High-energy neutrino measurements with FASERν

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On behalf of FASER collaboration

Supported by:
FASERν in FASER

- **FASER** is a new experiment to search for new long-lived particles and measure cross-sections of neutrinos, that are produced in pp collisions at ATLAS Interaction Point (IP), starting in 2022.
- The detector is installed 480 m downstream of ATLAS IP (TI12).
- **FASERν** is a part of FASER detector dedicated for neutrino measurements.
- FASER will be the first experiment to study three-flavor neutrinos at TeV energies.
FASER$\nu$ detector (Emulsion detector)

- 700 layers of an emulsion film and 1.1 mm tungsten plate
  - $25 \text{ cm} \times 30 \text{ cm} \times 1.1 \text{ m}$, 1.1 tons, $220 X_0$
- The emulsion films will be replaced every 30-50 fb$^{-1}$ during LHC technical stop.
- Measured particle (muon) flux was $\sim 500$ Hz at FASER with $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ in 2018 run which gives an acceptable detector occ. for physics.
- Measured radiation level was low enough for detector performance requirements ($<5 \times 10^7$ 1MeV $n_{eq}$/year).
FASERν detector (IFT & Veto)

• Silicon strip tracker (IFT: InterFace Tracker) is used as the interface for tracking with FASER spectrometer behind it.

➢ Charge identification of muons is possible with three 0.55 T dipole magnets in the spectrometer (3.5 m length in total).

• Veto scintillator system at the most front part of FASERν rejects charged particles coming from the upstream.

➢ Allows matching of the signal muon tracks in IFT and spectrometer.
Charged current interaction (1)

- FASERν will measure neutrino cross-sections at TeV region which is uncovered by existing experiments.
- All neutrino flavors in Charged Current (CC) interactions can be identified including τ-neutrino, thanks to excellent position resolution of the emulsion detector.

Expected # of CC interaction with 150 fb$^{-1}$ @FASERν [PRD 104, 113008 (2021)]

<table>
<thead>
<tr>
<th>Generators</th>
<th>Light hadrons</th>
<th>Heavy hadrons</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>SIBYLL</td>
<td>SIBYLL</td>
<td>901</td>
<td>4783</td>
<td>14.7</td>
<td></td>
</tr>
<tr>
<td>DPMJET</td>
<td>DPMJET</td>
<td>3457</td>
<td>7088</td>
<td>97</td>
<td></td>
</tr>
<tr>
<td>EPOS LHC</td>
<td>PYTHIA8 (Hard)</td>
<td>1513</td>
<td>5905</td>
<td>34.2</td>
<td></td>
</tr>
<tr>
<td>QGSJET</td>
<td>PYTHIA8 (Soft)</td>
<td>970</td>
<td>5351</td>
<td>16.1</td>
<td></td>
</tr>
<tr>
<td>Combination (all)</td>
<td></td>
<td>1710$^{+1746}_{-809}$</td>
<td>5782$^{+1306}_{-998}$</td>
<td>40.5$^{+56.6}_{-25.8}$</td>
<td></td>
</tr>
<tr>
<td>Combination (w/o DPMJET)</td>
<td></td>
<td>1128$^{+385}_{-227}$</td>
<td>5346$^{+558}_{-563}$</td>
<td>21.6$^{+12.5}_{-6.9}$</td>
<td></td>
</tr>
</tbody>
</table>

Existing measurements of $\nu N$ charged-current cross sections and the expected energy spectra for FASERν.
Charged current interaction (2)

- CC cross-section will be measured at TeV region, and its consistency with Standard Model (SM) will be studied.
- The anomaly of the third generation coupling will be explored.
  ➢ 4σ deviation from SM is reported in the quark-sector [here].
- The charge measurement in cooperation with spectrometer behind FASERν enables to separate $\nu_\mu/\bar{\nu}_\mu$.

Expected sensitivity to neutrino cross-sections @FASERν
• There are large number of difference between generator predictions, especially for $\nu_e$ and $\nu_\tau$ from large uncertainties in forward charm production.

• The forward charm production can be studied with $\nu_e$ above 500 GeV in FASER$\nu$. 

Electron neutrino in FASER$\nu$
The pilot runs took place for neutrino detection and flux measurement of charged particles at tunnels TI12 and TI18 in 2018.

- FASER/FASERν is installed at T12.
- TI18 is the tunnel at the same distance from ATLAS IP as TI12 but on the opposite side.

Neutrino detection was performed with a 30 kg emulsion detector installed at TI18, collecting 12.5 fb\(^{-1}\) of data (10 kg are used in the analysis).
• 18 candidates of the neutral vertex were detected.
• They are the first candidates of the neutrino interactions at a collider.
• $2.7\sigma$ excess of neutrino-like signal above muon-induced background is measured with a multivariate analysis.
• The results were published in [PRD 104, L091101 (2021)].
FASERν construction (1)

• 268 emulsion films (~20 m²) corresponding to ~30% of the full loading were produced in Japan for data-taking during commissioning period.

• 10 sets of a tungsten plate and emulsion film were assembled per module and vacuum-packed at CERN.
The first emulsion detector was prepared in March 2022.
- 22 emulsion modules were housed in the emulsion box with tungsten plates for the remaining volume.
- This is ~30% of the full emulsion for commissioning, and it will be replaced with a full detector for the first physics at the end of July.

IFT was built with spare ATLAS SCT modules with the same design as FASER main tracker, and the assembly was finished in July 2021.
Most of the FASER main detector was installed in spring 2020.

IFT was installed in November 2021.

The first emulsion box was installed in March 2022.

Placed on the LOS (Line Of Site) to maximize the flux of all neutrino flavors (the trench dug allows this).

The physics data-taking will start in July 2022.

The emulsion films will be replaced 11 times every 30-50 fb⁻¹.
MIP efficiency of the veto system was measured in testbeam at CERN-SPS H2 beam line, and better performance than the requirement (>99.98%) was obtained.

The commissioning is ongoing by using cosmic and beam collisions at LHC.
Simulated neutrino events in FASERν

$\nu_e$ interaction (437 GeV)

$\nu_\tau$ interaction ($\tau^-$ decaying to $\mu^-$)

interaction in the emulsion detector

hit events in the tracker of the FASER spectrometer
Summary & Conclusions

- FASERν is the detector in FASER experiment to measure cross-section of high energy neutrinos with ~1 TeV originated from proton-proton collisions at LHC.
  - First experiment making use of beam collisions as neutrino source.
- FASERν can measure cross-section for all neutrino flavors, thanks to excellent position resolution of the emulsion detector.
- The first candidates of the neutrino interactions at LHC was observed in the pilot data-taking in 2018.
- Both the first emulsion detector and IFT were installed at FASER site.
  - The emulsion films will be replaced every 30-50 fb\(^{-1}\).
- The data-taking will start in July 2022 at LHC Run3.
- A future 10 times larger upgrade of FASERν is being considered as a part of the proposed [Forward Physics Facility].
Backup
FASER collaboration consists of 75 collaborators, 22 institutes, and 9 countries.
Neutrino flux v.s. distance from LOS
Neutral current interaction

- FASERν also measures cross-section of Neutral Current (NC) neutrino interactions [arXiv: 2012.10500].
- Non-Standard Interaction (NSI) can be explored in conjunction with measurement of CC cross-section.
Forward charm production

- Atmospheric neutrinos from charm decays (prompt neutrino) could be an important background for astrophysics neutrino observations.
  - Only upper limit was given by IceCube.
- $gg \rightarrow cc$ is the leading order for charm production in perturbative QCD.
- Proton-proton collision at LHC corresponds to $\sim 100$ PeV proton interaction with fixed target.

Measurement of production cross-section of heavy mesons at LHC can provide constraint on the prompt flux (current syst. error is $O(1)$).
Charm/strange PDF

• There is a controversial prediction in which an additional charm component exists in a proton (so-called intrinsic charm).

• It only affects the forward charm production ($cg \rightarrow cg$) in pp collisions, to which $\nu_\tau/\nu_\tau$ energy spectrum in FASER$\nu$ is sensitive.

• $D$ meson production in $CC \nu_\mu$ interaction is sensitive to strange PDF in a proton where tension exists between ATLAS and predictions.
Theoretical interest in QCD

• FASERν can explore charm production (gg → cc) at Q ~ 2 GeV with x ~ 10^{-7}, where gluon saturation by color glass condensation appears.

• Measurement of muon/neutrino flux and energy spectrum constrains production of primary hadrons (mainly pions and kaons).
  ➢ The results can be used to validate/improve cosmic ray MC, especially to understand muon excess.

Muon excess from prediction (Snowmass LOI)
• Uncertainty on conventional atmospheric neutrino flux ($\Phi_{\text{conv}}$) is $\sim 30\%$ and absorbs any uncertainty which influences the global flux norm.

• The cosmic ray spectrum parameterized as $\Delta \gamma_{\text{CR}}$ also affects the expectation of $\Phi_{\text{conv}}$ and prompt flux ($\Phi_{\text{prompt}}$).

• $\Phi_{\text{prompt}}$ is a free parameter in the fitting and currently zero consistent.

• Astrophysical parameters ($\Phi_{\text{astoro}}, \gamma_{\text{astro}}$) are found to be almost independent from $\Phi_{\text{prompt}}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best-Fit</th>
<th>68% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{\text{astoro}}$</td>
<td>0.90</td>
<td>0.62 – 1.20</td>
</tr>
<tr>
<td>$\gamma_{\text{astro}}$</td>
<td>2.13</td>
<td>2.00 – 2.26</td>
</tr>
<tr>
<td>$\Phi_{\text{prompt}}$</td>
<td>0.00</td>
<td>0.00 – 0.19</td>
</tr>
</tbody>
</table>
Muon excess in extensive air showers

- Excess of muons with respect to the prediction (8σ) are observed in cosmic ray experiments.
- The hadronic interaction models used for the prediction were developed by using results of measurement in LHC and SPS.
- Measurement of muon/neutrino flux at FASER/FASERν will provide feedback to the interaction model.

Excess of muons from the predictions (EPOS-LHC and QGSJet-II-04) [Snowmass LOI]
Gluon saturation in proton (2)

From F. Kling’s presentation
Cham-associated neutrino events

- FASERν can measure neutrino interactions associated with D-mesons in the final states.
- 10-20% of neutrino interaction at FASERν is accompanied with D-mesons.
- The emulsion detector can identify D-mesons, measuring tracks and their decay products.
Beauty-associated neutrino events (1)

- Results in measurements of $B \rightarrow D^* \ell \nu$, $B \rightarrow K^* \ell \ell$ and $B^+ \rightarrow K^+ \ell \ell$ suggest lepton universality violation.

- The neutrino interactions in FASERν are the same as them, exchanging the internal/external lines in Feynman diagrams.

$\mathcal{R}(D) = \frac{\mathcal{B}(B \rightarrow D \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D \ell \nu_\ell)}$,

$\mathcal{R}(D^*) = \frac{\mathcal{B}(B \rightarrow D^* \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^* \ell \nu_\ell)}$

R(D) v.s. R(D*)
Beauty-associated neutrino events (2)

• Since cross-section of these processes are suppressed by a factor of \( O(V_{ub}^2) \sim 10^{-5} \), beauty-associated neutrino events cannot be observed at FASERν in Run3 in SM.

  ➢ Expected number of the events: \( O(0.1) \)

• But, the observation means discovery of new physics.

• In addition, lepton universality violation in the third generation can be investigated with sensitivity to \( \nu_\tau \).
Sterile neutrino oscillation

- SM excludes possibility of neutrino oscillation in FASER condition.
  - If appearance or disappearance events are observed, it indicates existence of sterile neutrino.
  - For $\nu_e$, FASER$\nu$ has sensitivity to $2.7\sigma$ discovery region with Gallium detector [arXiv:1006.3244].

**Neutrino energy dist. with sterile neutrino**

**Expected sensitivity to neutrino oscillation**

$\nu_e$  | $\nu_\mu$
---|---
Already excluded | Already excluded

![Graph showing expected sensitivity to neutrino oscillation for $\nu_e$ and $\nu_\mu$](image)