Neutrino Physics at the ForwArd Search ExpeRiment

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on behalf of the FASER collaboration
The FowArd Search ExpeRiment (FASER)

An experiment at LHC for Neutrino measurements & Long-lived particle search

In this talk, I focus on the Neutrino program
For Long-lived particle search, see Eli’s talk on Friday

Figures from arxiv 2207.11427 & 1908.02310
Neutrinos at the FASER detector

Figures from arxiv 2207.11427 & 1908.02310
Neutrino flux expectations

Expected charged-current neutrino interaction (250 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Generators</th>
<th>FASER$\nu$</th>
<th>$\nu_e + \bar{\nu}_e$</th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$\nu_\tau + \bar{\nu}_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>light hadrons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIBYLL</td>
<td></td>
<td>1501</td>
<td>7971</td>
<td>24.5</td>
</tr>
<tr>
<td>DPMJET</td>
<td></td>
<td>5761</td>
<td>11813</td>
<td>161</td>
</tr>
<tr>
<td>EPOSJET</td>
<td></td>
<td>2521</td>
<td>9841</td>
<td>57</td>
</tr>
<tr>
<td>QGSJET</td>
<td></td>
<td>1616</td>
<td>8918</td>
<td>26.8</td>
</tr>
<tr>
<td>Combination (all)</td>
<td></td>
<td>2850$^{+2910}_{-1348}$</td>
<td>9636$^{+2176}_{-1663}$</td>
<td>67.5$^{+94}_{-43}$</td>
</tr>
<tr>
<td>Combination (w/o DPMJET)</td>
<td></td>
<td>1880$^{+641}_{-378}$</td>
<td>8910$^{+930}_{-638}$</td>
<td>36$^{+20.8}_{-11.5}$</td>
</tr>
</tbody>
</table>

Neutrinos from light hadron decays, e.g. $\pi$, $K$, and charmed hadron decays, e.g. $D$, $\Lambda_c$. 

Felix Kling, Laurence J. Nevay, arxiv 2105.08270
Physics motivation for neutrino measurements

**Neutrino-nucleus interactions**

Interactions of TeV neutrinos and tungsten targets
Cross-section measurements for different flavors

*Expected neutrinos*

\[ \nu_e + \bar{\nu}_e \quad \nu_e \]

\[ \nu_\mu + \bar{\nu}_\mu \quad \nu_\mu \]

**Forward hadron productions using neutrinos**

Probing forward light hadron and charmed hadron productions
-> Good inputs for cosmic-ray physics

Figures from arxiv 2105.08270 & 1908.02310
The FASER detector

FASER Spectrometer

- Tracking spectrometer stations
- Electromagnetic Calorimeter
- Magnets
- Trigger / pre-shower scintillator system
- Neutrino interaction in Tungsten targets

Three tracker stations

0.57 T dipoles

Front Scintillator veto system

Decay volume

To ATLAS IP

Interface Tracker (IFT)

FASERν detector

Emulsion films between tungsten plates

Successful data-taking during 2022 and 2023

Total \(\sim 68.4 \text{ fb}^{-1}\)

FASERν detector was installed 5 times in total
**The FASER$\nu$ detector**

FASER$\nu$ detector
Emulsion films between tungsten plates
1.1 mm tungsten plates x 730: target
Emulsion film x 730: to measure tracks

Emulsion films (25cm x 30cm)
Track in emulsion
Microscope in Nagoya Univ.
Analysis using the FASER spectrometer

Detection of $\nu_\mu + \bar{\nu}_\mu$

Event selections

- Collision event with good data quality (35.4 fb\(^{-1}\))
- No signal in two front veto scintillators (<40 pC ~ 0.5 MIP)
- Signal in last two veto layers
- Signal in calorimeter consistent with $\geq 1$ MIPs
- Exactly one good quality spectrometer track with $> 100$ GeV
- Track in fiducial tracking volume, <95 mm
- Track extrapolate to <120 mm in front veto scintillator

FASER Collaboration,
Phys.Rev.Lett. 131 (2023) 3, 031801, July 2023

Signals

One track with $> 100$ GeV

designed to observe neutrinos for the first time at a collider
Backgrounds

Neutral hadron background
0.11 ± 0.06

Scattered muons
0.08 ± 1.83

Veto inefficiency
Negligible
Neutrino detections by the FASER spectrometer

153 events passed, 16 $\sigma$

The number of neutrino events:
$153^{+12}_{-13}$

Expected by simulations $151 \pm 41$
(Average & differences btw two generators)

First direct detection of neutrinos produced at a collider experiment
Analysis using the FASER$\nu$ detector

- Emulsion film
- Tungsten plate

Muon momentum estimation
- Multiple coulomb scattering
- Momentum dependency in the scattering angle
  - Resolution: ~20% at 200 GeV

EM shower energy estimation
- Resolution: ~25% at 200 GeV

Position resolution
- $\sigma = 0.28 \, \mu m$
Event selection

2nd module of 2022,
Installed from July 26th to September 1, 9.5 fb$^{-1}$

Scanned volume (255 films) (this time)

FASERν
730 films and tungsten plates

Target volume for the first analysis
(150 tungsten plates)

Main background: neutral hadrons
- lower energy
- Well removed by applying a track or a EM shower more than 200 GeV

Event selections

- 5 or more tracks attached to a vertex
- No charged parent track
- 4 or more tracks with $\tan\theta < 0.1$
- $\tan\theta > 0.005$ for muon or EM shower
- An EM shower or a track of more than 200 GeV
- $\phi > 90^\circ$
Background expectations and candidates

Background estimation by simulation

<table>
<thead>
<tr>
<th>Background</th>
<th>$\nu_\mu$ CC</th>
<th>$\nu_e$ CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral-hadron interactions</td>
<td>$0.32 \pm 0.15$ (stat.) $\pm 0.16$ (syst.)</td>
<td>$0.002 \pm 0.002$ (stat.) $\pm 0.002$ (syst.)</td>
</tr>
<tr>
<td>NC neutrino interactions</td>
<td>$0.19 \pm 0.15$</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>$0.51 \pm 0.27$</td>
<td>$0.002 \pm 0.003$</td>
</tr>
</tbody>
</table>

3 $\nu_e$ candidate and 4 $\nu_\mu$ candidate

$\rightarrow$ over 5$\sigma$ for $\nu_e$
Summary

• The FASER experiment at LHC is measuring high-energy neutrinos using the FASER spectrometer and the FASER\(\nu\) emulsion detector.
• In 2023, we reported the first direct observation of muon neutrinos using the FASER spectrometer.
  • We found 153 events, corresponding to 16 \(\sigma\) over the background-only hypothesis.
• Also, we reported the preliminary result of the electron neutrino analysis using the FASER\(\nu\) detector.
  • We found 3 \(\nu_e\) candidates corresponding to >5 \(\sigma\)
• We have lots more data already taken to increase the precision of the neutrino studies
• We proposed upgrades as part of the Forward Physics Facility could provide millions of neutrino interactions
Backup slides
### The number of expected signals

<table>
<thead>
<tr>
<th>Detector</th>
<th>Mass</th>
<th>Coverage</th>
<th>Luminosity</th>
<th>$\nu_e+\bar{\nu}_e$</th>
<th>$\nu_\mu+\bar{\nu}_\mu$</th>
<th>$\nu_\tau+\bar{\nu}_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FASER$\nu$</td>
<td>1 ton</td>
<td>$\eta \gtrapprox 8.5$</td>
<td>150 fb$^{-1}$</td>
<td>901 / 3.4k</td>
<td>4.7k / 7.1k</td>
<td>15 / 97</td>
</tr>
<tr>
<td>SND@LHC</td>
<td>800kg</td>
<td>$7 &lt; \eta &lt; 8.5$</td>
<td>150 fb$^{-1}$</td>
<td>137 / 395</td>
<td>790 / 1.0k</td>
<td>7.6 / 18.6</td>
</tr>
<tr>
<td>FASER$\nu$2</td>
<td>20 tons</td>
<td>$\eta \gtrapprox 8.5$</td>
<td>3 ab$^{-1}$</td>
<td>178k / 668k</td>
<td>943k / 1.4M</td>
<td>2.3k / 20k</td>
</tr>
<tr>
<td>FLArE</td>
<td>10 tons</td>
<td>$\eta \gtrapprox 7.5$</td>
<td>3 ab$^{-1}$</td>
<td>36k / 113k</td>
<td>203k / 268k</td>
<td>1.5k / 4k</td>
</tr>
<tr>
<td>AdvSND</td>
<td>2 tons</td>
<td>$7.2 \lesssim \eta \lesssim 9.2$</td>
<td>3 ab$^{-1}$</td>
<td>6.5k / 20k</td>
<td>41k / 53k</td>
<td>190 / 754</td>
</tr>
</tbody>
</table>
νμ analysis using FASER Spectrometer

Expected signals

The predicted numbers of neutrino and anti-neutrino interactions from SIBYLL and DPMJET are listed in Table II. Results are shown requiring the interactions to be (1) in the FASERν detector volume or (2) in the target region and within a radius of 95 mm from the center of the FASER detector. Note that no additional acceptance and efficiency corrections are applied and the second requirement approximates the fiducial volume used in the analysis.

<table>
<thead>
<tr>
<th>Volume</th>
<th>Type</th>
<th>0 &lt; $E_\nu$ &lt; 500 GeV</th>
<th>500 &lt; $E_\nu$ &lt; 1000 GeV</th>
<th>$E_\nu$ &gt; 1000 GeV</th>
<th>$\sum$</th>
<th>$E_\nu$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FASERν</td>
<td>$\nu_\mu$</td>
<td>359 / 379</td>
<td>239 / 273</td>
<td>291 / 790</td>
<td>890 / 1442</td>
<td>880 / 1376</td>
</tr>
<tr>
<td>FASERν</td>
<td>$\bar{\nu}_\mu$</td>
<td>116 / 130</td>
<td>62 / 85</td>
<td>49 / 151</td>
<td>227 / 367</td>
<td>657 / 1028</td>
</tr>
<tr>
<td>$r &lt; 95$ mm</td>
<td>$\nu_\mu$</td>
<td>147 / 154</td>
<td>105 / 118</td>
<td>141 / 375</td>
<td>394 / 647</td>
<td>943 / 1477</td>
</tr>
<tr>
<td>$r &lt; 95$ mm</td>
<td>$\bar{\nu}_\mu$</td>
<td>48 / 53</td>
<td>28 / 37</td>
<td>23 / 67</td>
<td>99 / 157</td>
<td>687 / 1057</td>
</tr>
</tbody>
</table>

TABLE II. The expected numbers of neutrino and anti-neutrino events from SIBYLL (first number) and DPMJET (second number) for an integrated luminosity of 35.4 fb$^{-1}$ and different energy intervals, along with the sum over all energy intervals, and the average neutrino energy $\bar{E}_\nu$. Results are shown requiring the interactions to be (1) in the FASERν detector volume or (2) in the target region and within a radius of 95 mm from the center of the FASER detector.
Geometrical backgrounds for the FASER spectrometer

### Sideband method

**FASER**

\[ \mathcal{L} = 35.4 \text{ fb}^{-1} \]

Sideband: 90 mm < \( r_{\text{IFT}} \) < 95 mm, \# IFT Clusters ≤ 8

- fit: 0.2 ± 4.1 events with \( p_\mu > 100 \text{ GeV} \)
- No \( r_{\text{veto}} \) selection
- \( r_{\text{veto}} < 120 \text{ mm} \)

**Event selections**

- Collision event with good data quality (35.4 fb-1)
- No signal in two front veto scintillators (<40 pC ∼ 0.5 MIP)
- Signal in last two veto layers
- Signal in calorimeter consistent with \( \geq 1 \) MIPs
- Exactly one good quality spectrometer track
- Track in fiducial tracking volume, 90-95 mm
- at most 8 IFT clusters

(0.2 ± 4.1)x (upper limit of N with \( r_{\text{veto}} \))/(N without \( r_{\text{veto}} \)) = 0.01 ± 0.23

Scaling factor from background region to signal region: \( f_{\text{geo}} = 7.8 ± 2.3 \)

Final value of backgrounds

0.08 ± 1.83
The blue bands correspond to the statistical error of the simulated samples and are luminosity scaled for $q/p\mu$ and $p\mu$. The other figures are normalized to unity.
FASER $\nu$ EM shower energy estimation

Count the number of segments in ±3 films around the shower maxim (total 7 films)

The number of backgrounds was estimated and subtracted by counting the number of segments at the cylinder randomly opened.

Resolution: ~25% at 200 GeV
FASERμ track momentum estimation

Momentum dependency in the scattering angle

\[ \theta_{\text{RMS}}^{\text{plane}} = \frac{0.0136}{\beta pc} \sqrt{\frac{z}{X_0}} \left( 1 + 0.038 \ln \left( \frac{z}{X_0 \beta^2} \right) \right), \]

z: thickness
p: momentum

Momentum is estimated by measuring displacements for every 1 plate, every 2 plates, every 4 plates, every 8 plates, and every 16 plates and calculating RMS for each case.

Resolution: \( \sim 21\% \) at 200 GeV
FASER$\nu$: MC and neutral hadron-like events

The MC simulation distributions are normalized to the number of observed track vertices. 137 vertices, 4 vertices are $\nu_\mu$ CC candidates.
The MC simulation distributions are normalized to the number of observed track
FASER$\nu$: candidates

Event display for $\nu_e$ candidate

Event display for $\nu_\mu$ candidate
FASER$\nu$: vertices positions

![Graph showing vertices positions](image)