Snowmass2021 - Letter of Interest

Physics with Sub-GeV Atmospheric Neutrinos

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (TF11) Theory of neutrino physics
■ (NF10) Neutrino detectors
■ (CF1) Dark Matter: Particle-like

Authors:

Kevin J. Kelly (Fermilab) [kkelly12@fnal.gov]
Pedro Machado (Fermilab) [pmachado@fnal.gov]
Ivan Martinez-Soler (Northwestern, Fermilab) [ivan.martinezsoler@northwestern.edu]
Stephen J. Parke (Fermilab) [parke@fnal.gov]
Yuber Perez-Gonzalez (Northwestern, Fermilab) [yfperezg@northwestern.edu]

Abstract:

Atmospheric neutrinos with energy below the GeV scale can yield significant complementary information on the CP violating phase. Liquid argon time projection chambers, such as the DUNE far detector, are uniquely positioned to probe this sample due to their excellent topological capabilities. Measuring sub-GeV atmospheric neutrinos at DUNE will have important consequences in searches for diffuse supernova neutrino background, dark matter and neutrinos from primordial black holes.

The measurement of the atmospheric neutrino flux bring us one of the first indications that neutrinos are massive particles[1]. That flux is created by the collision of cosmic rays with the atmospheric nuclei. Covering almost six orders of magnitude, from roughly 10 MeV to 10 TeV, those neutrinos may cross the Earth before arriving at the detector, which makes atmospheric neutrinos a valuable sample to study the neutrino properties.

The atmospheric neutrino flux has already been measured at several energy regions. In the region $\sim 1 - 100$ GeV, the matter potential induced when neutrinos traverse the Earth are comparable to the atmospheric neutrino mass splitting. Particularly around ~ 6 GeV and for the trajectories crossing the Earth's mantle, the matter effects and the atmospheric mass parameters are of the same order. This leads to a flavor resonance for neutrinos or anti-neutrinos depending on the mass hierarchy. Those flavor oscillations have been already measured by several experiments like Super-Kamiokande[2] and DeepCore[3].

At higher scales, from 100 GeV to tens of TeVs, the neutrino telescope IceCube[4] has measured the ν_μ neutrino flux for more than 8 years. At those high energies, neutrino evolution is dominated by the presence of matter, both via matter effects that suppress oscillations and by scattering on the Earth which reduce the atmospheric neutrino flux at such high energies. Due to the important role of matter in both aforementioned regions, several studies on beyond standard model scenarios have been performed, particularly on nonstandard interactions (see e.g. Refs.[5–7]) and eV-scale sterile neutrinos[4;8–13].

Below the GeV scale, the neutrino phenomenology is exceptionally rich[14–23]. The physical reason behind this is twofold. First, for baselines comparable to the Earth's radius, oscillation of neutrinos with energies in the 100 MeV to 1 GeV region are strongly affected by both solar and atmospheric mass splittings. This enhances the interference between these two oscillation amplitudes, and thus CP violation effects. Second, the long baseline and large matter effects induced by the Earth lead to non-

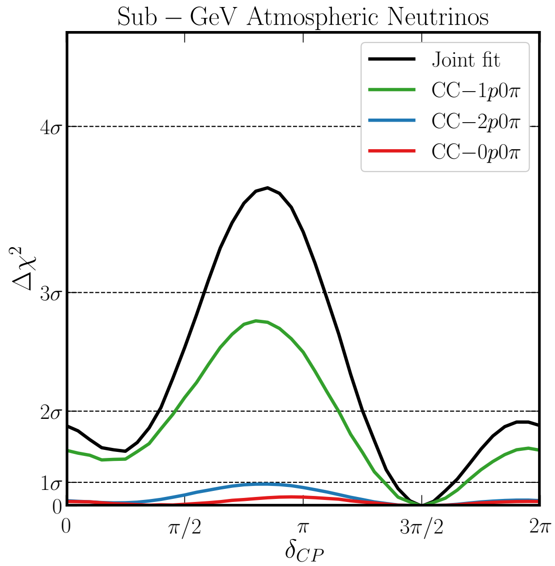

Figure 1: *DUNE sensitivity to CP violation using only the sub-GeV atmospheric neutrino sample, assuming $\delta_{CP} = 3\pi/2$ and normal mass ordering as input.*

trivial oscillation effects. Sub-GeV atmospheric neutrinos are subject to both MSW and parametric resonances[17]. A parametric resonance happens when changes to the matter density profile occur on the same scale as the neutrino oscillation length. The phenomenon is analogous to a resonant spring oscillator. More importantly, the CP-interference term is much larger, roughly tenfold, than the corresponding one in accelerator neutrinos. Thus, measuring sub-GeV atmospheric neutrinos can yield significant new information on δ_{CP}[23;24].

The difficulty in studying these neutrinos is related to the event reconstruction which is very challenging for Cherenkov detectors like Super-Kamiokande at such low energies. Neutrinos interacting with nuclei could, for instance, up-scatter to a charged lepton and recoil a proton. Protons with less than about 1.4 GeV of kinetic energy do not emit Cherenkov radiation, being completely invisible in these detectors. Besides, kinematics lead to a large spread in outgoing lepton angles. Finally, the lack of charge identification makes it impossible to distinguish events originated from neutrinos or antineutrinos. All this results in very poor reconstruction of the neutrino energy and direction, making impractical the use of sub-GeV atmospheric neutrinos to probe CP violation in Cherenkov detectors, unless they are gigantic at the multi-megaton scale[25].

In liquid argon time projection chambers (LArTPCs), the situation is completely different. The liquid argon technology allows for excellent reconstruction of neutrino event topologies by detecting the tracks of all charged particles and identifying them by topology and energy loss. The MicroBooNE experiment has already demonstrated the capability of correctly reconstructing the direction of electromagnetic showers, which are much more challenging than muon tracks, within 3° precision[26]. Moreover, the ArgoNeuT collaboration have shown that protons with kinetic energy above 21 MeV can be efficiently identified in LArTPCs and their three momentum can be reconstructed with good resolution[27]. Besides, the capability of detecting individual outgoing protons allows for statistical separation between neutrinos and antineutrinos, since the former significantly more likely to kick out a single proton from Argon than the latter (and the total cross section for neutrinos is about a factor of 2 larger than the one for antineutrinos)[28]. For the DUNE far detector, it has been shown that by leveraging these LArTPC capabilities, DUNE will be able to use this sub-GeV atmospheric neutrino sample to have a measurement of the CP violation phase independently from the beam neutrino program[23]. We also expect cross section and reconstruction studies at SBND[29;30] to play an important role in the future DUNE measurement, as typical neutrino energies at SBND are within the 100 MeV to 2 GeV range.

Besides providing a complementary measurement of the CP phase, the determination of the sub-GeV atmospheric neutrino flux will have important consequences in other searches, such as the diffuse supernova neutrino background[31;32], neutrinos from Primordial Black Holes[33], and dark matter direct detection (see e.g. Ref.[34]). Besides CP violation, sub-GeV atmoepheric neutrinos at DUNE may be very relevant for new physics searches, and may be used to perform an Earth tomography study. In this letter of interest, we propose to the community to investigate atmospheric neutrinos in the energy region below the GeV, particularly at the DUNE far detector due to its unique capabilities.

References

[1] T. Kajita, Rev. Mod. Phys. **88**, 030501 (2016).

[2] Super-Kamiokande, M. Jiang *et al.*, PTEP **2019**, 053F01 (2019), 1901.03230.

[3] IceCube, M. Aartsen *et al.*, Phys. Rev. Lett. **120**, 071801 (2018), 1707.07081.

[4] IceCube, M. Aartsen *et al.*, (2020), 2005.12943.

[5] O. Miranda and H. Nunokawa, New J. Phys. **17**, 095002 (2015), 1505.06254.

[6] Y. Farzan and M. Tortola, Front. in Phys. **6**, 10 (2018), 1710.09360.

[7] *Neutrino Non-Standard Interactions: A Status Report* Vol. 2, 2019, 1907.00991.

[8] H. Nunokawa, O. Peres, and R. Zukanovich Funchal, Phys. Lett. B **562**, 279 (2003), hep-ph/0302039.

[9] G. H. Collin, C. A. Argüelles, J. M. Conrad, and M. H. Shaevitz, Phys. Rev. Lett. **117**, 221801 (2016), 1607.00011.

[10] M. Dentler *et al.*, JHEP **08**, 010 (2018), 1803.10661.

[11] J. Liao, D. Marfatia, and K. Whisnant, Phys. Rev. D **99**, 015016 (2019), 1810.01000.

[12] S. Böser *et al.*, Prog. Part. Nucl. Phys. **111**, 103736 (2020), 1906.01739.

[13] A. Diaz, C. A. Argüelles, G. H. Collin, J. M. Conrad, and M. H. Shaevitz, (2019), 1906.00045.

[14] V. D. Barger, T. J. Weiler, and K. Whisnant, Phys. Lett. B **440**, 1 (1998), hep-ph/9807319.

[15] A. Friedland, C. Lunardini, and M. Maltoni, Phys. Rev. D **70**, 111301 (2004), hep-ph/0408264.

[16] P. Huber, M. Maltoni, and T. Schwetz, Phys. Rev. D **71**, 053006 (2005), hep-ph/0501037.

[17] E. K. Akhmedov, M. Maltoni, and A. Y. Smirnov, JHEP **06**, 072 (2008), 0804.1466.

[18] O. Mena, I. Mocioiu, and S. Razzaque, Phys. Rev. D **78**, 093003 (2008), 0803.3044.

[19] E. Fernandez-Martinez, G. Giordano, O. Mena, and I. Mocioiu, Phys. Rev. D **82**, 093011 (2010), 1008.4783.

[20] V. Barger *et al.*, Phys. Rev. Lett. **109**, 091801 (2012), 1203.6012.

[21] E. Akhmedov, S. Razzaque, and A. Smirnov, JHEP **02**, 082 (2013), 1205.7071, [Erratum: JHEP 07, 026 (2013)].

[22] W. Winter, Phys. Rev. D **88**, 013013 (2013), 1305.5539.

[23] K. J. Kelly, P. A. Machado, I. Martinez Soler, S. J. Parke, and Y. F. Perez Gonzalez, Phys. Rev. Lett. **123**, 081801 (2019), 1904.02751.

[24] I. Martinez-Soler and H. Minakata, PTEP **2019**, 073B07 (2019), 1904.07853.

[25] S. Razzaque and A. Yu. Smirnov, JHEP **05**, 139 (2015), 1406.1407.

[26] MicroBooNE, C. Adams *et al.*, JINST **15**, P02007 (2020), 1910.02166.

[27] ArgoNeuT, R. Acciarri *et al.*, Phys. Rev. D **99**, 012002 (2019), 1810.06502.

[28] ArgoNeuT, O. Palamara, JPS Conf. Proc. **12**, 010017 (2016).

[29] MicroBooNE, LAr1-ND, ICARUS-WA104, M. Antonello *et al.*, (2015), 1503.01520.

[30] P. A. Machado, O. Palamara, and D. W. Schmitz, Ann. Rev. Nucl. Part. Sci. **69**, 363 (2019), 1903.04608.

[31] J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. **93**, 171101 (2004), hep-ph/0309300.

[32] A. de Gouvea, I. J. Martinez Soler, Y. F. Perez-Gonzalez, and M. Sen, (2020), 2007.13748.

[33] B. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, (2020), 2002.12778.

[34] DARWIN, J. Aalbers *et al.*, JCAP **11**, 017 (2016), 1606.07001.