Common physics challenges of modern neutrino event generators

NTN Workshop

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Many thanks to

Artur Ankowski

Shirley Li

Why cross sections now?

In two decades, we went from this:

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

Massive Neutrinos and Lepton Mixing, Searches for

For excited leptons, see Compositeness Limits below.

See the Particle Listings for a Note giving details of neutrinos, masses, mixing, and the status of experimental searches.

No direct, uncontested evidence for massive neutrinos or lepton mixing has been obtained. Sample limits are:

ν oscillation: $\overline{\nu}_e \not\to \overline{\nu}_e$

$\Delta(m^2) < 0.0075$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 0.02$, CL = 90% (if $\Delta(m^2)$ is large)

ν oscillation: $\nu_\mu \to \nu_e$ (θ = mixing angle)

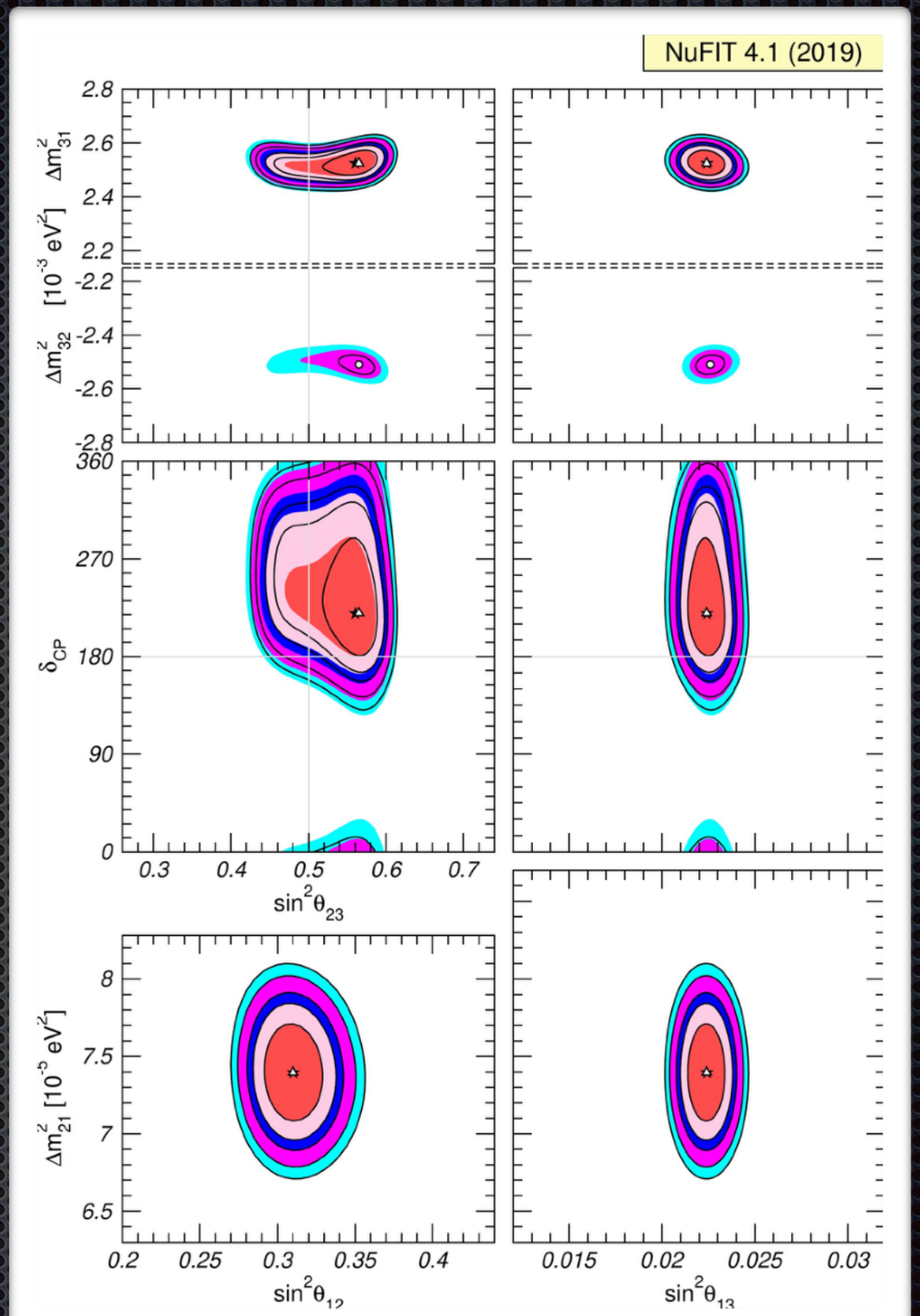
$\Delta(m^2) < 0.09$ eV^2, CL = 90% (if $\sin^2 2\theta = 1$)
$\sin^2 2\theta < 2.5 \times 10^{-3}$, CL = 90% (if $\Delta(m^2)$ is large)

PDG 1996

http://pdg.lbl.gov/1996/www_2ltab.ps

... to this:

FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

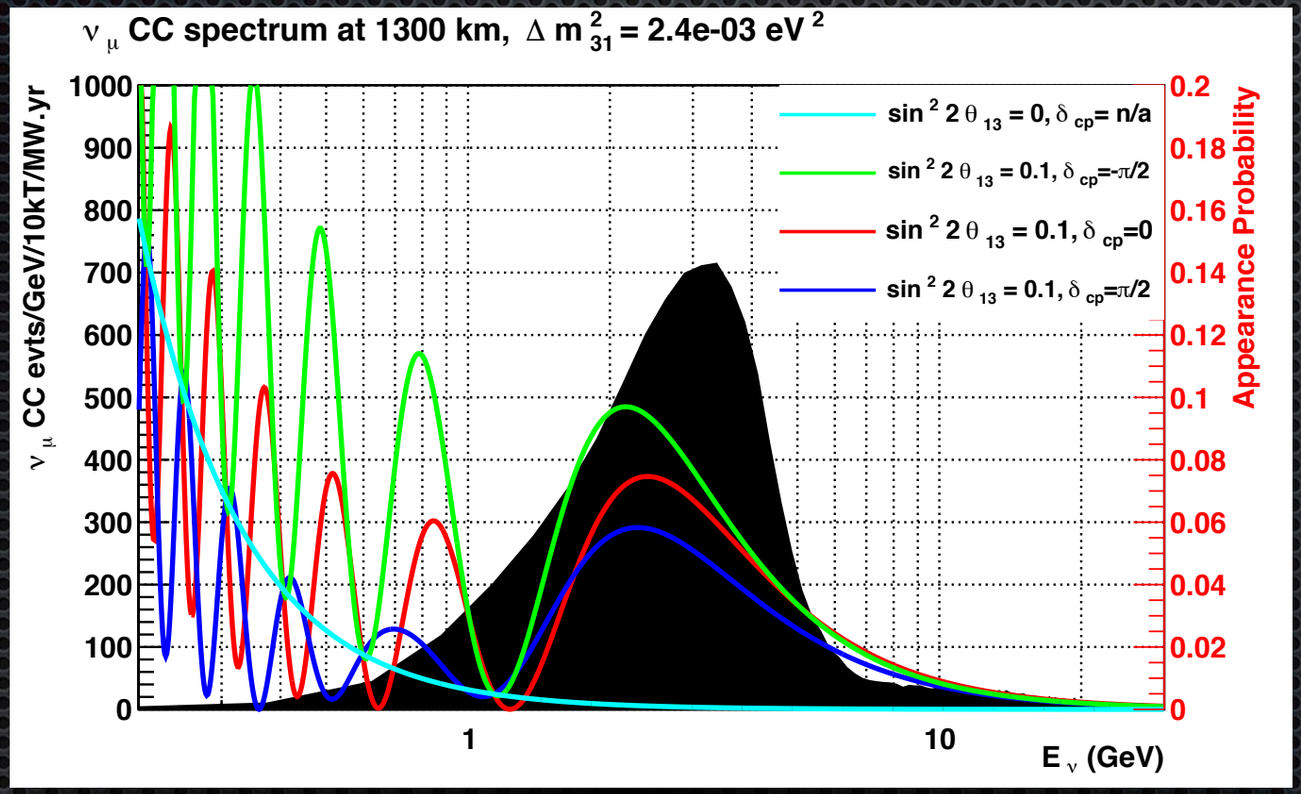


.... without having to understand cross sections precisely. What changes now?

Discovery era ⟶precision era

- In the early days, signals were large and observables robust
  - Atmospheric neutrinos: oscillations reduce ν_μ flux by a factor of 2, up/down asymmetry cancels uncertainties (SuperK)
  - Solar neutrinos: oscillations reduce ν_e flux by a factor of 3, measurements with both charged and neutral current (SNO)
- Modern experiments look for O(10%) effects in search for subtle signatures of CP violation, mass hierarchy, new physics

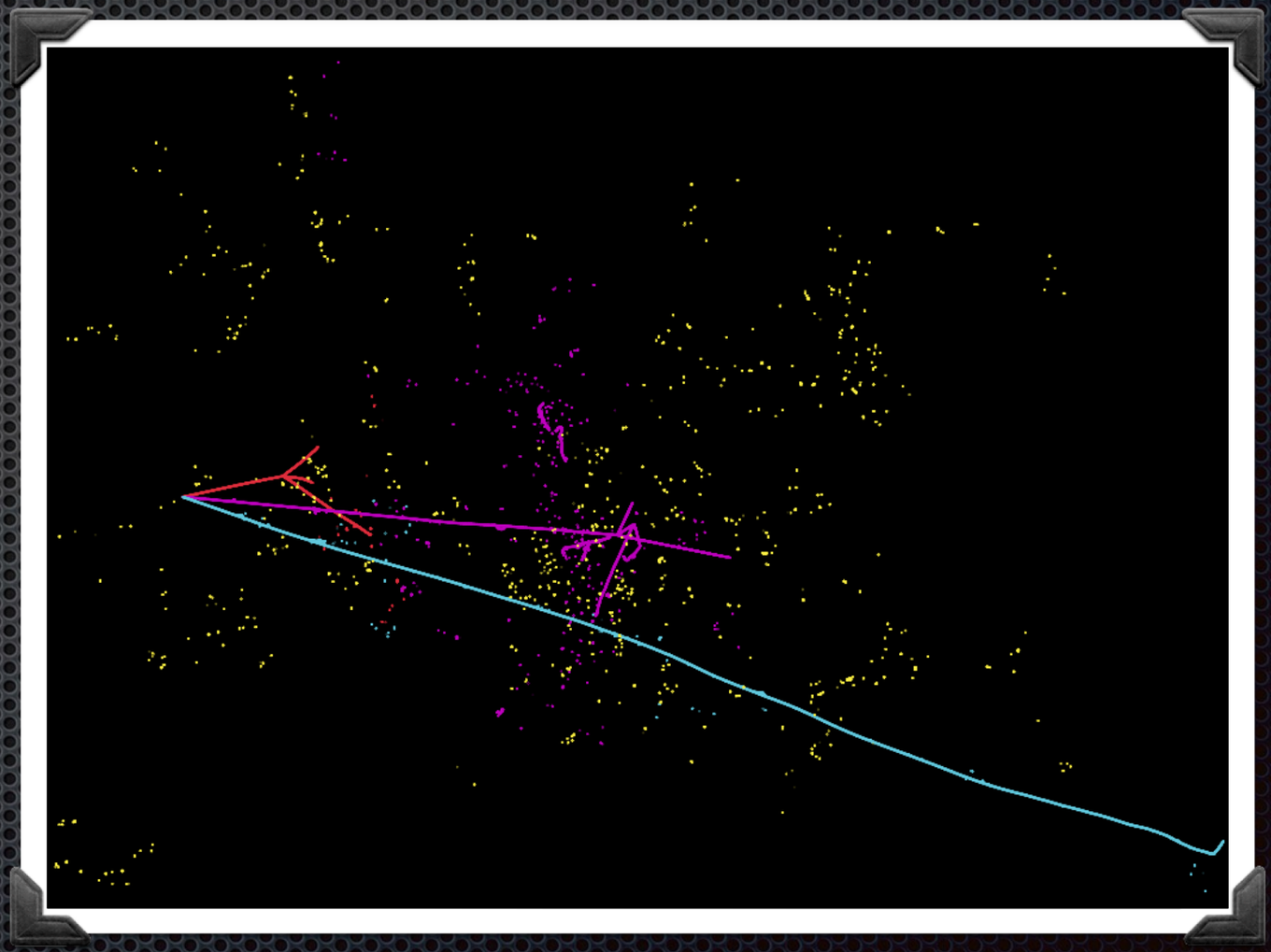
Goal: precision studies of neutrino oscillations *as a function of energy*



- Reconstruction of energy is key and for this we need accurate cross section models

Measuring neutrino energy at DUNE/NOvA

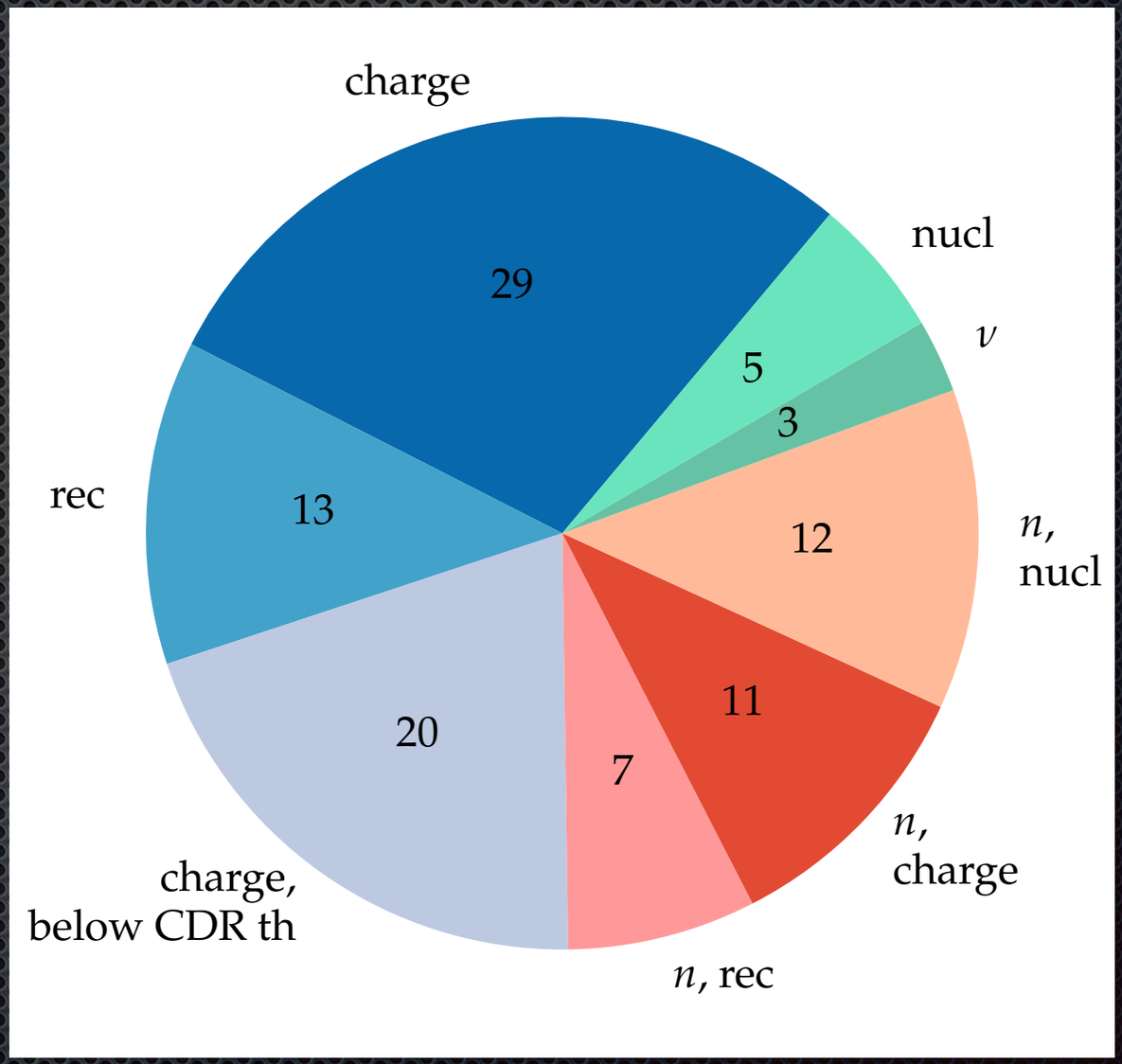
- In the beam of 1-4 GeV, a variety of final states are produced, with protons, pions, and neutrons
- Because of this, lepton kinematics alone is insufficient to infer E_ν
- Have to use calorimetric reconstruction: measure energy of all final-state particles



see AF, S. Li, arXiv:1811.06159, arXiv:2007.13336

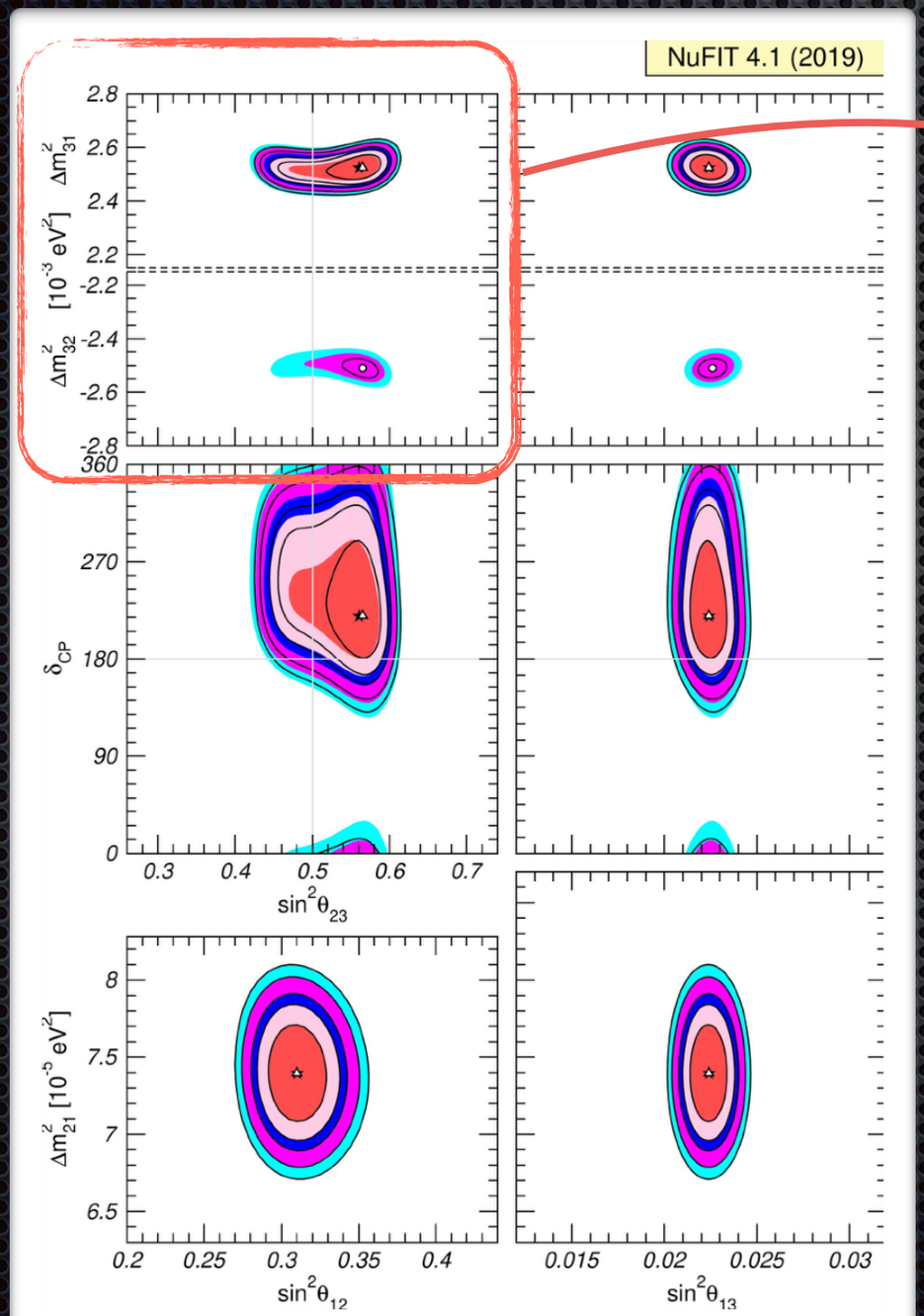
Typical 4 GeV neutrino in LAr

- A number of missing energy channels
- Generators are needed to fill in missing information
  - E.g., neutron losses, low-energy p/pi-discrimination, etc



see AF, S. Li, arXiv:1811.06159, arXiv:2007.13336

Does this really matter for oscillation measurements?



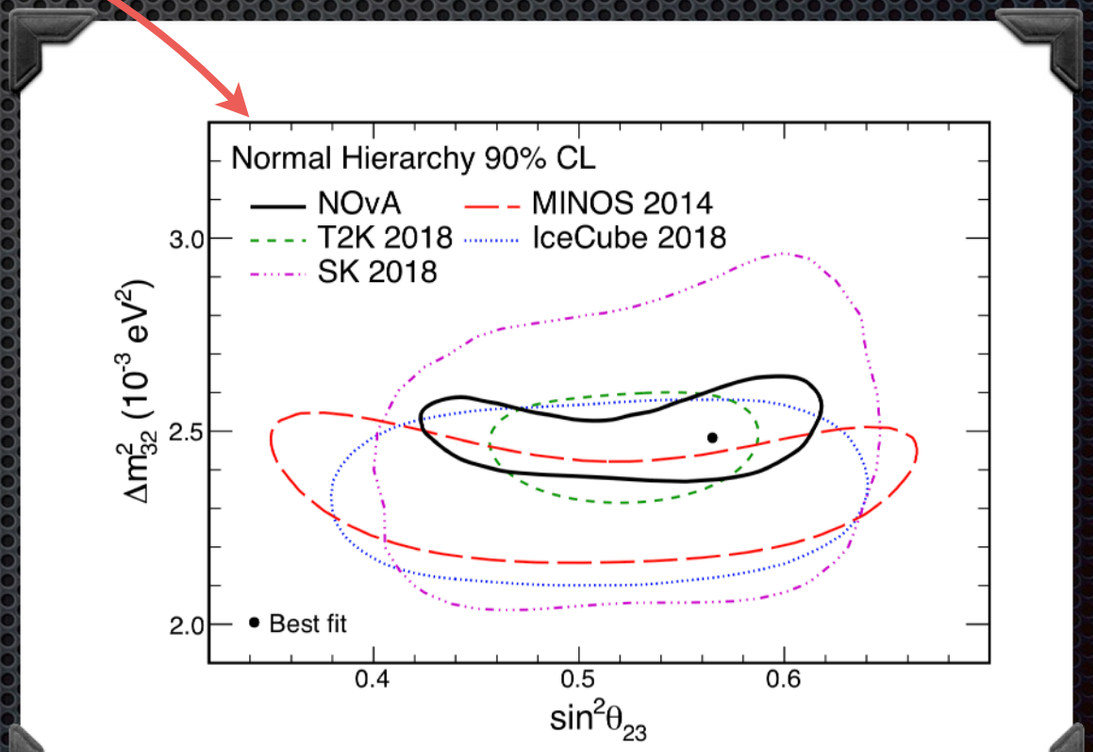
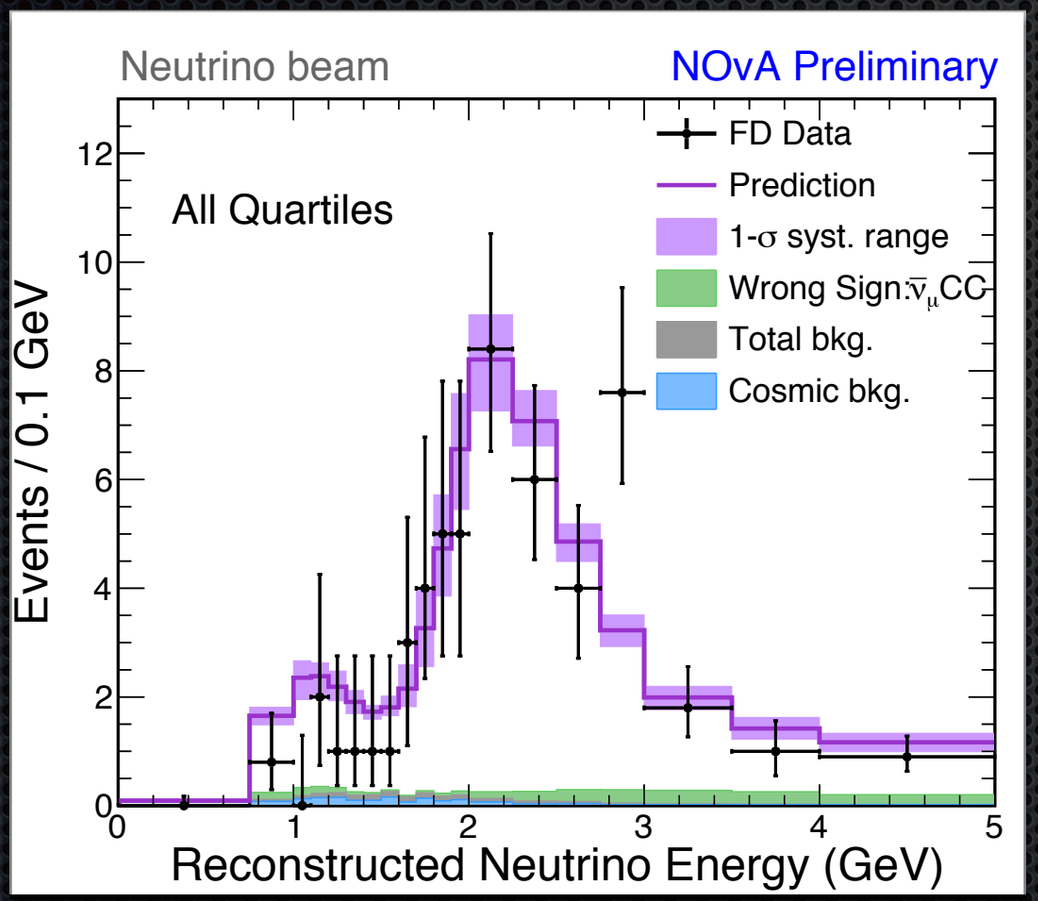
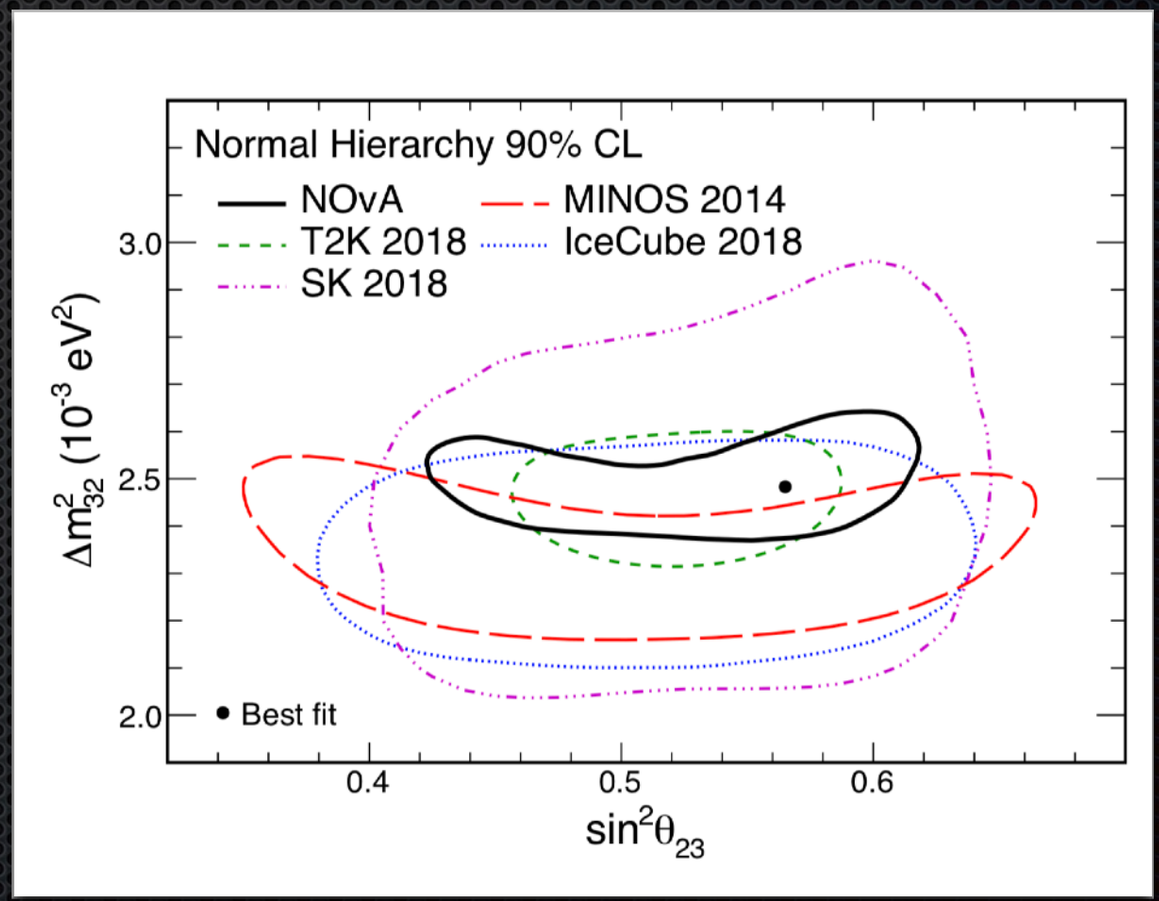


Figure from NOvA, arXiv:1906.04907

NOvA 2019

Figure from NOvA, arXiv:1906.04907

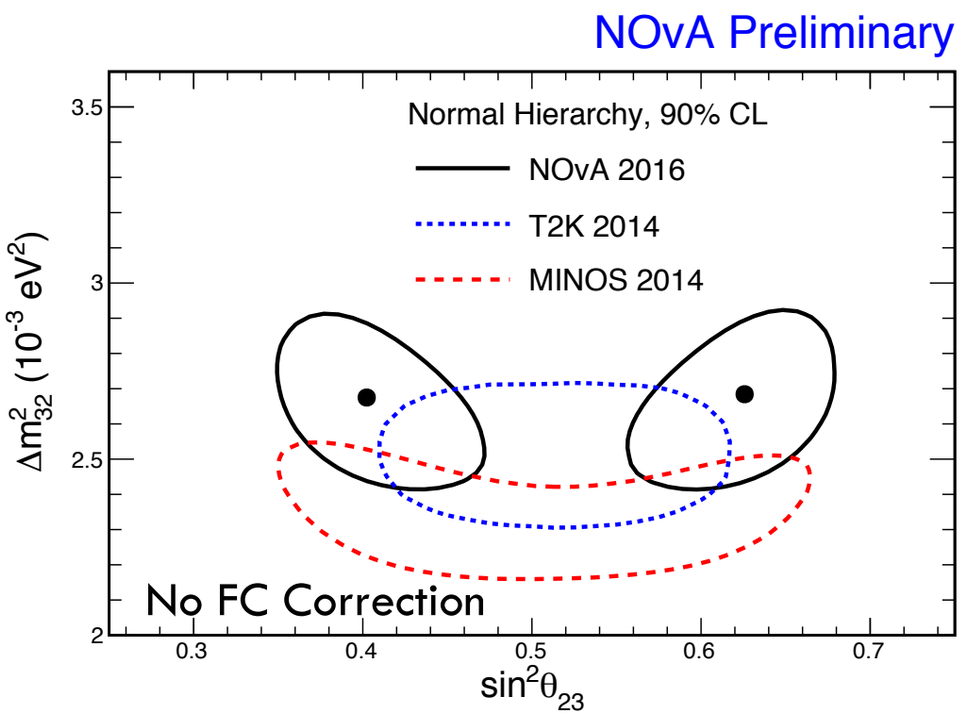


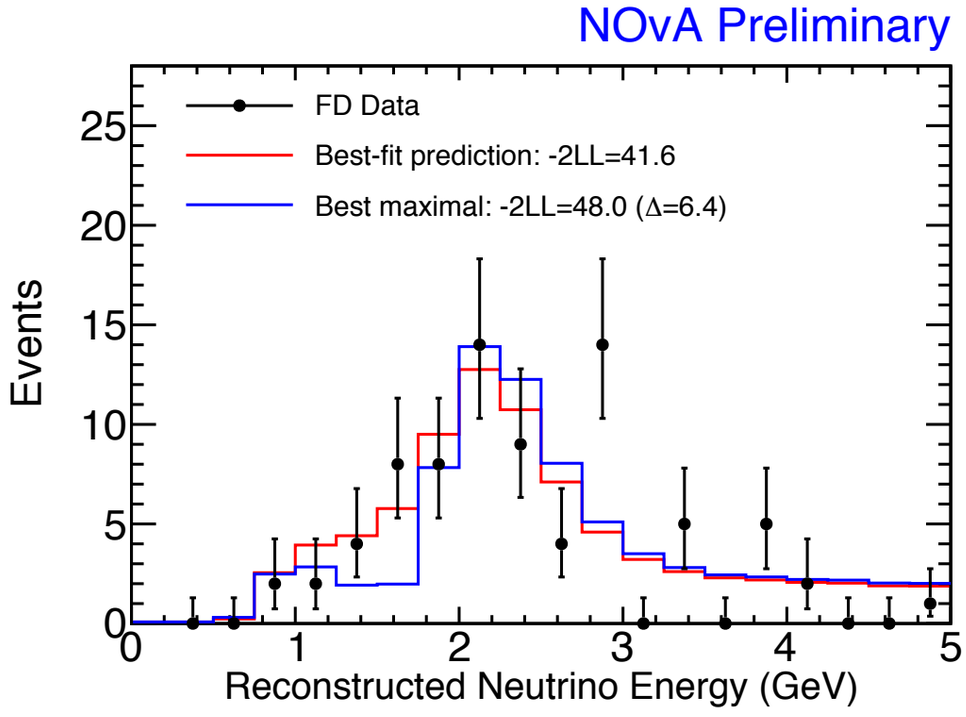


- $\theta_{23} = \pi/4$ implies a steeply rising spectrum

cf. NOVA 2016

- More events in the dip could be interpreted as evidence of nonmaximal mixing





Best Fit (in NH):

$$\left|\Delta m^2_{32}\right| = 2.67 \pm 0.12 \times 10^{-3}\text{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

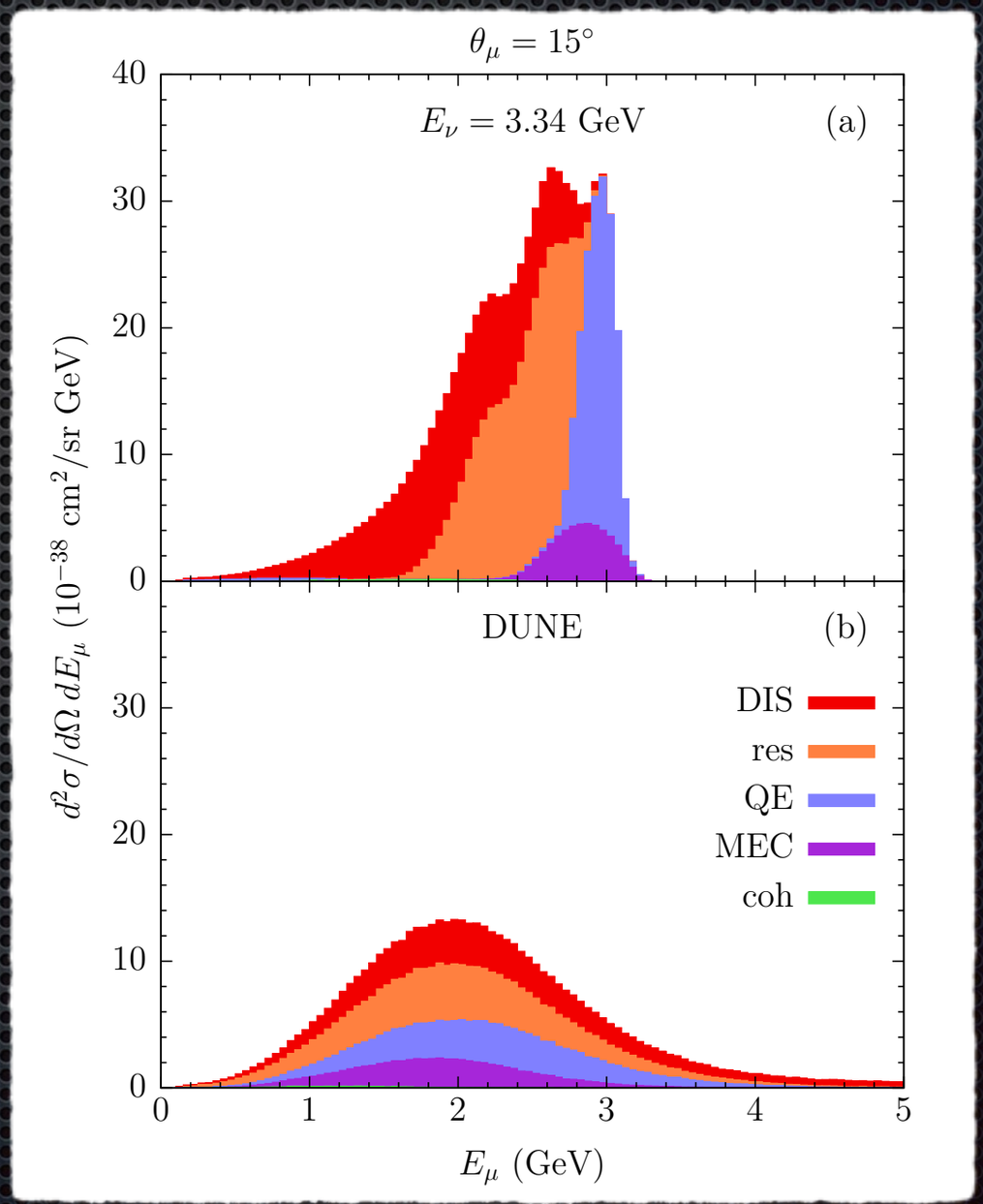
Maximal mixing excluded at 2.5σ

What are the greatest challenges?

- The problem is very rich, has many ingredients, as implemented
  - QE, RES, DIS, FSI, multi-nucleon, etc
- Which processes are the most challenging to model? Which are behind the largest discrepancies?
  - This is asked as a physics question here, not in a Snowmass sense

Neutrino scattering at several GeV

- Testing everything with neutrino scattering is challenging
  - neutrino beams are not monochromatic and energy reconstruction requires good generators, see above!
- Find an independent way to systematically test all these processes

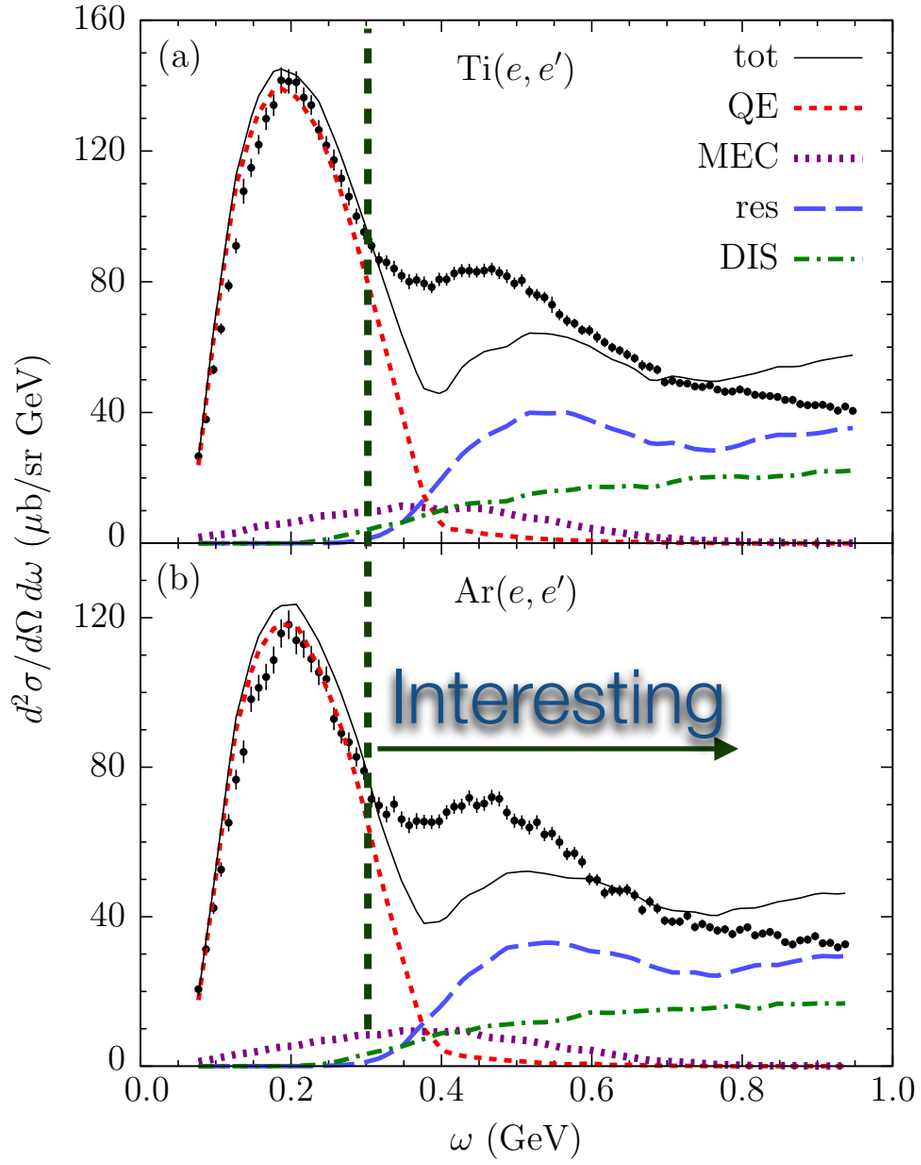


- Figure: A. Ankowski, AF, Phys Rev (2020) e-Print: 2006.11944

Use electron scattering

- Despite the different primary vertex, much physics in common:
  - Vector part of the interaction
  - Initial nucleon momentum distribution (spectral function)
  - Final state interactions (rescattering, optical potential, nuclear transparency)
  - DIS limit, hadronization at several GeV, etc
    - discussion in Sec. 2 of 1912.06140 [10.1103/PhysRevD.101.053004]
- Systematic study of generator models using a large inclusive electron scattering dataset

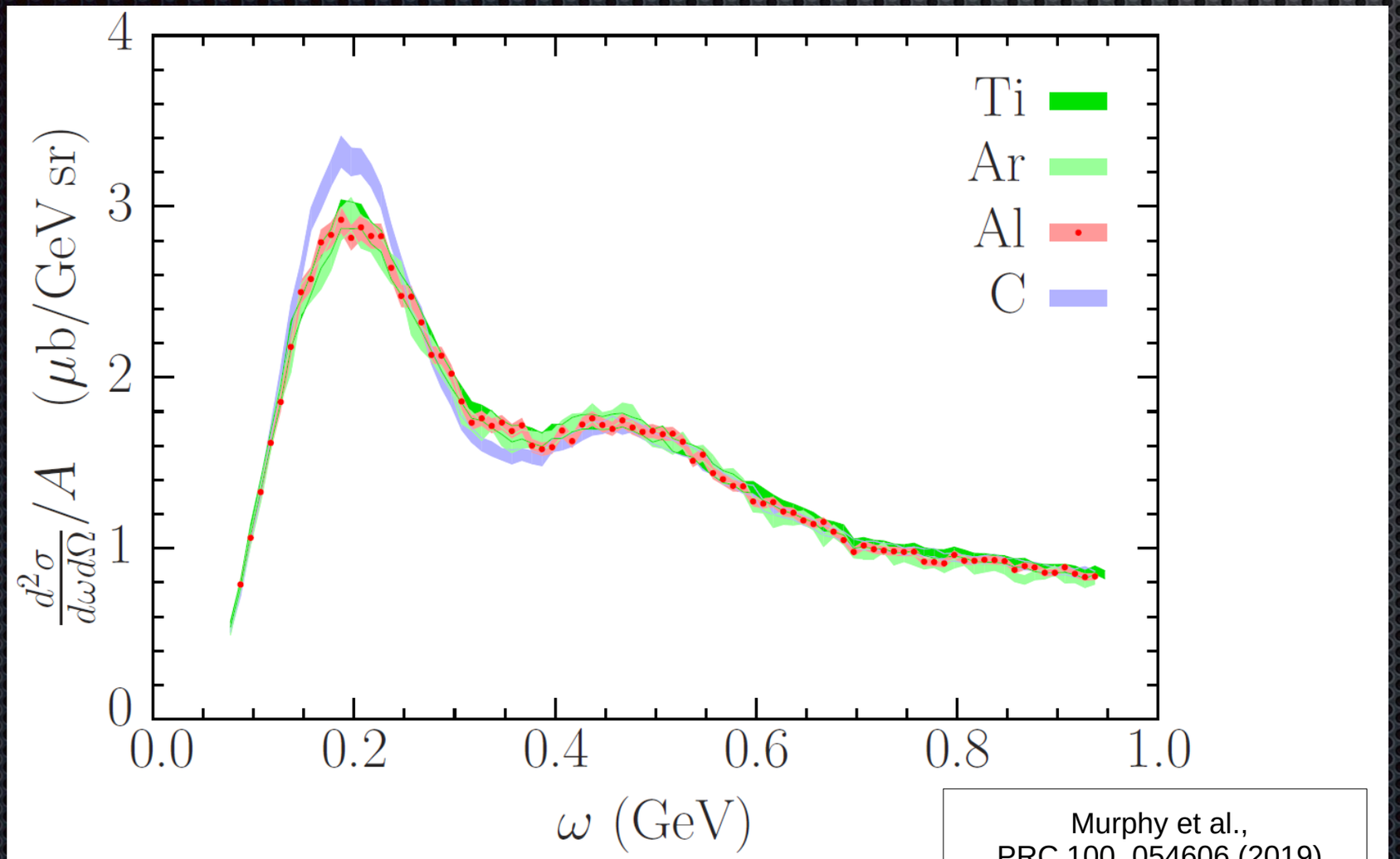
Invitation



2.2 GeV electron beam
JLAB

- Predictions of GENIE v2.12.10 beyond the quasielastic peak are in dramatic disagreement with the data

A-dependence

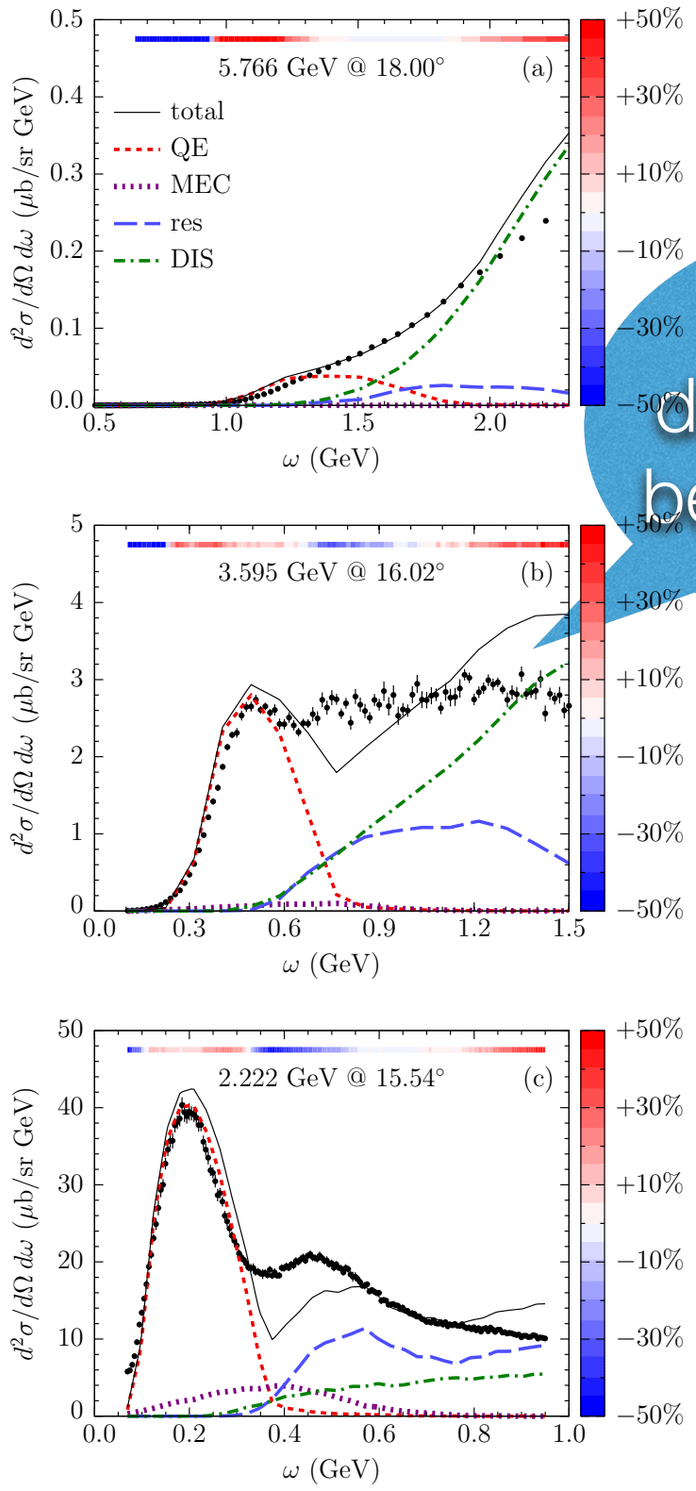


2.2 GeV electron beam
JLAB

Murphy et al.,
PRC 100, 054606 (2019)

- The same pattern for Ar, Ti, Al and C. -> not nucleus-specific -> use carbon data, for which there is abundant data gathered over decades

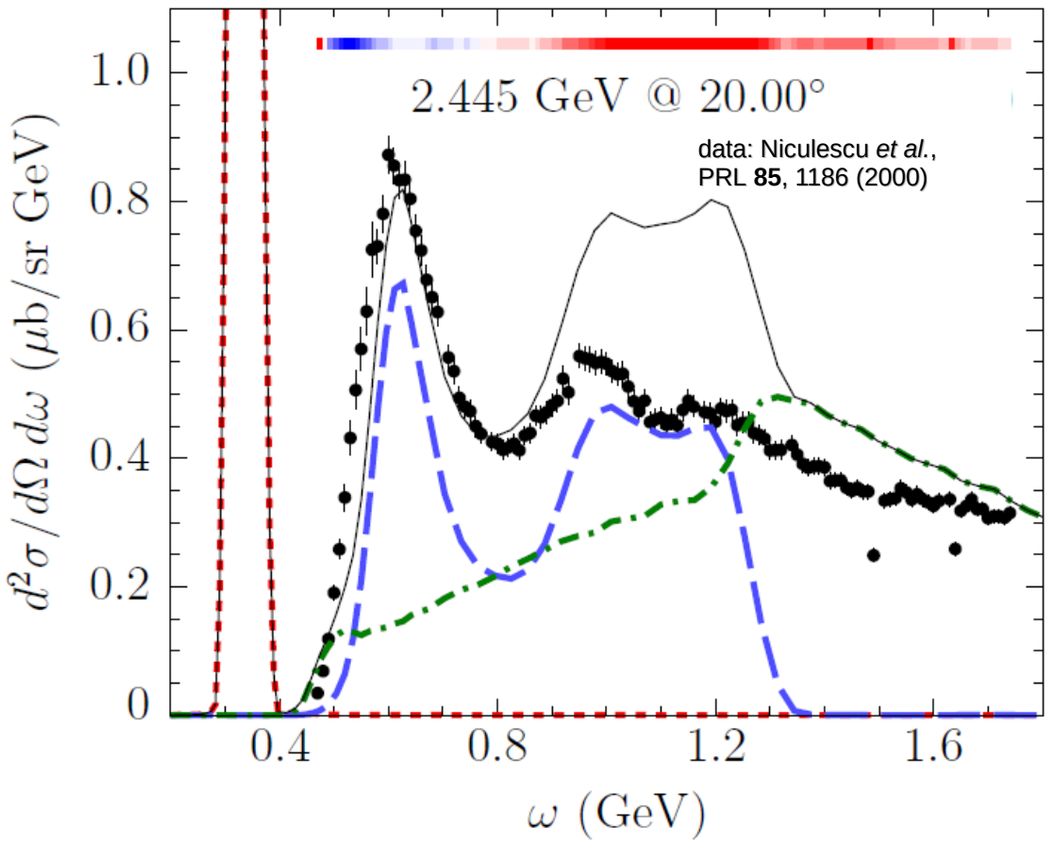
Different kinematic regimes

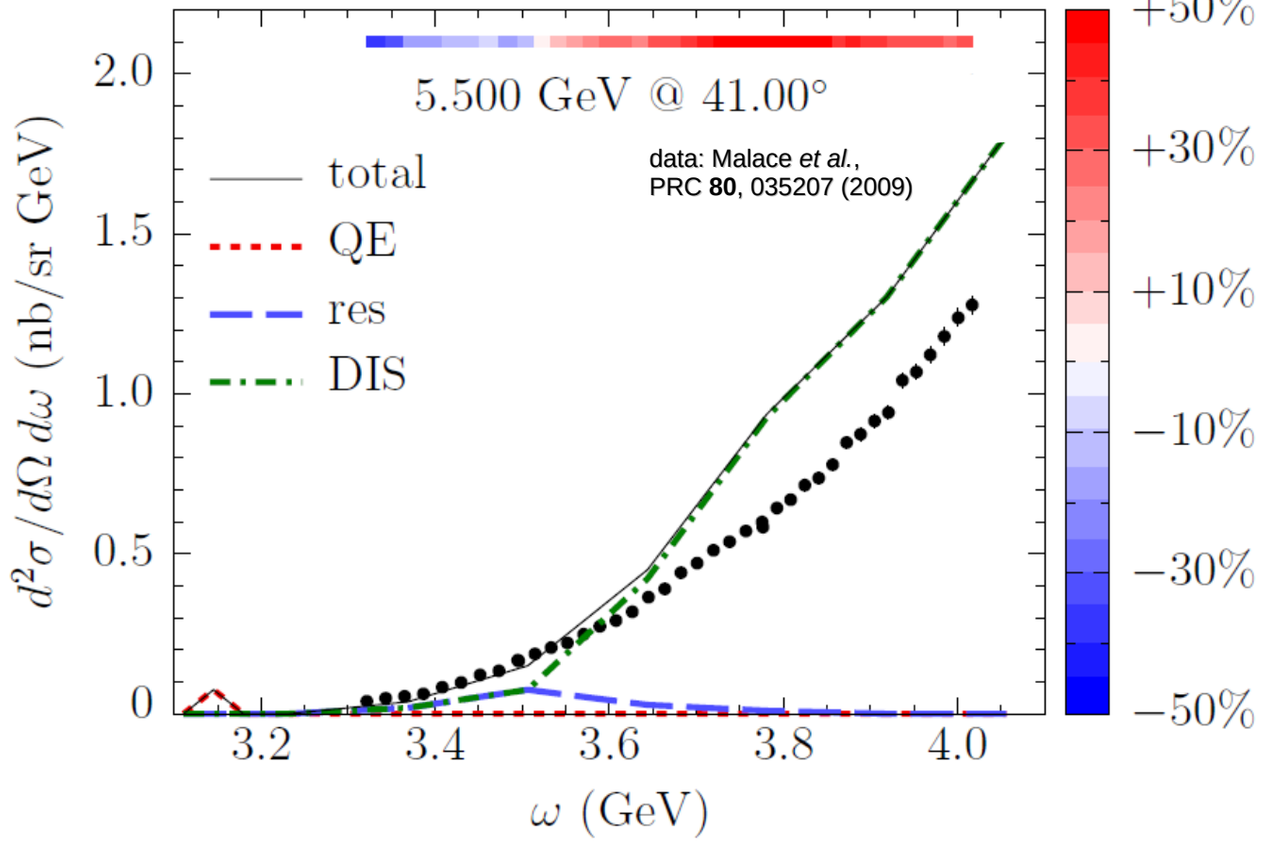


Systemic discrepancies beyond CCQE

- Problems with many other datasets

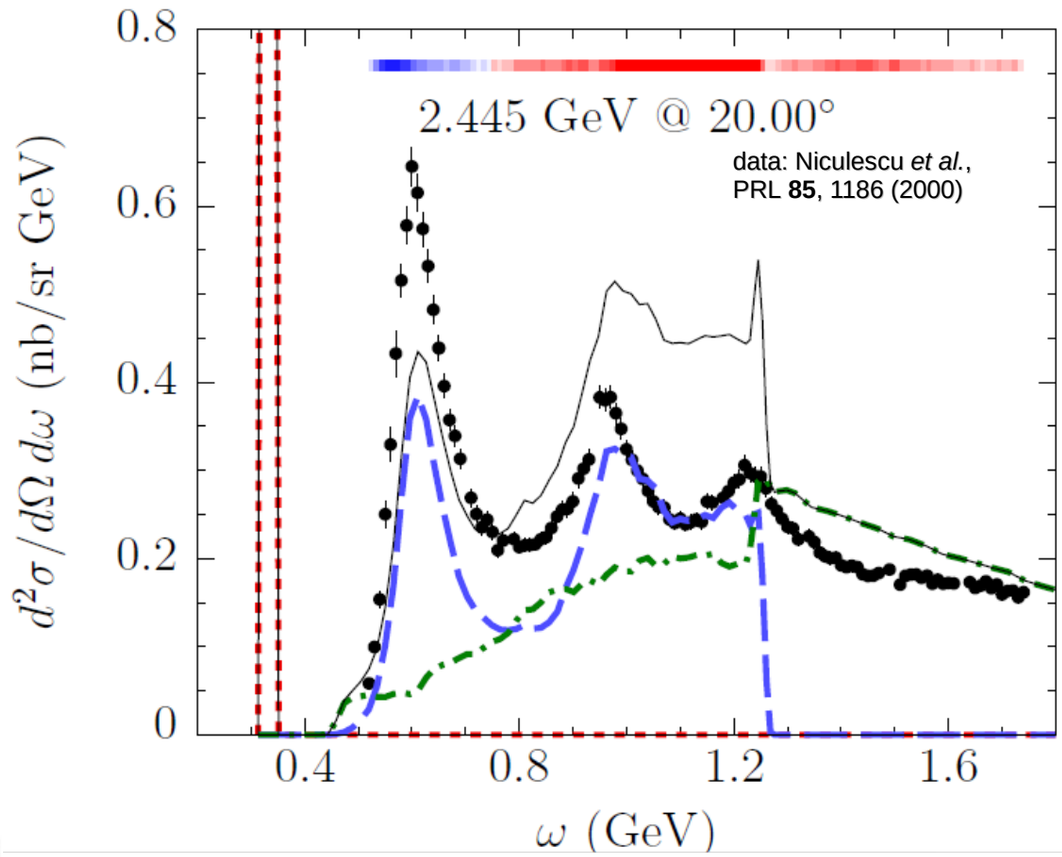
Zeroing in on the source of the error: go to simple targets

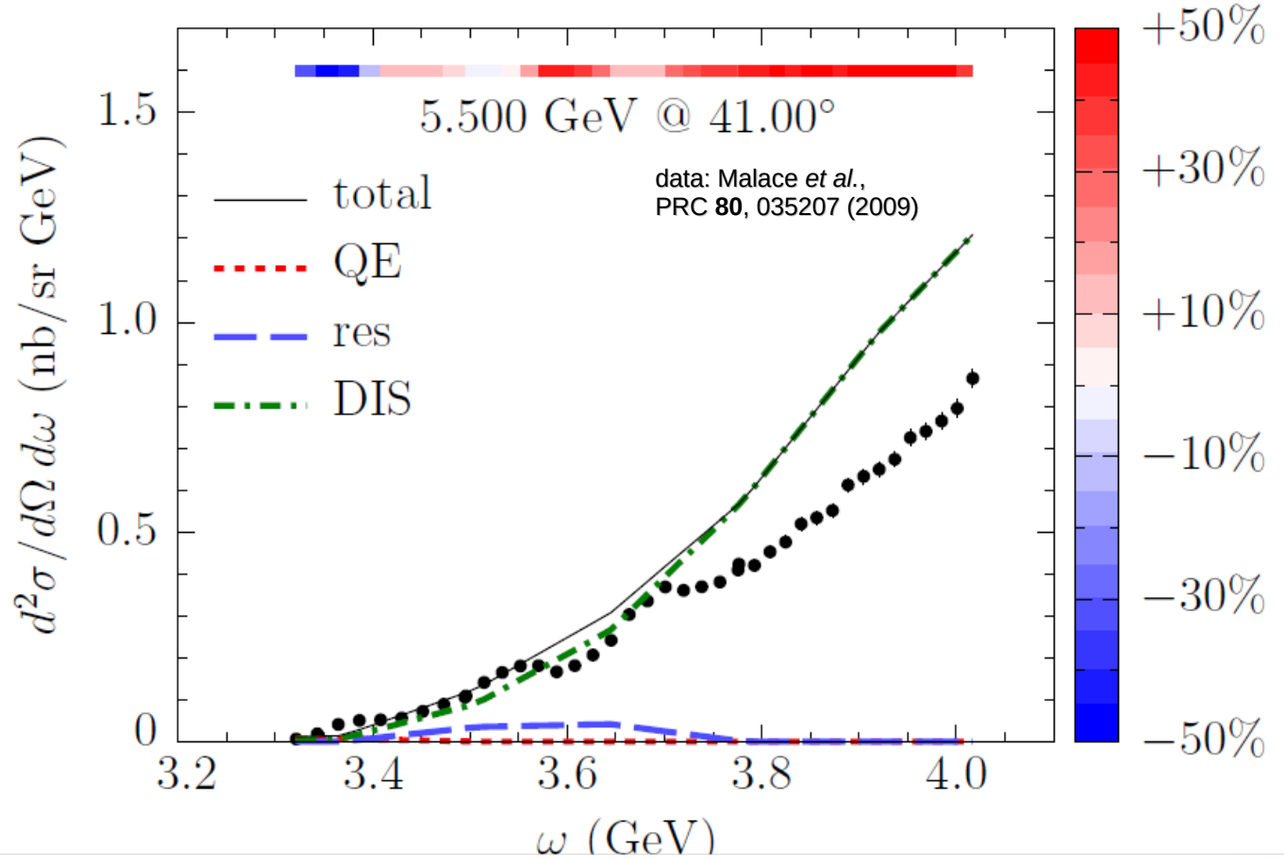




- Deuterium

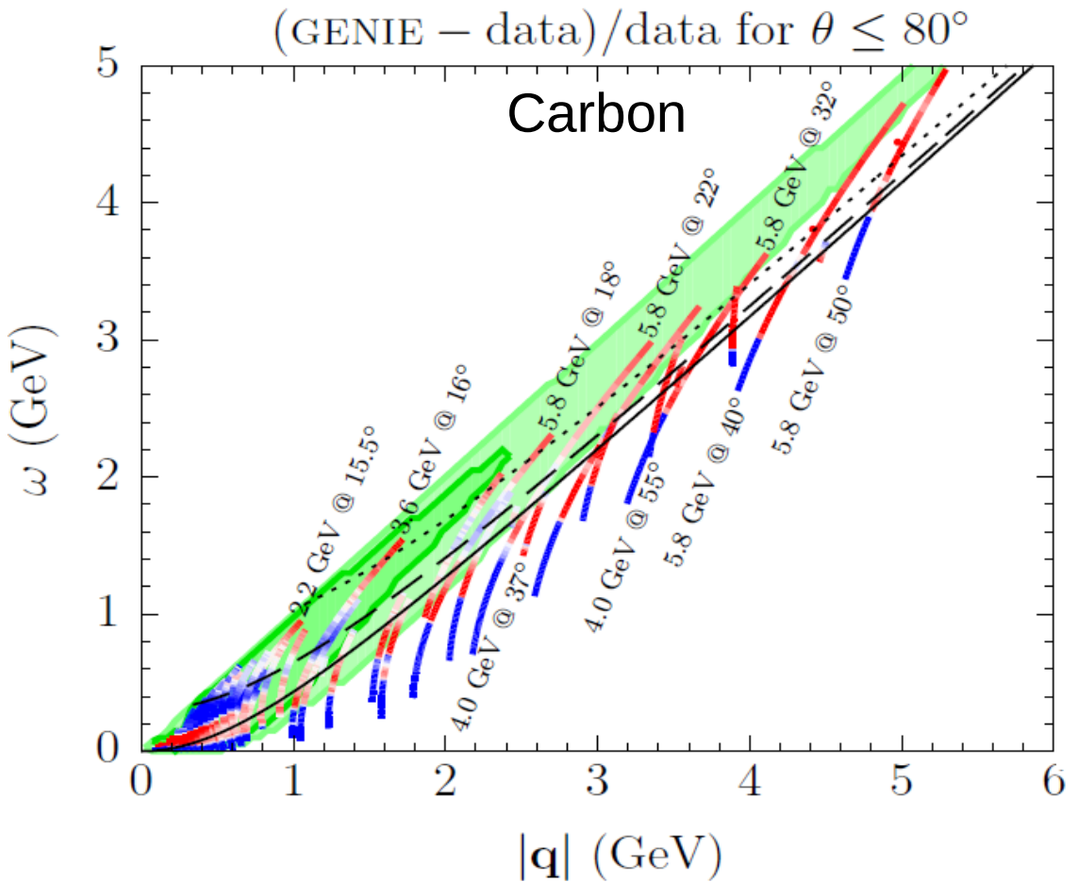
For details, see e-Print: 2006.11944
DOI: 10.1103/PhysRevD.102.053001

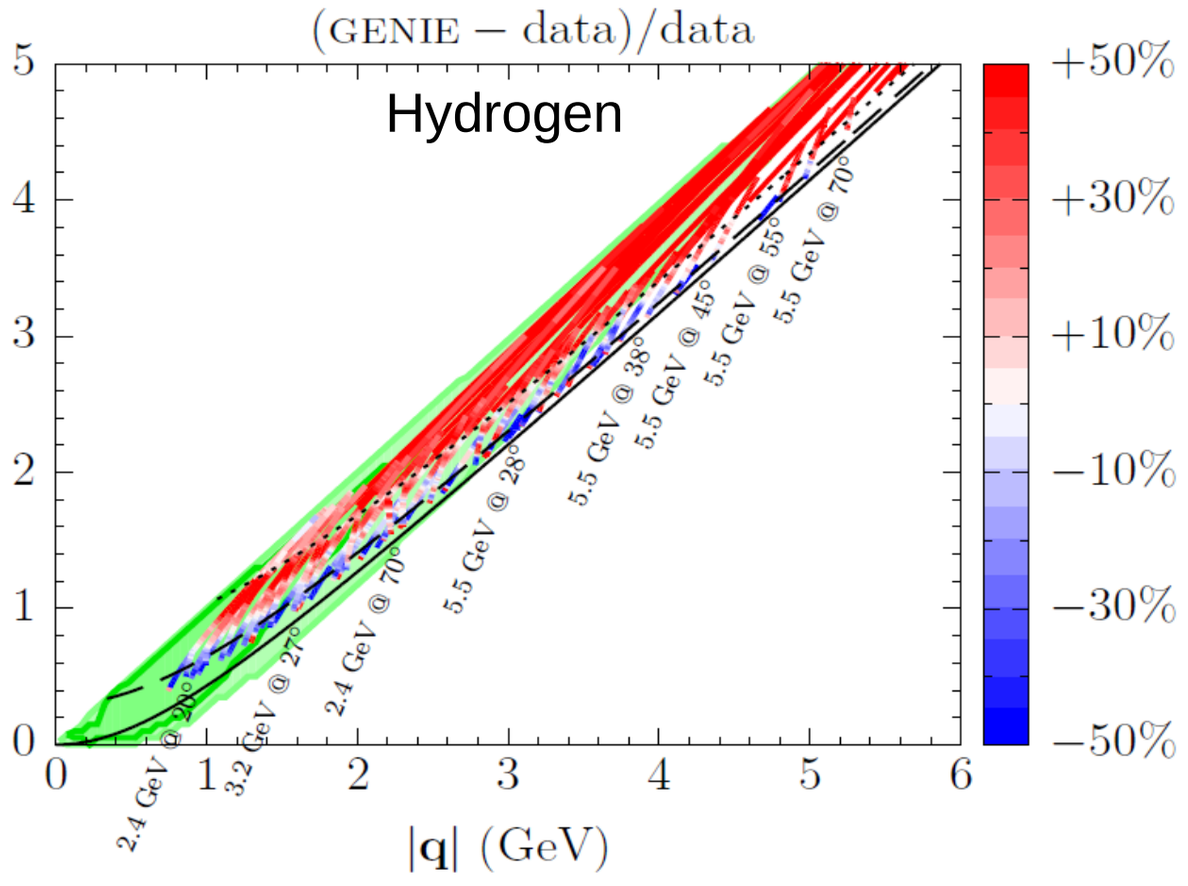




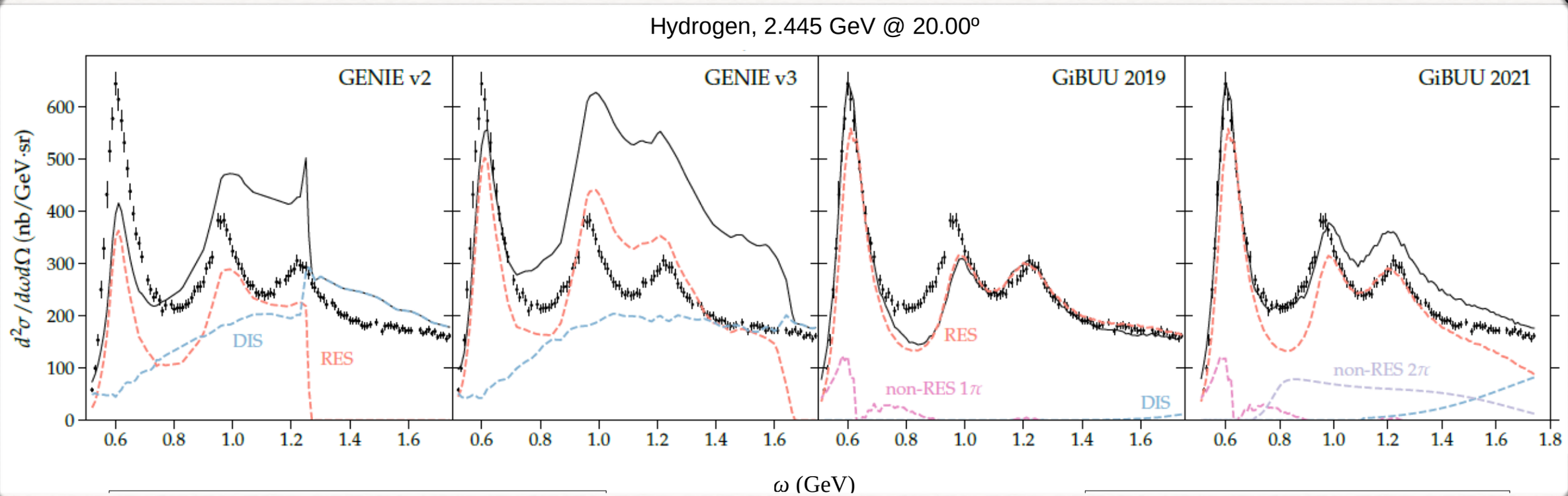
- Hydrogen
- Large discrepancies originate from the (mis)modeling of hadronic processes
- Notable double counting in the RES->DIS region

Mapping out the pattern of discrepancies





Large discrepancies persist for other generators



At high energies, the SIS region is especially challenging

A. Ankowski., A. F. & S.W. Li, in preparation
Data: Niculescu et al., PRL 85, 1186 (2000)

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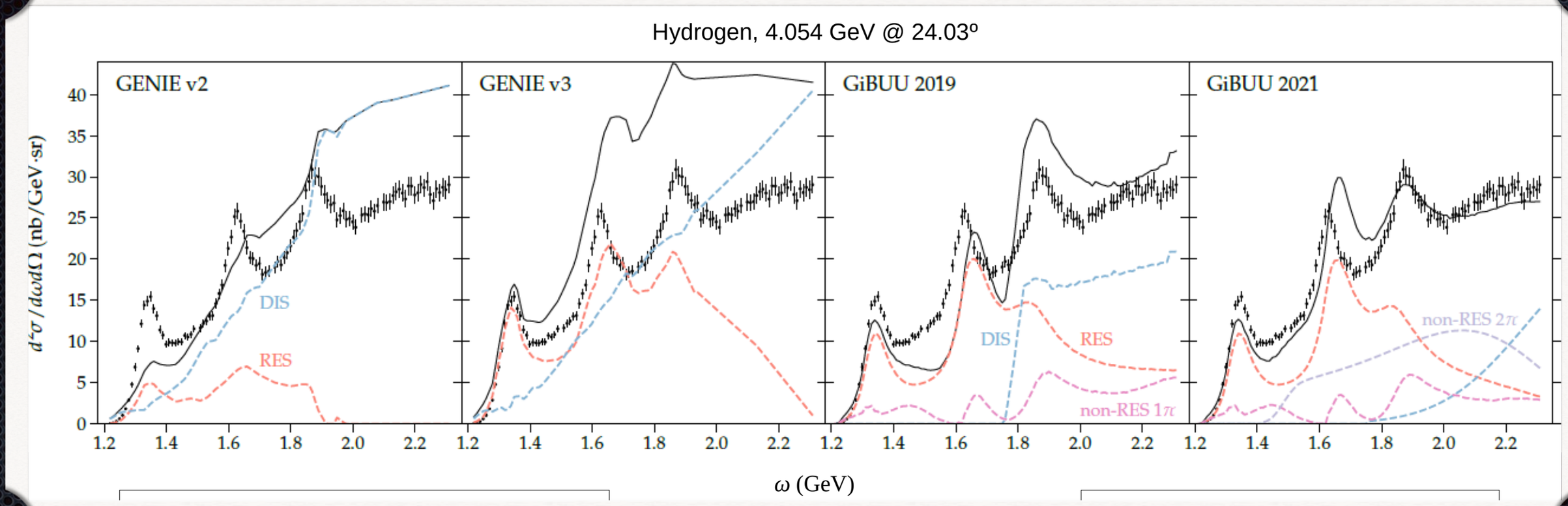

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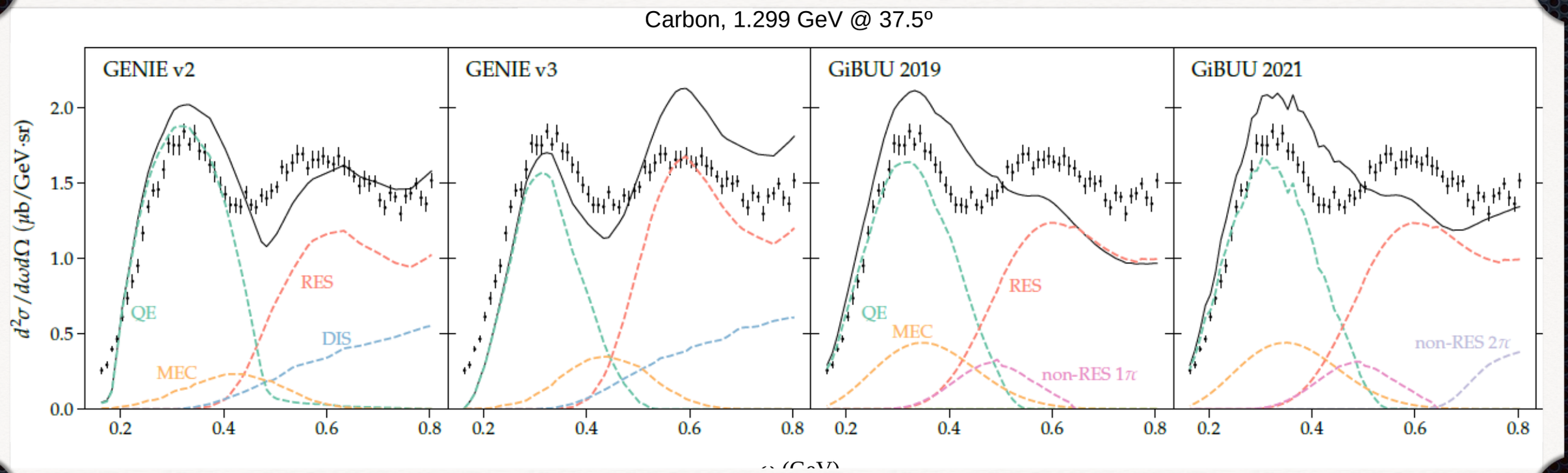
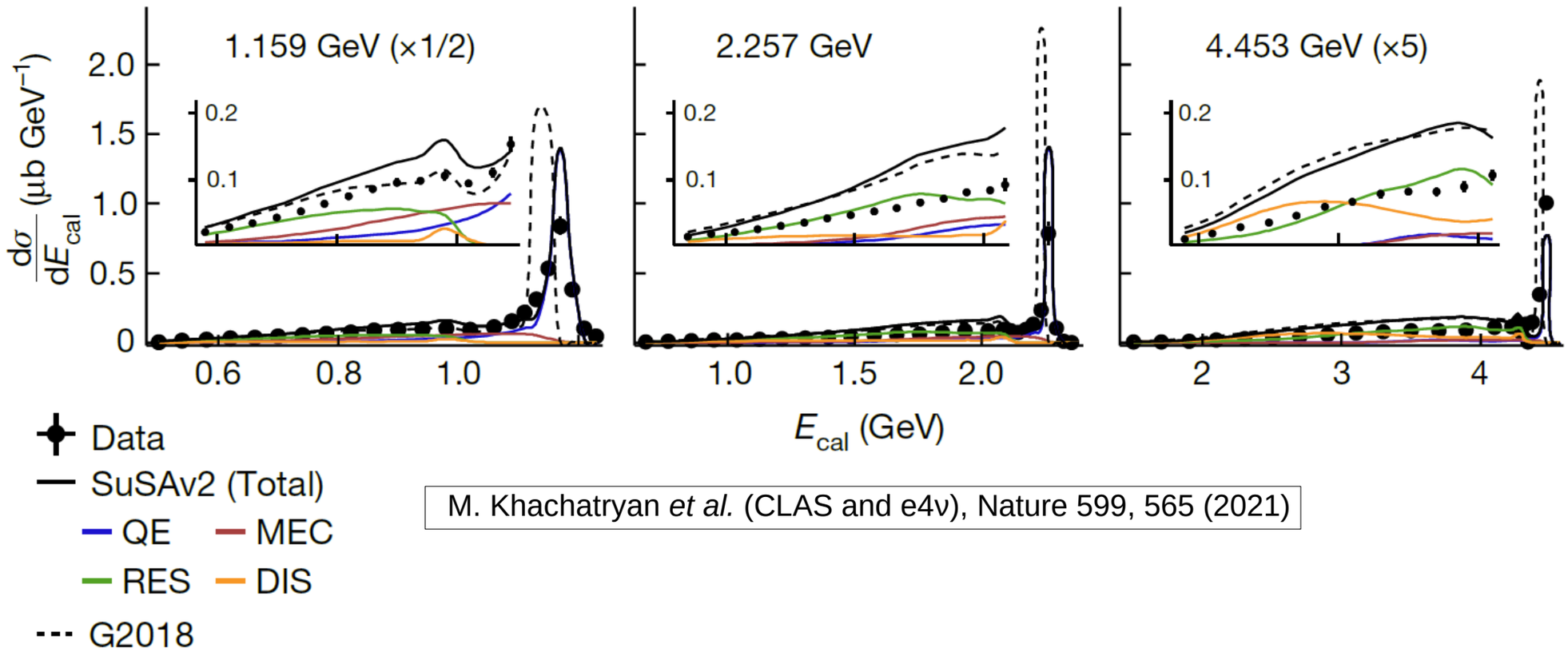


Generally, *overlaps between different mechanisms present a lot of conceptual challenge*

Instructive: comparison with e4nu data



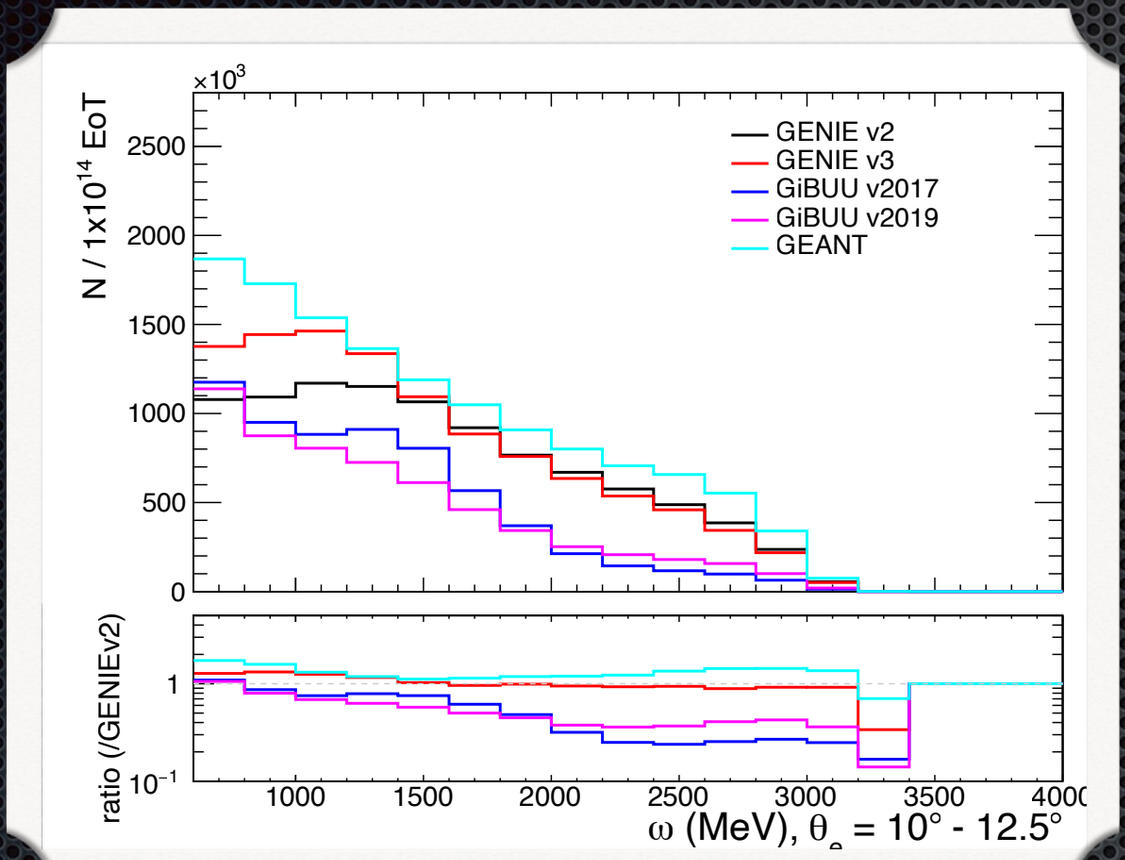
M. Khachatryan *et al.* (CLAS and e4ν), Nature 599, 565 (2021)

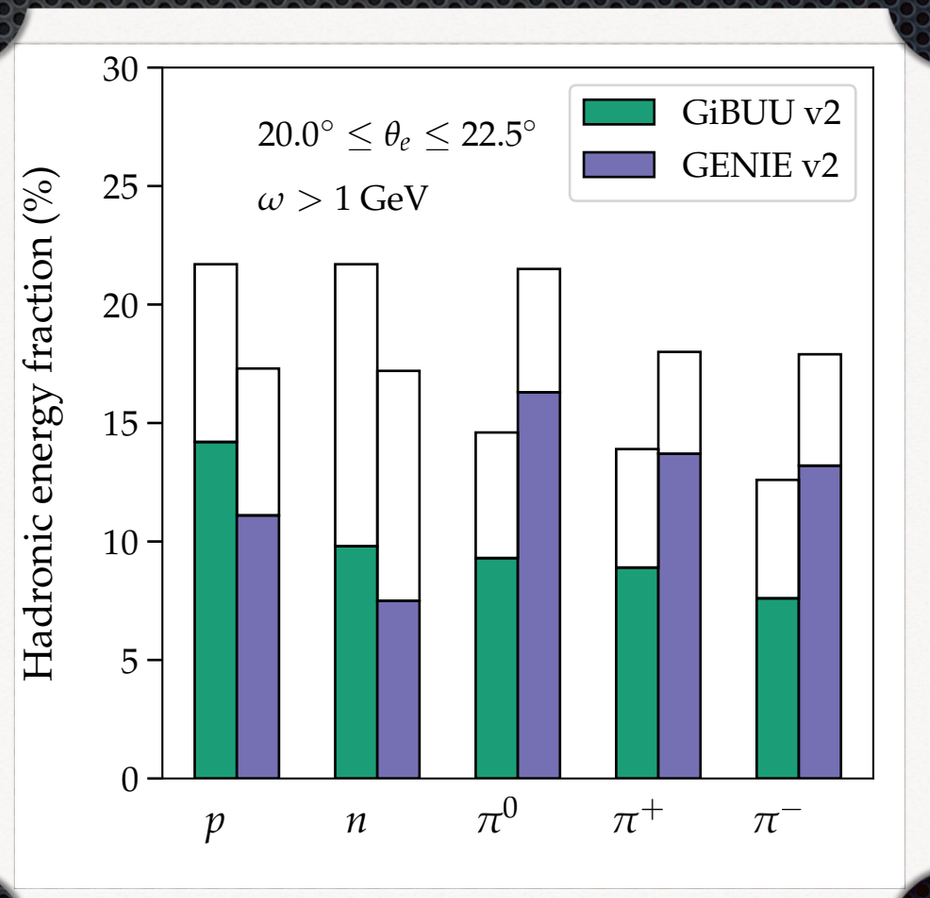
The same double-counting is manifested at high E

Summary: state of the art of MC generators

- Modern generators model the regime of several GeV as a combination of different channels. The problem is not specific to any generator version:
  - Transition from higher resonances to DIS is problematic. Yet, nearly half of DUNE events fall into this regime
  - MEC contribution added to QE by hand, typically worsens the description of the QE peak
- Generator developers must resort to ad hoc prescriptions, due to the lack of a consistent theoretical approach. This leads to discontinuities, double-counting, and other inaccuracies.
- In general, the accuracy for pion production is worse than for QE

Note I: large discrepancies among generator predictions for exclusive channels





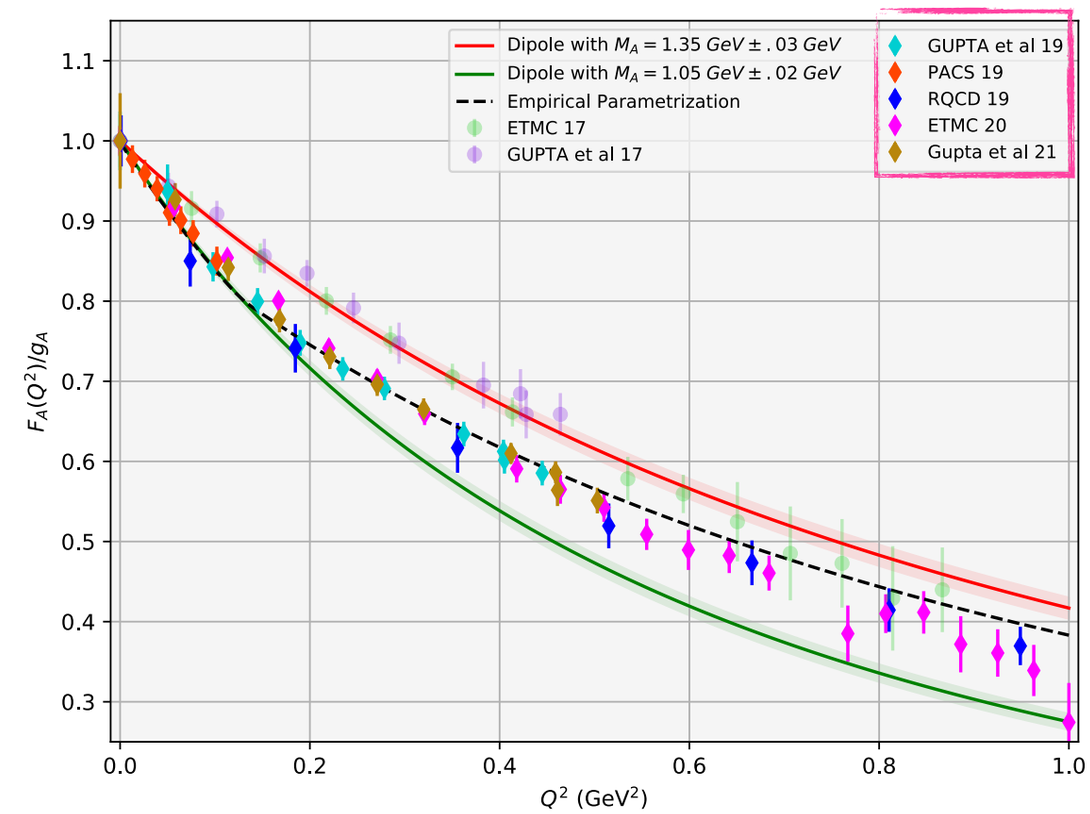
Simulation for the LDMX detector

e-Print: 1912.06140 [hep-ph]
DOI: 10.1103/PhysRevD.101.053004

Note II:Another ingredient is the nucleon axial FF

- Lattice QCD has made tremendous progress in the last decade
- Excited state contamination identified and subtracted, different methods by different groups (ETMC,NME, RQCD)
- Results agree between the groups, conserve PCAC, <u>disagree with the old dipole</u>
  - Cf. work by Hill, Paz, Meyer et al

Figure by Kevin Quirion, IU



Work with E. Passemar and her students at IU