Modeling nuclear effects in precise oscillation experiments

Artur M. Ankowski
Virginia Tech

in collaboration with O. Benhar and C. Mariani

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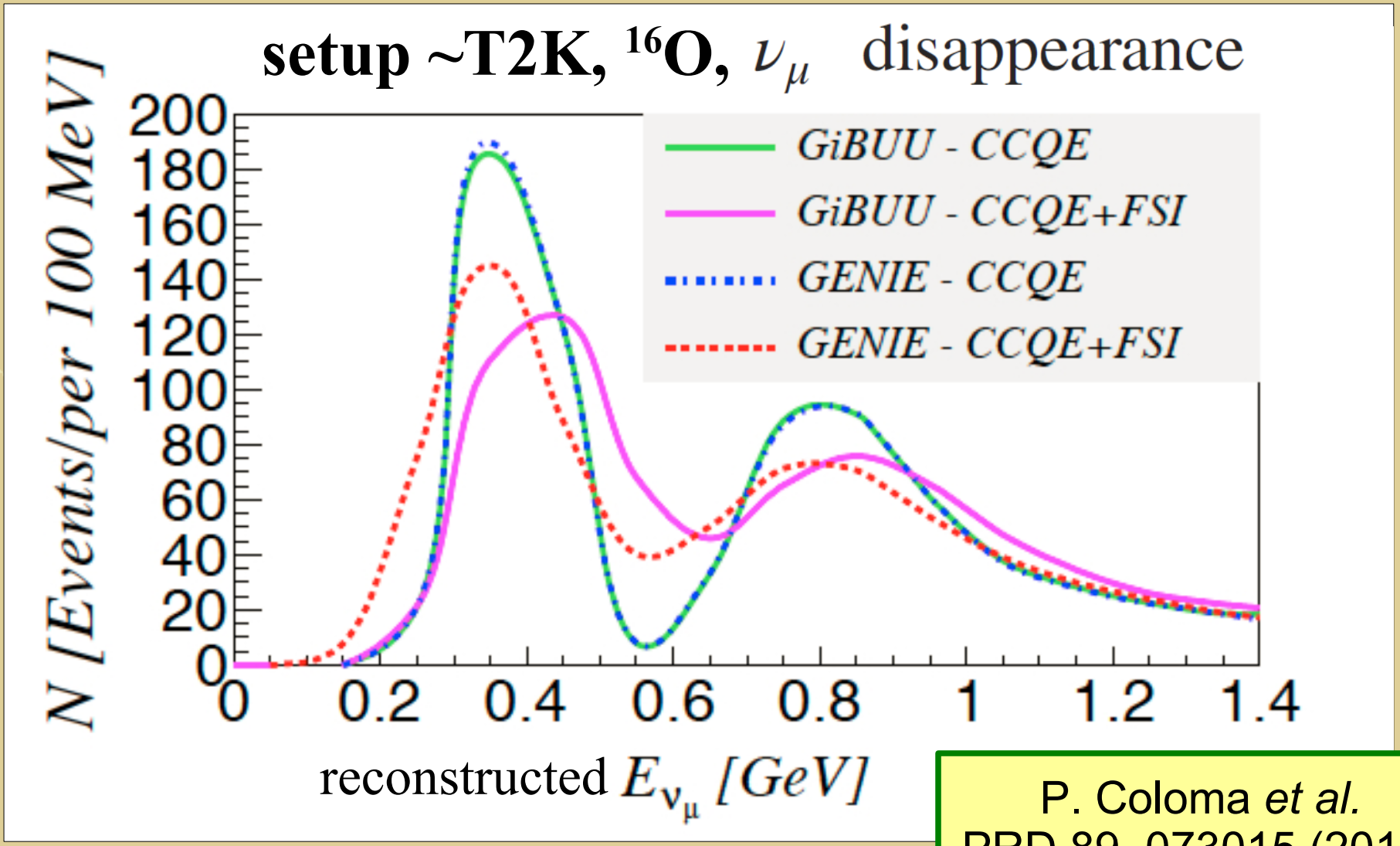
How relevant are nuclear effects?



P. Coloma *et al.*
PRD 89, 073015 (2014)

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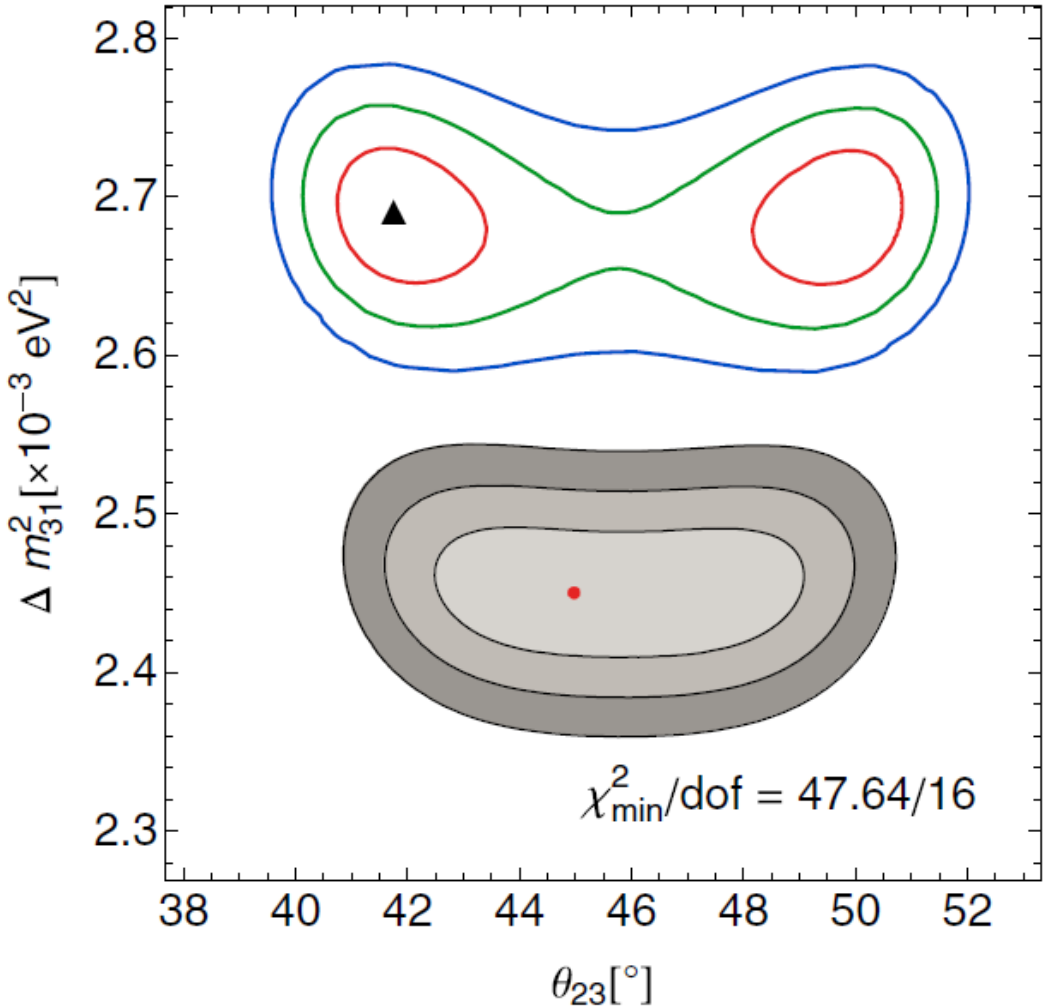


Events from GiBUU, migration matrices from GENIE

$\theta_{23} = 45^\circ \rightarrow 41.75^\circ$

$\Delta m^2_{31} = 2.45 \times 10^{-3}\ \mathrm{eV}^2$

$\rightarrow 2.69 \times 10^{-3}\ \mathrm{eV}^2$

P. Coloma *et al.*
PRD 89, 073015 (2014)

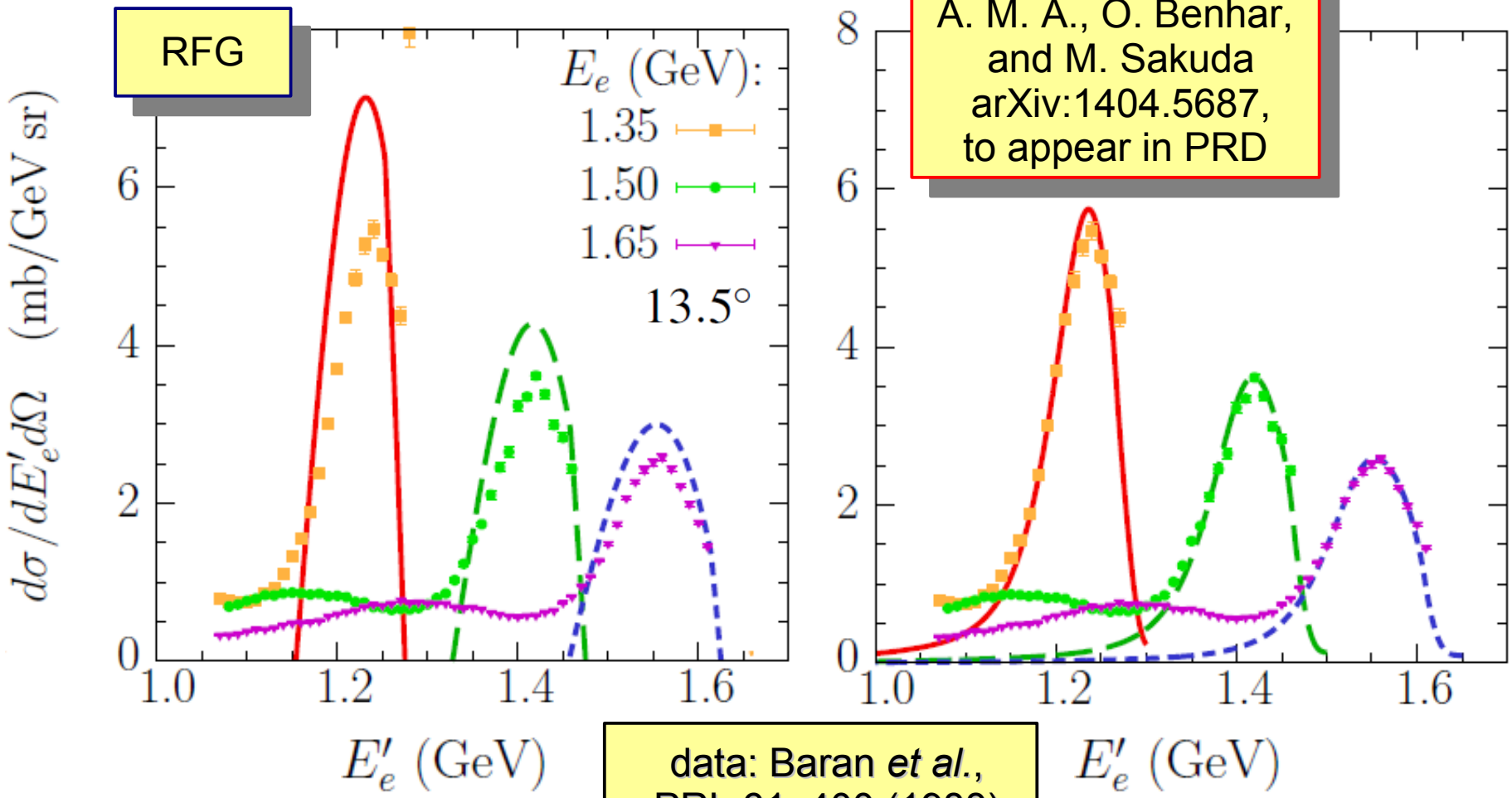
General remarks

- In neutrino scattering, uncertainties come from (i) interaction dynamics and (ii) nuclear effects

- It is **highly improbable** that theoretical approaches unable to reproduce *(e,e')* data would describe nuclear effects in neutrino interactions at similar kinematics.

- To be **reliable**, a description of nuclear effects has to be validated by **systematic comparisons** to *(e,e')* data, allowing its uncertainties to be estimated.

Comparisons to C(*e*,*e*′) data



data: Baran *et al.*, PRL 61, 400 (1988)

Impulse approximation (IA)

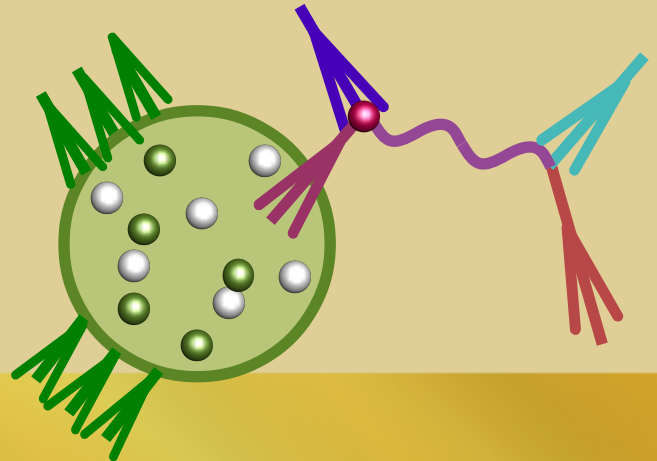
The cross section separates to

Elementary cross section

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

Hole spectral function

Particle spectral function ~δ(...)



Final state interactions (FSI)

In the convolution approach,

$$\frac{d\sigma^{\mathrm{FSI}}}{d\omega d\Omega} = \int d\omega' f_{\mathbf{q}}(\omega - \omega') \frac{d\sigma^{\mathrm{IA}}}{d\omega' d\Omega},$$

with the folding function

$$f_{\mathbf{q}}(\omega) = \delta(\omega)\sqrt{T_A} + \left(1 - \sqrt{T_A}\right) F_{\mathbf{q}}(\omega),$$

Nucl. transparency

SF + FSI

Nuclear structure described by the **realistic hole SF** [Benhar *et al*., NPA 579, 493 (1994)] calculated in the local-density approximation, combining

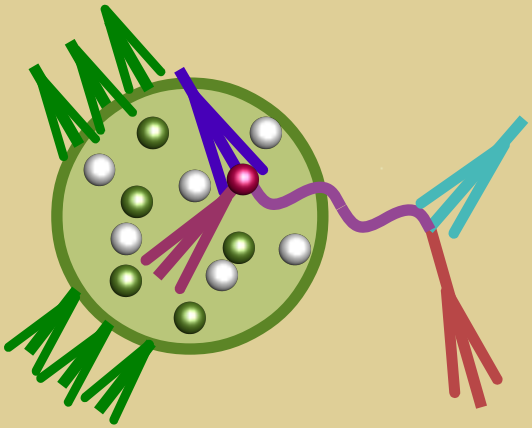
- the **shell structure** from the Saclay *(e,e'p)* data
- the **correlation contribution** resulting from NN (Urbana v_{14}) and 3N interactions

Final-state interactions accounted for in the correlated Glauber approximation [Benhar, PRC 87, 024606 (2013)] including the effect of the real part of the optical potential [Cooper et al., PRC 47, 297 (1993)]

No free parameters

A. M. A., O. Benhar, and M. Sakuda
arXiv:1404.5687

SF approach

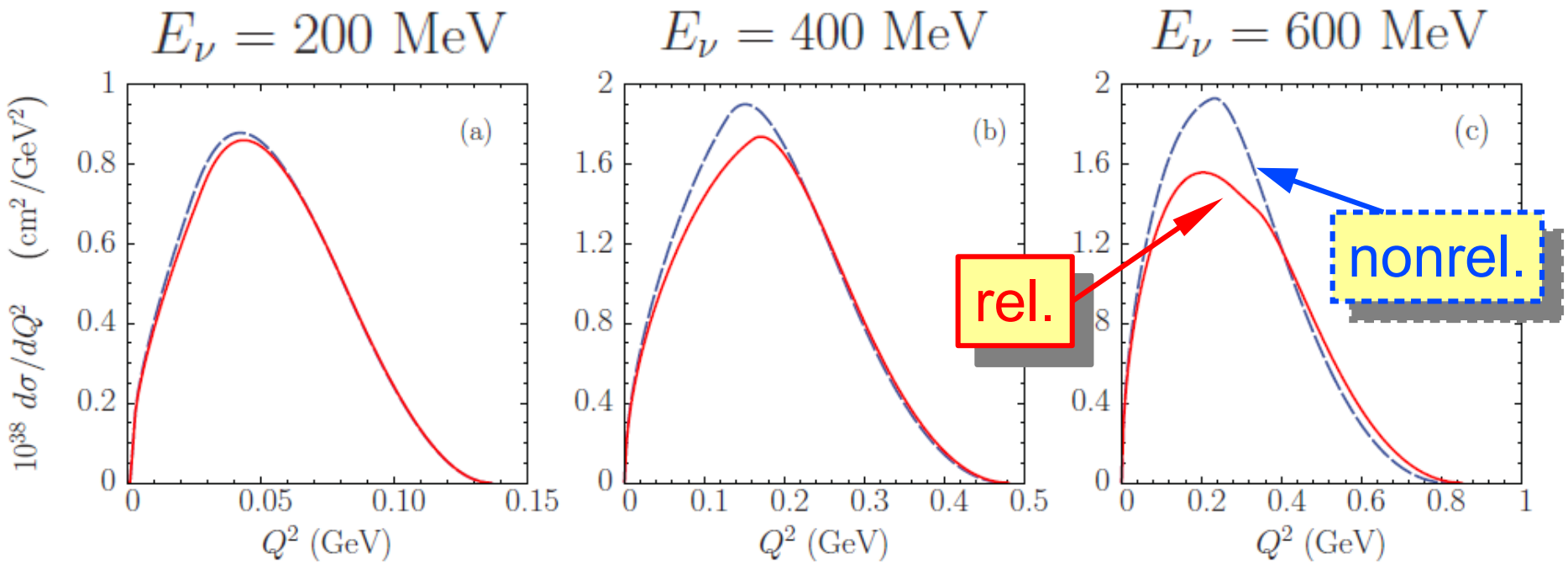


The struck nucleon is treated separately from the (A-1)-nucleon spectator system: **nuclear dynamics is decoupled from propagation of the relativistic particle** and described by nonrelativistic nuclear many-body theory.

Ongoing efforts to add **two-nucleon reaction mechanisms** (*e.g.* involving meson-exchange currents) in a consistent manner [Benhar *et al.*, arXiv:1312.1210], including (sizable) interference between different processes leading to 2*p*2*h* final states.

Relativistic vs. nonrelativistic

Energies much lower then those in LBNE



A. M. A. and O. Benhar, PRC 83, 054616 (2011)

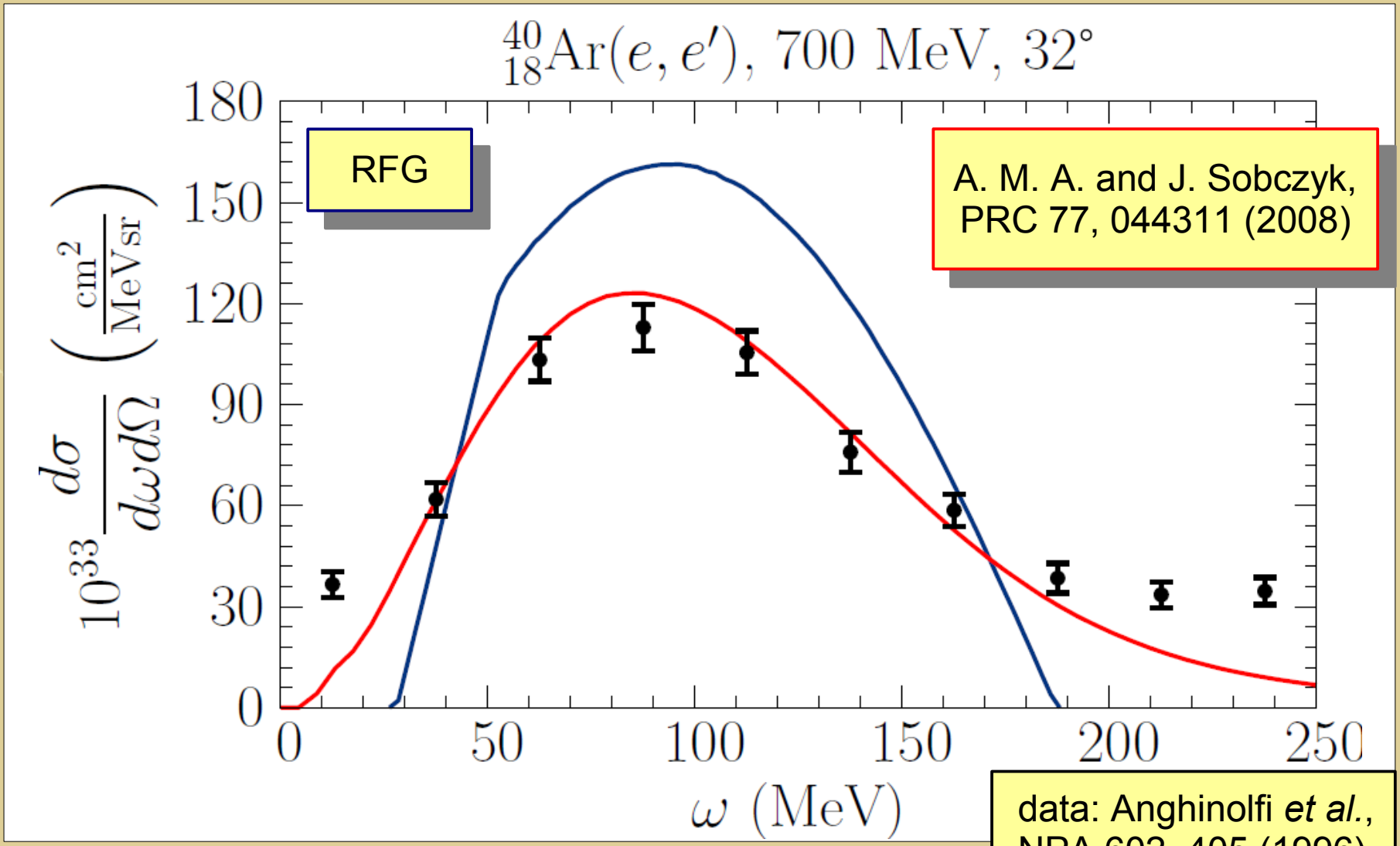
Argon SF

Owing to **lack of experimental (*e,e'p*) data**, the realistic SF of argon cannot be currently calculated in the local-density approximation.

The only existing, approximate, SF is found from very scarce information available on the nuclear structure, applying rather crude approximations.

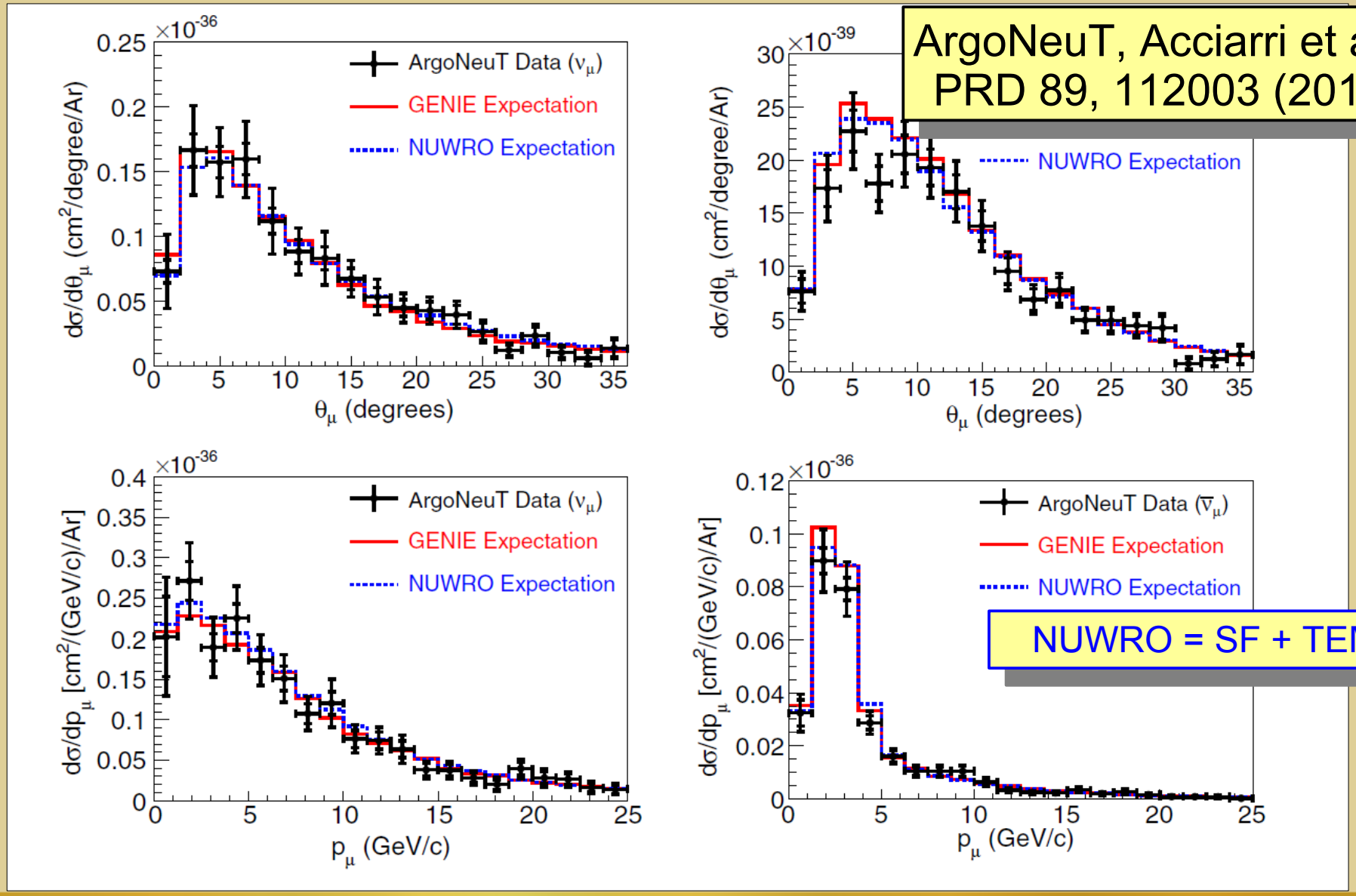
A. M. A. and J. Sobczyk,
PRC 77, 044311 (2008)

Comparisons to argon data



data: Anghinolfi *et al.*, NPA 602, 405 (1996)

Comparisons to argon data



Measurement of the Spectral Function of ^{40}Ar through the (e, e′p) reaction

Proposal (PR12-14-012) submitted to the

Jefferson Lab Program Advisory Committee PAC 42

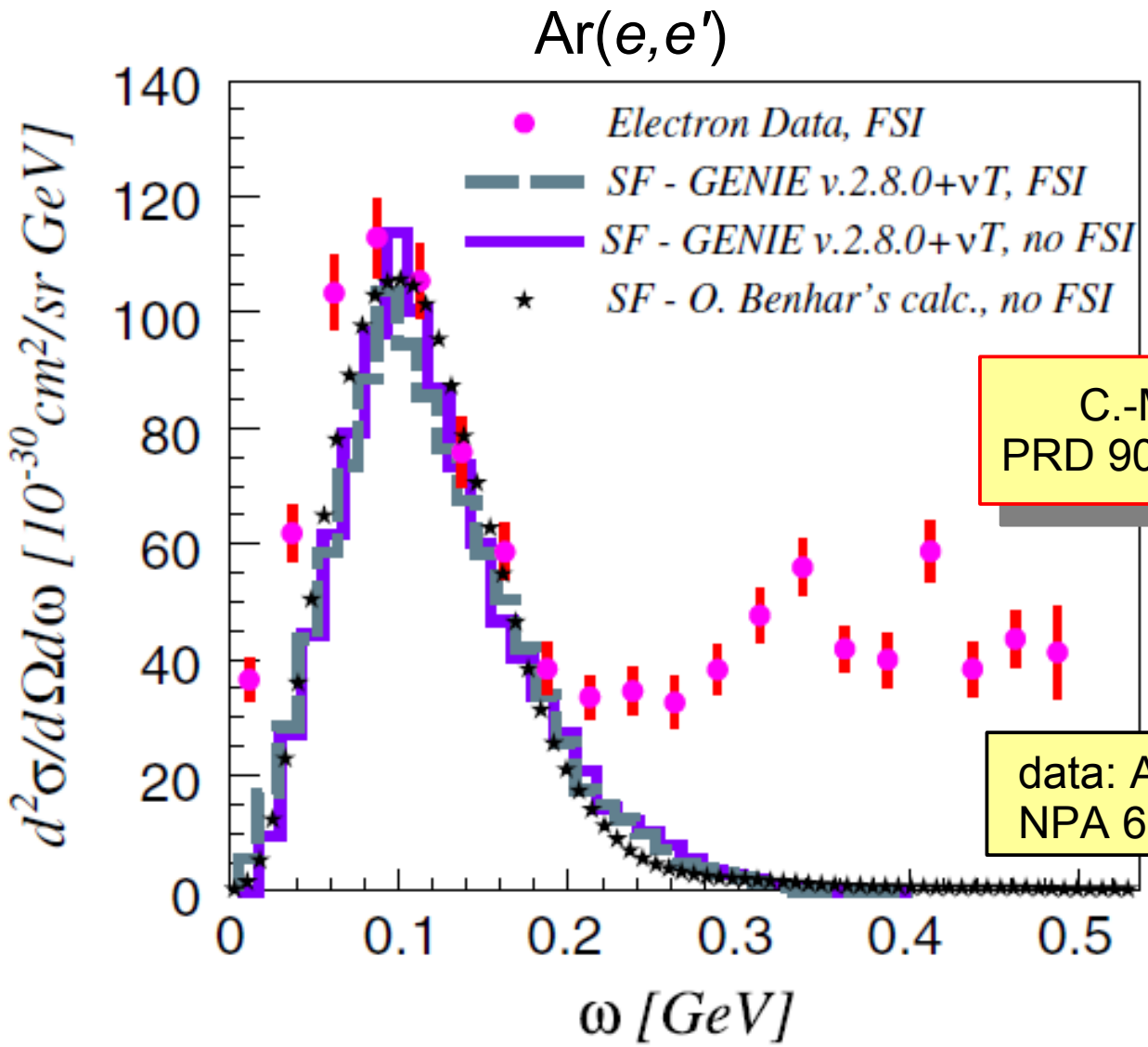
APPROVED

O. Benhar *et al.*, arXiv:1406.4080

Nuclear structure of protons in the argon nucleus to be determined for $0 < |p_m| < 400$ MeV/c and $8 < E_m < 60$ MeV

The result can be used to construct the realistic SF in the local-density approximation and improve description of nuclear effects in argon.

νT package to GENIE



C.-M. Jen *et al.*,
PRD 90, 093004 (2014)

data: Anghinolfi *et al.*,
NPA 602, 405 (1996)

Summary

❶ An accurate description of nuclear effects, including final-state interactions, is crucial for accurate reconstruction of neutrino energy.

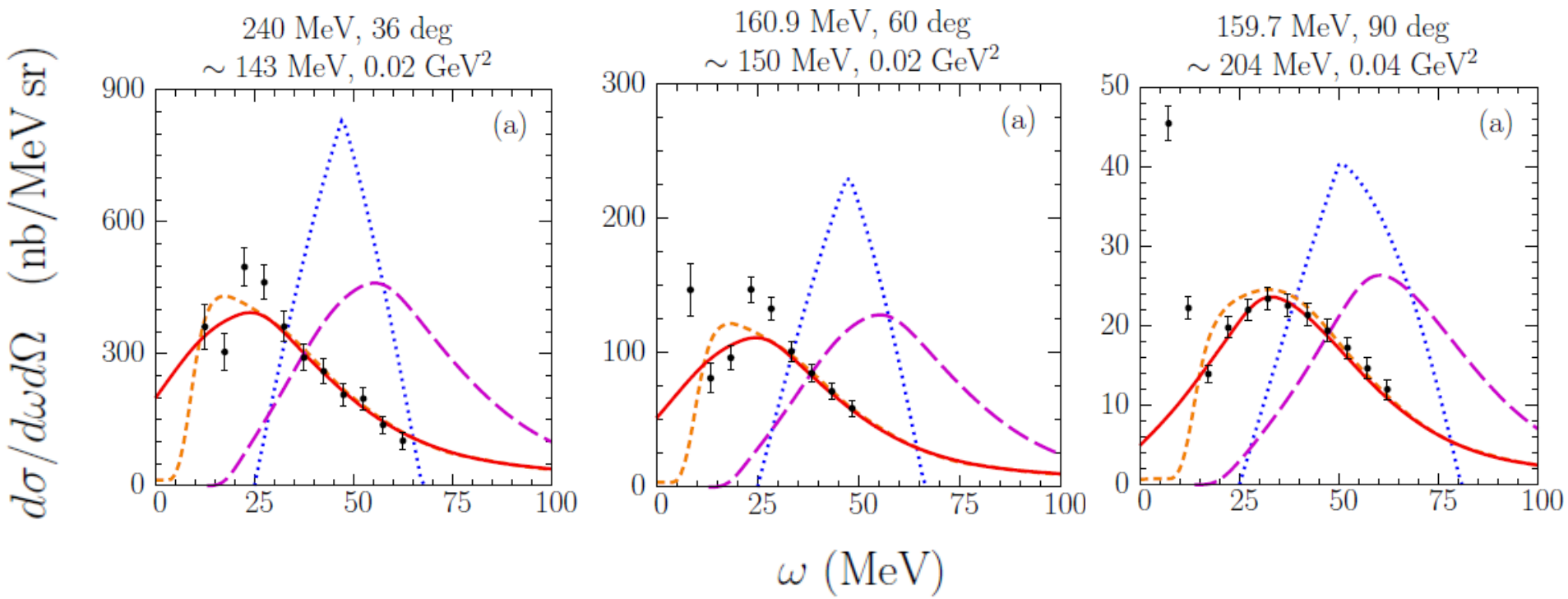
❷ Theoretical models must be validated against (e,e') data to estimate their uncertainties.

❸ The spectral function formalism can be used in Monte Carlo simulations be to improve the accuracy of description of nuclear effects.

❹ Important progress can be expected both from theoretical development and experimental measurements.

Backup slides

Impulse approximation



High energy data