Path to accuracy for neutrino cross sections

Artur M. Ankowski
SLAC, Stanford University

Interdisciplinary Developments in Neutrino Physics,
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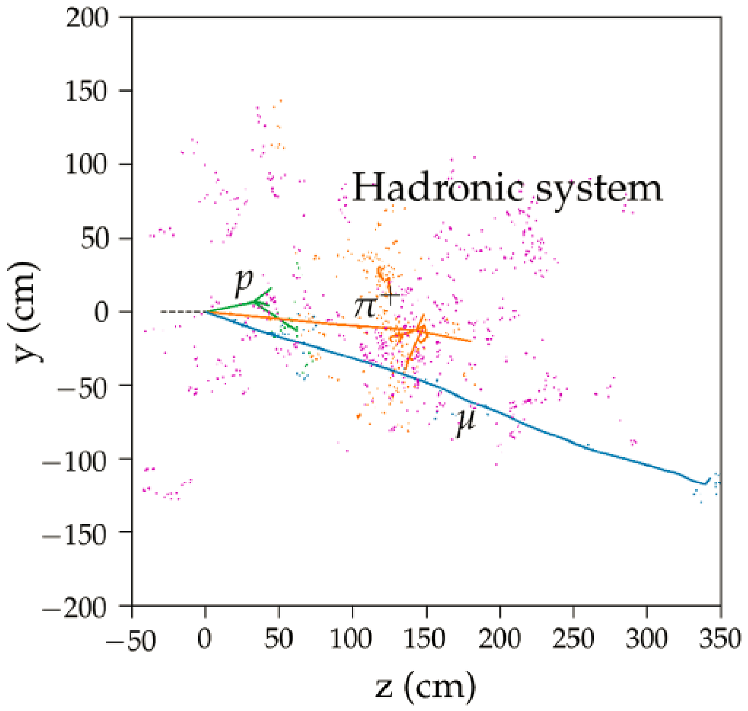
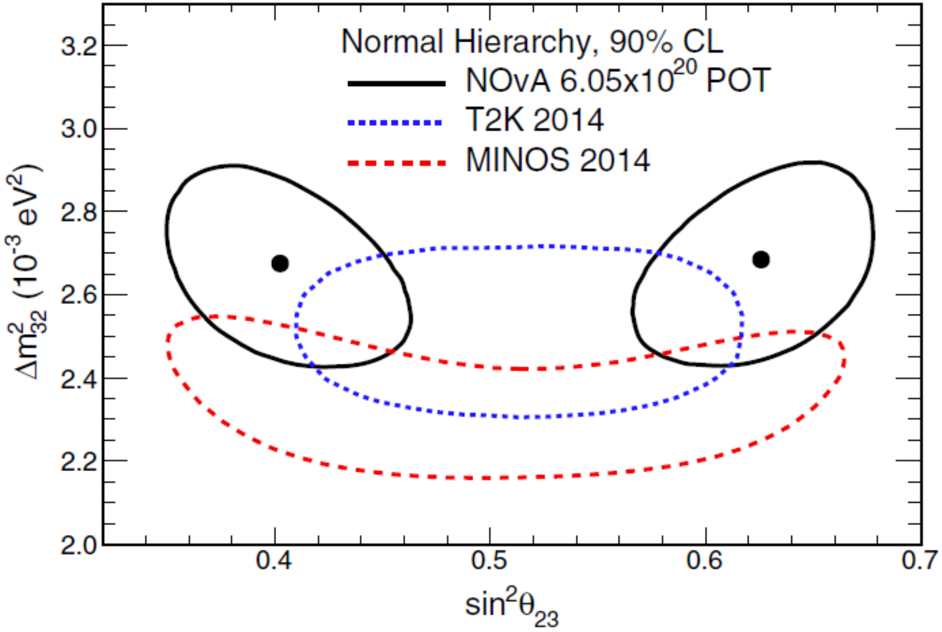
MC Generators in long-baseline neutrino physics

- Goal: extract the ν & $\bar{\nu}$ oscillation probabilities.
- Polychromatic beams, neutrino energy reconstructed from visible energy deposited by interaction products.
- Monte Carlo essential to account for the missing energy, near-far flux differences, backgrounds etc.
- For example, in DUNE, the average energy is 3.926 and 4.208 GeV (unoscillated spectrum) in the near and far detector, respectively (2021 fluxes).
- Accuracy of simulations translates into the accuracy of the extracted oscillation parameters.
- We are no longer after $\mathcal{O}$ (1) effects, **without reliable cross sections DUNE cannot succeed.**

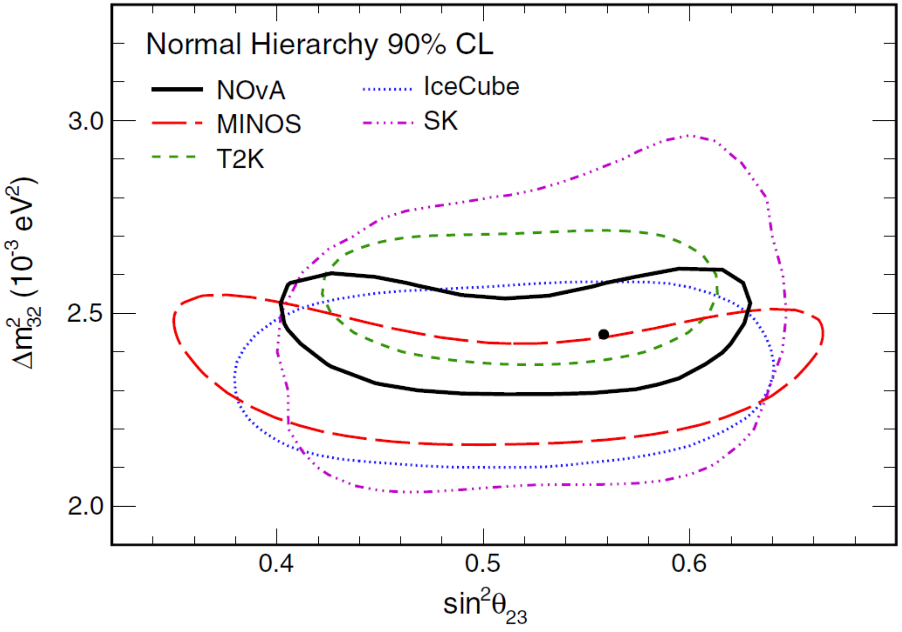


A. Friedland & S.W. Li, PRD 99, 036009 (2019)

Concrete example: NOvA

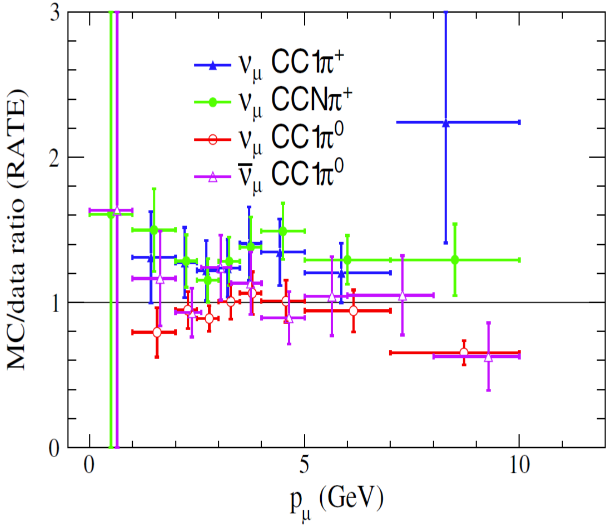


Acero *et al.* (NOvA), PRL 118, 151802 (2017)

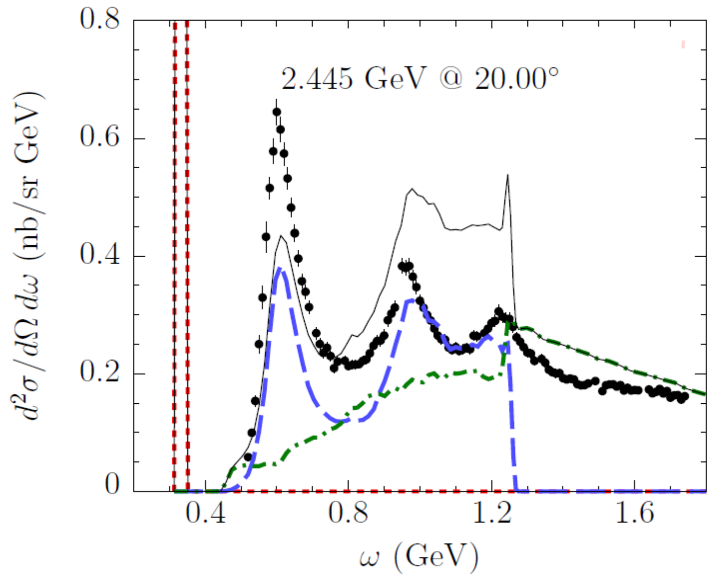


Acero *et al.* (NOvA), PRD 98, 032012 (2018)

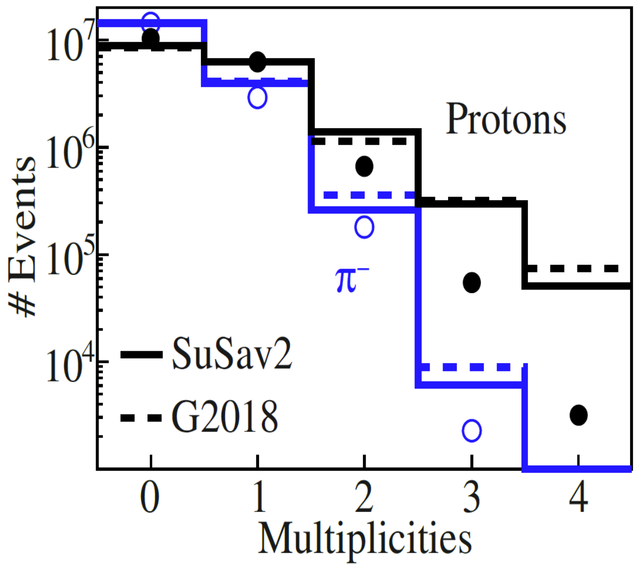
"This change was caused by three changes ... The largest effect was due to new simulations and calibrations."



P. Stowell *et al*. (MINERvA), PRD 100, 072005 (2019)



A.M.A. & A. Friedland, PRD 102, 053001 (2020)



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

Are neutrino data sufficient?

"… fitting to individual MINERvA pion production channels produces [ν_μCC1$\pi^\pm$, ν_μCC$N\pi^\pm$, ν_μCC1π^0, and $\bar{\nu}_\mu$CC1π^0] **different best-fit parameters** …"

"Because the four channels cover different kinematic regions and contain different physics, it is **difficult to pinpoint the origin of the discrepancy** …"

"The main conclusion … is that current **neutrino experiments** … **should think critically about single pion production** models and uncertainties, as the Monte Carlo models which are currently widely used in the field are unable to explain multiple datasets, even when they are from a single experiment."

P. Stowell *et al*. (MINERvA), PRD 100, 072005 (2019)

Are neutrino data sufficient?

"… **nuclear models available to modern neutrino experiments give similar results** … **none of which is confirmed by the data.** … More theoretical work is needed to correctly model nuclear effects … from the quasielastic to the deep inelastic regime."

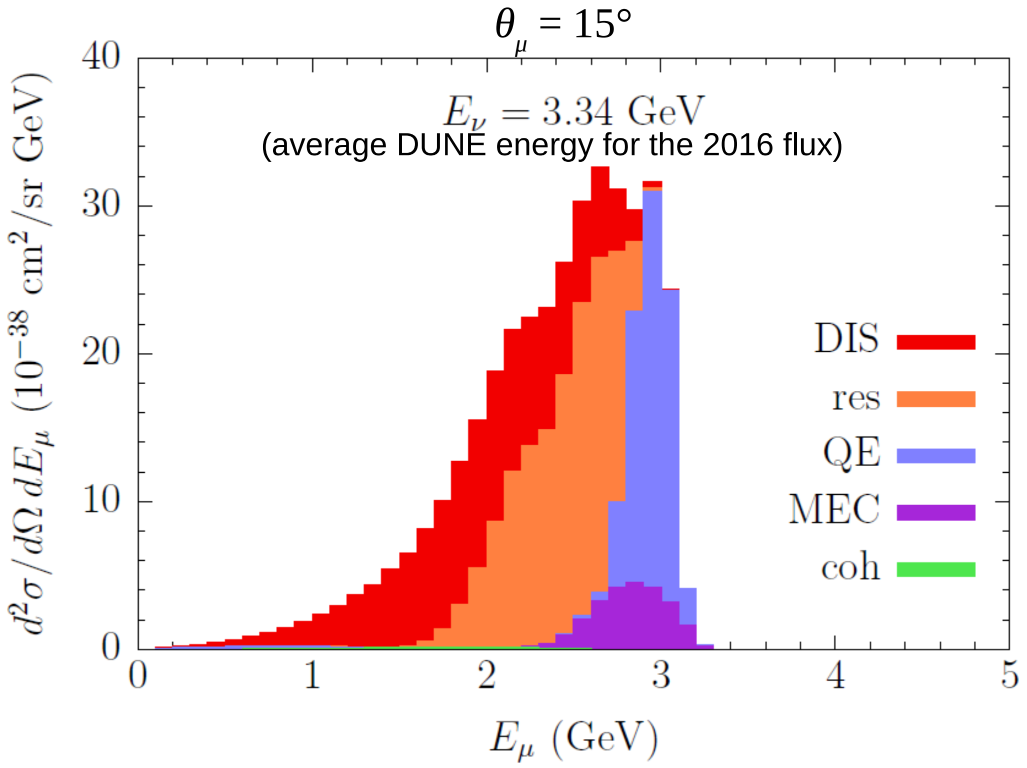
B. G. Tice *et al.* (MINERvA), PRL 112, 231801 (2014)

"This measurement indicates that some form of **a low Q^2 RES suppression helps** to achieve better agreement …"

"The double- and single-differential cross sections show similar tensions with the model predictions. These results demonstrate that **improvements will need to be made to neutrino-interaction models if precision neutrino oscillation experiments hope to better constrain the systematics** …"

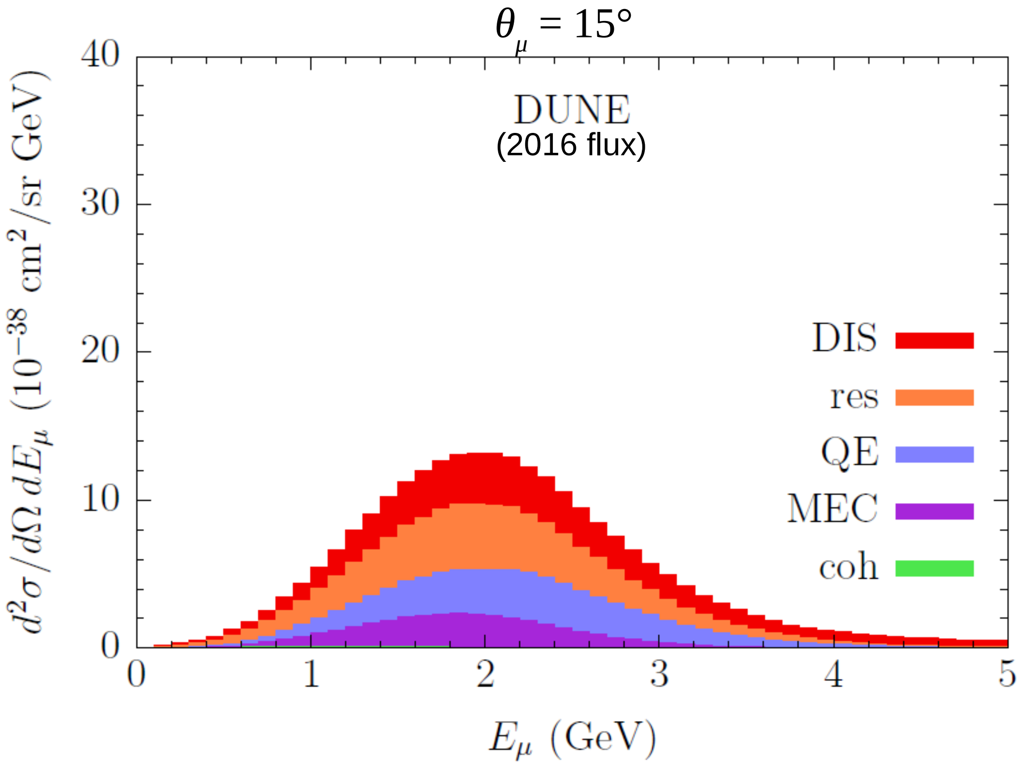
A. Filkins *et al.* (MINERvA), PRD 101, 112007 (2020)

Neutrino double differential cross section



A.M.A. & A. Friedland, PRD 102, 053001 (2020)

Neutrino double differential cross section

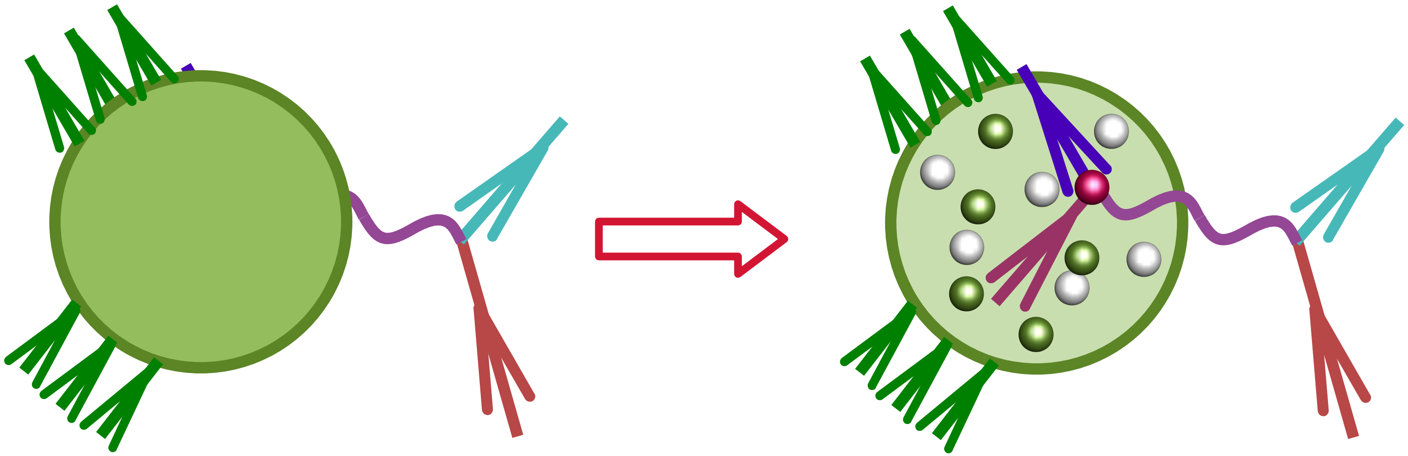


A.M.A. & A. Friedland, PRD 102, 053001 (2020)

Impulse approximation

At DUNE kinematics, the dominant process of neutrino-nucleus interaction is **scattering off a single nucleon**, with the remaining nucleons acting as a spectator system.

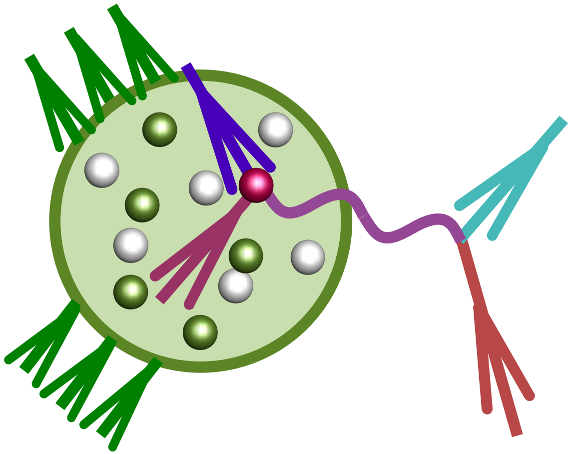
This description is valid when the momentum transfer |**q**| is high enough (|**q**| ≳ 200 MeV).



Impulse approximation

To calculate the neutrino-argon cross sections we need to know

- elementary cross sections (QE, resonant pion production, DIS ...)
- proton and neutron spectral functions (distributions of the initial momenta and energies, correlations between nucleons, …)
- final-state interactions (nuclear transparency, optical potentials)
- hadronization



Electrons and neutrinos

For scattering in a given angle and energy, ν's and e's differ almost exclusively due to the elementary cross sections.

Electron-scattering data can provide information on

- the vector contributions to elementary neutrino cross sections
- proton and neutron spectral functions (Ar & Ti targets)
- hadronization (H & D targets)
- final-state interactions (Ar & Ti + H & D targets)

Electron data allow MC validation, reduction of systematic uncertainties, as well as their rigorous determination.

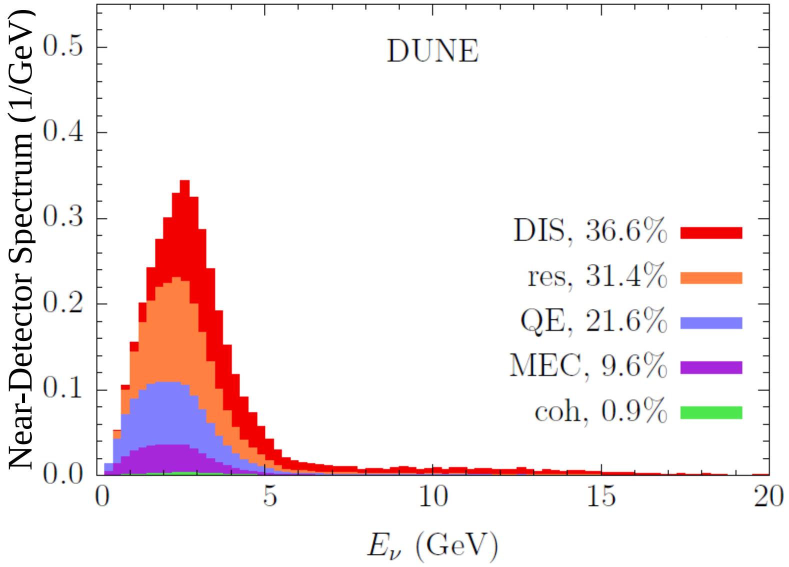
A.M.A., A. Friedland, S. W. Li, O. Moreno, P. Schuster, N. Toro & N. Tran, PRD 101, 053004 (2020)

Which cross sections deserve most attention?

Different channels contribute. To address the needs of DUNE we need to understand

- which channels are most problematic?
- what are the origins of the discrepancies?
- what are possible improvements?

As e^{-}'s and ν's probe nuclei in a very similar way, we can use electron-scattering data to test our Monte Carlo generators.



A.M.A. & A. Friedland, PRD 102, 053001 (2020)

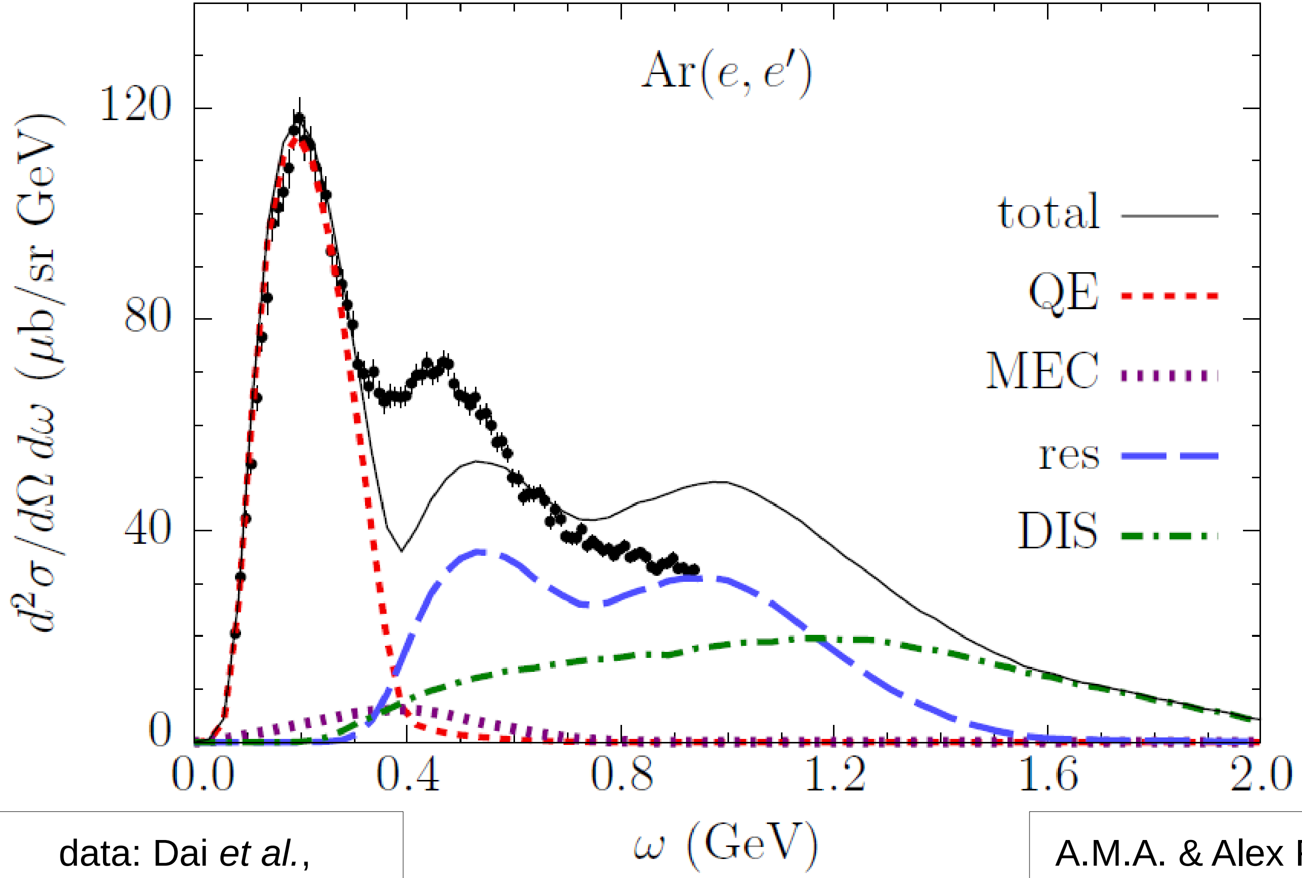
GENIE 2 in a nutshell

The MC generator most broadly used in neutrino physics, including DUNE studies.

Mission statement: “The GENIE Collaboration shall provide electron-nucleus, hadron-nucleus and nucleon decay generators in the same physics framework as the neutrino-nucleus generator.”

- Nuclear model: Fermi gas (Bodek & Ritchie ‘81)
- Quasielastic (Rosenbluth ‘50, Llewellyn-Smith ‘72)
  + MEC (Lightbody & O’Connell ‘88, Dytman ‘13)
- Resonance excitation (Rein & Sehgal ‘81)
- Deep-inelastic scattering (Bodek & Yang ‘05)

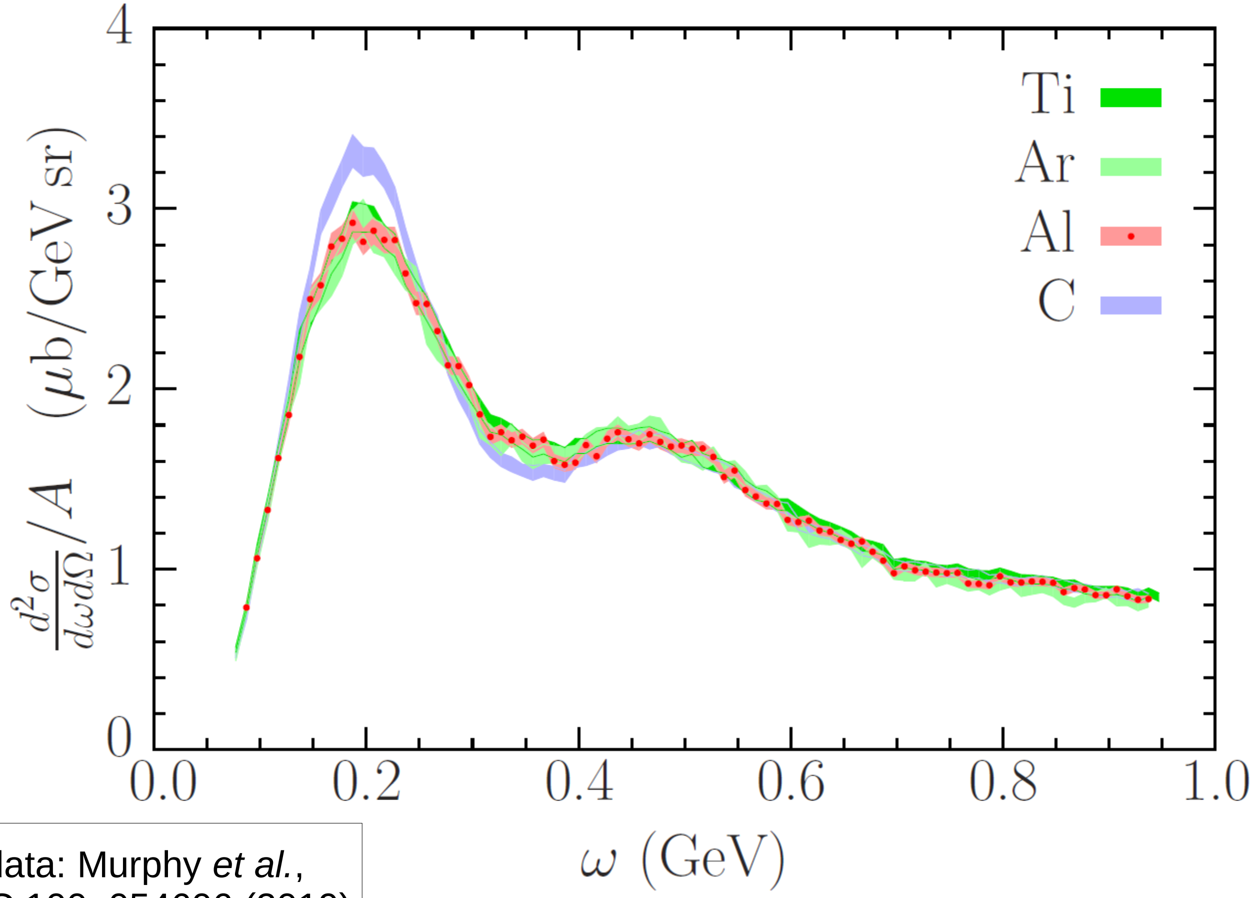
Electron scattering on argon



data: Dai *et al.*,
PRC 99, 054608 (2019)

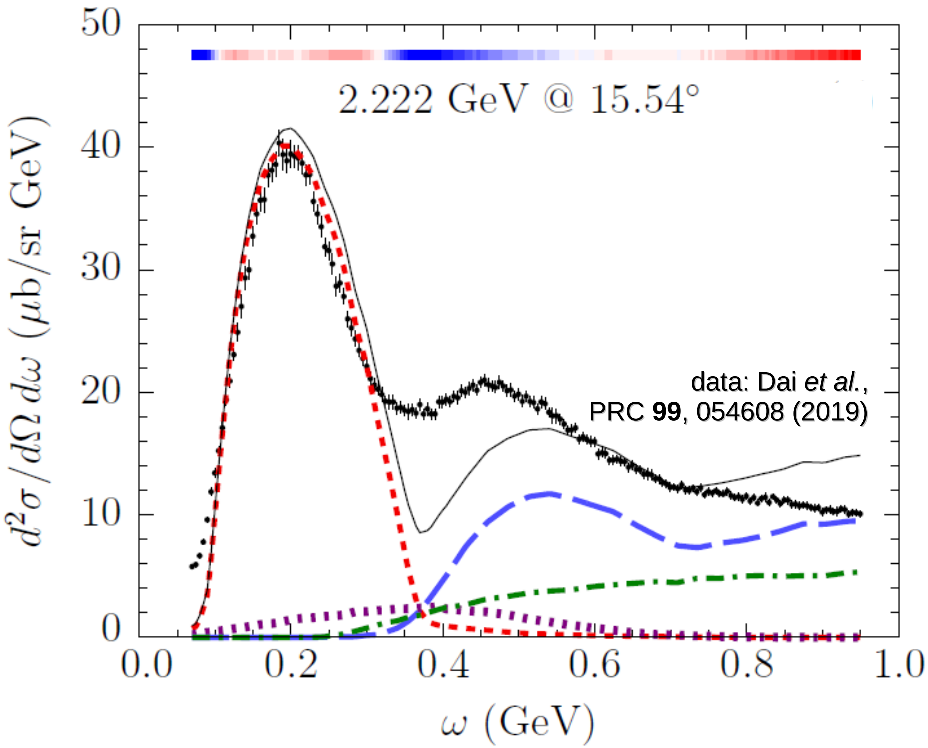
A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

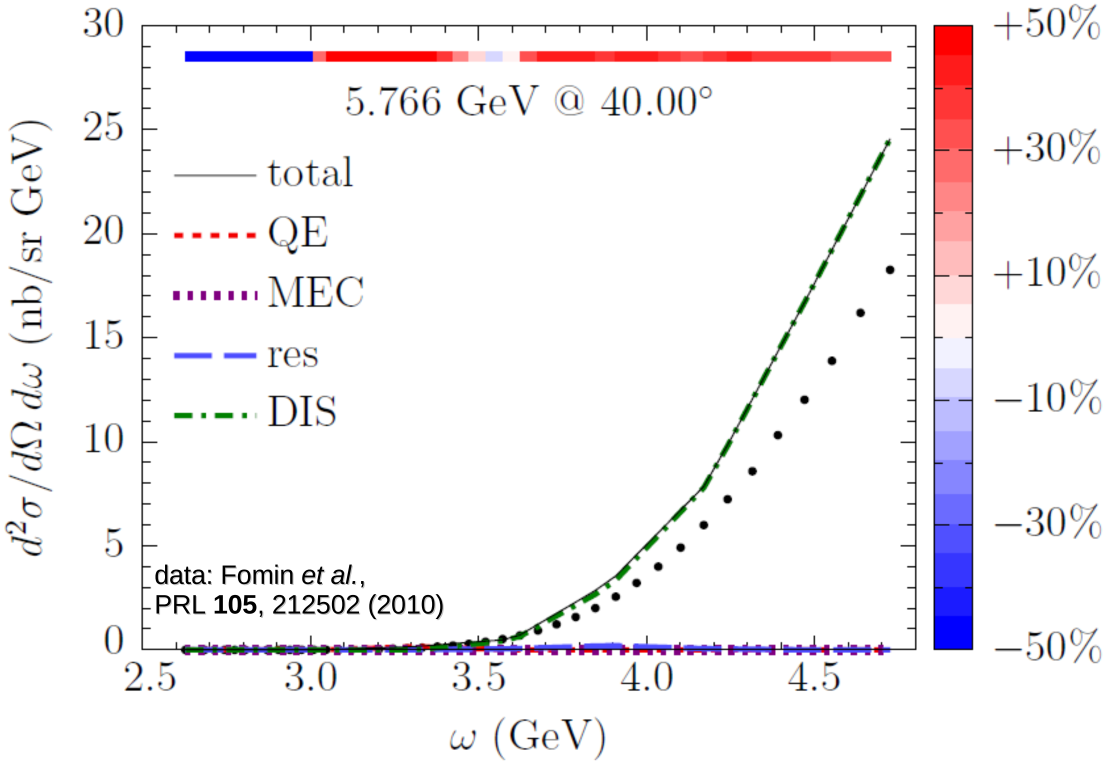
Data *A*-dependence



data: Murphy *et al.*,
PRC 100, 054606 (2019)

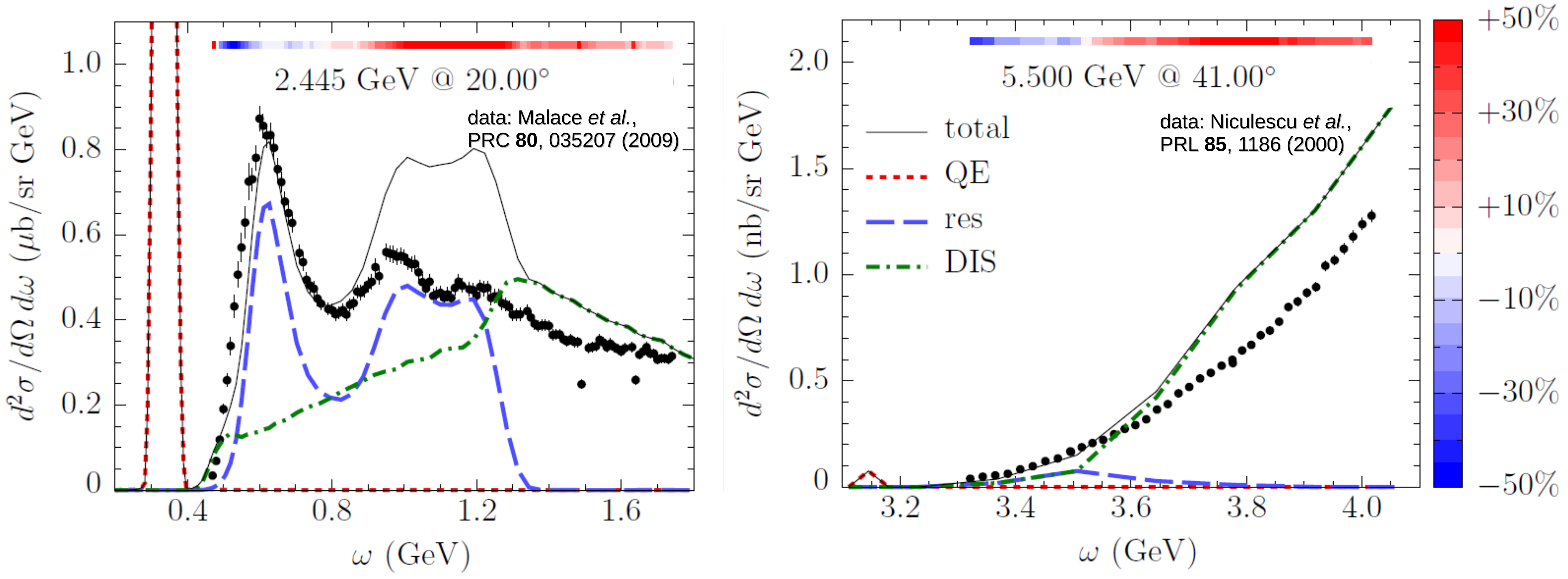
Electron scattering on carbon





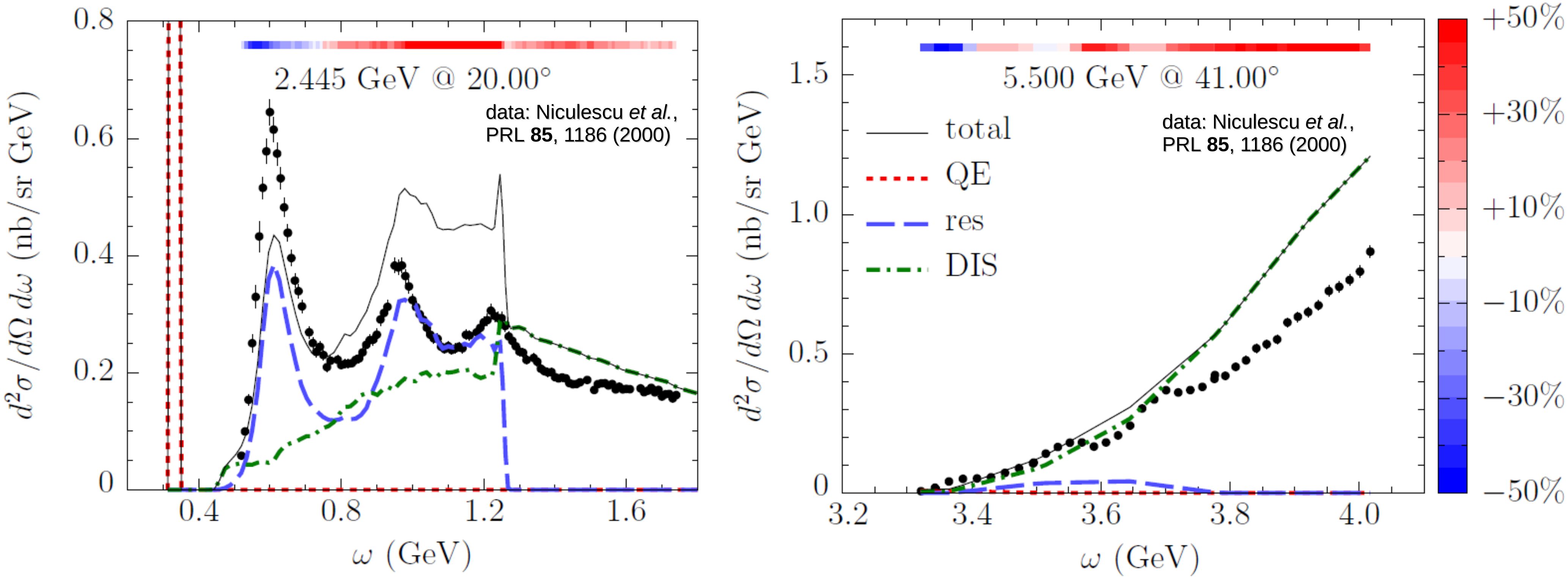
A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

Electron scattering on deuterium



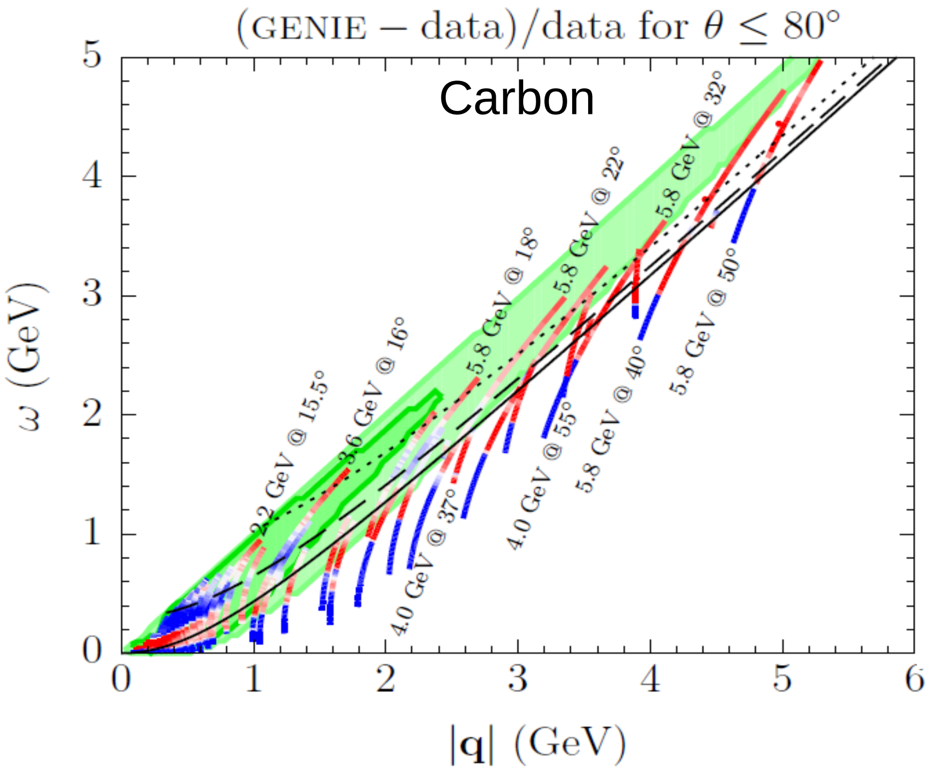
A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

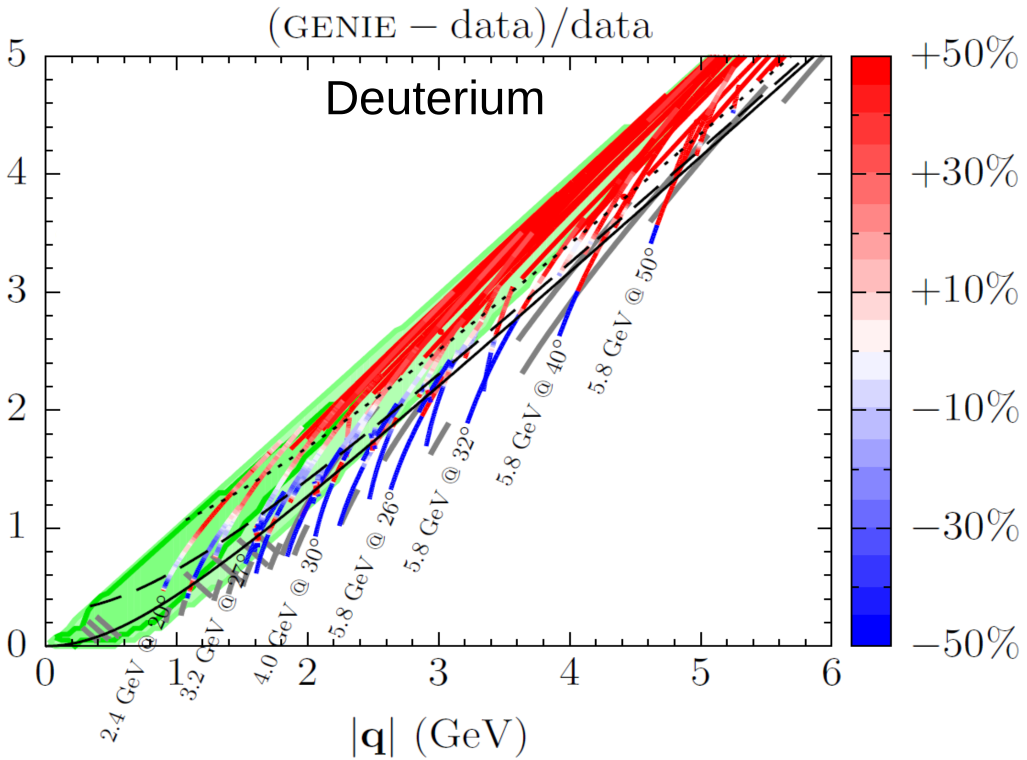
Electron scattering on hydrogen



A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

Are these issues general and relevant?





A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

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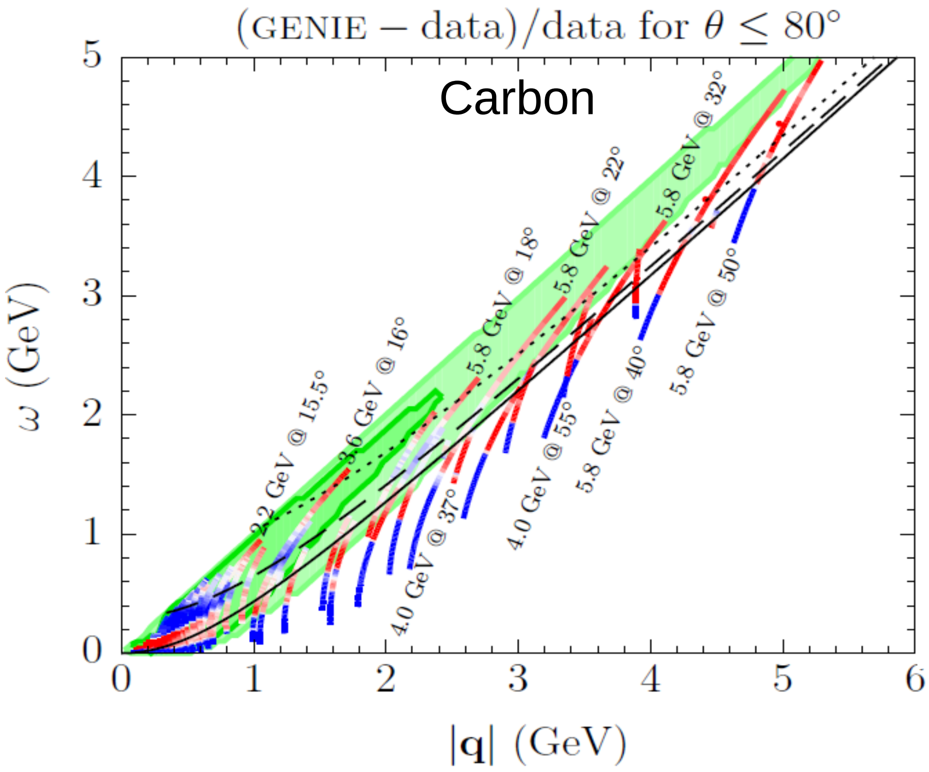
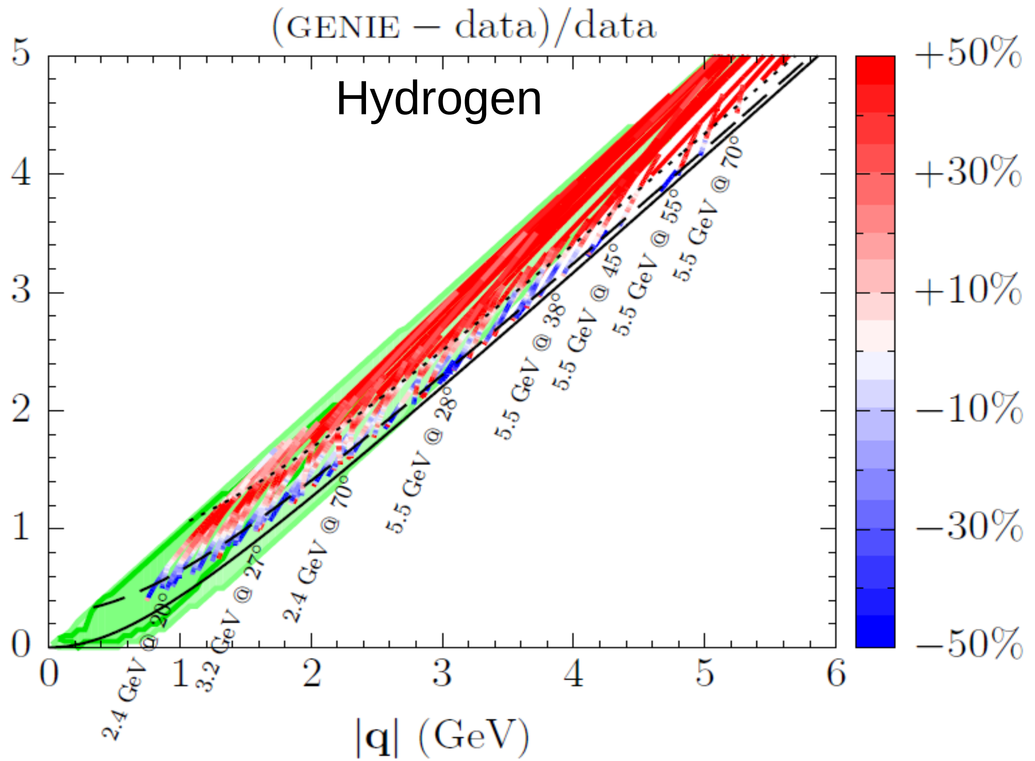




A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

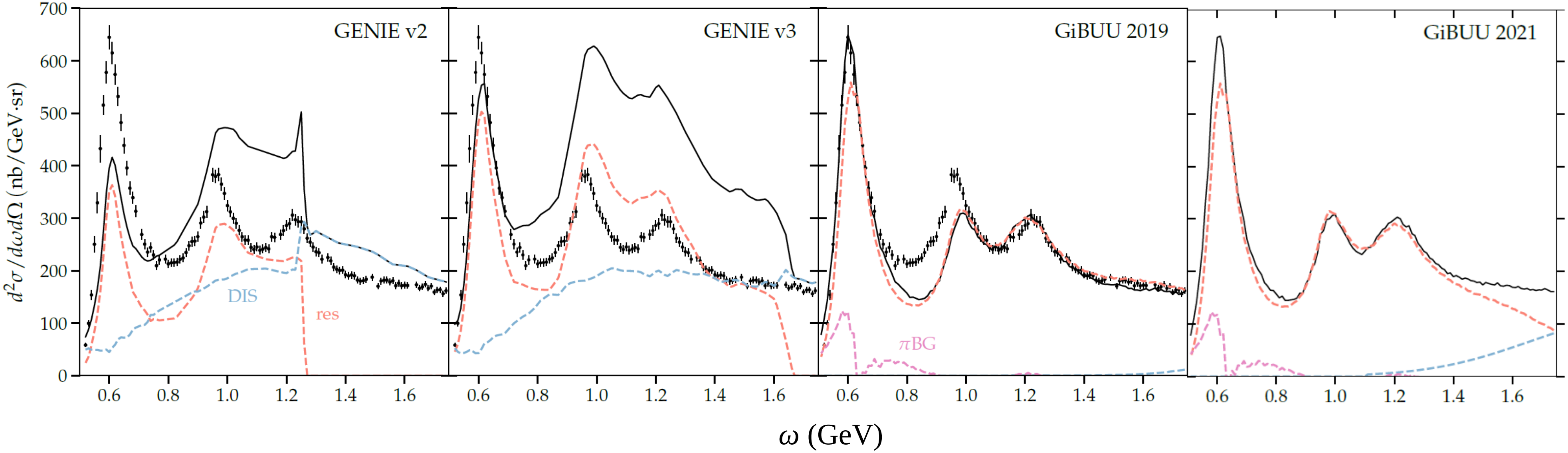
Findings for GENIE 2

- In the quasielastic peak GENIE works best (some implementation issues observed), but the contribution of meson-exchange currents worsens it for higher energy transfers.
- In complex nuclei, the Δ peak position is not correct. Nuclear implementation issue. Strength underestimated. Better pion production model necessary.
- Higher resonances clearly overestimated (double counting and lack of interference). Conceptual problem: no theory available.
- Deep-inelastic scattering significantly overestimated, also for the data used by Bodek & Yang. Implementation issue.

A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

Are these issues common between generators?

Hydrogen, 2.445 GeV @ 20.00º

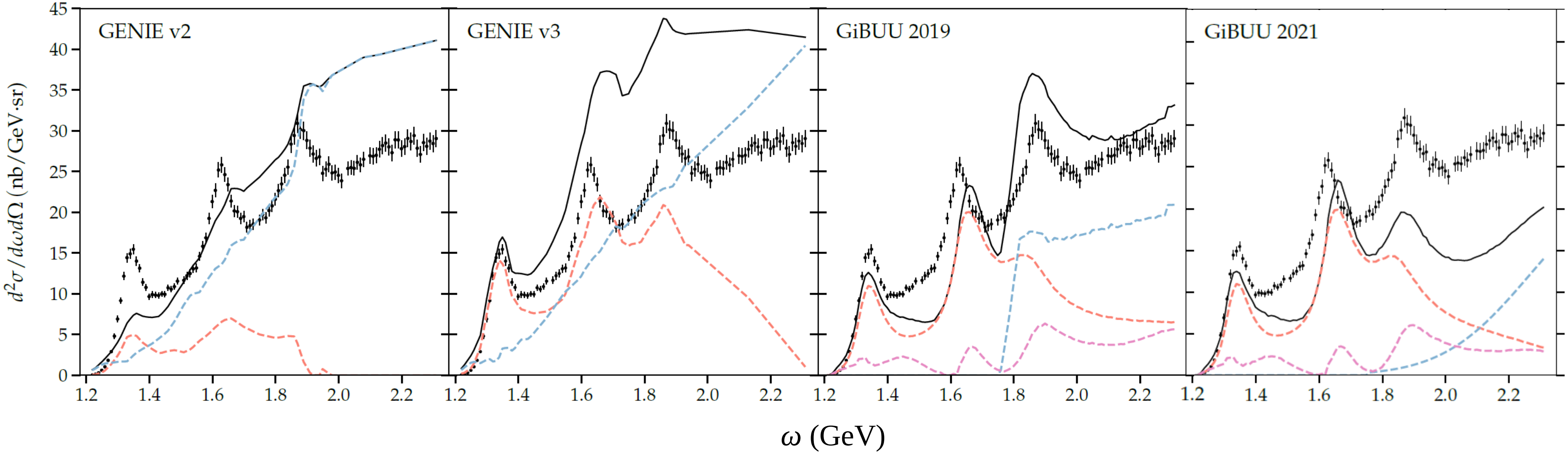


data:
Niculescu *et al.*, PRL 85, 1186 (2000)

A.M.A., A. Friedland & S.W. Li,
in preparation

Are these issues common between generators?

Hydrogen, 4.054 GeV @ 24.03º

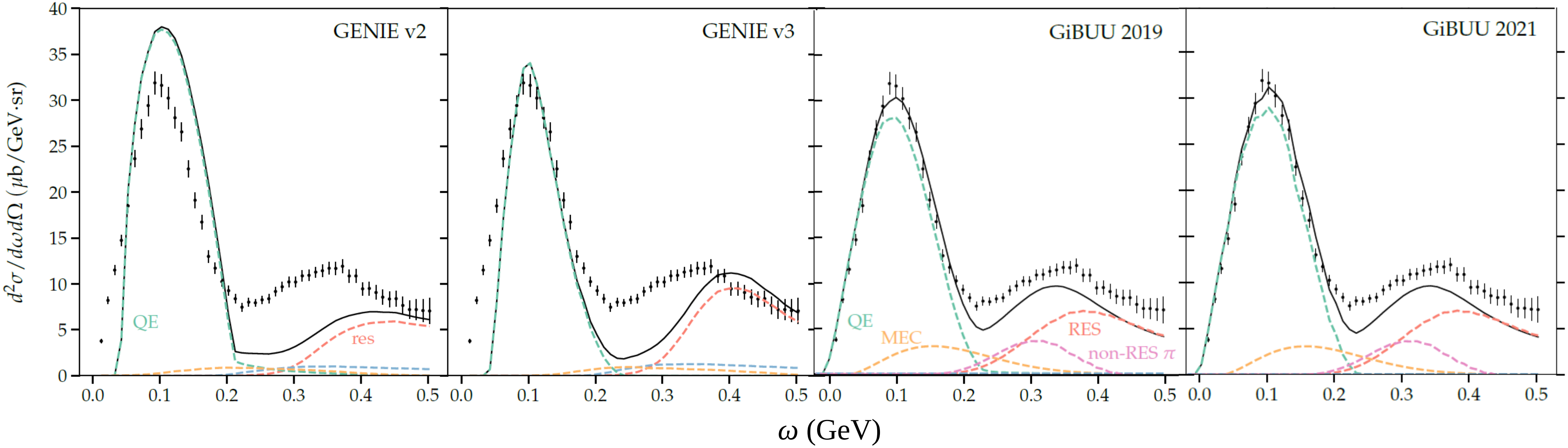


data:
Niculescu *et al.*, PRL 85, 1186 (2000)

A.M.A., A. Friedland & S.W. Li, in preparation

Are these issues common between generators?

Carbon, 0.68 GeV @ 36º

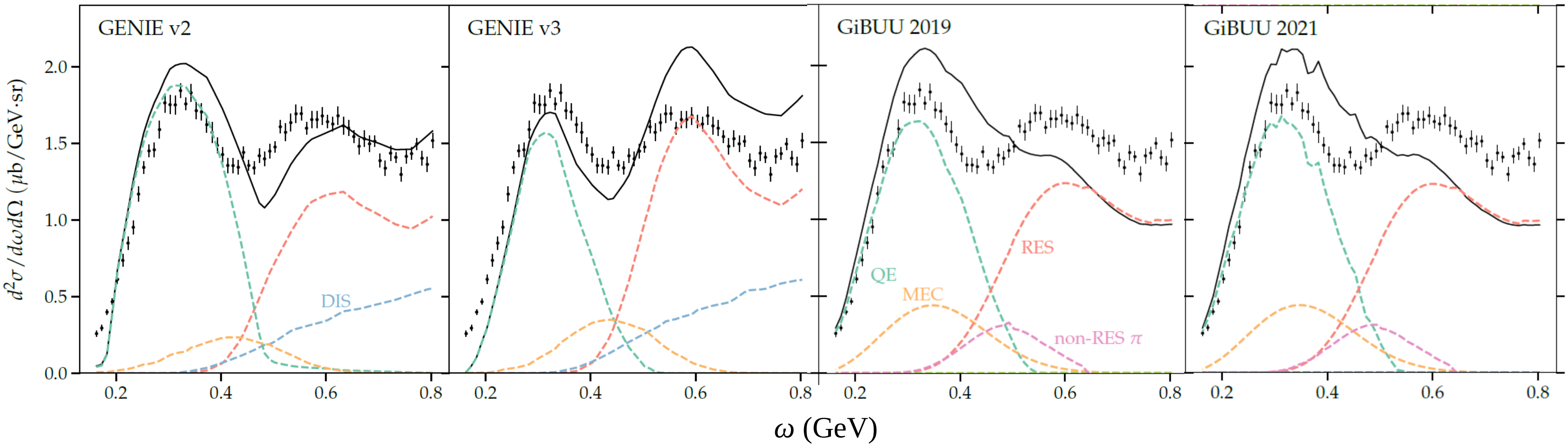


data:
Barreau *et al.*, NPA 402, 515 (1983)

A.M.A., A. Friedland & S.W. Li,
in preparation

Are these issues common between generators?

Carbon, 1.299 GeV @ 37.5º



data:
Barreau *et al.*, NPA 402, 515 (1983)

A.M.A., A. Friedland & S.W. Li,
in preparation

State of the art of MC generators

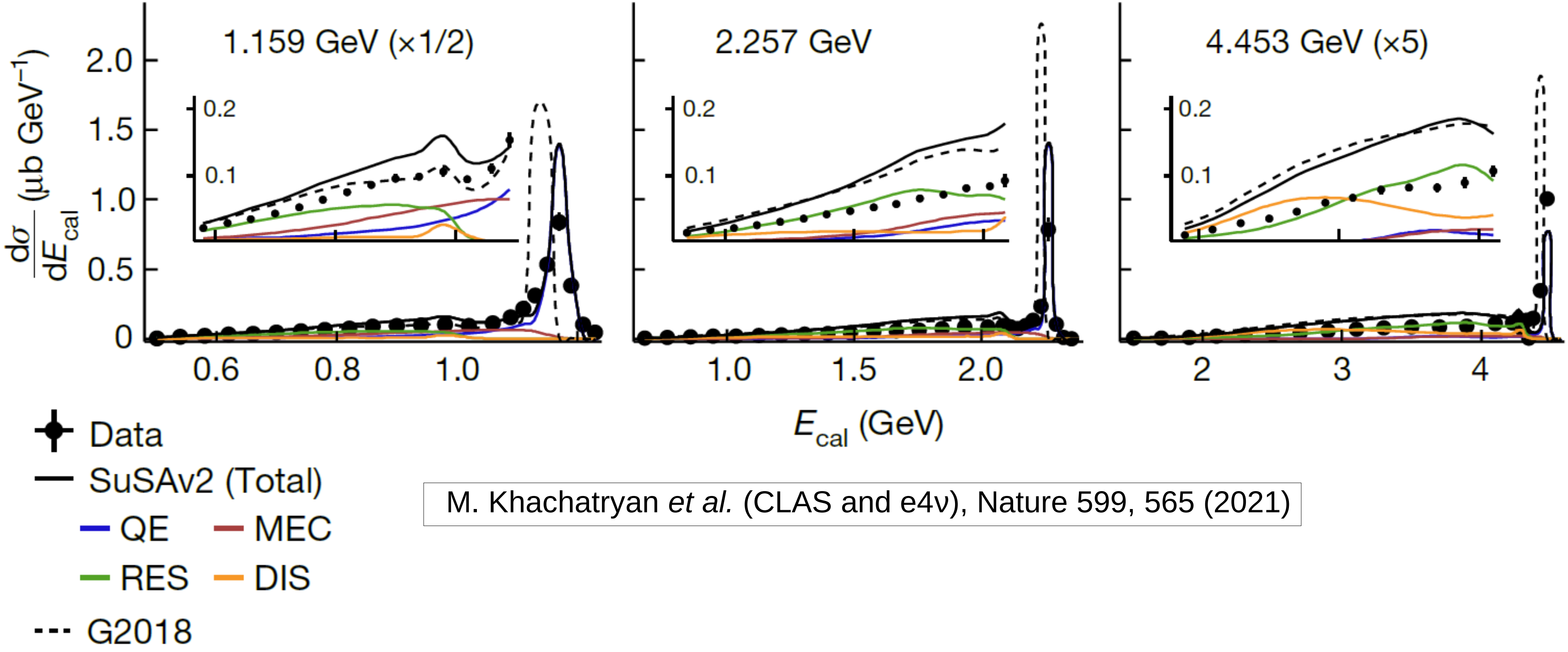
Consistent description of all interaction channels over the whole relevant kinematics is a general problem

- MEC contribution added to QE by hand, typically worsens the description of the QE peak.
- Transition from higher resonances to DIS is problematic.

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.

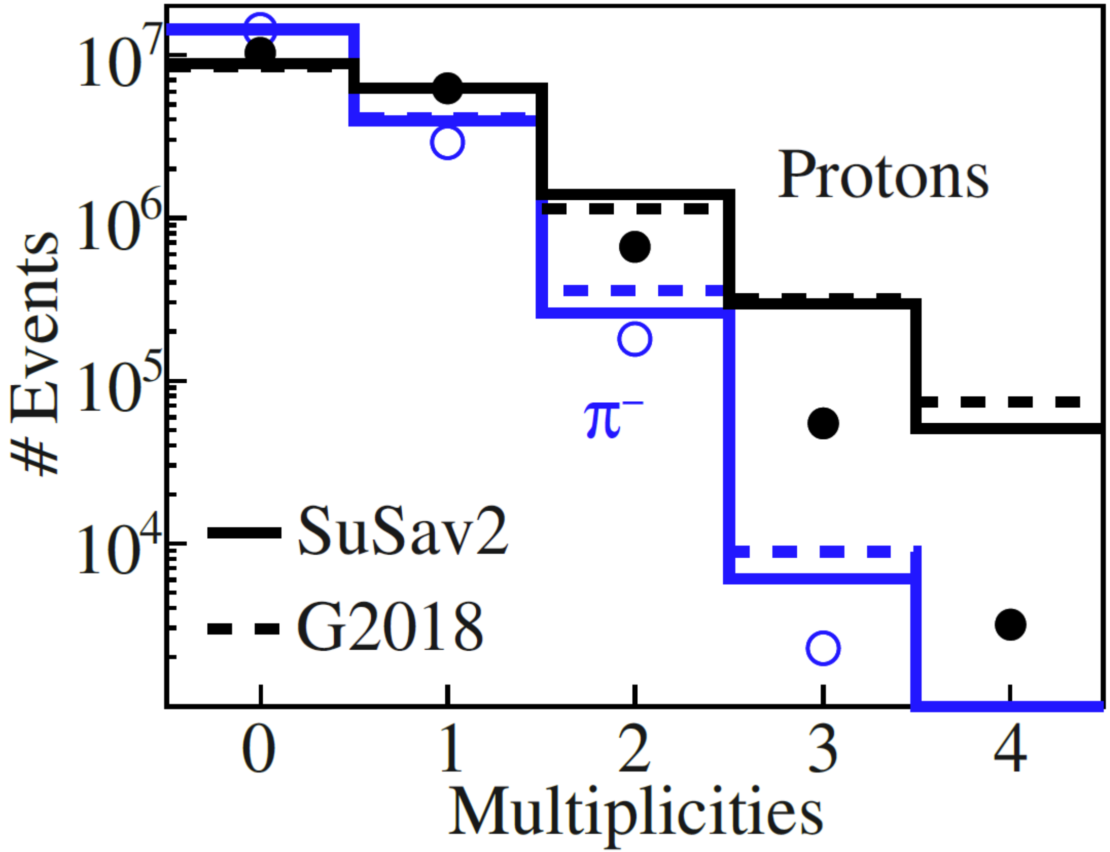
In general, the accuracy for pion production is worse than for QE.

(Semi)exclusive (*e*,*e'p*) cross section



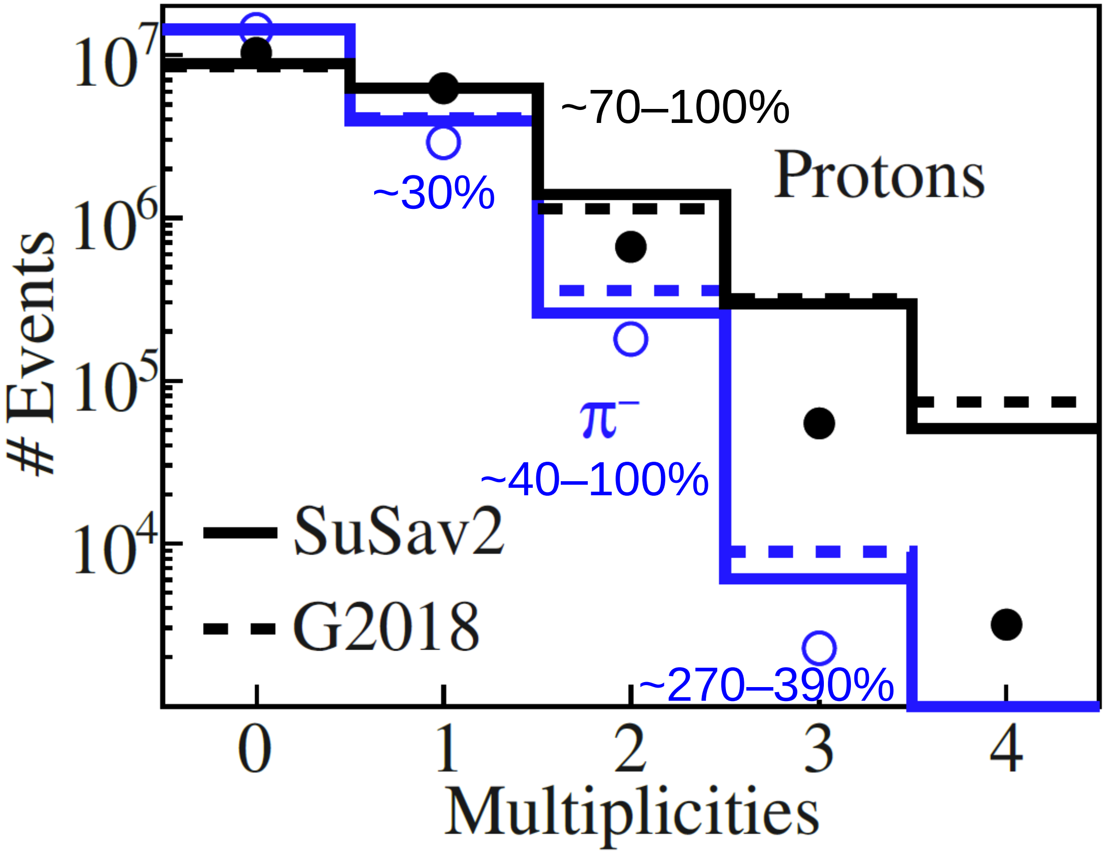
M. Khachatryan *et al.* (CLAS and e4ν), Nature 599, 565 (2021)

Hadron multiplicities



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

Hadron multiplicities



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

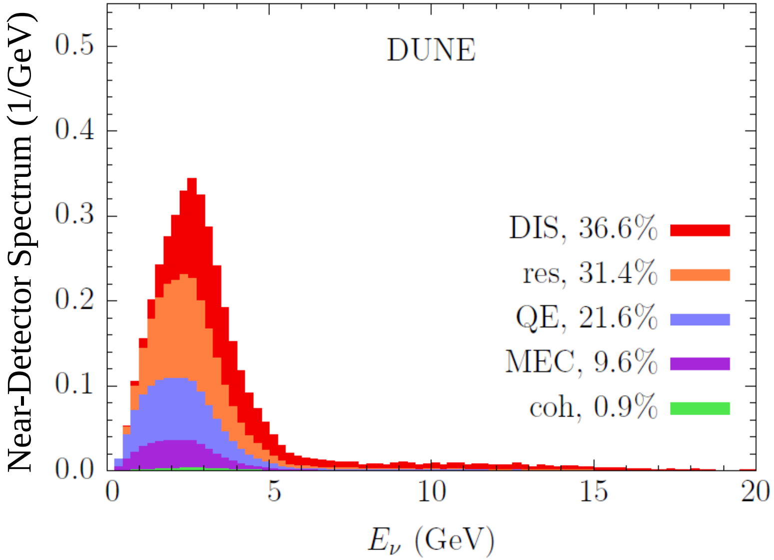
Summary

- Consistent treatment of electrons and neutrinos is indispensable.
- Electron-scattering data should be extensively used to validate the MC codes, increase precision, and assign uncertainties. They are invaluable in braking parameter degeneracy of near-detector fits.
- We need more data, especially for argon and exclusive ones, also to stimulate theoretical developments.
- For theory, a consistent framework for all mechanisms is now the main concern.
- Pion production, of fundamental importance for DUNE, needs to receive more attention. Correct interpretation of data relies on it, also in pionless channels.

Thank you!

What are the challenges?

- Different mechanisms may yield the same final state
- Relativistic energies
- Broad-band beam
- Exclusive predictions essential for calorimetry

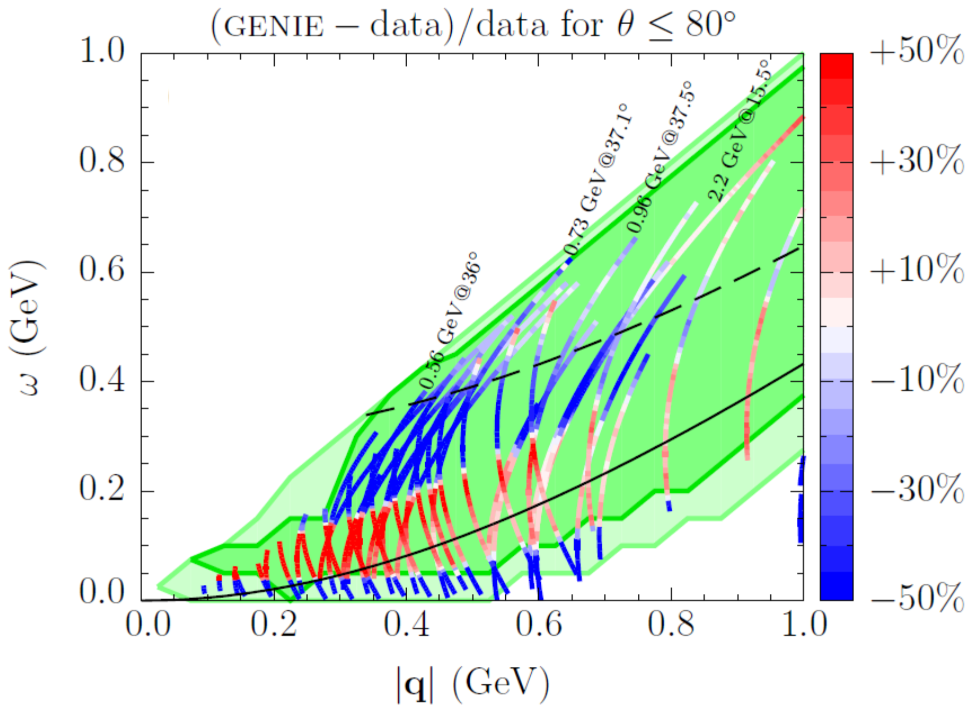


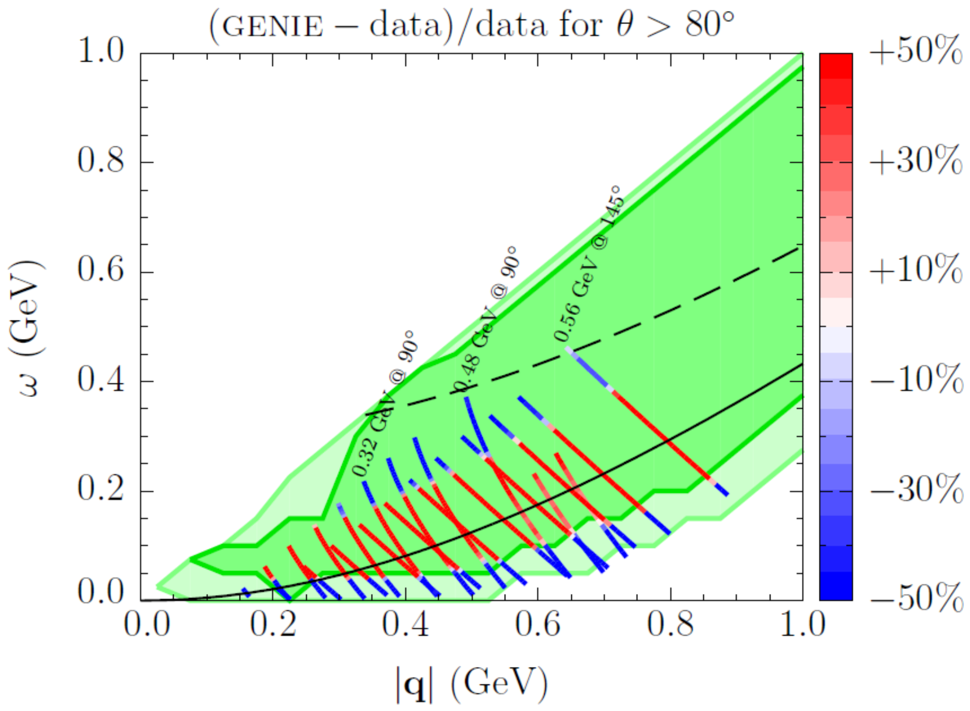
A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

To be fully useful, nuclear cross-section models need to

- cover all relevant interaction channels,
- describe them consistently,
- provide exclusive, relativistic spectra of final particles.

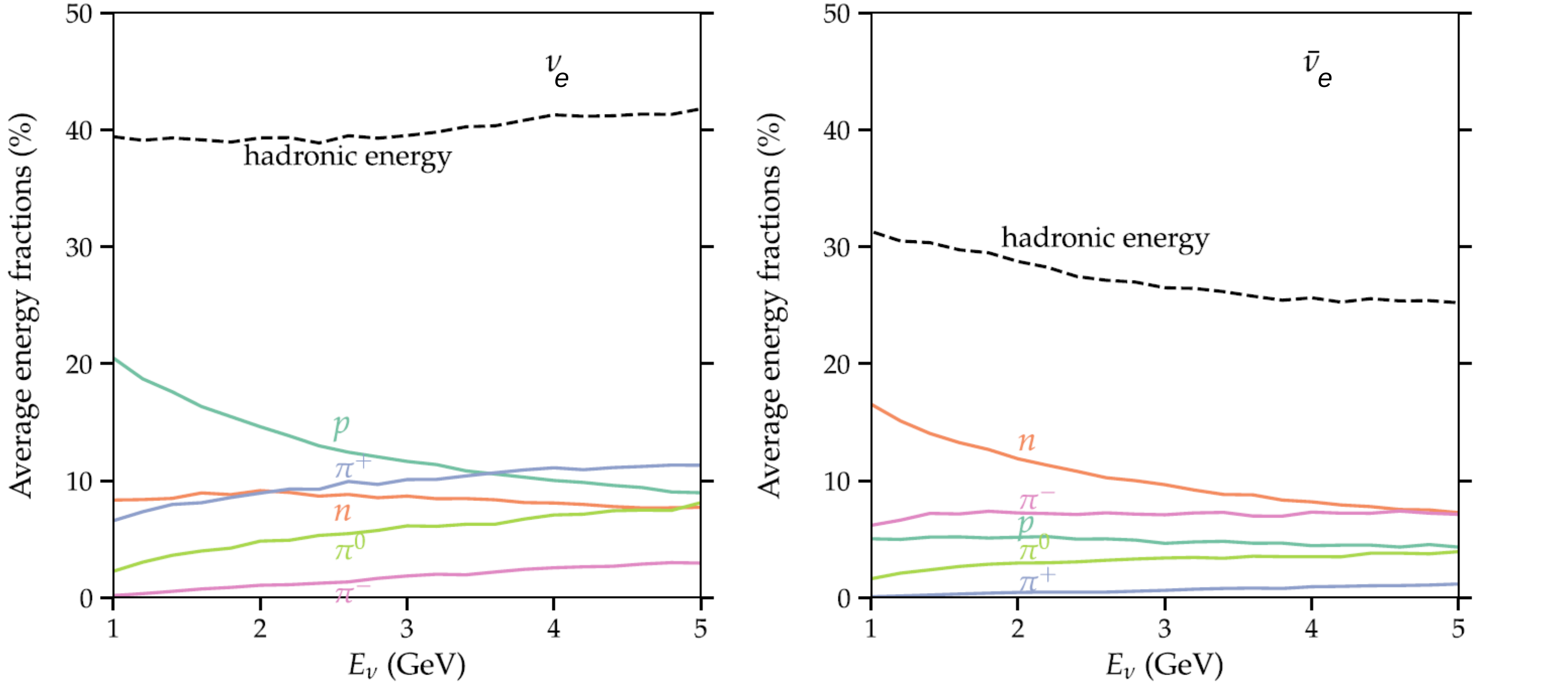
Are these issues general and relevant?





A.M.A. & A. Friedland,
PRD 102, 053001 (2020)

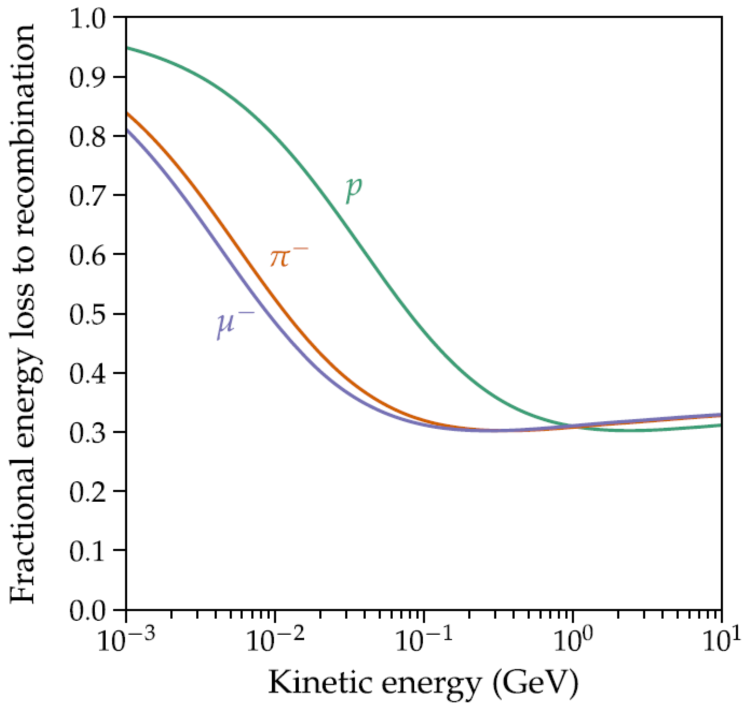
Neutrino energy reconstruction

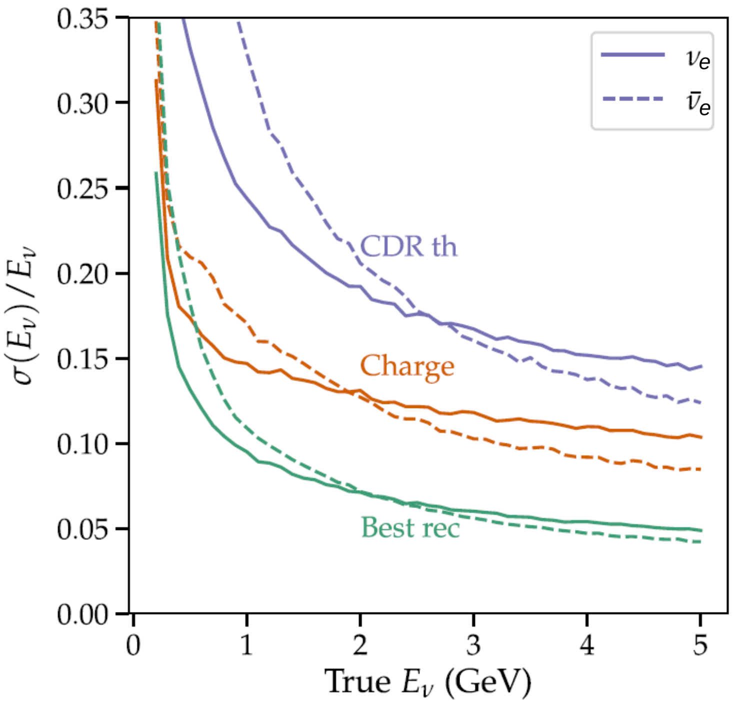


- Sizable fraction of (anti)neutrino energy carried by hadrons
- Neutrons' energy estimate heavily dependent on Monte Carlo

A. Friedland and S. W. Li, PRD 99, 036009 (2019)

Importance of particle identification



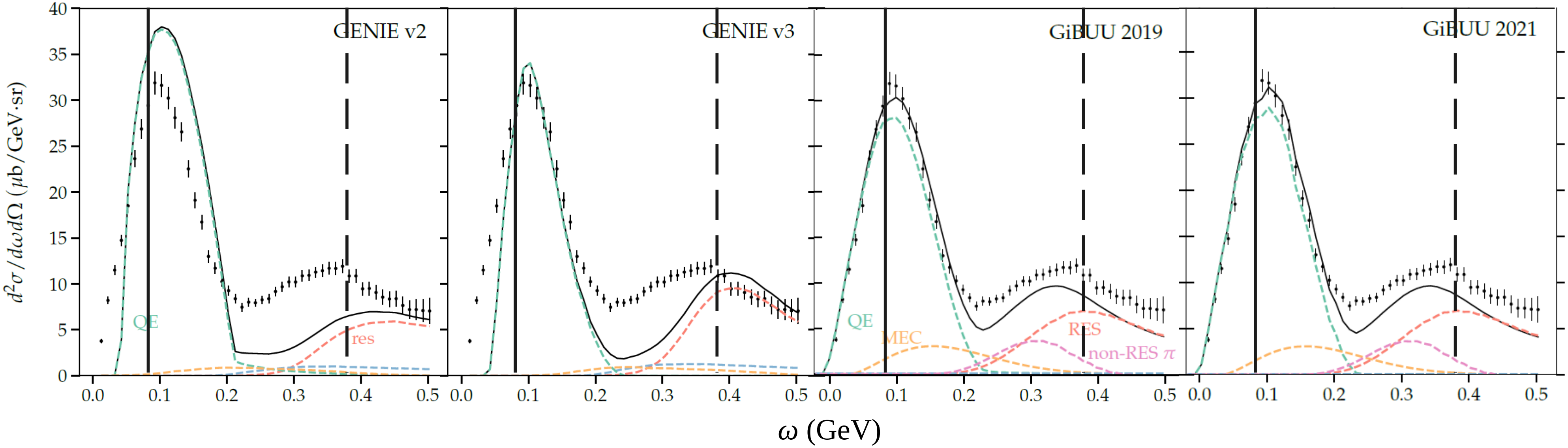


Clear improvement in energy resolution from individual recombination corrections

A. Friedland and S. W. Li,
PRD 102, 096005 (2020); PRD 99, 036009 (2019)

Are these issues common between generators?

Carbon, 0.68 GeV @ 36º



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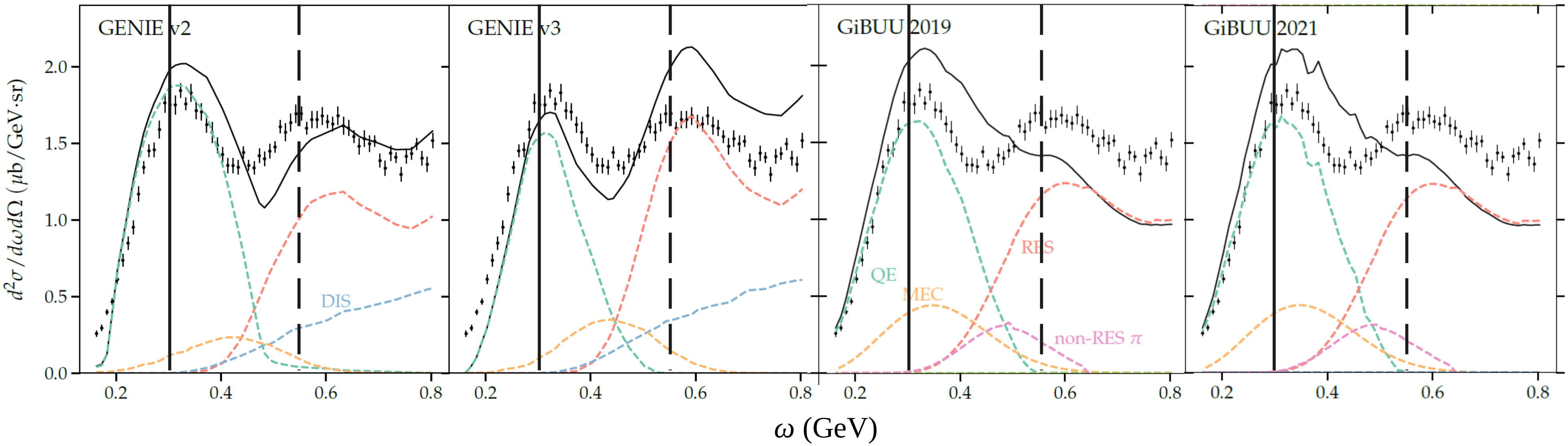


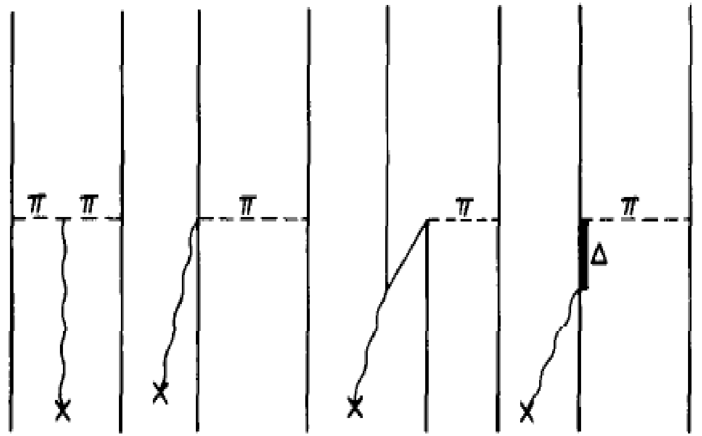
data:
Barreau *et al.*, NPA 402, 515 (1983)

A.M.A., A. Friedland & S.W. Li,
in preparation

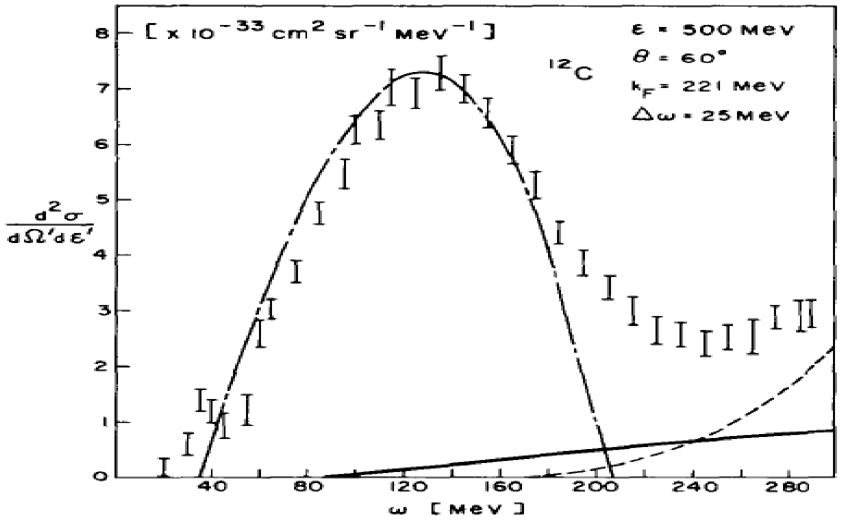
MEC: how the story goes

- The nuclear cross section is ~20% higher than the free one.
- The additional cross section comes from multinucleon final states.
- Multinucleon final-states ≡ 2-body currents (such as MEC)
- We simulate MEC for neutrinos and electrons in a consistent fashion.

Donnelly *et al.* (1978)

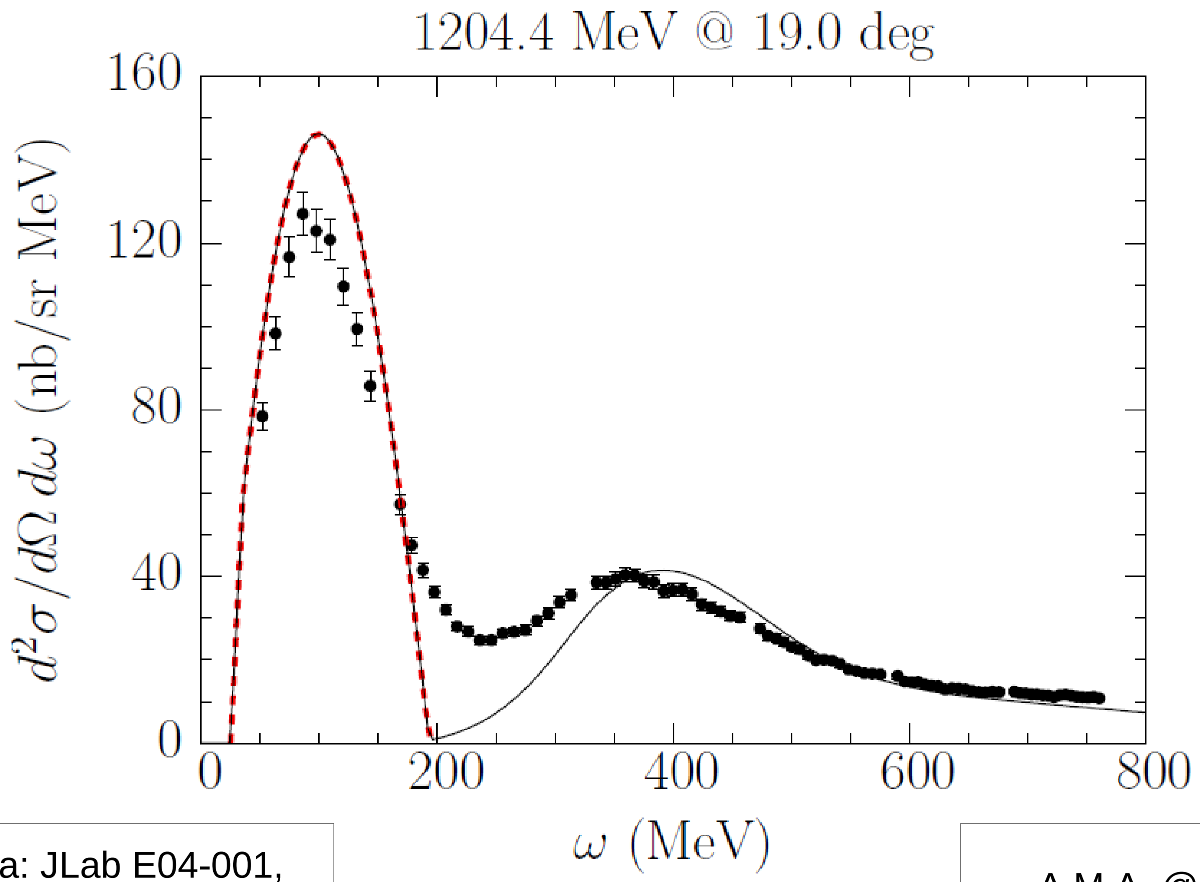


Donnelly, van Orden, de Forest & Hermans,
Phys. Lett. B 76, 393 (1978)



"Calculations of [QE + Δ] with a simple uncorrelated Fermi gas model of the nucleus have provided a surprisingly good fit to experiment [Moniz *et al.*('71)] ... in the region between the peaks, however, has consistently underestimated the experimental values. In this paper we investigate **whether MEC contributions can fill in this "dip" region."**

Relativistic Fermi gas

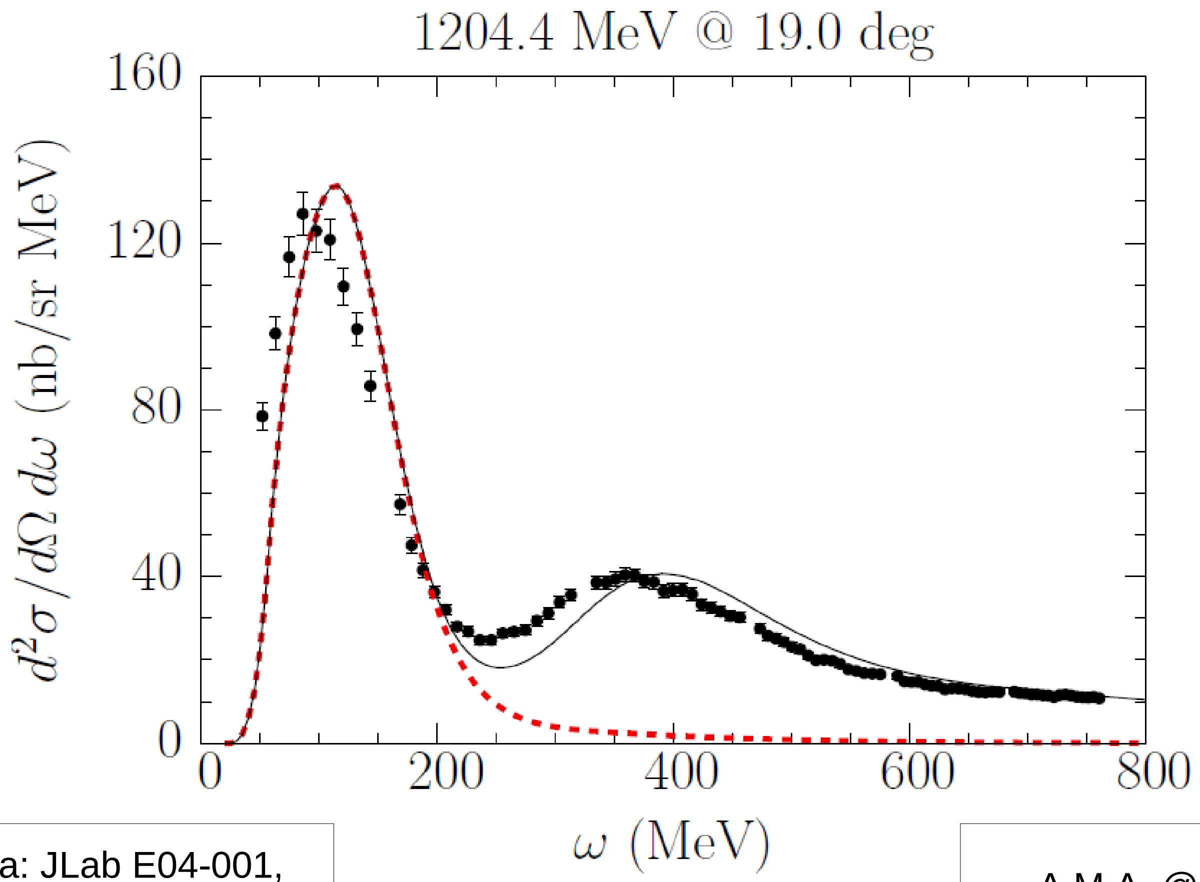


data: JLab E04-001, preliminary

A.M.A. @ NuInt18

Spectral function, no FSI

QE treated as in
A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

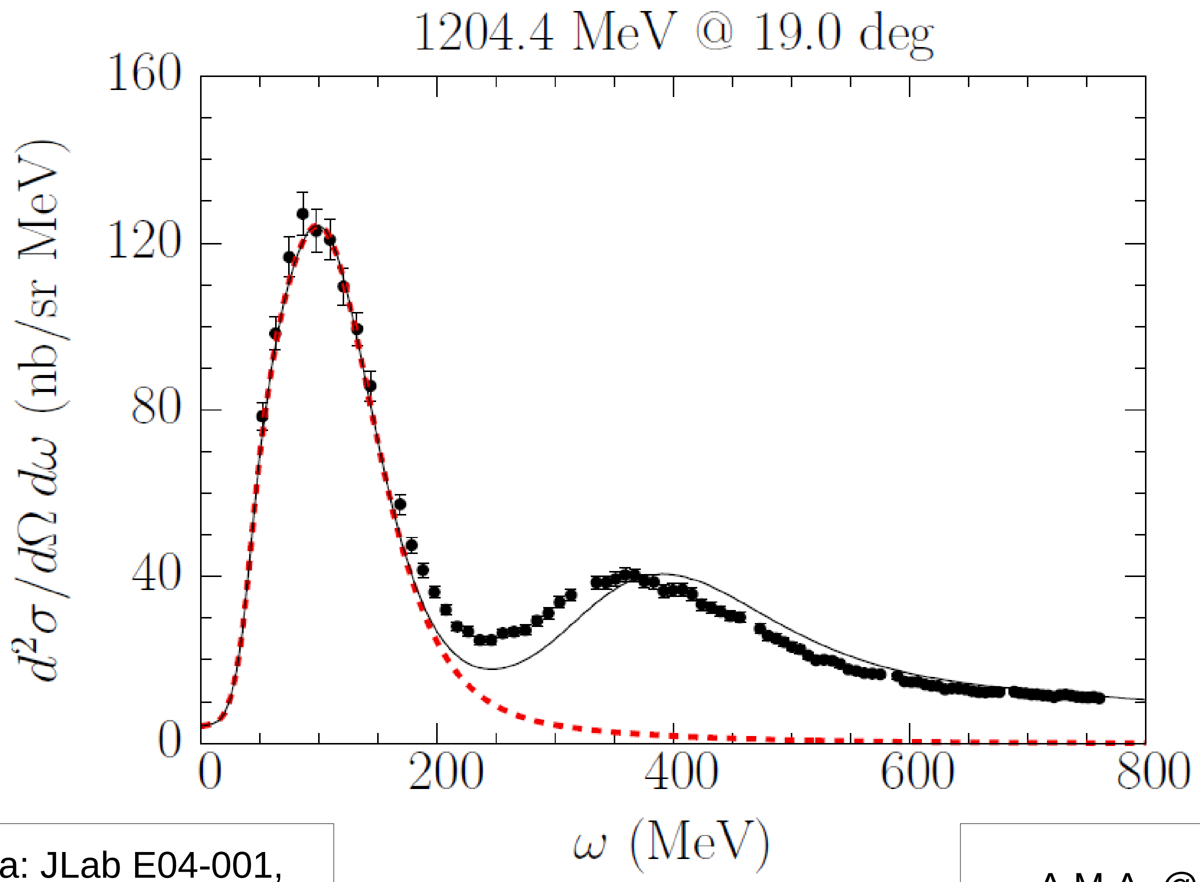


data: JLab E04-001,
preliminary

A.M.A. @ NuInt18

Spectral function, FSI for QE

QE treated as in
A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

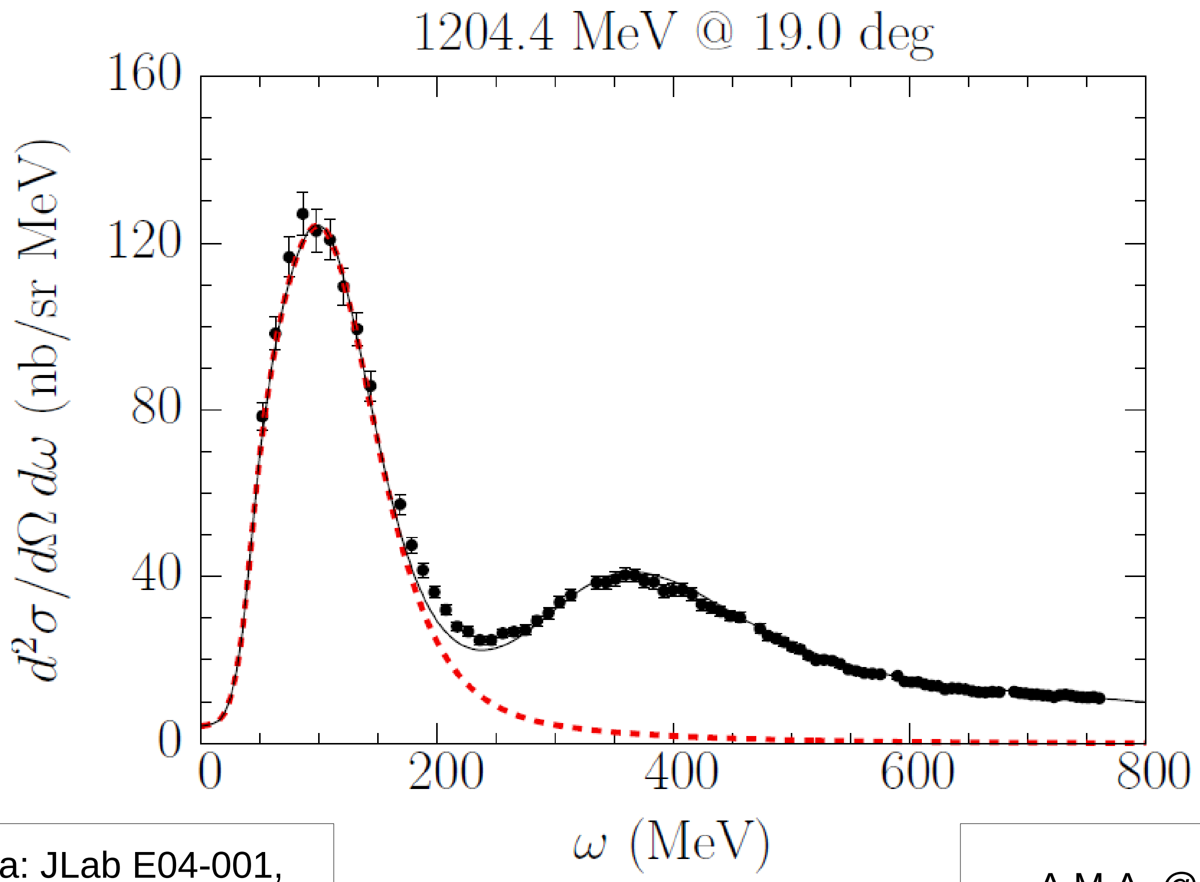


data: JLab E04-001, preliminary

A.M.A. @ NuInt18

Spectral function, FSI for QE, shifted Δ

QE treated as in
A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)



data: JLab E04-001, preliminary

A.M.A. @ NuInt18

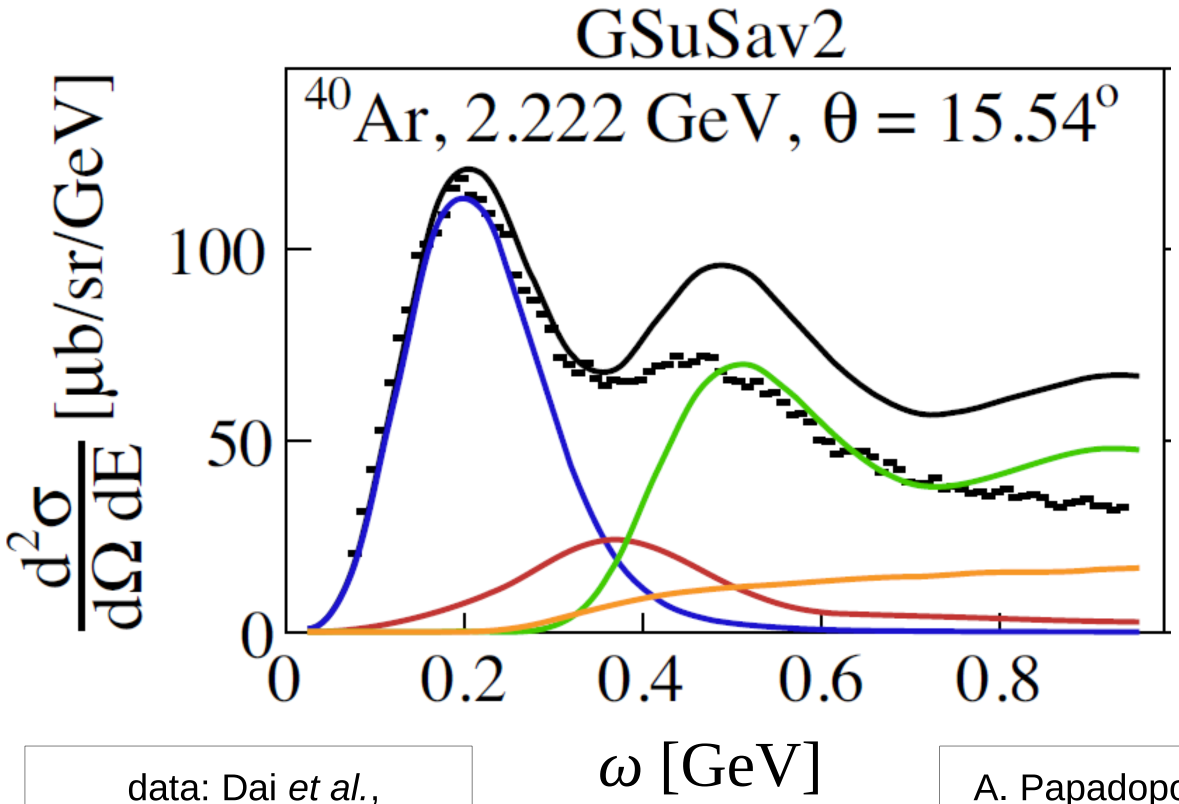
Multinucleon final states

Final states involving two (or more) nucleons may originate from

- Initial-state correlations
- Final-state interactions
- 2-body currents (such as MEC)

Shimizu & Faessler, Nucl. Phys. A 333, 495 (1980);
Alberico *at al.*, Ann. Phys. 154, 356 (1984).

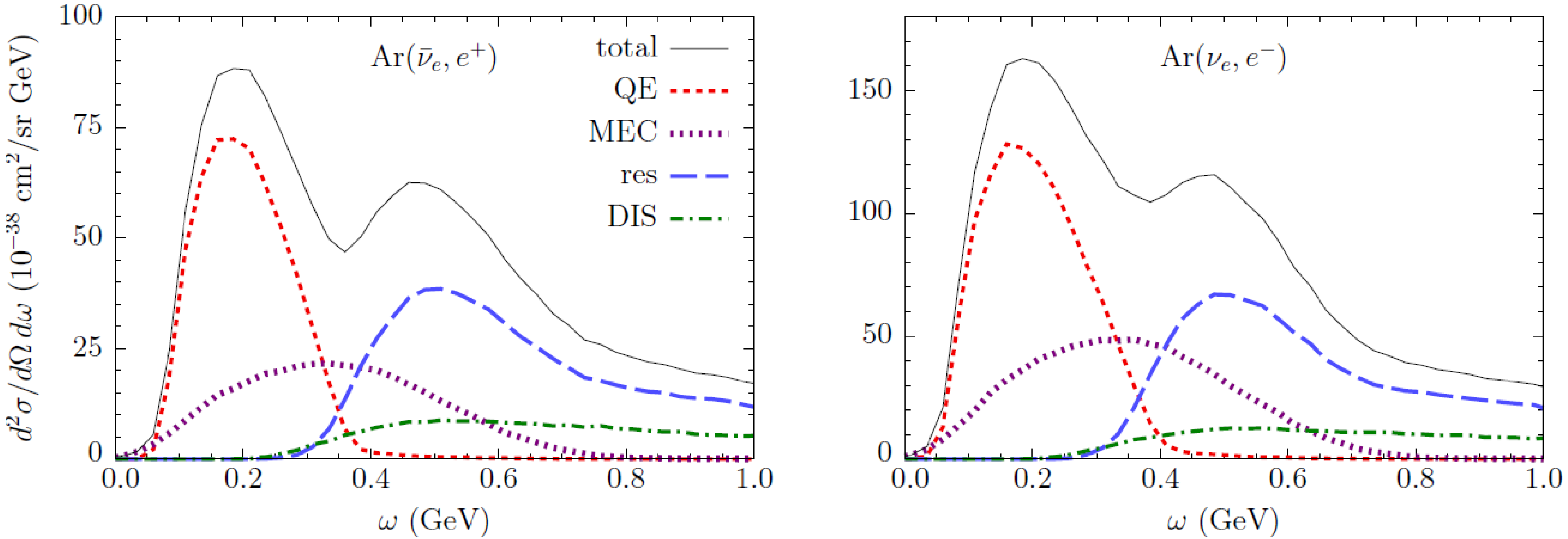
MEC in GENIE



data: Dai *et al.*,
PRC 99, 054608 (2019)

A. Papadopoulou et al.,
PRD 103, 113003 (2021)

MEC in GENIE



A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

Size of MEC

- Baran *et al.* [PRL 61, 400 (1988)] report MEC/QE

  0.00 ± 0.05 for C and 0.03 ± 0.05 for Fe.

- Over the range of the data, GENIE 2.12 gives for C

  1.9% (3.0%) for 1.500 GeV @ 11.95 (13.54°),

  2.9% (4.8%) for 1.650 GeV @ 11.95 (13.54°).

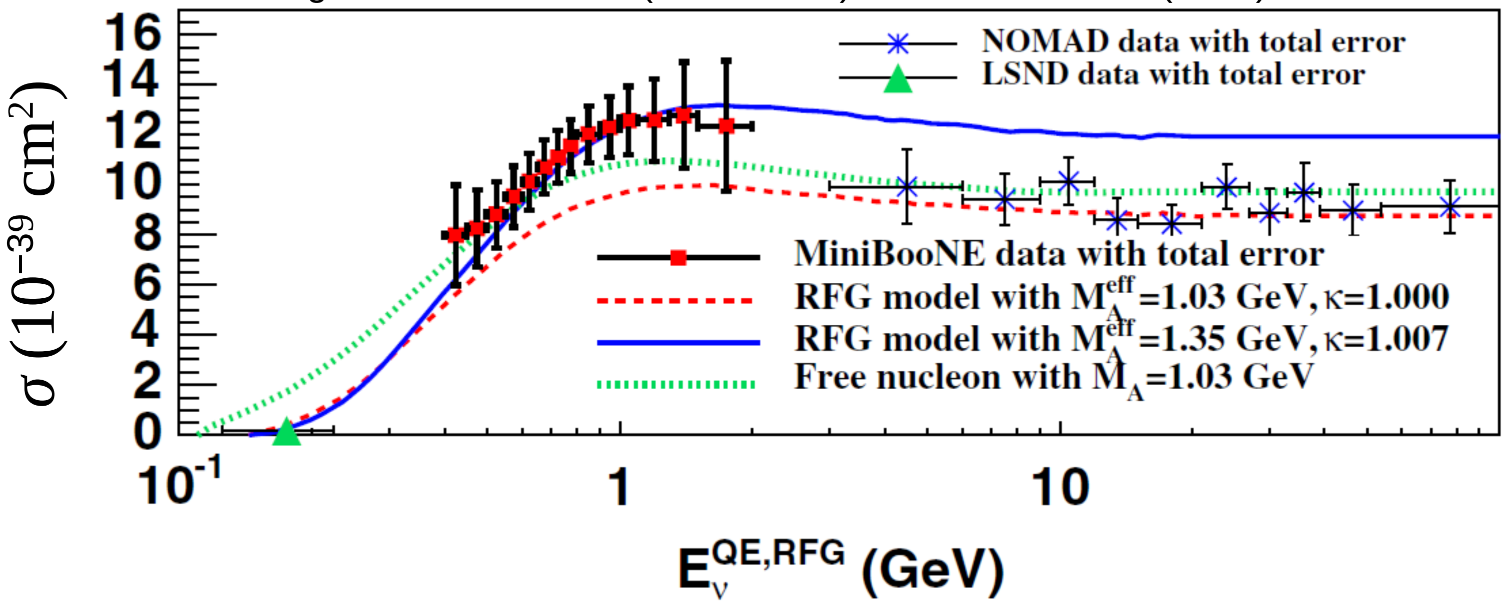
- In general, the parameter `EmpiricalMEC-FracXXQE` is set to

  0.05 for `EM` and 0.45 for `CC` and `NC` in GENIE 2.12,

  0.05 for `EM` and 0.30 for `CC` and `NC` in GENIE 3.06.

MiniBooNE

Aguilar-Arevalo *et al*. (MiniBooNE), PRD 81, 092005 (2010)



- Shape of the Q^2 distribution gives M_A = 1.35 ± 0.17 GeV
- Cross section higher than for free nucleons (assuming M_A = 1.03 GeV)

Takeaway messages

- It is important to simulate electron and neutrino interactions consistently.
- Multinucleon final states can have different origins. Their measurements will open new avenues for studies.
- Consistent treatment of pion production and 2-body currents is called for.
- Lattice points towards “much higher M_A values”.

M_A value

Bernard, Elouadrhiri and Ulf-G Meißner, JPG 28, R1 (2002)