Neutrino-nucleus cross sections and electron scattering experiments
SLACmass meeting

Alex Friedland, *theory group*

SLAC NATIONAL ACCELERATOR LABORATORY

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All-star team

Artur Ankowski

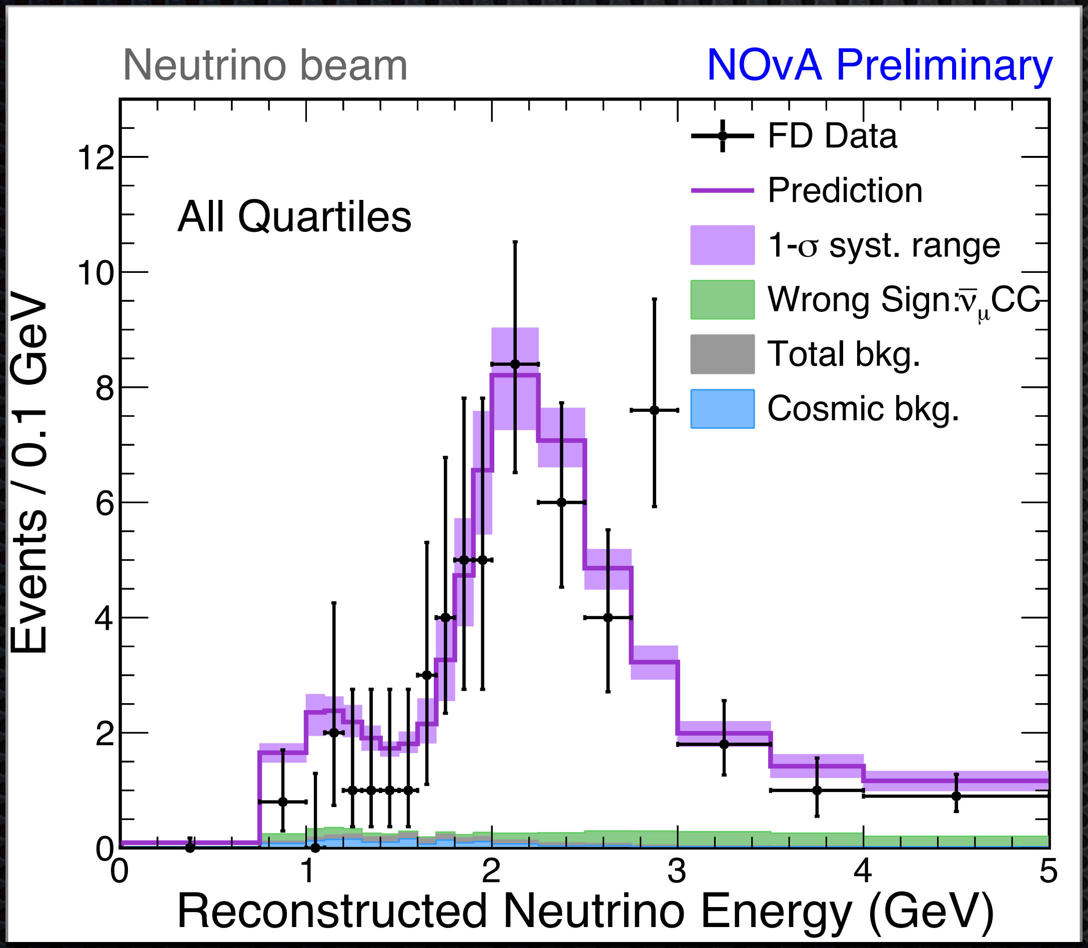
Shirley Li

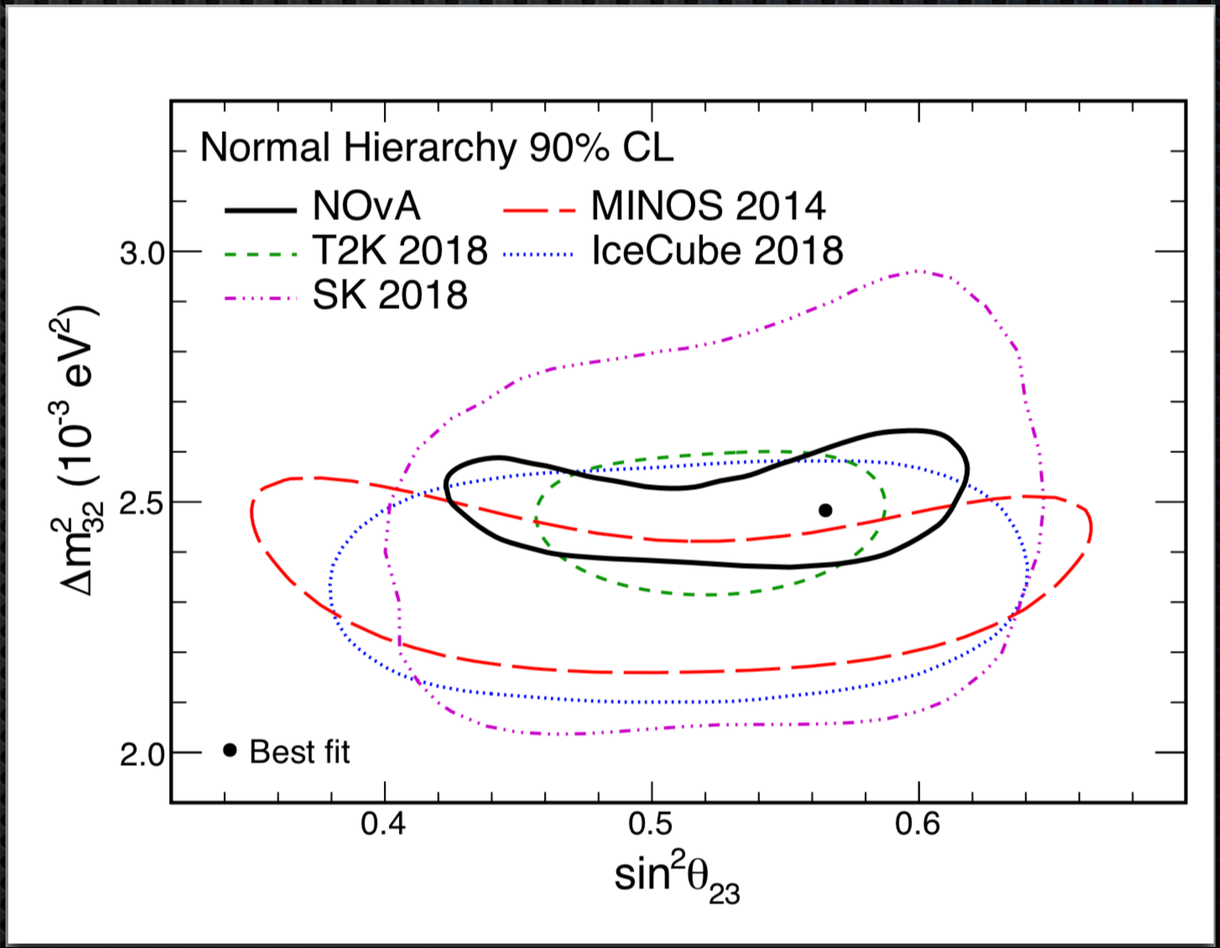
Snowmass white paper contributions

- *Event Generators for High-Energy Physics Experiments*, 2203.11110
- *Electron Scattering and Neutrino Physics*, 2203.06853
- *The Forward Physics Facility at the High-Luminosity LHC*, 2203.05090
- *Low-Energy Physics in Neutrino LArTPCs*, 2203.00740
- *Theoretical Tools for Neutrino Scattering*, 2203.09030

Energy reconstruction is crucial NOvA 2019

Figure from NOvA, arXiv:1906.04907



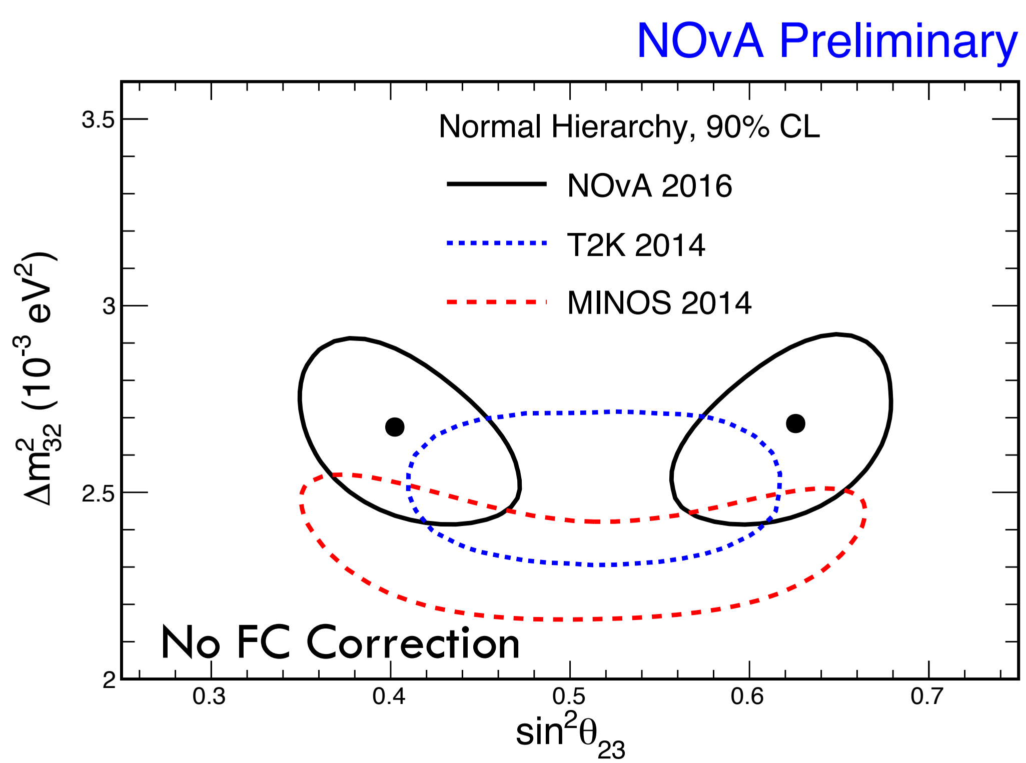


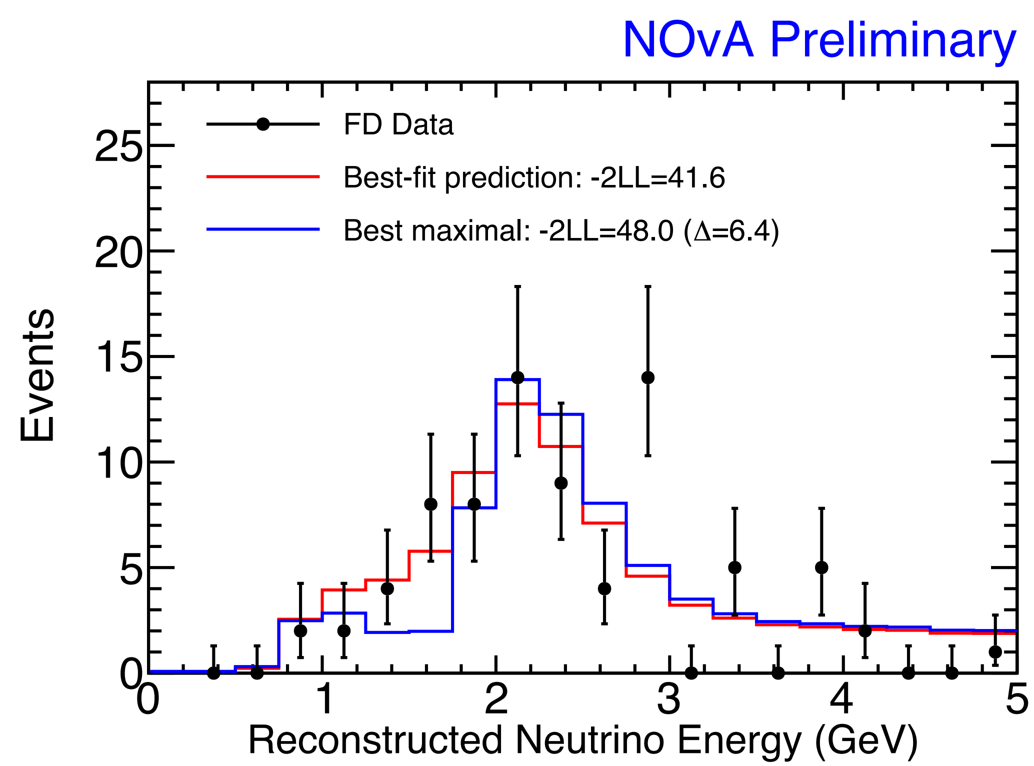
- $\theta_{23} = \pi/4$ implies a steeply rising spectrum

cf. NOVA 2016

- Events in the oscillation dip were interpreted as evidence of nonmaximal mixing

18 P. Vahle, Neutrino 2016





Best Fit (in NH):

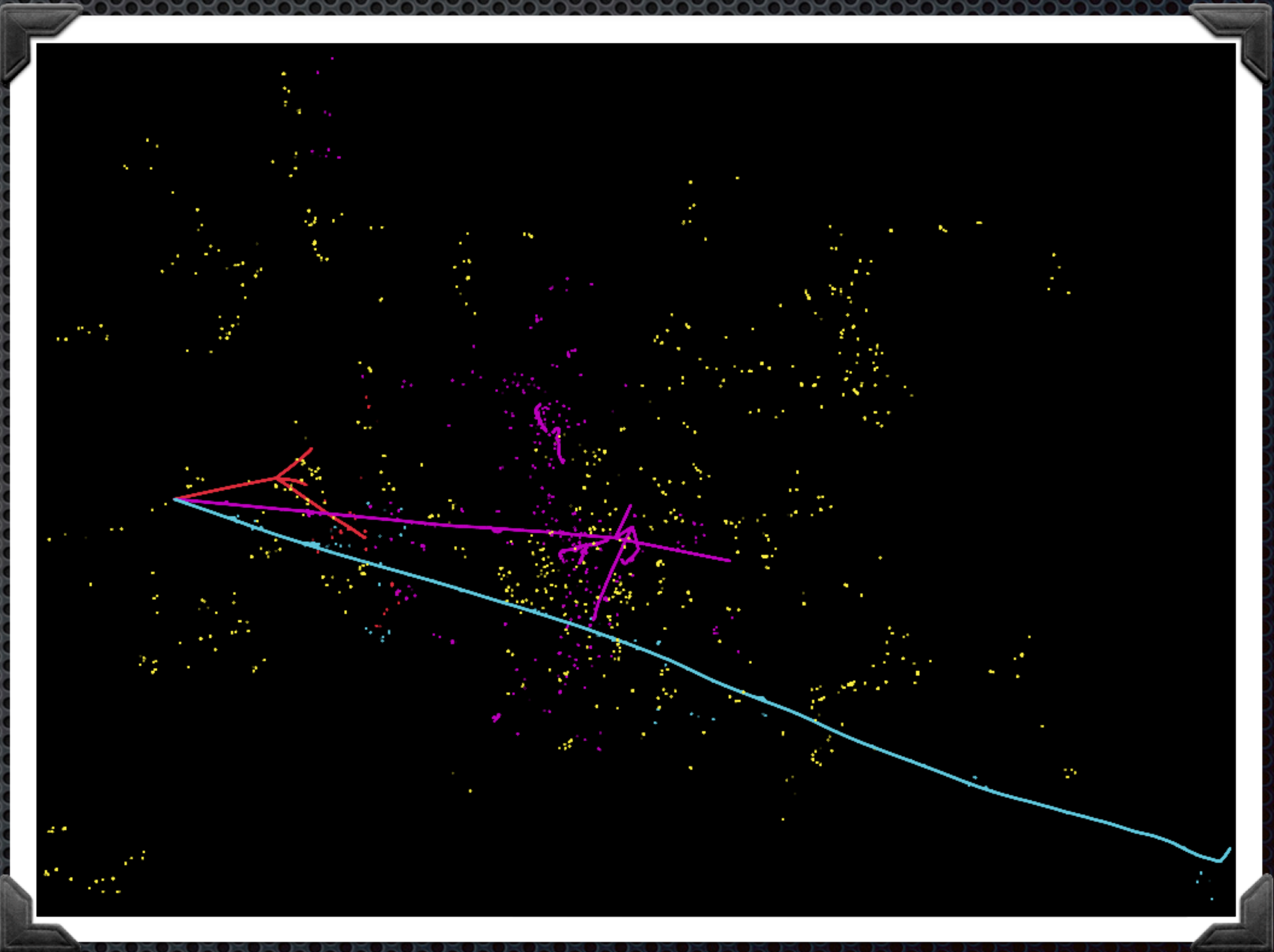
$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

Measuring neutrino energy at DUNE/NOvA

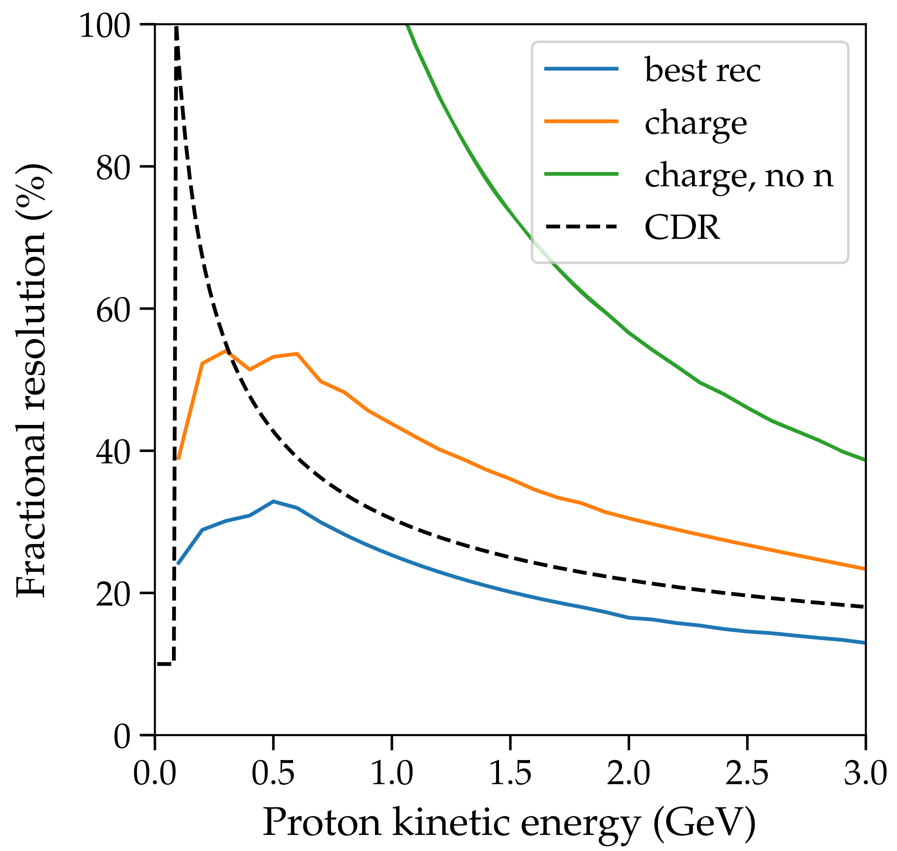
- In 1-4 GeV beams, a variety of final states are produced:
  - protons,
  - pions,
  - gammas,
  - neutrons
- Lepton kinematics alone is insufficient to infer E_ν
- Have to use calorimetric reconstruction: measure the energy of all final-state particles



A.F., S. Li,
Phys.Rev.D **99**, 036009 (2019)
Phys.Rev.D **102**, 096005 (2020)

Calorimetry challenge

- Directly connecting ionization charge to neutrino energy is a non-trivial task!
  - low-energy p/pi-discrimination
  - neutron losses
  - Opportunity to connect to ML reconstruction at SLAC
- *Generators are needed to fill in missing information*
  - Predicting the composition and properties of the hadronic final state



A.F., S. Li,
Phys.Rev.D **99**, 036009 (2019)
Phys.Rev.D **102**, 096005 (2020)

Also to correct for different event containment

A.F., S.Li, DOI: 10.1103/PhysRevD.102.096005

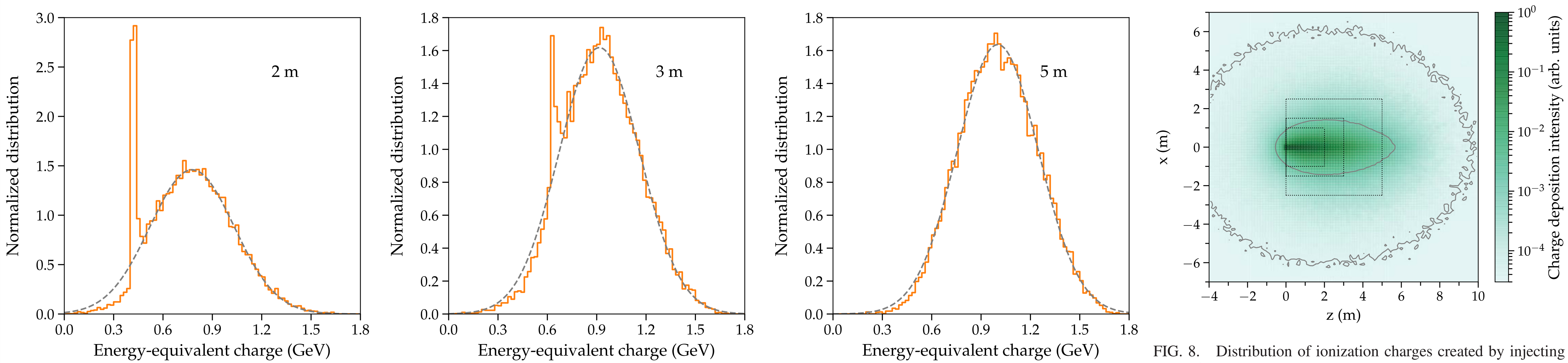


FIG. 8. Distribution of ionization charges created by injecting 4×10^5 protons of 2 GeV kinetic energy at position (0, 0, 0). The

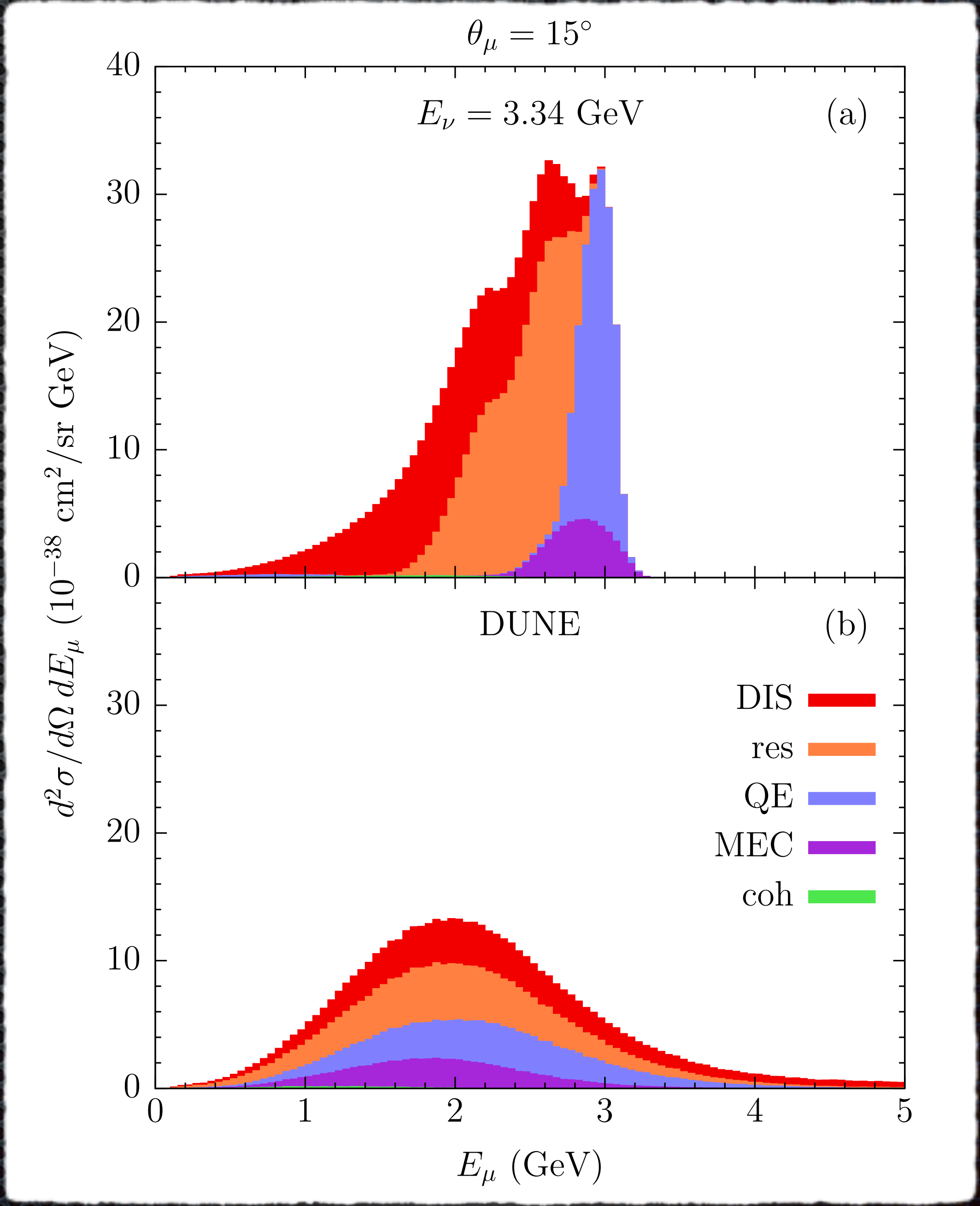
- Connecting near and far detectors requires robust interaction modeling

Which aspects of the generators should be improved as the highest priority?

- In theory, any improvement to the models in the generators is a positive development
- in practice, fixating on one process while neglecting greater sources of discrepancies may lead to
  - misallocation of resources,
  - lull the community into complacency,
  - leading to uncontrolled systematic errors

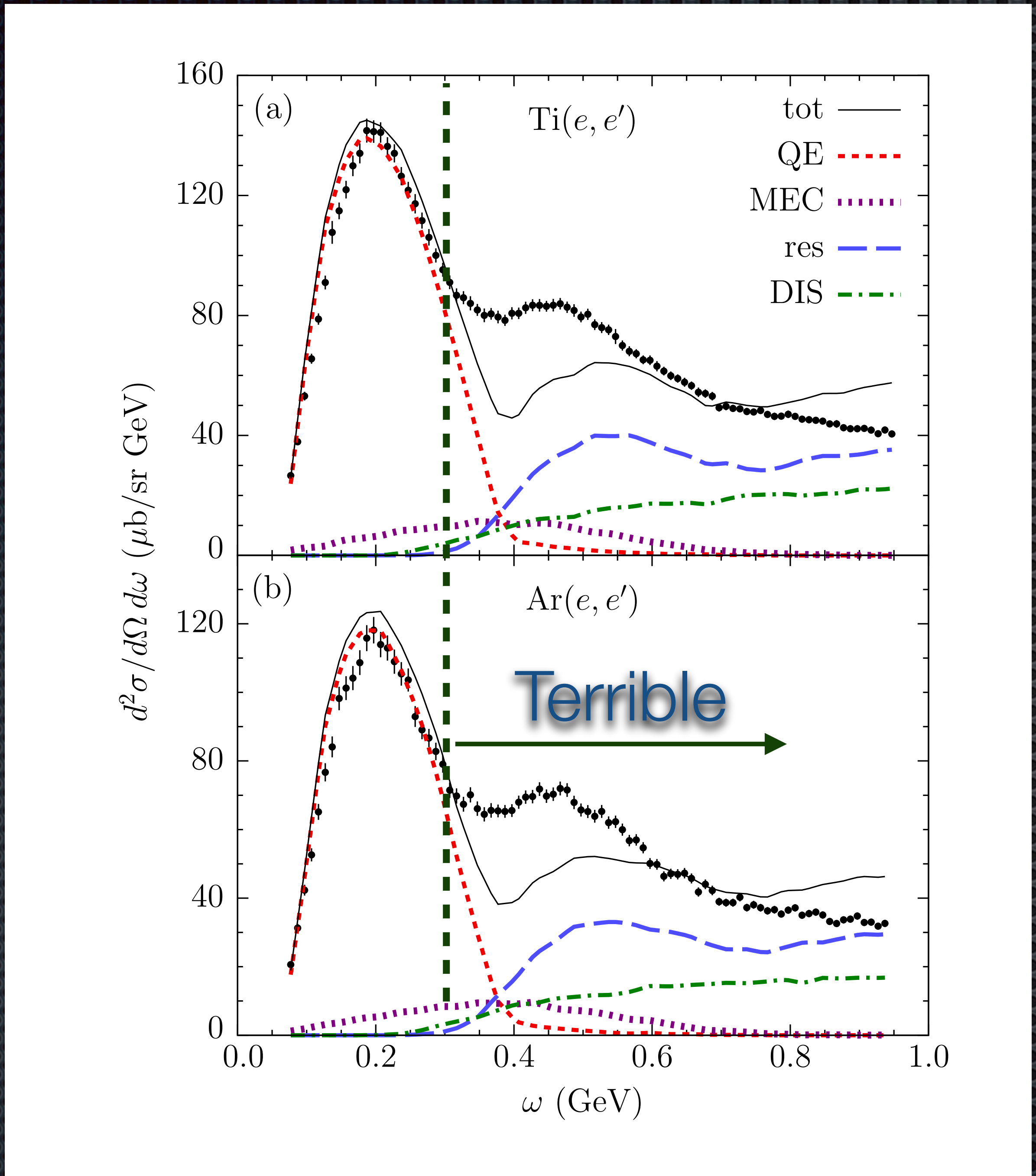
Neutrino scattering at several GeV

- Need to evaluate the different physics ingredients:
  - QE, resonant and non-resonant pion production, DIS-like, multi-nucleon
- neutrino beams are not monochromatic and energy reconstruction requires good generators, see above!
- Find an independent way to systematically test all these processes



- arXiv: 2006.11944

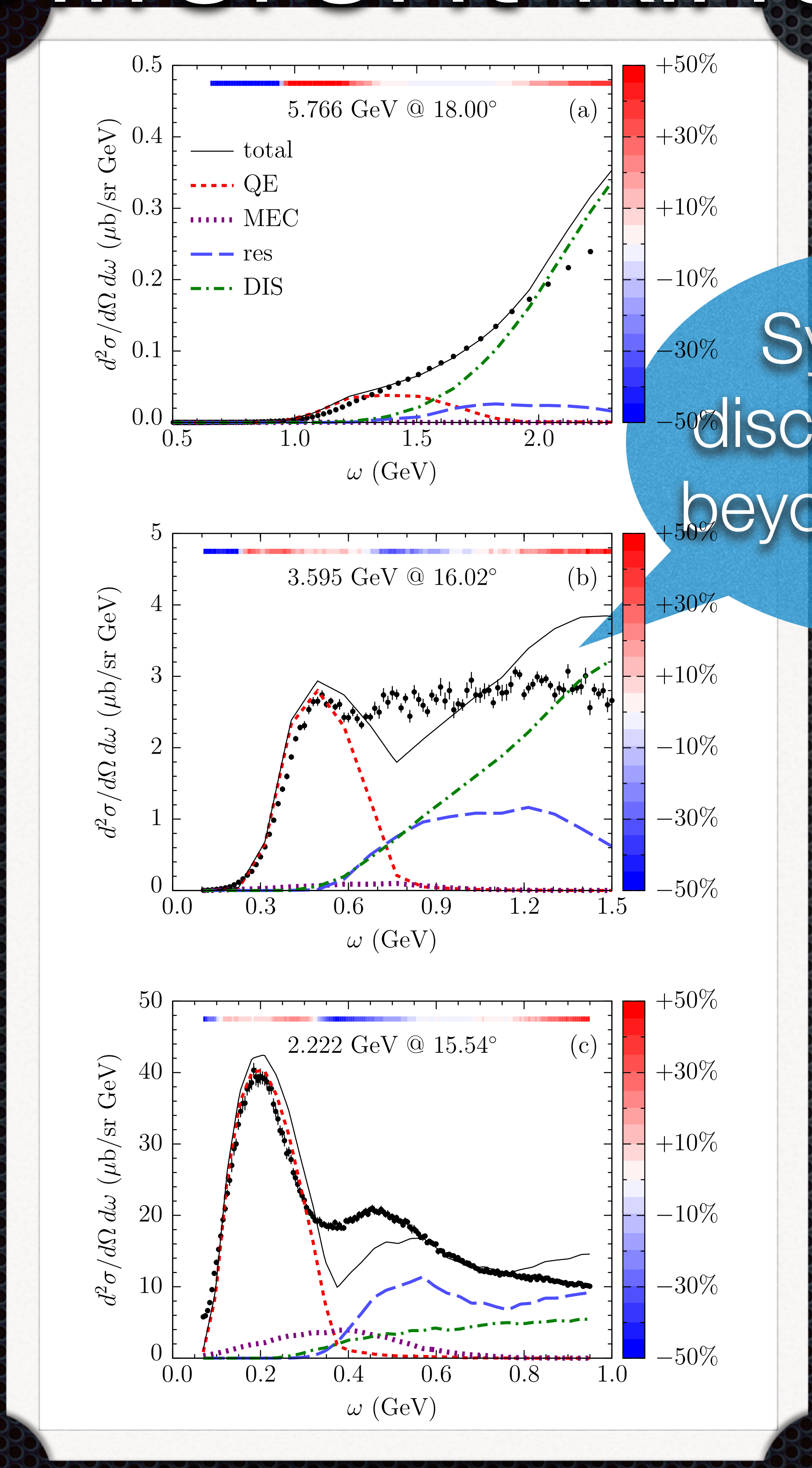
GENIE vs JLAB



2.2 GeV electron beam
JLAB

- Predictions beyond the quasielastic peak are in dramatic disagreement with the data

Different kinematic regimes



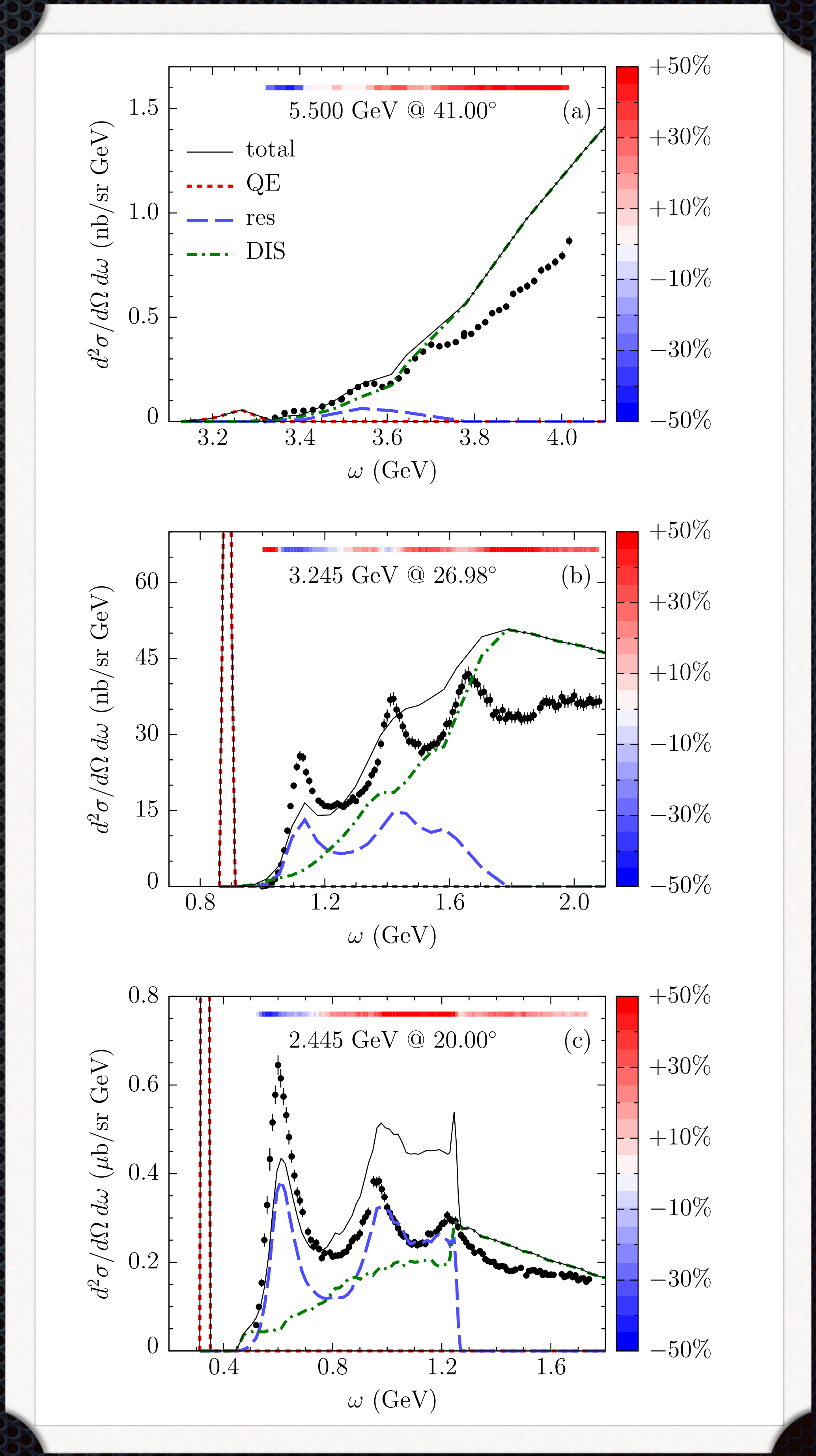
Systemic discrepancies beyond CCQE

- Chronic problems with many other datasets.

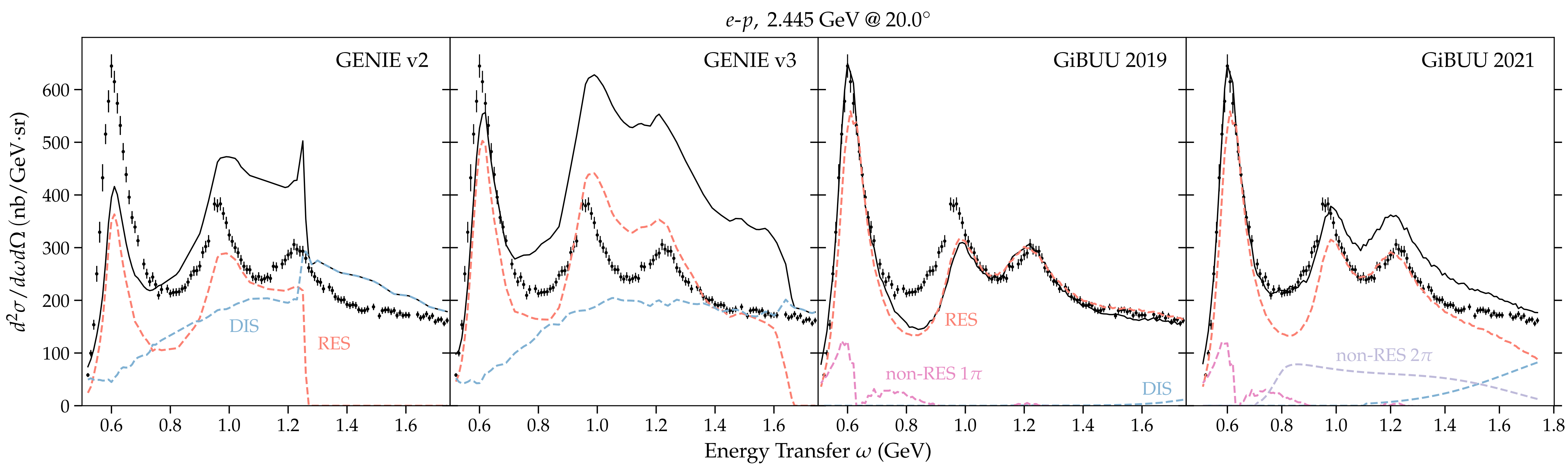
Decisive test: comparison to hydrogen and deuterium

- Surprising findings:
  - Large discrepancies originate in (mis)modeling of hadronic processes
  - Prominent double-counting in the RES -> DIS region

For details, see A. Ankowski, A.F., DOI: 10.1103/PhysRevD.102.053001

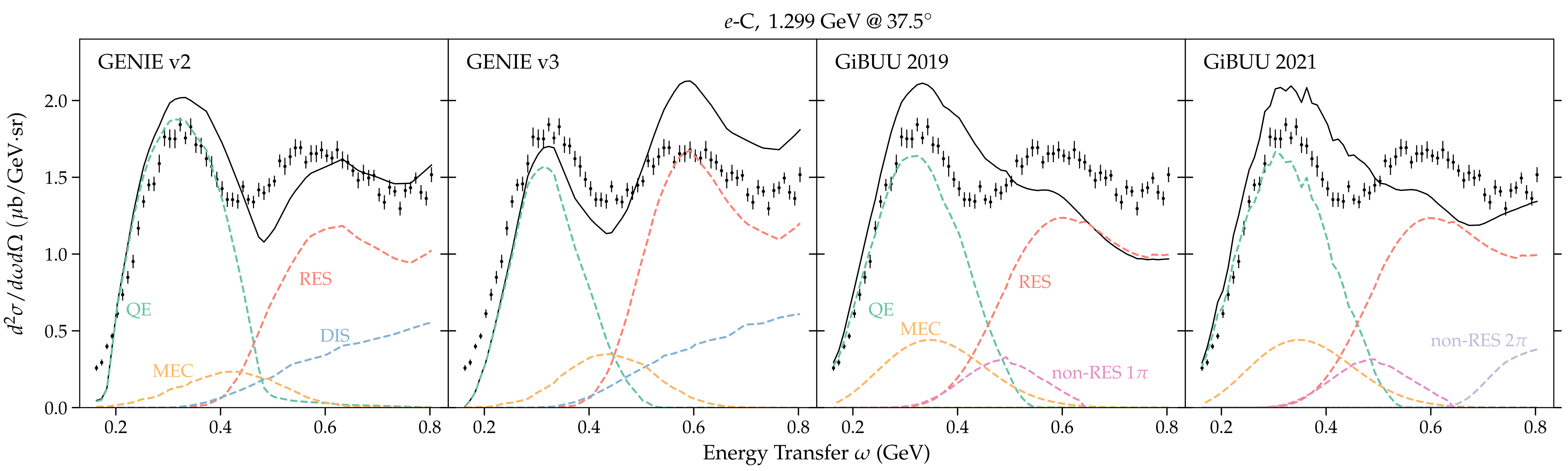


Large discrepancies persist for other generators



Ankowski, A.F., Li, *to appear*

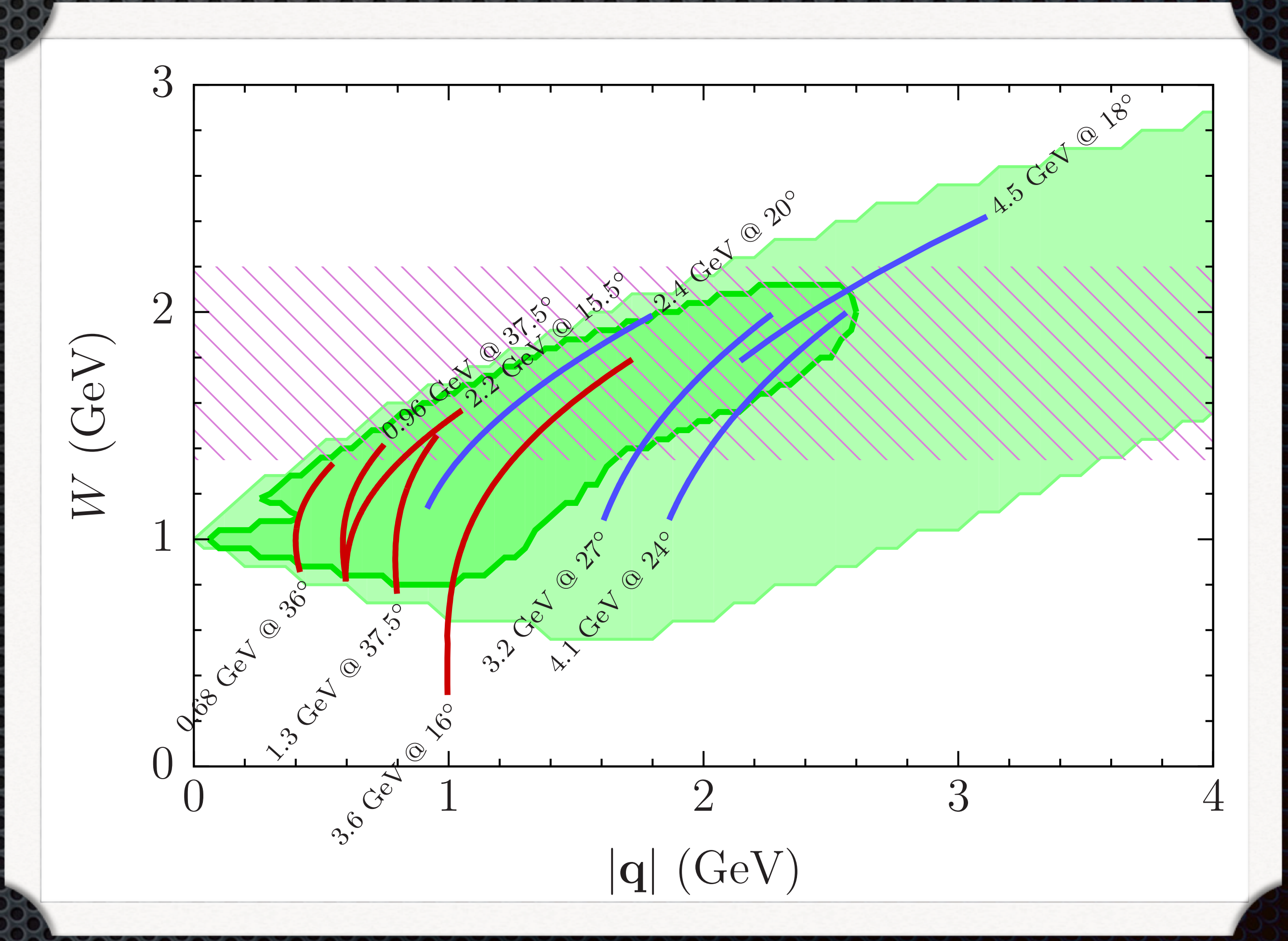
Large discrepancies persist for other generators



Ankowski, A.F., Li, *to appear*

Common physics challenges of modern neutrino event generators

- We find that kinematic regimes in which the scattering is modeled as an overlap of different physical processes are especially prone to mis-modeling
- Transition between higher resonances and the DIS regime, encompasses *nearly half* of all expected events for DUNE
- Requires an improved theoretical framework validated against extensive inclusive and exclusive data



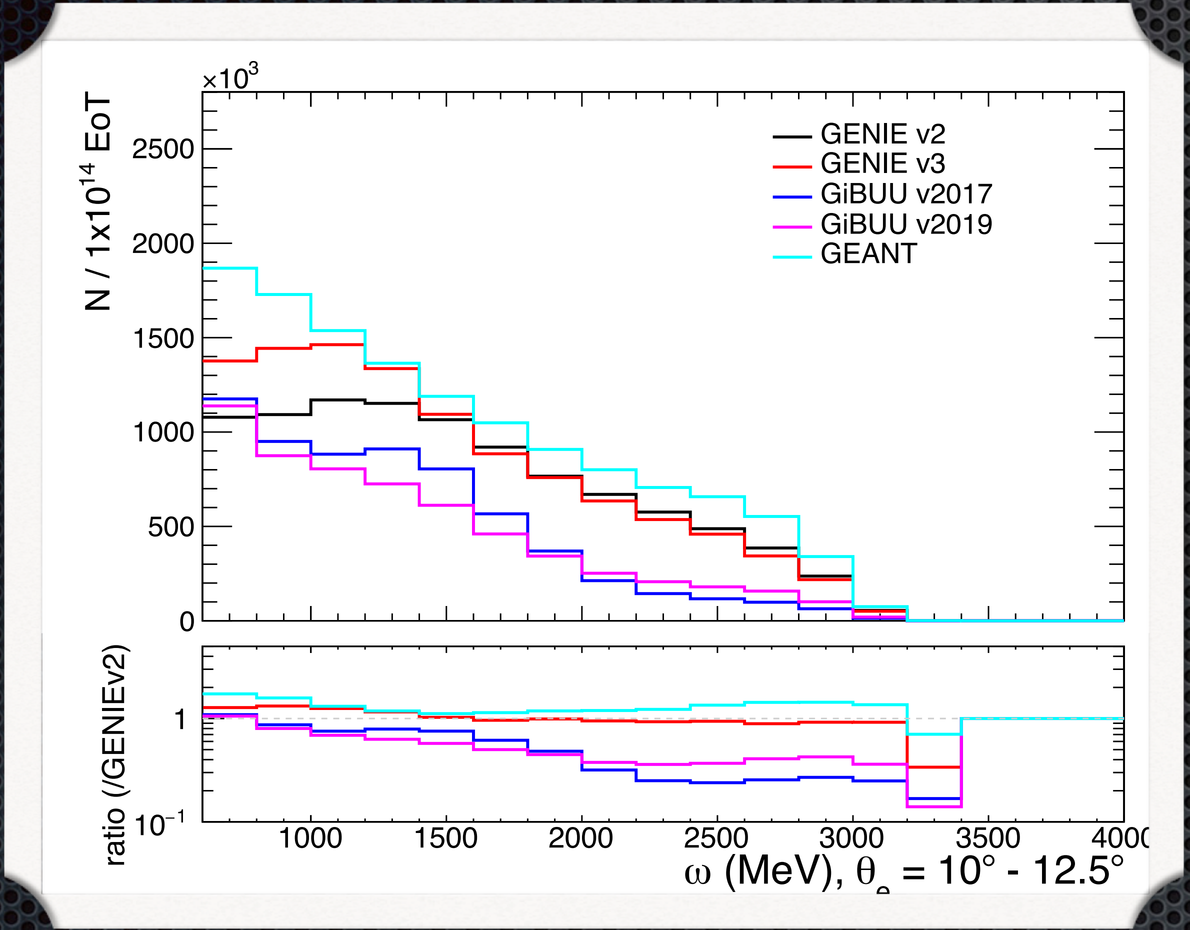
New data!

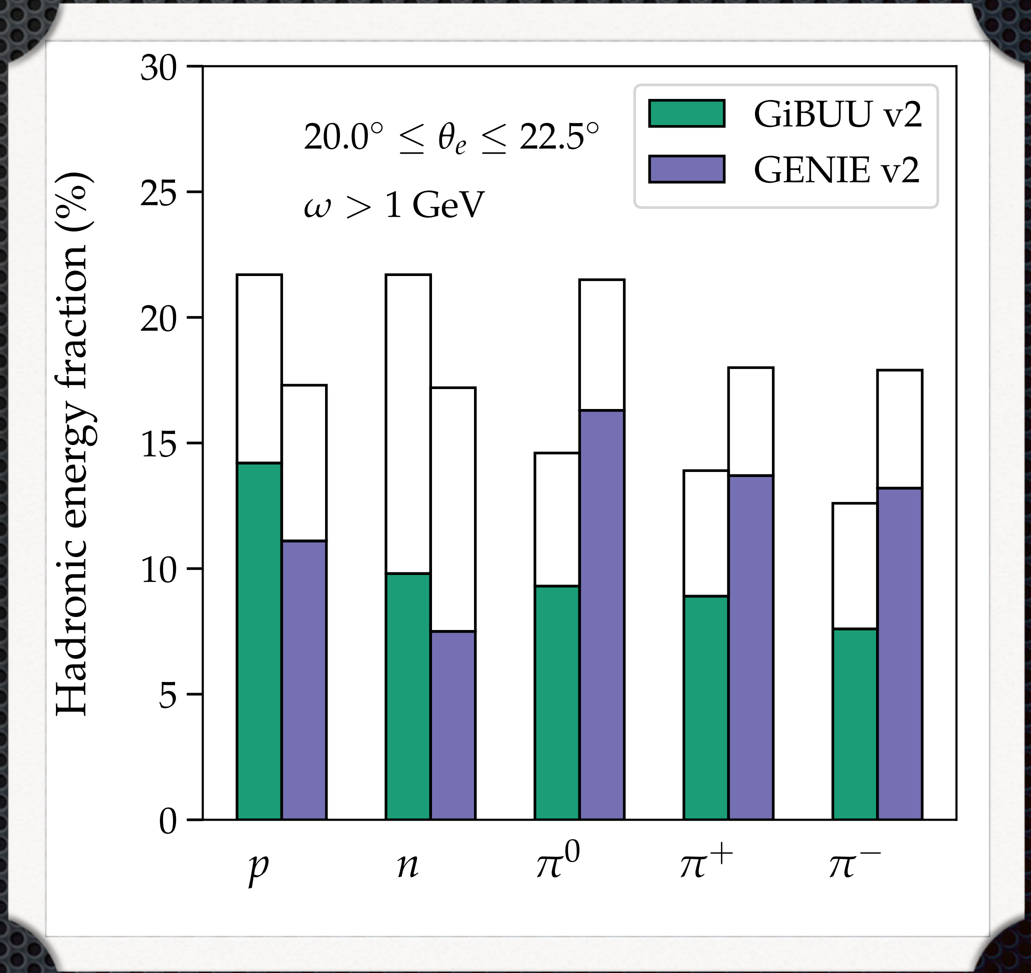
- To make progress on the foundational challenges, we need to collect new data, both neutrino and electron
- Both the final-state electron and the hadronic system should be measured
  - Composition and energy distribution between protons, pions, gammas, neutrons
  - Large solid angle coverage in the forward cone

Exciting opportunity to study e-A physics at SLAC

- LDMX (Light Dark Matter eXperiment) was conceived to search for light dark matter
- Electron beam energy in the S30XL beam line is 4 GeV (8 GeV), great to make measurements for DUNE
- LDMX happens to have advantageous characteristics: wide angular acceptance of charged hadrons, good momentum resolution, ability to detect neutrons
- Opportunity to gather both inclusive data and detailed information about the final-state hadronic system

Important: large discrepancies among generator predictions for exclusive channels





Simulation for the LDMX detector

- Ankowski, et al, 1912.06140 [hep-ph]
- DOI: 10.1103/PhysRevD.101.053004