

Toward the accurate neutrino energy reconstruction in CCQE scattering off nuclear targets

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based on
A. M. A, Omar Benhar, and Makoto Sakuda, arXiv:1404.5687

NuInt14
Surrey, UK, 19-24 May 2014

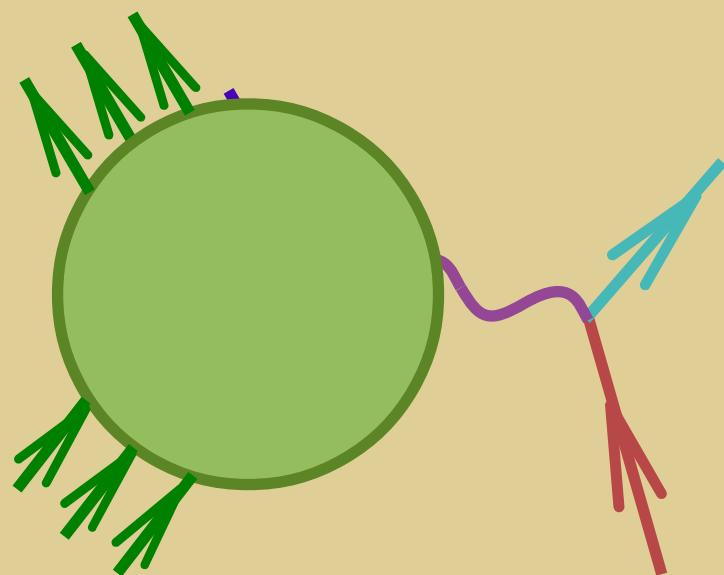
Outline

- ① Impulse approximation approach
and final state interactions
- ② Comparisons to electron-carbon scattering data
- ③ Neutrino energy reconstruction
- ④ Summary

Impulse approximation approach and final state interactions

Impulse approximation (IA)

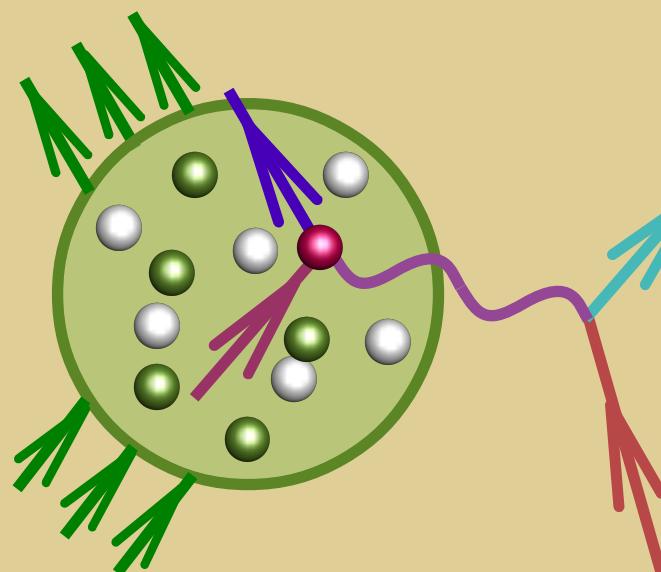
Assumption: the dominant process of lepton-nucleus interaction is **scattering off a single nucleon**, the remaining nucleons act as a spectator system.



Impulse approximation (IA)

Assumption: the dominant process of lepton-nucleus interaction is **scattering off a single nucleon**, the remaining nucleons act as a spectator system.

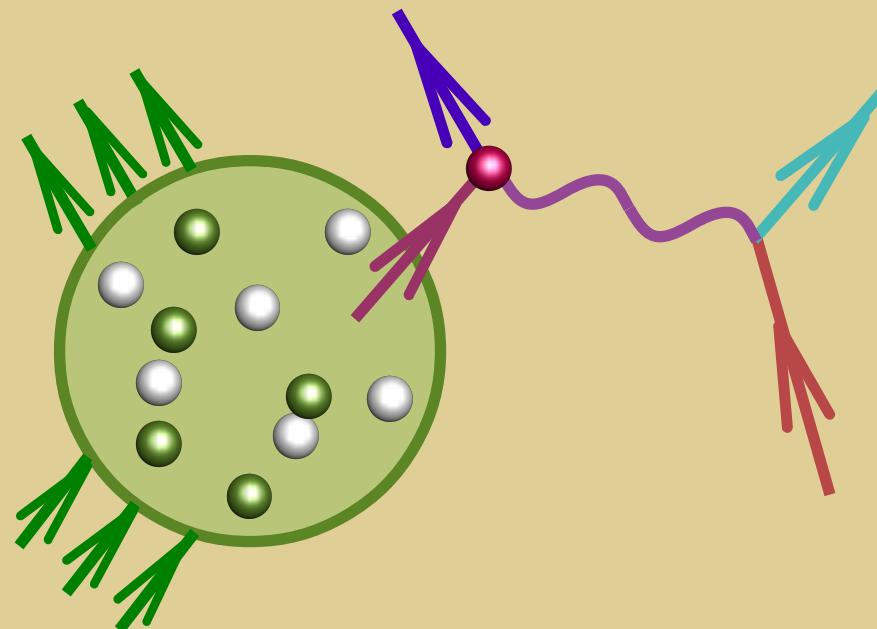
It is valid when the momentum transfer $|q|$ is high enough, as the probe's spatial resolution is $\sim 1/|q|$.



Results at
 $140 \lesssim |q| \lesssim 450 \text{ MeV}$
 $0.02 \lesssim Q^2 \lesssim 0.20 \text{ GeV}^2$

Impulse approximation (IA)

The simplest implementation of the IA assumes that the struck nucleon is on **the mass shell** ($E_p = \sqrt{M^2 + p^2}$), neglecting its interactions with the spectator system.



Picture idea from
Alberico et al.,
NPA 623, 471 (1997)

Impulse approximation (IA)

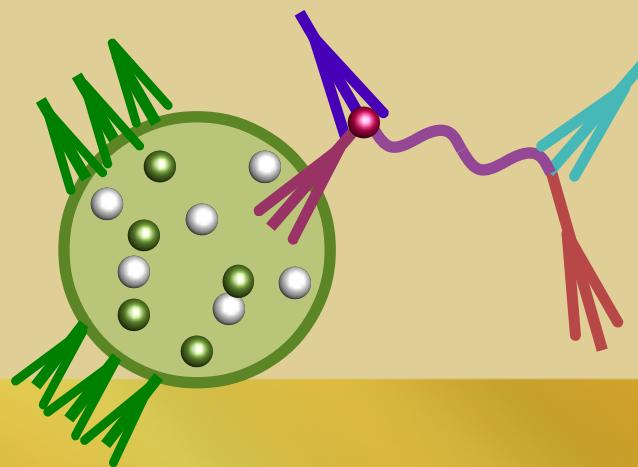
Then, the cross section is

Elementary cross section

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

Hole spectral function

Particle spectral function $\sim \delta(\dots)$



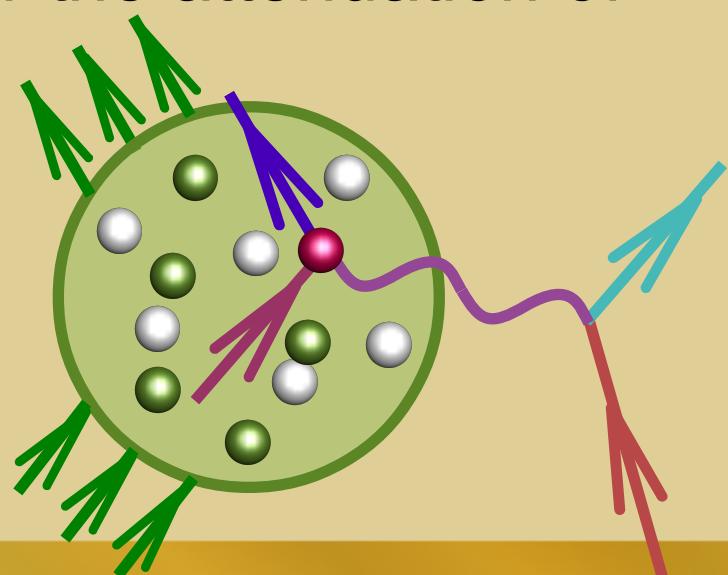
Final state interactions (FSI)

Their effect on the cross section is easy to understand in terms of the complex optical potential [(Horikawa et al., PRC **22**, 1680 (1980))]

$$E_{p'} = \sqrt{M^2 + p'^2} + U$$

- the **real part** modifies the struck nucleon's energy spectrum
- the **imaginary part** accounts for the attenuation of the single-nucleon final states

$$e^{i(E+U)t} = e^{i(E+U_V)t} e^{-U_W t}$$



Final state interactions (FSI)

In the convolution approach,

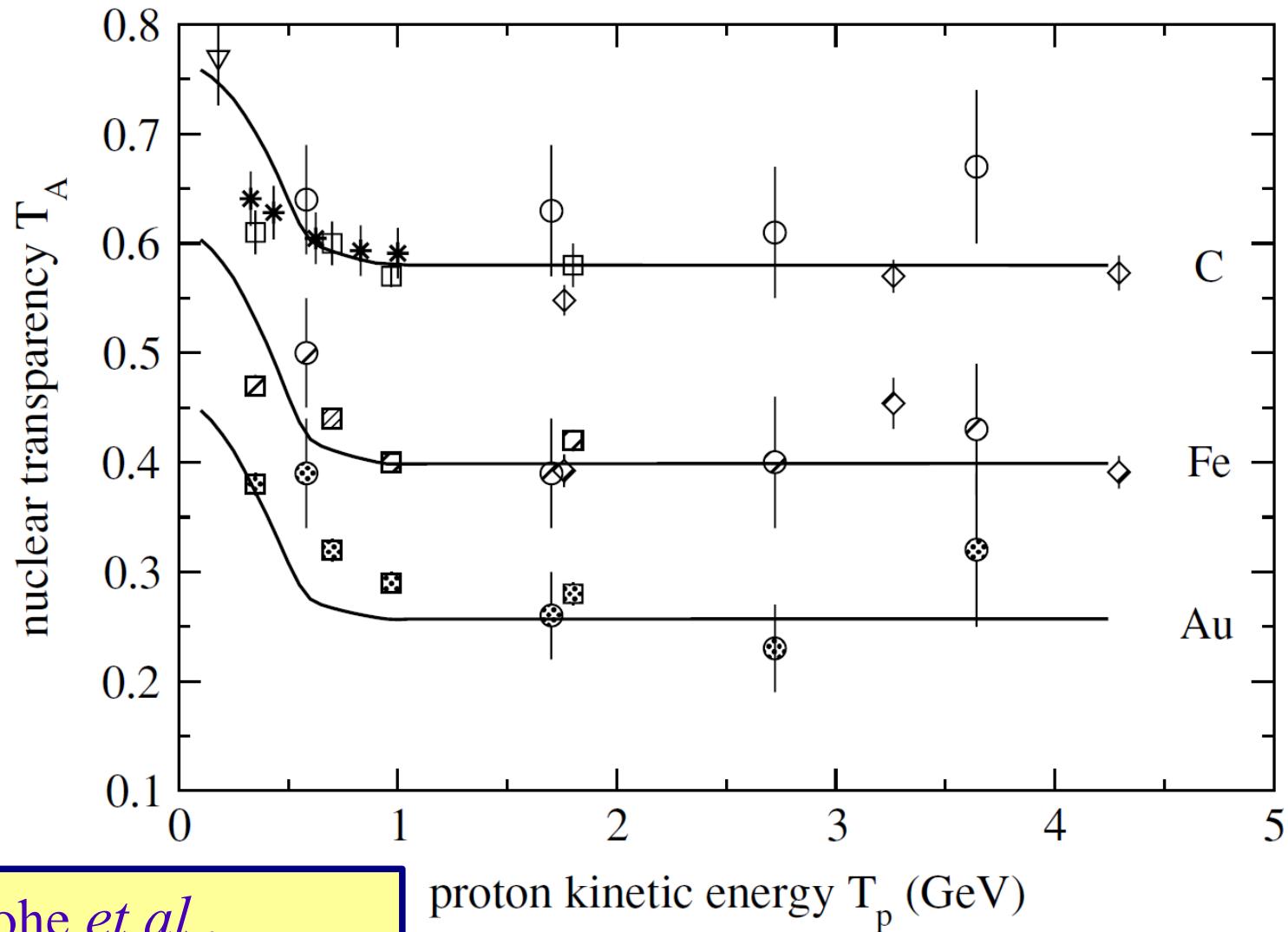
$$\frac{d\sigma^{\text{FSI}}}{d\omega d\Omega} = \int d\omega' f_{\mathbf{q}}(\omega - \omega') \frac{d\sigma^{\text{IA}}}{d\omega' d\Omega},$$

with the folding function

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

Nucl. transparency

Nuclear transparency



Rohe *et al.*,

PRC 72, 054602 (2005)

Real part of the optical potential

We account for the spectrum modification by

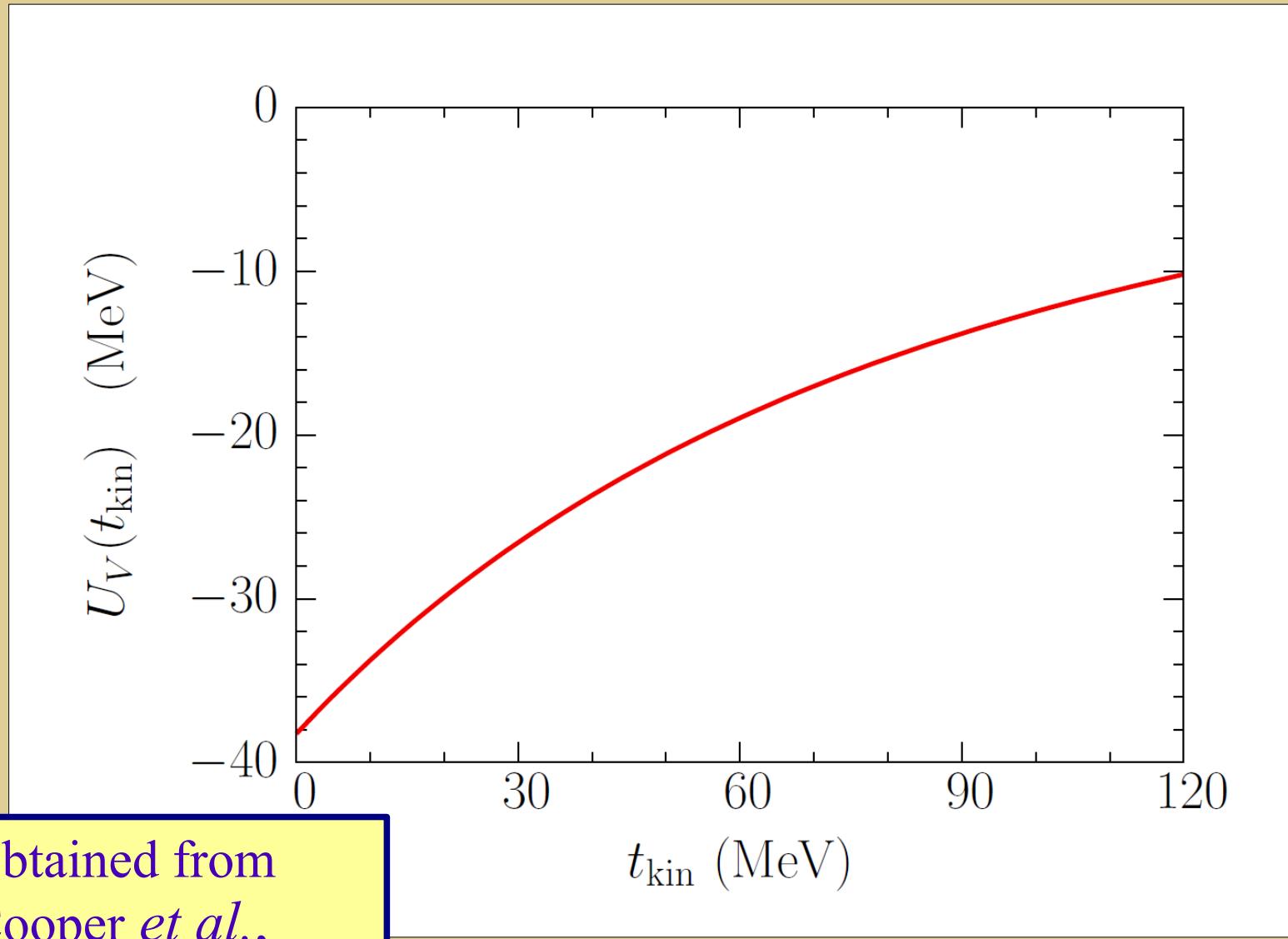
$$f_{\mathbf{q}}(\omega - \omega') \rightarrow f_{\mathbf{q}}(\omega - \omega' - U_V).$$

This procedure is similar to that from the Fermi gas model to introduce the binding energy in the argument of the δ function.

$$U_V = U_V(t_{\text{kin}})$$

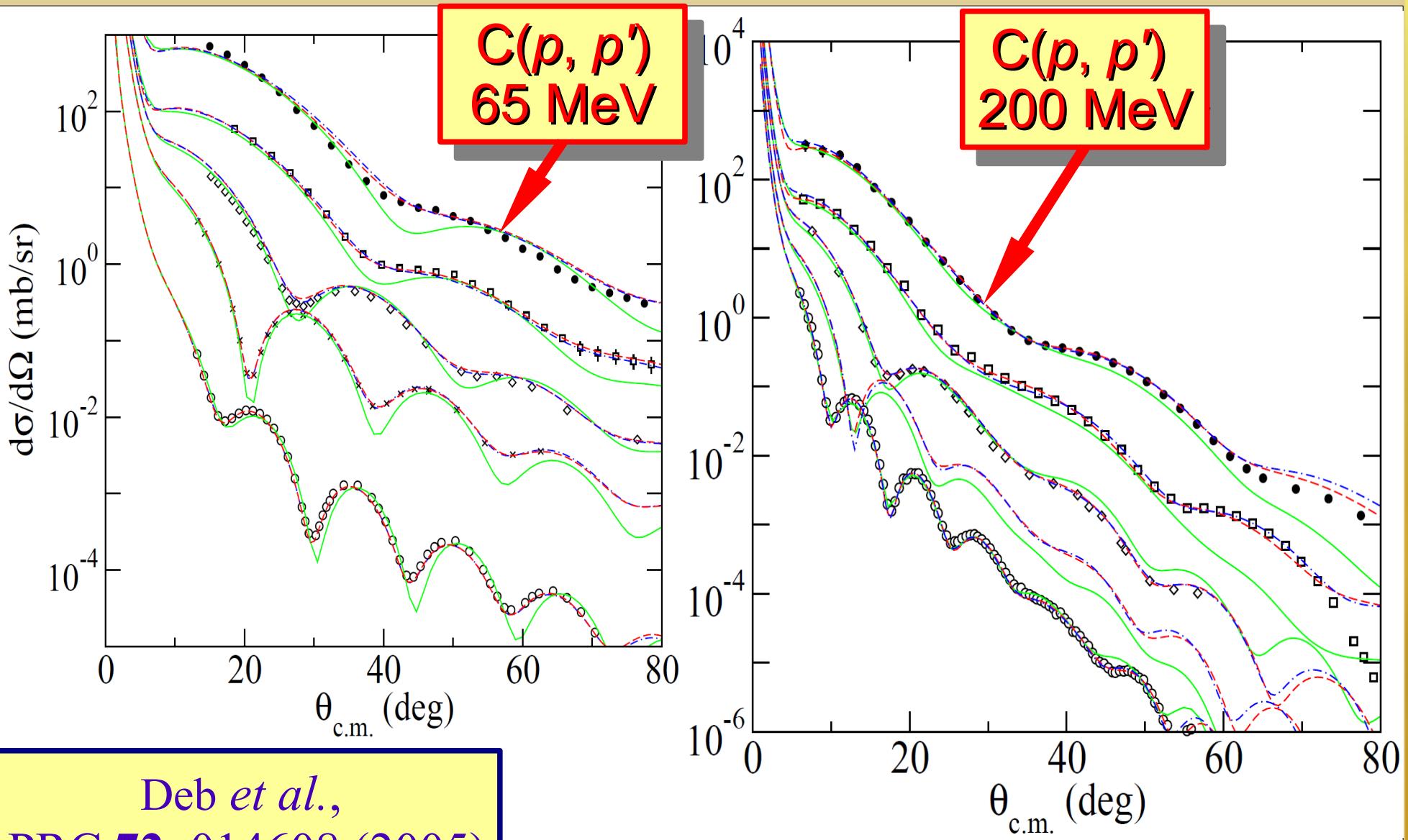
$$t_{\text{kin}} = \frac{E_{\mathbf{k}}^2(1 - \cos \theta)}{M + E_{\mathbf{k}}(1 - \cos \theta)}$$

Real part of the optical potential



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

Optical potential by Cooper *et al.*



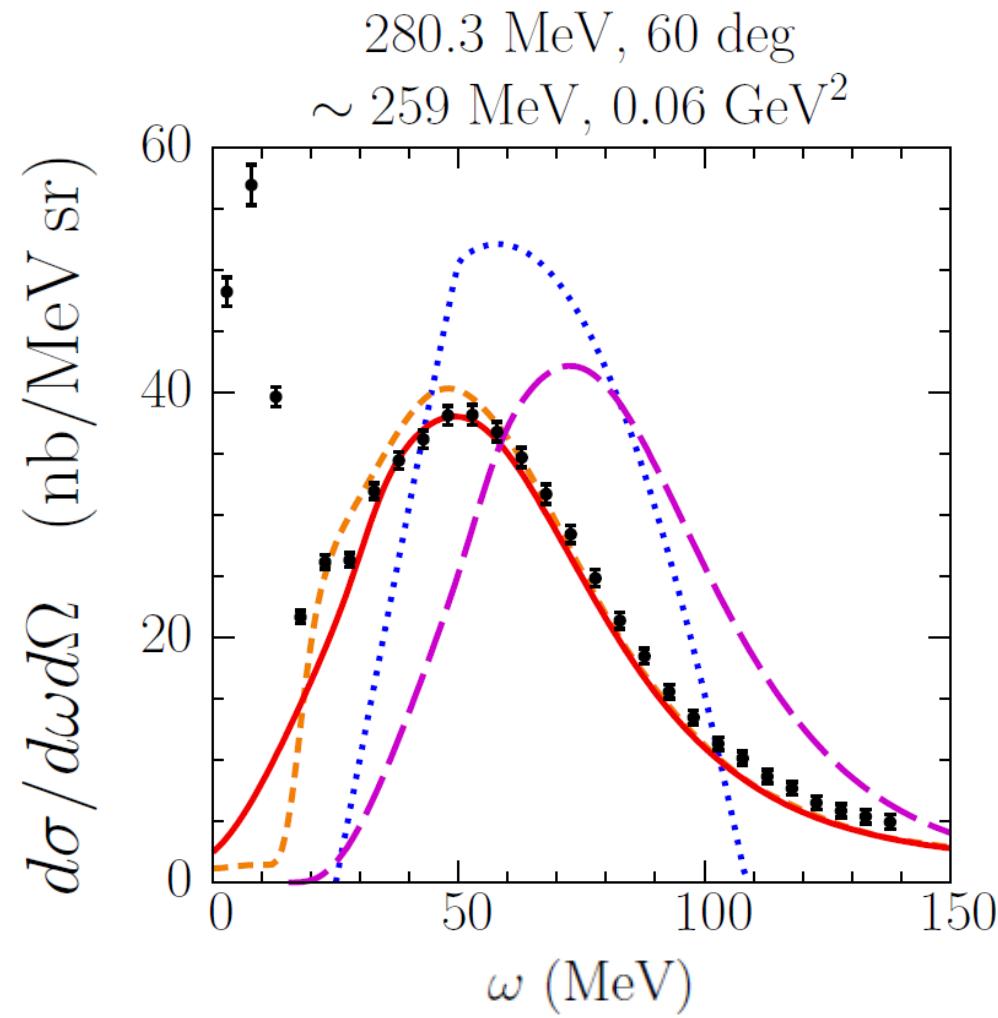
Deb *et al.*,
PRC 72, 014608 (2005)

Comparisons to $C(e, e')$ data

Compared approaches

Our calculation,
LDA treatment
of Pauli blocking,
Phys. Rev. D **82**,
013002 (2010)

Our calculation,
step function

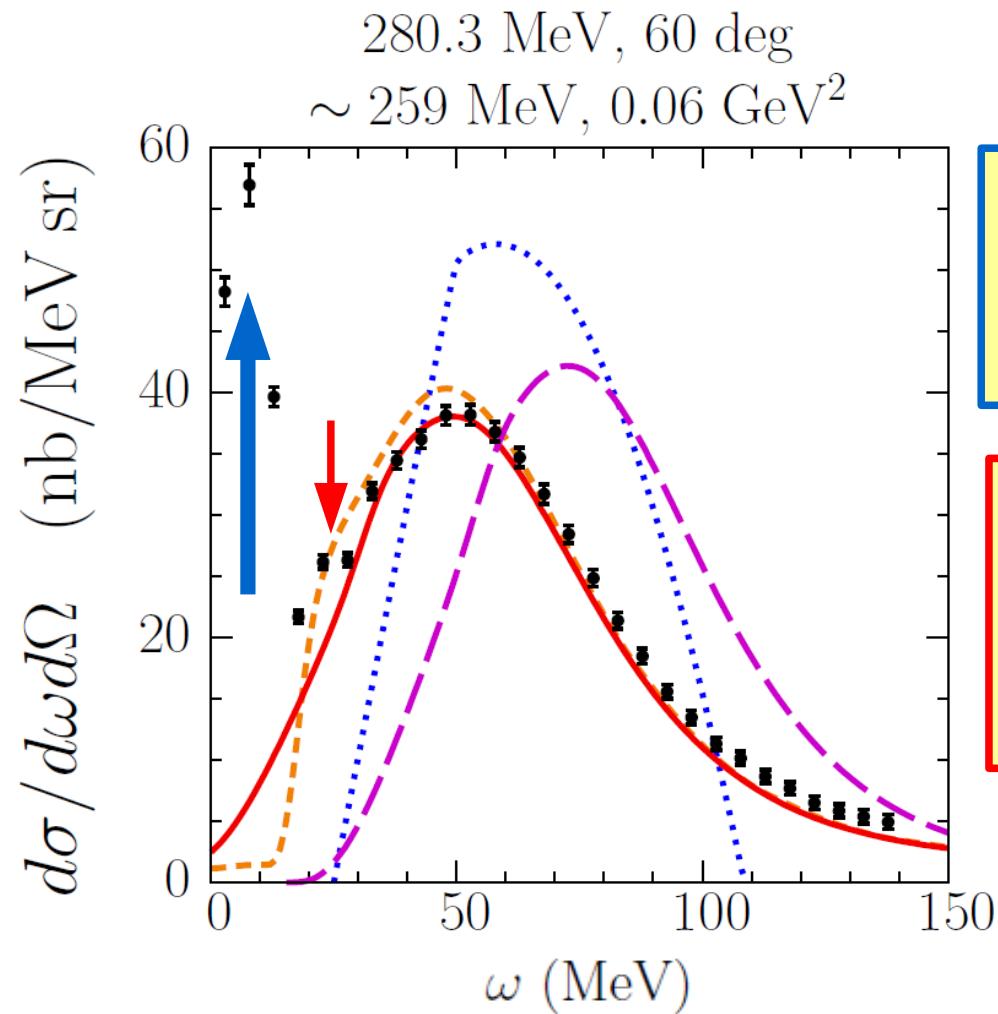


RFG model
 $\varepsilon = 25$ MeV
 $p_F = 221$ MeV

SF calculation
without FSI

Low excitation-energy phenomena

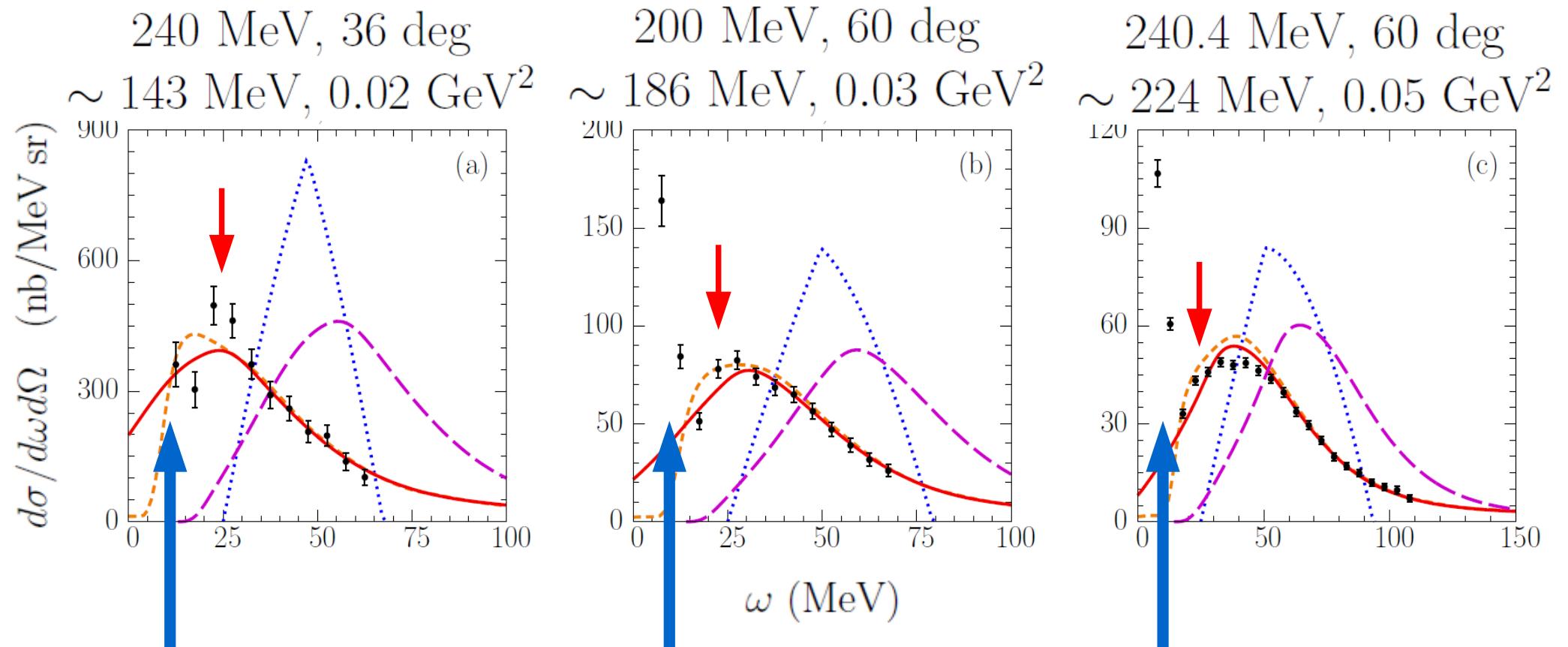
Calcs. include
QE by 1-body
current only



Elastic scattering
and excitation
of low- E_x levels

Giant resonance
 $E_x = 22.6$ MeV,
 $\Gamma = 3.2$ MeV

Comparisons to C(e,e') data



Comparisons to C(e,e') data

280.3 MeV, 60 deg

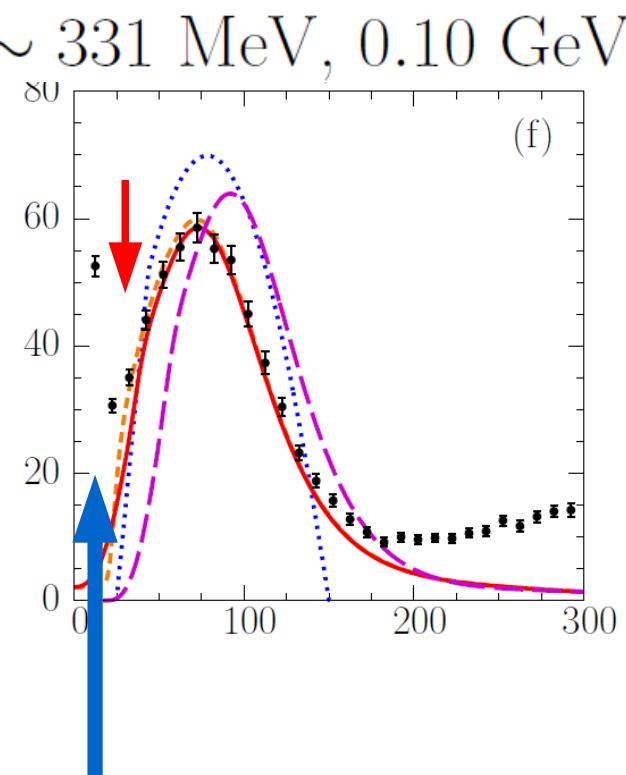
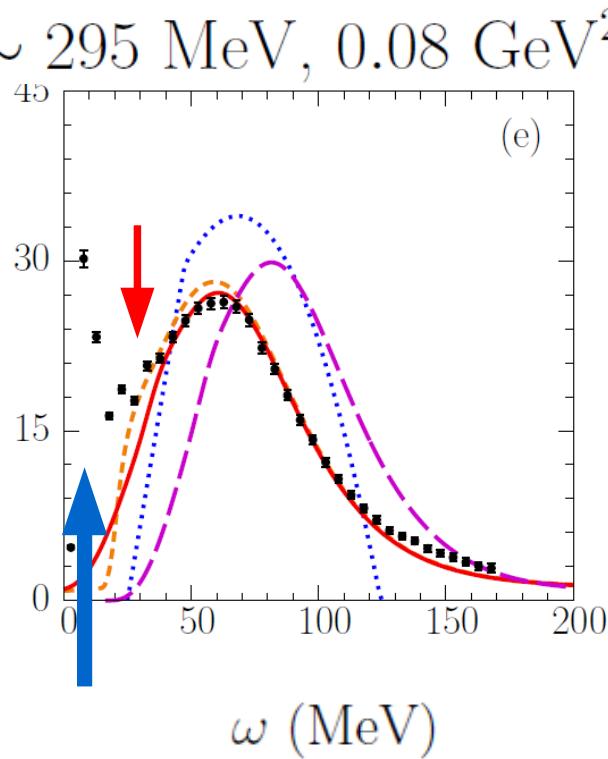
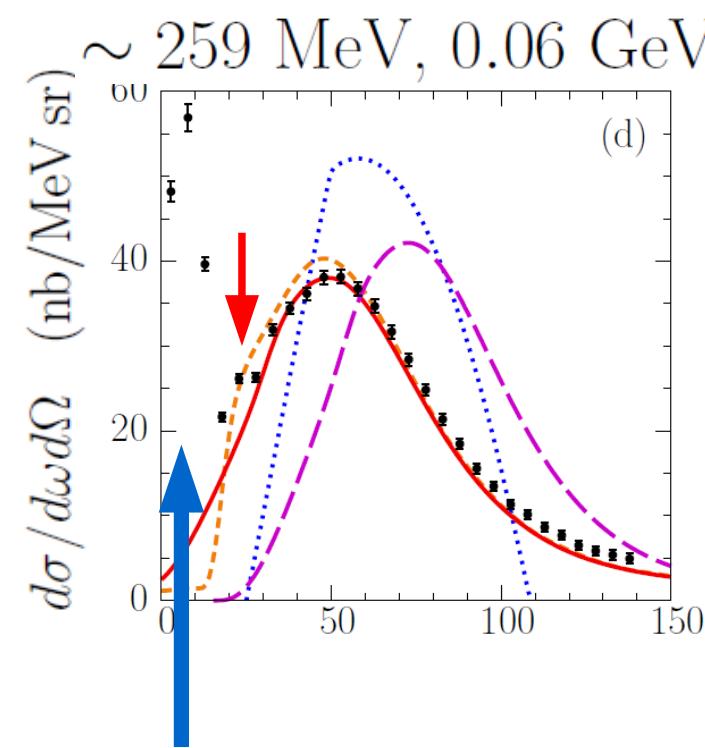
~ 259 MeV, 0.06 GeV^2

320.3 MeV, 60 deg

~ 295 MeV, 0.08 GeV^2

560 MeV, 36 deg

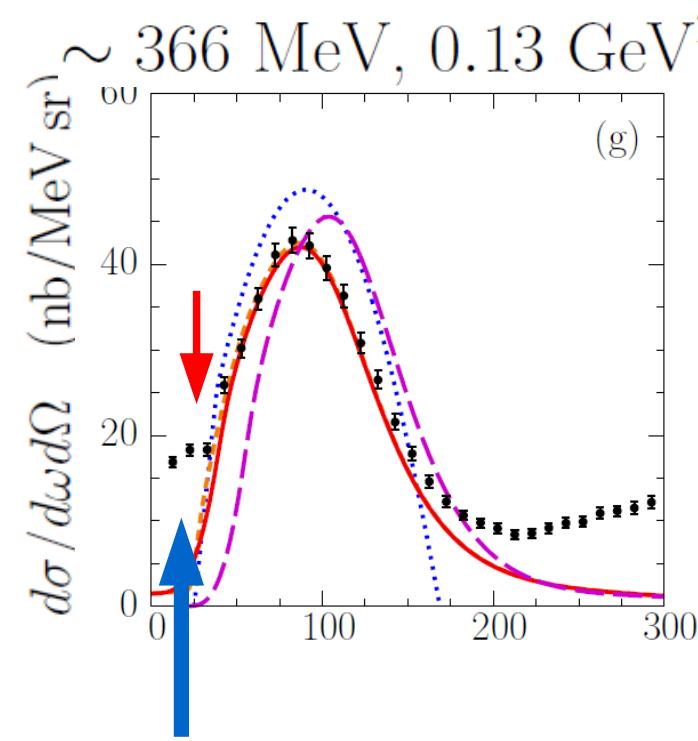
~ 331 MeV, 0.10 GeV^2



Comparison to C(e,e') data

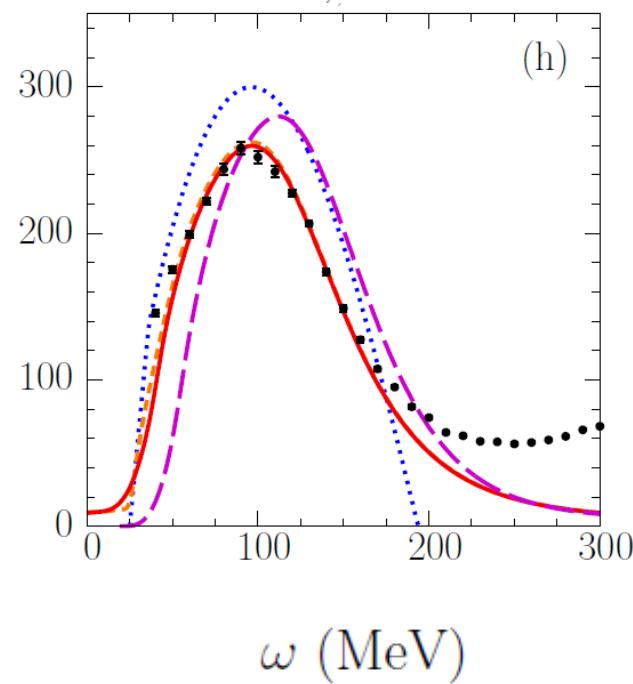
620 MeV, 36 deg

~ 366 MeV, 0.13 GeV^2



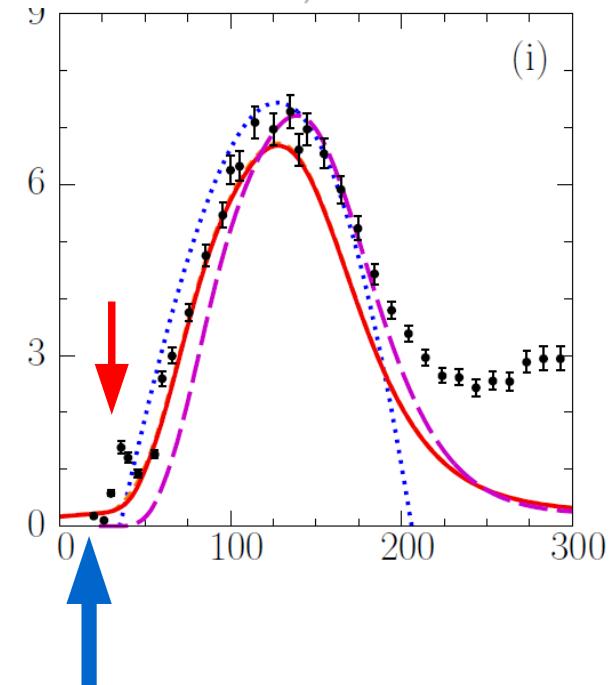
1650 MeV, 13.5 deg

~ 390 MeV, 0.14 GeV^2



500 MeV, 60 deg

~ 450 MeV, 0.19 GeV^2



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

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

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

Comparisons to C(e,e') data

In the supplemental material of [arXiv:1404.5687](#)
we show comparisons to the data sets collected
at **54 kinematical setups**

- energies from ~ 160 MeV to ~ 4 GeV,
- angles from 12 to 145 degrees,
- at the QE peak, values of momentum transfer from
 ~ 145 to ~ 1060 MeV/c and $0.02 \leq Q^2 \leq 0.86$ (GeV/c) 2 .

Comparisons to C(e, e') data

In the supplemental material
we show comparisons to the
at **54 kinematical setups**

- energies from ~ 160 MeV to
- angles from 12 to 145 degrees
- at the QE peak, values of m
 ~ 145 to ~ 1060 MeV/c and 0

See them all during the poster session

QUASIELASTIC $^{12}_6C(e, e')$ SCATTERING OVER A BROAD KINEMATIC REGION

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in collaboration with O. Benhar and M. Sakuda
arXiv:1404.5687

Motivation

The accuracy of neutrino energy reconstruction is limited by the accuracy to which nuclear effects are described by the Monte Carlo simulations involved in data analysis.

For an approach to be trustworthy, it has to be compared to precise electron scattering data, with the uncertainties understood and quantified.

Formalism

We account for the final-state interactions between the struck particle and the spectator system in the convolution scheme,

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

integrating the impulse-approximation prediction σ^{IA} with a folding function, which can be decomposed as

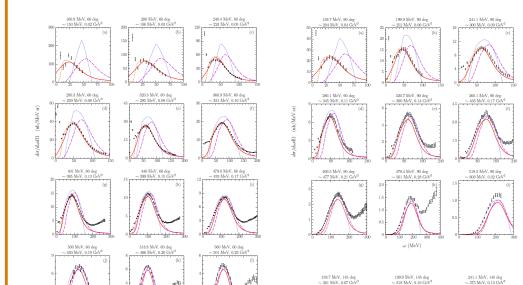
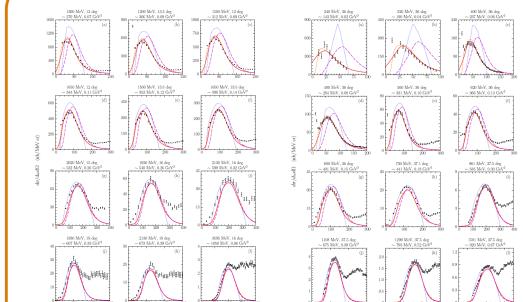
$$f_{\mathbf{q}}(\omega) = \delta(\omega)\sqrt{T_A} + (1 - \sqrt{T_A})F_{\mathbf{q}}(\omega),$$

where T_A is the nuclear transparency, and $F_{\mathbf{q}}(\omega)$ is a finite-width function.

In the energy spectrum of the struck nucleon, we include the **real part of the optical potential**, U_V , obtained from the Dirac phenomenological analysis of Cooper *et al.* [1].

Conclusions

- Our approach has reached a remarkable accuracy over a **broad kinematic region**.
- The uncertainties are under control at a **quantitative level**.
- These features allow a consistent and accurate determination of the ν and $\bar{\nu}$ cross sections required the **CP** measurements.
- A consistent inclusion of $2p2h$ excitations is left for future studies.



Our calculations, involving **no adjustable parameters**, are here compared to the data from Refs. [2, 3, 4, 5, 6, 7, 8].

References

- [1] E. D. Cooper, S. Hama, B. C. Clark, and R. L. Mercer, Phys. Rev. C **47**, 297 (1993).
- [2] D. T. Barran *et al.*, Phys. Rev. Lett. **61**, 400 (1988).
- [3] D. B. Day *et al.*, Phys. Rev. C **48**, 1849 (1993).
- [4] D. S. Baghchessaran *et al.*, YERPH-1077(40)-88.
- [5] P. Barreau *et al.*, Nucl. Phys. A **402**, 515 (1983).
- [6] J. S. O'Connell *et al.*, Phys. Rev. C **35**, 1063 (1987).
- [7] R. M. Scalock *et al.*, Phys. Rev. Lett. **62**, 1350 (1989).
- [8] R. R. Whitney *et al.*, Phys. Rev. C **9**, 2230 (1974).

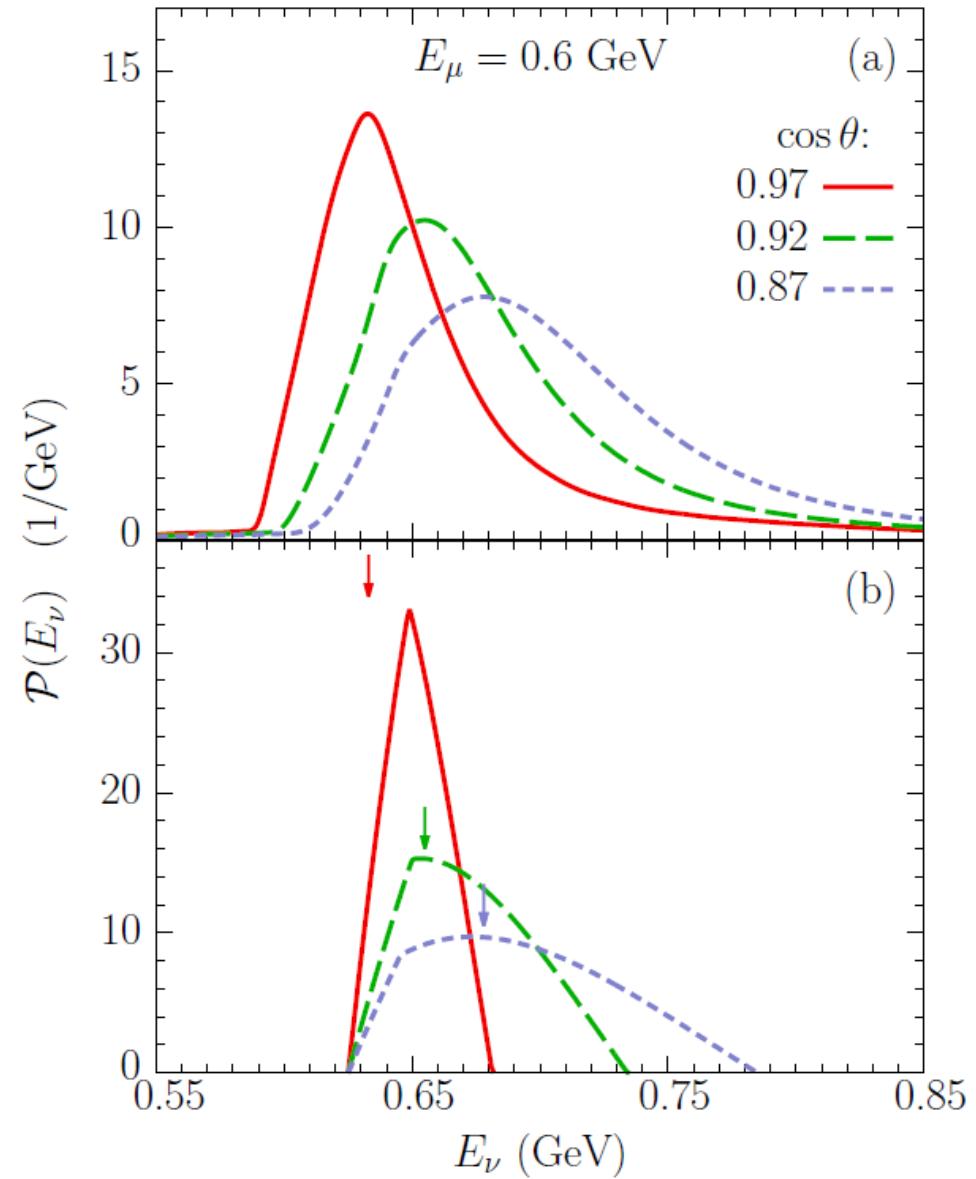


Neutrino energy reconstruction

Energy reconstruction

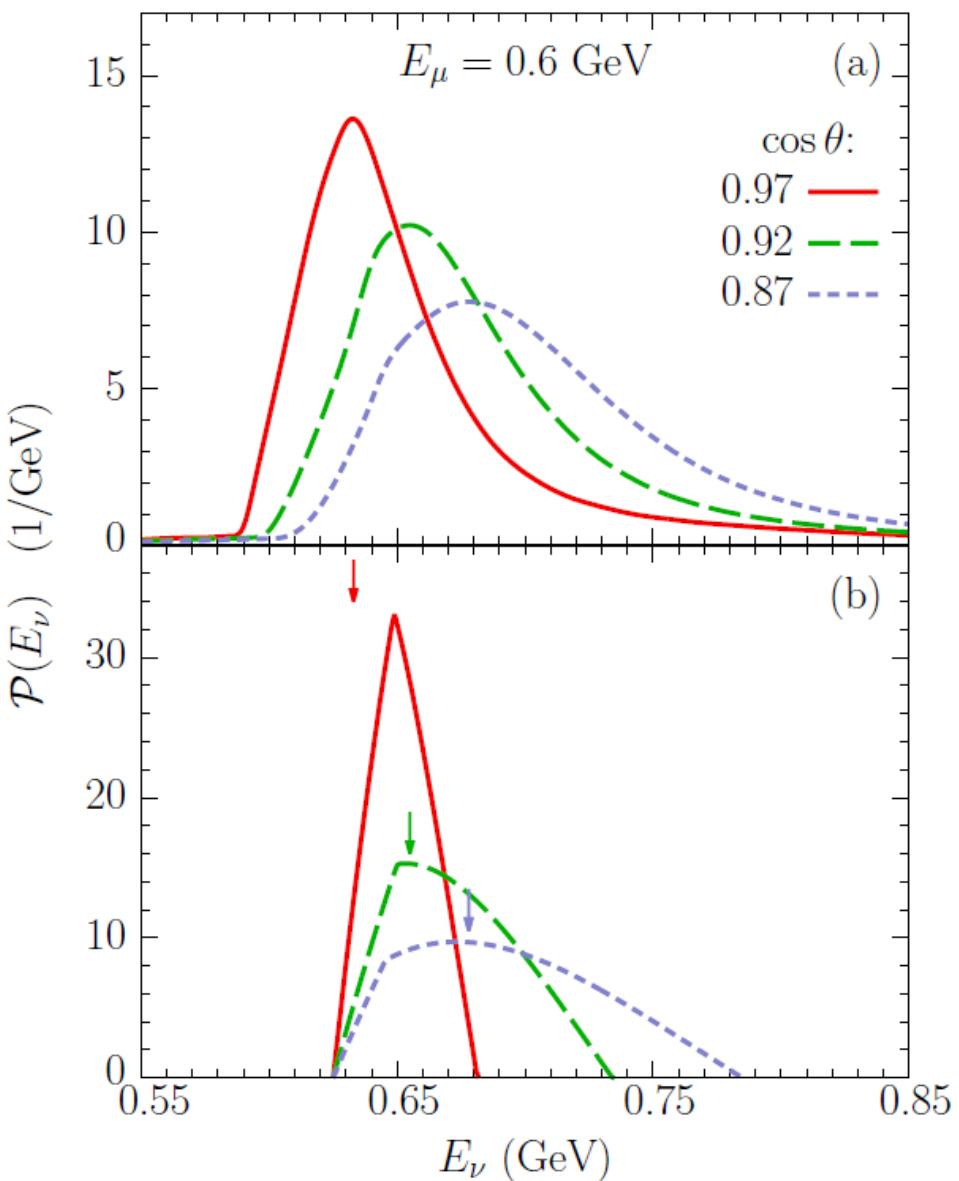
Consider the probability distribution that a muon of given energy and scattering angle is produced by a neutrino of energy E_ν

$$\mathcal{P}(E_\nu) \Big|_{E_\mu, \cos \theta} = \frac{\frac{d\sigma(E_\nu)}{dE_\mu d \cos \theta}}{\int dE_\nu \frac{d\sigma(E_\nu)}{dE_\mu d \cos \theta}}$$



kinematics relevant to
the T2K experiment

At $\cos = 0.97$
the difference is $\sim 16 \text{ MeV}$
for RFG with $\varepsilon = 25 \text{ MeV}$

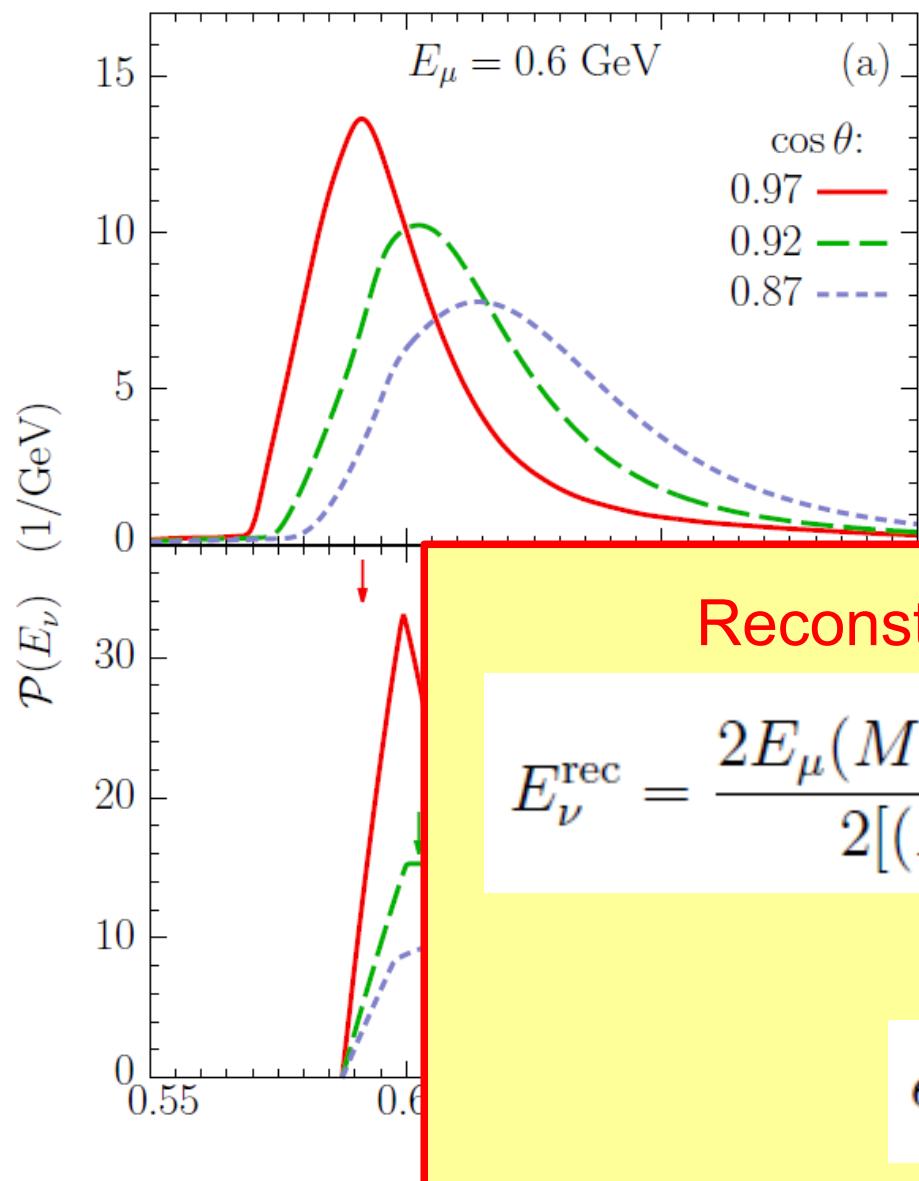


kinematics relevant to
the T2K experiment

At $\cos = 0.97$
the difference is $\sim 16 \text{ MeV}$
for RFG with $\varepsilon = 25 \text{ MeV}$

To get the maxima right

$\varepsilon = 9 \text{ MeV} @ \cos = 0.97$
 $\varepsilon = 27 \text{ MeV} @ \cos = 0.92$
 $\varepsilon = 29 \text{ MeV} @ \cos = 0.87$



kinematics relevant to
the T2K experiment

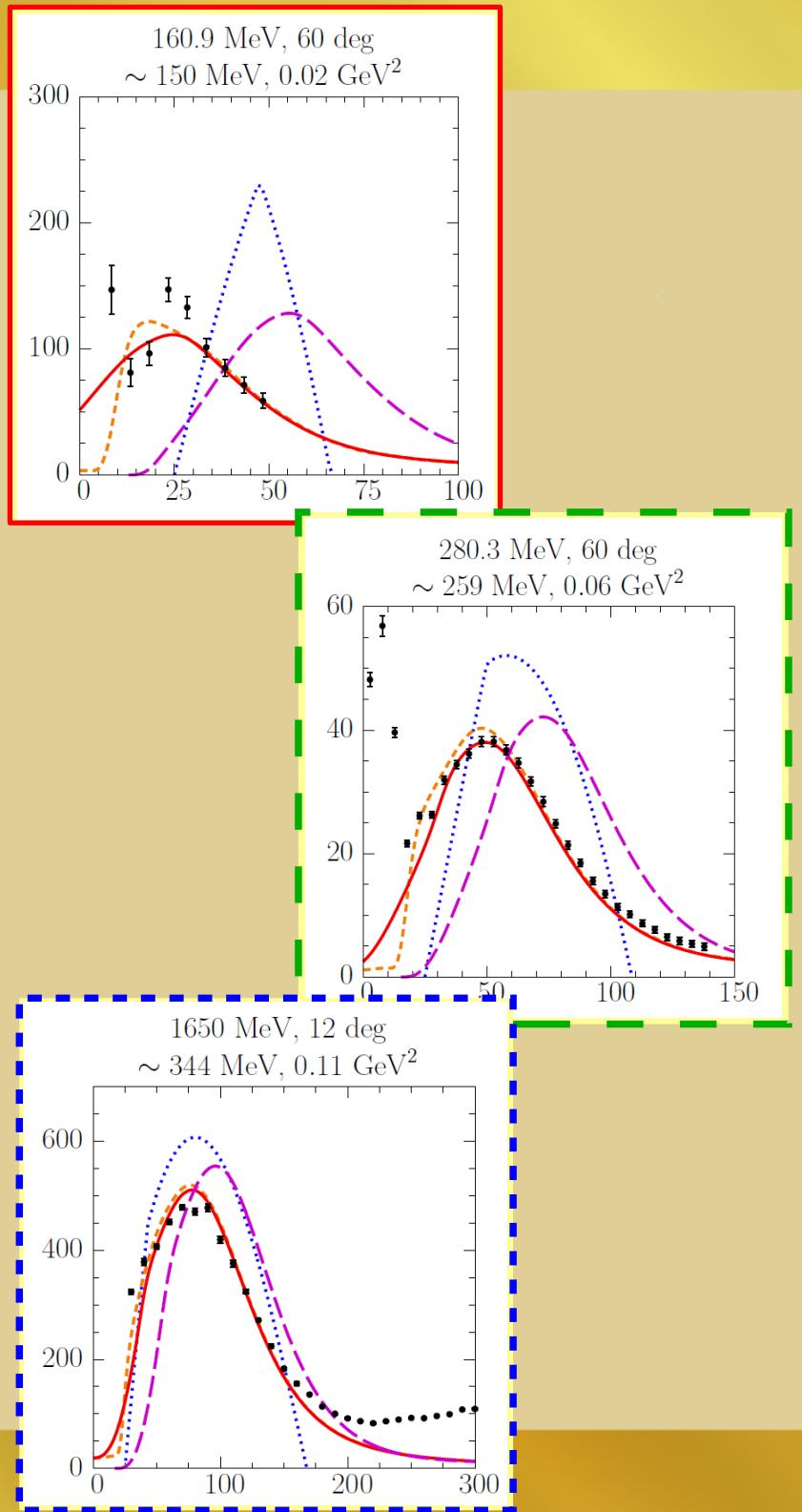
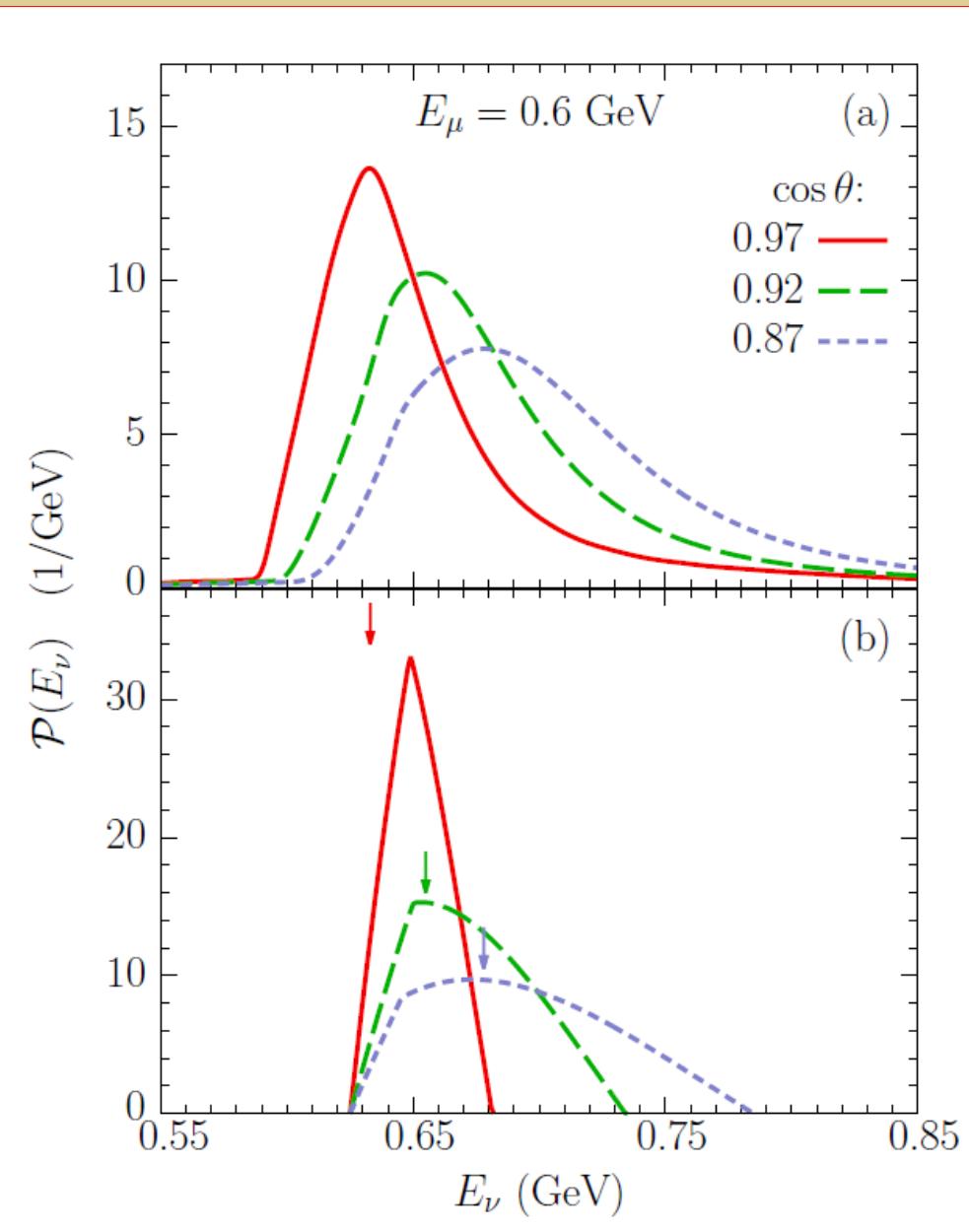
At $\cos = 0.97$
the difference is $\sim 16 \text{ MeV}$
for RFG with $\epsilon = 25 \text{ MeV}$

Reconstructing the energy from

$$E_\nu^{\text{rec}} = \frac{2E_\mu(M - \epsilon) - (M - \epsilon)^2 - m'^2 + M'^2}{2[(M - \epsilon) - E_\mu + |\mathbf{k}|_\mu \cos \theta]},$$

we need

$$\epsilon = \epsilon(\cos \theta, E_\mu)$$



Neutrino vs antineutrino

muon energy 600 MeV

	$\cos \theta = 0.97$	$\cos \theta = 0.92$	$\cos \theta = 0.87$
neutrino	633	655	678
antineutrino	619	639	661
difference	13.9	16.0	17.6

muon energy 400 MeV

	$\cos \theta = 0.97$	$\cos \theta = 0.92$	$\cos \theta = 0.87$
neutrino	422	435	444
antineutrino	406	421	428
difference	15.6	14.4	15.7

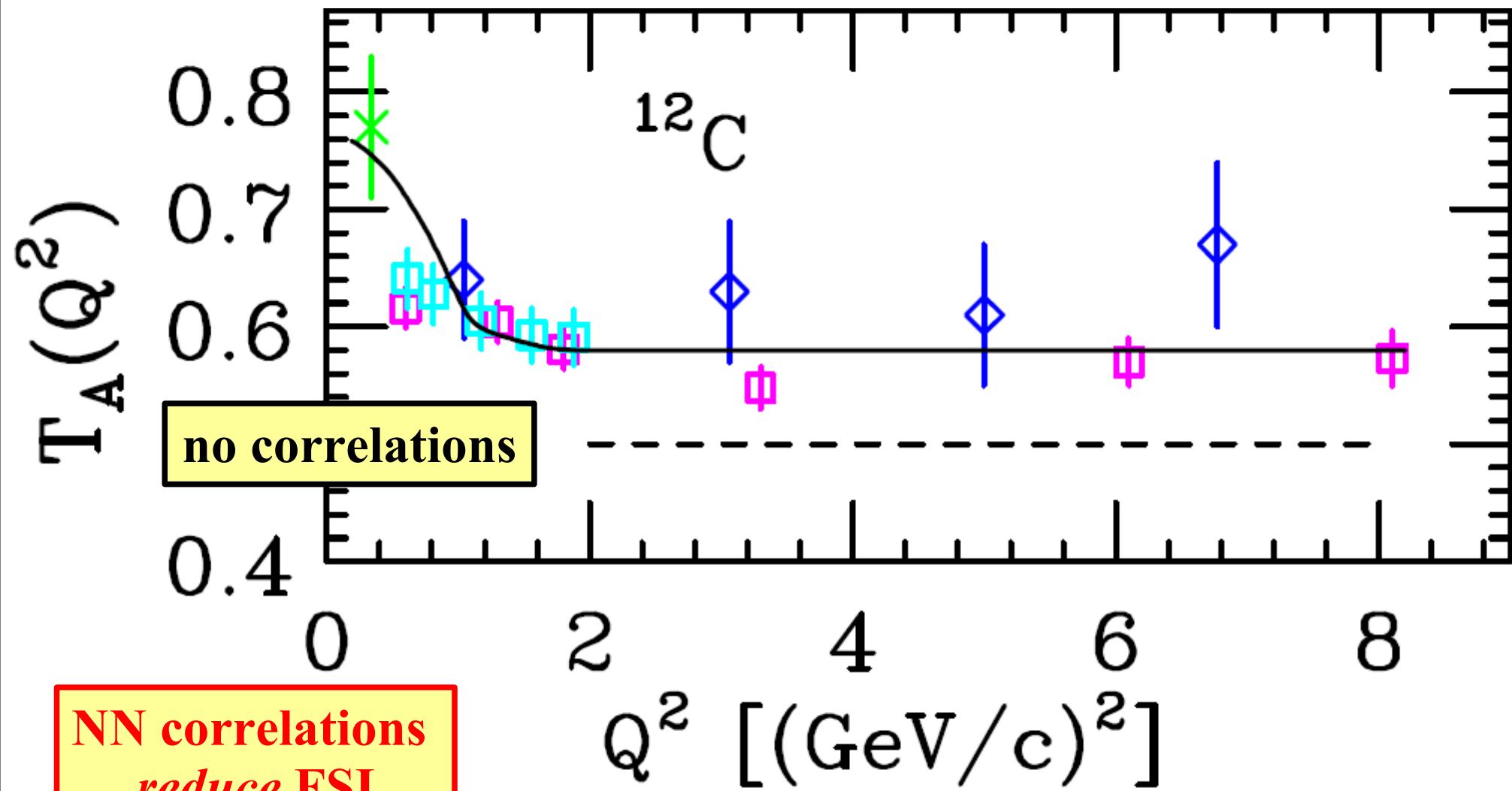
Summary

- ① The SF calculations accounting for FSI can describe the (e,e') cross section down to $|q| \sim 150$ MeV ($Q^2 \sim 0.02\text{GeV}^2$) accurately reproducing features of the QE peak.
- ② An accurate description of nuclear effects is crucial for the accurate reconstruction of neutrino energy from the charged lepton's kinematics.
- ③ Accurate estimate of the neutrino-antineutrino difference is essential for determination of the CP violating phase.

Backup slides

Nuclear transparency

O. Benhar
@ NuInt05



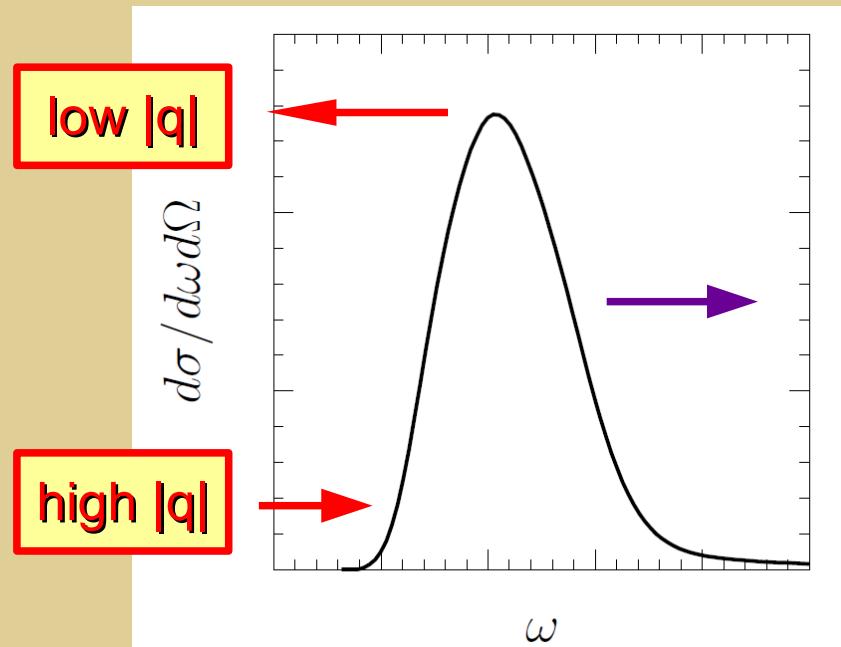
Quick and dirty comparison

Real part of the OP

- acts in the **final** state
- shifts the QE peak to **low ω** at low $|q|$
(to high ω at high $|q|$)

Binding energy

- acts in the **initial** state
- shifts the QE peak to **high ω**



Neutrino vs antineutrino

muon energy 600 MeV

	$\cos \theta = 0.97$	$\cos \theta = 0.92$	$\cos \theta = 0.87$
neutrino	633	655	678
antineutrino	619	639	661
difference	13.9	16.0	17.6

muon energy 450 MeV

	$\cos \theta = 0.97$	$\cos \theta = 0.92$	$\cos \theta = 0.87$
neutrino	476	488	502
antineutrino	461	474	485
difference	15.1	14.5	16.9

Neutrino vs antineutrino

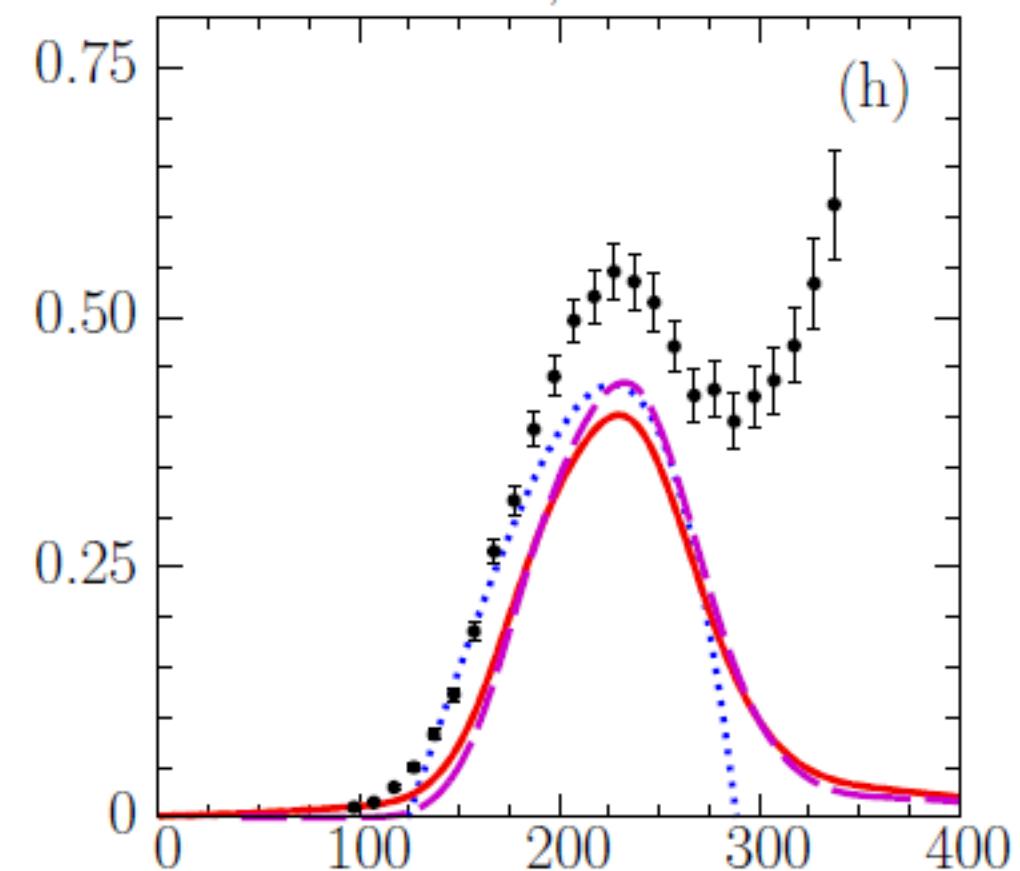
muon energy 700 MeV

	$\cos \theta = 0.97$	$\cos \theta = 0.92$	$\cos \theta = 0.87$
neutrino	736	768	801
antineutrino	723	752	782
difference	13.9	15.9	19.2

muon energy 500 MeV

	$\cos \theta = 0.97$	$\cos \theta = 0.92$	$\cos \theta = 0.87$
neutrino	529	542	561
antineutrino	515	528	544
difference	14.2	14.9	16.8

440.0 MeV, 145 deg
 ~ 624 MeV, 0.34 GeV^2



479.4 MeV, 145 deg
 ~ 671 MeV, 0.38 GeV^2

