Neutrino Monte Carlo generators: current state of the art

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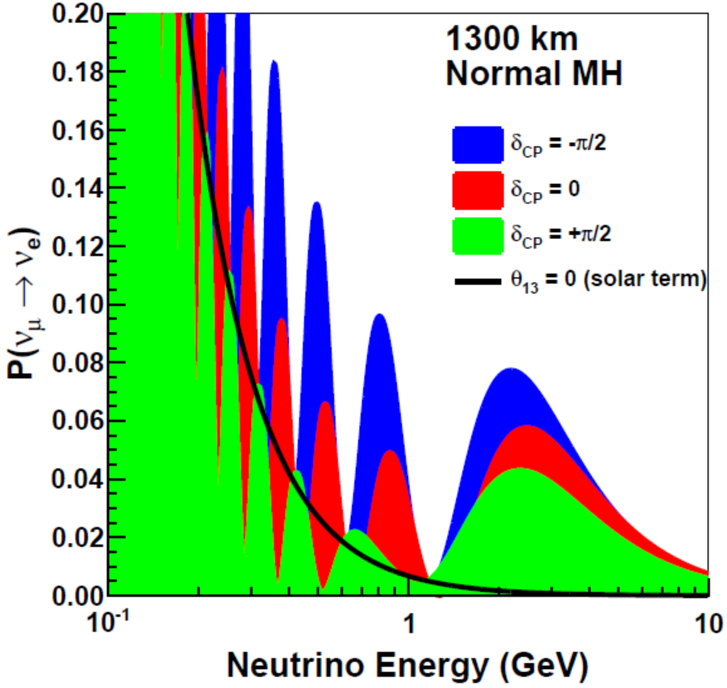
MC Generators in accelerator neutrino physics

- Main 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 O (1) effects, **without reliable cross sections we cannot succeed**.



DUNE Collaboration, arXiv:1512.06148

Neutrino oscillations in a nutshell

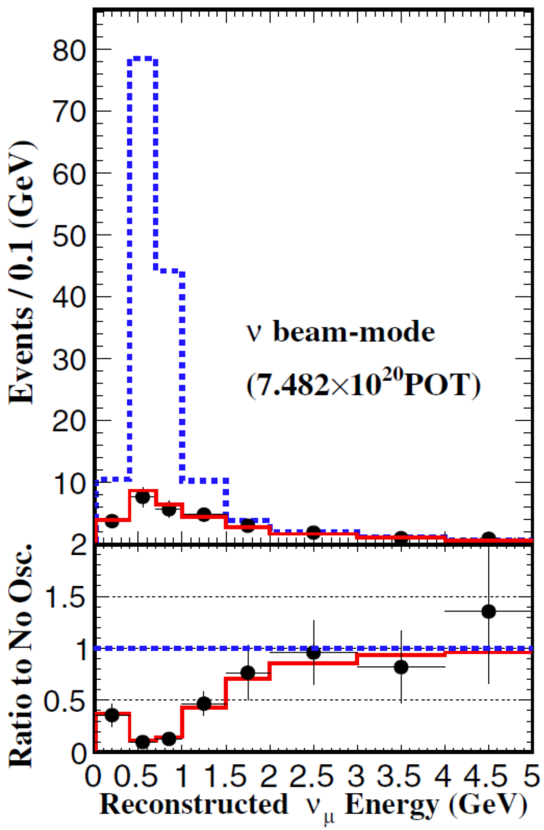
In the simplest case of two flavors

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

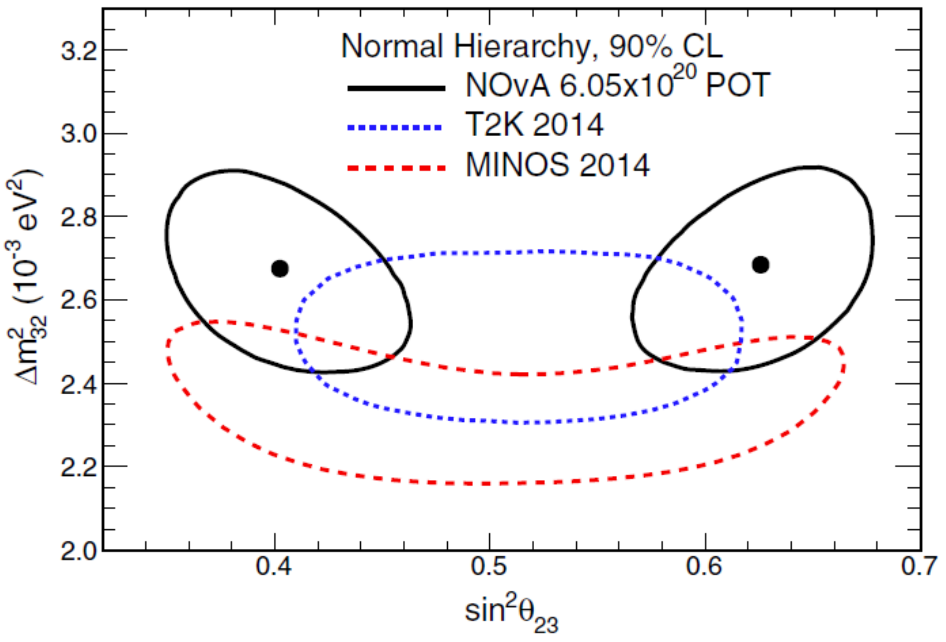
In the ratio of the observed to unoscillated events,

- the position of the dip determines Δm^2,
- its depth determines θ

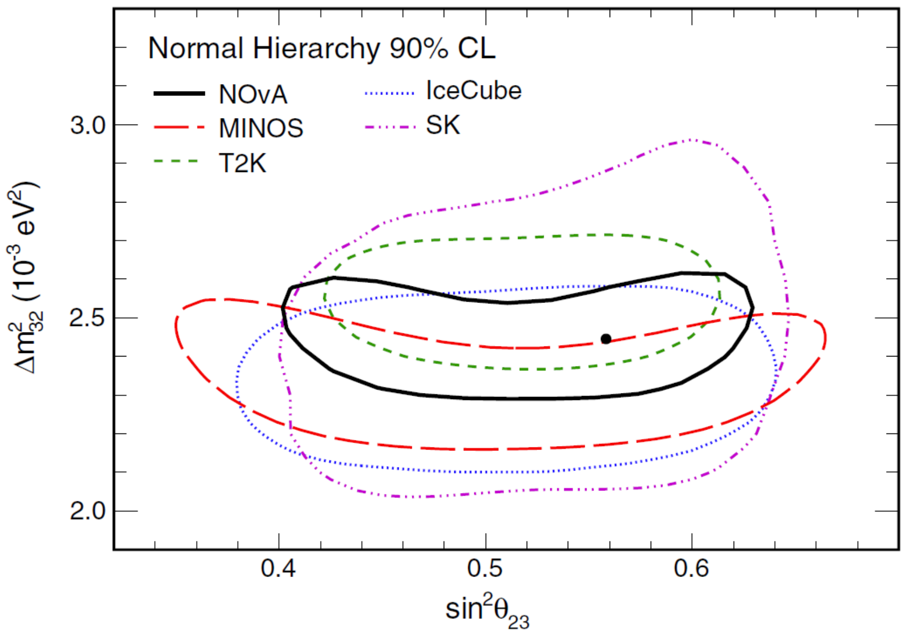
Abe *et al.* (T2K),
PRD 96, 011102(R) (2017)



Concrete example: NOvA



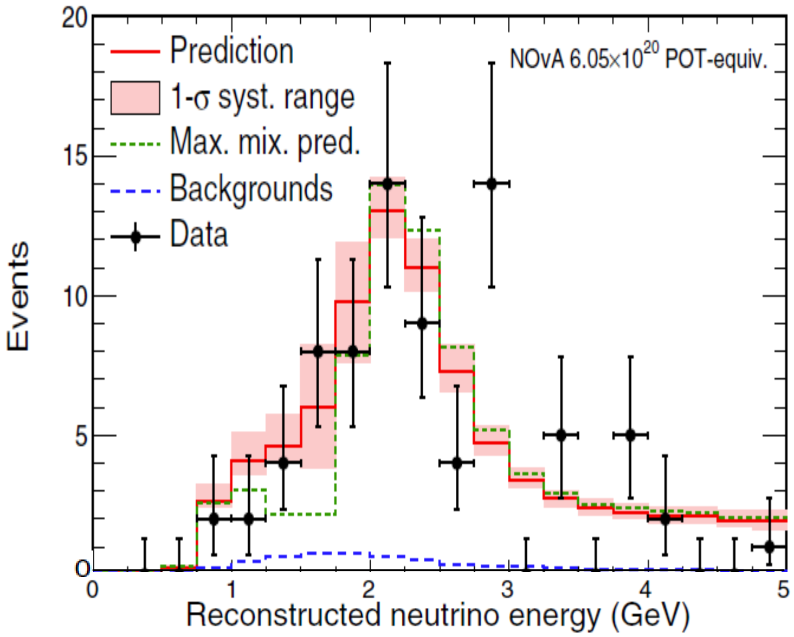
Acero *et al.* (NOvA), PRL 118, 151802 (2017)



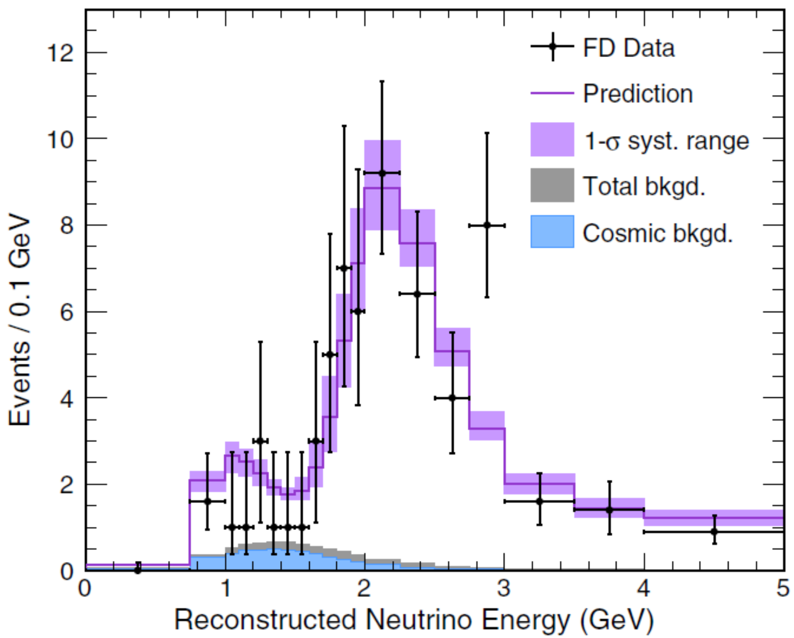
Acero *et al.* (NOvA), PRD 98, 032012 (2018)

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

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."

Current situation

"… **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)

"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)

Are neutrino data sufficient?

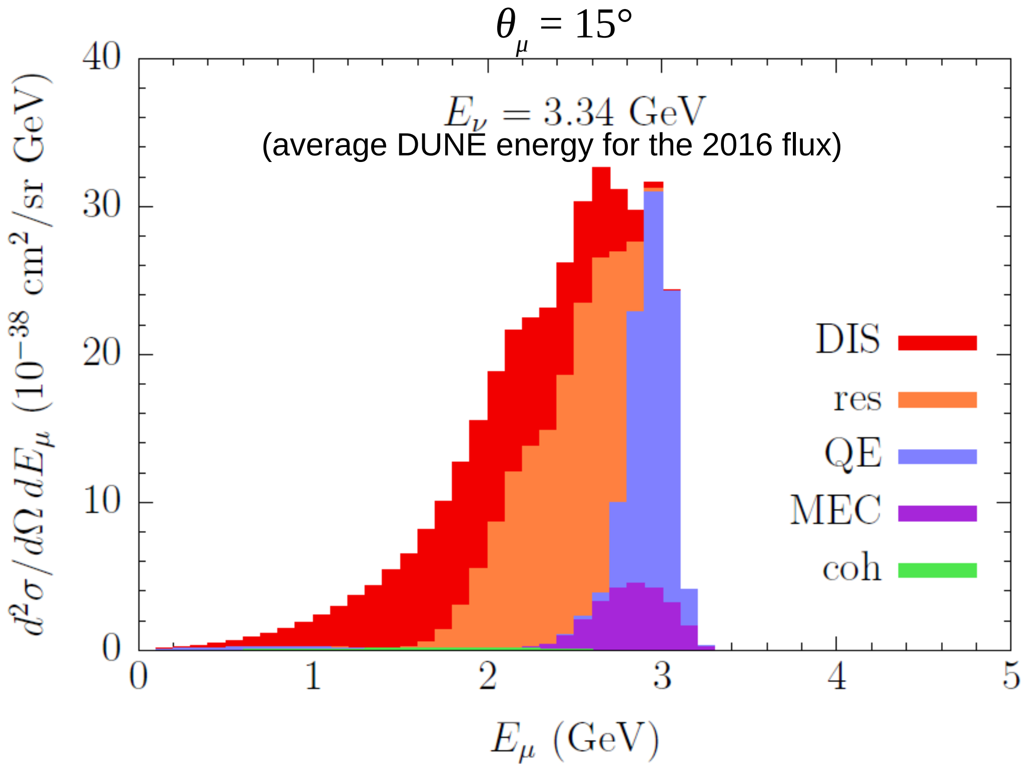
"… fitting to individual MINERvA pion production channels [$1\pi^{\pm}$ and $N\pi^{\pm}$ for ν_{μ}, and $1\pi^{0}$ for ν_{μ} and $\bar{\nu}_{\mu}$] produces **different best-fit parameters** …"

"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."

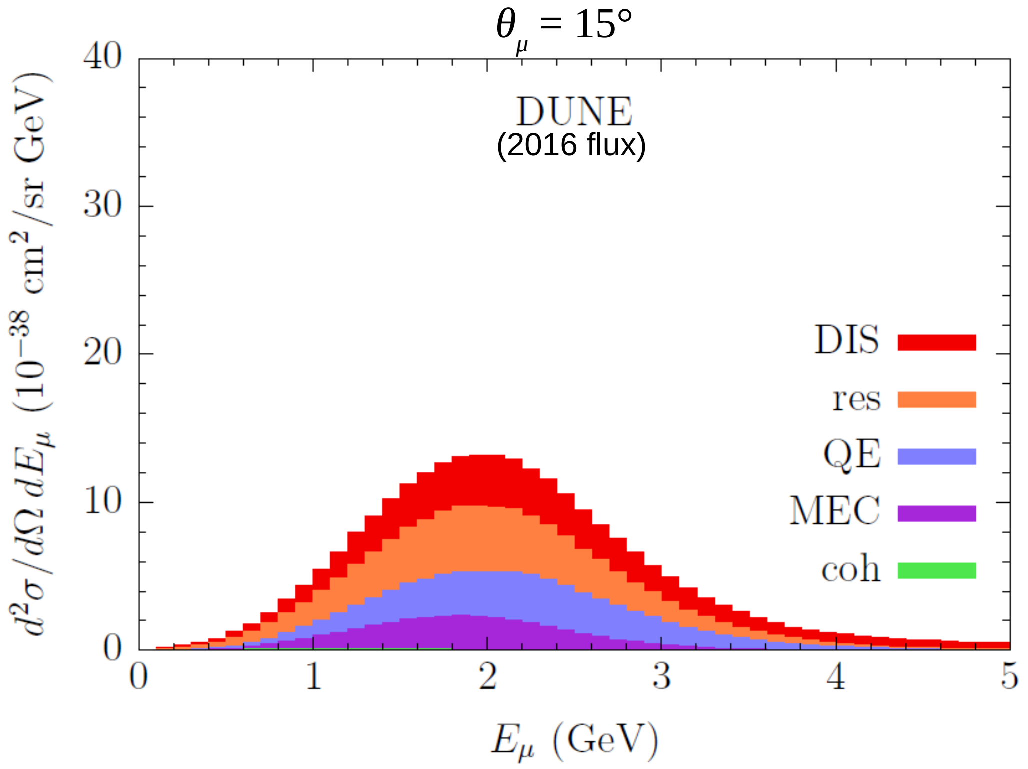
P. Stowell *et al*. (MINERvA), PRD 100, 072005 (2019)

Neutrino double differential cross section



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

Neutrino double differential cross section

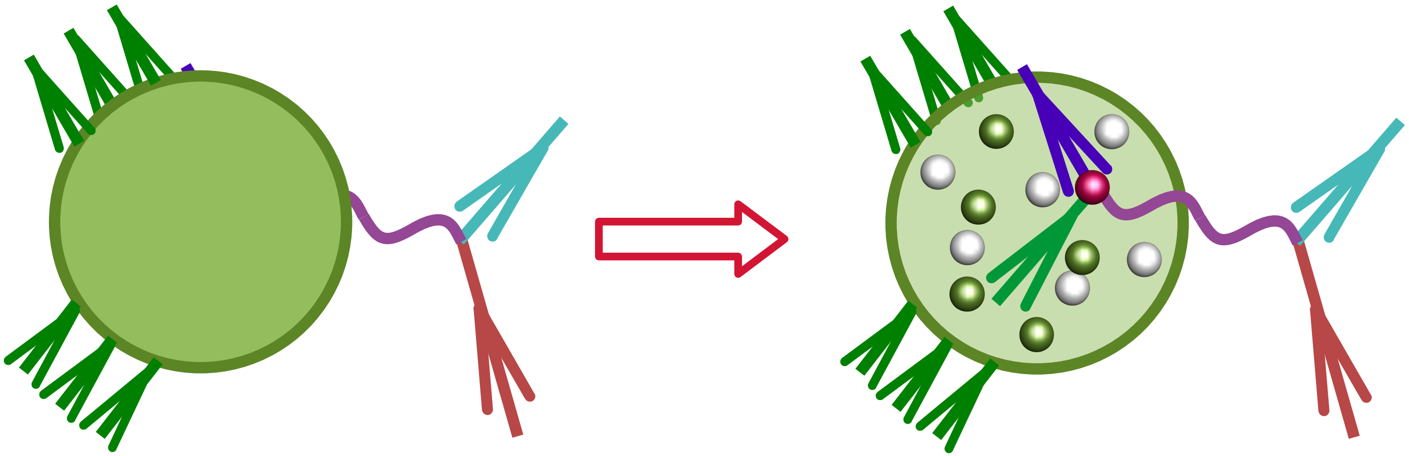


A.M.A. & A. Friedland, PRD 102, 053001 (2020)

Impulse approximation

At relevant 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 $|\mathbf{q}|$ is high enough ($|\mathbf{q}| \gtrsim 200$ MeV).



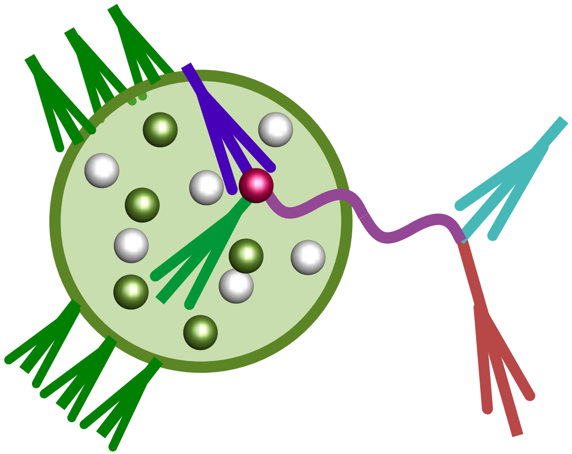
Impulse approximation

$$\frac{d\sigma_{\ell A}^{\mathrm{IA}}}{d\omega d\Omega} = \sum_N \int d^3p\, dE\, P_{\mathrm{hole}}^N(\mathbf{p}, E)\, \frac{M}{E_{\mathbf{p}}} \frac{d\sigma_{\ell N}^{\mathrm{elem}}}{d\omega d\Omega}\, P_{\mathrm{part}}^N(\mathbf{p}', \mathcal{T}')$$

average over the initial nucleon state

nucleon cross section

final-state interactions



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.

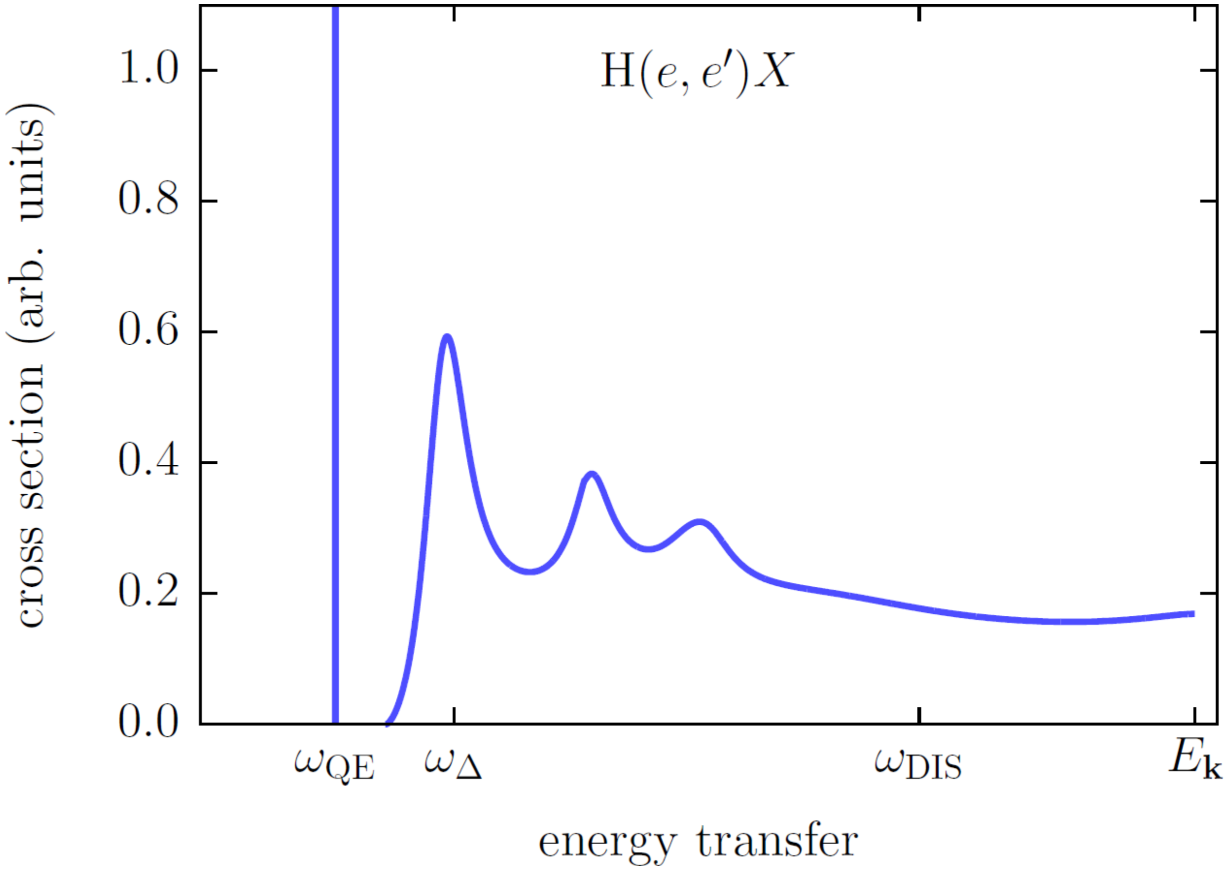
Electron-scattering data can provide information on

- 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)

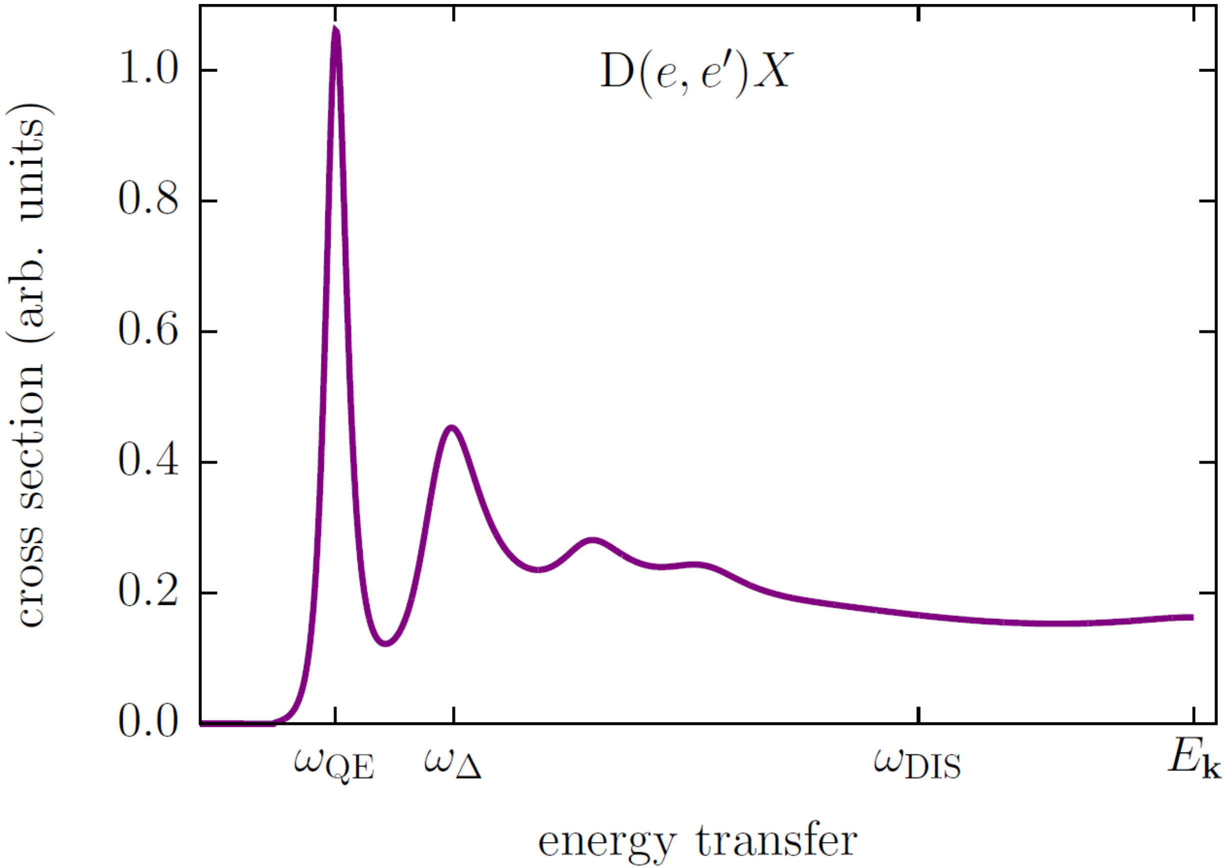
Electron data allow MC validation, reduction of systematic uncertainties, as well as their rigorous determination.

A.M.A. *et al.*, PRD 101, 053004 (2020)
A.M.A. *et al.*, JPG 50, 120501 (2023)

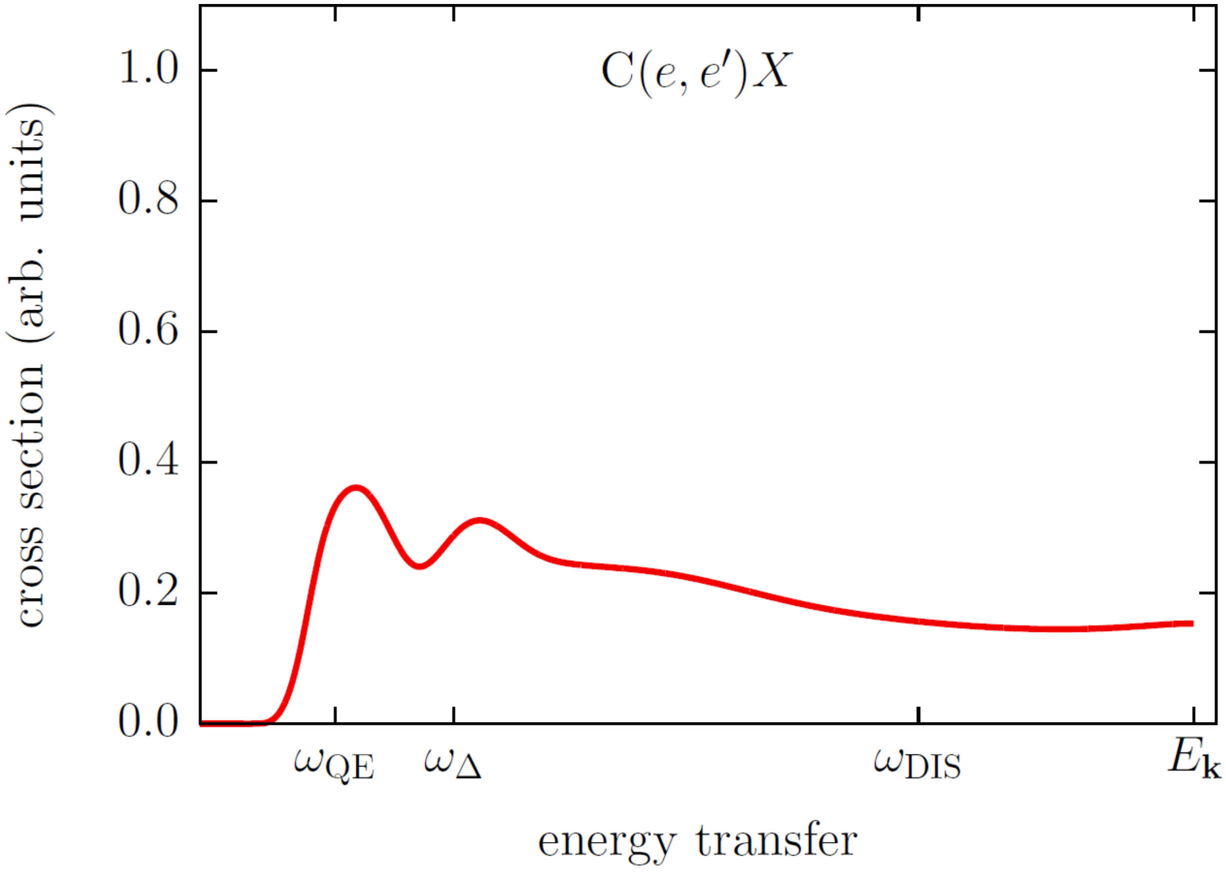
Double differential cross section



Double differential cross section



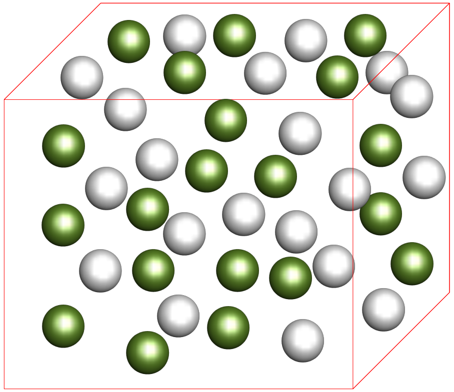
Double differential cross section



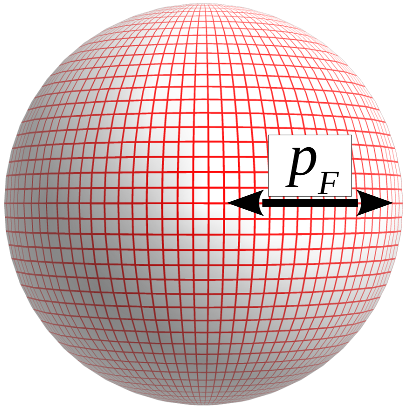
Global Fermi gas

Nucleus treated as a fragment of non-interacting infinite nuclear matter of constant density.

Eigenstates have definite momenta and energies $E_p = \sqrt{M^2 + \mathbf{p}^2} - \epsilon$.



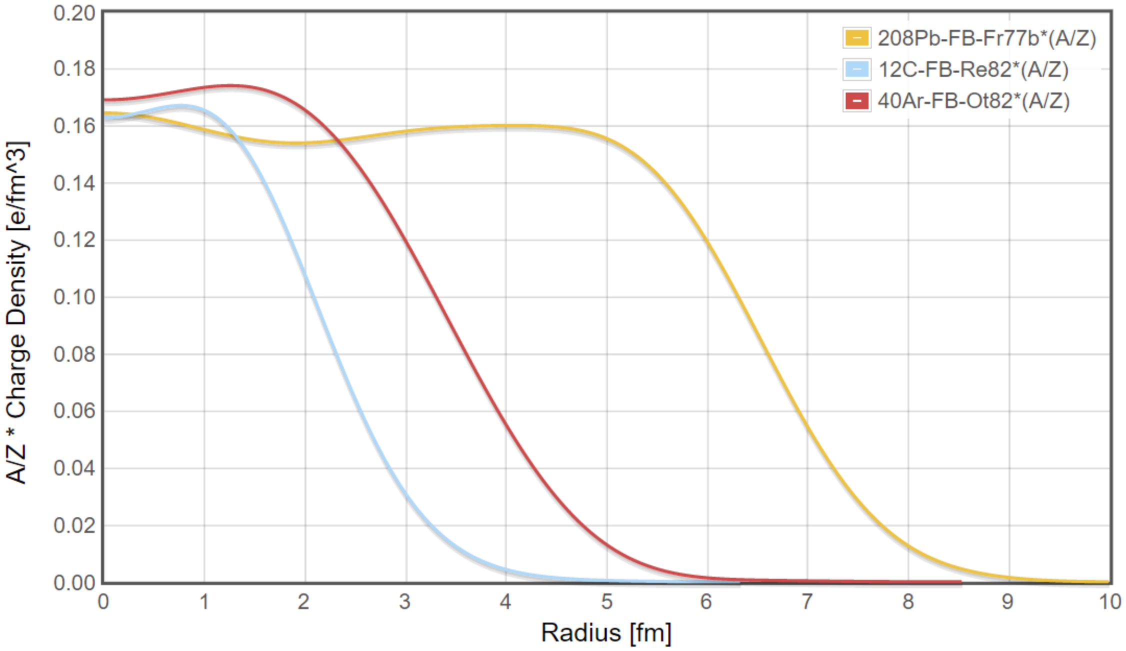
Coordinate space



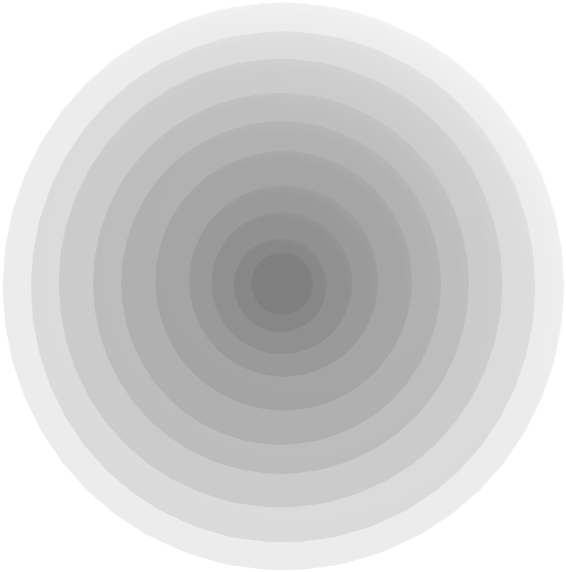
Momentum space

Local Fermi gas

Nucleus treated as set of concentric spheres of varying densitiy, each treated as the global Fermi gas

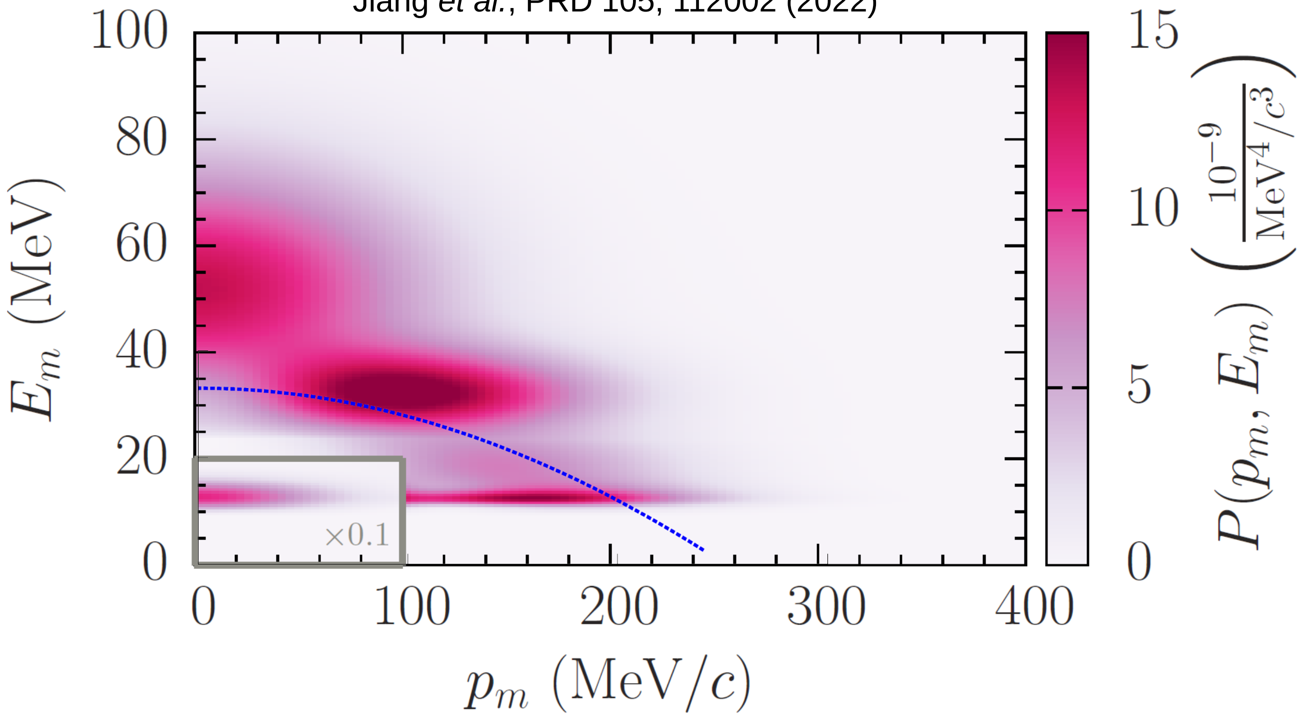


http://discovery.phys.virginia.edu/research/groups/ncd/index.html

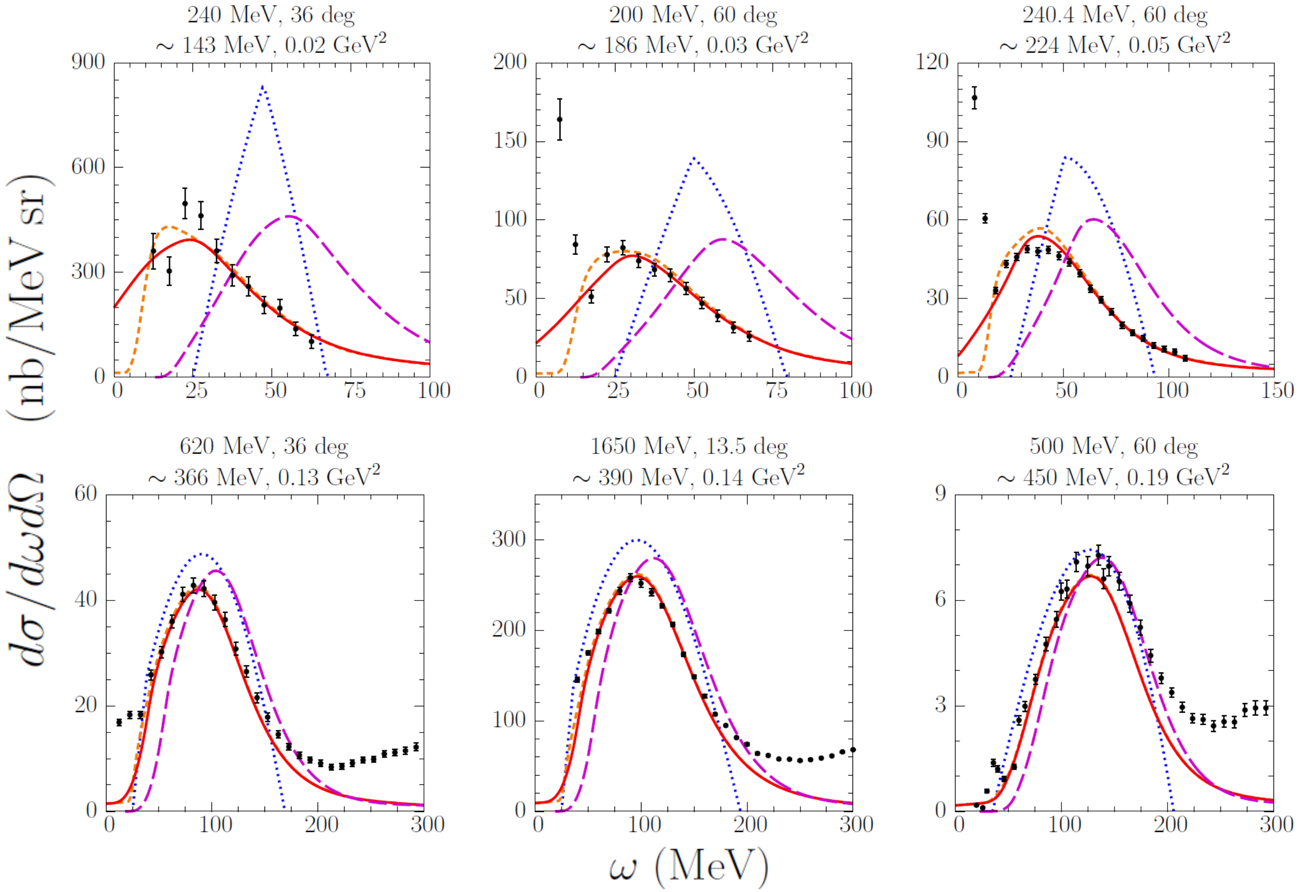


Fermi gas vs. spectral function

Jiang *et al.*, PRD 105, 112002 (2022)



Realistic description of the nucleus: C(*e*,*e*')



A.M.A., O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

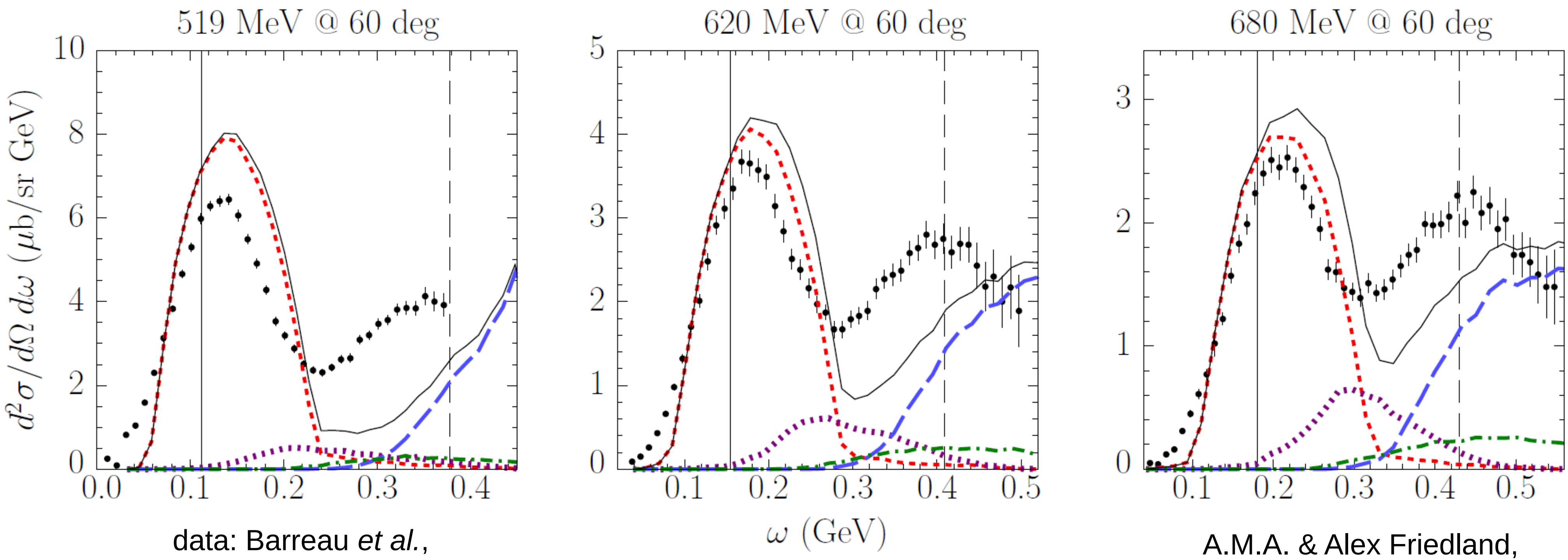
GENIE 2 in a nutshell

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)

Low energies

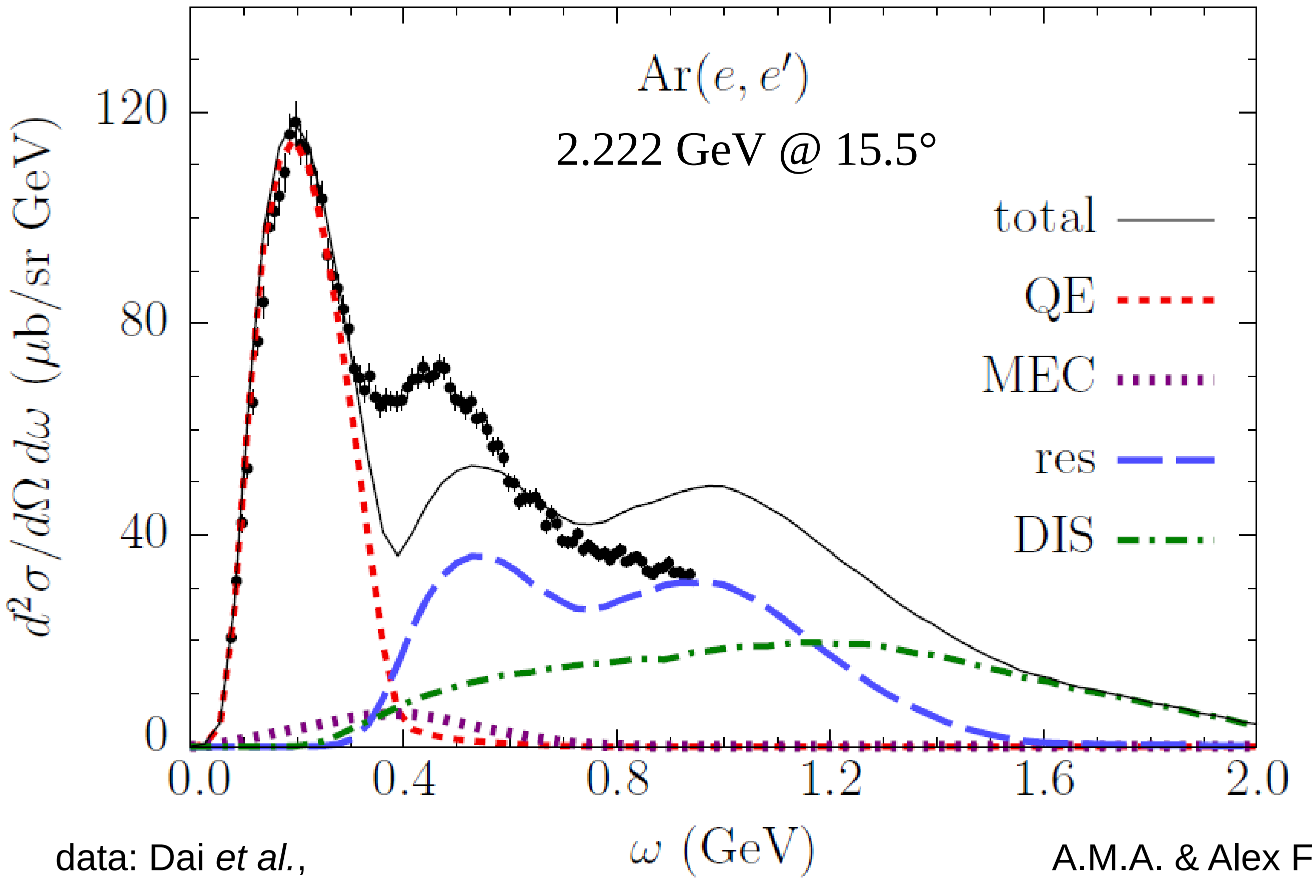


data: Barreau *et al.*,
NPA 402, 515 (1983)

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

Relevant for T2K/Hyper-K, SBND, etc.

Electron scattering on argon

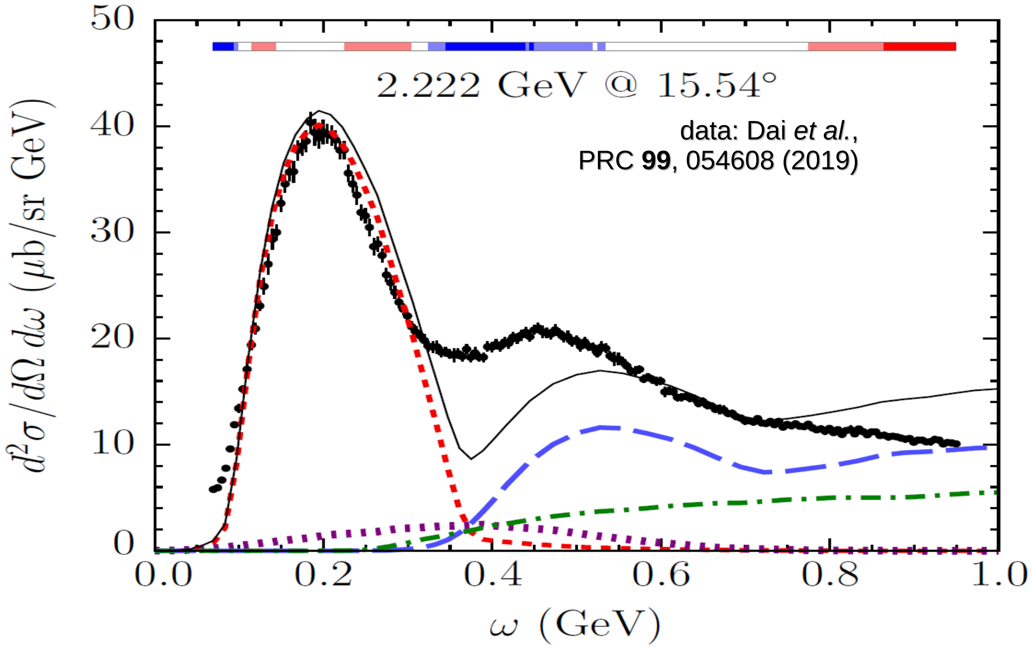


data: Dai *et al.*,
PRC 99, 054608 (2019)

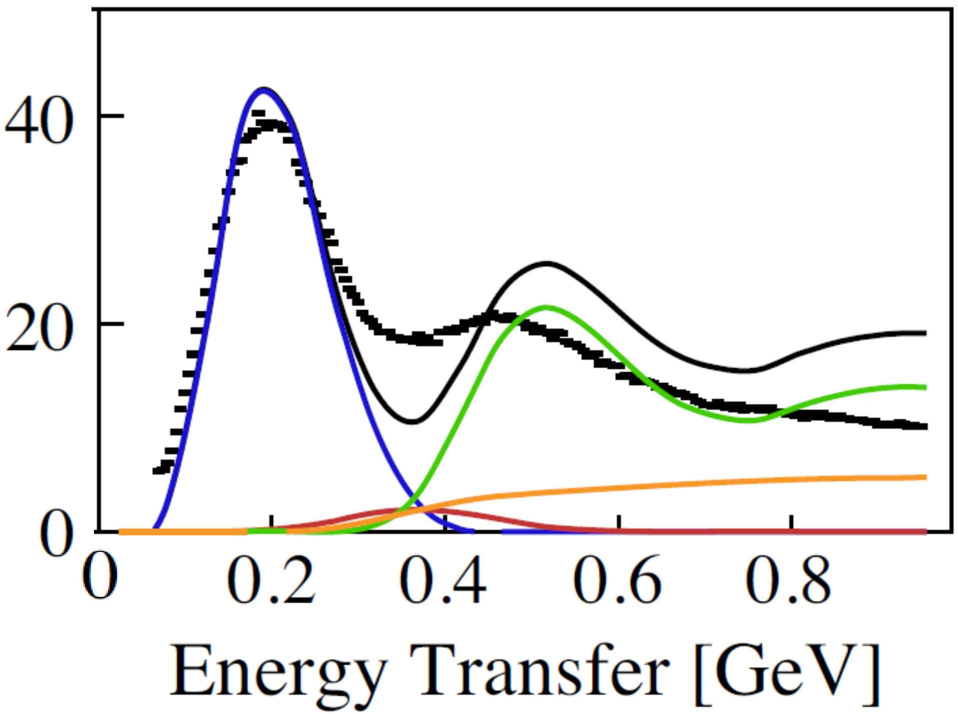
A.M.A. & Alex Friedland,
PRD 102, 053001 (2020)

GENIE 3 update

2.12

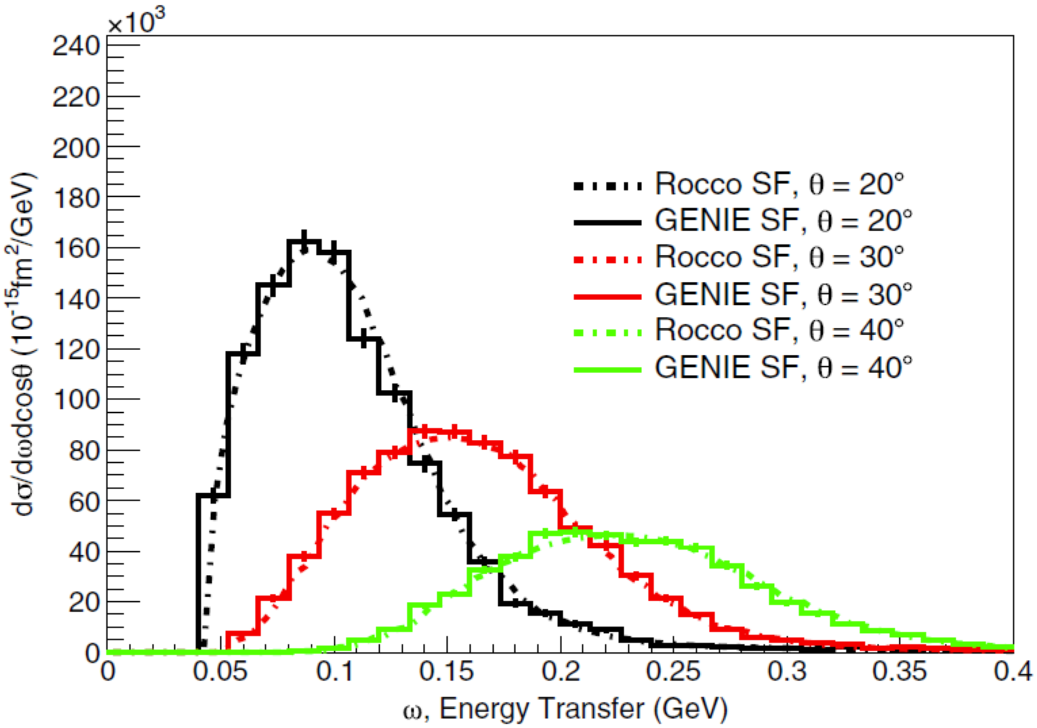


3.2



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

Spectral function in (a future) GENIE



Betancourt *et al.*,
PRD 108, 113009 (2023)

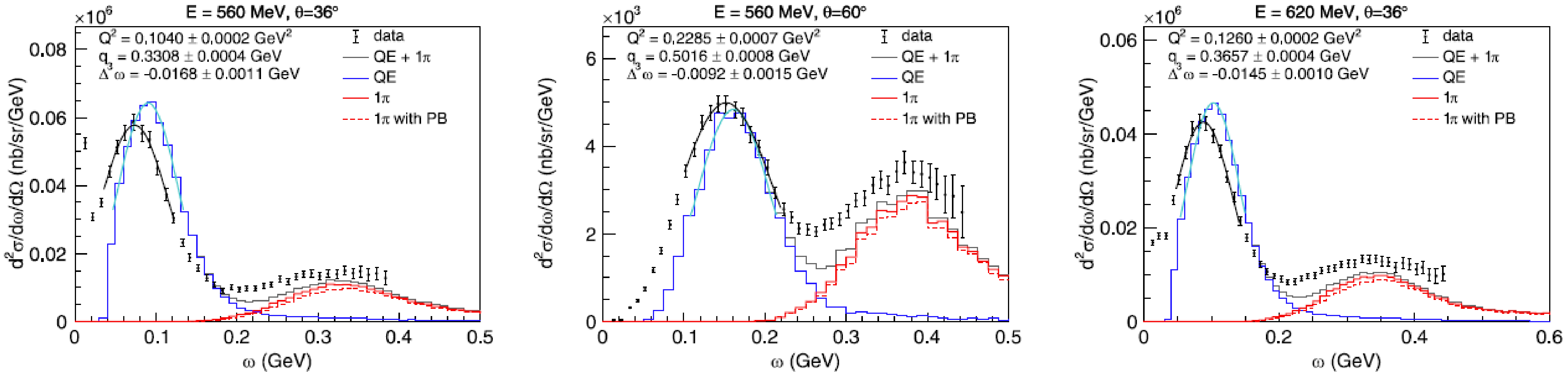
NEUT 5.9

- Updated spectral function implementation for QE interactions
  S. Abe, PRD 111, 033006 (2025)

- Dynamical coupled-channels model for single pion production
  H. Kamano, S. X. Nakamura, T.-S. H. Lee, and T. Sato, PRC 94, 015201 (2016)

- Bodek-Yang approach for deep inelastic scattering
  A. Bodek and U. K. Yang, Nucl. Phys. B, Proc. Suppl. 112, 70 (2002).

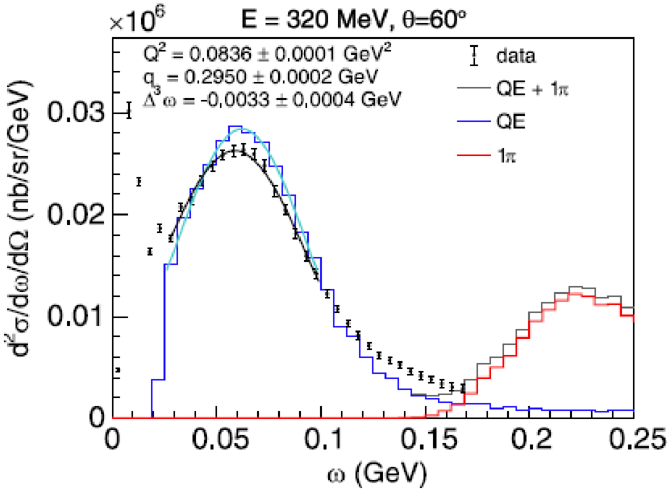
C(*e*,*e*’) in NEUT

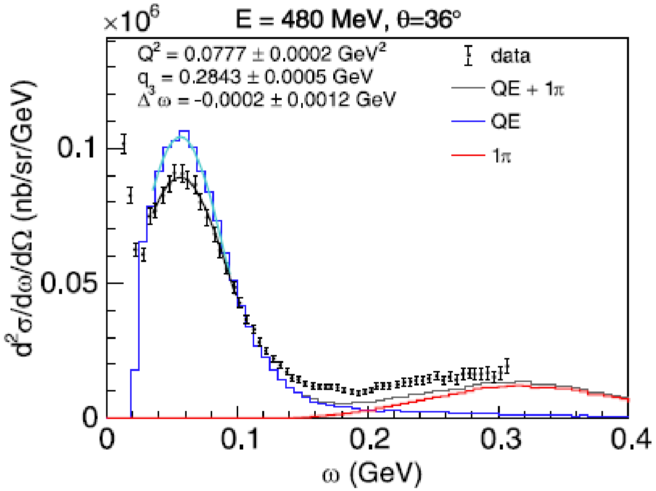


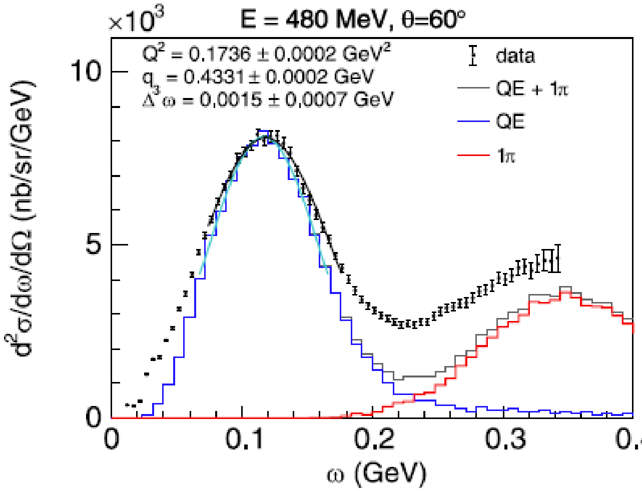
data: Barreau *et al.*,
NPA 402, 515 (1983)

S. Abe,
PRD 111, 033006 (2025)

C(*e*,*e*’) in NEUT: FSI







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

S. Abe,
PRD 111, 033006 (2025)

Upcoming NuWro 25 in a nutshell

- Updated spectral function implementation for QE interactions, including a consistent treatment of correlated nucleons in the initial state
  C. Ciofi degli Atti and S. Simula, Phys. Rev. C 53, 1689 (1996).
  L. Jiang *et al.*, PRD 105, 112002 (2022); L. Jiang *et al.*, PRD 107, 012005 (2023)

- Implementation of final state interactions (for inclusive and exclusive x-sections)
  A. M. Ankowski., O. Benhar, and M. Sakuda, PRD 91, 033005 (2015)

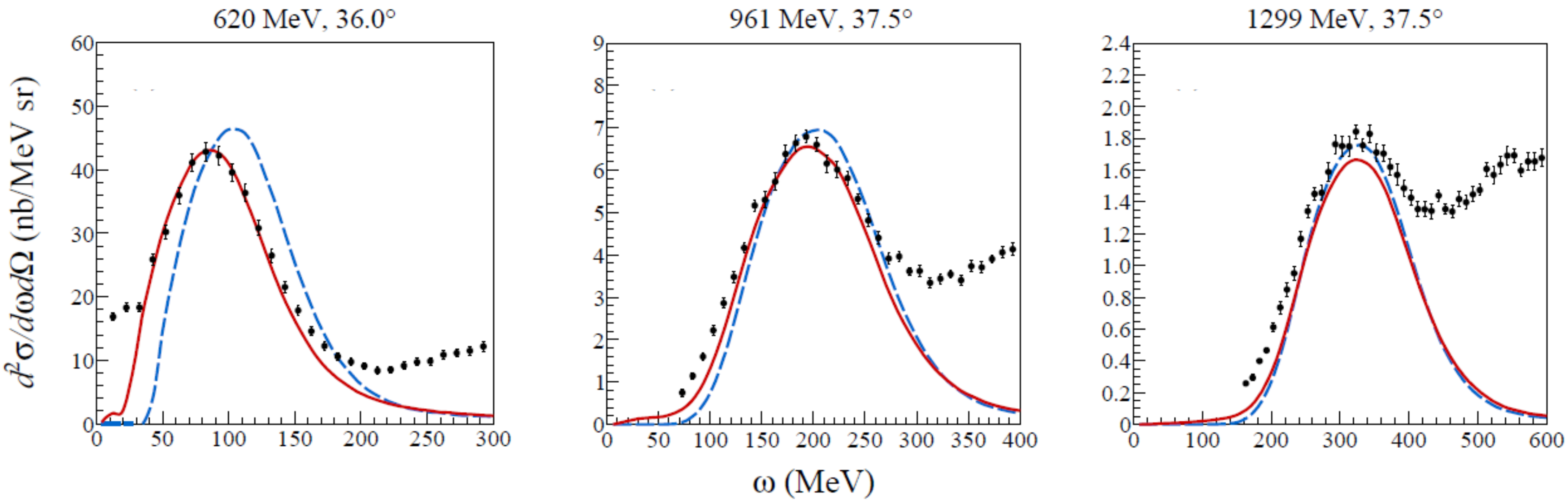
- Valencia 2020 to model MEC: exclusive final states
  J. E. Sobczyk, J. Nieves, and F. Sánchez, PRC 102, 024601 (2020)
  H. Prasad, J. T. Sobczyk, A. M. Ankowski, J. L. Bonilla, R. Dharmapal Banerjee, K. M. Graczyk, and B. E. Kowal, PRD 111, 036032 (2025)

  More details in the talk of Hemant Prasad on Monday!

- Ghent hybrid model for single pion production: inclusion of higher resonances
  Q. Yan, K. Niewczas, A. Nikolakopoulos, R. González-Jiménez, N. Jachowicz, X. Lu, J. Sobczyk, and Y. Zheng, JHEP 12 (2024) 141

- Bodek-Yang approach for deep inelastic scattering
  A. Bodek and U. K. Yang, Nucl. Phys. B, Proc. Suppl. 112, 70 (2002).

C(*e*,*e'*) in NuWro



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

data: Sealock *et al.*,
PRL 62, 1350 (1989)

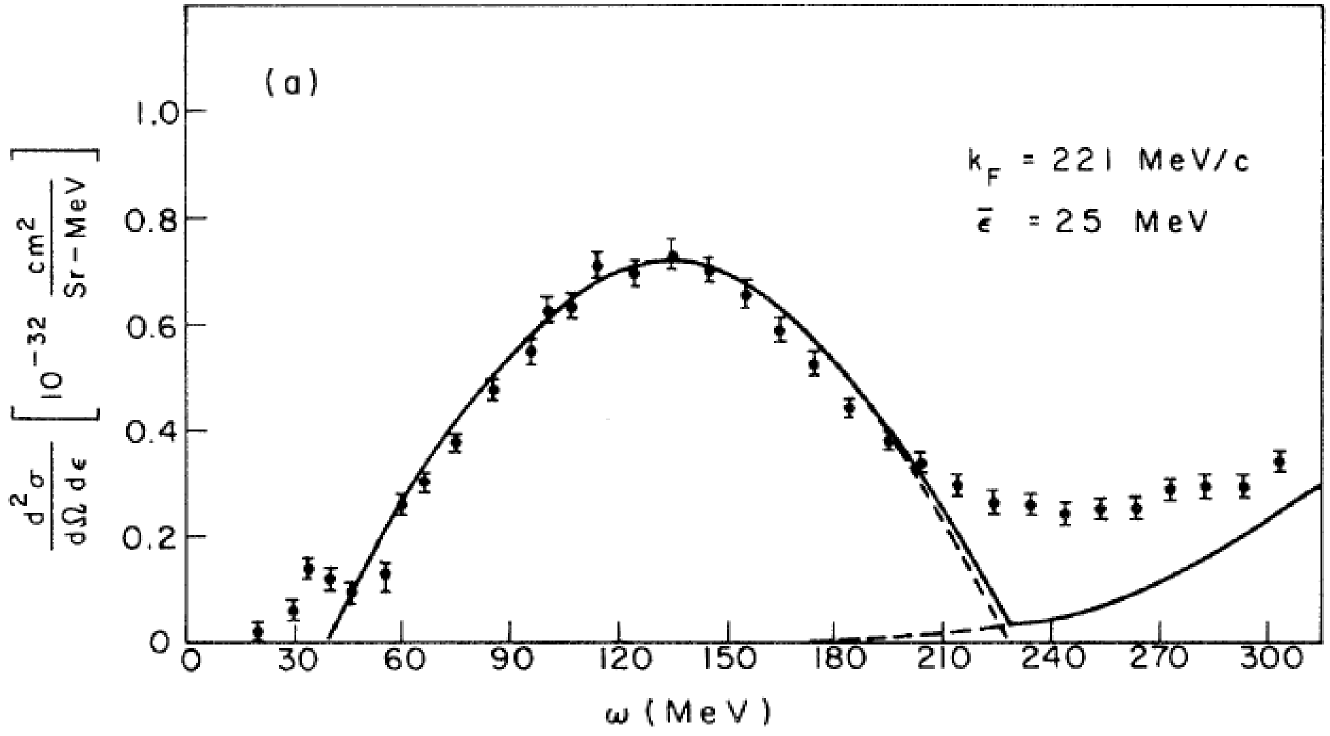
For more details, see the talk by
Rwik Dharmapal Banerjee!

Summary

- The success of the long-baseline neutrino program requires reliable cross sections.
- Substantial progress is required to meet this demand, but first steps can be readily made.
- Comparisons to precise electron data covering the whole relevant kinematics are essential to validate the employed models and determine their systematic uncertainties.
- Great deal of progress in the quasielastic channel.
- Main challenge ahead remains pion production.

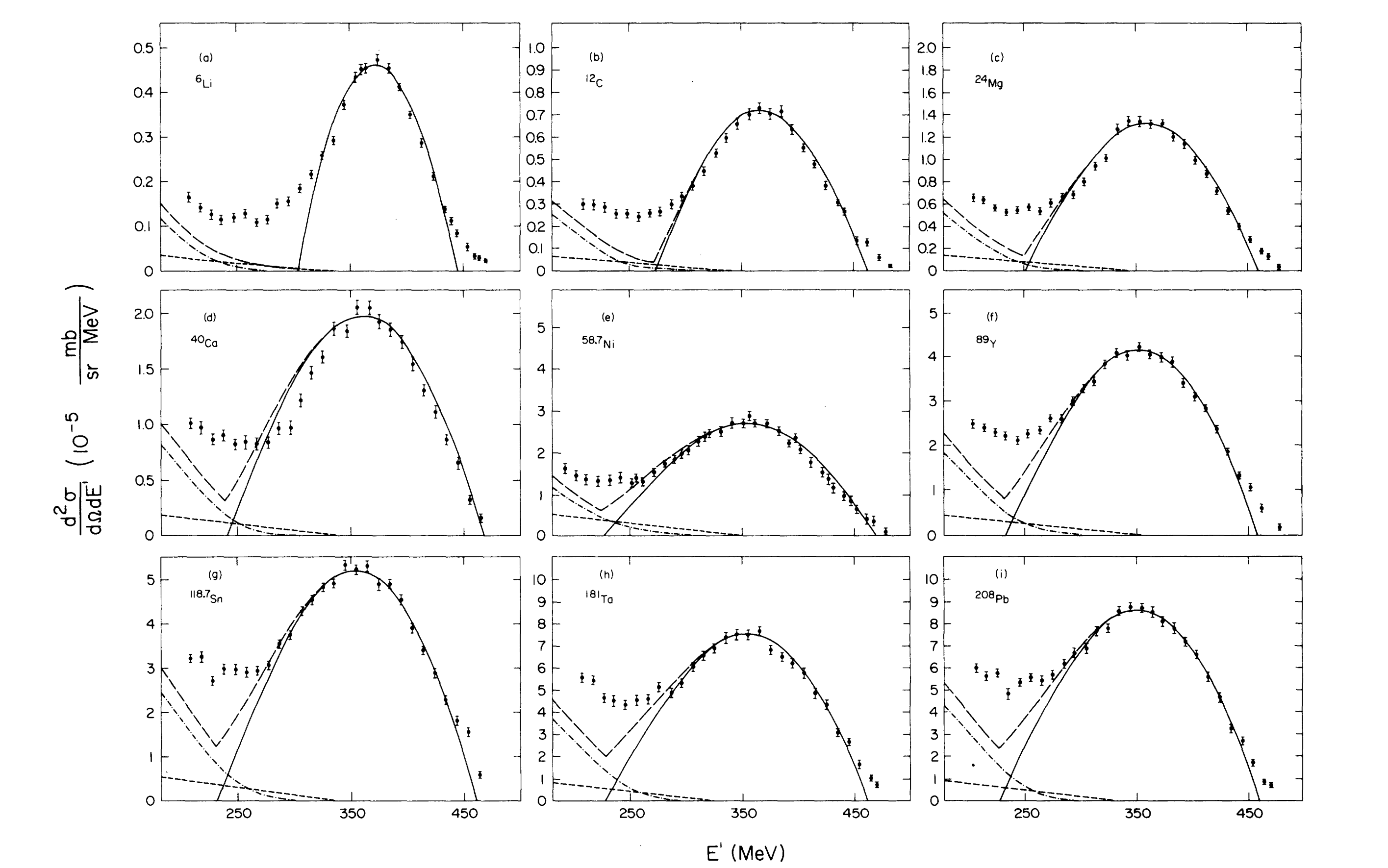
Thank you!

Electron scattering on carbon



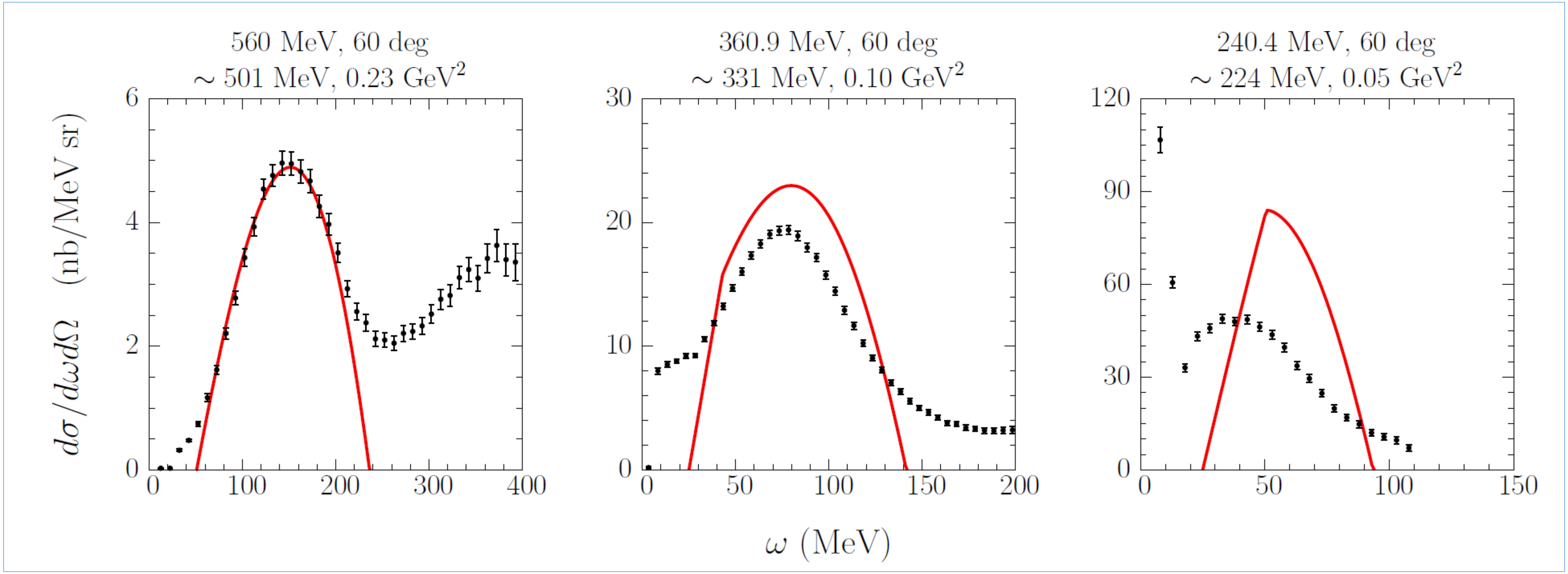
Moniz *et al.*, PRL 26, 445 (1971)

How about other targets?



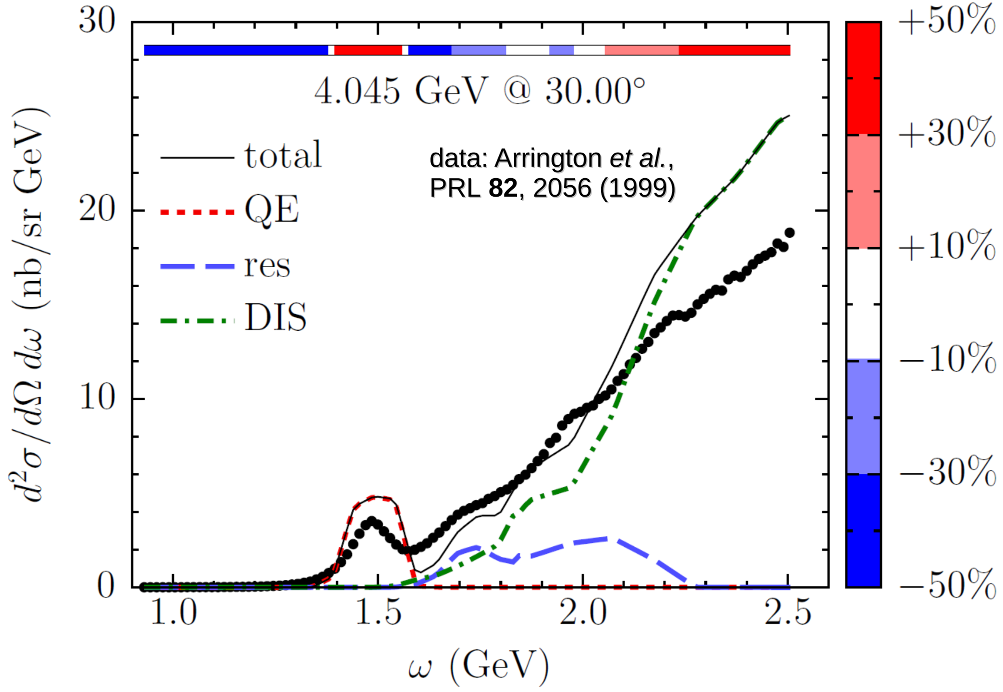
Whitney *et al.*, PRC 9, 2230 (1974)

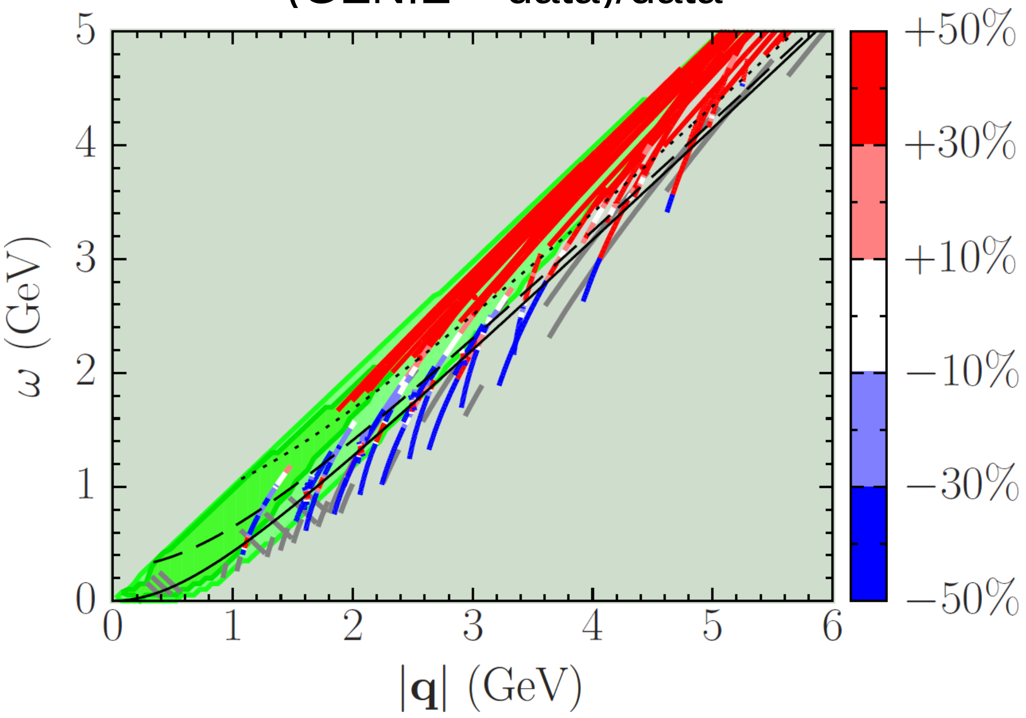
How about other *kinematics*?



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

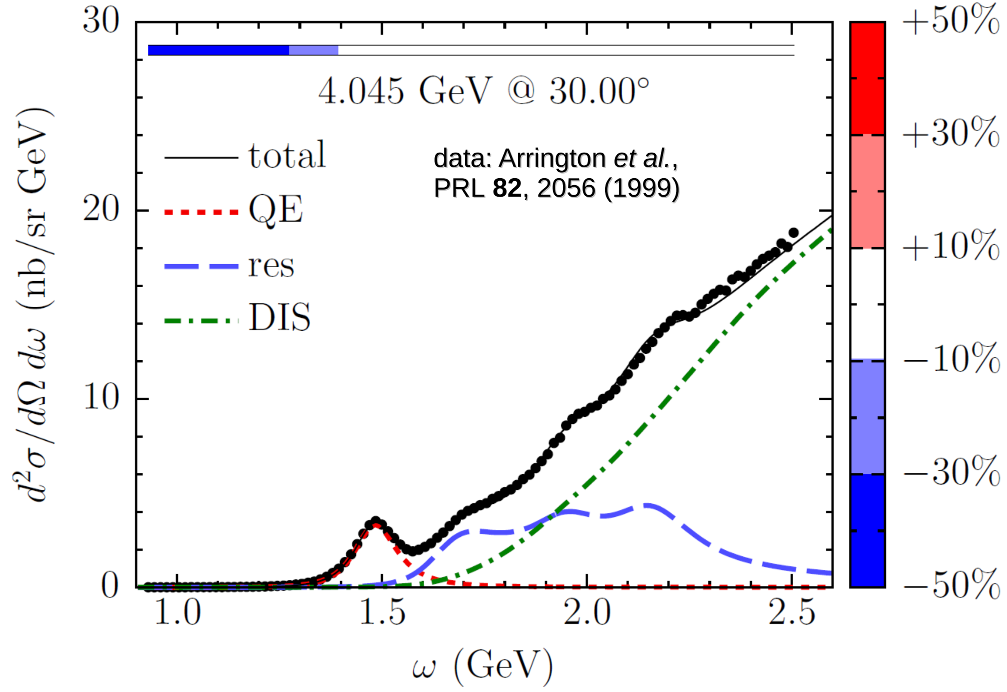
D(*e*,*e'*) in the Monte Carlo generator GENIE





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

Realistic description of D(*e*,*e'*)



(calc − data)/data