Measurement of TeV neutrinos with FASERν at the LHC

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Supported by

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HEISING-SIMONS FOUNDATION
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KAKENHI
Motivation

- LHC collision products in forward direction can be high energy neutrino source.
- No data on the neutrino interactions at $E_n$ in several 100 GeV to several TeV.
- The interaction cross section at $\sim$TeV region is the knee point of its energy dependence and start behave $\sigma \neq \sigma_0 E$.
- Measuring neutrino cross section of 3 type of neutrinos at unexplored energy.

- Lepton Universality check, especially tau neutrino interactions and others, possible anomaly indication by B mesons.

$$R(D) = \frac{B(B \rightarrow \tau \nu_\tau D)}{B(B \rightarrow \mu \nu_\mu D)}$$
Another Motivation

• Charm hadron production properties study through detection of especially tau neutrinos.

• Very forward going Charm production from LHC collision point is not well studied.

• Tau neutrinos in forward direction is the decay product of such Charm and contain information of Charm energy or its production flux.

• Measuring the neutrino flux as a function of energy, lateral position will provide charm differential cross section $d\sigma/ dx_F$. 
FASERν layout

$p$-$p$ collision at ATLAS

FASERν

LHC magnets

Neutrinos

Charged particles

Neutral hadrons

Mean interacting energy $\sim 1$ TeV

$5 \times 10^{11} \nu_e$

$3 \times 10^{12} \nu_\mu$

$1 \times 10^{10} \nu_\tau$

Backgrounds

$O(10^9) \mu$

$O(10^4) n/K^0$

$p$-$p$ collisions

$150 \text{ fb}^{-1}$

$\sim 1.5 \times 10^{16} p$-$p$

480 m
FASER/FASERν detector in Run3 (2022-2025)

• **Tungsten** as neutrino interacting target.
• **Emulsion trackers**
  - sub-micron spatial resolution, $\sigma \approx 0.4 \, \mu m$
  - 770 1-mm-thick tungsten target and emulsion films
  - 25x30 cm², 1.1 m, **1.1 tons** ($8 \lambda_{int}$, 220$X_0$)

• **Sensitive to 3 flavor** neutrinos
• **Muon ID** in track length in tungsten
• Replace emulsions 3 times a year
FASER/FASERν detector in Run3 (2022-2025)

- Global reconstruction with FASER spectrometer with silicon (80um pitch) microstrip detectors (SCTs) → muon charge identification → $\nu_\mu/\overline{\nu}_\mu$ separation
- Improve energy resolution
Physics studies in the LHC Run 3 (1):
Cross sections

- **Three flavors neutrino cross section measurements** at unexplored energies
- **~10,000 ν interactions expected in LHC Run 3**
- **Large differences in the expected neutrino rates between MC generators, due to large uncertainties in very forward high energy hadron production**

<table>
<thead>
<tr>
<th>Generators</th>
<th>FASERν</th>
</tr>
</thead>
<tbody>
<tr>
<td>light hadrons</td>
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</tr>
<tr>
<td>SIBYLL</td>
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</tr>
<tr>
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</tr>
<tr>
<td>EPOS-LHC</td>
<td>Pythia8 (Hard)</td>
</tr>
<tr>
<td>QGSJET</td>
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</table>

Combination (all):
- \( \nu_e + \bar{\nu}_e \): \( 1710^{+1746}_{-909} \)
- \( \nu_\mu + \bar{\nu}_\mu \): \( 5782^{+1306}_{-998} \)
- \( \nu_\tau + \bar{\nu}_\tau \): \( 40.5^{+56.6}_{-25.8} \)

Combination (w/o DPMJET):
- \( \nu_e + \bar{\nu}_e \): \( 1128^{+385}_{-227} \)
- \( \nu_\mu + \bar{\nu}_\mu \): \( 5346^{+558}_{-563} \)
- \( \nu_\tau + \bar{\nu}_\tau \): \( 21.6^{+12.5}_{-6.9} \)

*Expected CC interactions with 150 fb\(^{-1}\)*
Physics studies in the LHC Run 3 (2):

Heavy-flavor-associated channels

• Measure charm production channels
  • Large rate \( \sim 15\% \nu \text{ CC events}, \mathcal{O}(1000) \) events
  • First measurement of \( \nu_e \) induced charm prod.

\[
\frac{\sigma(\nu_\ell N \rightarrow \ell X_c + X)}{\sigma(\nu_\ell N \rightarrow \ell + X)} \quad \ell = e, \mu, \tau
\]

• Search for Beauty production channels
  • Expected SM events (\( \nu_\mu \) CC \( b \) production) are \( \mathcal{O}(0.1) \) events due to CKM suppression, \( V_{ub} \approx 10^{-5} \)

\[
\bar{\nu}_N \rightarrow \ell \bar{B}X \\
\nu N \rightarrow \ell BDX
\]

Physics studies in the LHC Run 3 (3): Further insights on QCD

- Asymmetric gluon-gluon interaction, \textit{small-}x \times \textit{large-}x
- \textbf{Neutrinos from charm decay} could allow to test transition to small-\(x\) factorization, probe intrinsic charm
- Deep understanding of neutrinos from charm decays (\textit{prompt neutrinos}) is important for astrophysical neutrino observations
Status of pre-analysis

1. **Feasibility test**
   
   Background track density acceptable for emulsion detector?

   Concern: Emulsion accumulate all charged particle tracks before its chemical development.
   
   More than $10^6$/cm$^2$ make emulsion detector analysis difficult.
   
   Is track density in situ acceptable for analyzing neutrino interaction by emulsion detector?

2. **Pilot neutrino detector run in 2018**

   Demonstrating neutrino interaction detection at realistic background track density.
   
   FASER detector was not yet ready.
   
   → Test with small size **Emulsion detector alone**.
1. Feasibility test
back ground track flux at the site

- *In-situ* measurements in 2018

<table>
<thead>
<tr>
<th>Flux in main peak [fb/cm²]</th>
<th>TI18 data</th>
<th>1.7 ± 0.1 × 10⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI12 data</td>
<td>1.9 ± 0.2 × 10⁴</td>
<td></td>
</tr>
<tr>
<td>FLUKA MC</td>
<td>2.5 × 10⁴</td>
<td></td>
</tr>
</tbody>
</table>

(uncertainty 50%)

BDSim result for TI12, Lefebvre ICHEP2020

Observed angular distribution of background tracks
2. Pilot neutrino detector in 2018

- A 30 kg emulsion based (lead, tungsten target) detector was installed on axis, 12.2 fb\(^{-1}\) of data was collected in Sep-Oct 2018 (4 weeks).
- Proof of principle by just Emulsion detector.
- Combined analysis with FASER for Muon ID/charge in Physics run.
Pilot run result

- Analyzed target mass of **11 kg** and luminosity of **12.2 fb⁻¹**
- **18** neutral vertices were selected
  - by applying # of charged particle ≥ 5, etc.
  - Expected signal = 3.3^{+1.7}_{-0.95} events, BG = 11.0 events
- Note: no lepton ID in the pilot run → High BG
- In BDT analysis, **an excess of neutrino signal** (6.1 events) is observed. Statistical significance = 2.7 σ from null hypothesis
- This result demonstrates the detection of neutrinos from the LHC
Preparation for Run 3: FASERν detector

- Vacuum packed sub-module assembling at CERN
  - 10 tungsten plates + 10 emulsion films
  - Double-sided emulsion film after two processes
  - Achieved production speed of ~8 m²/day

- Emulsion films produced at NAGOYA University
- The total image transfer rate is 48 Gbytes/s
- Under operating for:
  - NINJA (J-PARC)
  - NA65/DsTau (CERN)
  - FASERν (CERN)
  - GRAINE (Balloon)
  - Radiography
Preparation for Run 3 at site

First emulsion detector installed!

FASERν

3/2021

3/2022

3/2022
First light of Physics run : LHC run3

The Beam commissioning just started.

- All detector components have been installed.
- We are observing the first “events”, beam background muons.
FASERν/FASERν2 schedule

- LHC Run-3 will start in 2022, FASERν.
- HL-LHC, starting in 2028, 10 times more integrated luminosity → FASERν2
Forward Physics Facility (FPF) at the HL-LHC

• HL-LHC will give $\times 20$ more collisions.

• FPF is proposed new facility to house larger experiments in the very forward region (neutrino target mass $x10$ FASER$\nu$).

• Extending sensitivities for new particle searches and neutrino physics by two orders of magnitude $\rightarrow$ FASER2, FASER$\nu2$, ... much more

• FPF White Paper (429 pages, 236 authors, 156 endorsers) http://arxiv.org/abs/2203.05090
Summary

• FASER is a project to analyze high energy neutrinos coming from LHC collision products.
• Study neutrino interactions at the unexplored energy region by each neutrino species.
• Charm / Beauty production analysis in neutrino CC interactions is a Physics target.
• It is also study on decaying parent especially Charms properties in Forward direction.

• After confirmation of track density in situ as well acceptable for emulsion detector who can identify 3 types of neutrino CC interactions.
• In 2018 a small sized emulsion detector succeed to detect some neutrino candidates under the realistic background track density condition (ie. In situ.)
• In 2022, Tungsten target with emulsion detector 1.1 ton will detect unexplored energy region neutrinos.

• FASER physics run just started.
• All detector components are installed in time, and observed first light of LHC run3 recently.
• Emulsion detector and FASER detector are waiting for detecting forward “neutral particles”.

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Expected CC interactions with 150 fb^{-1}
BACK UP
77 collaborators, 21 institutions, 9 countries
Neutrinos = proxy of forward hadron production

- Pion, Kaon, charm contribute to different part of energy spectra and flavor

- FASER$\nu$ provides important inputs to validate/improve generators $\rightarrow$ Muon excess, prompt neutrinos
The 1st $\nu_\tau$ candidate OPERA

NEUTRINO2010

5 candidates till 2015 Sep, 5.1$\sigma$
10 candidates final 2018 May, 6.1$\sigma$

$\tau \rightarrow \rho^- \nu_\tau$
$\rho^- \rightarrow \pi^0 \pi^-$
$\pi^0 \rightarrow \gamma \gamma$

Background for neutrino analysis

- **Muons** rarely produce neutral hadrons in upstream rock or in detector, which can mimic neutrino interaction vertices
  - Probability of $O(10^{-5})$
- **Pilot neutrino detector** doesn’t have lepton ID
  - Separation from neutral hadron BG (produced by muons) is challenging
  - **tighter cuts**
- The produced neutral hadrons are low energy
  - Discriminate by event topology

<table>
<thead>
<tr>
<th>Production rate per muon ($E_{had} &gt; 10$ GeV)</th>
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</thead>
<tbody>
<tr>
<td>Negative Muons</td>
</tr>
<tr>
<td>$K_L$</td>
</tr>
<tr>
<td>$K_S$</td>
</tr>
<tr>
<td>$\eta$</td>
</tr>
<tr>
<td>$\bar{\eta}$</td>
</tr>
<tr>
<td>$\Lambda$</td>
</tr>
<tr>
<td>$\bar{\Lambda}$</td>
</tr>
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<table>
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<tr>
<th>Vertex detection efficiency</th>
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<tr>
<td><strong>Signal</strong></td>
</tr>
<tr>
<td>$\nu_e$</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>$\nu_\mu$</td>
</tr>
<tr>
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</tr>
<tr>
<td>$\nu_\tau$</td>
</tr>
<tr>
<td>$\bar{\nu}_\tau$</td>
</tr>
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Variables for MVA

Expected distributions of the variables

5 variables used in the analysis
1. the number of tracks with \( \tan \theta \leq 0.1 \) with respect to the beam direction
2. the number of tracks with \( 0.1 < \tan \theta \leq 0.3 \) with respect to the beam direction
3. the absolute value of vector sum of transverse angles calculated considering all the tracks as unit vectors in the plane transverse to the beam direction (\( a_{sum} \))
4. for each track in the event, calculate the mean value of opening angles between the track and the others in the plane transverse to the beam direction, and then take the maximum value in the event (\( \phi_{mean} \))
5. for each track in the event, calculate the ratio of the number of tracks with opening angle \( \leq 90 \) degrees and >90 degrees in the plane transverse to the beam direction, and then take the maximum value in the event (\( r \)).

Conceptually why these variables are good:

Variable 1, 2: The neutrino energy is higher than the neutral hadron energy. Higher energy, more particles are produced in forward direction, i.e. \( \tan(\theta) \leq 0.1 \) (var 1), and higher ratio of var1/var2.

Variable 3: Momentum in the transverse plane is more balanced in hadron interactions than neutrino CC and NC interactions. Outgoing leptons in neutrino interactions take a major energy, which distorts this variable.

Variable 4, 5: For CC interactions, we expect the outgoing lepton and hadron system are back to back in the transverse plane.
Detection efficiency

Vertex detection efficiency (charged multiplicity $\geq 5$)

Tau decay detection efficiency $= 75\%$ ($\tau \rightarrow 1$ prong)

Mean flight length $\approx 30$ mm
Particle momentum measurement
by multiple Coulomb scattering (MCS)

- Sub-micron precision alignment using muon tracks
  - Our experience = 0.4 \(\mu\)m (in the DsTau experiment)
  - This allow to measure particle momenta by MCS, even above 1 TeV.

\[ (s_{\text{RMS}})^2 = \left( \frac{2.13.6(\text{MeV})}{3\beta P} x \sqrt{\frac{x}{X_0}} \right)^2 + \left( \sqrt{6} \sigma_{\text{pos}} \right)^2 \]

Performance with position resolution of 0.4 \(\mu\)m, in 100 tungsten plates (MC)

Measurable energy vs position resolution
Energy reconstruction ($\nu_\mu CC$)

- Sum of visible energy (model independent) already gives a reasonable resolution.
- ANN can solve problem at high energy and gives about 30% resolution at relevant energy range.
• Neutrino spectra at unexplored energy range
  • Study production / propagation / interaction
  • CC Cross section measurements of $\nu_e$, $\nu_\mu$, $\nu_\tau$
  • Heavy flavor physics, NC, QCD, NSI, oscillations
  • Complementarity between FASER$\nu$ (on axis) and SND (off axis)

Expected CC event statistics

<table>
<thead>
<tr>
<th>Generators</th>
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<th>SND@LHC</th>
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</tr>
<tr>
<td>SIBYLL</td>
<td>1343</td>
<td>5736</td>
</tr>
<tr>
<td>DPMJET</td>
<td>4614</td>
<td>1345</td>
</tr>
<tr>
<td>EPOS-LHC</td>
<td>2109</td>
<td>1459</td>
</tr>
<tr>
<td>QGSJET</td>
<td>1437</td>
<td>1328</td>
</tr>
<tr>
<td>Combination (all)</td>
<td>2376±2328</td>
<td>7549±1475</td>
</tr>
<tr>
<td>Combination (w/o DPMJET)</td>
<td>1630±248</td>
<td>7000±920</td>
</tr>
</tbody>
</table>

Projected precision of FASER$\nu$ measurement at 14-TeV LHC (150 fb$^{-1}$)

inner error bars: statistical uncertainties, outer error bars: uncertainties from neutrino production rate corresponding to the range of predictions obtained from different MC generators.


F. Kling, arXiv:2105.08270
Tracking device of FASER

- Thee tracking station and a interface tracker to FASERnu.
- Each containing 3 layers of double sided silicon micro-strip detectors
- Spare ATLAS SCT modules, 80um strip pitch, 40mrad stereo angle.
- SCT modules a 24cm x 24cm tracking layers by 8 SCT modules.
FASER\(\nu_2\) at the FPF

- **Tau neutrino physics**, with >100 times statistics of FASER\(\nu\)
  - FASER\(\nu_2\): Beam x 20, 20 tons mass
  - \(\sim 10^5 \nu_e, 10^6 \nu_\mu, 10^3 \nu_\tau\) CC events
- **Rich physics programs in neutrino physics, flavor physics, QCD and cosmic-rays**
**FASER detector & sensitivity**

- Dark photon: Photon in dark sector, and it has mass
- Signal: Dark photon decay into $e^+e^-$ pair