Neutrino Oscillation Measurements with DUNE

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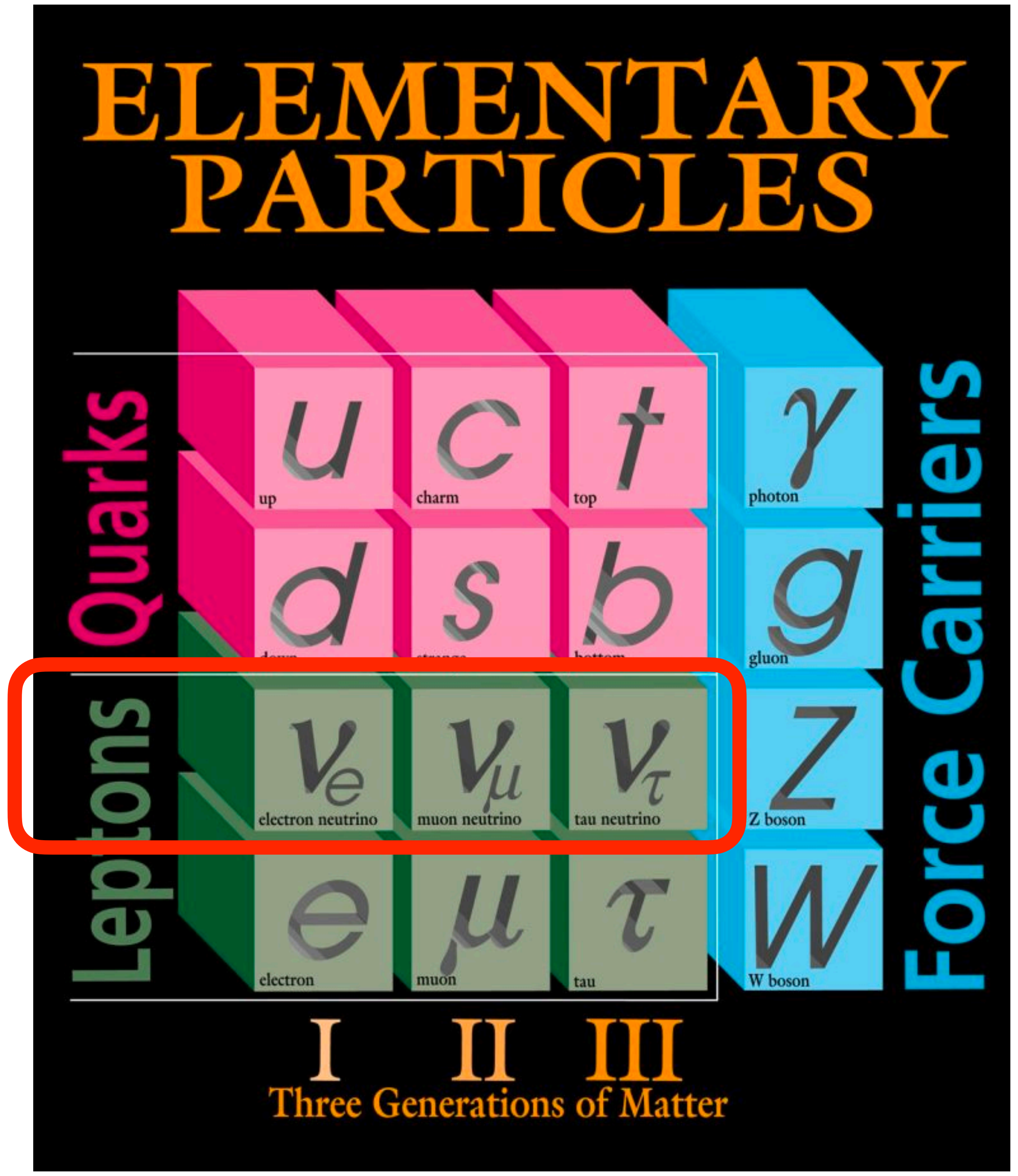
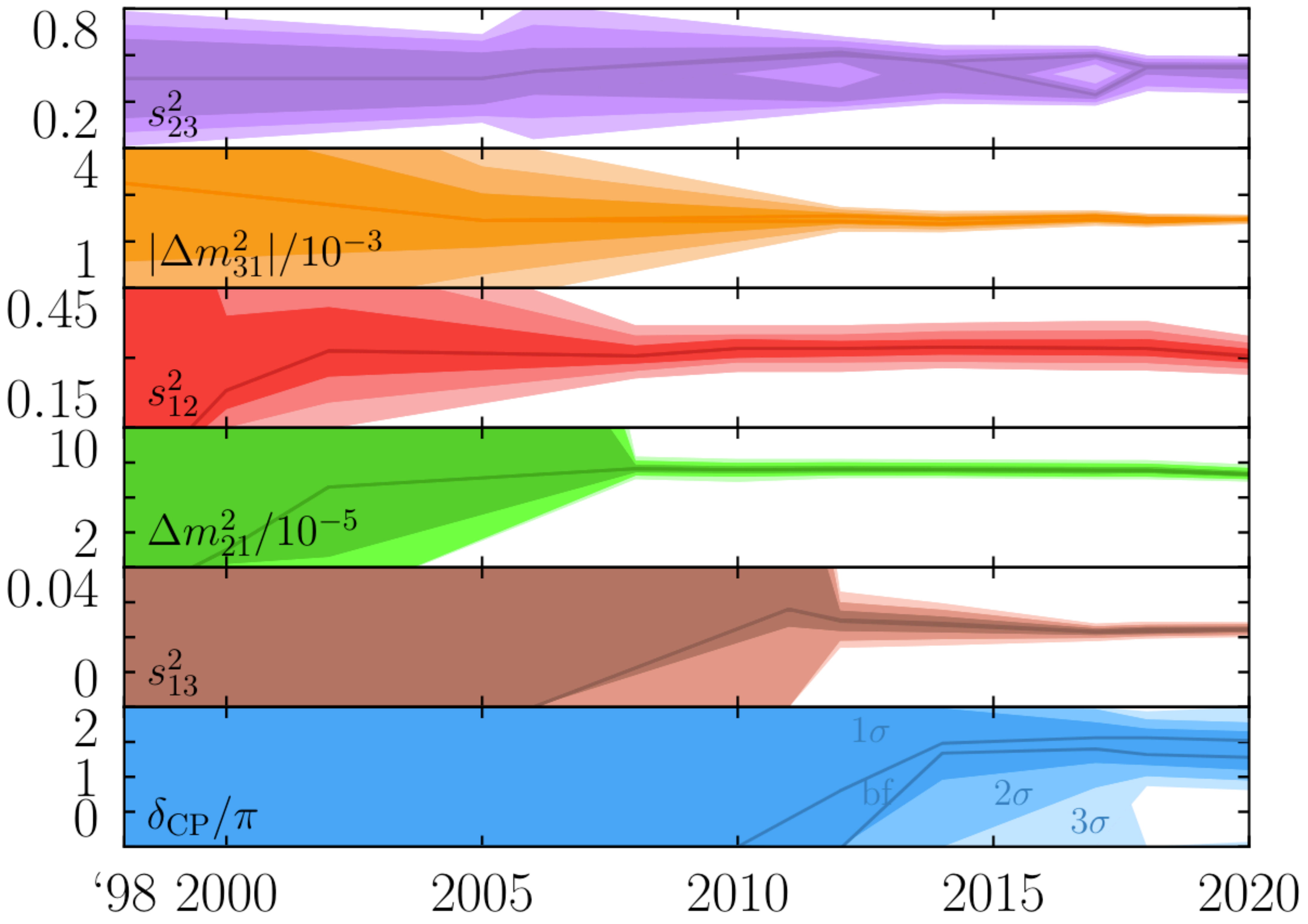
Neutrino Oscillations

Standard model has been highly successful, but we know it's not complete



The basic building blocks are the six leptons, six quarks, four force carriers, and the Higgs boson. Credit: Fermilab

The allowed ranges of neutrino oscillation parameters have been narrowed through tremendous efforts

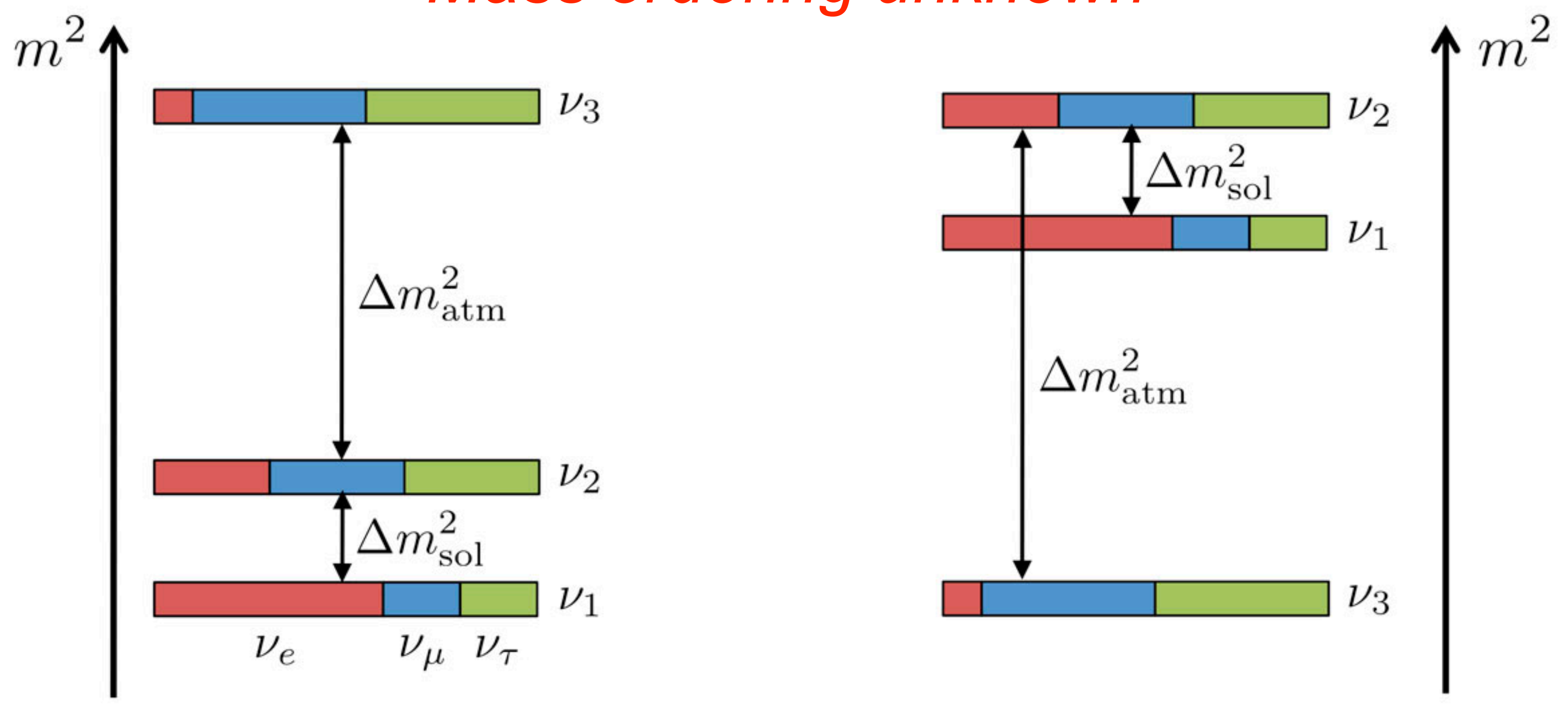


Snowmass NF01 Topical Report, *arXiv:2212.00809*

Neutrino Oscillations

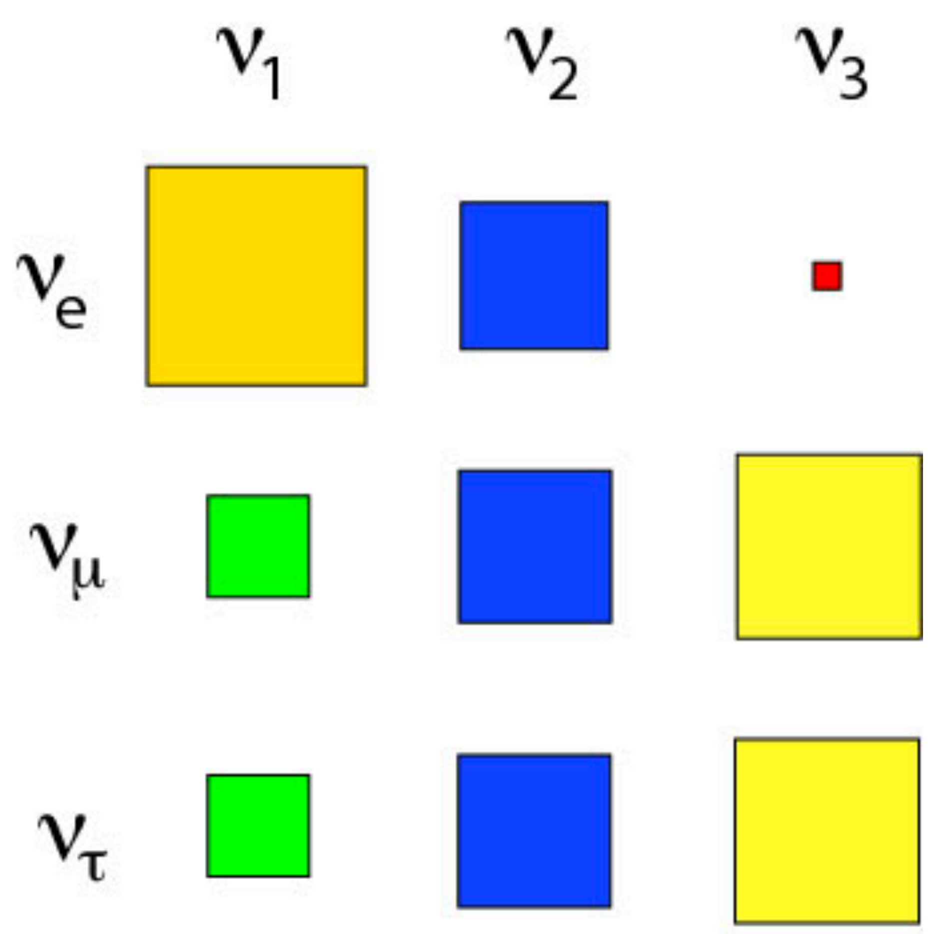
- Many questions remain unanswered
  - What are the masses of the neutrinos?
  - What kind of masses do neutrinos have? Are neutrinos their own antiparticles?
  - Are there more than 3 kinds of neutrinos?
  - Do neutrinos follow a "normal ordering" or an "inverted ordering"?
  - Do neutrino oscillations violate charge-parity symmetry?
  - ……

Mass ordering unknown



Credit: JUNO Collaboration / JGU-Mainz

Possible to answer given that θ_{13} is relatively large



Credit: Sheldon Stone

Deep Underground Neutrino Experiment

SURF

Large, deep underground LArTPC far detectors

Fermilab

High intensity neutrino beam
Near detector complex

Highlight talk of DUNE by Xin Qian on July 7

Precision neutrino oscillation measurements, MeV-scale neutrino physics, BSM searches, ……

Long-baseline Oscillation Experiment

$$\Phi \times P_{\nu\to\nu} \times \sigma \propto N_\nu^{\text{obs}}$$

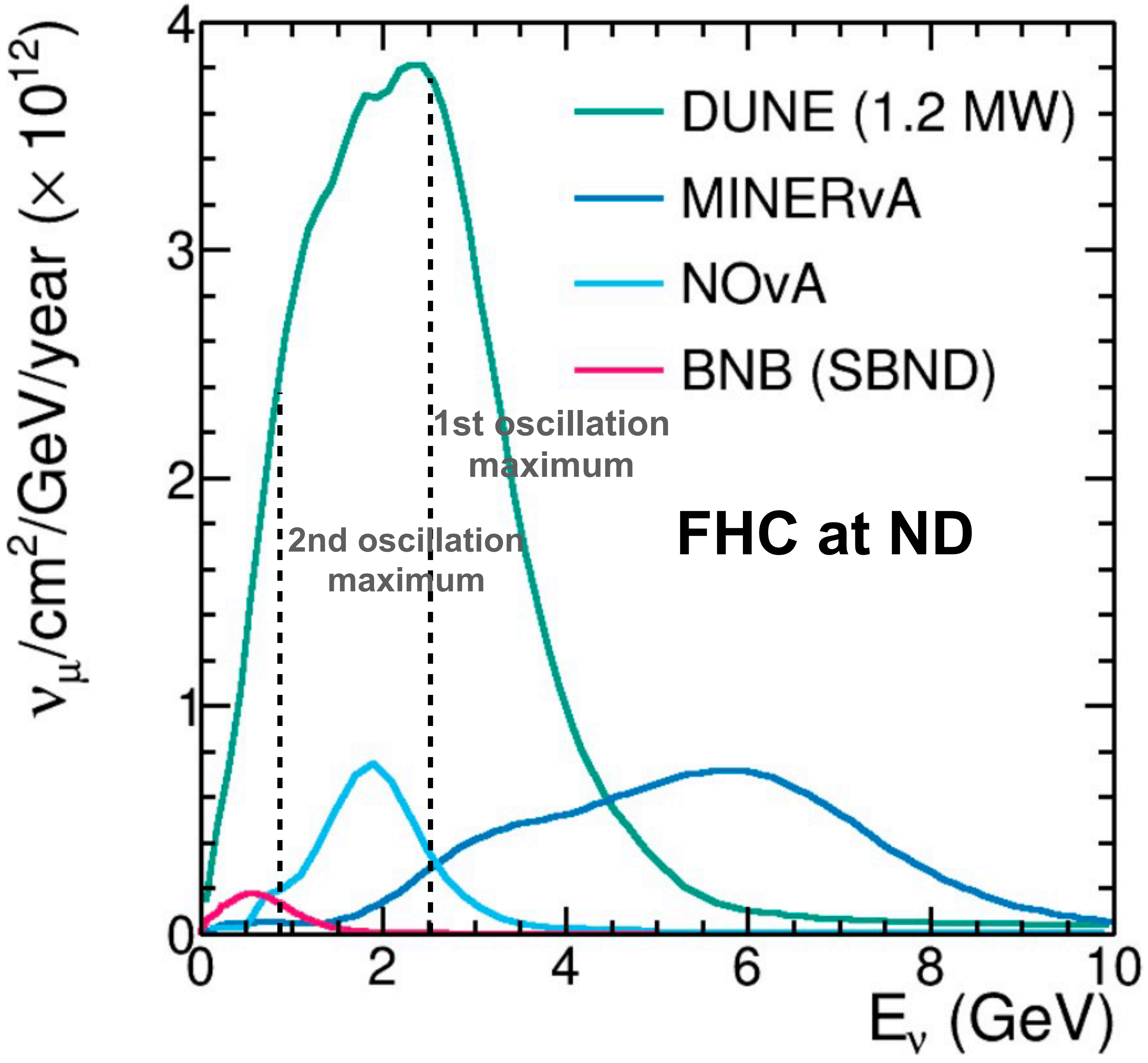
Neutrino flux — Oscillation Probability — *Cross section* — Observed neutrinos

- Oscillation parameters are inferred from observed event (N_ν^{obs})
- Powerful neutrino beam gives high statistics (Φ)
- Highly-capable near detector to constrain neutrino flux and cross-section uncertainties (σ)
- High-resolution detectors reduce ambiguities due to detector response effects

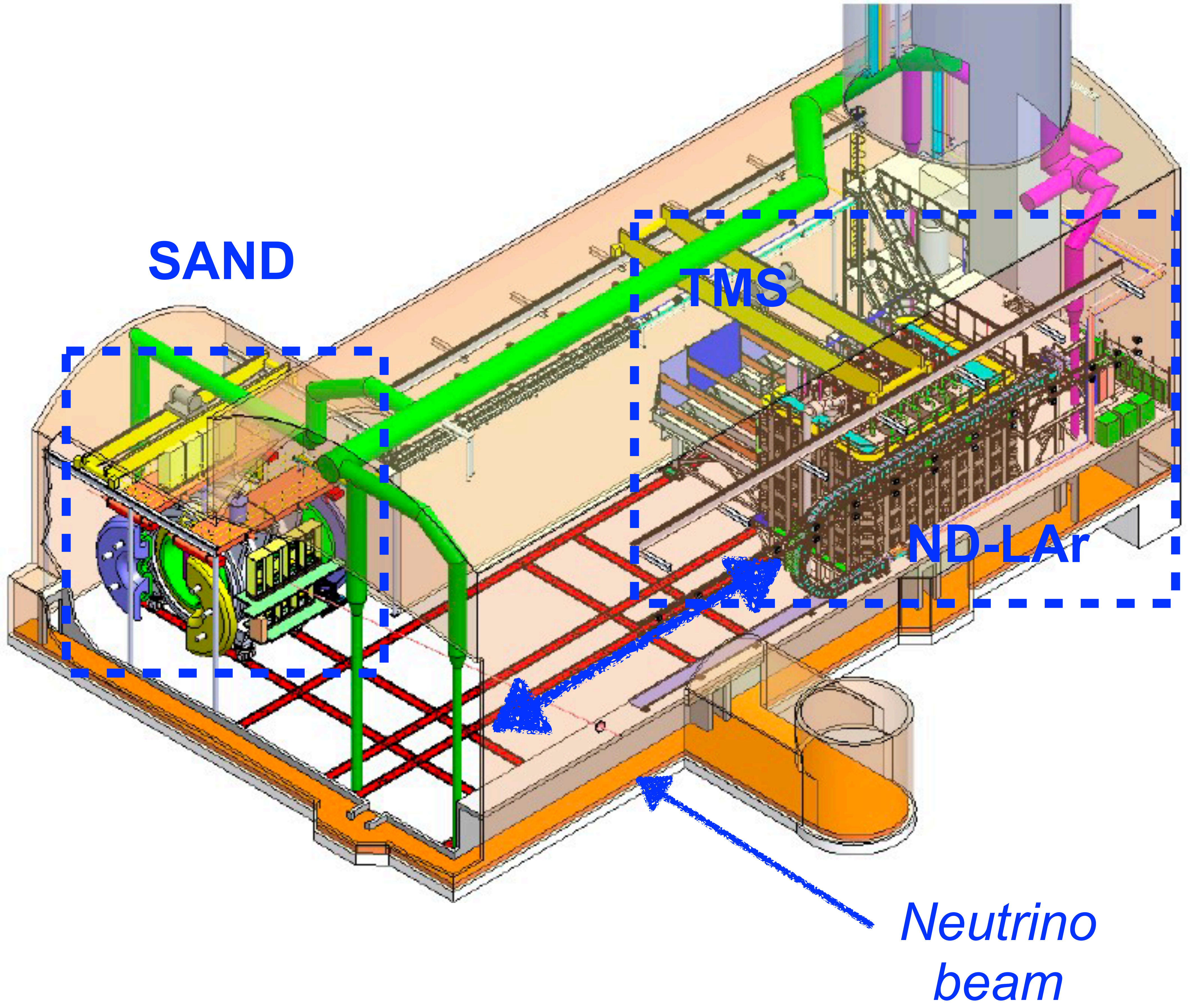
DUNE's Role in the 3F Paradigm

1.2 MW proton beam, upgradeable to 2.4 MW

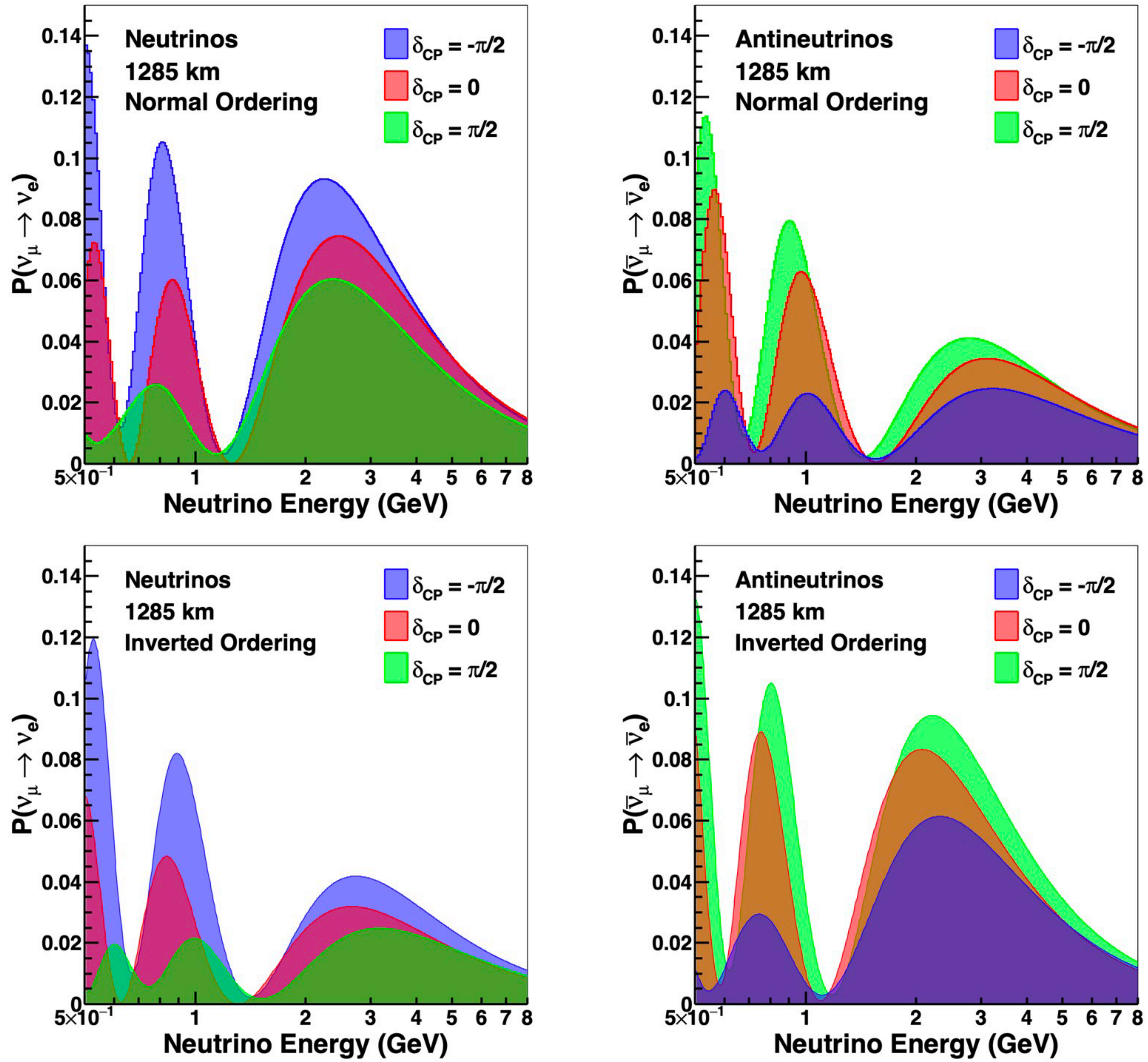
* On axis, wide band beam



* Dedicated near detector complex



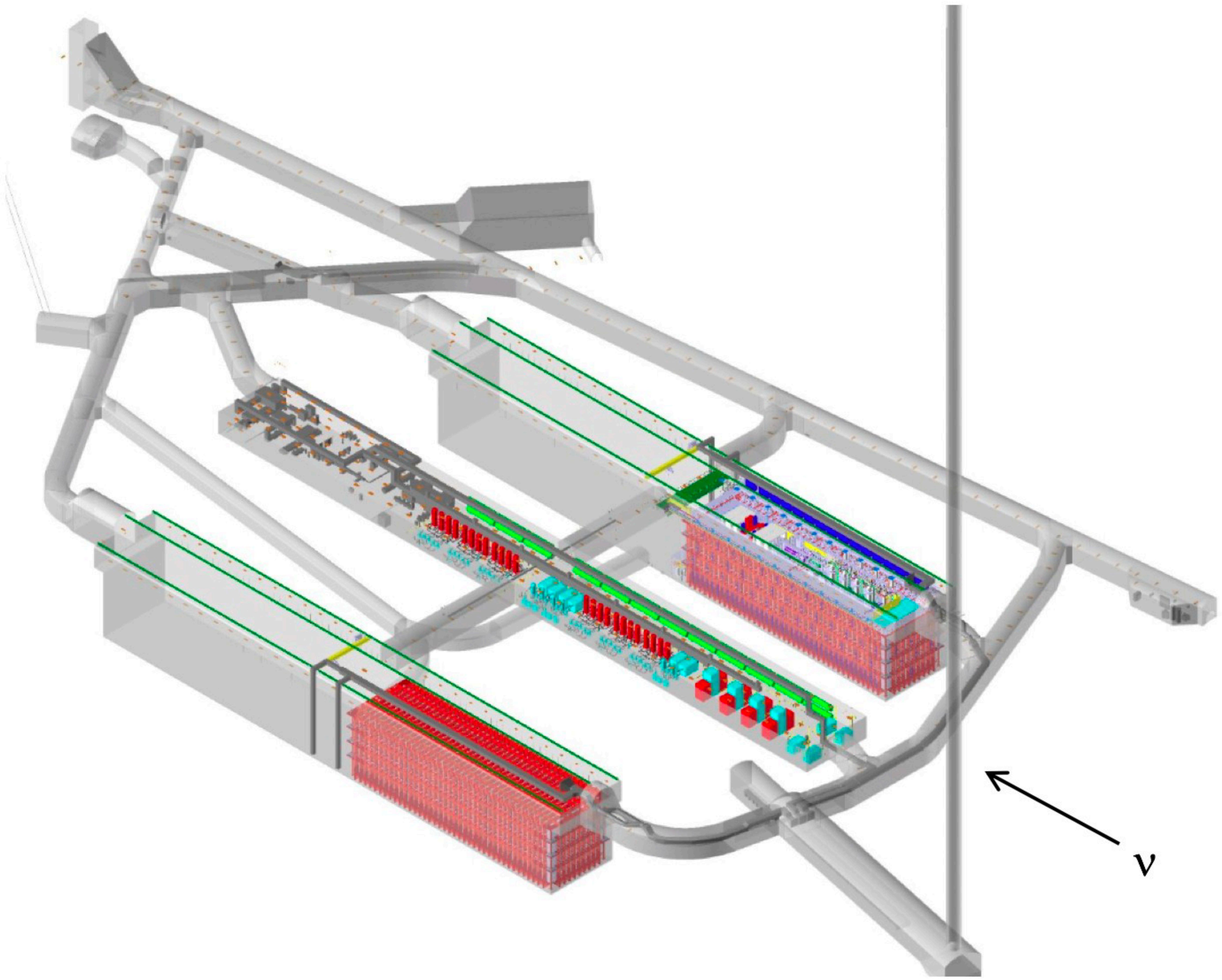
DUNE's Role in the 3F Paradigm



- Large matter effect from the long baseline (1300 km)
  - Mass ordering and CP violation are totally non-degenerate.
  - DUNE measures oscillations over more than a full period, which helps resolve degeneracies.
- This is unique to DUNE, and complementary to other experiments with narrow flux spectra.

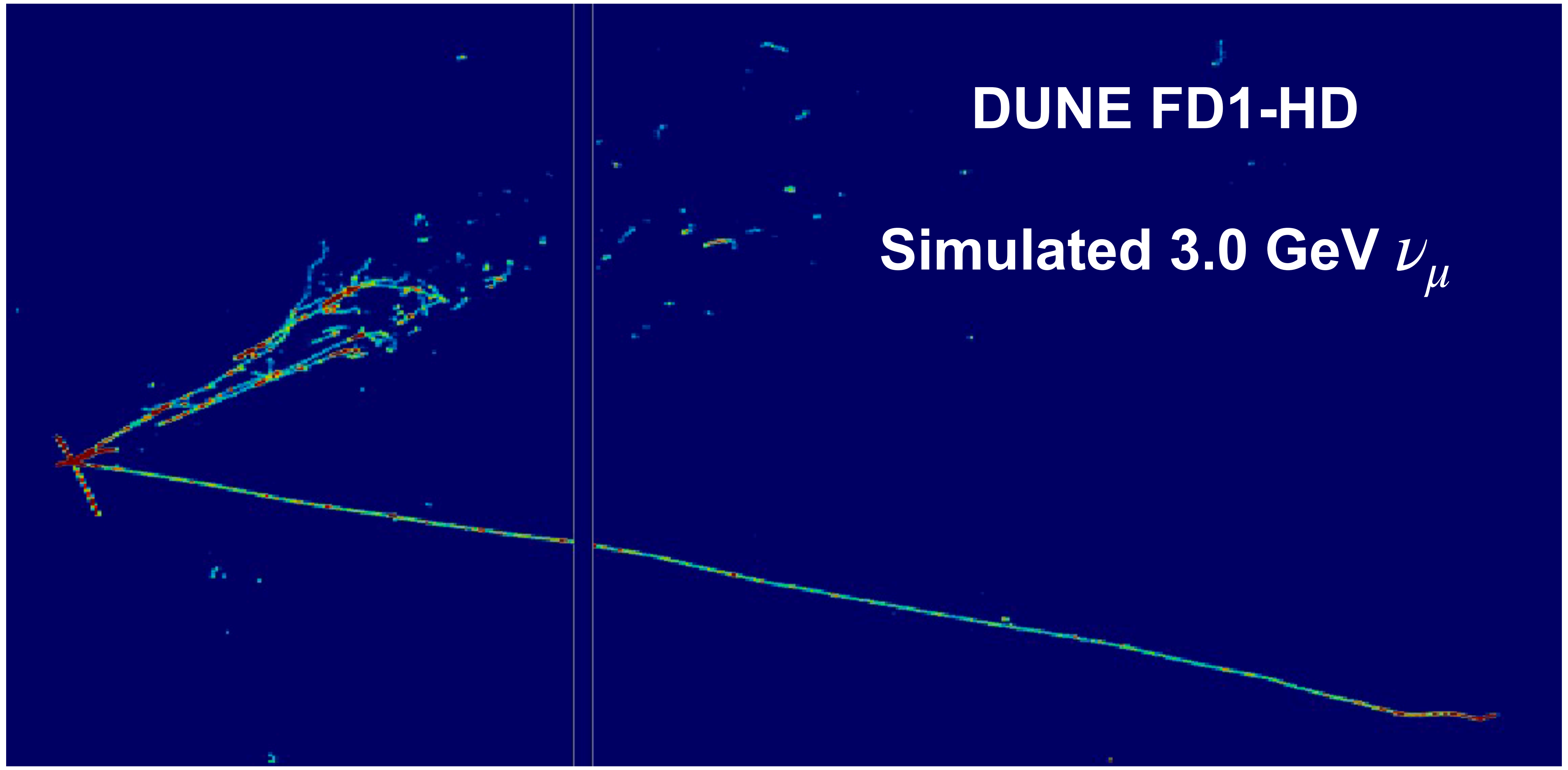
DUNE's Role in the 3F Paradigm

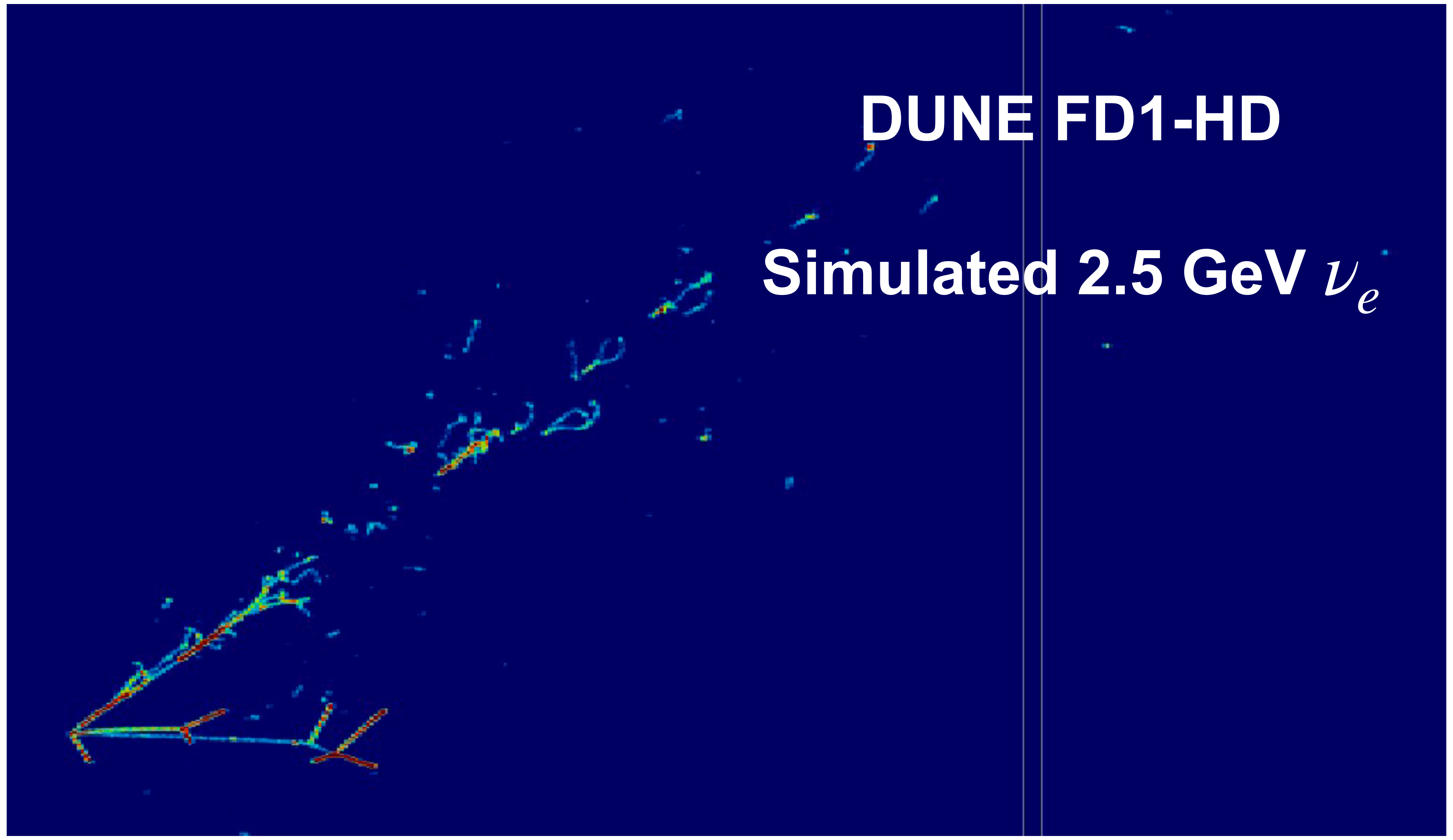
Four 17 ktons Liquid Argon Time Projection Chamber far detectors, 1490 m underground



- Four detectors
  - Each of them have a different design
- Phase I
  - First two detectors will start operation around 2028
  - Both of them are liquid argon TPCs
    - FD1 - Horizontal Drift LArTPC
    - FD2 - Vertical Drift LArTPC
- Other two detectors are to be determined for Phase II

Liquid Argon TPC

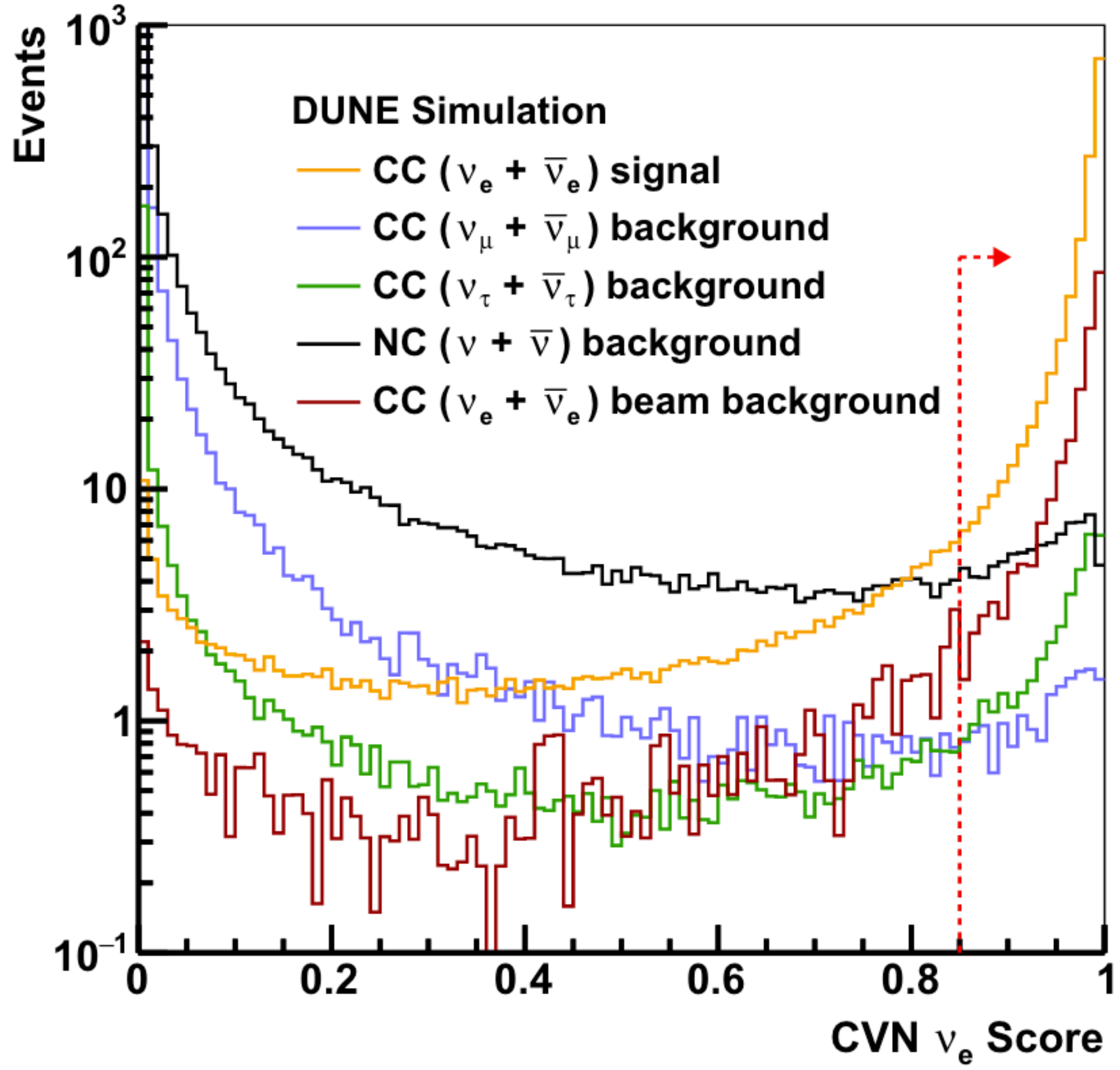


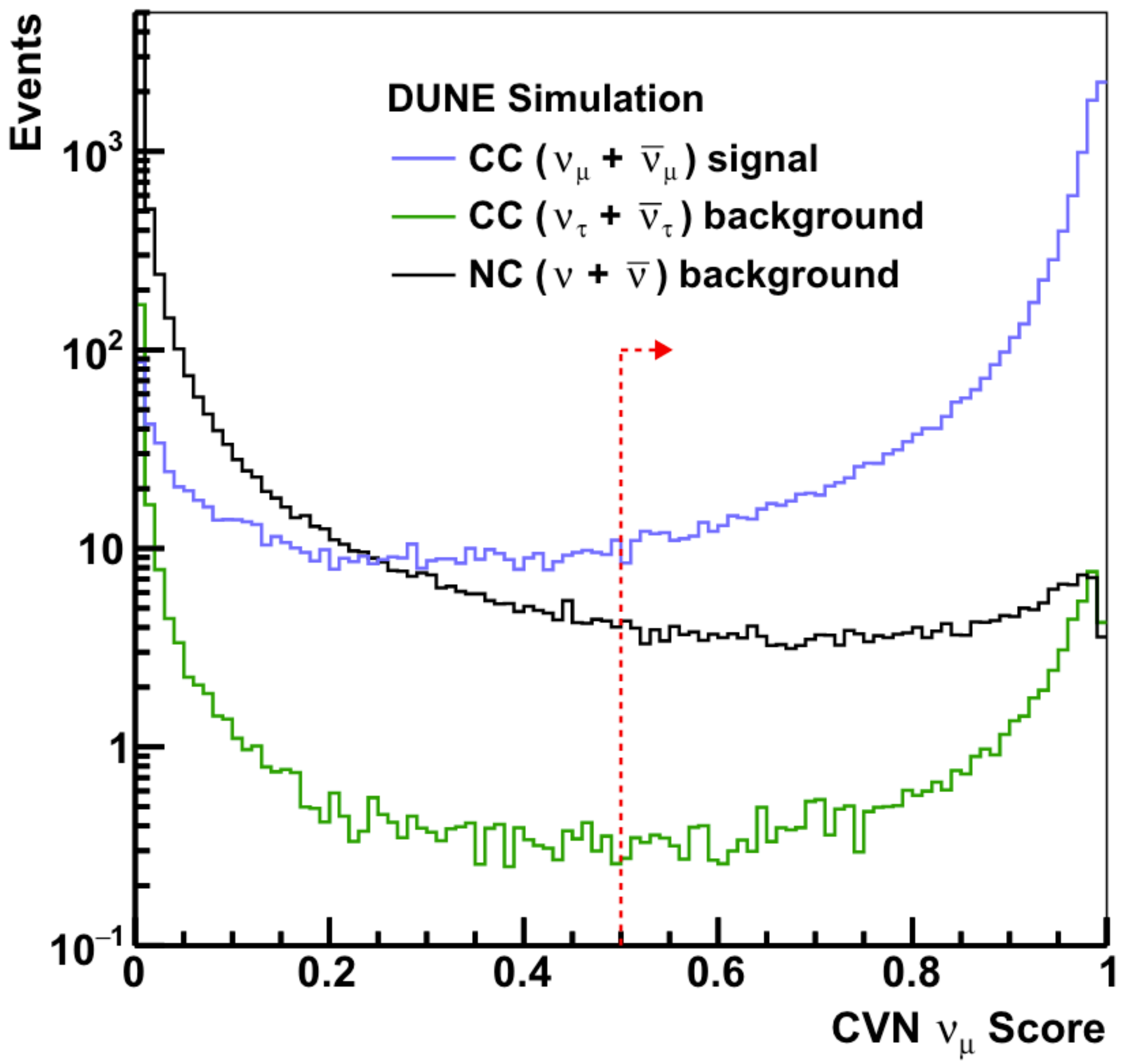


- LArTPC provides precise 3D spatial location of energy deposition for particle ID
  - Clean separation of ν_μ and ν_e CC events
- LArTPC also provides good neutrino energy reconstruction over a broad energy range, benefits from its low thresholds for charged particles

Event Selection

- Event classification is carried out through image recognition techniques using a convolutional neural network, named convolutional visual network (CVN)
  - Build upon the three readout views of the LArTPC, using the reconstructed hits on individual planes

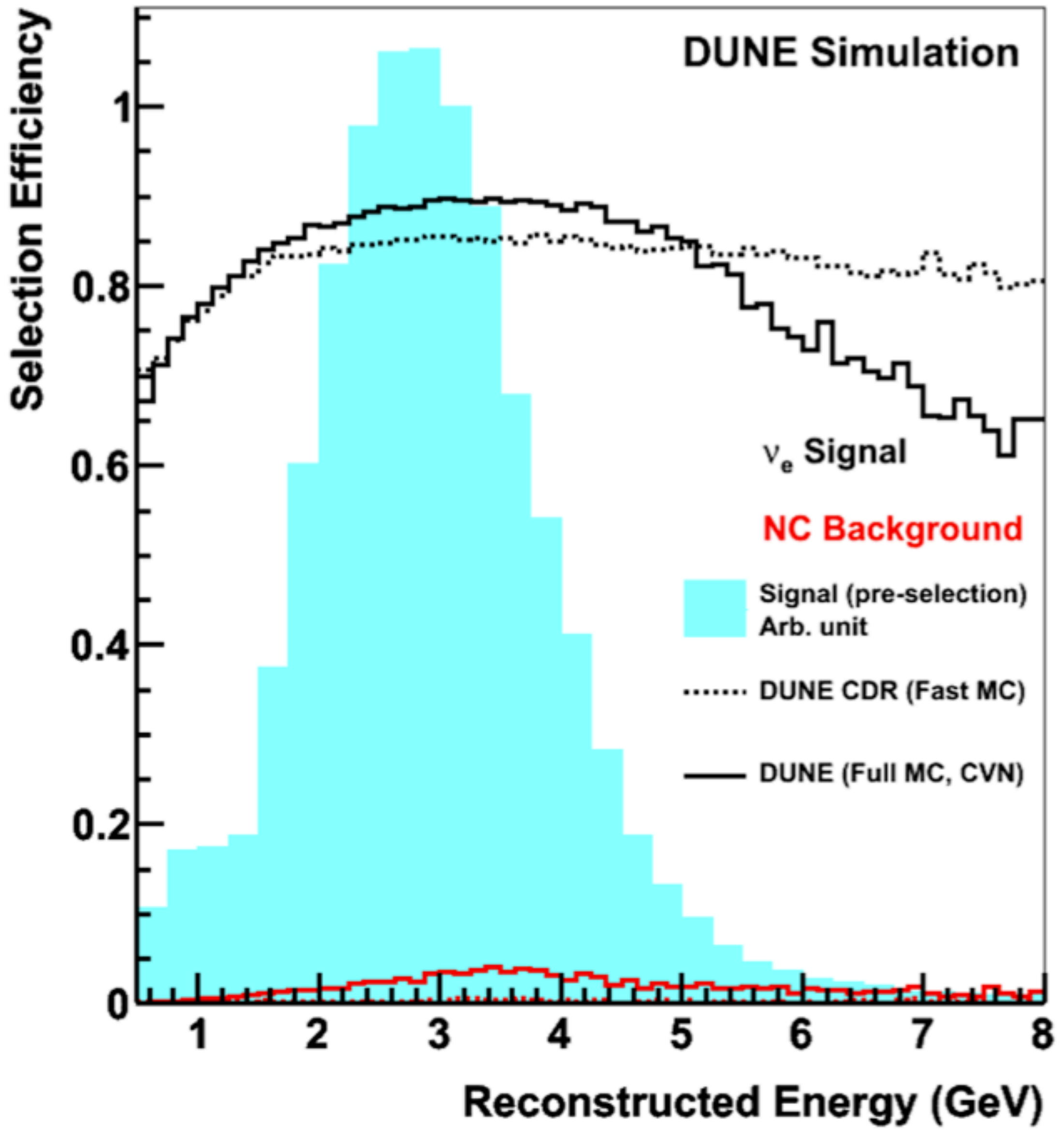




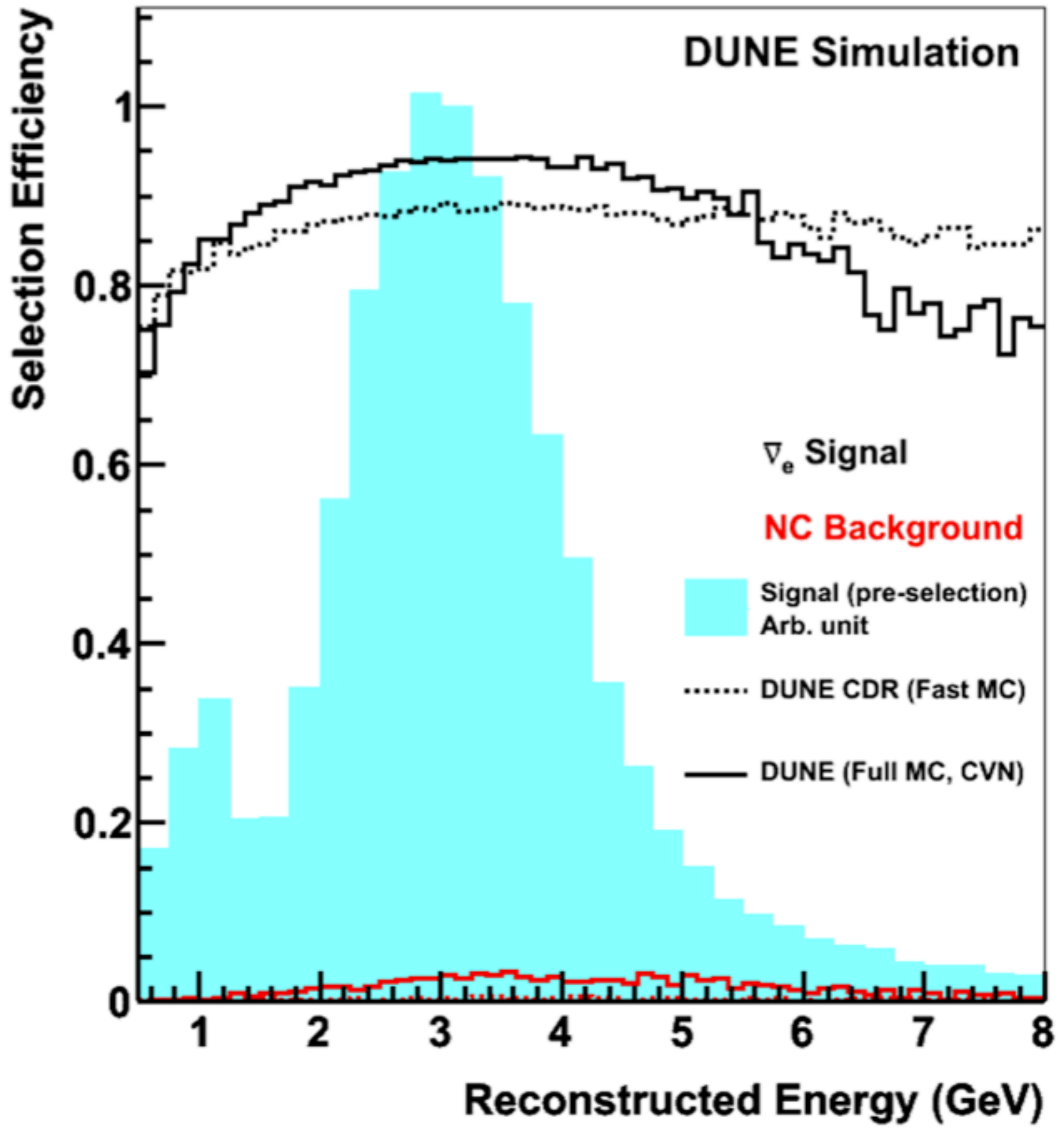
Event Selection

- The primary goal of the CVN is to efficiently and accurately produce event selection of ν_e CC and ν_μ CC in FHC, $\bar{\nu}_e$ CC and $\bar{\nu}_\mu$ CC in RHC
- The ν_e and ν_μ efficiencies in both FHC and RHC beam modes all exceed 90% in the neutrino flux peak

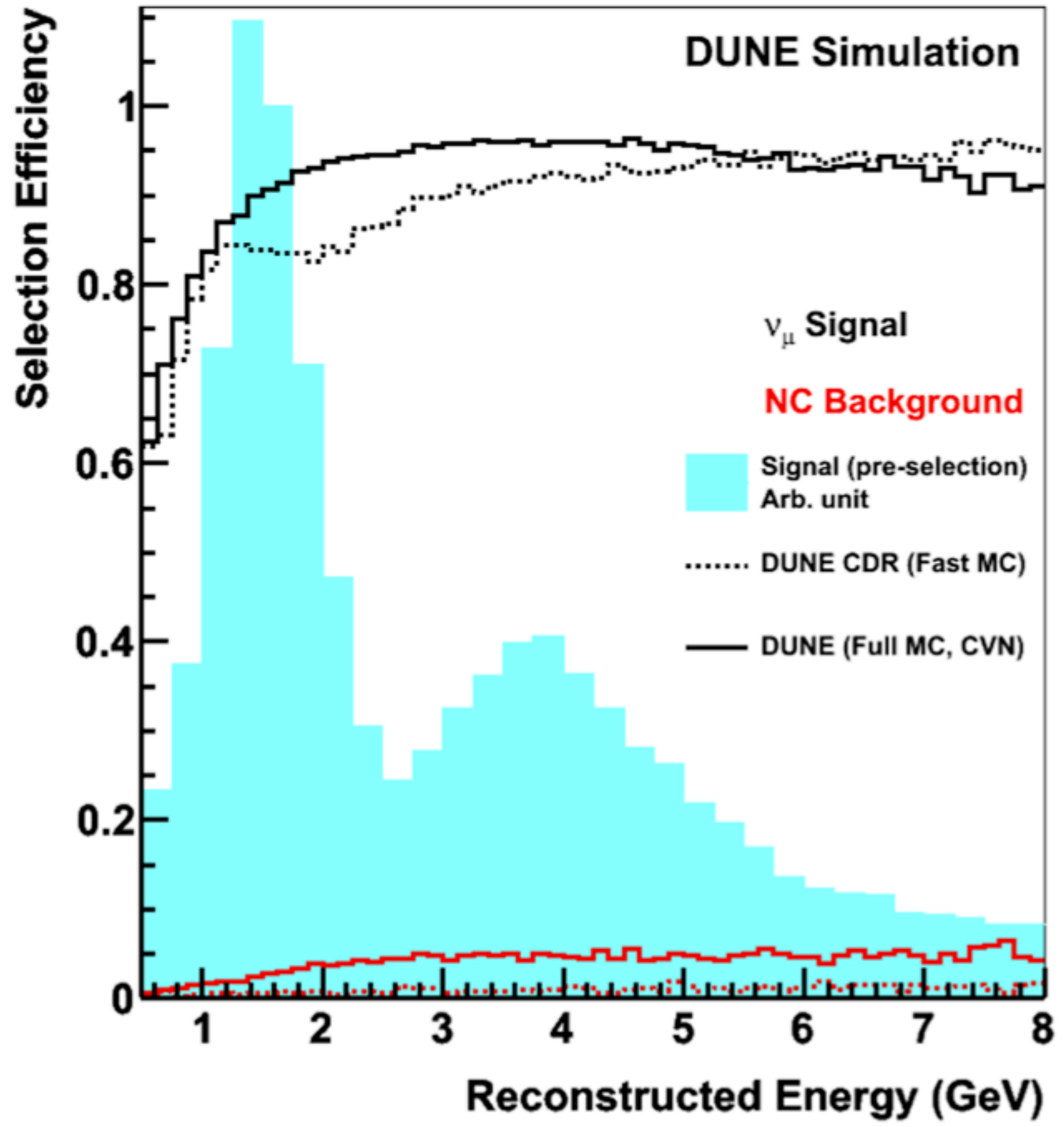
ν_e CC FHC



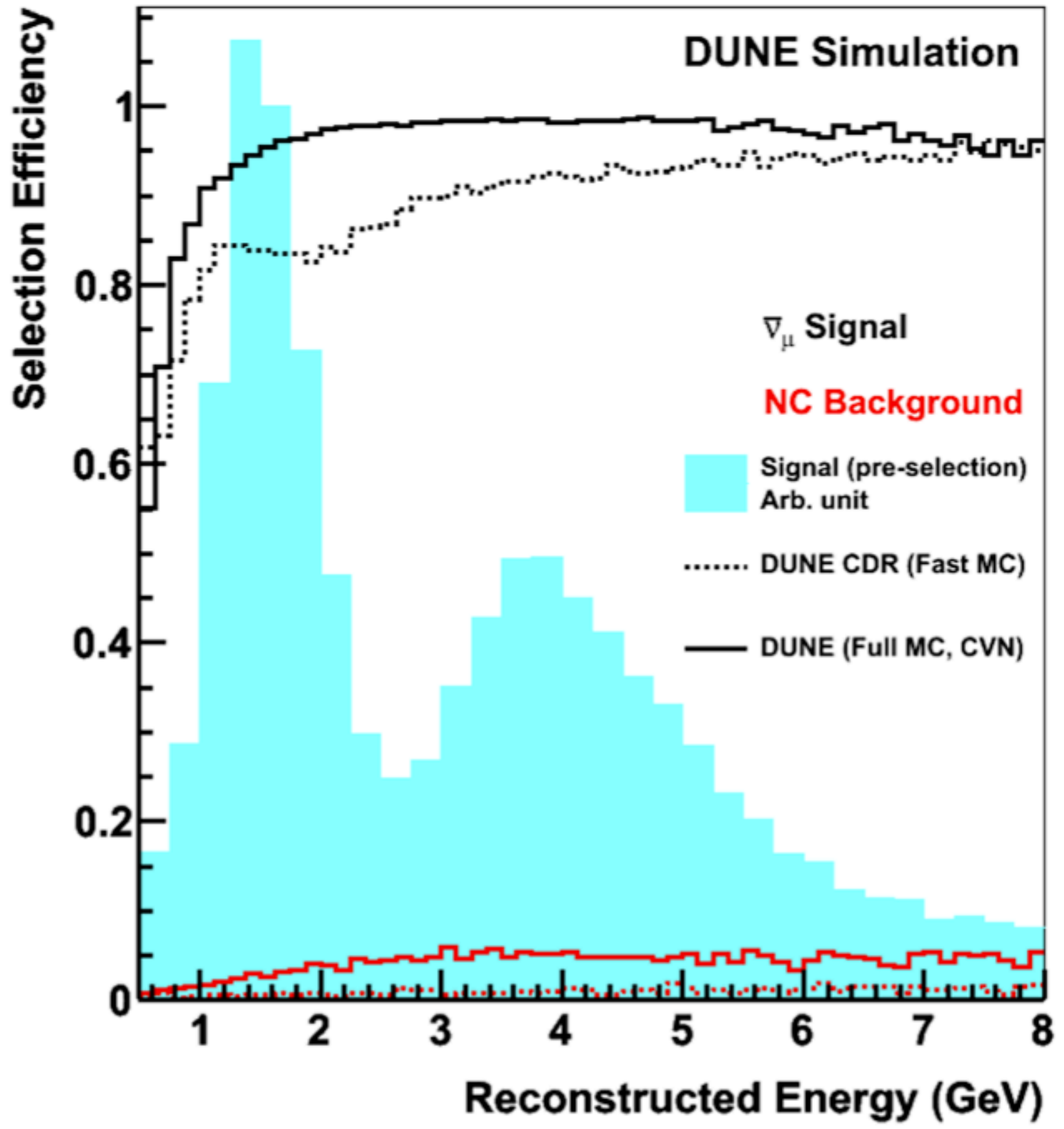
$\bar{\nu}_e$ CC RHC



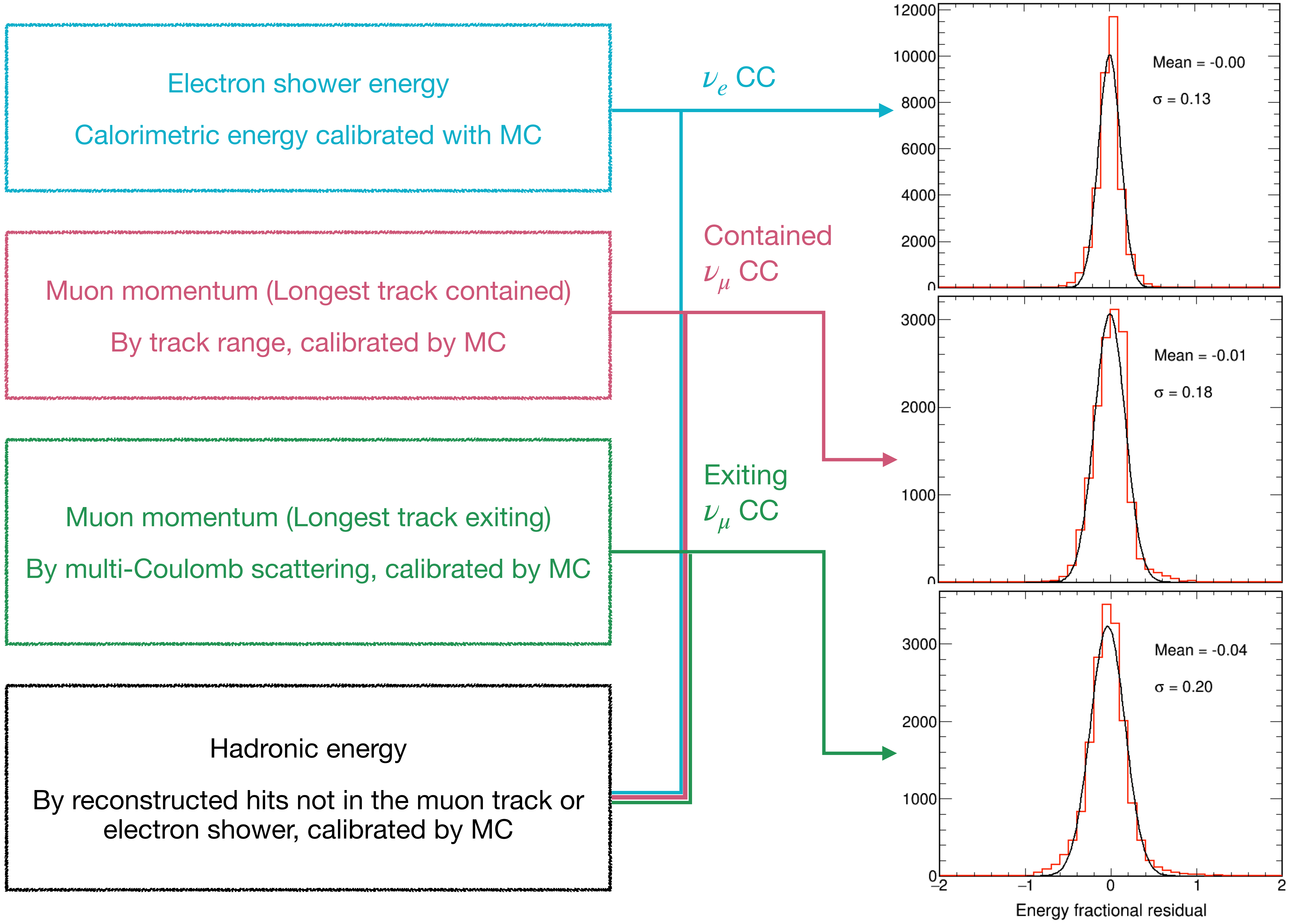
ν_μ CC FHC



$\bar{\nu}_\mu$ CC RHC



Energy resolution



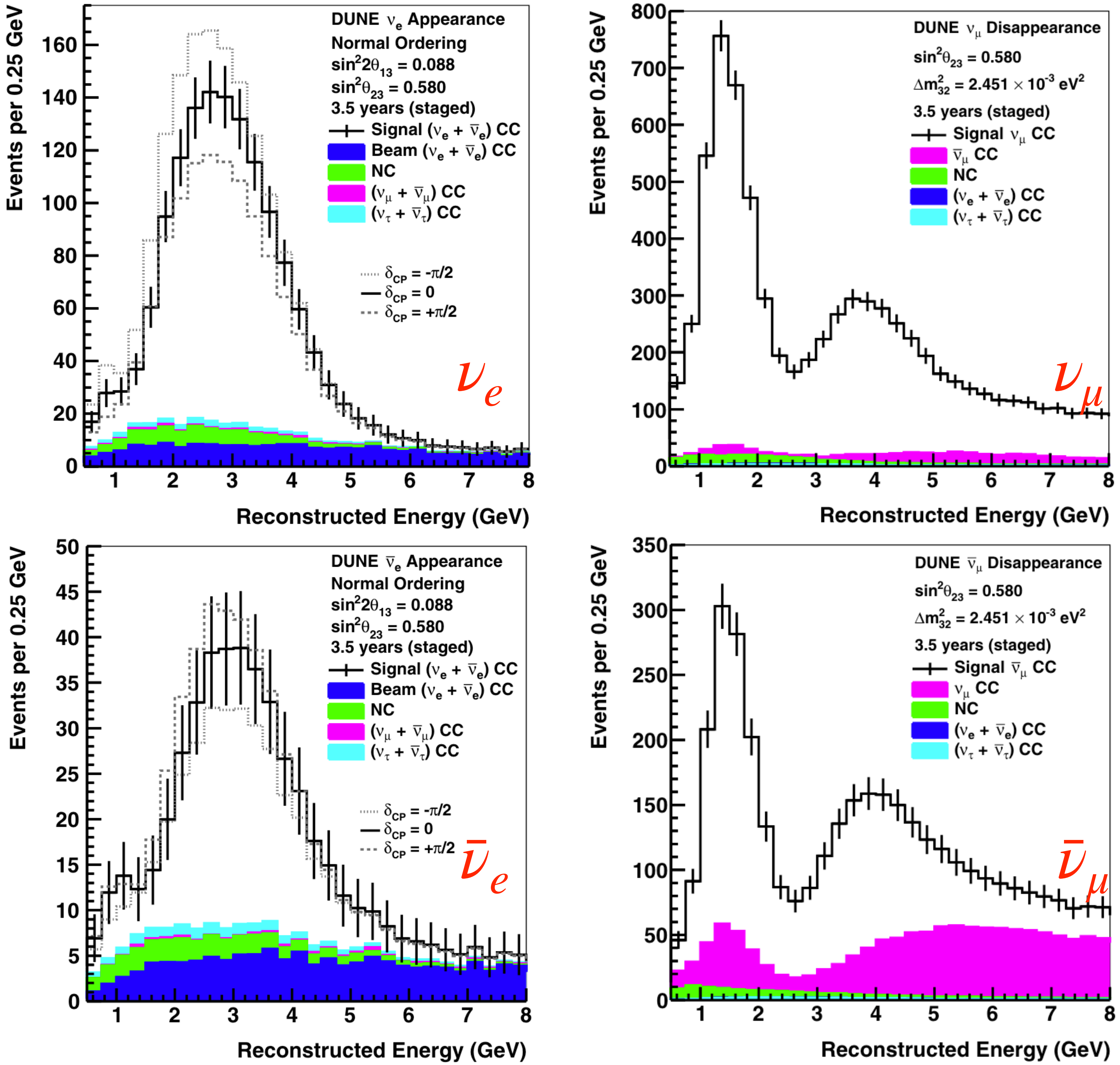
$$E_\nu = E_{\mathrm{lep}}^{\mathrm{cor}} + E_{\mathrm{had}}^{\mathrm{cor}}$$

- ν_e CC energy: sum of the energy of the reconstructed EM shower with the highest energy and the hadronic energy
- ν_μ CC energy: sum of the energy of the longest reconstructed track and the hadronic energy
- 15-20% energy resolution in the range of 0.5-4 GeV that is the most relevant for oscillation measurements

FD Data Samples

FHC - ν

RHC - $\bar{\nu}$



- Oscillation sensitivities are obtained by simultaneously fitting the disappearance and appearance spectra
  - $\nu_\mu \to \nu_\mu, \nu_\mu \to \nu_e,$ $\bar{\nu}_\mu \to \bar{\nu}_\mu, \bar{\nu}_\mu \to \bar{\nu}_e$
  - ND sample is incorporated in order to constrain flux and xsec uncertainties

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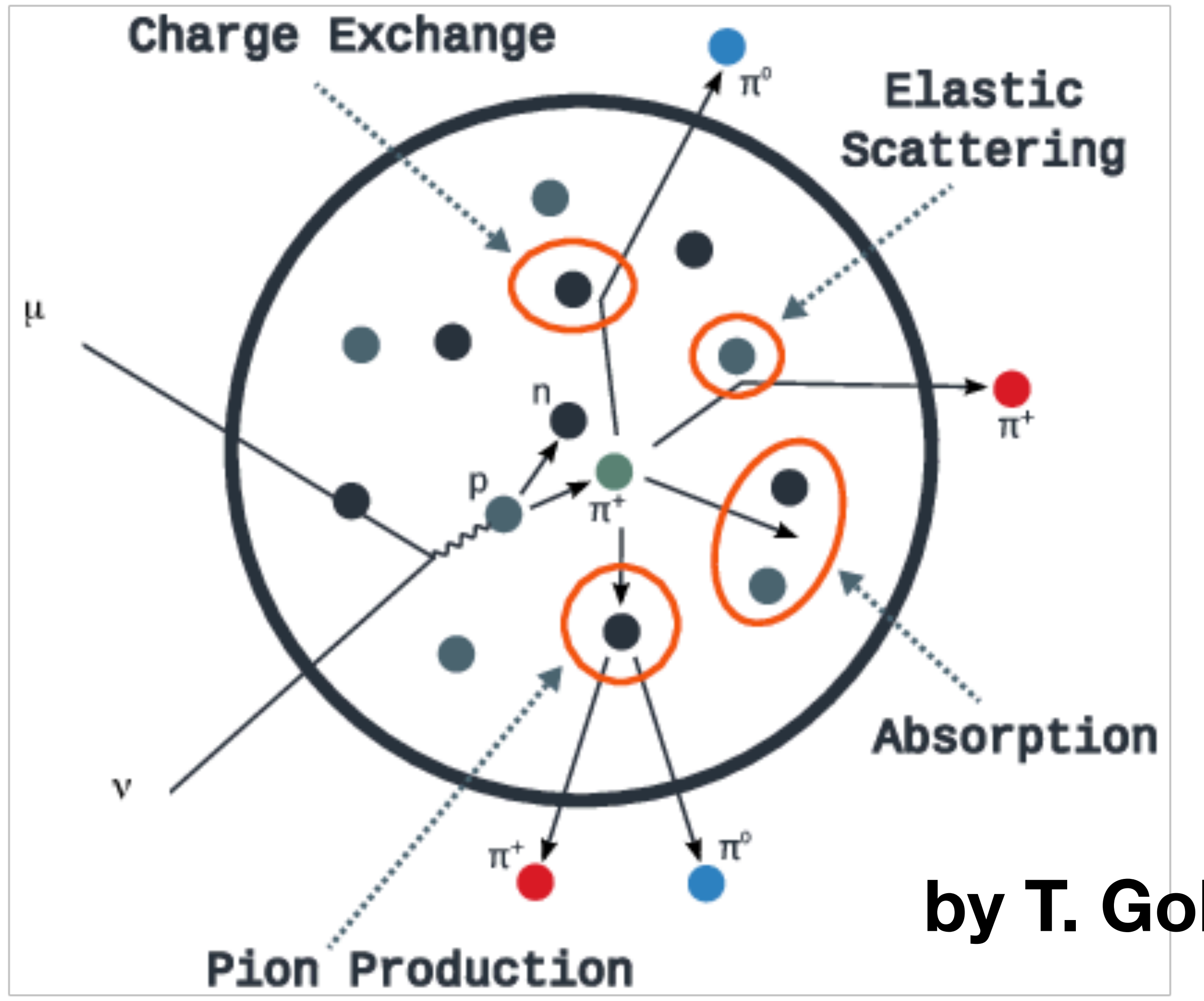
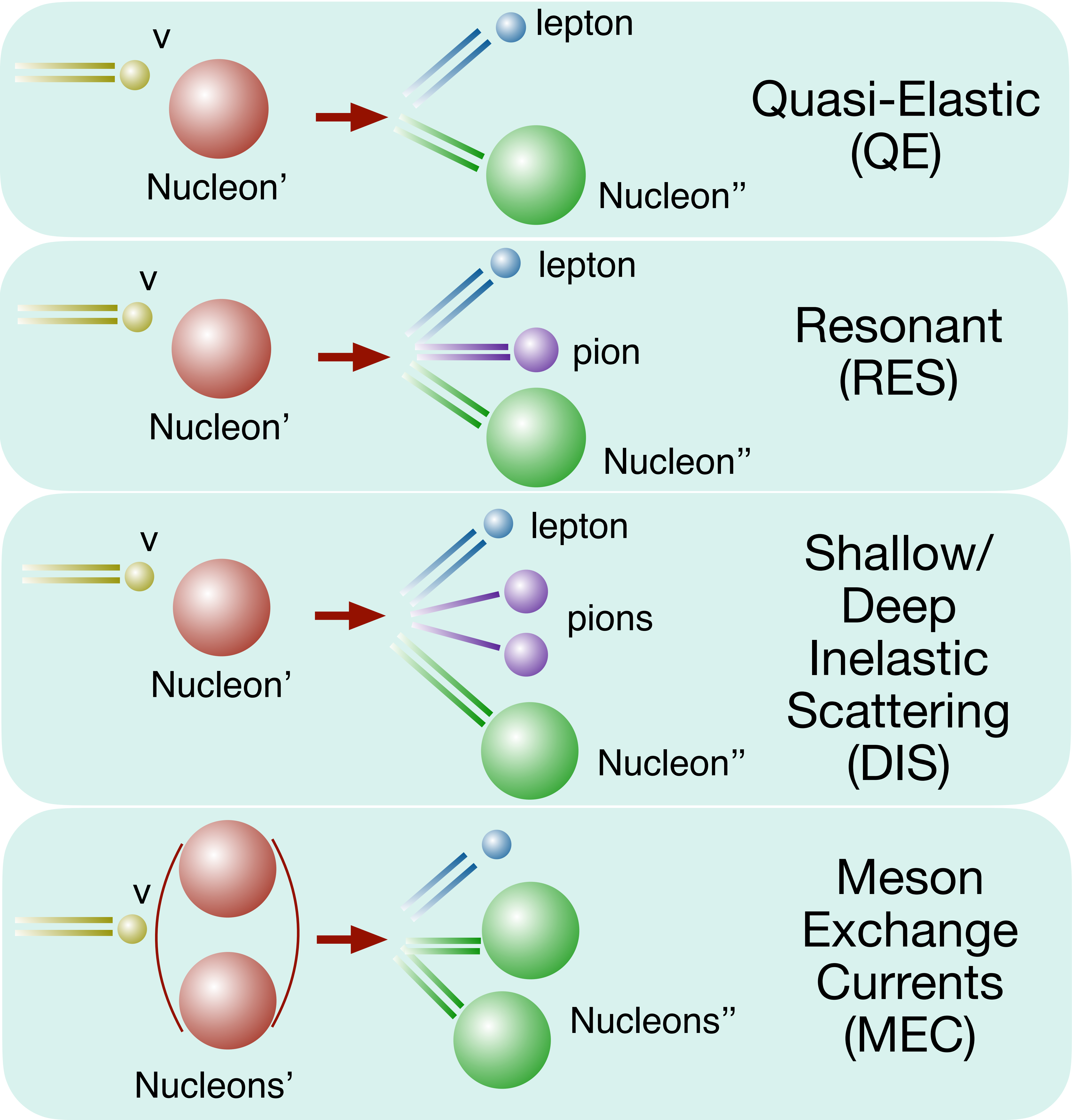
Neutrino Interactions

- Interactions at the ~GeV scale remain an active area of study.
  - Several types of interactions can occur.
  - All of which take place in a complex nuclear environment that impacts both initial conditions and what is observed in the final state.

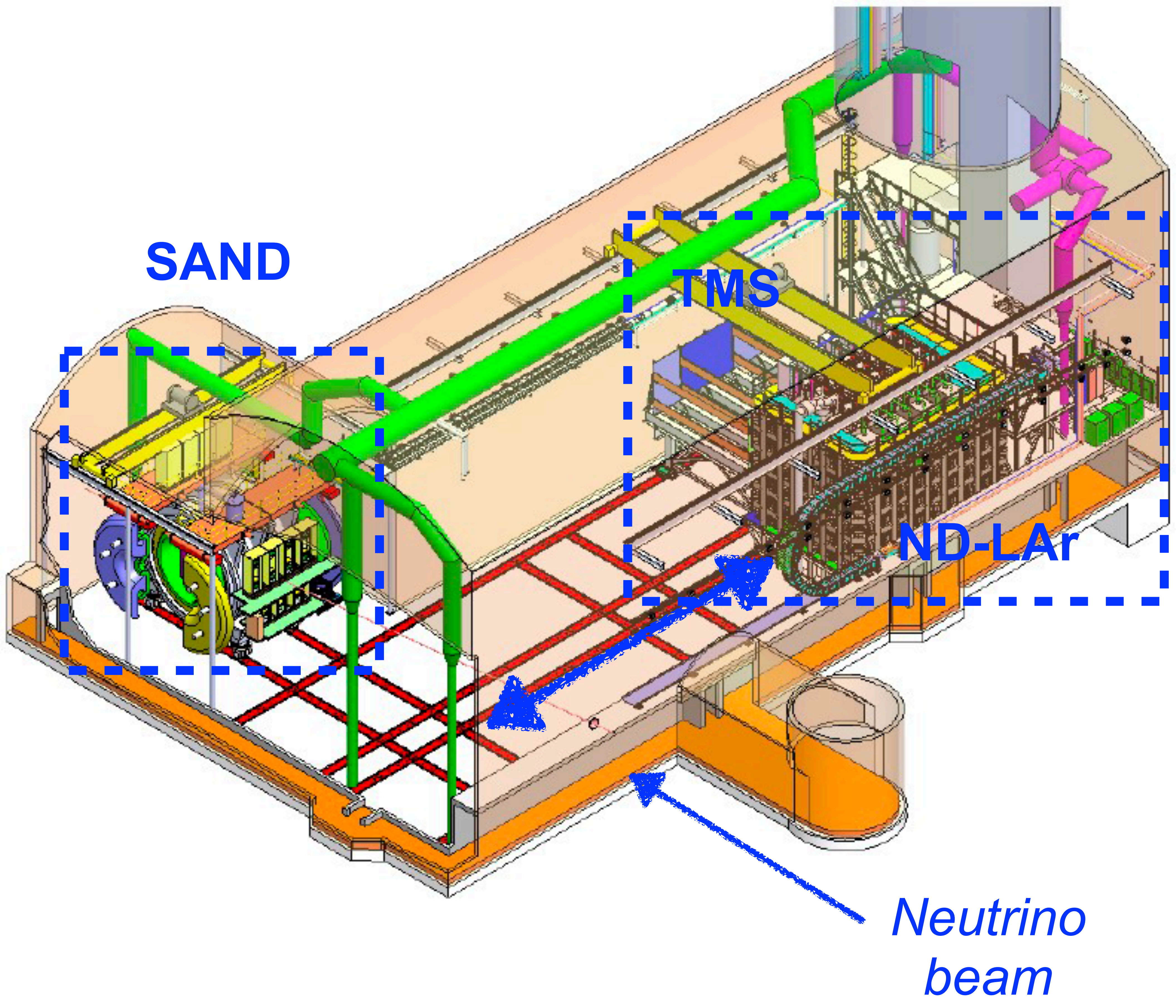


by T. Golan



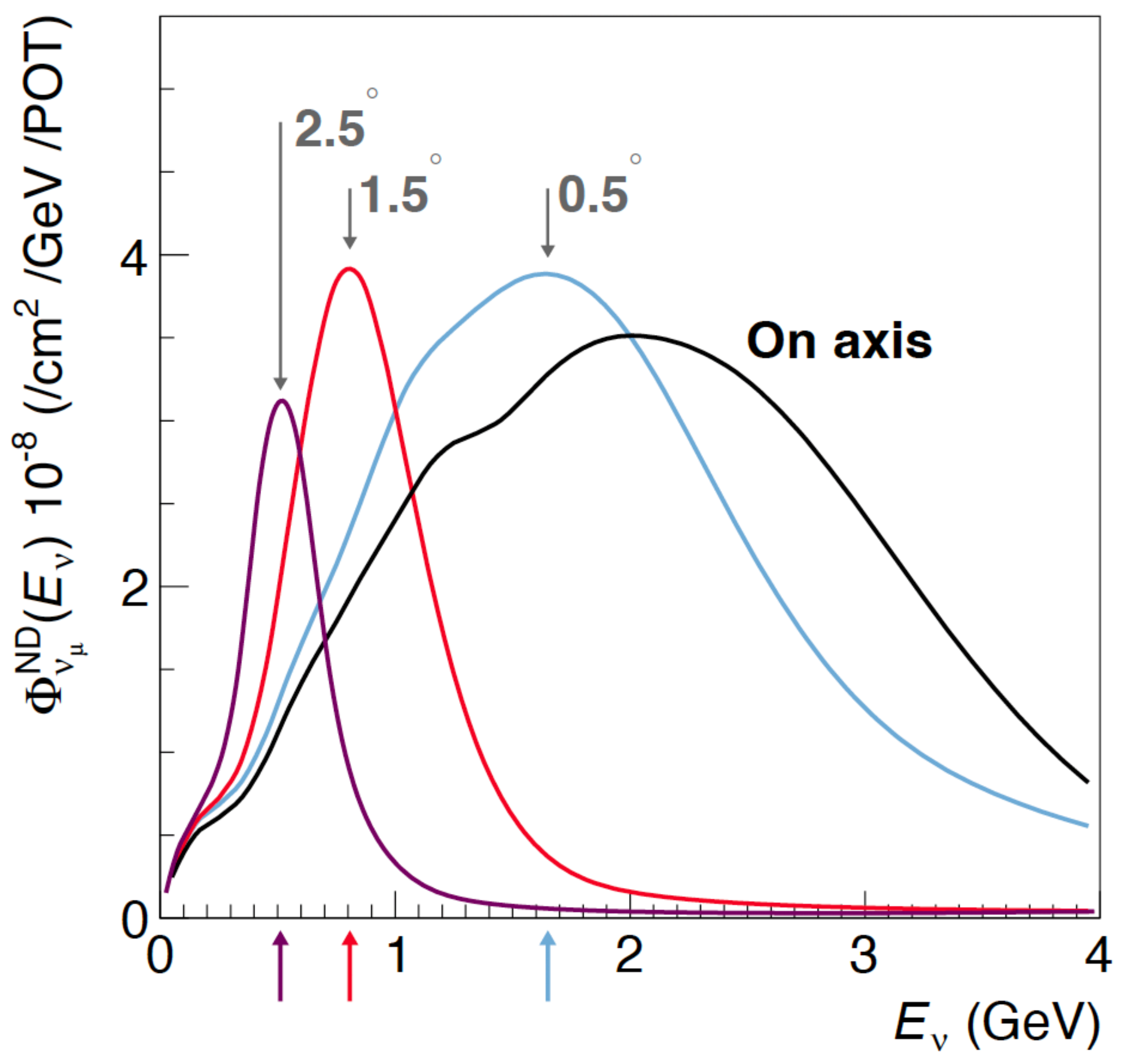
DUNE Near Detector Complex

- Large uncertainties on flux, cross sections, and detector response are constrained to the few percent level by the suite of detectors in ND
- ND-LAr+TMS: measure neutrino interactions on the same Ar target, with same detector technology as FD
  - System moves up to 30 m off axis
- SAND: on-axis detector measures neutrino interactions on various targets and monitors beam stability



DUNE-PRISM

DUNE ND CDR, arXiv:2103.13910



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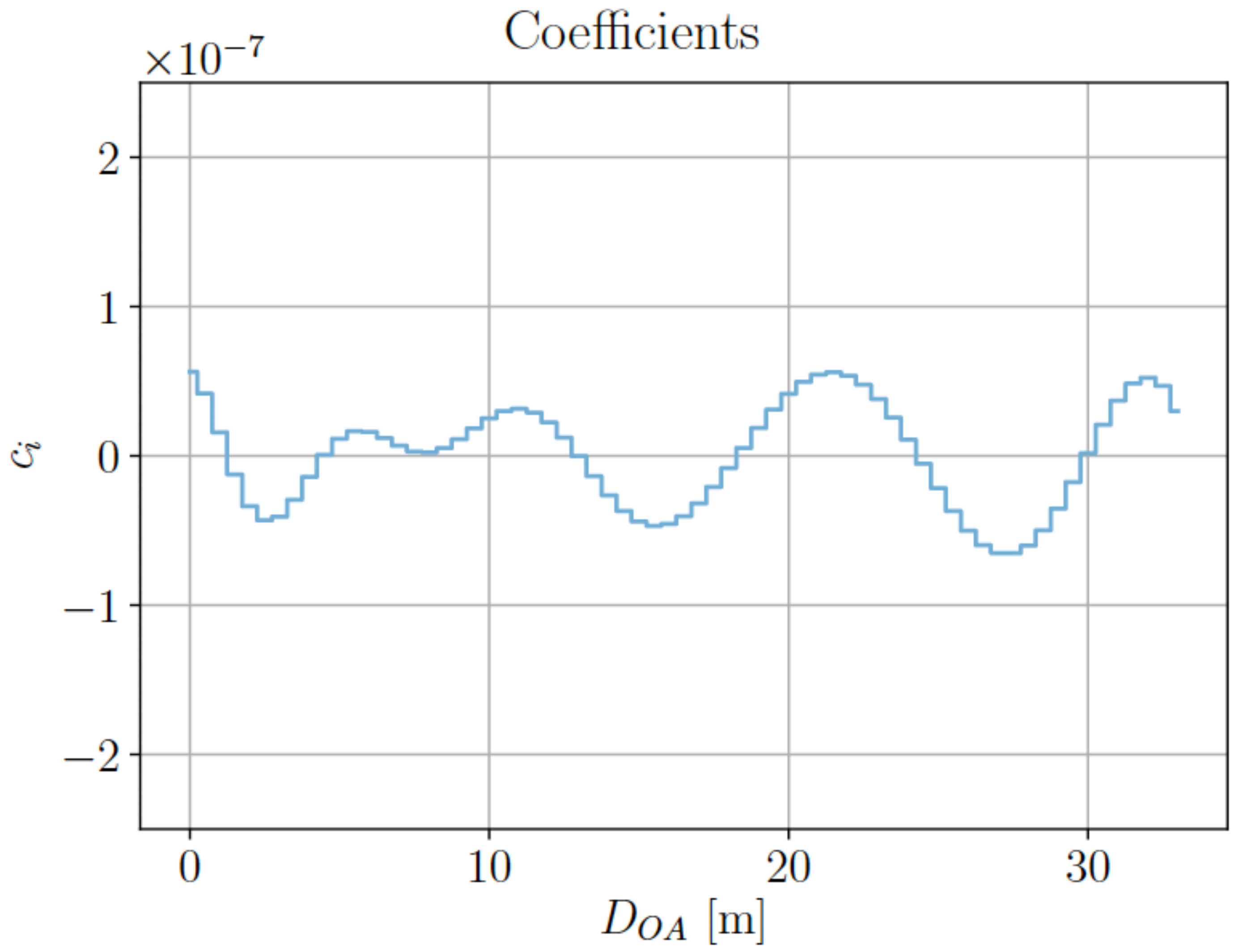

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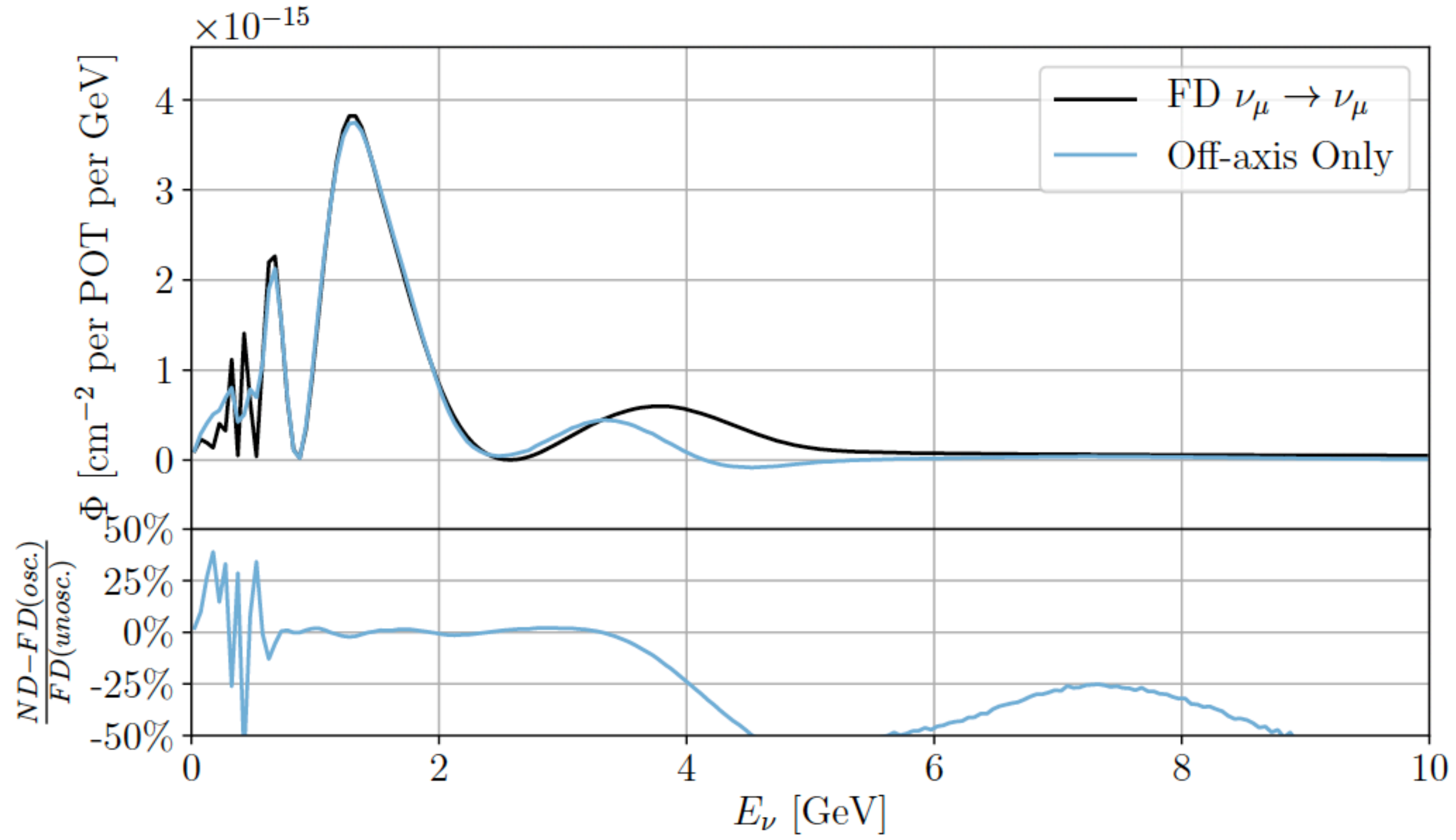
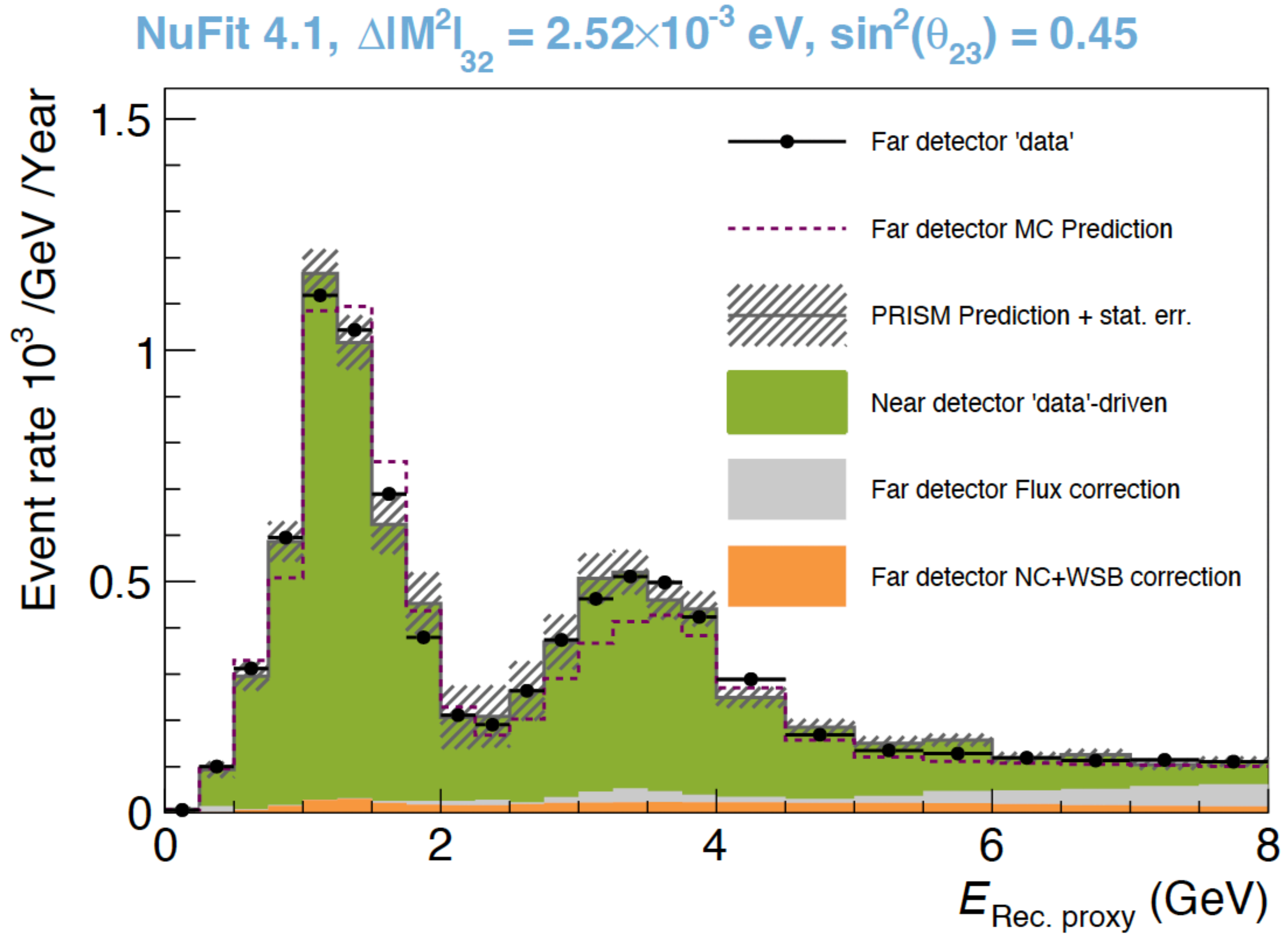
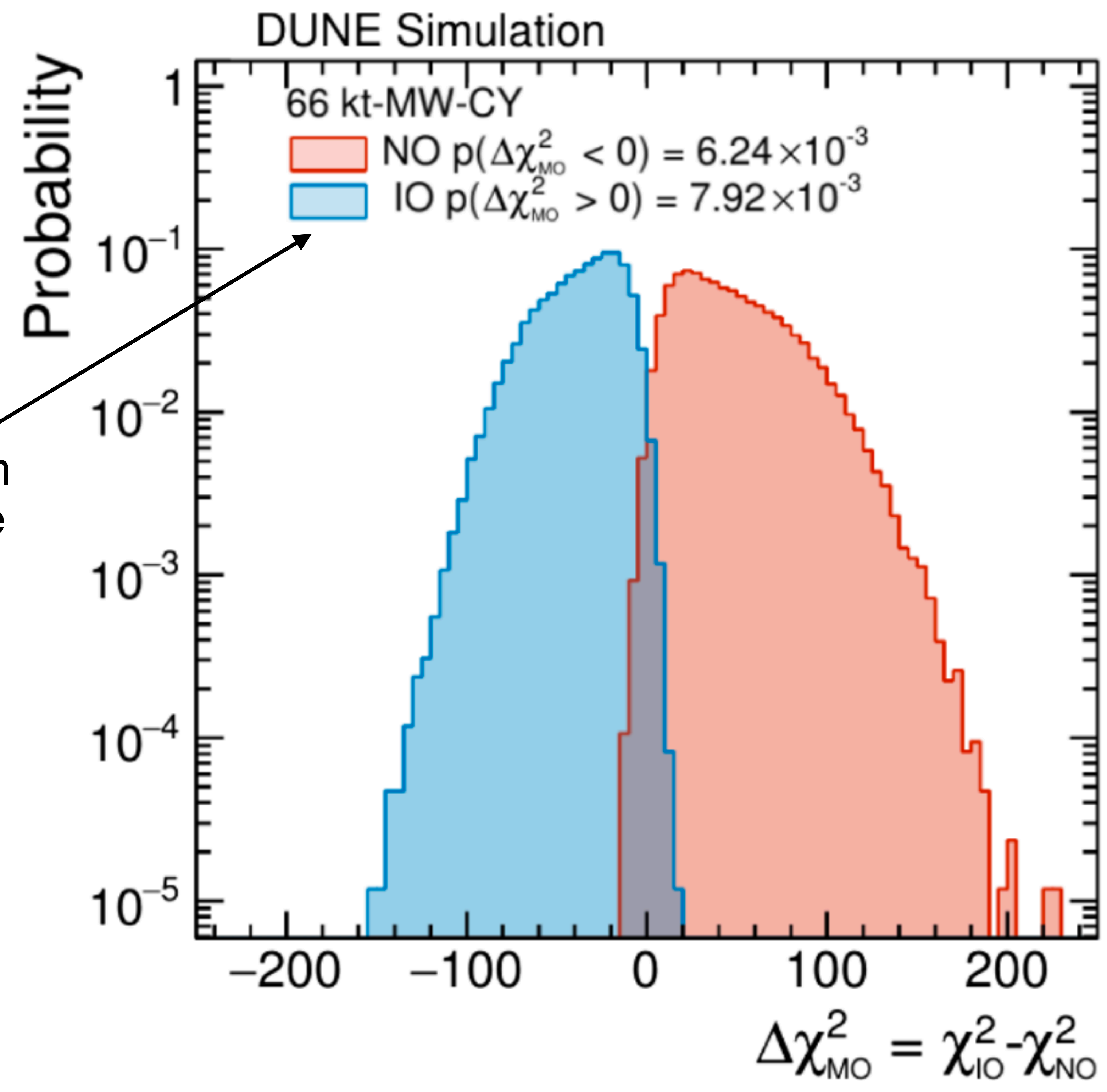


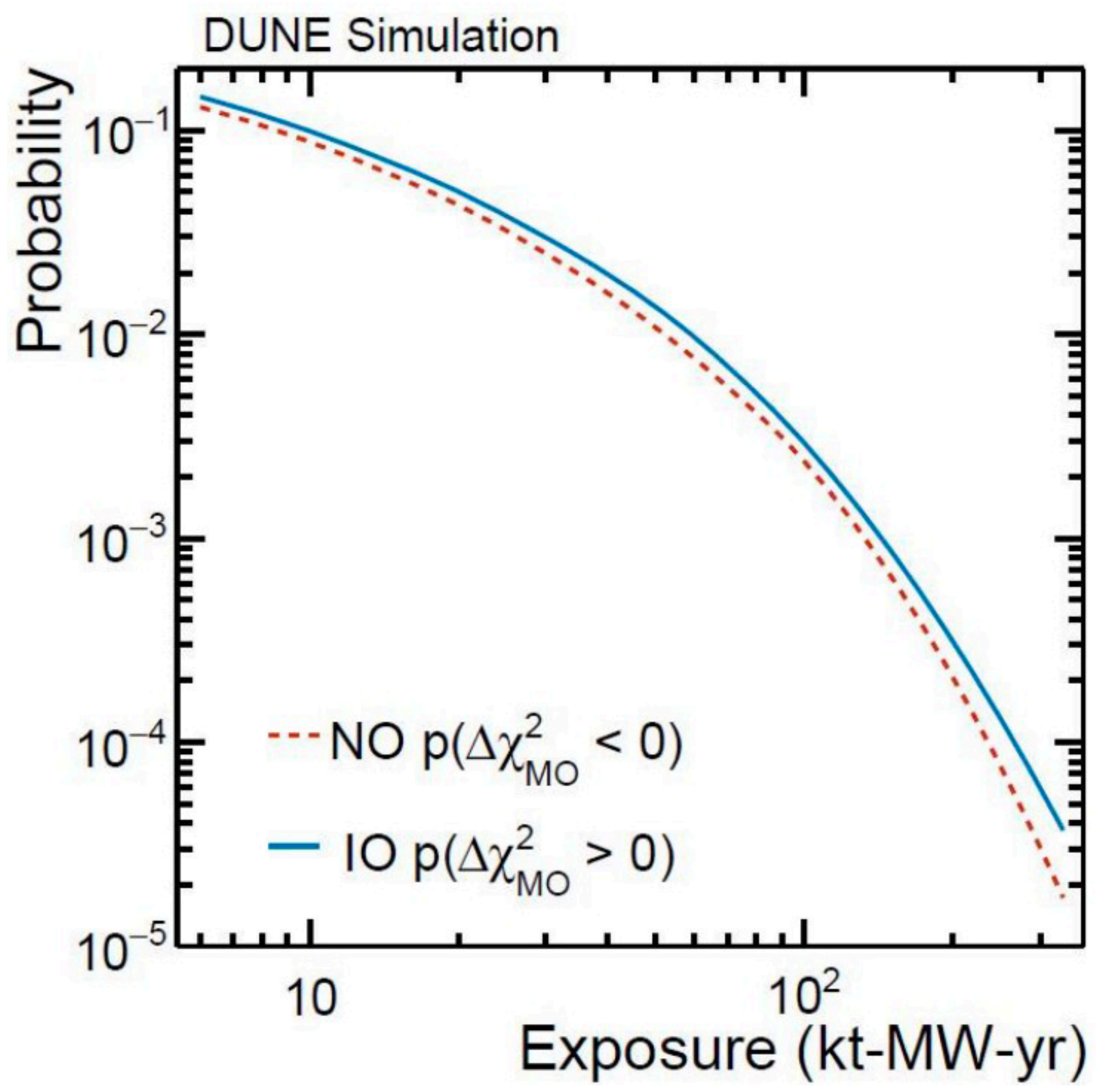
- PRISM: Precision Reaction-Independent Spectrum Measurement
- Use off-axis data to uncover interaction modeling problems that might induce an unexpected bias in the extracted oscillation parameters
- GENIE-based FD prediction is a poor predictor for the FD data, where as the linear combination of ND data correctly predicts the FD spectrum



Mass Ordering: Definitive Resolution

The probability of random toys appear more like the incorrect ordering

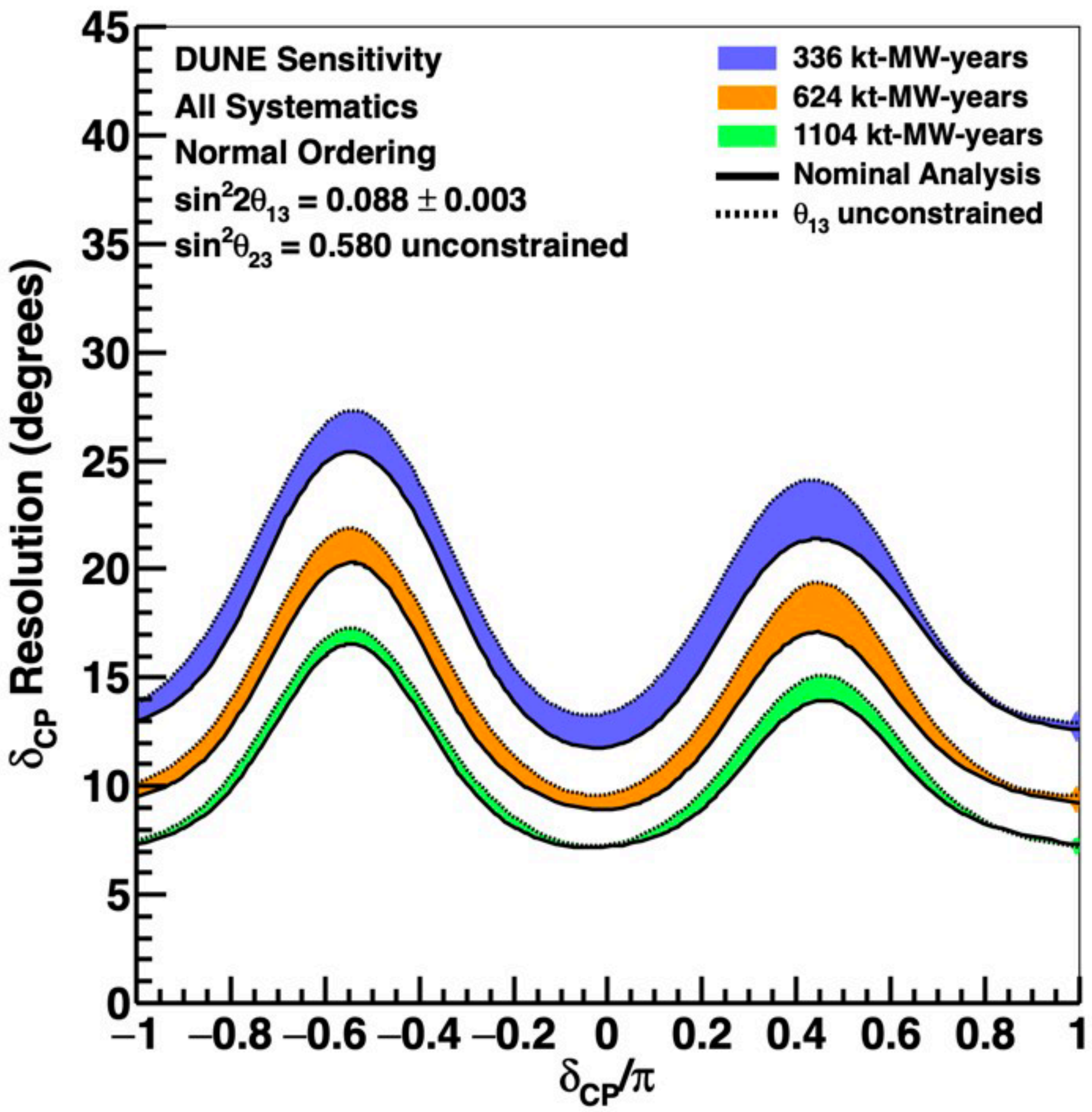


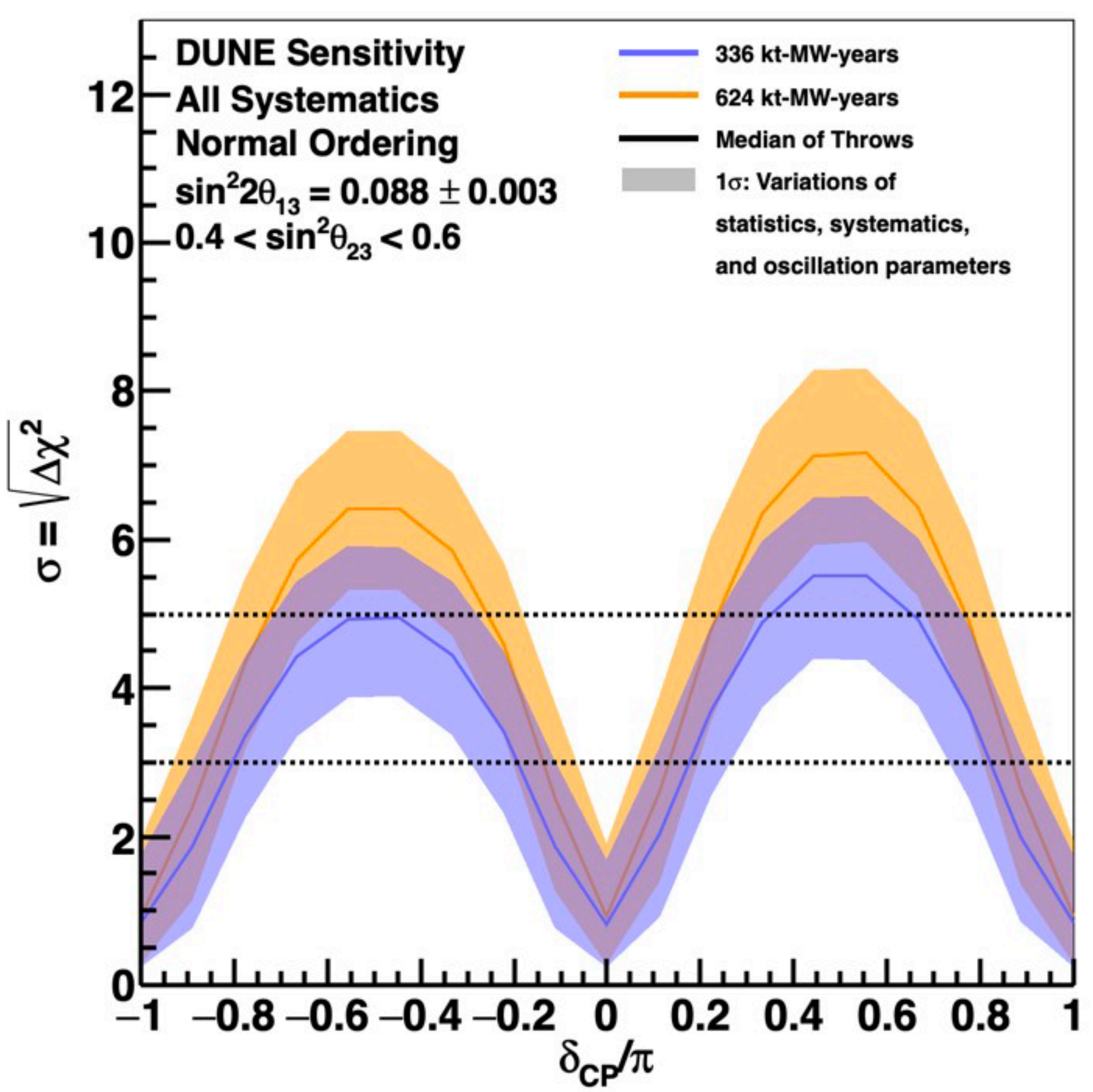


PhysRevD.105.072006

- DUNE is sensitive to the mass ordering from very low exposures: ~97% correct after ~1-2 years
- Long term → >10σ for any parameter combination

CP Violation: δ resolution 6-16°

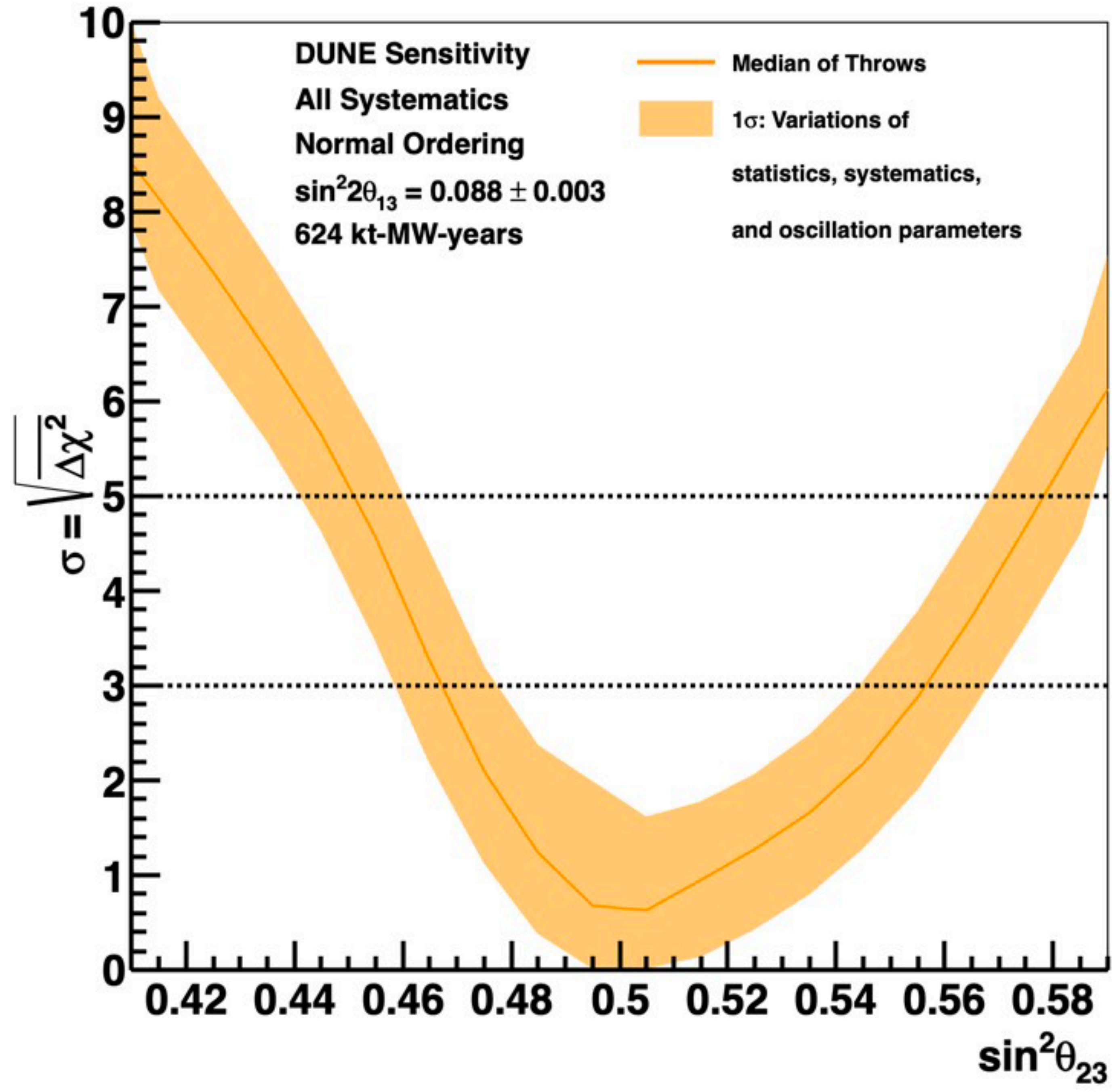


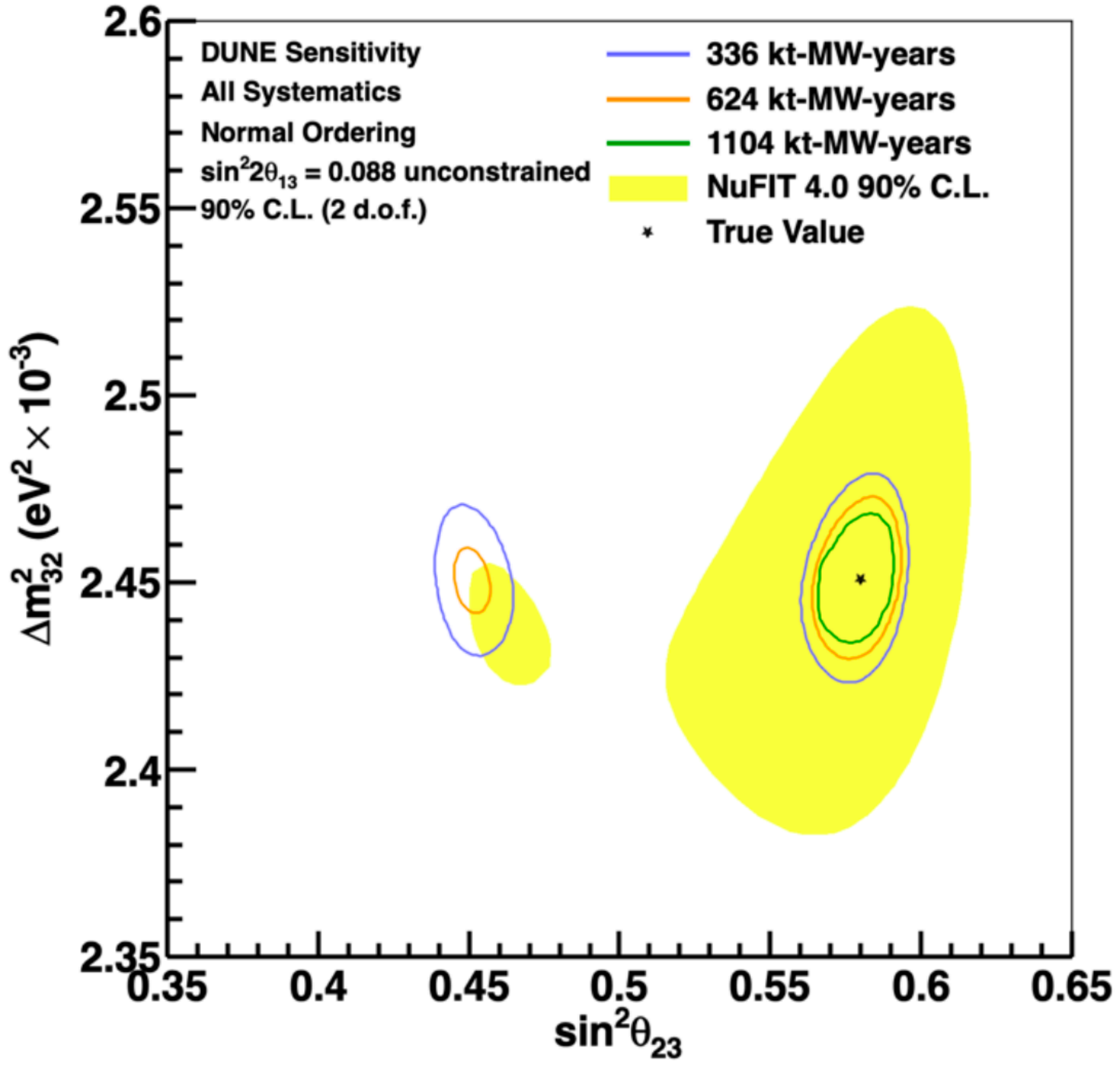


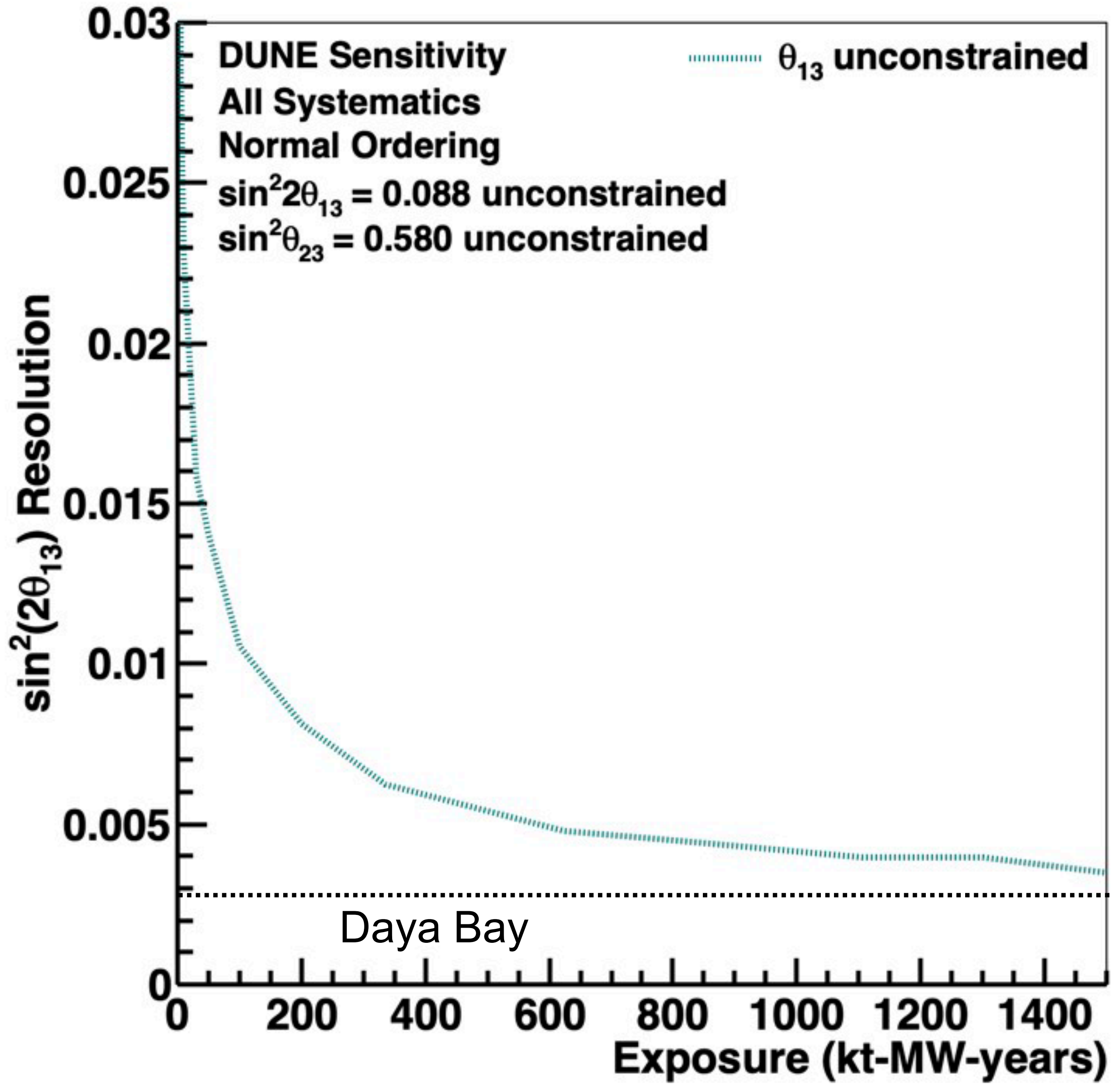
PhysRevD.105.072006
Snowmass: "DUNE Physics Summary", arXiv:2203.06100

- Phase II: > 5σ discovery potential for > 50% of δ_{CP} values
- 6-16° resolution to δ_{CP} without dependence on other experiments, discovery sensitivity to CP violation over a broad range of possible values

Precision Measurements







Eur. Phys. J. C ***80***, *978 (2020)*

- Excellent on Δm^2_{32} and θ_{23}, including octant discovery potential
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor directly tests PMNS unitarity

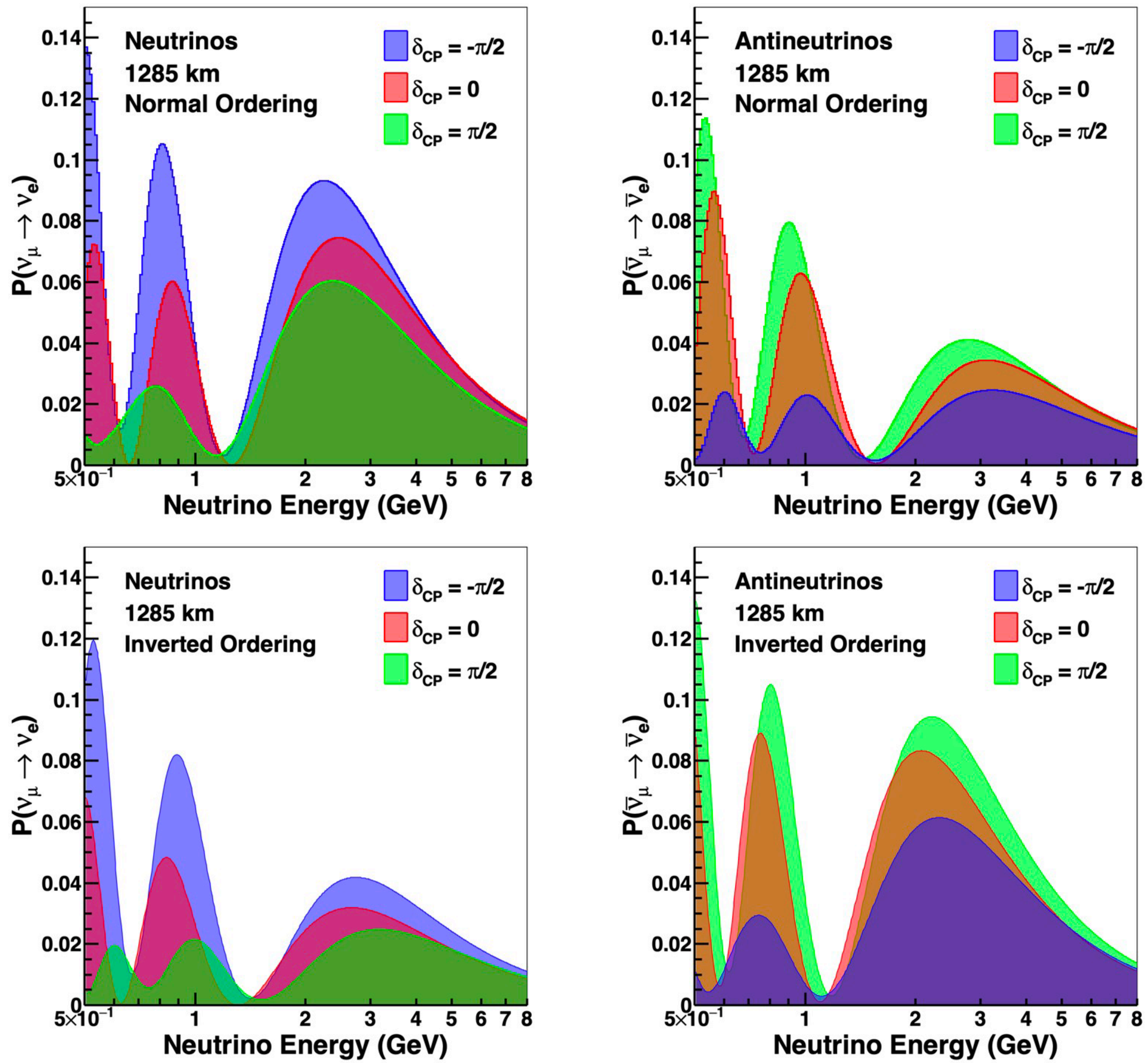
Summary

- DUNE will resolve the neutrino mass ordering, and measure δ_{CP} with CP violation sensitivity over a broad range of parameter space.
- DUNE will precisely measure θ_{13}, θ_{23}, and Δm^2_{32}, and 3-flavor oscillations to test the 3-flavor paradigm.
- DUNE has unique sensitivity to MeV-scale neutrinos and a rich BSM program (not covered in this talk, Highlight talk of DUNE by Xin Qian on July 7).
- We are on track to deliver Phase-I and paving the way for Phase-II.

Stay tuned !

Backup Materials

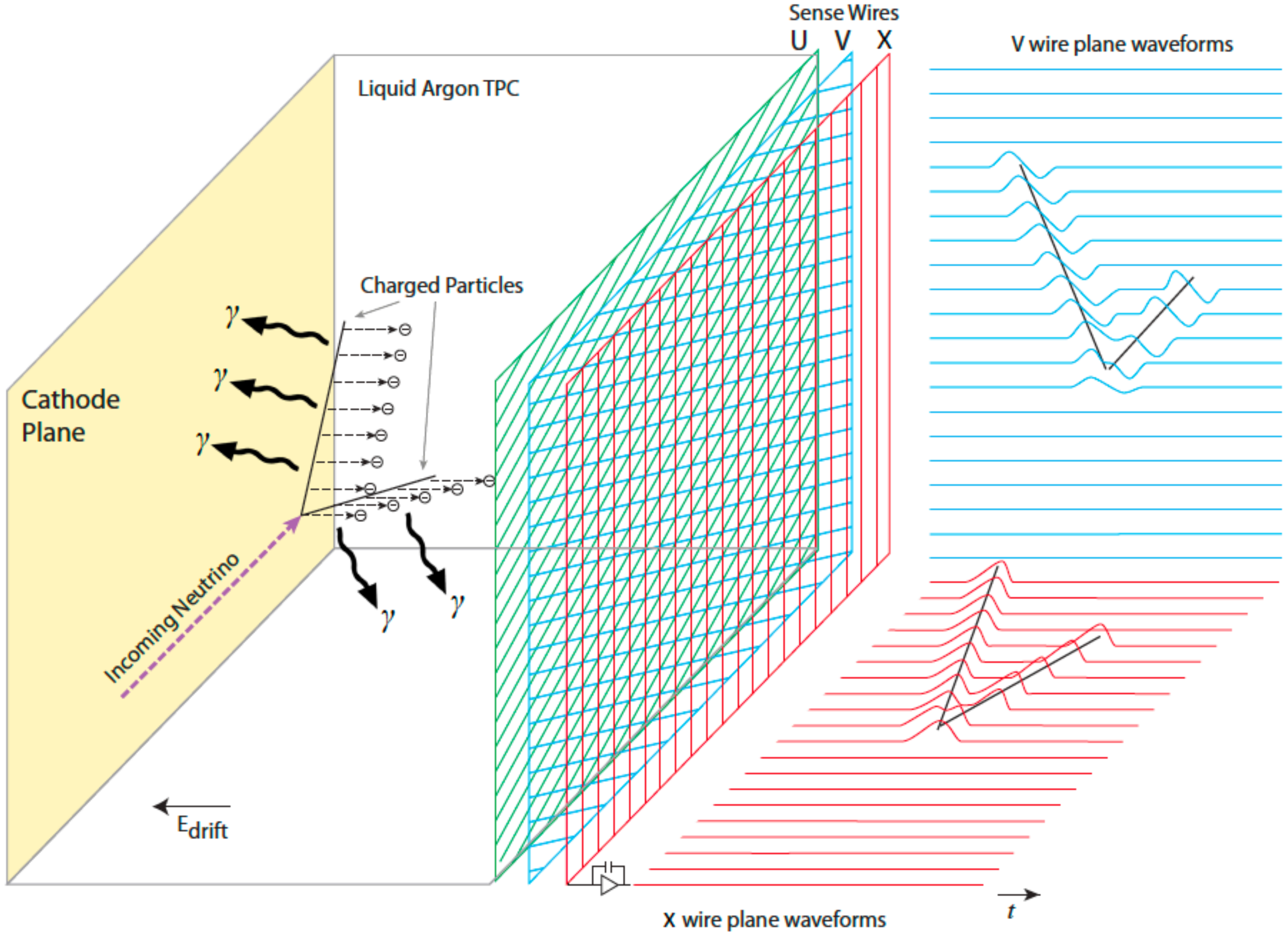
DUNE's Role in the 3F Paradigm



$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}$$
$$\times\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{\rm CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$a = \pm\frac{G_F N_e}{\sqrt{2}} \approx \pm\frac{1}{3500\ \text{km}}\left(\frac{\rho}{3.0\ \text{g/cm}^3}\right)$$

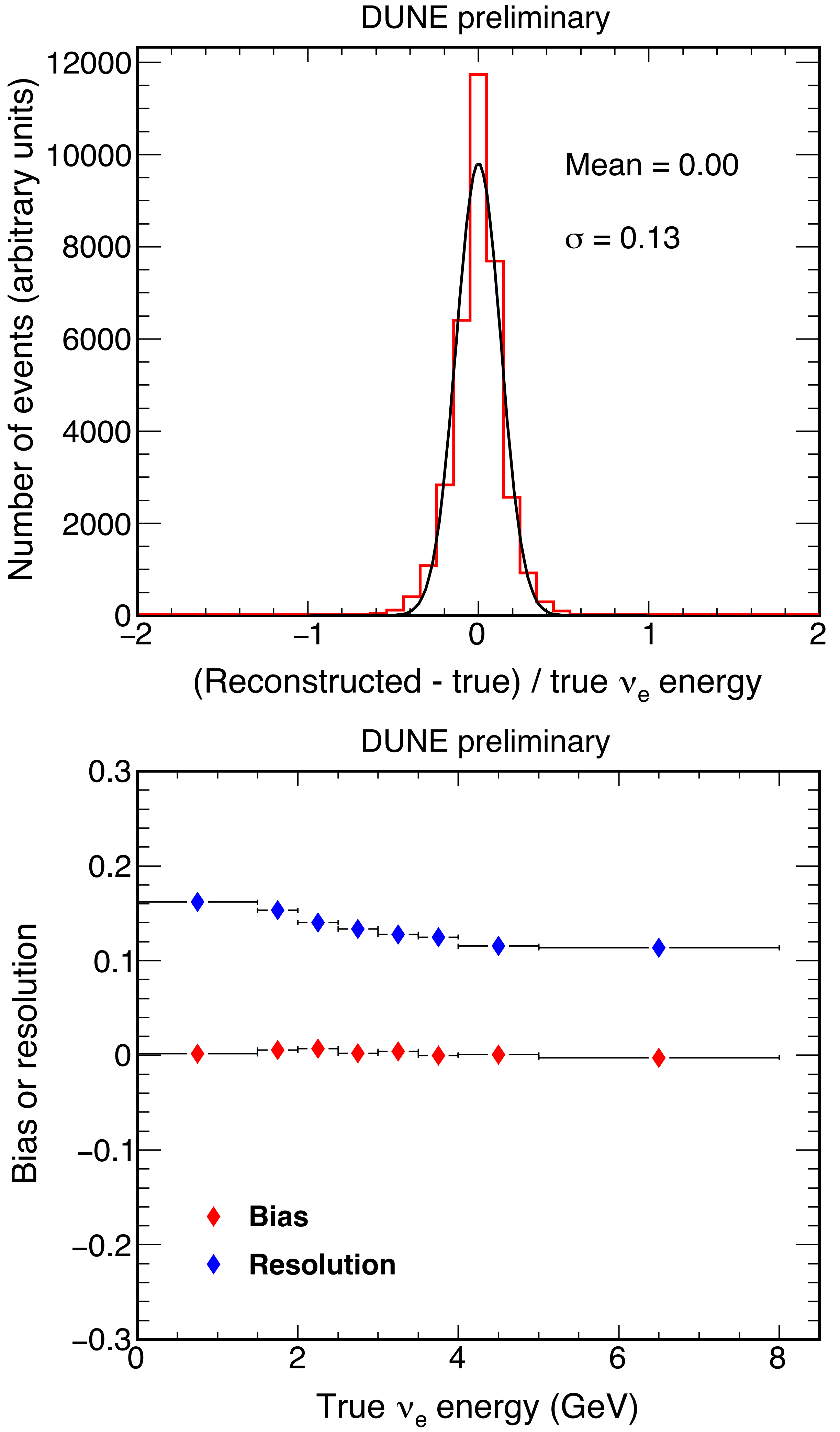
Liquid Argon TPC



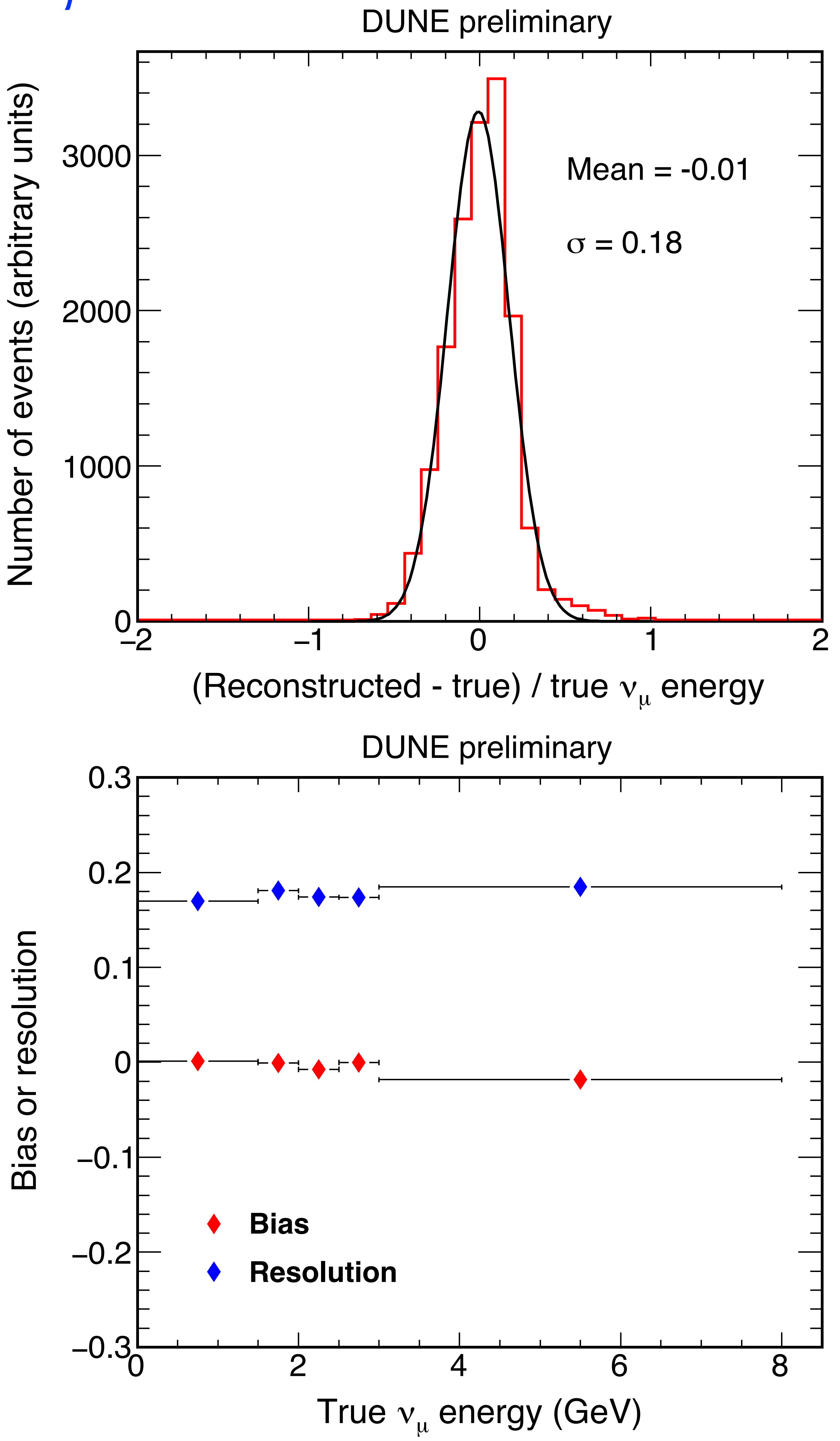
- Charged particles ionize argon atoms
- Ionized electrons drift horizontally opposite to the E field in the LAr and are collected on the anode wire planes (~ ms) → 2D spatial location
- Electron drift time projection → enable 3D spatial location
- Argon scintillation light (~ ns) detected by photon detectors, providing event start time t_0
- Key factors: LAr purity and noise on the readout electronics

Energy resolution

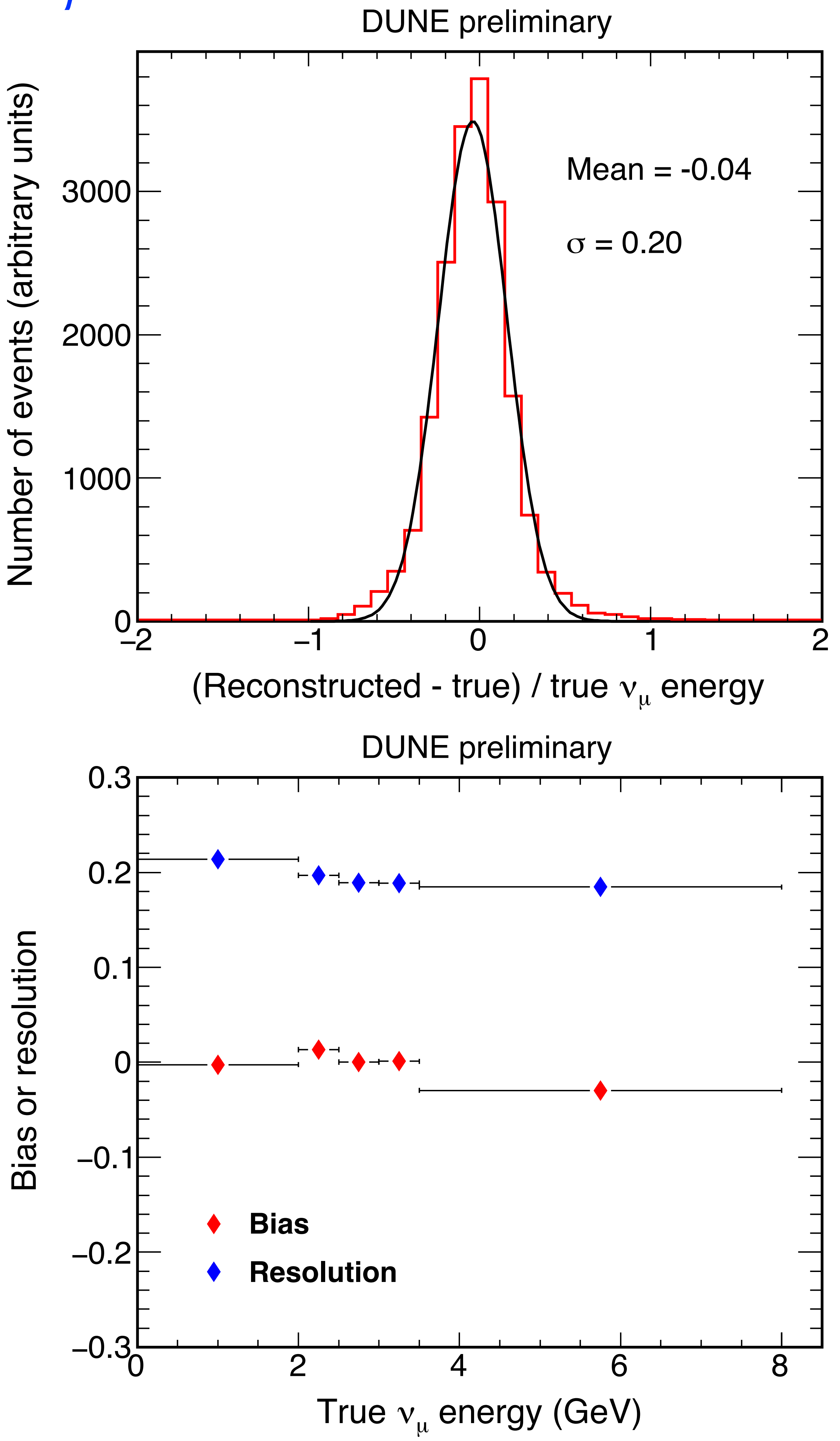
ν_e CC



ν_μ CC with contained tracks



ν_μ CC with exiting tracks



DUNE Plans and Installation

- DUNE construction is phased to provide continuous progress towards physics goals beginning this decade

Snowmass: "DUNE Physics Summary", arXiv:2203.06100

Parameter	Phase I	Phase II	Impact
FD mass	20 kt fiducial	40 kt fiducial	FD statistics
Beam power	up to 1.2 MW	2.4 MW	FD statistics
ND config	ND-LAr,TMS, SAND	ND-LAr, ND-GAr, SAND	Syst. constraints

- Far and near detector prototyping and validation underway
  - ProtoDUNEs successfully operated at CERN, and are preparing for the phase 2 running
  - ND prototype tested at BERN with cosmic rays and being tested at Fermilab with neutrino beam
- Far site civil construction to be complete in 2024 with far detector installation starting right after
- Near site and beamline are fully designed, and in construction in parallel with far site activities