JLab spectral functions in NuWro and multinucleon final states

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University of Wrocław

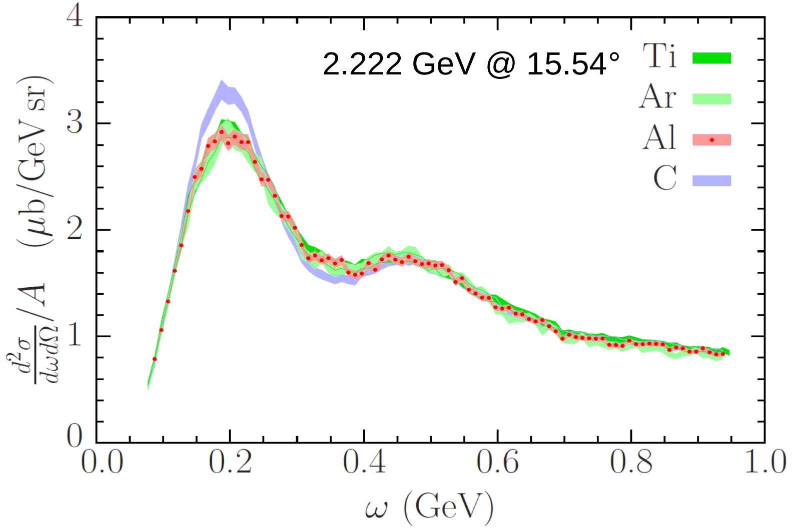
based on
A.M.A. *et al.*, in preparation
R. Dharmapal Banerjee *et al.*, PRD 109, 073004 (2024)

Marciana 2025 – Lepton Interactions with Nucleons and Nuclei
Marciana Marina, Isola d'Elba, June 22-27, 2025

E12-14-012 in JLab: (*e*,*e'*) and (*e*,*e'p*) on Ar and Ti

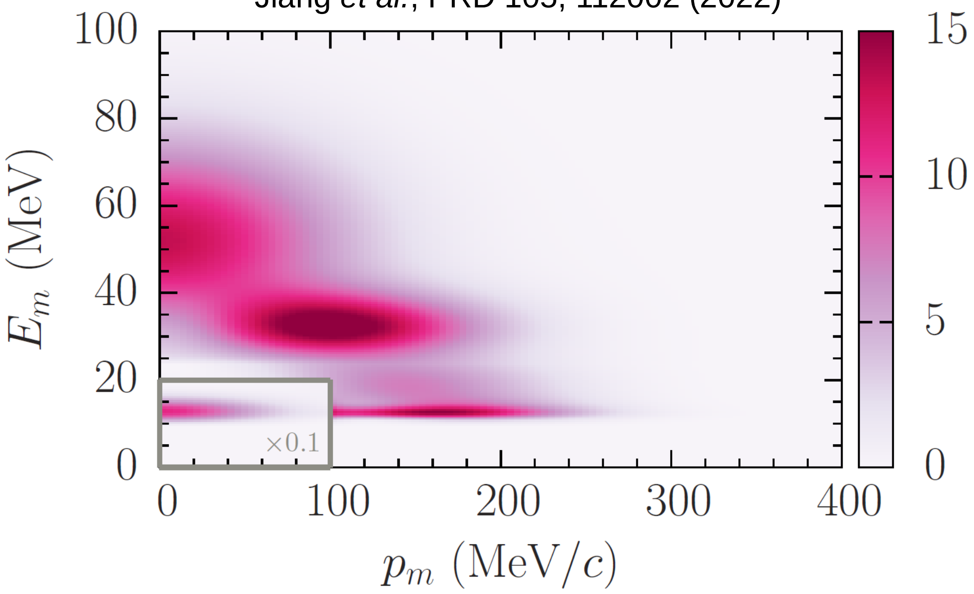
Aim: Obtaining the experimental input indispensable to construct the argon spectral function, thus paving the way for a reliable estimate of the neutrino cross sections in DUNE. In addition, stimulating a number of theoretical developments, such as the description of final-state interactions.
[Benhar *et al.*, arXiv:1406.4080]

- C(*e*,*e'*) and Ti(*e*,*e'*)
  Dai *et al.*, PRC 98, 014617 (2018)
- Ar(*e*,*e'*)
  Dai *et al.*, PRC 99, 054608 (2019)
- Al-7075(*e*,*e'*) & *A*-, *y*-, *ψ*-scaling
  Murphy *et al.*, PRC 100, 054606 (2019)

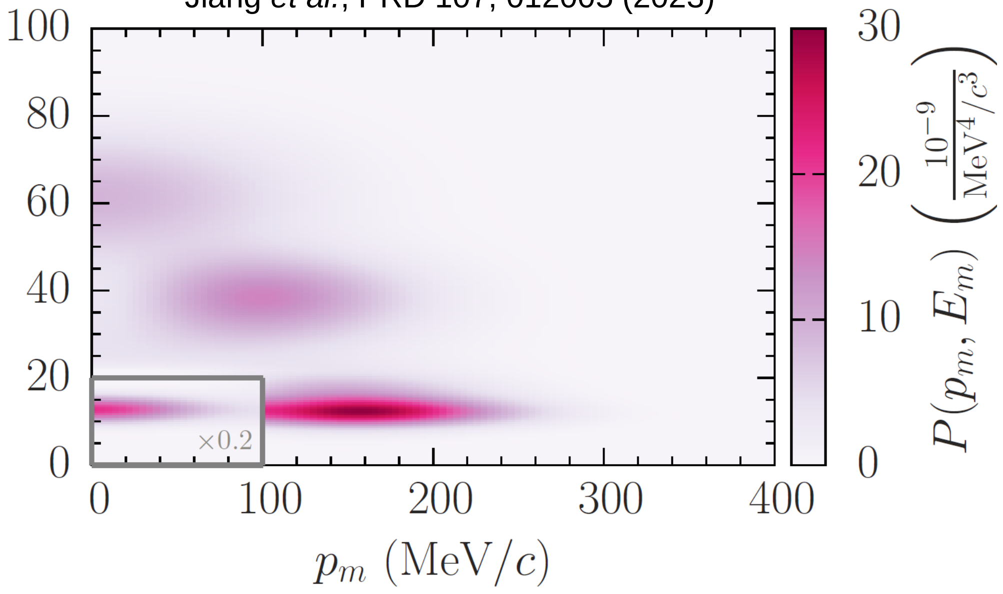


Ar & Ti spectral functions

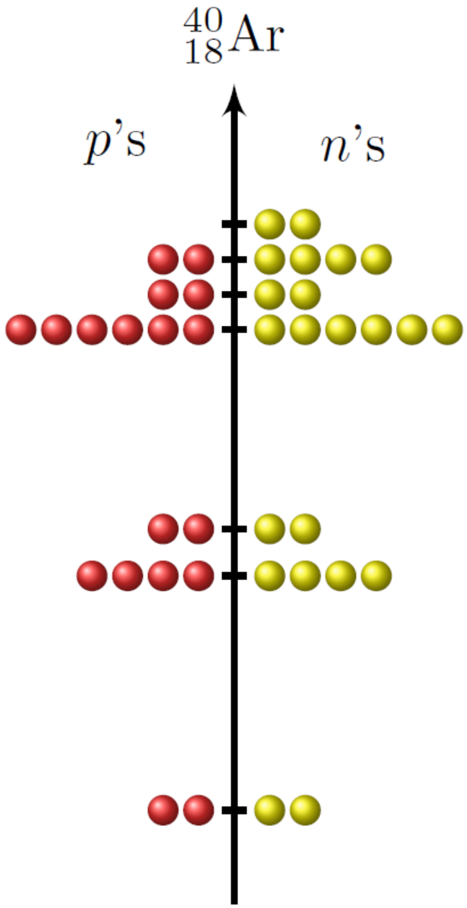
Jiang *et al.*, PRD 105, 112002 (2022)

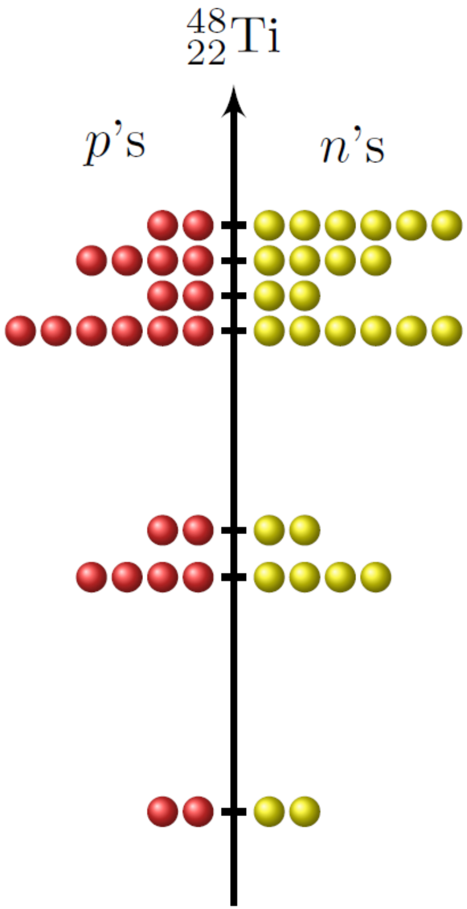


Jiang *et al.*, PRD 107, 012005 (2023)



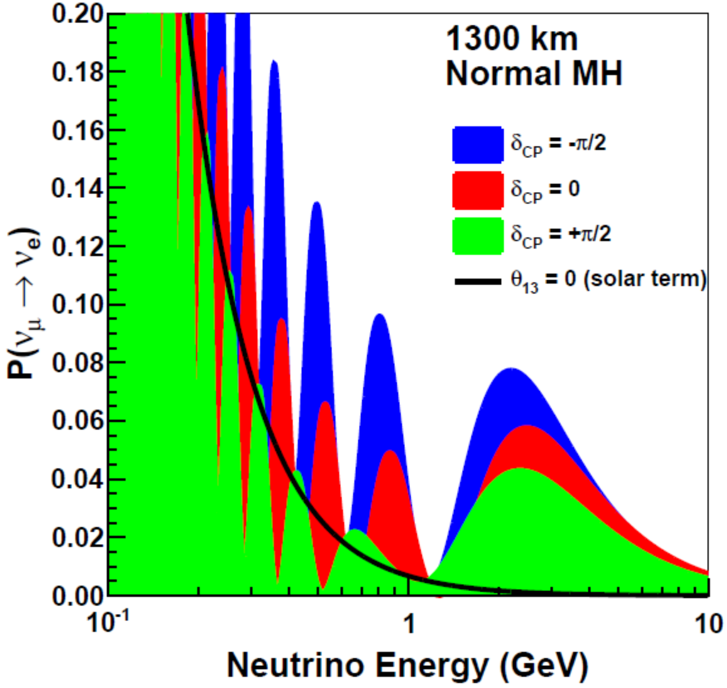
Why titanium?





MC Generators in long-baseline neutrino physics

- Main goal: extract the ν & $\bar{\nu}$ oscillation probabilities.
- Polychromatic beams, neutrino energy reconstructed from visible energy deposited by interaction products.
- Calorimetric reconstruction of neutrino energy.
- Sizable contributions of hadrons. Neutrons' energy estimate heavily dependent on Monte Carlo.
- 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 precise measurements cannot succeed.**

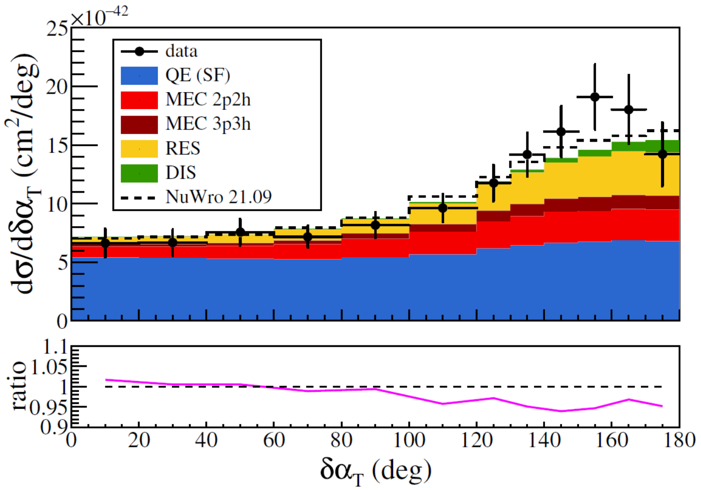


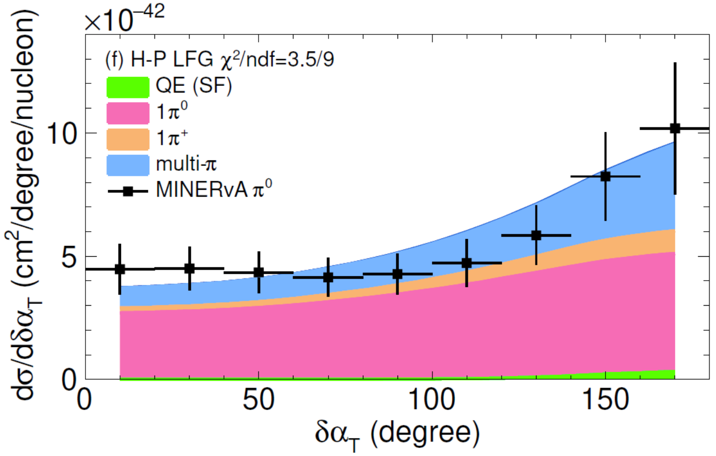
DUNE Collaboration, arXiv:1512.06148

What’s new in NuWro 25.03

- 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)

- 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





Previous updates of the NuWro’s SF approach

R. Dharmapal Banerjee *et al.*, PRD 109, 073004 (2024)

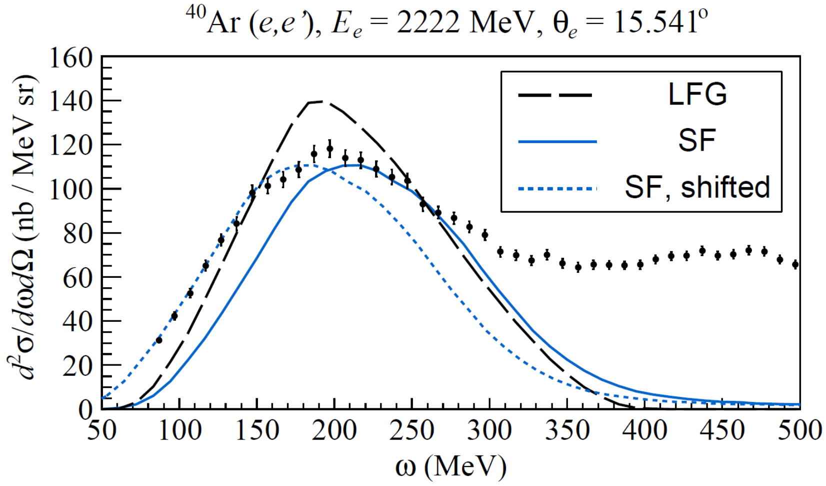
- JLab spectral functions for protons and neutrons in Ar
  L. Jiang *et al.*, PRD 105, 112002 (2022); PRD 107, 012005 (2023)

- Coulomb shift for neutron energy levels in C, O, and Fe

- EMA’ for Coulomb effects for charged particles inside nuclei
  A. Aste and J. Jourdan, Europhys. Lett. 67, 753 (2004)
  A. M. Ankowski, O. Benhar & M. Sakuda, PRD 91, 033005 (2015)

- Nuclear recoil in energy conservation

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



Spectral function for complex nuclei

Mean-field part

- describes the shell structure
- can be determined from experimental data
- 70–80% of nucleons

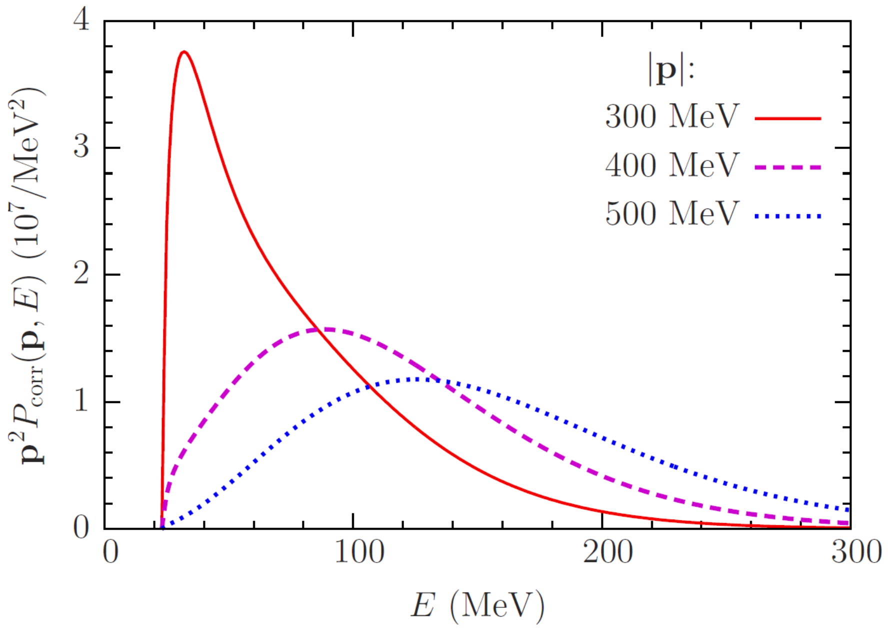
Correlated part

- describes correlated nucleons
- easier to determine from theoretical estimates

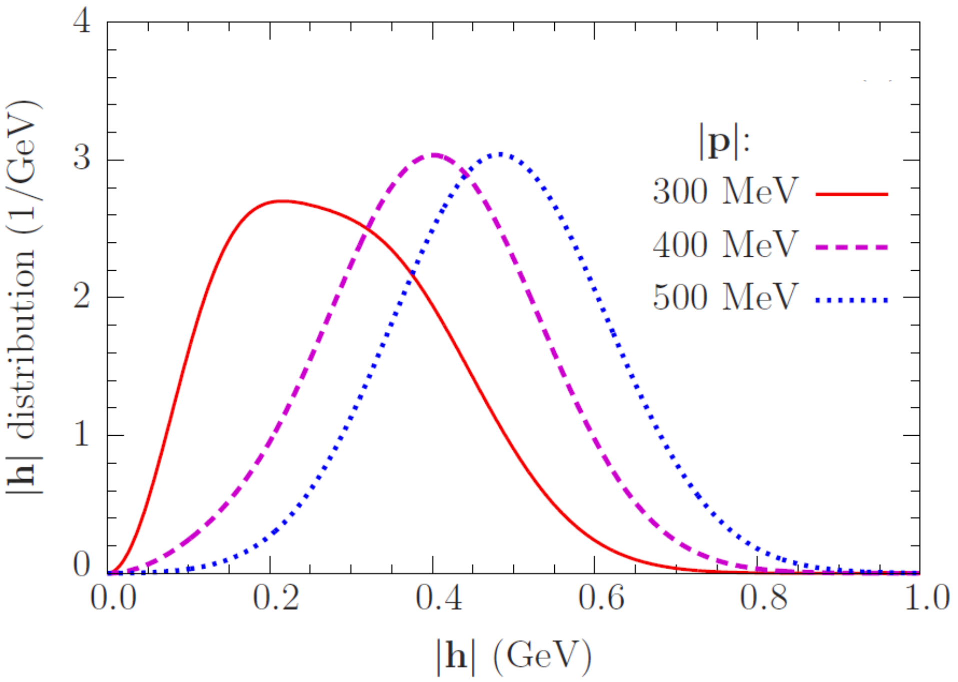
Correlated part of the spectral function

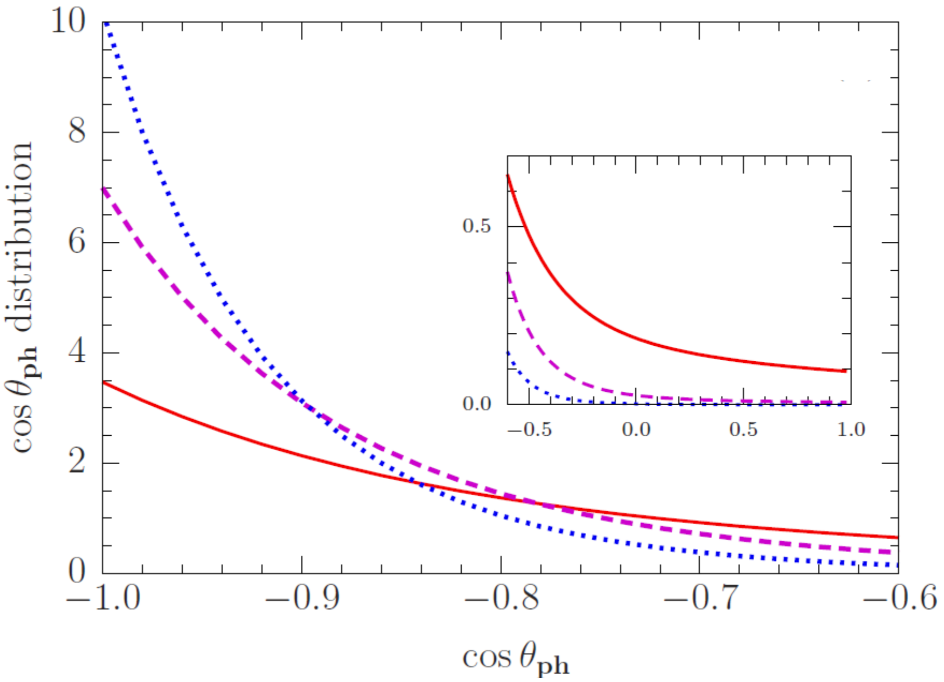
- Correlated *pn* pairs with the relative momentum distributed as in deuteron.
- Pairs undergo CM motion (Gaussian distrib.)
- Excitation energy of the $(A-1)$-nucleons is their kinetic energy plus the *pn* knockout threshold

Ciofi degli Atti and Simula, PRC 53, 1689 (1996)

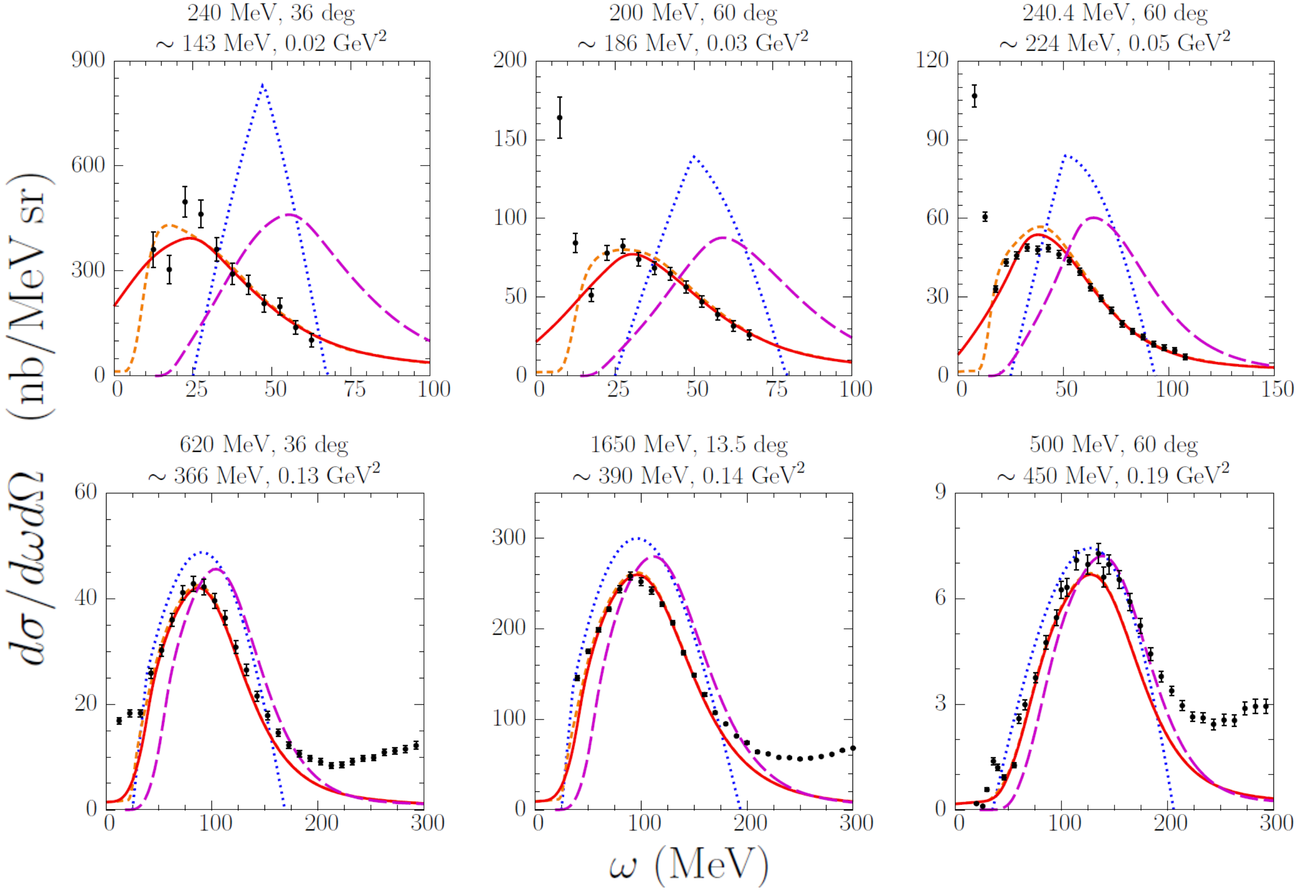


Correlated part of the spectral function





C(*e*,*e'*)



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

Final-state interactions

The convolution approach,

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

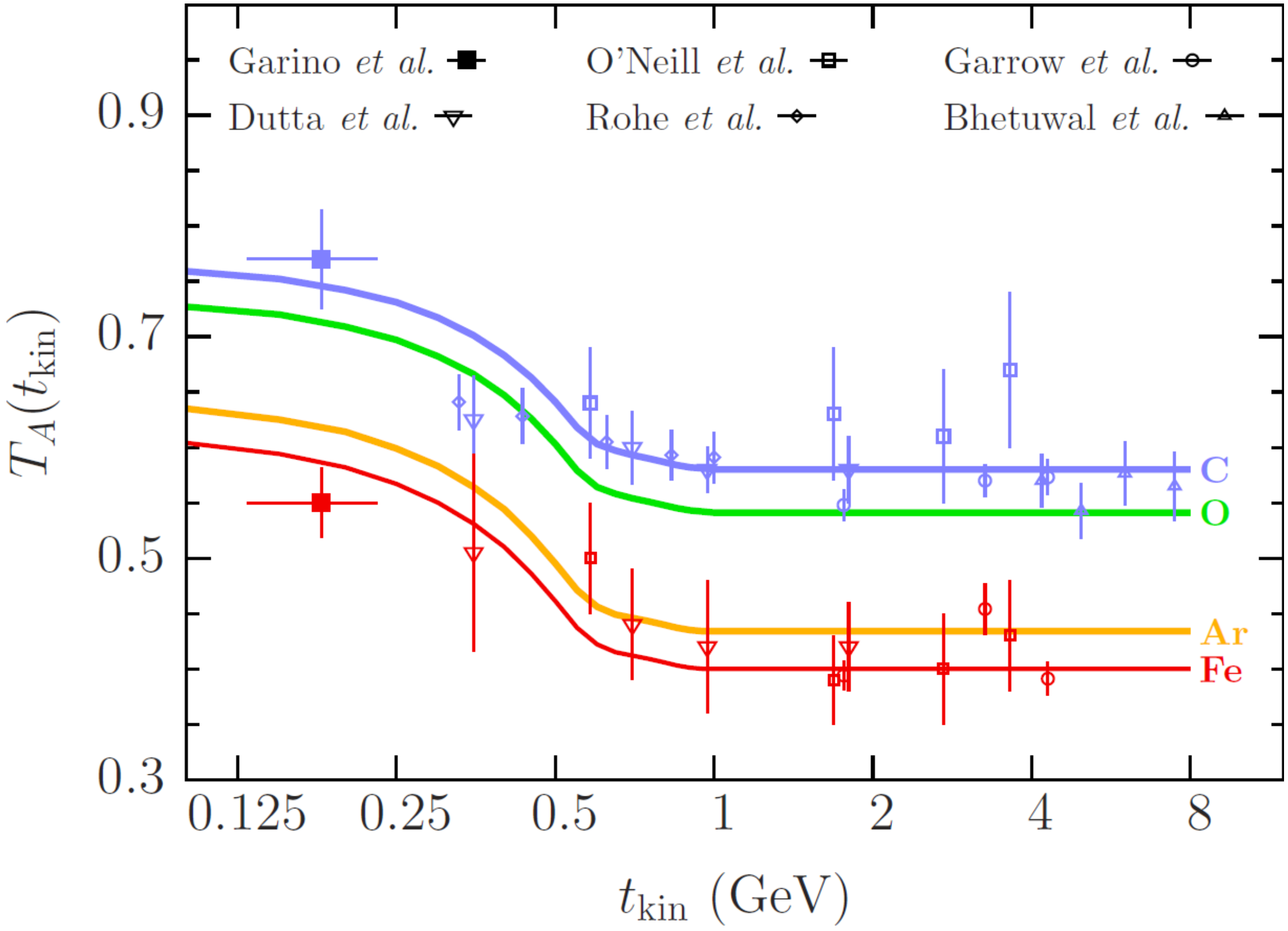
with the folding function

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

and nuclear transparency T_A.

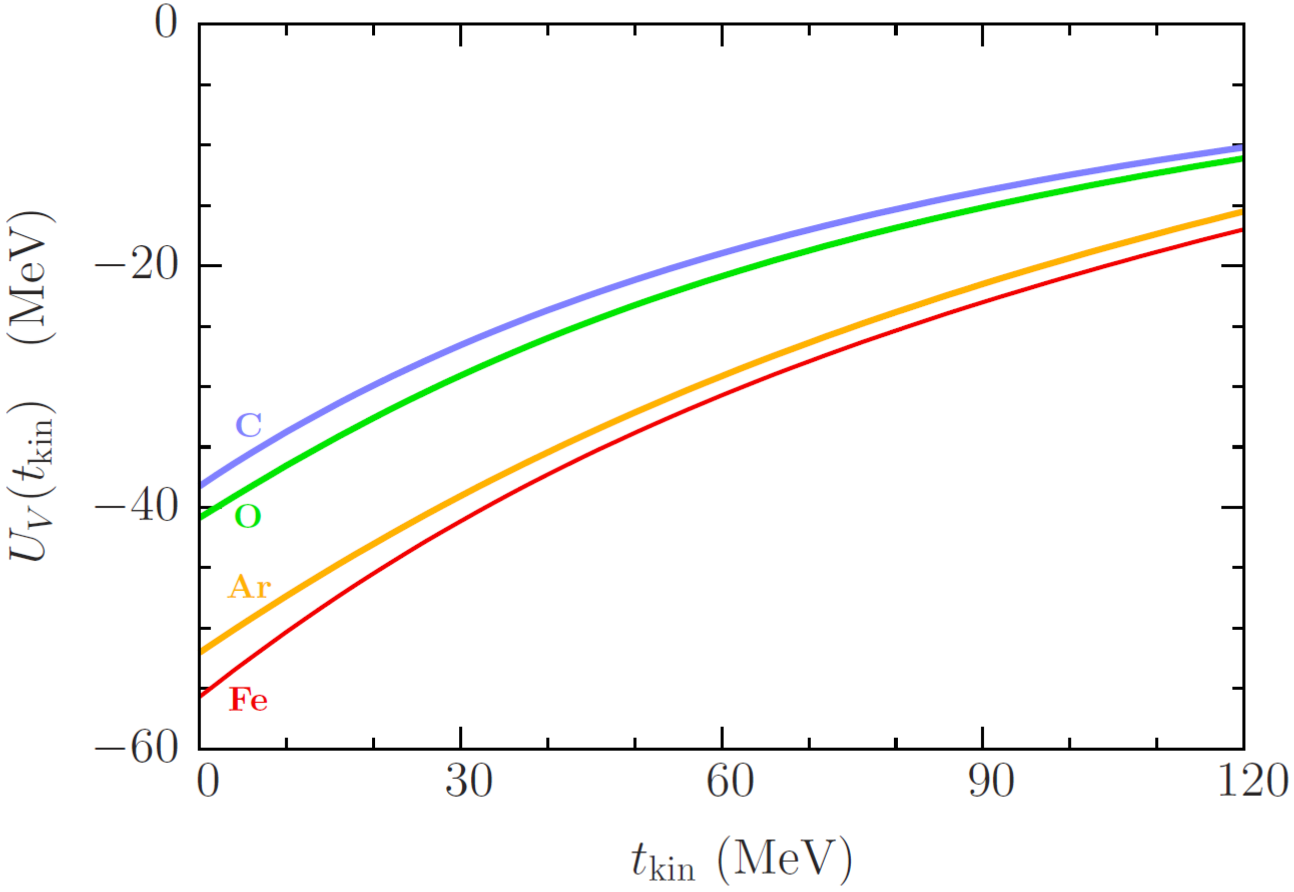
O. Benhar, PRC 87, 024606 (2013)

Nuclear transparency in NuWro



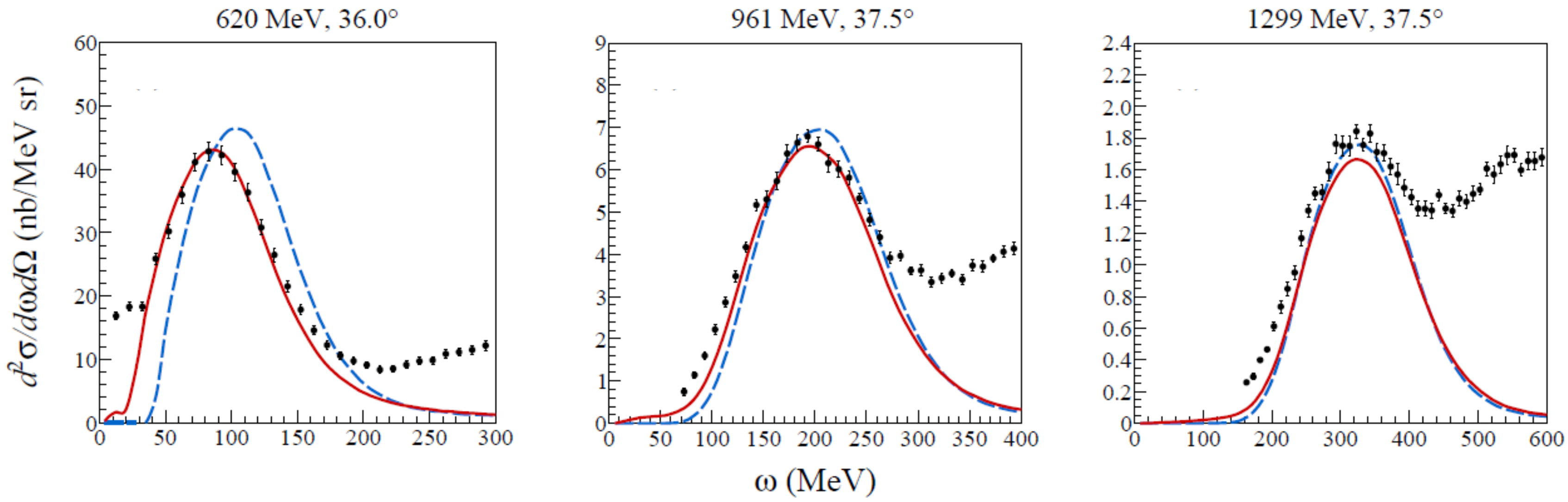
O. Benhar calculations for C and Fe in Rohe *et al.* (E97-006), PRC 72, 054602 (2005)

Real optical potentials in NuWro



Cooper *et al.*, PRC 47, 297 (1993)

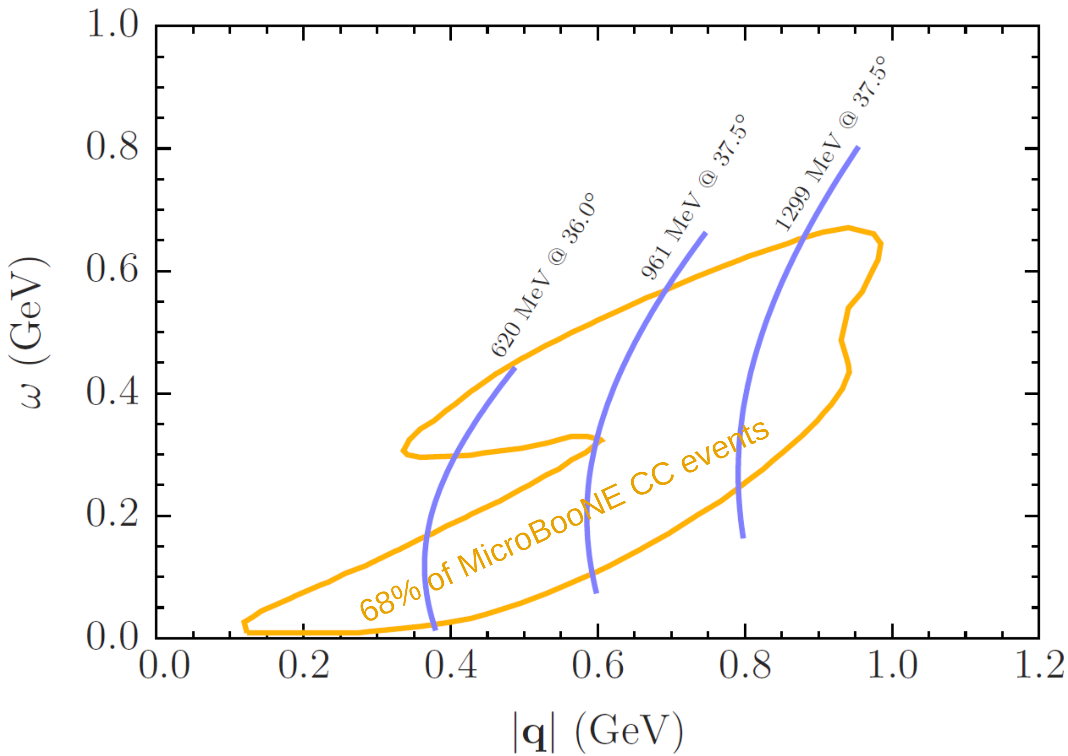
C(*e*,*e'*) in NuWro



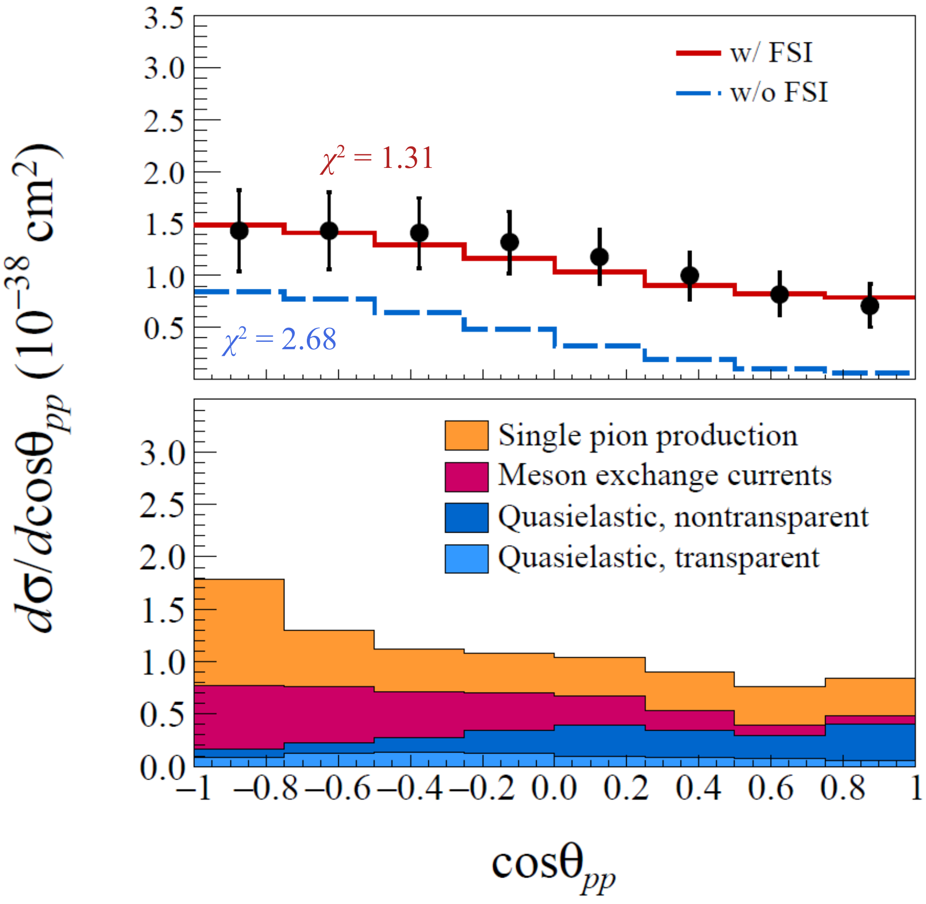
data: Barreau *et al.*,
NPA 402, 515 (1983)

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

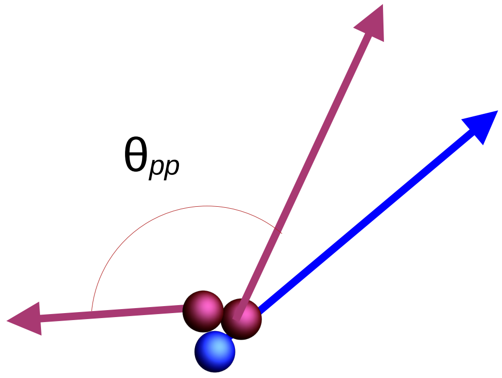
Why these kinematics?



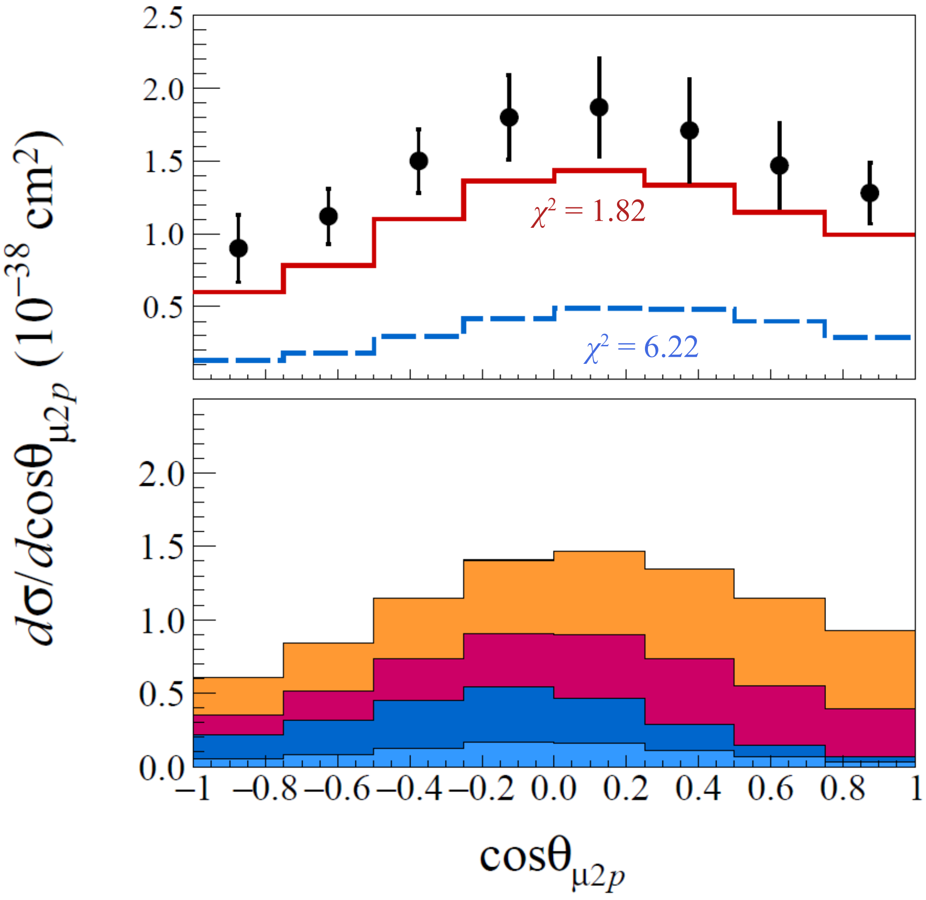
MicroBooNE CC2p0π



data: Abratenko *et al.*, arXiv:2211.03734



MicroBooNE CC2p0π



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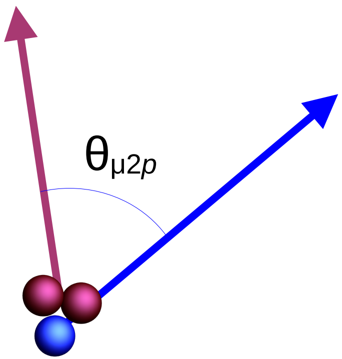
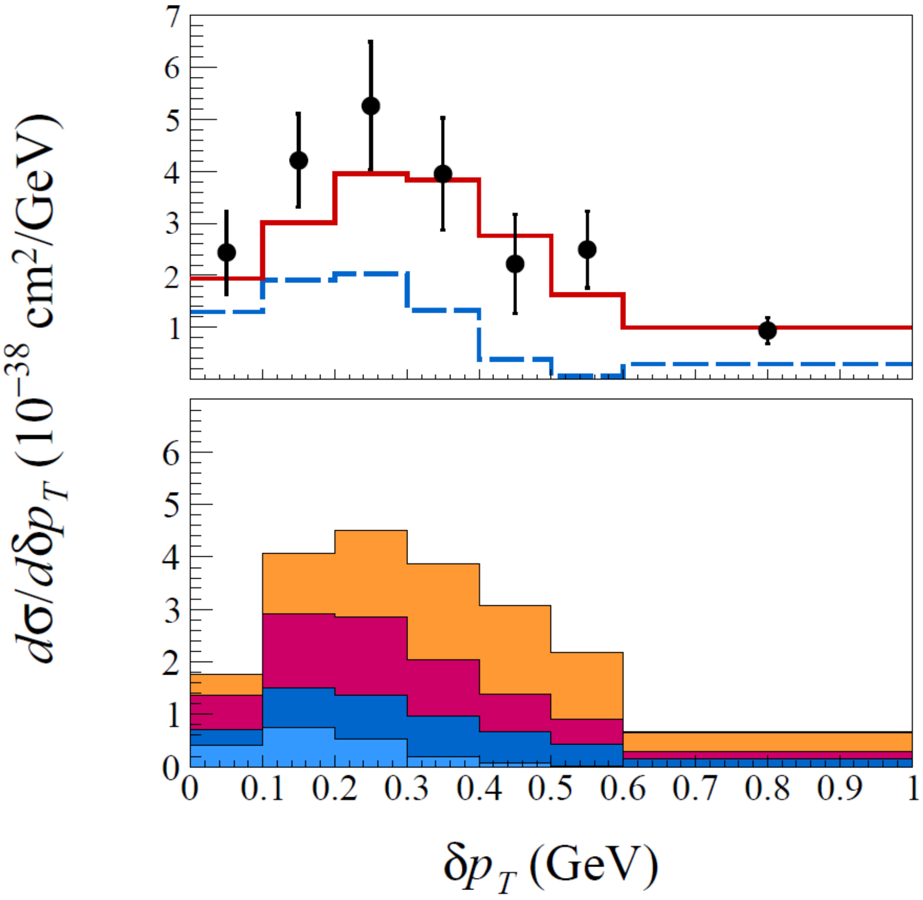
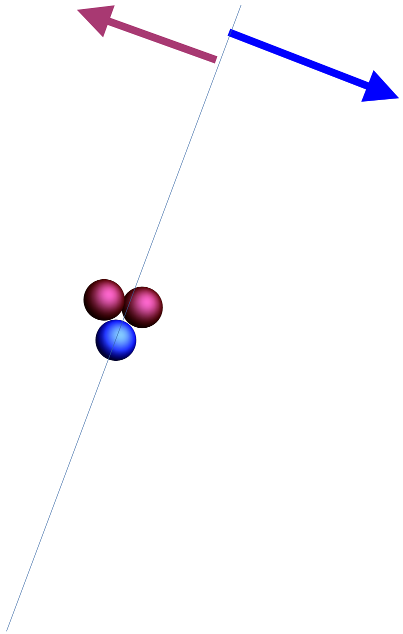


MicroBooNE CC2p0π

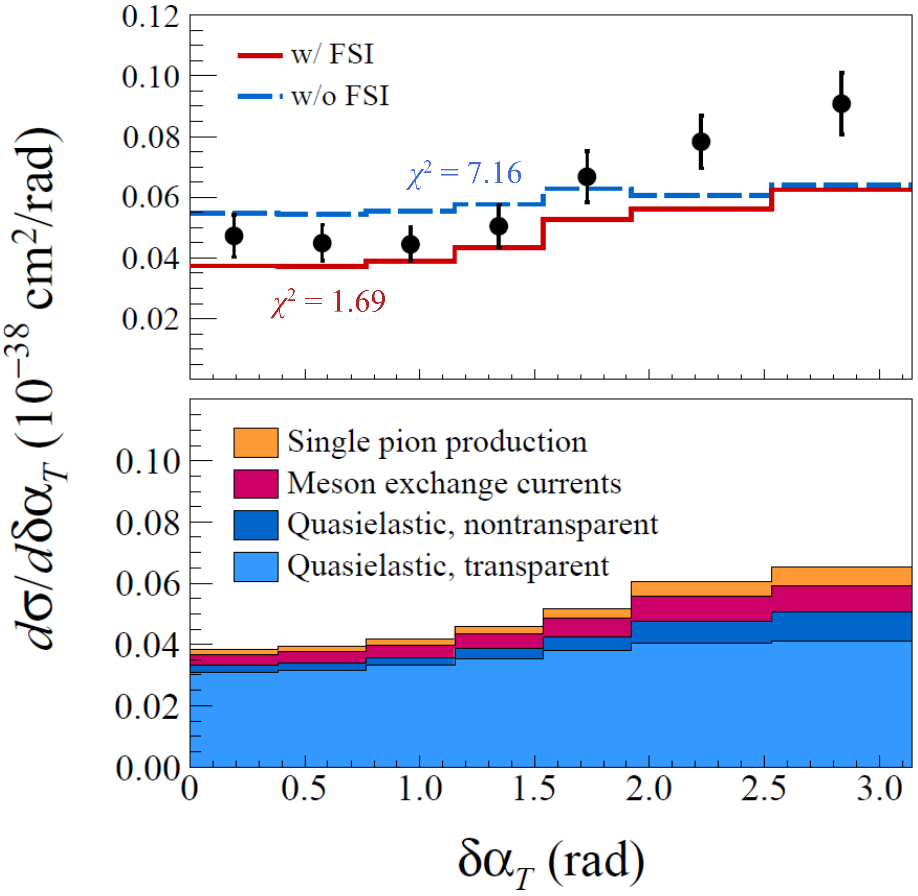


data: Abratenko *et al.*, arXiv:2211.03734

$$\delta p_T = |\delta \mathbf{p}_T^\mu + \delta \mathbf{p}_T^1 + \delta \mathbf{p}_T^2|$$

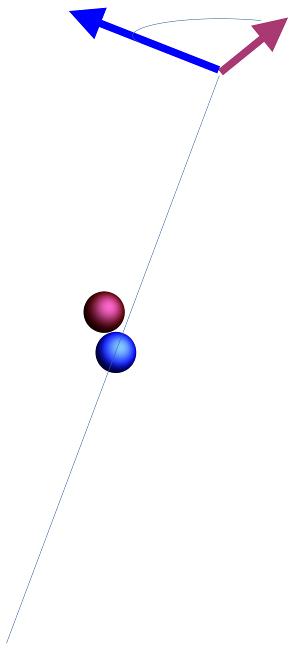


MicroBooNE CC1p0π

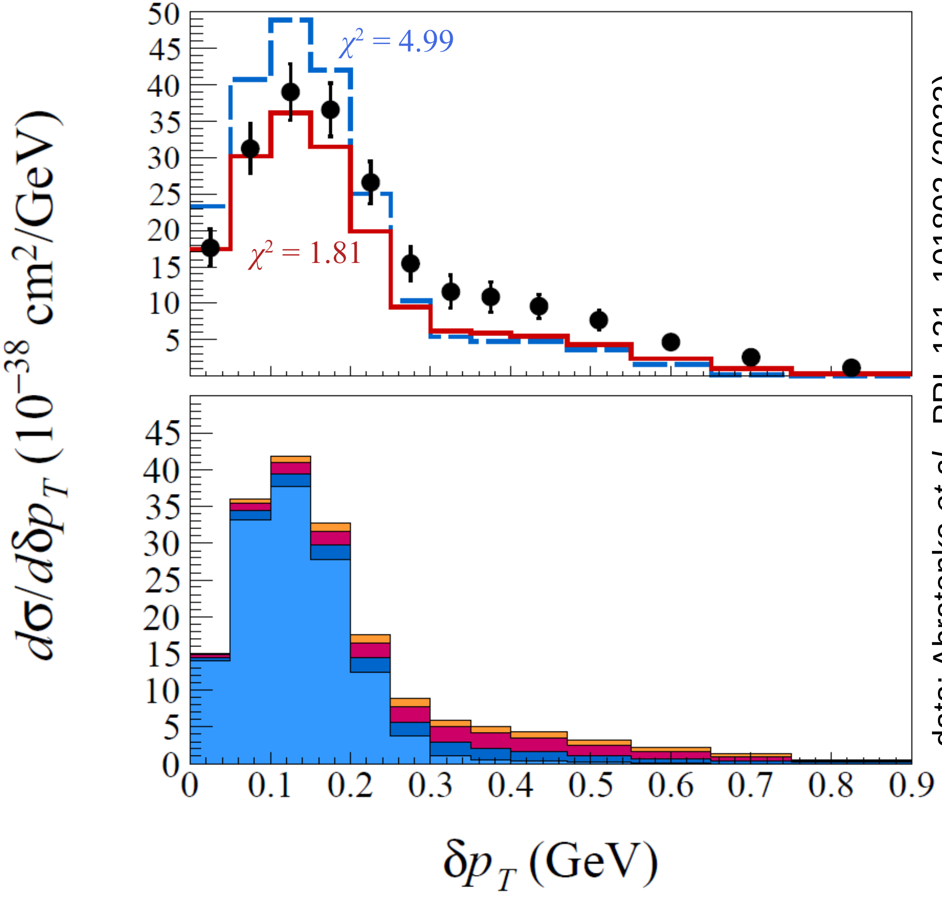


data: Abratenko *et al.*, PRL 131, 101802 (2023)

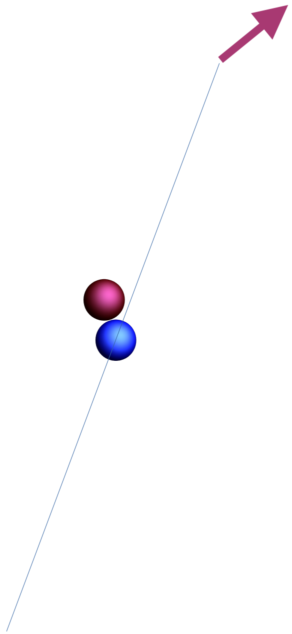
$$\delta\alpha_T = \arccos \frac{q^T \cdot \delta\mathbf{p}_T}{|\mathbf{q}^T||\delta\mathbf{p}_T|},$$



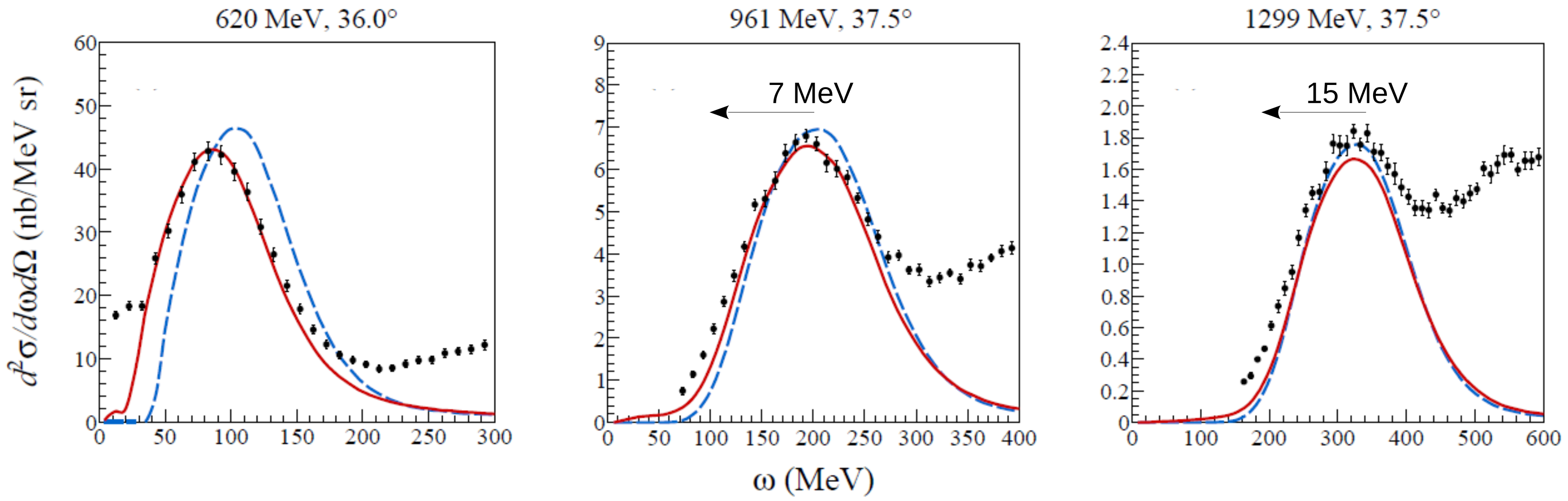
MicroBooNE CC1p0π



data: Abratenko *et al.*, PRL 131, 101802 (2023)



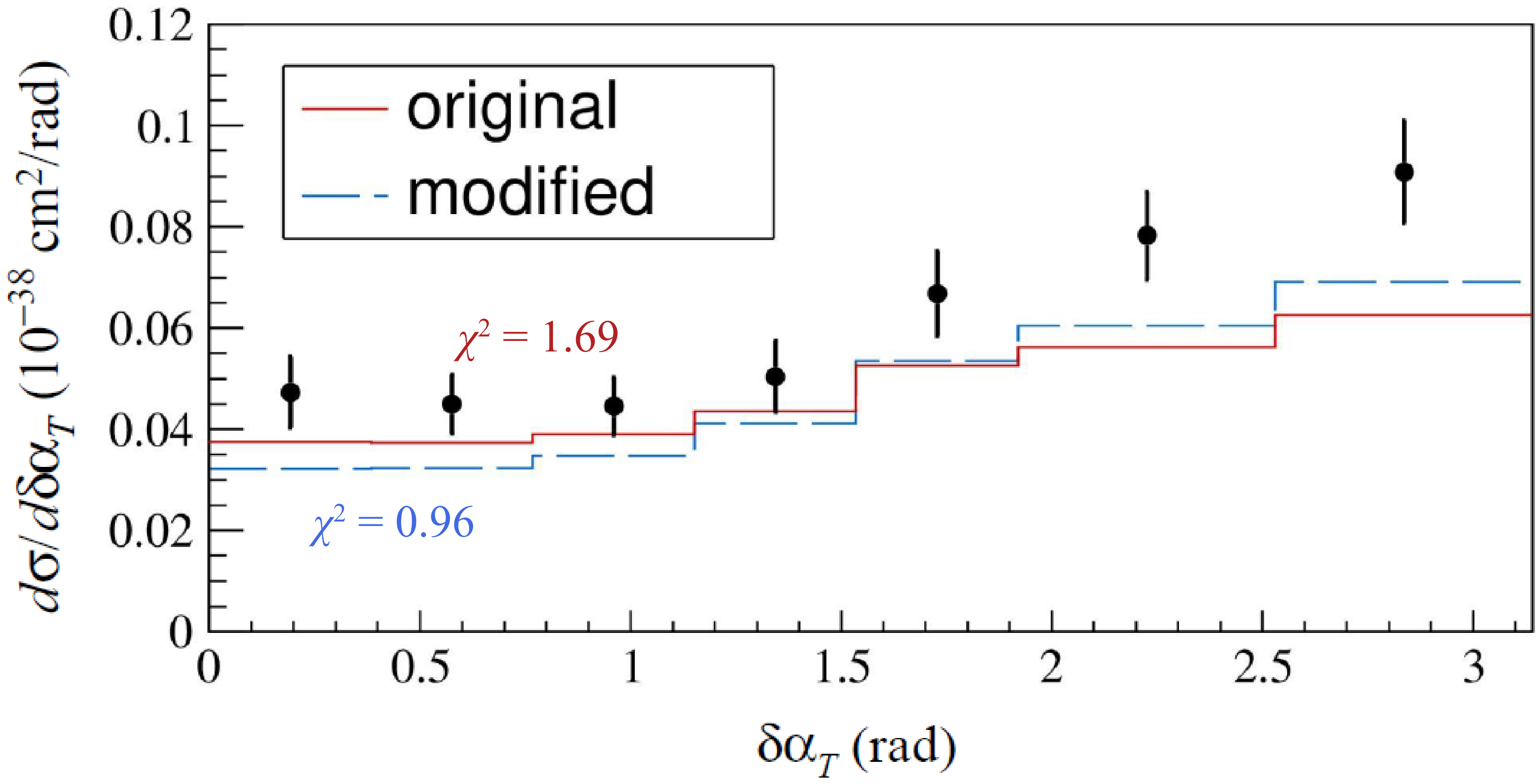
C(*e*,*e*’) in NuWro



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

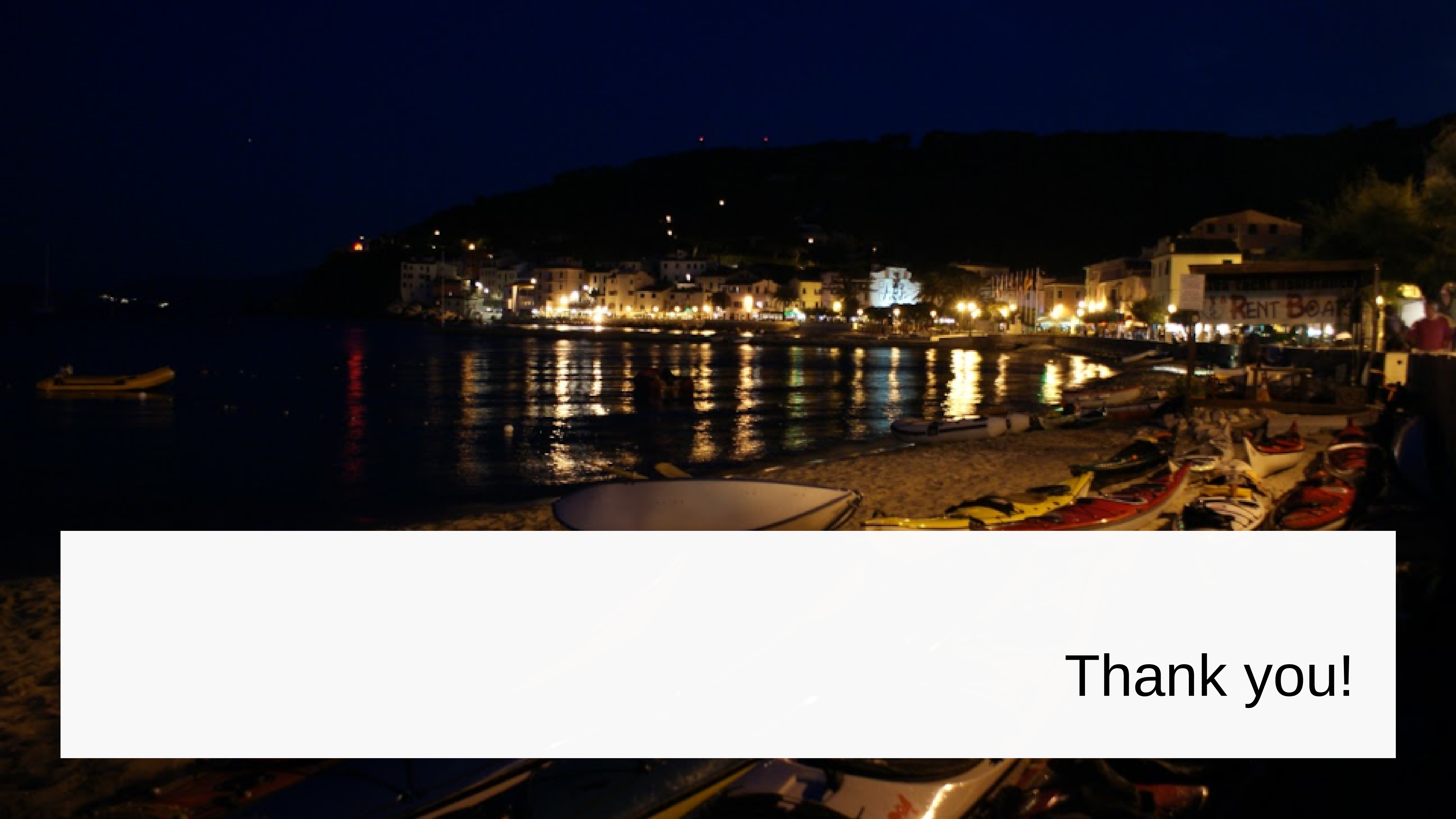
data: Sealock *et al.*,
PRL 62, 1350 (1989)

Sensitivity to the potential



Summary

- JLab experiment E12-14-012 greatly improved our knowledge of nuclear effects in argon.
- Its findings are now implemented in NuWro, both at the inclusive and exclusive levels.
- Good agreement with the MicroBooNE CC2$p0\pi$ and CC1$p0\pi$ data.
- Further progress requires the Ar(e,e') cross sections covering the broad kinematics of relevance to neutrino-oscillation experiments. Huge scientific impact for a modest beamtime allotted!



Thank you!

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)

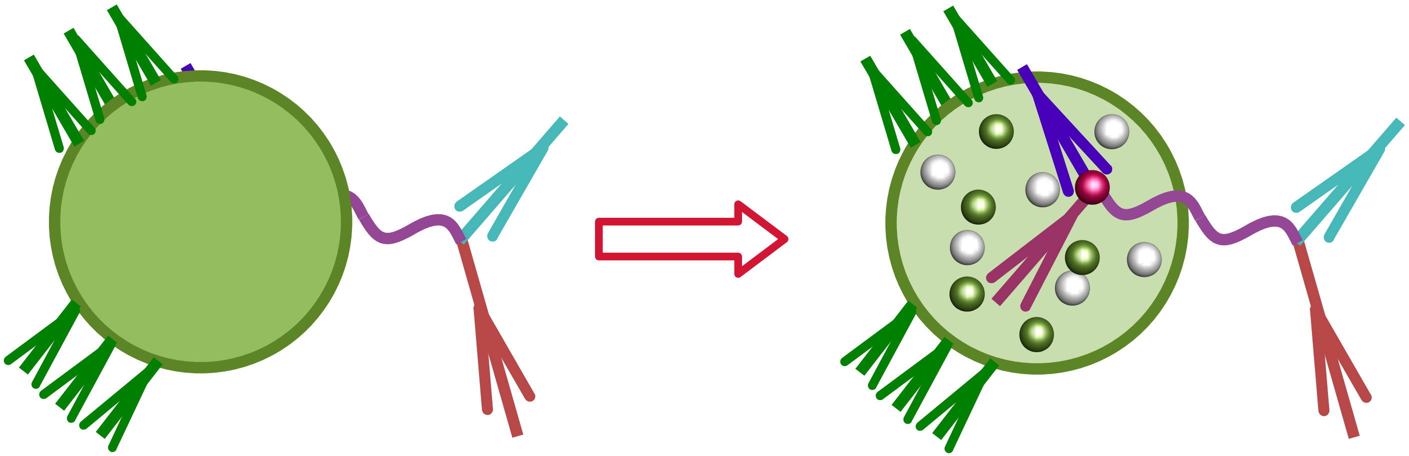
Electron data allow MC validation, reduction of systematic uncertainties, as well as their rigorous determination.

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

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.

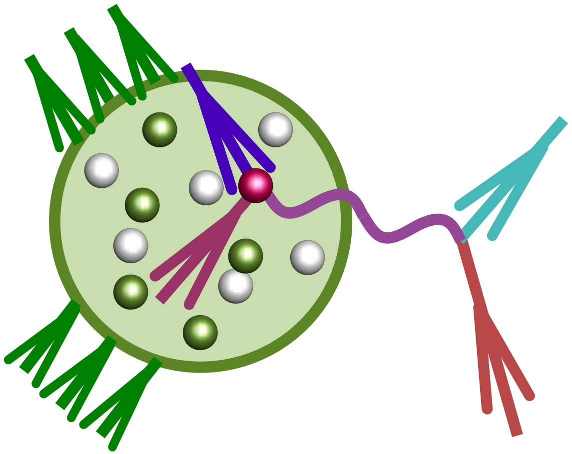
This description is valid when the momentum transfer $|\mathbf{q}|$ is high enough ($|\mathbf{q}| \gtrsim 200$ MeV).

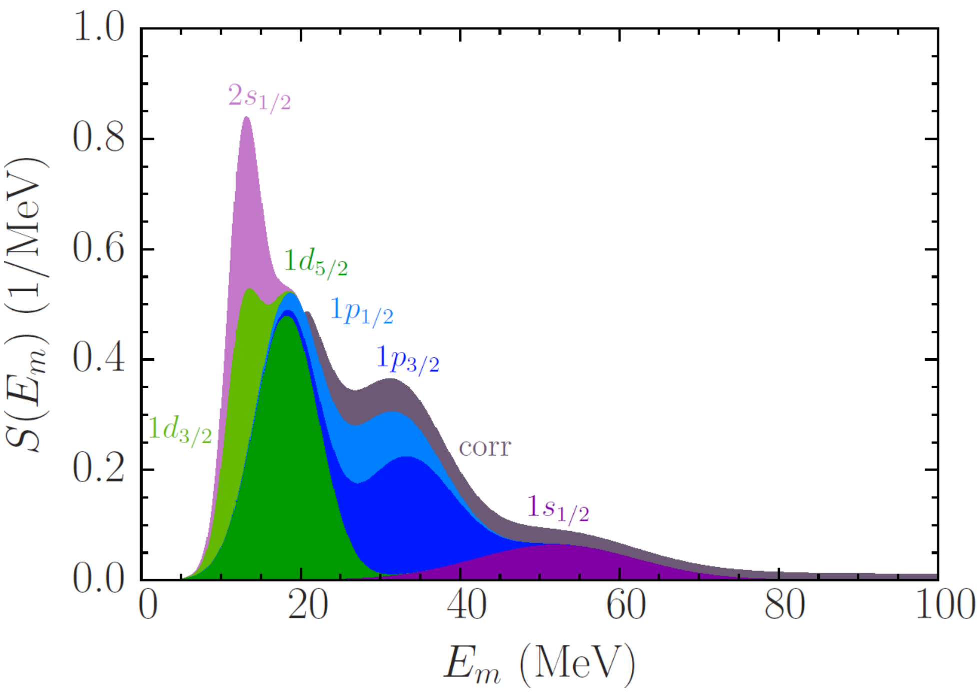


Impulse approximation

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

- elementary cross sections (QE, resonant pion production, DIS ...)
- proton and neutron spectral functions (shell structures, correlations between nucleons)
- final-state interactions (nuclear transparency, optical potentials)
- hadronization




$S(E_m)$ (1/MeV)
E_m (MeV)
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1d_{3/2}$
corr
$1s_{1/2}$
1.0
0.8
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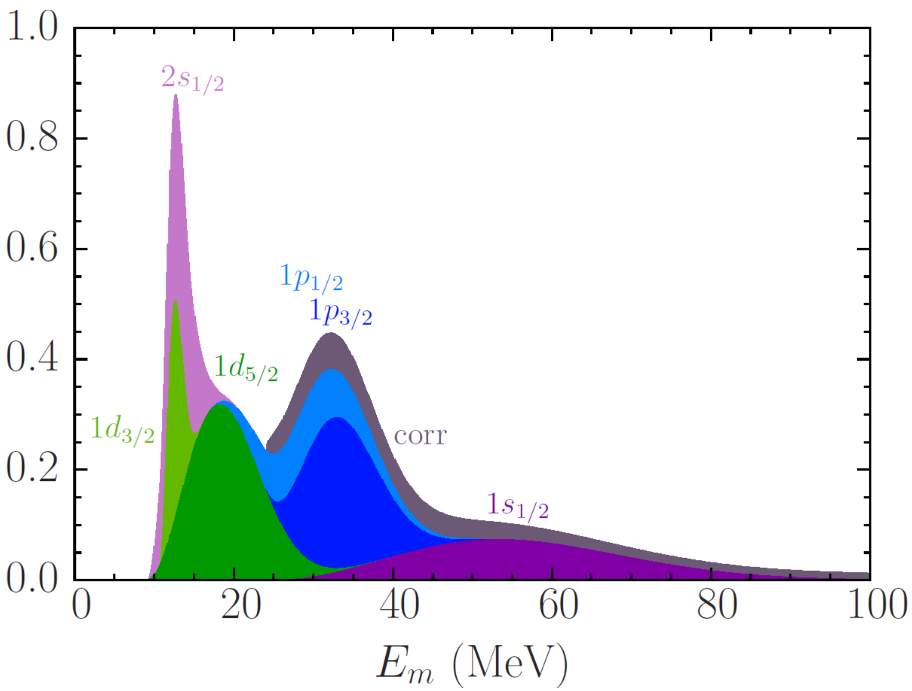
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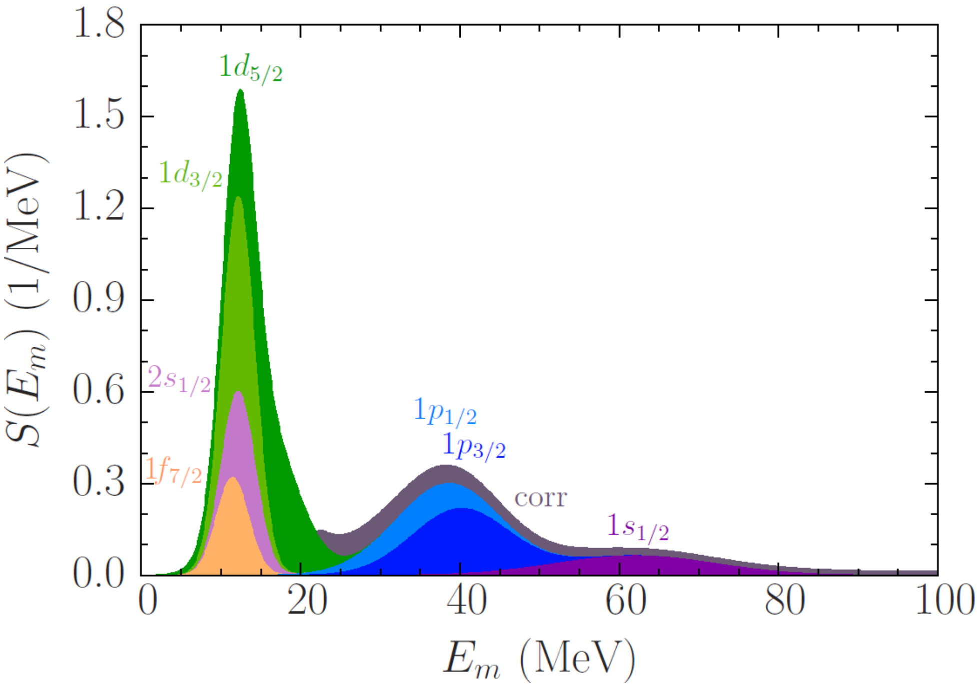

$S(E_m)$ (1/MeV)
1.8
1.5
1.2
0.9
0.6
0.3
0.0
$1d_{5/2}$
$1d_{3/2}$
$2s_{1/2}$
$1f_{7/2}$
$1p_{1/2}$
$1p_{3/2}$
corr
$1s_{1/2}$
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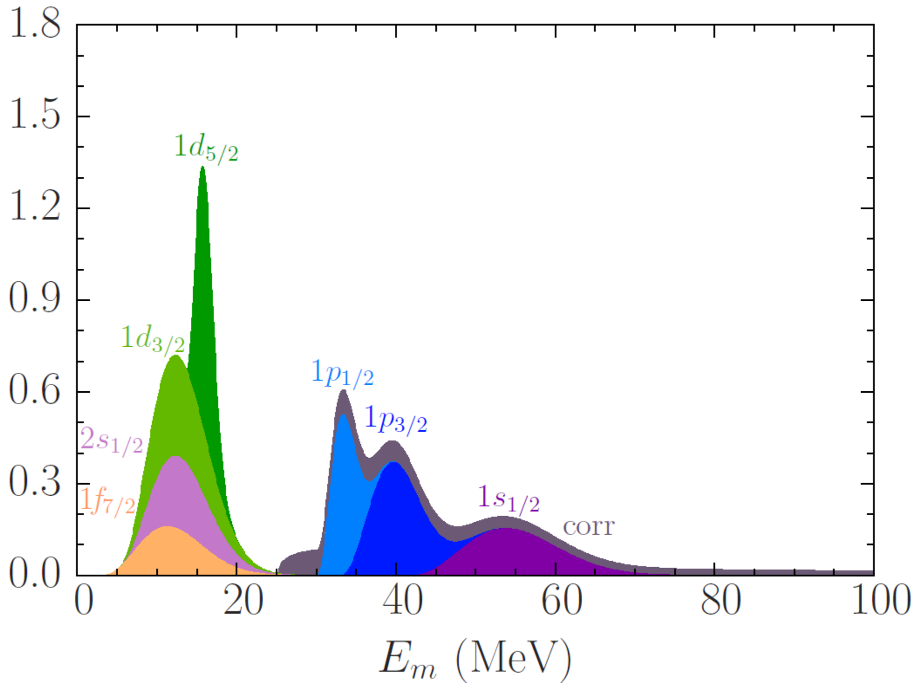
20
40
60
80
100
E_m (MeV)



1.8
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