FASER Neutrino Results

LHCP Conference, 22 - 26 May 2023, Belgrade
Tobias Böckh on behalf of the FASER collaboration
Collider Neutrinos

- Observed neutrinos from a variety of sources:
  nuclear reactors, beam dump experiments, cosmic rays, Sun, earth, supernovae, …
- Neutrinos produced copiously at hadron colliders, but no direct observation yet!
  - Neutrinos interact extremely weakly
  - Highest energy neutrinos produced in forward direction (parallel to beamline)
- Energy spectrum complementary to existing neutrino experiments
  - Measurement at highest man-made neutrino energies

[Graphs showing energy spectra and distributions for neutrinos]
The ForwArd Search ExpeRiment

- FASER is a new, small experiment at the LHC
  - Constructed and installed in 2019 - 2021
- Located 480 m downstream of ATLAS interaction point on collision axis line of sight
  - LHC magnets and 100 m of rock shield most backgrounds
- Targets long-lived BSM particles: A', ALPs, … (talk from Noshin Tarannum) and neutrinos (this talk)
- Successfuly operated during all of 2022, restarted data taking in April 2023
  - All detector components perform excellently
  - Recorded 37.0 fb$^{-1}$ of data in 2022 (96 % of delivered luminosity)
- Possible Future Upgrade: FASER2 at the proposed Forward Physics Facility (talk from Roshan Mammen Abraham)
FASER Detector

Aperture: 20 cm
Length: 7 m
Neutrino Signature in Emulsion Detector

FASERν analysis:
- 730 layers of 1.1 mm thick tungsten plates and emulsion films, 1.1 tones tungsten target
- Excellent position and angular resolution
- Reconstruct tracks and vertices of charged current (CC) and neutral current (NC) interactions of all neutrino flavors
- Analysis still ongoing

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Neutrino Signature in Electronic Detector

Electronic Neutrino analysis:
- Detect CC $\nu_\mu$ interactions using spectrometer and scintillators
- Use FASER$\nu$ only as target for neutrino interactions
- Signature:
  - Collision event timing and good data quality
  - No signal (<40 pc) in 2 front scintillators
  - Signal (>40 pC) in all scintillators downstream of decay volume
  - Exactly 1 good fiducial track ($p > 100$ GeV, $r < 120$ mm at front veto, …)

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Arxiv: 2207.11427

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Background Estimate

- Estimated from events with just one veto scintillator firing
- Expect \((3.7 \pm 2.5) \times 10^{-7}\) events

- Expect \(O(300)\) neutral hadrons with \(E > 100\) GeV
- Most hadrons absorbed in tungsten (8 int. lengths)
- Estimate \(0.11 \pm 0.06\) events

- Estimated from control region (90 < \(r < 95\) mm, # clusters ≤ 8)
- Expect \(0.08 \pm 1.83\) events
Neutrino Observation

- Based on GENIE simulation expect 151 ± 41 neutrino events
  - Uncertainty from difference between DPMJET and SIBYLL event generators
  - No experimental uncertainties → cannot translate to cross section / flux yet
- Observe 153 events with no veto signal with an expected background of 0.2 ± 1.8
- First direct observation of collider neutrinos!
  - Signal significance of 16 σ
  - Recently accepted by PRL

[Graphs showing data points and significance]
Neutrino Characteristics

- Neutrino events match expectations from simulation
  - Most events at high momentum ($E_\mu > 200$ GeV)
  - More $\nu_\mu$ than $\bar{\nu}_\mu$
  - High occupancy in front tracker station
  - Large angle $\theta$ with respect to line-of-sight

- No experimental uncertainties included in these plots!
Neutrinos in FASER$_\nu$

- Analysis of emulsion detector still ongoing
- Have multiple candidates, including highly $\nu_e$ like, high energy event:
  - 11 tracks at the vertex
  - Electron-like track from vertex
    - Single track for 2 $X_0$
    - Shower max at 7.82 $X_0$
    - Back-to-back topology: 175° angle to other tracks
  - $\theta_e = 11$ mrad w.r.t. beam
Summary

● Observed 153 $\nu_\mu$ CC interactions with electronic detectors
  ○ Many neutrinos with large momentum ($E_\mu > 200$ GeV)
  ○ Charge indicates neutrinos and anti-neutrinos
  ○ First direct observation of collider neutrinos!
● Neutrino candidates from FASER$_\nu$ emulsion detector
● Plan to measure neutrino cross section and flux in future
● FASER operating well for start of the 2023 LHC run
● Up to an order of magnitude more data expected during LHC Run 3
Additional Slides
Acknowledgments

- FASER is supported by:
  - HEISING-SIMONS FOUNDATION
  - SIMONS FOUNDATION
  - Swiss National Science Foundation
  - NSF

- Additionally would like to thank:
  - LHC for the excellent performance in 2022
  - ATLAS Collaboration for providing luminosity information
  - ATLAS SCT Collaboration for spare tracker modules
  - ATLAS for the use of their ATHENA software framework
  - LHCb Collaboration for spare ECAL modules
  - CERN FLUKA team for background simulation
  - CERN PBC and technical infrastructure groups for excellent support during design, construction and installation
FASER Detector

- 0.57 T dipole magnets
- 200 mm aperture
- 1.5 m decay volume
- 10 mm thick scintillators with dual PMT readout ($\sigma=400$ps)
- 4 LHCb outer EM calorimeter modules
- 3 layers per station with 8 ATLAS SCT barrel modules in each layer

Electromagnetic Calorimeter
- 1.1 ton detector
- 730 layers of 1.1 mm tungsten and emulsion film

Tracking spectrometer stations
- Three 20 mm scintillators
- 300x300 mm wide

Scintillator veto system
- Two 20 mm scintillators
- 350x300 mm wide

Trigger/timing scintillator station
- 10 mm thick scintillators with dual PMT readout ($\sigma=400$ps)

FASERv emulsion detector

Interface Tracker (IFT)
- 1.1 ton detector
- 730 layers of 1.1 mm tungsten and emulsion film

arxiv:2207.11427
Detected installed between March – Nov 2021, ready for LHC run 3
Neutrino Analysis

- Count number of events with hits in none, one or both front veto layers
  - n0: both scintillator layers have charge < 40 pC, signal, geom and hadronic background
  - n10, n01: only one of the two scintillators layers has charge > 40 pC, veto inefficiency background
  - n2: both scintillators layers have charge > 40 pC, background dominated

- Likelihood function is product of 4 Poisson terms for observables $n_i$ and 3 Gaussian constraint terms for background:

$$
\mathcal{L} = \prod_{i}^{4} \mathcal{P}(n_i | \nu_i) \cdot \prod_{j}^{3} \mathcal{G}_j
$$

<table>
<thead>
<tr>
<th>Category</th>
<th>Events</th>
<th>Expectation</th>
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<tr>
<td>$n_0$</td>
<td>153</td>
<td>$n_{\nu} + n_b \cdot p_1 \cdot p_2 + n_{\text{had}} + n_{\text{geo}} \cdot f_{\text{geo}}$</td>
</tr>
<tr>
<td>$n_{10}$</td>
<td>4</td>
<td>$n_b \cdot (1 - p_1) \cdot p_2$</td>
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<td>$n_{01}$</td>
<td>6</td>
<td>$n_b \cdot p_1 \cdot (1 - p_2)$</td>
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<td>$n_2$</td>
<td>64014695</td>
<td>$n_b \cdot (1 - p_1) \cdot (1 - p_2)$</td>
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</table>

- Maximum likelihood fit gives 153 signal candidates
Physics Potential

- Study neutrino interactions at high energy
- Search for BSM physics in neutrino production, propagation and interaction
- Study PDFs by Deep Inelastic Scattering (DIS) of neutrino in the target
- Study forward hadron production via neutrino flux measurements (forward charm from high energy $\nu_e$)
Event Display

57 IFT Clusters

1 good track with hits in all layers, 
\( p = 843 \text{ GeV}, r = 54.6 \text{ mm}, \text{ charge} = -1 \)
Detector Performance: Emulsion

- Track multiplicity measured in initial emulsion
  - Consistent with FLUKA simulation
- Excellent hit resolution ($< 0.2 \, \mu m$) after layer alignment

![Graphs showing track multiplicity and hit resolution](image)

Emulsion film Tungsten plate (1 mm thick) (25 cm x 25 cm)
Detector Performance: Trigger + DAQ

- DAQ running smoothly up to 1.3 kHz with deadtime only 1.3%
- Total trigger rate falls off faster than luminosity during run (higher beam-induced backgrounds) but coincidence trigger rate flat with respect to luminosity
Detector Performance: Veto Scintillators

- All veto scintillator layers have inefficiencies < $2 \times 10^{-5}$
- Efficiencies measured by extrapolating tracks triggered in timing scintillator to layer, no requirement on other scintillator layers
Detector Performance: Tracker

- Tracker fully timed in with respect to LHC clock
- Hit efficiency of 99.64 % at 150 V bias and 1 fC threshold

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Detector Performance: Alignment

- Tracker modules aligned using local iterative $\chi^2$ method
  - Validated using simulation with misalignments
- Currently only aligning two most sensitive parameters (vertical shift, in-plane rotation)
- Aligned resolution close to ideal geometry simulation
FASER Collaboration

- 87 members across 24 institutes from 10 countries