Feebly interacting particles (example)

**Production example:** a scalar \( \chi \) particle coupled to the SM via a leptophobic portal:

\[
\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu (\partial_\mu \chi^\dagger \chi + \chi^\dagger \partial_\mu \chi),
\]

**Detection:** \( \chi \) elastic/inelastic scattering off nucleons of the target

\[
\begin{align*}
\bar{\chi} & \rightarrow \chi \\
&p, n \\
\chi & \rightarrow \chi
\end{align*}
\]

\[
\begin{align*}
\bar{\chi} & \rightarrow \chi \\
&p \\
\chi & \rightarrow \chi
\end{align*}
\]

\[
\begin{align*}
\bar{\chi} & \rightarrow \chi \\
\gamma & \rightarrow \chi
\end{align*}
\]

Proton bremsstrahlung

Meson decay

Drell-Yan

\[
m_\chi = 20 \text{ MeV}, \ \alpha_\chi = 0.5
\]
SND@LHC: Detector Layout (additional details)
Further SciFi Performance studies

**Muon test beam data**

Measured without any material between stations

Run 3   SND@LHC Preliminary

**Gap between SiPM arrays**

**Gap between boards**

\[ \sigma_t \sim 250 \text{ ps} \]

**single-station (x and y)**
Muon tracking efficiency

SciFi + Simple tracking

Muon system + Hough transform
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 IPFiducial volume cuts