Prospects for Beyond the Standard Model Studies at the Deep Underground Neutrino Experiment

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ABSTRACT

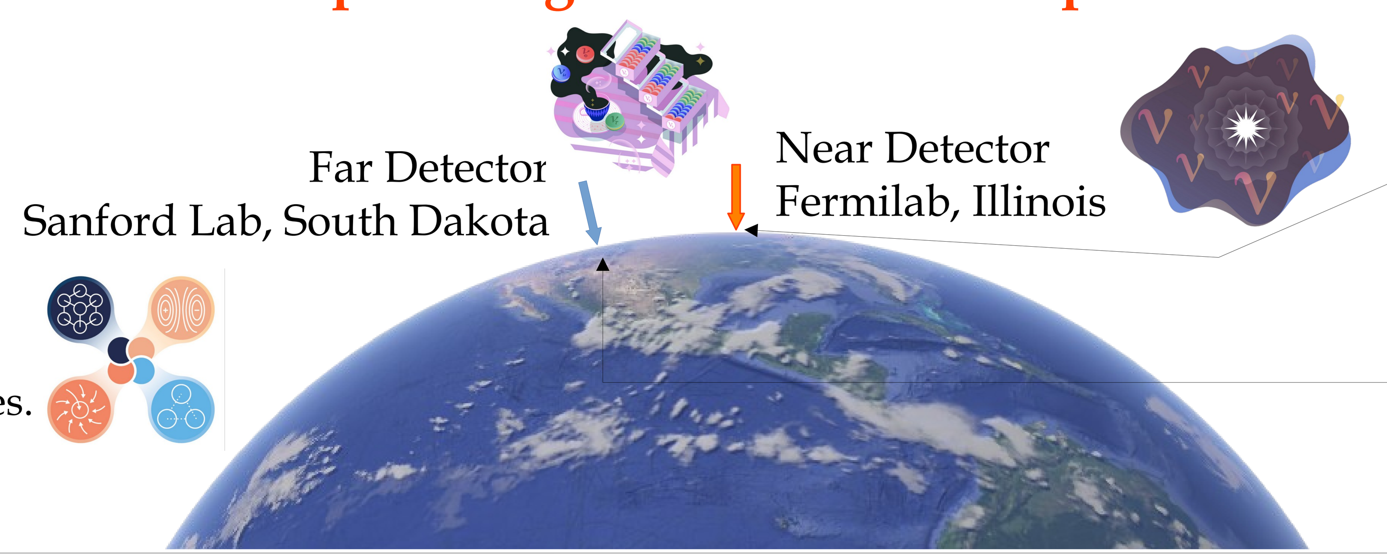
The Deep Underground Neutrino Experiment (DUNE) is an international particle physics experiment and its primary scientific objective is a precision measurement of neutrino oscillation parameters. While the experiment was designed to focus on understanding neutrinos accurately, interestingly, this unique experimental environment of DUNE is expected to provide excellent opportunities to search for new physics Beyond the Standard Model (BSM). The high-intensity proton beams and precision detector system provide a rich opportunity for the potential discovery of new particles and unveil new interactions and symmetries of BSM. DUNE will consist of two detector complexes and the beam source. The beam will be a 1.2 MW with a corresponding protons-on-target of 1.1×10^{21} per year, upgradable to multi-megawatt power. The Near Detector complex will be located 574 m from the neutrino source and it consists of a liquid argon Time Projection Chamber (TPC), a magnetized gaseous argon TPC, and a large, magnetized beam monitor. The Far Detector complex will be located 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota, at a distance of 1300 km from the neutrino source, and will consist of 70 kt liquid argon TPC. This environment provides excellent conditions to probe many BSM physics topics, and we will review those various BSM scenarios and discuss their prospects at DUNE.

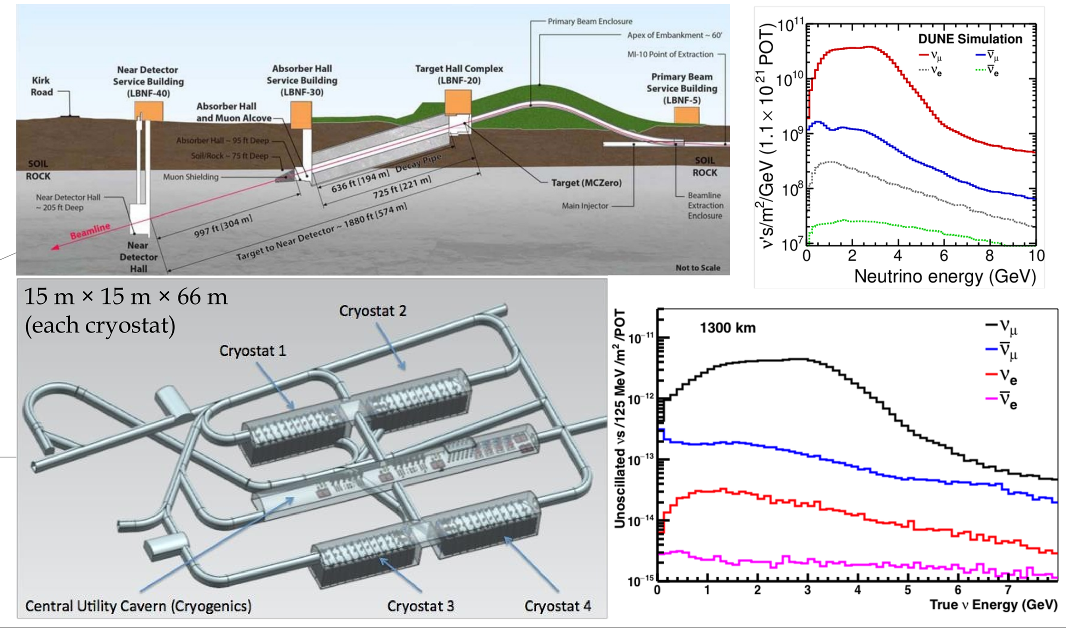
Primary Scientific Goals

1) Precision measurements of the υ-oscillation parameters
   - Neutrino mass hierarchy
   - Mixing angles (PMNS matrix)
2) CP-violation in neutrino sector
   - Oscillation patterns of neutrinos and anti-neutrinos
3) Grand unification problem – proton decay
   - $p\rightarrow e^{+}\pi^{0}$, $p\rightarrow K^{+}\upsilon$
4) Neutrino astronomy about core-collapse supernovae to understand the formations of neutron stars and black holes.

→ 1) and 2) require high-intensity proton beam.
→ This opens up great potential for BSM physics!

The Deep Underground Neutrino Experiment

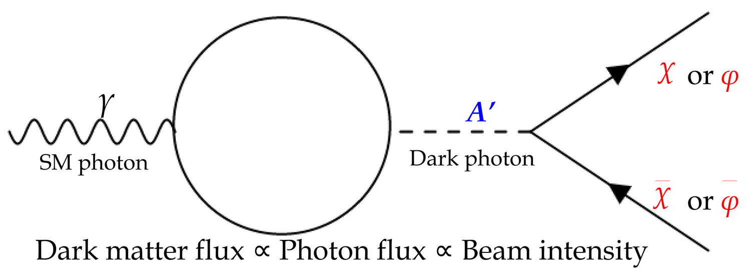




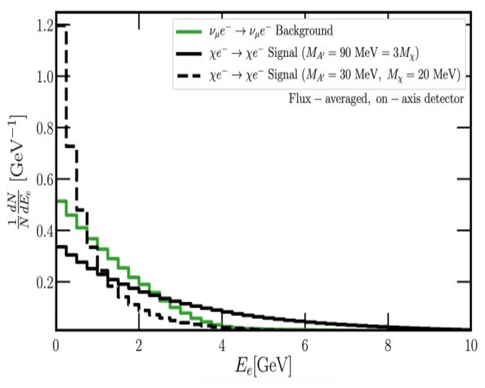
BSM Searches at DUNE Near Detector (ND)

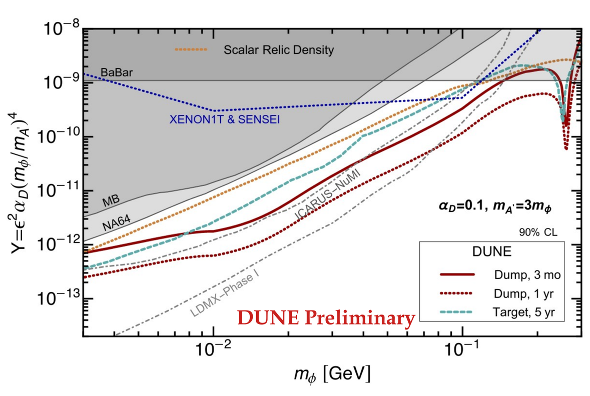
Light Dark Matter (LDM)

- LDMs are produced in the proton beam-target interaction. SM γ kinetically mixed 'dark photon', produced by bremsstrahlung, and neutral meson decays. This dark photon decays into dark matter pair.
- Signals: recoiled e^-/nucleon.
- Background: υ_μ scattering off of e^- / nucleon.
- Many interesting ideas such as DUNE PRISM (PRD100.095010, 2019) and Targetless DUNE(2206.06380 – preliminary result) are suggested and have been studied.



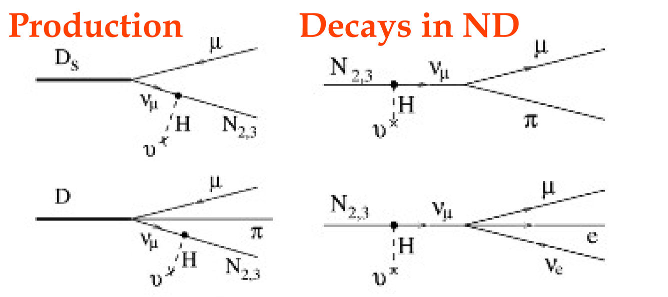
Dark matter flux ∝ Photon flux ∝ Beam intensity

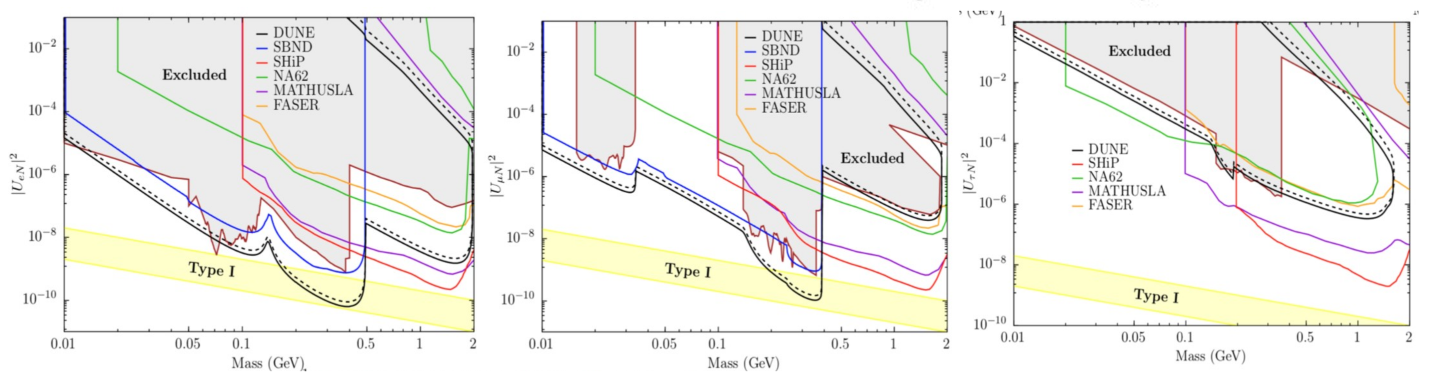




Heavy Neutral Leptons (HNL)

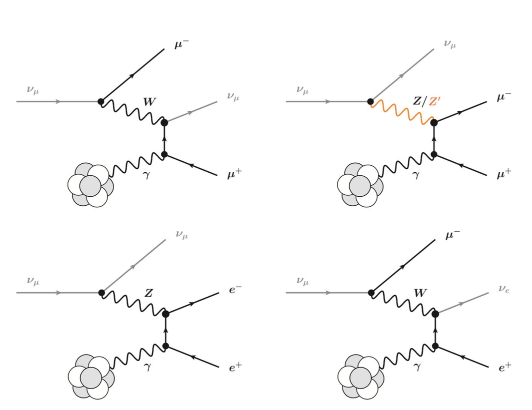
- Proton beam + target → produce heavy mesons (such as D)
- Such heavy mesons can be a source of HNL.
- HNL signature: charged leptons + lighter mesons
- 90% C.L. sensitivities to the mixing parameters with the light leptons assume six years of running.





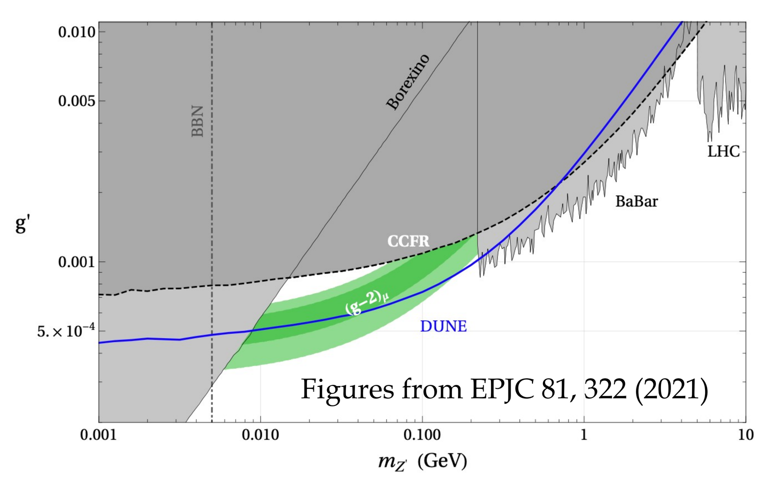
Neutrino Trident

- Neutrino tridents - rare SM weak processes
- Signature: a pair of charged leptons
- Δ=(SM expected rate – Observed event rate) suggests unknown gauge boson couplings.



Feynman Diagrams of "Neutrino Tridents"

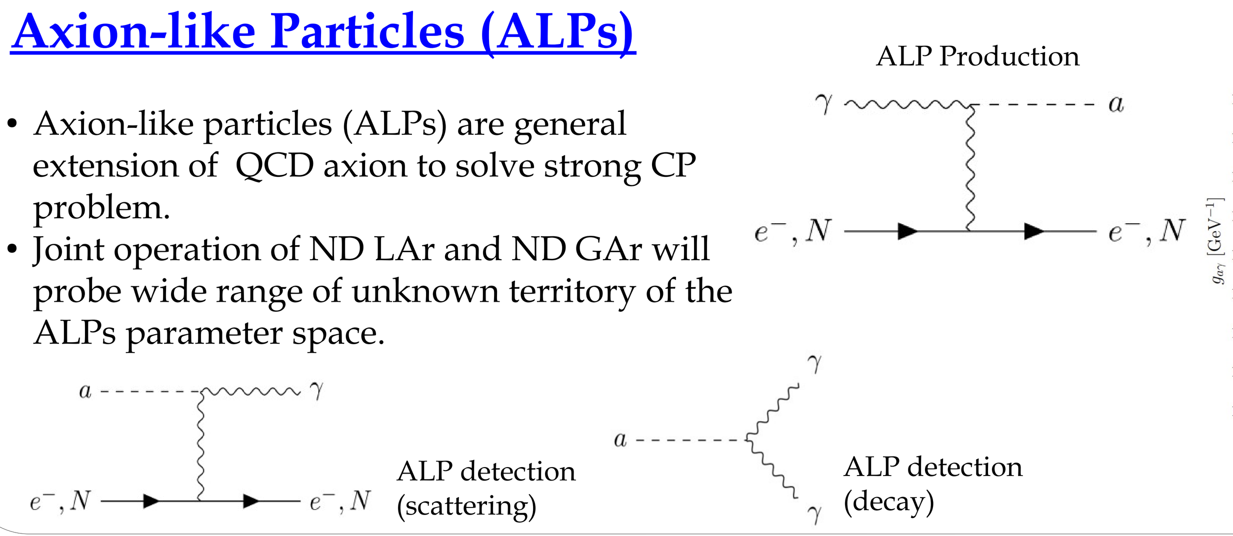
- The DUNE sensitivity shown by the solid blue line assumes 6.5 years running in neutrino mode, leading to a measurement of the trident cross section with 40% precision. This sensitivity curve is laid down in the region where $(g-2)_\mu$ anomaly can be explained at the 1σ and 2σ levels.

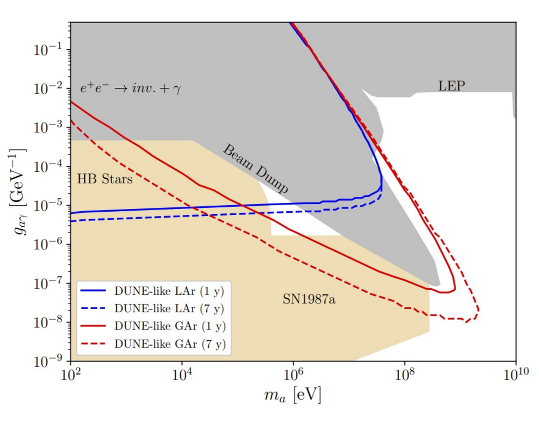


Figures from EPJC 81, 322 (2021)

Axion-like Particles (ALPs)

- Axion-like particles (ALPs) are general extension of QCD axion to solve strong CP problem.
- Joint operation of ND LAr and ND GAr will probe wide range of unknown territory of the ALPs parameter space.



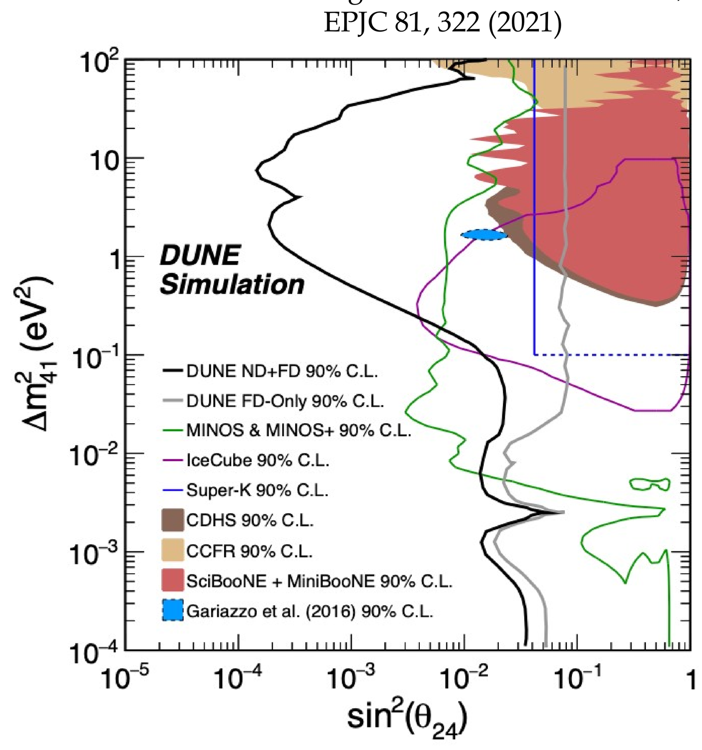


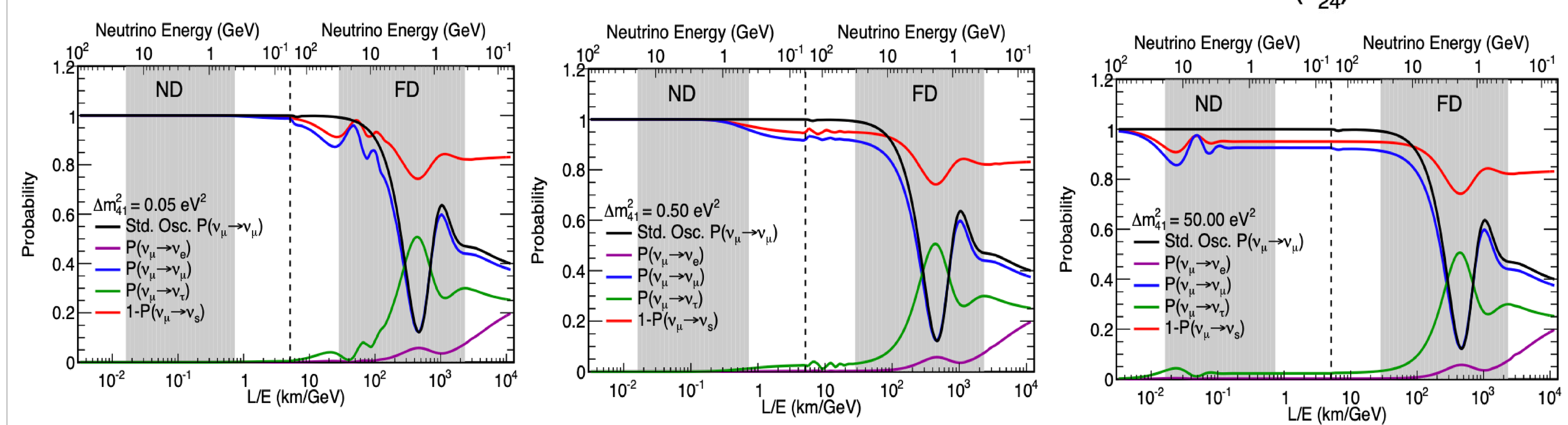
BSM Searches at DUNE Far Detector (FD)

Figures from Mike Walbank, EPJC 81, 322 (2021)

Sterile Neutrino

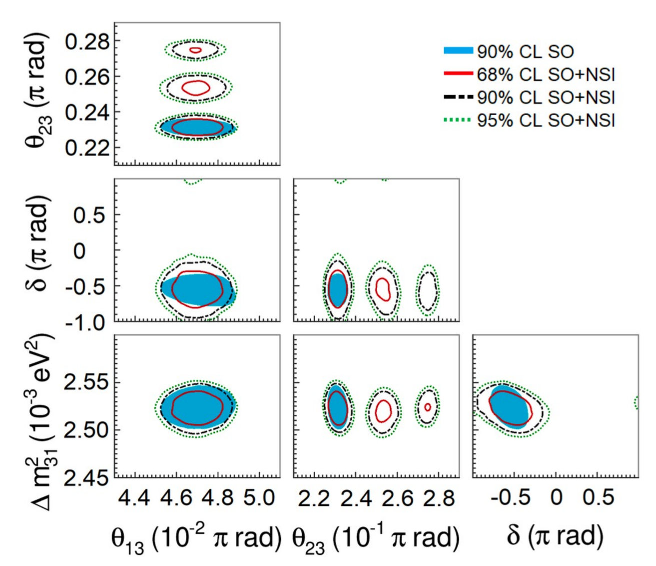
- Sterile neutrino is a hypothetical particle which could cause a deficiency of active 3-neutrinos in the detector, and it is considered as a way to explain the anomalies that appeared as the results of LSND and MiniBooNE experiments.
- Primary signature: disappearance of NC and υ_μCC events.
- DUNE will look for active-to-sterile neutrino mixing using the reconstructed energy spectra of both NC and CC neutrino interactions in the FD, and their comparison to the extrapolated predictions from the ND measurement.





Non-standard Interactions (NSI)

- DUNE has features of long-baseline, and wide-band beam → This makes DUNE very sensitive to NSI.
- Since NSI can affect the precision measurements neutrino oscillation of DUNE, a close investigation for this is highly required.
- The Figure on the right shows projections of the standard oscillation parameters with nonzero NSI for 68, 90, and 95% C.L. The allowed regions considering negligible NSI are superposed to the SO + NSI.



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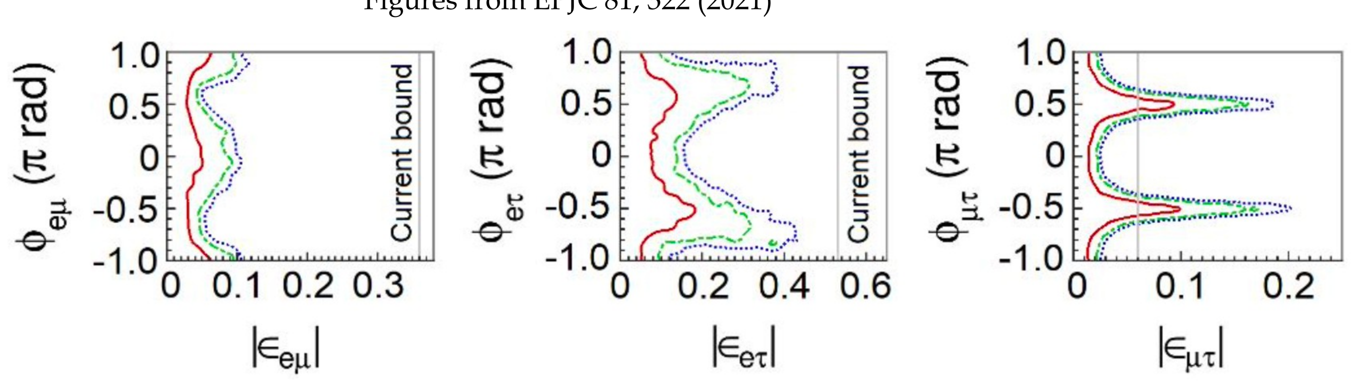

Conclusion

- DUNE will be a very powerful tool for precision neutrino science.
- At the same time, thanks to its high-intensity proton beam, DUNE provides an excellent environment for exploring the Beyond the Standard Model physics.
- DUNE BSM program will cover various physics topics, including LDM, HNL, neutrino tridents, ALPs, sterile neutrino, and non-standard interactions. Each of the topics shows very promising physics results.
- The DUNE Collaboration strongly supports cooperation between theorists and experimentalists and will provide significant opportunities for exciting discoveries in the next few decades.