Operation and results of the FASERν detector

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25th of August 2023, NuFACT 2023
ForWArd Search ExpeRiment

• New small experiment based at the LHC at CERN, taking data since 2022.
• Investigating light, long-lived, weakly-interacting particles in the far-forward region of 13.6 TeV proton-proton collision at the ATLAS collision point (IP1).
• Aligned with the collision axis line-of-sight, maximising both the number and energy of neutrino interactions of all 3 flavours.
• First collider neutrino experiment!
High Energy Neutrinos in FASER

- FASER takes advantage of the intense forward hadron production in proton-proton collisions to produce a collimated neutrino beam.
- 3-flavour cross-section measurement for previously unexplored energy range → highest $E_{\nu}$ from artificial source.
- Neutrino induced heavy quark production → $O(1000)$ events via charm production channels expected.

FASER expected sensitivity

* Inner error bars: statistical uncertainties.
* Outer error bars: uncertainties from neutrino production rate.
Neutrino spectrum at FASER

• Expect > 10,000 neutrino interactions in FASER in LHC Run 3 (2022 - 2025) → 250 fb⁻¹.

<table>
<thead>
<tr>
<th>Main source</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>Kao/Charm decay</td>
<td>~ 2850</td>
<td>~ 9600</td>
<td>~ 70</td>
</tr>
<tr>
<td>Pion/Kao n decays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charm decay</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Number of expected CC events in FASERν:

- \( \nu_e \) ~ 2850
- \( \nu_\mu \) ~ 9600
- \( \nu_\tau \) ~ 70

Projected precision of FASERν measurement at 14-TeV LHC (150 fb⁻¹)

(Based on PhysRevD.104.113008)
The FASER Detector

- The detector is composed of both spare parts from other experiments as well as new dedicated components.

0.57 T permanent magnet, 10 cm aperture radius, 1.5 m decay length
The FASERν Sub-Detector

• Module: 730 alternating FASERv emulsion films and 1.1 mm thick tungsten plates (25 x 30 cm$^2$).
• Target mass 1.1 tonnes; 1.1 m ($220 X_0$, $8\lambda$).
• Module replaced 3 times per year every 30fb$^{-1}$ to keep track occupancy $< 10^6$/cm$^2$.
• Temperature kept constant at 0.1°C level with dedicated cooling system.
• Neutrino events can be flavour tagged using topological and kinematical variables.
FASERν Process

Japan
- Film production
- Assembly

CERN
- Exposure
- Disassembling
- Development

Japan
- Readout

Offline analysis
- Physics analysis
- $e, \mu$ ID
- $\tau$ decay search
- charge ID
- etc...

- Vertex reconstruction
- Track reconstruction
- Alignment

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FASERv Assembly at CERN

- FASERv sub-modules: 10 alternating emulsion films and tungsten plates.
- 2 dedicated assembly table for parallel assembly.
- Pressure is applied to keep the alignment between sub-modules inside the FASERv module.

73 sub-modules installed

Vacuum sealed sub-module
FASERν Exchange

• Irradiated module extracted, and new module installed.
• Performed by FASER members with CERN technical teams.

Assembly complete
Moving modules over LHC
Exchange
FASER tunnel
Towards IP21
Installed module

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FASERν Development at CERN

- Development campaign lasts ~12 days.
- Films are extracted and labelled.
- 200 films developed with one set of chemicals in 3 days (1 cycle).
- 25 films developed together (1 chain) → 3.5 hours + 1 day drying.
- 25-minute shift between chains.
Film Readout in Nagoya

Hyper Track Selector (HTS): complex microscope system scans films for digital readout.
- Images made at different focal depths in emulsion;
- 5.1 x 5.1 mm² field of view;
- Each film scanned in 8 zones;
- 60 – 80 minutes for each film.
FASERν Event Reconstruction

- Dedicated film alignment is performed using high-momentum muon tracks ($\mathcal{O}(10^5)$ tracks/cm$^2$).
- Track reconstruction links base-tracks on different films using position and angular information.
- Single film hit efficiency found by considering whether a selected film has a hit given that 2 films either side have hits → observed efficiency > 90%.
FASERv Performance

- Position resolution found using position displacement between hit and linear track fit.
- Observed $<0.3 \, \mu m$ hit resolution after dedicated film alignment.
Momentum Measurement

• Particle momenta calculated using Multiple Coulomb Scattering (MCS) via the Coordinate Method.
• Allows particle momenta to be measured using MCS even for $> 1$ TeV.
• Momentum resolution $\sim 20\%$ at 200 GeV.
**FASERννν_e candidate event**

- **Vertex with 11 tracks**
  - 615 µm inside tungsten

- **e-like track from vertex**
  - Single track for $2X_0$
  - Shower max at 7.8$X_0$
  - $\theta_e = 11$ mrad to beam

- **Back-to-back topology**
  - 175° between e & rest

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$E_e = 1.5$ TeV

Jeremy Atkinson, Universität Bern
New FASERν Results – Background Study using Data

- First analysis: interactions occurring in 150 tungsten plates (target mass = 68.2 kg).
- Detected vertices before high-energy selection dominated by neutral hadron interactions.
- Expectation: 216 vertices ($K_S, K_L, n, \bar{n}, \Lambda, \bar{\Lambda}$ interactions)
- Data: 133 vertices → 140 detected; 7 ν CC candidates.
- Lies within 50% uncertainty.

MC normalized to number of observed events.
New FASERν Results – Observed Events

• 7 selected ν CC events after applying kinematic selection (p_{lep} > 200 GeV).

• 3 ν_e CC → 5σ exclusion of the background-only hypothesis.

• Highest energy ν_e observed!

• First direct observation of ν_e CC interactions at the LHC!

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Expected background</th>
<th>Expected signal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hadron interactions</td>
<td>ν NC interactions</td>
</tr>
<tr>
<td>ν_e CC</td>
<td>0.002 ± 0.002</td>
<td>1.2^{+4.0}_{-0.6}</td>
</tr>
<tr>
<td>ν_μ CC</td>
<td>0.32 ± 0.16</td>
<td>4.4^{+4.2}_{-1.4}</td>
</tr>
</tbody>
</table>

See also Tomoko Ariga’s Plenary talk on 21/08: “New results on LHC neutrinos from the FASER experiment”
New FASERν Results – Data/MC Comparison

Vertex information of the $\nu_\mu$ CC candidates.

- N tracks
- Lepton angle
- Lepton momentum
- $\Delta\phi$

Tracks from the vertices.

Vertex information of the $\nu_e$ CC candidates.

- N tracks
- Lepton angle
- Lepton momentum
- $\Delta\phi$

MC normalized to number of observed events.
The FASERν emulsion detector measures TeV-scale neutrinos of all 3 flavours → **First collider neutrino experiment!**

- FASER is successfully operating during CERN LHC Run 3.
- 5 FASERν modules have been irradiated, collecting 60 fb$^{-1}$ to date, with another 200 fb$^{-1}$ expected in Run 3.
- FASERν operations include:
  - Emulsion film production;
  - Detector assembly and development;
  - Developed film scanning using HTS microscope.

New results from FASERν: $\nu_e$ and $\nu_\mu$ CC interaction candidates presented → **First observation of $\nu_e$ CC interactions at the LHC, at highest $\nu_e$ energies measured!**

First physics results with FASERν demonstrate the ability to carry out neutrino measurements with emulsion-based detectors in the challenging conditions at the LHC → a lot more physics to come...
Backup
0.57 T permanent magnet, 10 cm aperture radius, 1.5 m decay length

FASER detector

3 layers per station, 8 ATLAS SCT barrel modules per layer

4 LHCb outer EM calorimeter modules

Electromagnetic Calorimeter

Tracking spectrometer stations

Trigger / pre-shower scintillator system

Magnets

Decay volume

Front Scintillator veto system

To ATLAS IP

Interface Tracker (IFT)

FASERv emulsion detector

Two 20 mm scintillators, 35x30 cm wide

Two 20 mm scintillators, 30x30 cm wide

10mm thick scintillators with dual PMT readout for triggering and timing measurement (sigma=400ps)
FASER Operations

- Successful running in 2022.
- Recorded 96% of delivered luminosity \( \rightarrow > 35 \text{ fb}^{-1} \).
- FASERν module exchanged twice due to occupancy in emulsion.
- Example event: muon leaving track in full detector \( \rightarrow \) all detector components working well.
Film production

• Emulsion gel and films produced at Nagoya University in dedicated facility.
• Silver bromide crystals, diameter 200 nm.
• 110 m² of emulsion for every module.
• Resetting procedure performed in Nagoya University and Kyushu University.
Emulsion Facility at CERN

- New facility set up at CERN for emulsion experiments – includes modern climate control and ventilation system, access card entry, and full dark room capabilities for emulsion handling.
- 3 dedicated room: assembly, development and drying.
- Shared with NA65/DsTau, SND@LHC and SHiP Collaborations.
- Darkroom operations: module assembly and development.
Development

- FASERv module disassembly is performed in darkroom conditions by 2 people.
- 5 sub-modules (50 films) are extracted, disassembled, labelled and sorted into 2 packs of 25 films → Odd and Even films are separated and are developed in different batches of chemicals.
- Labelling is performed using a digital label maker.
Development

• 730 FASER\nu films in one FASER\nu module.

• 200 FASER\nu films → one cycle.

• 25 FASER\nu films hung using clips per rack → one chain.

• 4 cycles of 9 chains → each cycle takes approximately 3 days.

• Can have 3 chains going in parallel with around 25 minute shift.

• Approximately same number of films per chain in sets of 3 chains.

• Odd and Even films from the same sub-module are never developed in the same cycle.
Module temperature control

- Temperature of the FASERv module is kept constant at 0.1°C level with dedicated cooling system.
- Water in heat exchanger is kept at 15°C, and a fan system mixes the air in the FASERv trench, with a slanted perforated plate which helps further mix the air on all sides of the module.
- An insulating layer is placed between the FASERv module and rest of FASER, and the trench is closed with an insulated metal cover → this is to ensure temperature stability which both increases alignment and minimises the fading effect of emulsion, as well as to understand the long-term properties.
- 4 temperature sensors are placed in and around the module to monitor the temperature.
Shower Energy Measurement

- Performed by counting number of segments within a cylinder along an electron candidate → shower maximum has the highest number of segments.
- Background segments are sizable → cylinder size limited to \( r = 100 \, \mu m \), length = 8 cm; segment angle with respect to shower axis < 10 mrad; minimum distance to segment < 50 \( \mu m \).
- Average background estimated by using random cylinders and subtracting from the shower before energy estimation.

• Resolution: approx. 25% for \( e \) 200 GeV, 25-40% at higher energies (depending on electron angle).
Generator flux uncertainty

- Uncertainties come from the difference between DPMJET and SIBYLL generators in modelling pp collisions.
- Mainly in the high-E range due to charm production.
- Charm hadrons produce $\nu_\tau$, high-E $\nu_\mu$, $\nu_e \rightarrow$ by deconvolving charm contribution, this can help constrain neutrino flux.
Heavy-flavour-associated channels

- Measure charm production channels:
  - \(~10\%\ \nu\, \text{CC event} \rightarrow \mathcal{O}(1000)\) events via charm production channels expected;
  - 1\textsuperscript{st} measurement of \(\nu_e\) induced charm production;
  - Can be observed in FASER\(\nu\) due to secondary charm decay vertex.

\[
\frac{\sigma(\nu_\ell N \rightarrow \ell X_c + X)}{\sigma(\nu_\ell N \rightarrow \ell + X)}
\]

- Search for Beauty production channels
  - Expected SM events (\(\nu_\mu\, \text{CC}) \mathcal{O}(0.1)\) in Run 3 \(\rightarrow\) CKM suppression \(V_{ub}^2 \approx 10^{-13}\).
  - BSM physics could amplify, such \(W'\) boson, charged Higgs boson, TeV scale leptoquark.
FASER “Electronic” Neutrino Search

- Selection criteria:
  - Collision event in good data periods (35.4 fb⁻¹);
  - No signal in front 2 veto scintillators (<40 pC);
  - Signal in last 2 veto stations (>40 pC);
  - Signal in timing and pre-shower scintillators consistent with ≥1 MIP;
  - Exactly 1 good spectrometer track with \( p > 100 \) GeV;
  - \( r_{\text{max}} < 95 \) mm in fiducial tracking volume;
  - Extrapolating to front veto station, \( r < 120 \) mm;
  - \( \theta < 25 \) mrad.

- 151 ± 41 neutrino events expected from simulation:
  - Uncertainty from difference between generators (DPMJET & SIBYLL).
  - No experimental errors were included.
Background estimation

• Neutral hadrons $0.11 \pm 0.06$:
  • Expect approx. 300 with $E > 300$ GeV;
  • Tungsten absorbs the majority;
  • Estimated from 2-step simulation.

• Scattered muons $0.08 \pm 1.83$:
  • Extrapolated from sideband control region;
  • Single track in the front tracker station;
  • Scaled to full detector volume using simulation.

• Veto inefficiency negligible:
  • Estimated from events where only 1 veto scintillator fired;
  • Very high veto efficiency.
Results

- $153^{+12}_{-13}$ neutrino events observed.
- Corresponds to $16\sigma$.
- First direct observation of collider neutrinos.

<table>
<thead>
<tr>
<th>Category</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal ($n_0$)</td>
<td>15</td>
</tr>
<tr>
<td>$n_{10}$</td>
<td>4</td>
</tr>
<tr>
<td>$n_{01}$</td>
<td>6</td>
</tr>
<tr>
<td>$n_2$</td>
<td>64014695</td>
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</tbody>
</table>