

Studying neutrinos at the LHC: FASER and its impact to the cosmic-ray physics

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Studies of high energy proton interactions have been basic inputs to understand the cosmic-ray spectra observed on the earth. Yet, the experimental knowledge with controlled beams has been limited. In fact, uncertainties of the forward hadron production are very large due to the lack of experimental data. The FASER experiment is proposed to measure particles, such as neutrinos and hypothetical dark-sector particles, at the forward location of the 14 TeV proton-proton collisions at the LHC. As it corresponds to 100-PeV proton interactions in fixed target mode, a precise measurement by FASER would provide information relevant for PeV-scale cosmic rays. By studying three flavor neutrinos with the dedicated neutrino detector (FASER ν), FASER will lead to a quantitative understanding of prompt neutrinos, which is an important background towards the astrophysical neutrino observation by neutrino telescopes such as IceCube. In particular, the electron and tau neutrinos have strong links with charmed hadron production. And, the FASER measurements may also shed light on the unresolved muon puzzle at the high energy. FASER is going to start taking data in 2022. We expect about 8000 ν_{μ} , 1300 ν_{e} and 20 ν_{τ} CC interactions at the TeV energy scale during Run 3 of the LHC operation (2022-2024) with a 1.1 tons emulsion-based neutrino detector. We report here the overview and prospect of the FASER experiment in relation to the cosmic-ray physics, together with the first LHC neutrino candidates that we caught in the pilot run held in 2018.

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1. Introduction

Atmospheric leptons (muons, neutrinos) are created by air showers initiated from primary cosmic-rays from extrasolar sources. Following the hadron cascade production, some of the hadrons decay into leptons. The high energy components are in the forward direction with respect to the primary cosmic ray. The atmospheric leptons have been measured by many experiments, however, the recent studies are encountering puzzling results or lack of understanding. For example, in the estimation of mean atomic number of high energy primary cosmic-ray, a discrepancy between the number of muons and air shower profile has been reported [1]. If we trust the measurement of number of muons, the average atomic number of primary cosmic-ray is above iron, as shown in Figure 1. This sounds unnatural and it is recognized as a problem, which is called muon puzzle [2]. People doubt about the forward meson production, in particular pion/kaon ratio may be not well reproduced in the MC, which results in the excess of muons in data. For this we lack accelerator data at the proper energy range.

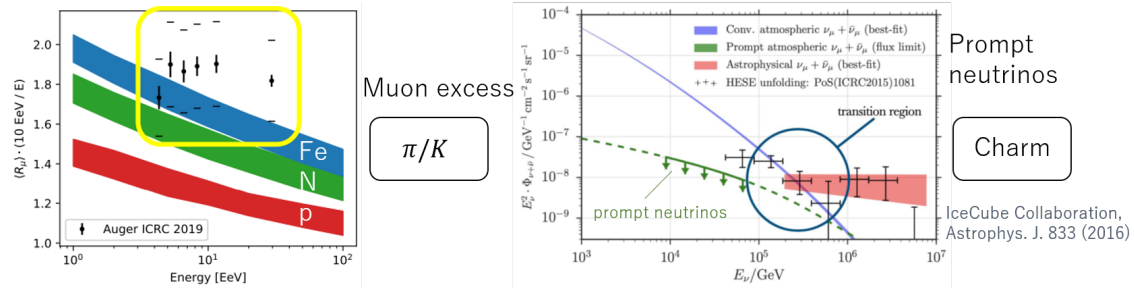


Figure 1: Muon excess problems and prompt neutrinos

Another example is the prompt atmospheric neutrino production. Prompt neutrinos are those from charmed hadron decays. As shown in Figure 1, it is expected to be a dominant background of astrophysical neutrino observations above 1 PeV by neutrino telescopes, such as IceCube. Therefore it is important to understand their flux and energy spectra. However, there is currently no quantitative estimate of prompt neutrino production [3], namely forward charm meson production.

In summary, the understanding of forward particle production with flavor sensitivity such as π , K and charm, is the key for future cosmic-ray experiments. This should be understood from beam experiments.

There are largely two kinds of experiments, fixed target experiments and collider experiments. Fixed target experiments like NA61 and NA65 can provide meson spectra with different target materials. However, they are limited in energy range. For example, \sqrt{s} at the CERN SPS is only ~ 30 GeV.

The collider method can go much higher. \sqrt{s} is 14 TeV at the LHC. This is equivalent to 100 PeV proton interaction in fixed target mode, covering above knee of cosmic ray flux, and also above the neutrino energy of interest. The data from the proton interactions at the LHC is at the proper energy range of interest. Yet, the conventional LHC experiments like ATLAS, CMS are not suitable because their angular acceptance is limited and they are not sensitive to forward emitted particles. Therefore, a dedicated forward detector is required. LHCf tried to measure neutral particles, namely γ , π^0 and n . That is still not enough to hit our questions related to flavors.

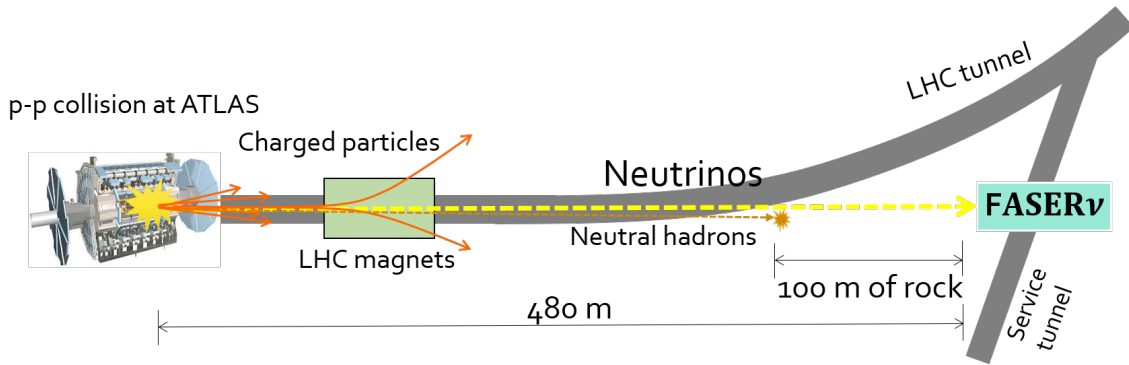


Figure 2: LHC’s “Neutrino beamline” layout

FASER ν [4] comes here. FASER ν is going to study neutrinos from the LHC. As neutrinos at FASER ν have implications for different meson flavor productions, namely π , K and charm particles as discussed in next section, FASER ν will provide important inputs to the hadron production models and to the cosmic-ray community.

2. Neutrino beam at the LHC

Figure 2 shows the LHC’s neutrino beamline. This was actually not designed as a neutrino beamline, but it functions as a high energy neutrino beamline. At the proton-proton interaction point, an intense beam of mesons is created in the forward direction. Some of them decay into neutrinos before the LHC magnet. Then, charged particles are deflected away by the magnets and neutral hadrons stop in the rock. Only neutrinos can go straight through 100 m of rock. By chance there is a disused service tunnel, where we will put FASER ν detector. In this way, we can exploit the intense neutrino beam from the LHC with a minimum cost for infrastructure. FASER ν is the first experiment using a collider as a neutrino source. FASER experiment [5], which is originally designed for new particle searches, and also FASER neutrino experiment [4, 6] were both approved by CERN in 2019.

Figure 3 shows the neutrino spectra at FASER ν . We can get neutrinos at the TeV energy scale where there is no data available. We can measure neutrinos at the highest energy for ν_e and ν_τ . For ν_μ , we will fill the gap between the IceCube measurement and accelerator data. Using these neutrinos, we can study production, propagation and interactions of high energy neutrinos at the completely new kinematical regime. The physics potential in general is described in [4].

It is worth stressing that FASER ν can study different hadron flavor productions by measuring neutrinos energy spectra and neutrino flavors. Figure 4 shows the neutrino flux contributions from different hadrons [7]. For muon neutrinos, low energy part is due to π decays, on the other hand, the high energy part is due to K decays. Furthermore, their contributions depend on neutrino flavors. For electron neutrinos, π contribution is negligible, but high energy part is made of charmed meson decays. Tau neutrinos are exclusively from charmed meson (mostly D_s) decays. Therefore, by measuring the neutrino energy spectrum, we can unfold the parental meson spectra. Therefore, FASER ν can provide important inputs to validate and improve hadron generators, eventually attacking muon puzzle and prompt neutrino production.

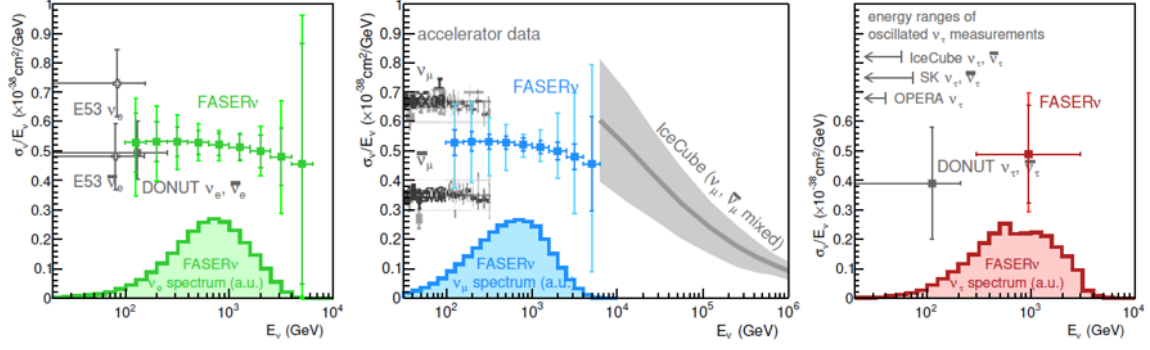


Figure 3: Neutrino fluxes at the FASER ν and the projected cross section sensitivities in Run 3 (2022-2024) [4]. The short error bars are due to statistical uncertainty, the long are uncertainty due to the range of neutrino flux predictions (DPMJET is not considered).

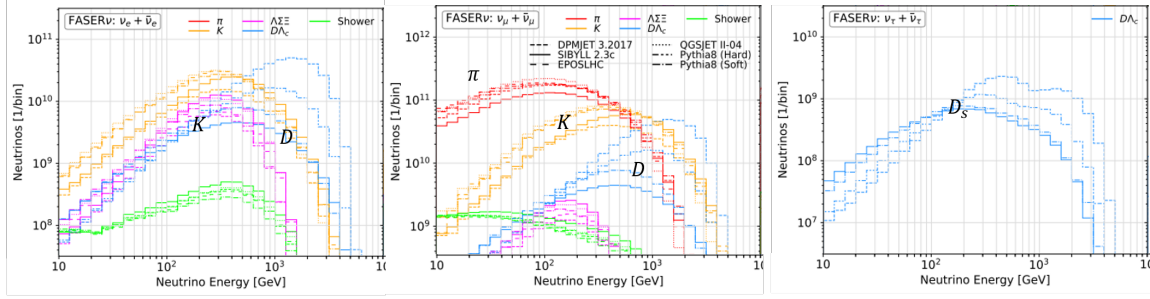


Figure 4: Neutrino fluxes, contributions from different mesons [7].

Furthermore, the neutrino measurements can provide deep insights on QCD. At the LHC energy, forward charm particles are created mostly by gluon-gluon interactions. Figure 5 shows the kinematical features of gluons which contribute to electron neutrino flux at FASER ν through charmed particles. Those are either large- x or very small- x below 10^{-5} . Such a characteristic kinematical feature is ideal to test the small- x factorization and also to test intrinsic charm. This is of interest of fundamental QCD processes, as well as important to understand prompt neutrinos.

3. FASER ν detector and expected performance in Run 3

The detector setup in Run 3 of LHC operation from 2022 to 2024 is shown in Figure 6. The FASER ν detector is made of emulsion tracker and tungsten target plates. It is followed by the FASER spectrometer. In the FASER ν detector, thanks to the high precision emulsion tracker, three neutrino flavors can be separated by their topology. Electron will quickly develop electromagnetic showers, muon will penetrate the detector, tau will make decay topology. The target mass of FASER ν is 1.1 tons. The energy resolution is estimated to be about $\Delta P/P \approx 30\%$. There is an interface detector, which allows to make a global reconstruction with the FASER spectrometer, making it possible to separate muon neutrino and anti-muon neutrinos.

It's a relatively small detector, however, we expect a lot of neutrino interactions of the order of 10^4 in Run 3. This table shows the expected number of CC interactions in FASER ν . Muon

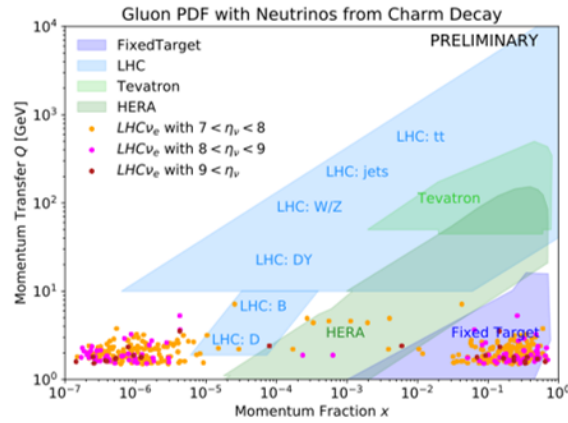


Figure 5: Gluon kinematical features for those contributing to electron neutrino fluxes at FASER ν through charmed particles.

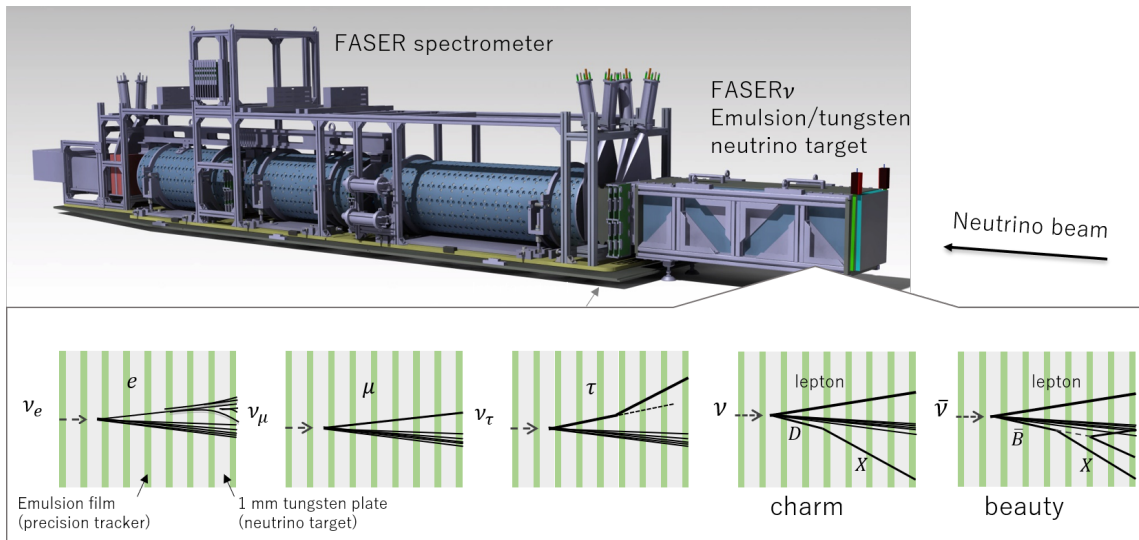


Figure 6: Detector configuration in Run 3

neutrinos are most abundant, but we will have electron neutrinos and even some tau neutrinos. The numbers largely depend on the hadron production models, meaning that FASER ν are sensitive to validate the hadron production models. The expected cross section sensitivities are shown in Figure 3.

For the proof of principle, we already carried out a pilot run in 2018. Figure 7-left the photo of the 30 kg neutrino detector, which was exposed to the LHC’s neutrino beam, collecting 12.2 fb $^{-1}$ of data. The observed tracks in a small volume of 2 mm \times 2 mm \times 10 emulsion films are shown here. There are a lot of tracks but they are found to be muons and electrons, so that they will not bother our neutrino measurements. After searching for neutrino interaction vertices, we found 18 candidates. Figure 8 shows the result of multivariate analysis, with signal (blue) and background (green) estimations, and data (black). The statistical significance from NULL hypothesis is calculated to be 2.7 σ [8]. This result demonstrates the detection of neutrino events

| | SIBYLL | Pythia 8 | DPMJET (used in FLUKA) |
|----------------------------|------------|------------|------------------------------|
| $\nu_e, \bar{\nu}_e$ | 800, 452 | 826, 477 | 3390, 1024 |
| $\nu_\mu, \bar{\nu}_\mu$ | 6571, 1653 | 7120, 2178 | 8437, 2737 |
| $\nu_\tau, \bar{\nu}_\tau$ | 16, 6 | 22, 11 | 111, 43 |

Table 1: The number of expected neutrino events and comparison among different hadron production generators.

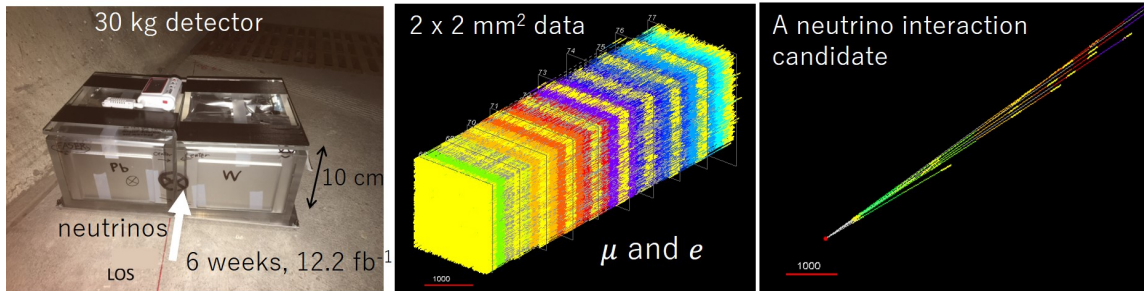


Figure 7: Left: A photo of pilot run detectors. Center: Reconstructed tracks in a small volume of detector. Right: A neutrino interaction candidate.

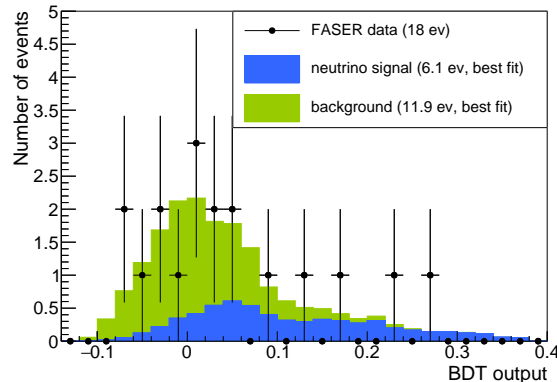


Figure 8: Output of the BDT (Boosted Decision Tree). The MC distributions are fitted to data.

at the actual LHC environment.

We are currently preparing for the physics run which is starting in 2022. Figure 9 shows some of photos from the activity. See the caption for the explanation. The FASER detector was installed in the LHC tunnel and under commissioning. The FASER ν detector structure is produced and its installation test was done (FASER ν is an replaceable module in order to exchange emulsion films.) The emulsion film production was tested and tungsten plates are being delivered. The FASER collaboration will make sure all the detector components are ready for data taking.



Figure 9: Preparation for the physics run starting in 2022. From top-left, the FASER detector installed in the LHC tunnel, the FASER ν detector installation test, a cosmic-ray track observed by the FASER's tracker at the LHC tunnel during the commissioning. From bottom-left, an emulsion film produced at the film production facility, tungsten plates, a sub-module of the emulsion/tungsten module.

4. Conclusion

FASER ν is the first experiment making use of neutrinos from a collider, which is approved and will start data taking in 2022. Thanks to its unique setup, we can study production, propagation and interactions of high energy neutrinos. In particular, it will provide vital inputs to the cosmic ray community in understanding of atmospheric lepton productions. The detection of neutrinos at the actual site was already demonstrated in 2018 samples. The FASER Collaboration is preparing the detector for the physics data taking in 2022.

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