Nuclear effects in neutrino and electron interactions

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Blind monks examining an elephant
Hanabusa Itchō

Outline

1) **Introduction**
- Impulse approximation
- Off-shell effects

2) **Nuclear models**
- Fermi gas model
- Shell model
- Spectral function approach

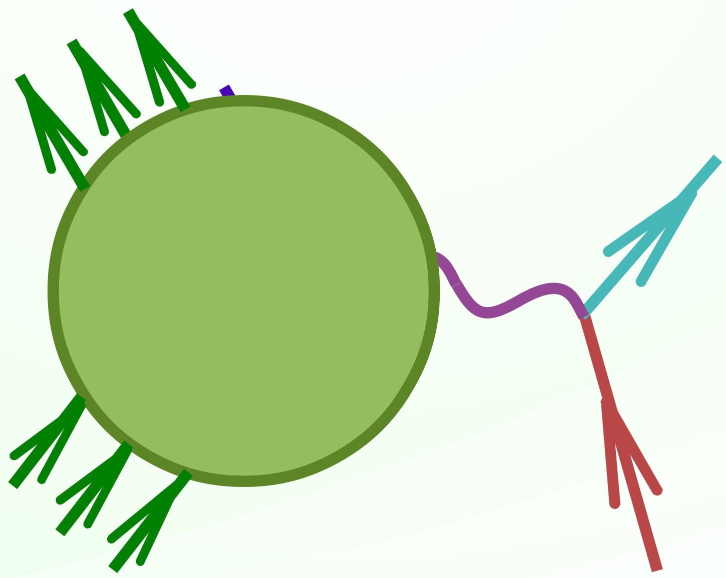
3) **Kinematic energy reconstruction**
- Simplest case
- Realistic case

4) **Summary**

Impulse approximation

Impulse approximation

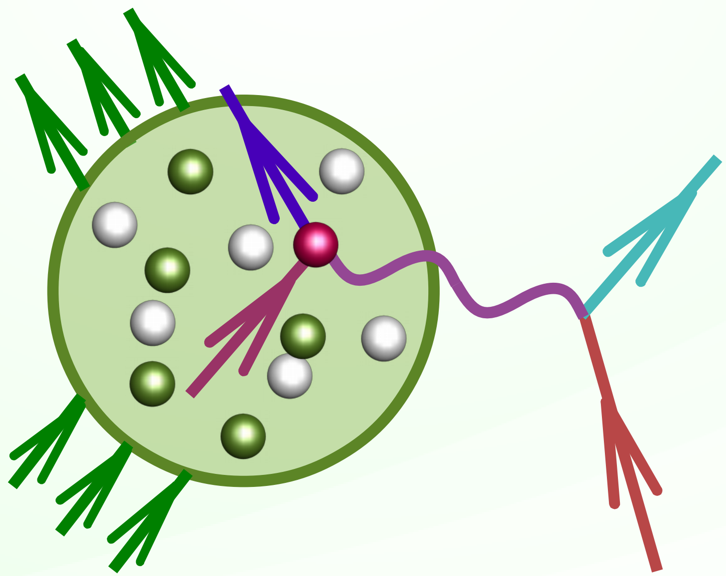
Assumption: the dominant process of lepton-nucleus interaction is **scattering off a single nucleon**, with the remaining nucleons acting as a spectator system.



Impulse approximation

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

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



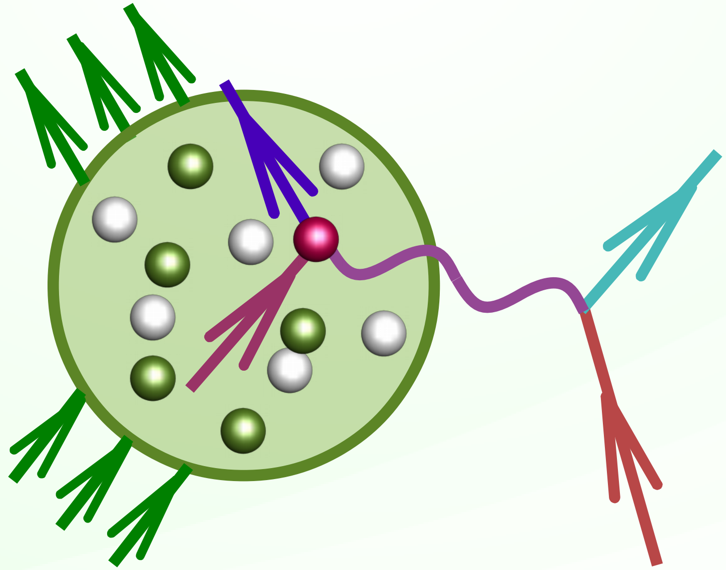
Impulse approximation

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

Spectral function

Elementary cross section

~δ(...) x Pauli blocking



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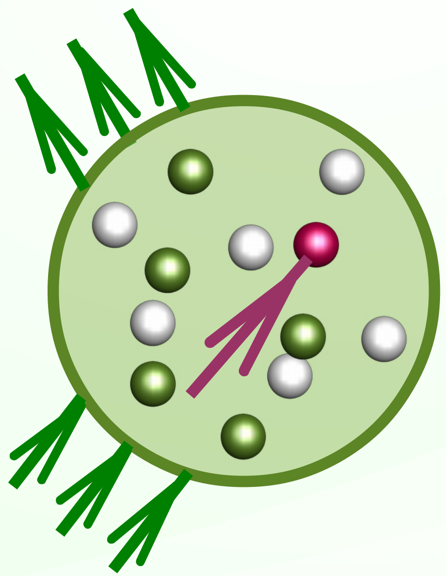
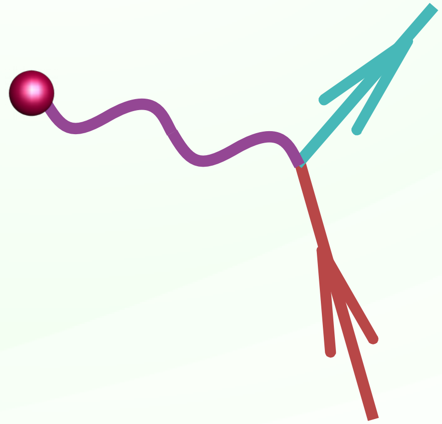
The (hole) spectral function describes the ground-state properties of the target nucleus.



Impulse approximation

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

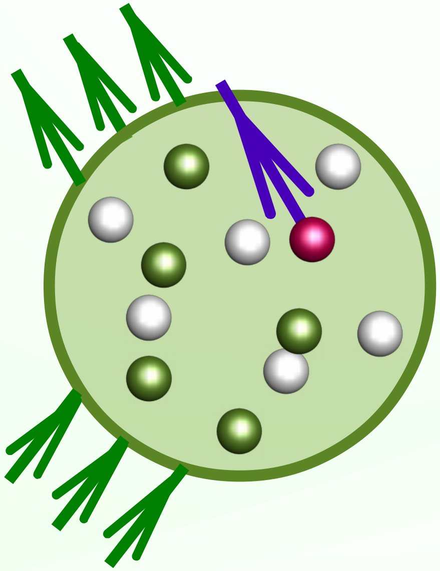
The elementary cross section characterizes the vertex



Impulse approximation

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

Ensures the energy conservation and Pauli blocking



Impulse approximation

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Spectral function

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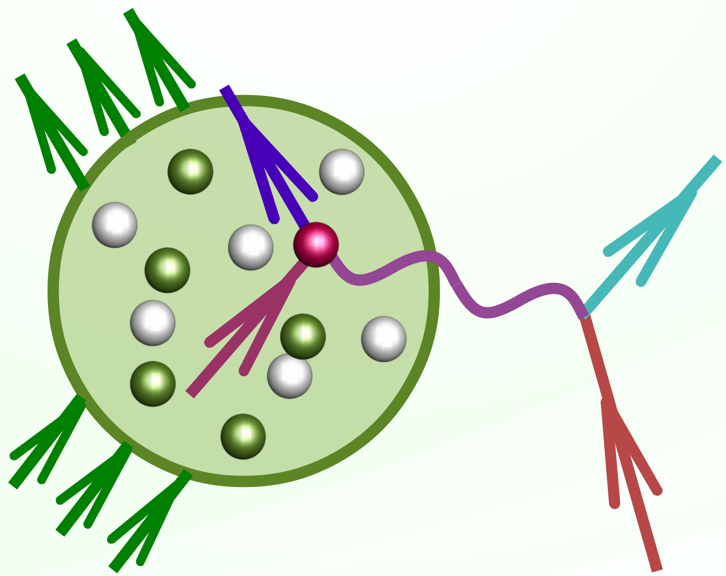


Impulse approximation

For scattering in a given angle, neutrinos and electrons differ only due to **the elementary cross section**.

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.

Impulse approximation

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.

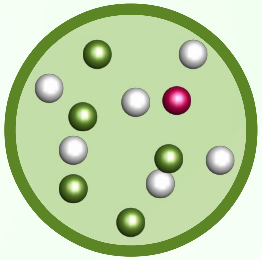
$$\boxed{\frac{d\sigma^{\rm IA}_{\ell A}}{d\omega d\Omega} = \sum_N \int d^3p\, dE\; P^N_{\rm hole}(\mathbf{p}, E)\, \frac{M}{E_{\mathbf{p}}} \frac{d\sigma^{\rm elem}_{\ell N}}{d\omega d\Omega}\; P^N_{\rm part}(\mathbf{p}', \mathcal{T}')}$$

Off-shell effects

Consider a nucleus stable against emission of nucleons.

As in its ground state, $E_A = M_A$, the energy cannot be decreased by emission of a nucleon

$$E_A = E_{A-1} + E_p < E_{A-1} + M$$



so the energy of a nucleon in the nucleus is lower than M.

V.R. Pandharipande, Nucl. Phys. B (Proc. Suppl.) 112, 51 (2002)

Off-shell effects

In a nuclear model, the initial nucleon's energy may

- differ from the on-shell energy by a constant

$$\boxed{E_p = \sqrt{M^2 + |\mathbf{p}|^2} - \epsilon}$$

- be a function of the momentum

$$\boxed{E_p = \sqrt{M^2 + |\mathbf{p}|^2} - \varepsilon(|\mathbf{p}|)}$$

- only be correlated with the momentum

increasing sophistication

Off-shell effects

The elementary cross section,

$$\boxed{\frac{d\sigma_{\ell N}^{\mathrm{elem}}}{dE_{\mathbf{k}'}d\Omega dE_{\mathbf{p}'}d\Omega_{\mathbf{p}'}} \propto L_{\mu\nu}H^{\mu\nu}}$$

contains two tensors

$$\boxed{L_{\mu\nu} \propto j_{\mu}^{\mathrm{lept}} j_{\nu}^{\mathrm{lept}*} \quad \text{and} \quad H^{\mu\nu} \propto j_{\mathrm{hadr}}^{\mu} j_{\mathrm{hadr}}^{\nu *}}$$

with **only the hadron one** affected by off-shell effects.

Off-shell effects

The current appearing in the hadron tensor is known on the mass shell,

$$\boxed{j^{\mu}_{\mathrm{hadr}} = \overline{u}(\mathbf{p}', s') \left(\gamma^{\mu} F_1 + i\sigma^{\mu\kappa} \frac{q_{\kappa}}{2M} F_2 + \ldots \right) u(\mathbf{p}, s)}$$

or equivalently

$$\boxed{j^{\mu}_{\mathrm{hadr}} = \overline{u}(\mathbf{p}', s') \left(\gamma^{\mu} (F_1 + F_2) - \frac{(p + p')^{\mu}}{2M} F_2 + \ldots \right) u(\mathbf{p}, s)}$$

Off-shell effects

The prescription of de Forest [NPA 392, 232 (1983)]:

to approximate the off-shell hadron tensor, one can use the on-shell expression with the same momentum transfer and a modified energy transfer,

$$\boxed{H^{\mu\nu}_{\text{off-shell}}(p,q) \to H^{\mu\nu}_{\text{off-shell}}(\tilde{p},\tilde{q})}$$

with

$$\boxed{\tilde{p} = \left(\sqrt{M^2+\mathbf{p}^2},\mathbf{p}\right) \quad \text{and} \quad \tilde{q} = (\tilde{\omega},\mathbf{q})}$$

Off-shell effects

The prescription of de Forest [NPA 392, 232 (1983)]:

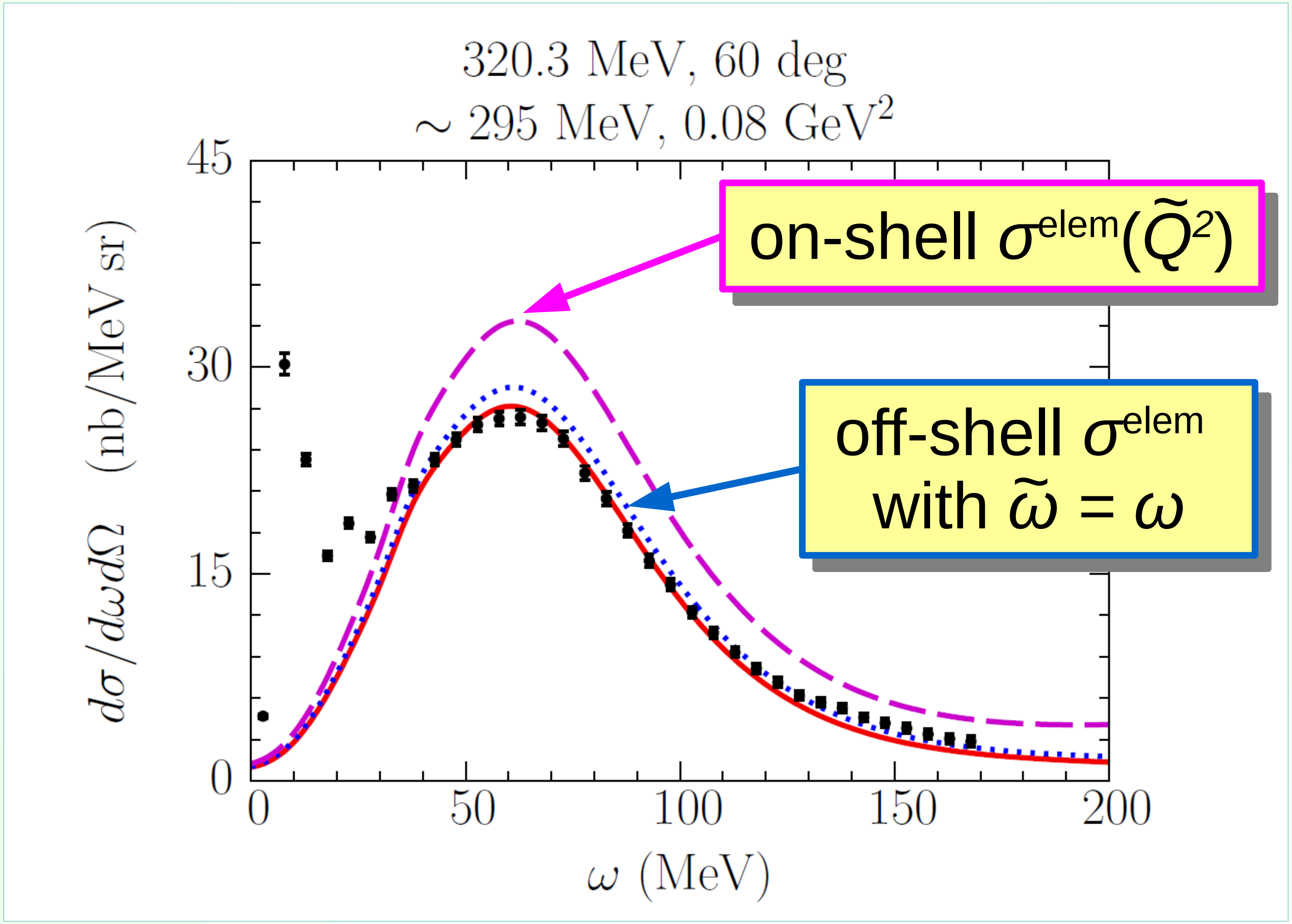
as the initial nucleon's energy is now $E_p = \sqrt{M^2 + \boldsymbol{p}^2}$
in our calculations, and the final energy is an observable,
the energy transfer has to be

$$\boxed{\tilde{\omega} = \sqrt{M^2 + (\mathbf{p} + \mathbf{q})^2} - \sqrt{M^2 + \mathbf{p}^2}}$$

the difference between the “lepton” ω and “hadron” $\widetilde{\omega}$
is transferred to the spectator system of (A-1) nucleons.

Off-shell effects

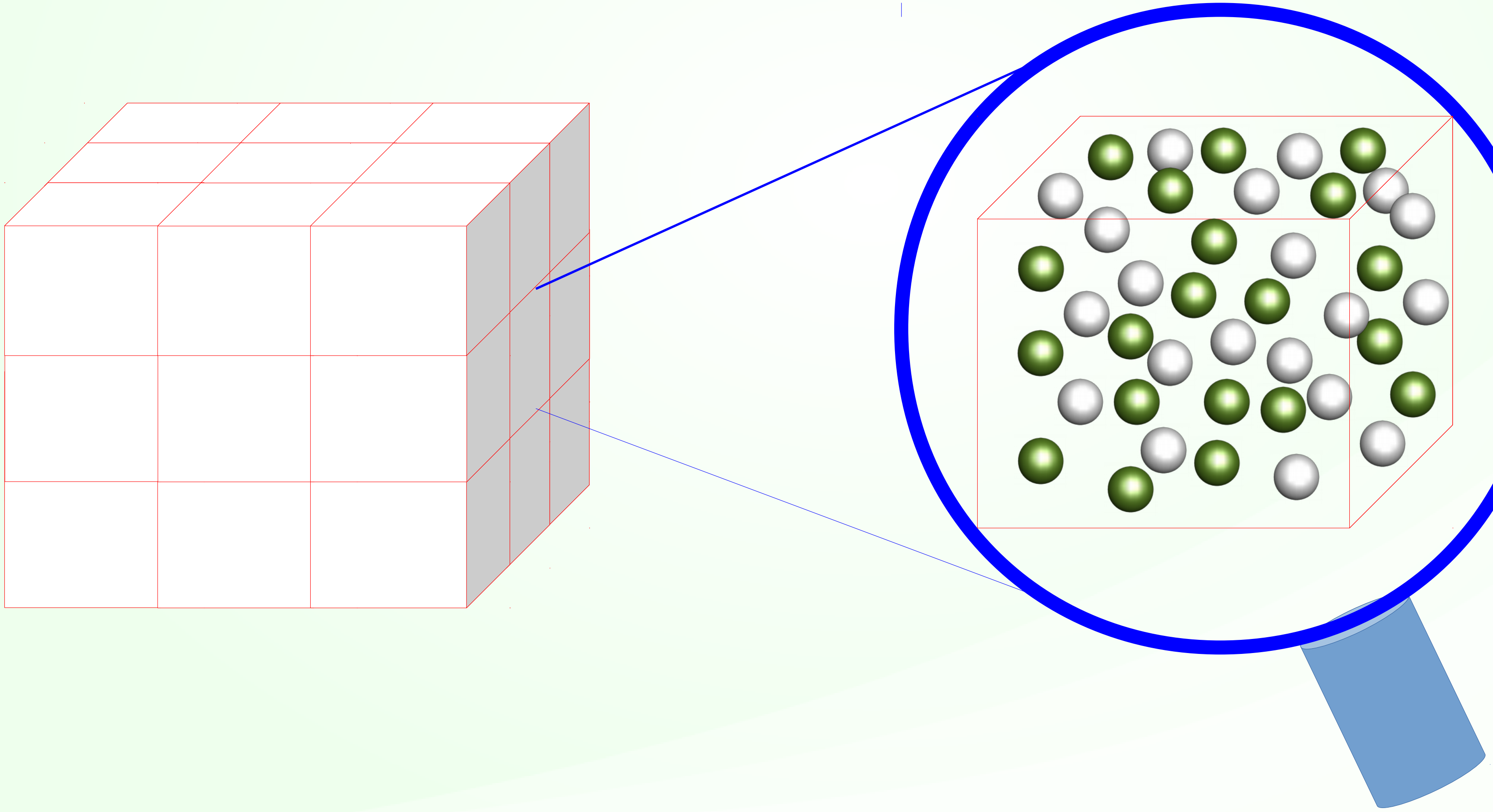
Examples of an oversimplified treatment:



Fermi gas model

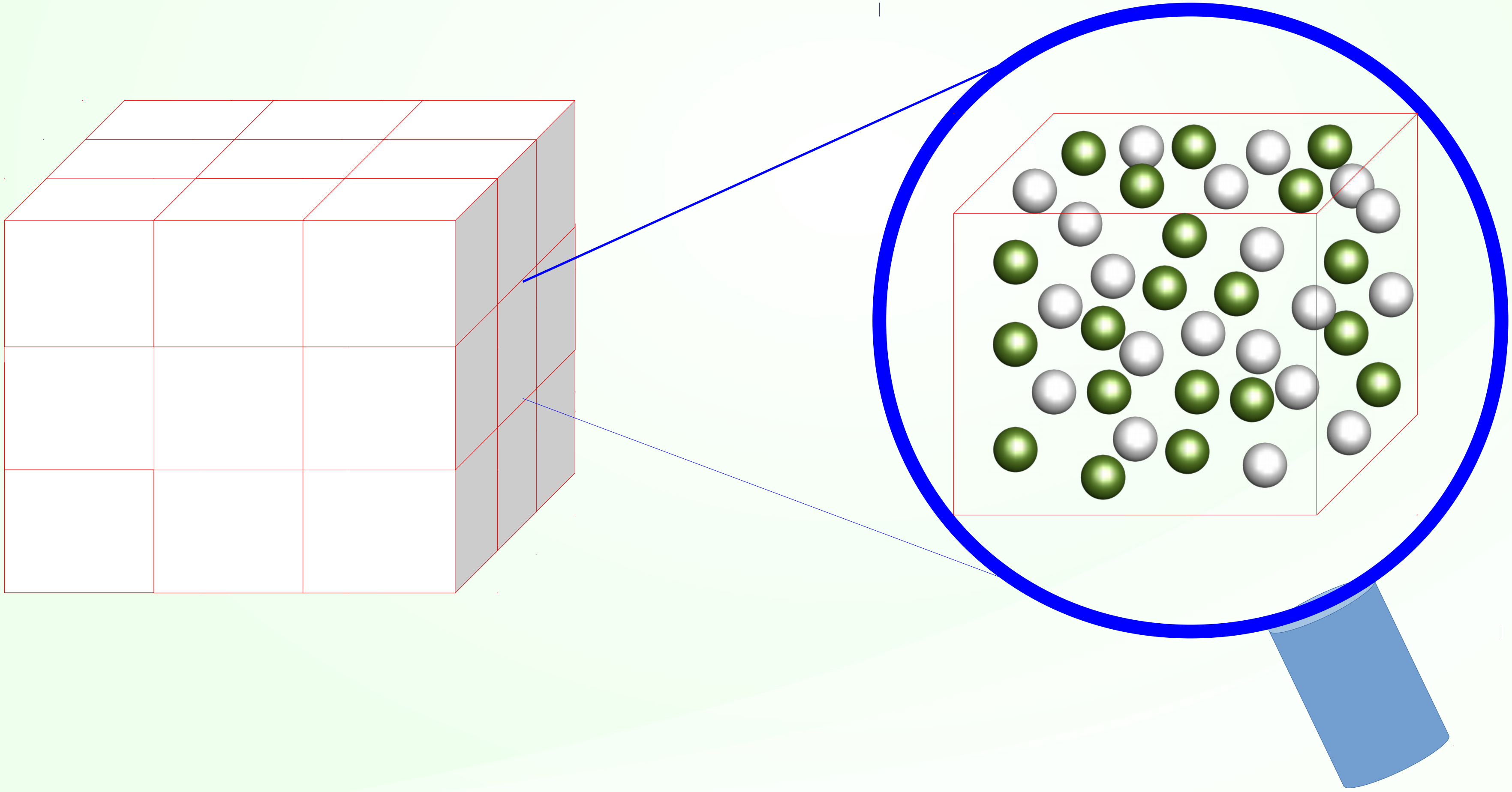
Fermi gas model

Imagine an infinite space filled uniformly with nucleons



Fermi gas model

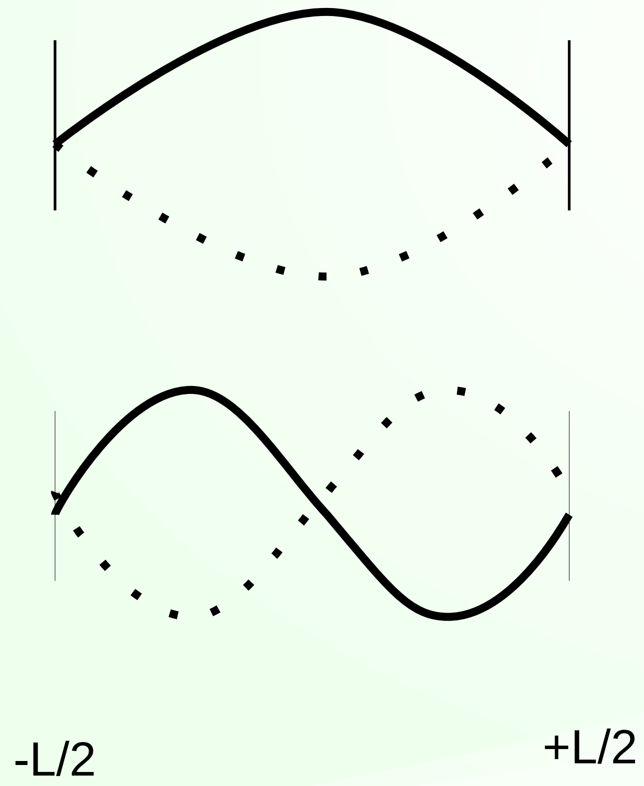
Due to the translational invariance, the eigenstates can be labeled using momentum, $\psi(x) = C e^{-ipx}$.

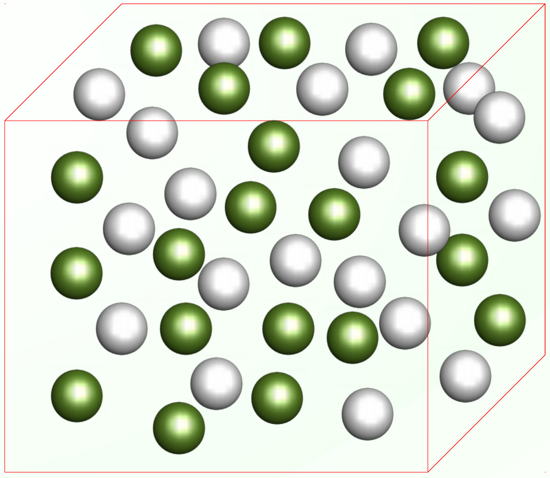


Fermi gas model

Due to the boundary conditions, $p_i \frac{L}{2} = \frac{\pi}{2} + n\pi$

every state occupies $(2\pi/L)^3$ in the momentum space





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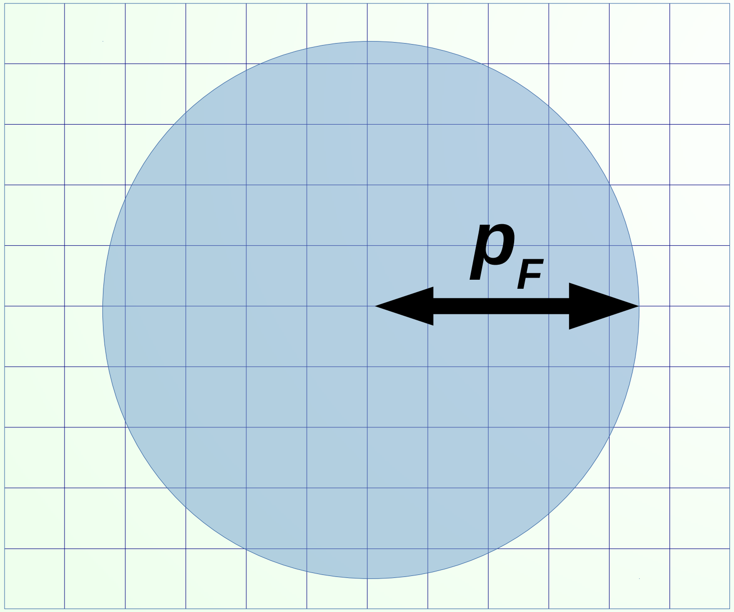
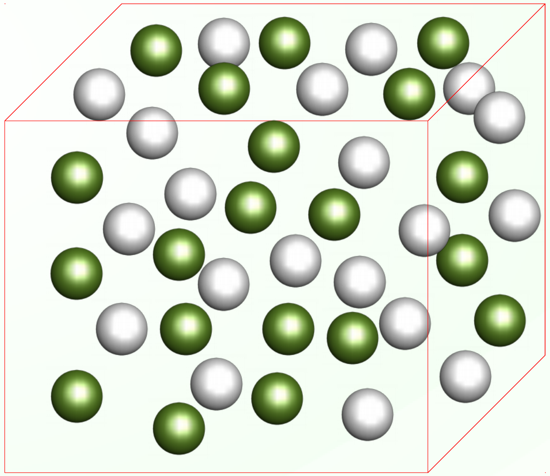




Momentum space

Coordinate space

Fermi gas model

The corresponding hole and particle spectral functions are

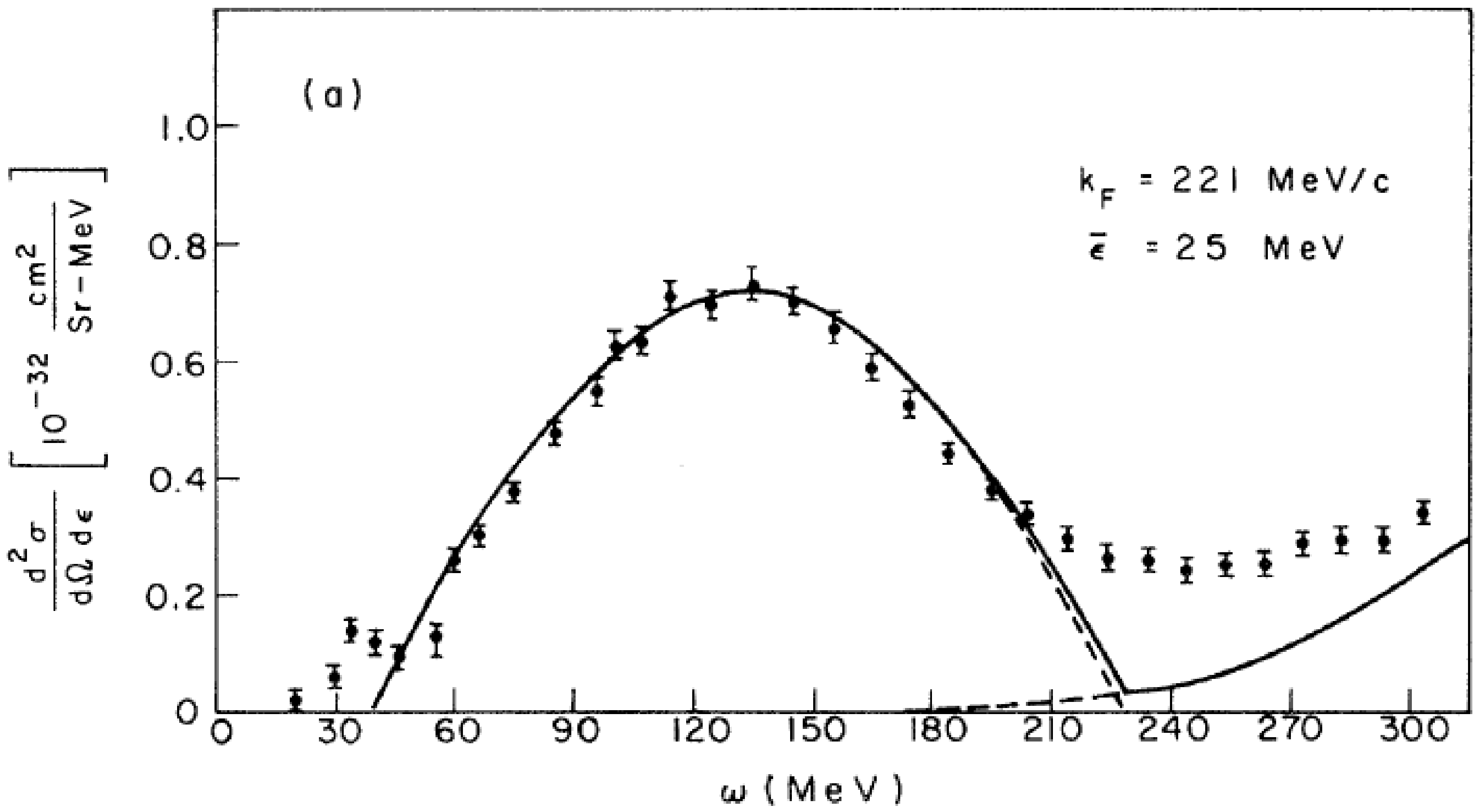
$$P^{\rm FG}_{\rm hole}(\mathbf{p}, E) = \frac{3}{4\pi p_F^3}\,\theta(p_F - |\mathbf{p}|)\,\delta(E_p - \varepsilon - M + E),$$

$$P^{\rm FG}_{\rm part}(\mathbf{p}', \mathcal{T}') = [1 - \theta(p_F - |\mathbf{p}'|)]\,\delta(E_{p'} - M - \mathcal{T}'),$$

putting them to the cross section (below), you can recover the standard formula for the Fermi gas.

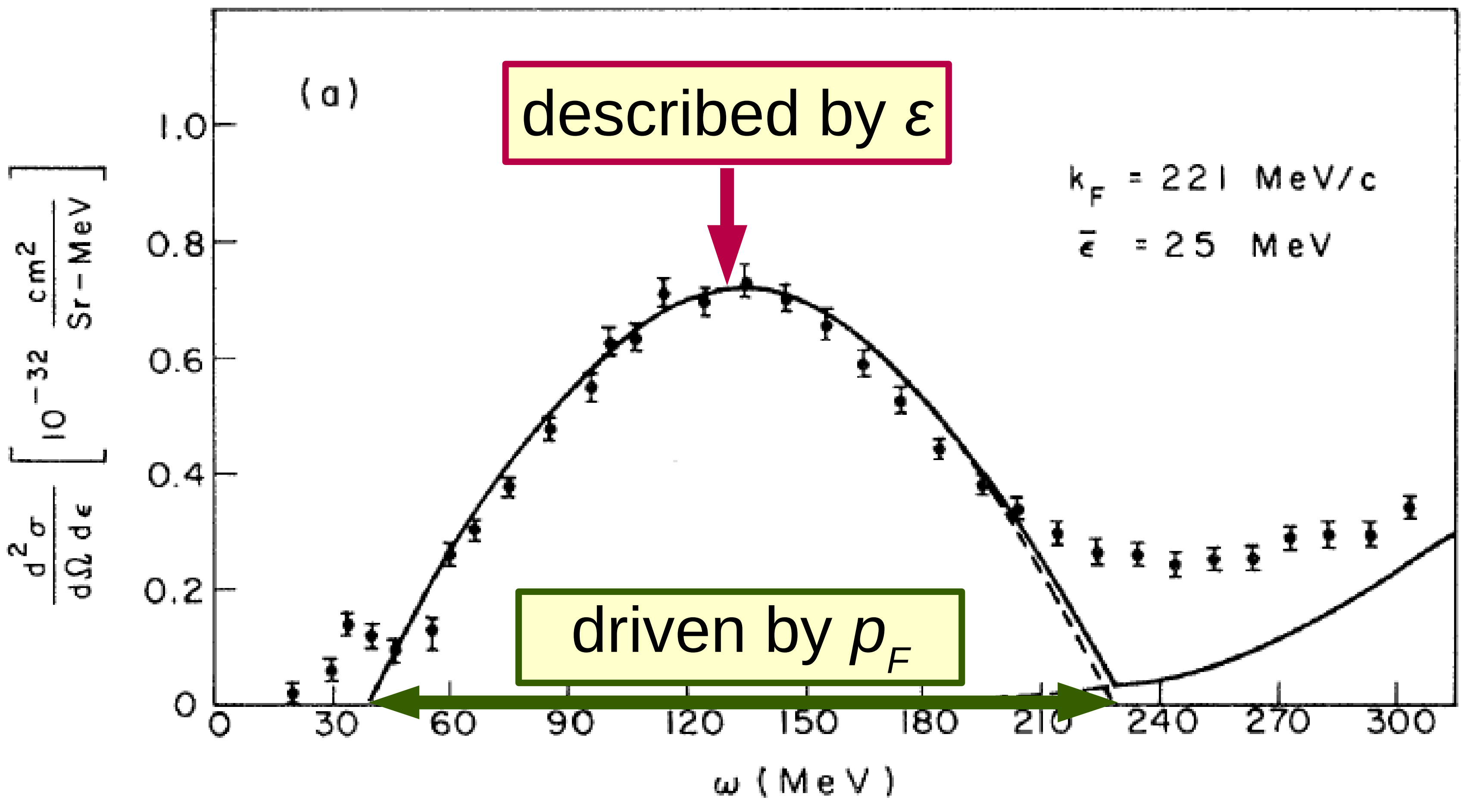
$$\frac{d\sigma^{\rm IA}_{\ell A}}{d\omega d\Omega} = \sum_N \int d^3p\, dE\, P^N_{\rm hole}(\mathbf{p}, E)\,\frac{M}{E_{\mathbf{p}}}\frac{d\sigma^{\rm elem}_{\ell N}}{d\omega d\Omega}\,P^N_{\rm part}(\mathbf{p}', \mathcal{T}')$$

Electron scattering off carbon, 500 MeV, 60 deg



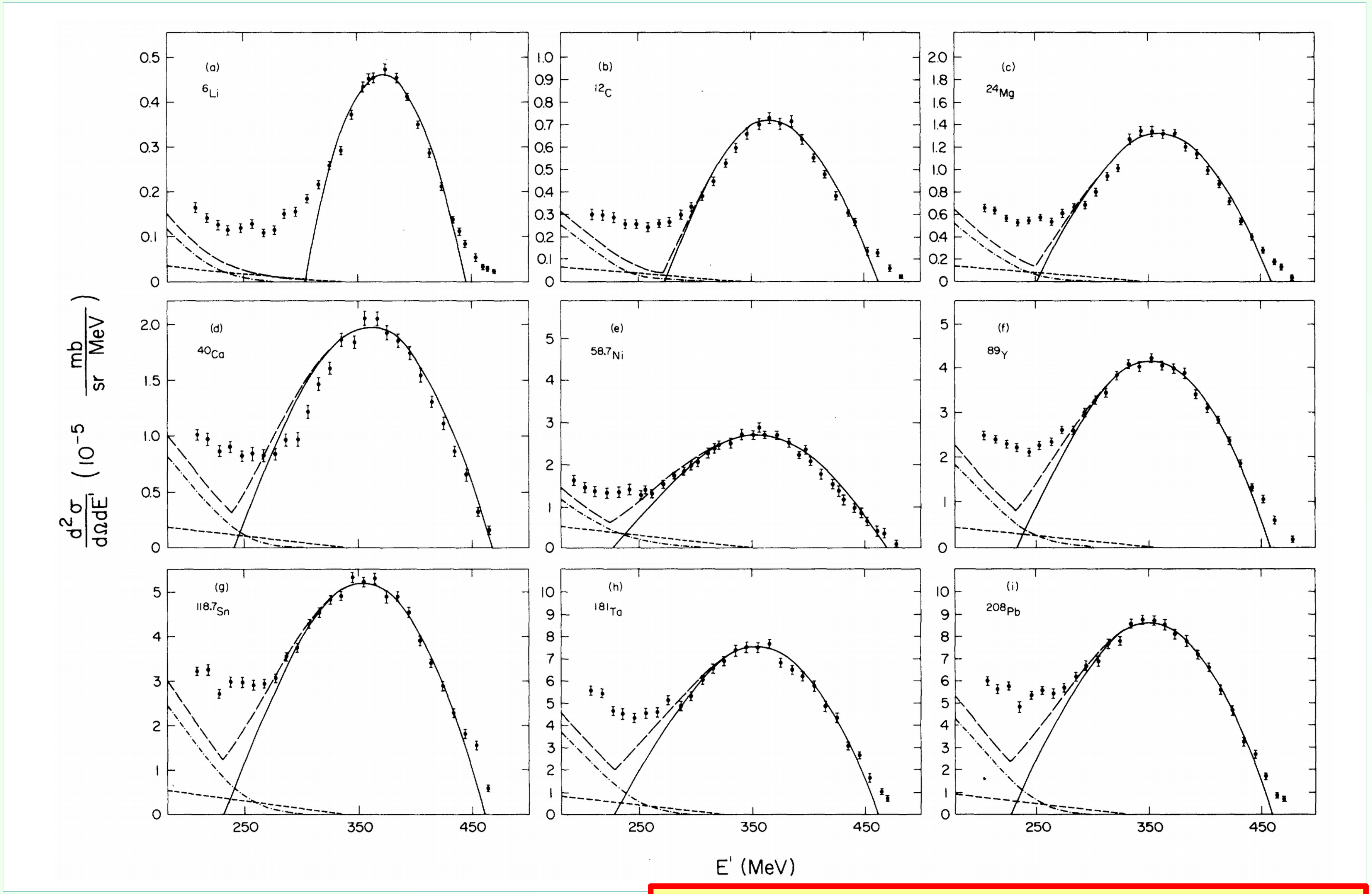
Moniz *et al.*, PRL 26, 445 (1971)

Electron scattering off carbon, 500 MeV, 60 deg



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

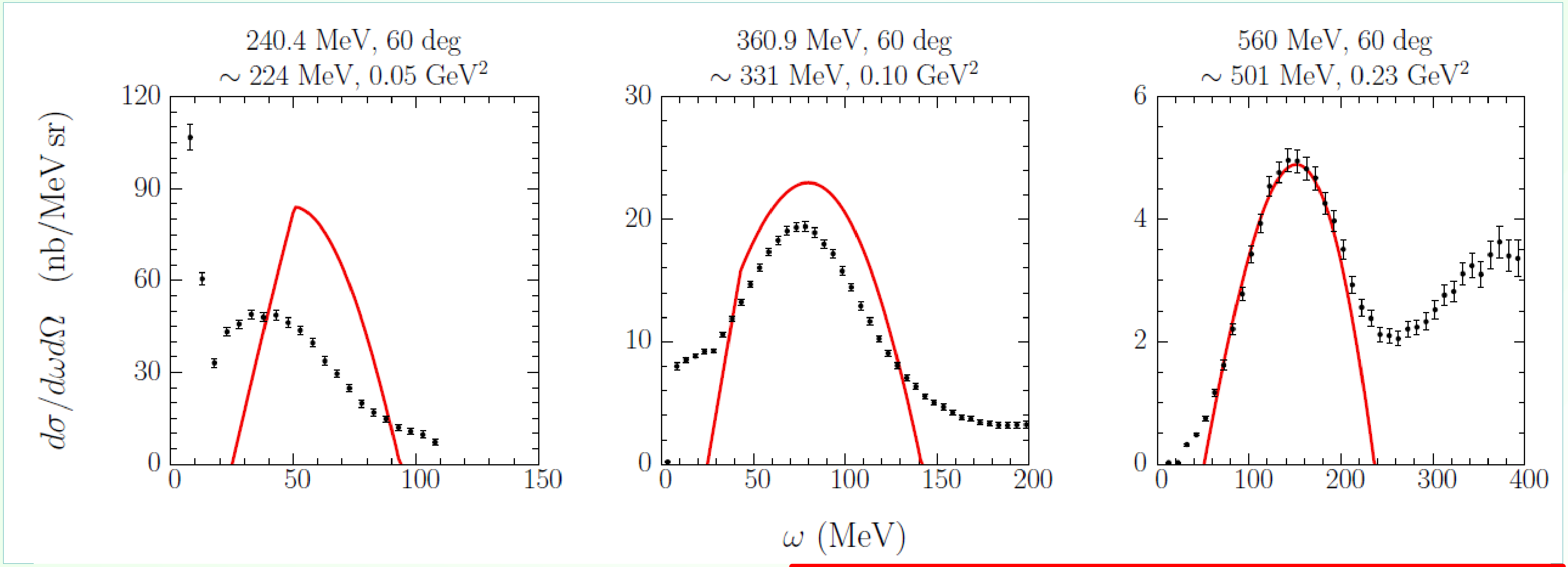
Fermi gas model



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

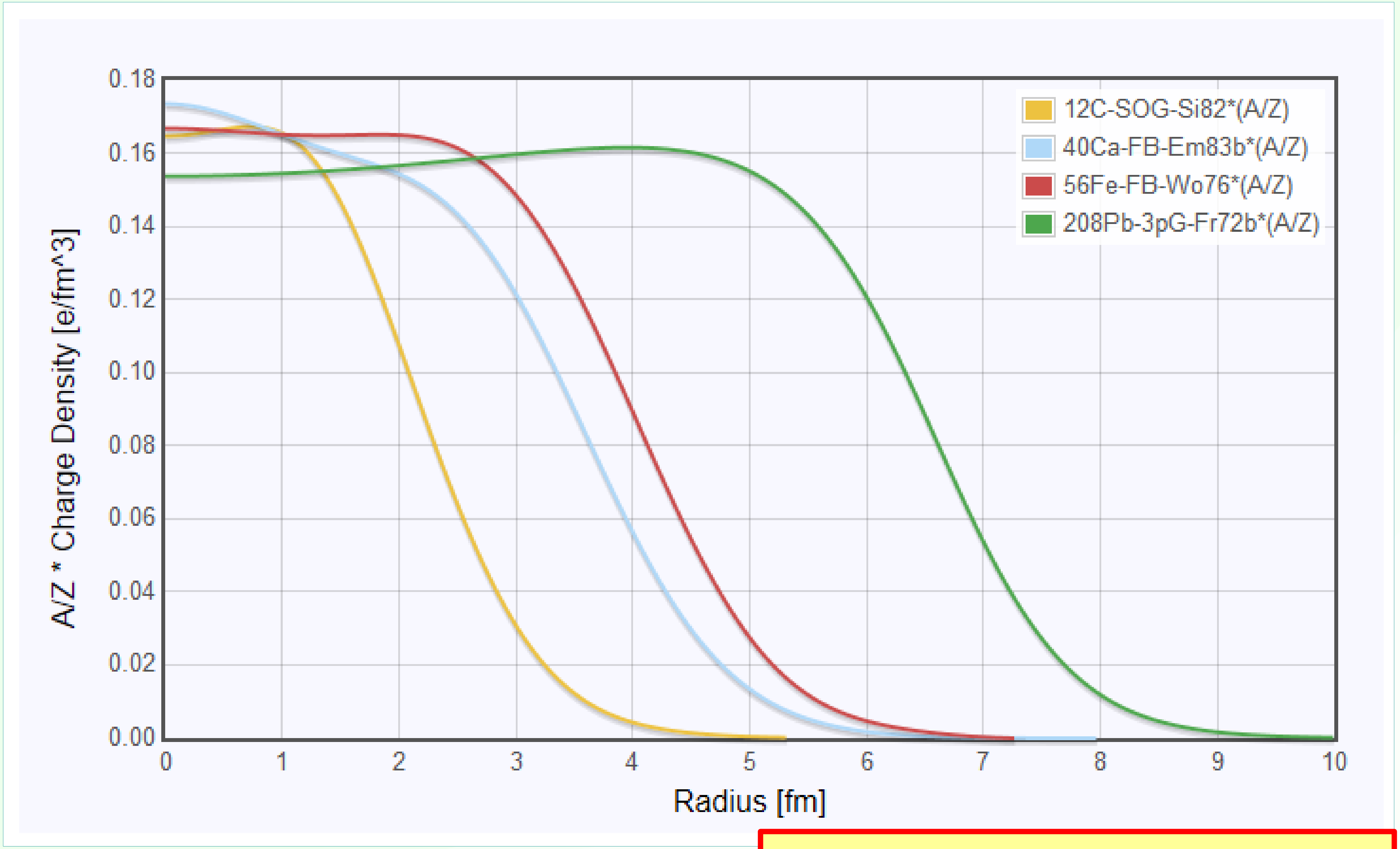
Fermi gas model

What happens at a kinematics other than 500 MeV, 60deg?



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

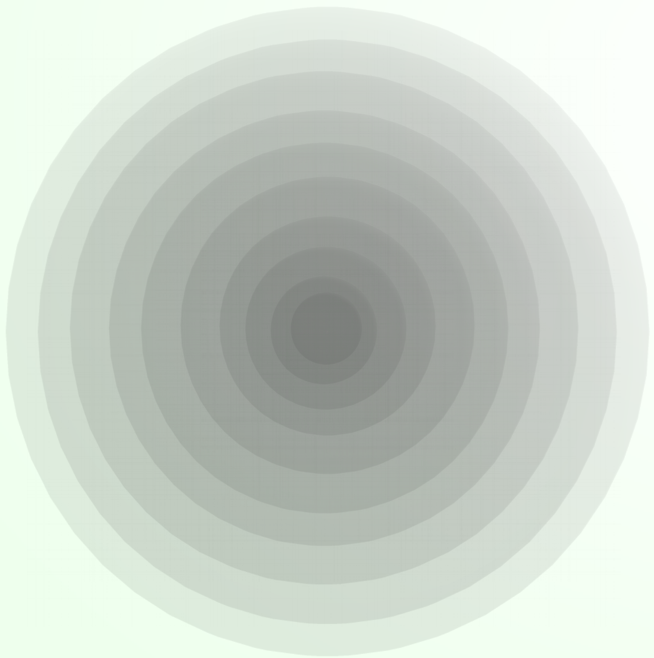
Charge-density in nuclei

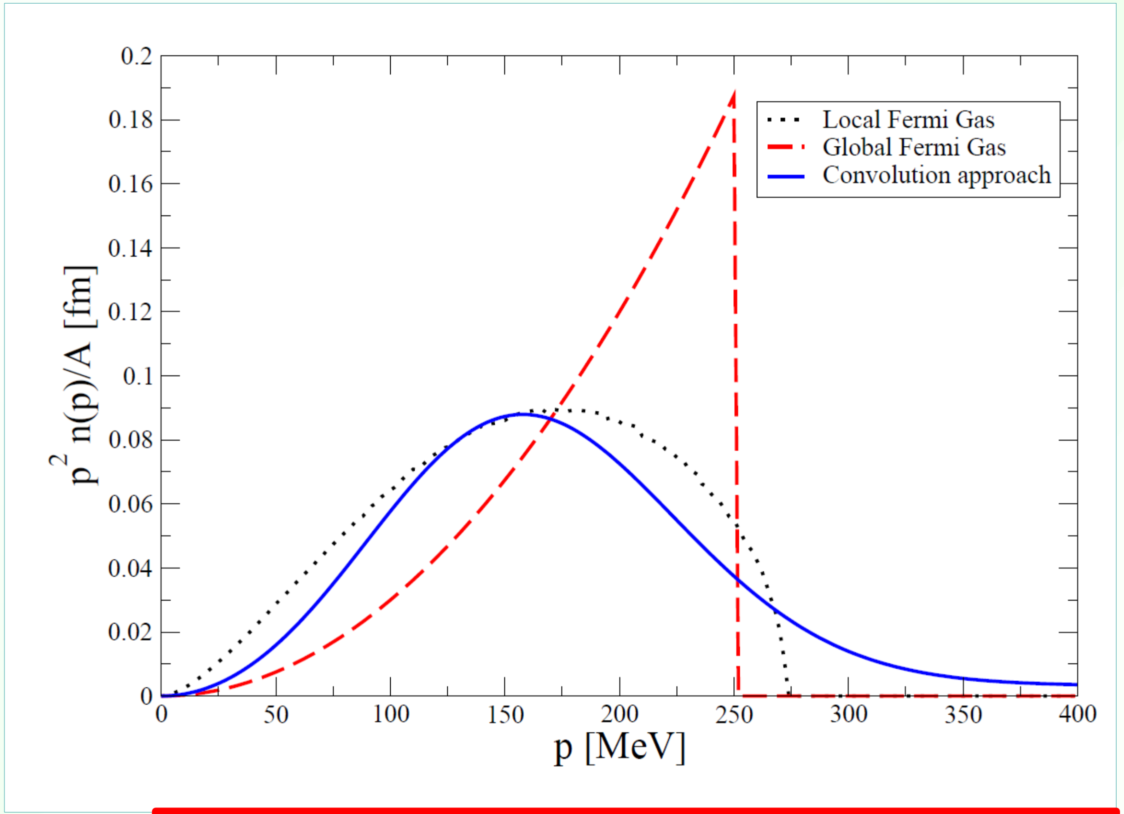


http://faculty.virginia.edu/ncd/index.html

Local Fermi gas model

A spherically symmetric nucleus can be approximated by concentric spheres of a constant density.



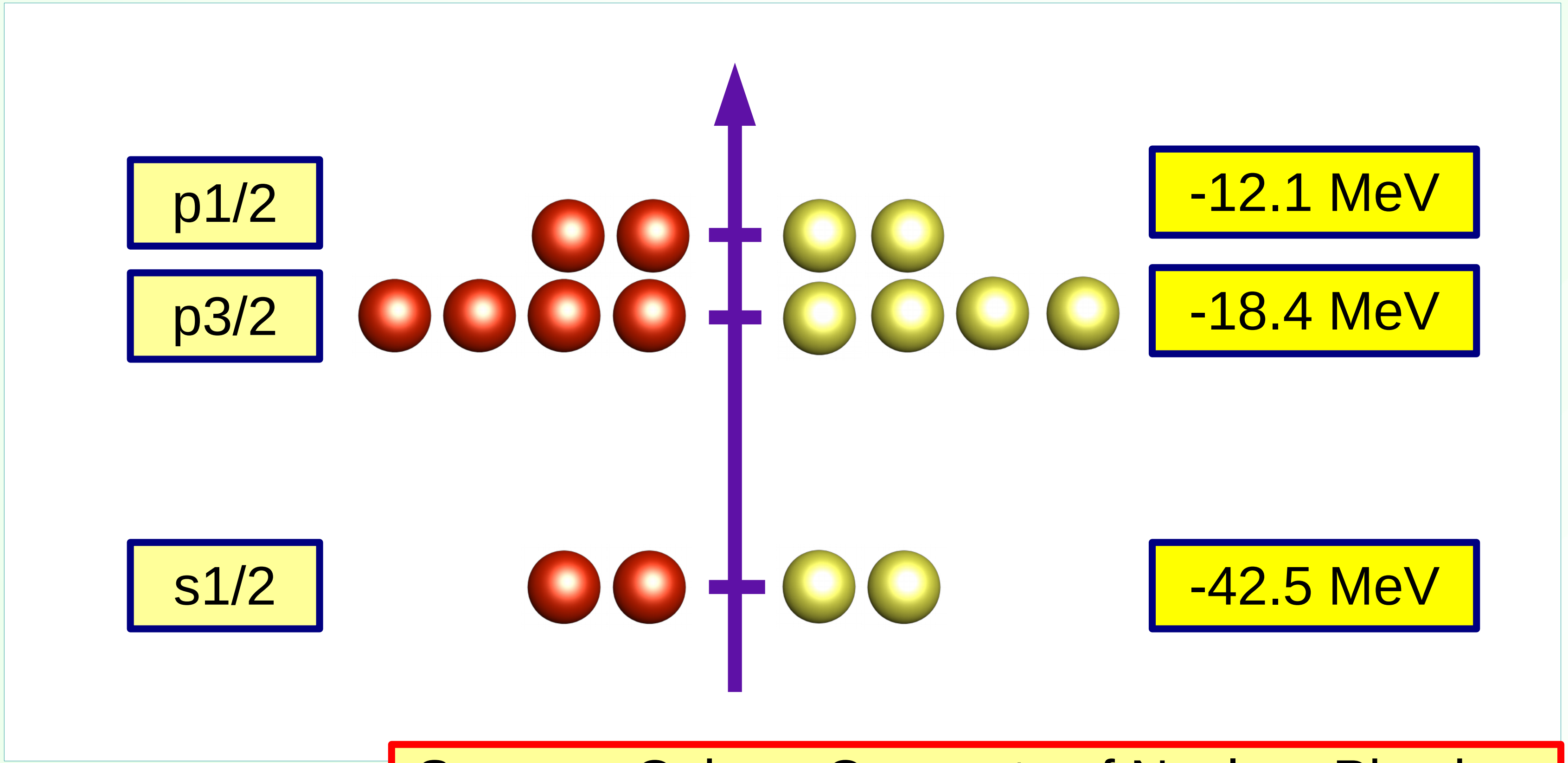


L. Alvarez-Ruso *et al.*,
New J.Phys. 16, 075015 (2014)

Shell model

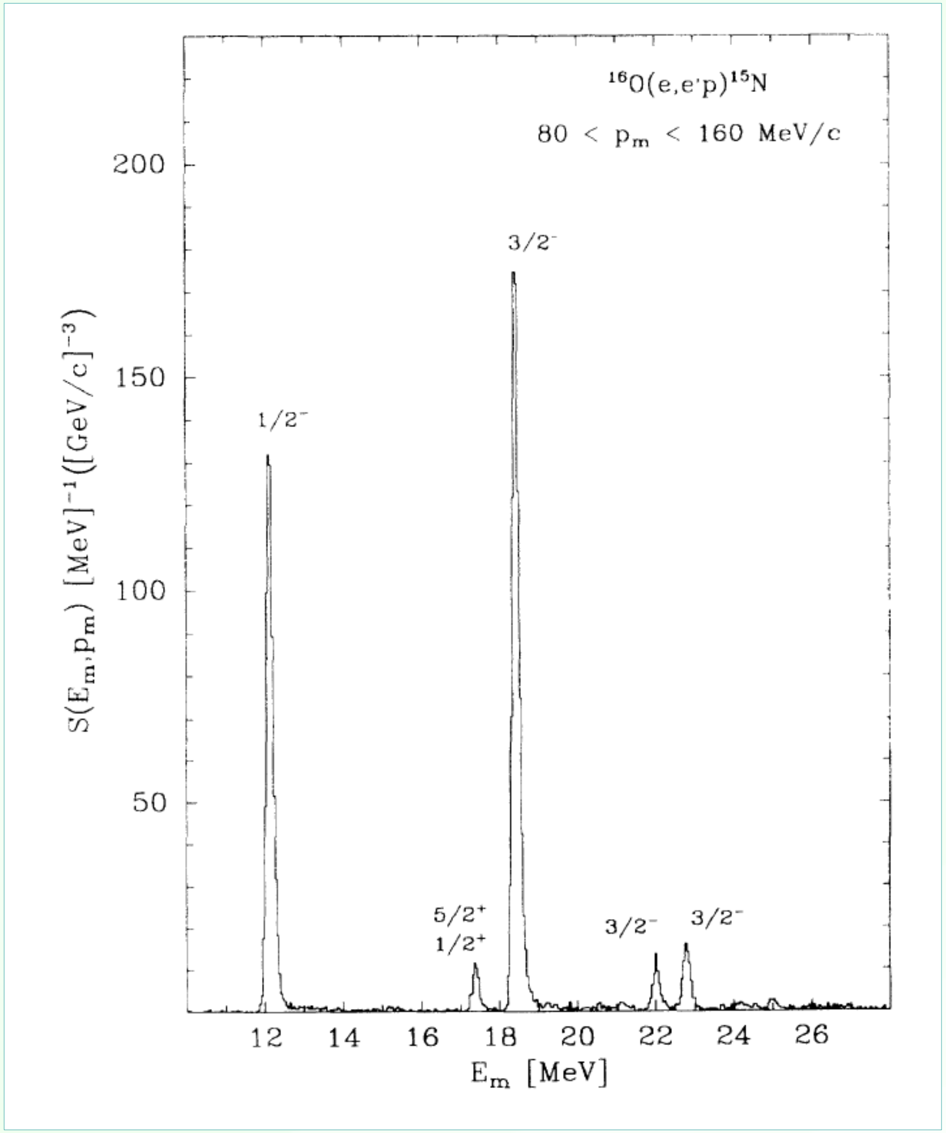
Example: oxygen nucleus

In a spherically symmetric potential, the eigenstates can be labeled using the total angular momentum.



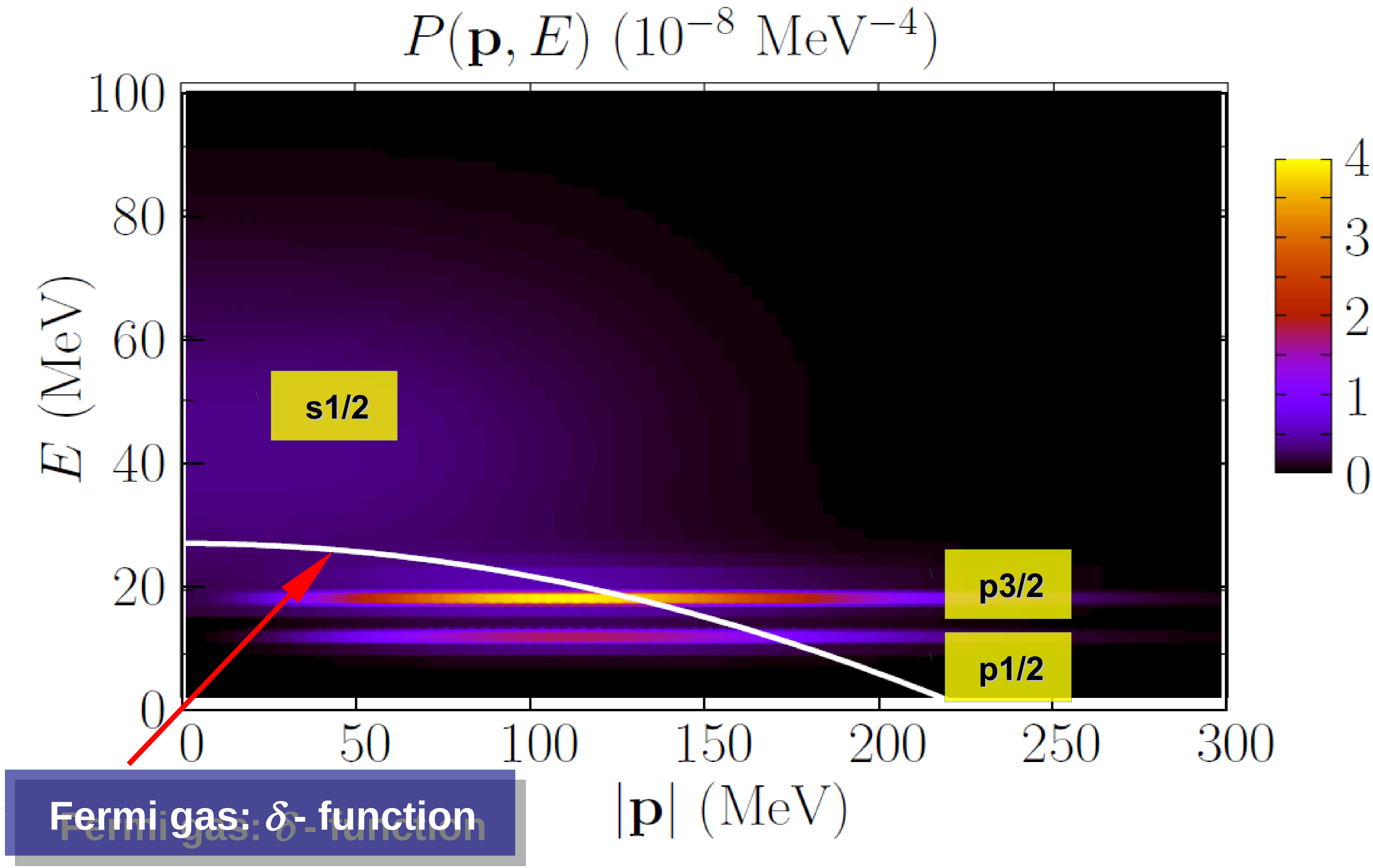
See e.g. Cohen, Concepts of Nuclear Physics, McGraw-Hill, 1791

Example: oxygen nucleus

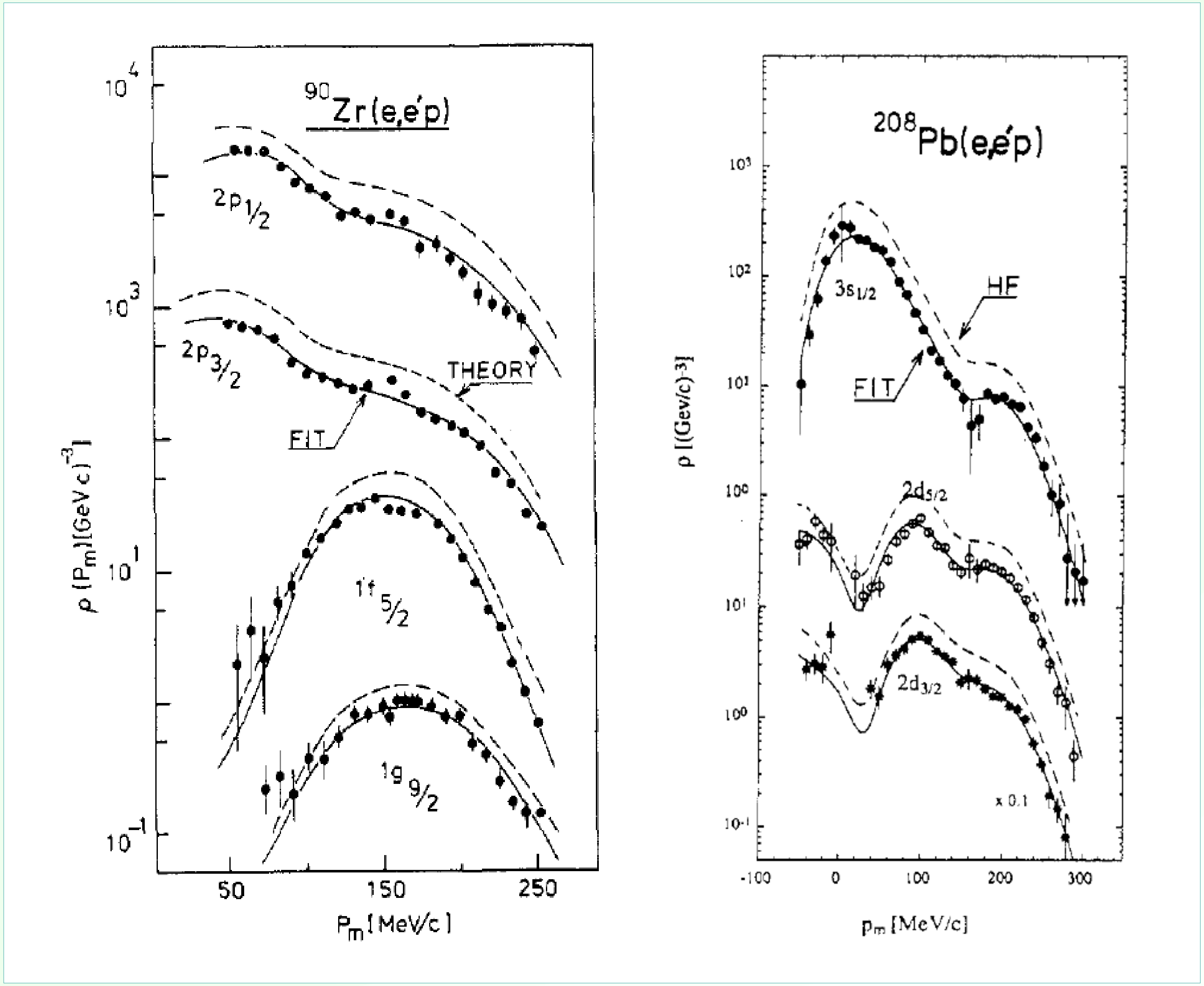


Leuschner *et al.*, PRC 49, 955 (1994)

Example: oxygen spectral function



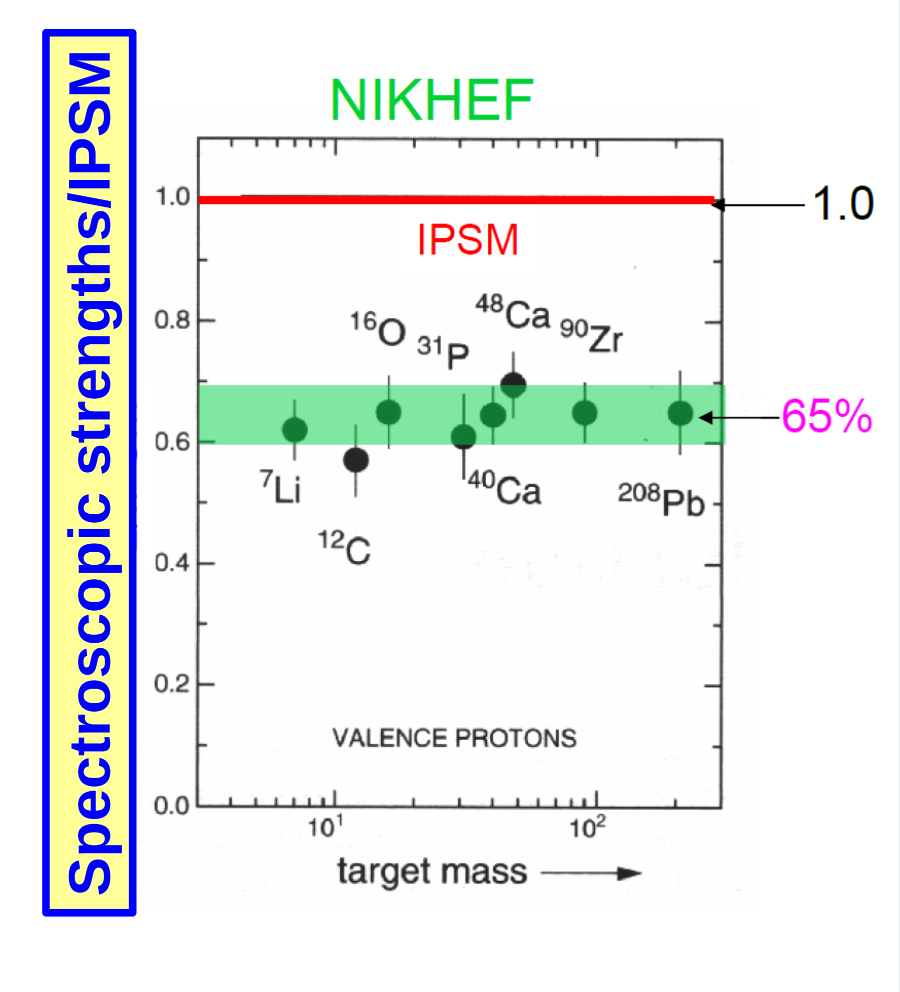
Depletion of the shell-model states



De Witt Huberts, JPG 16, 507 (1990)

Depletion of the shell-model states

The observed depletion is ~35% for the valence shells and ~20% overall, when higher missing energy is probed.



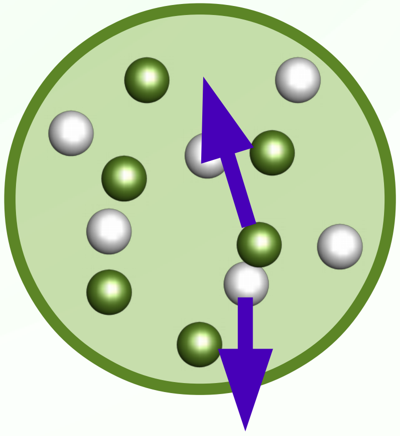
D. Rohe, NuInt05

Spectral function approach

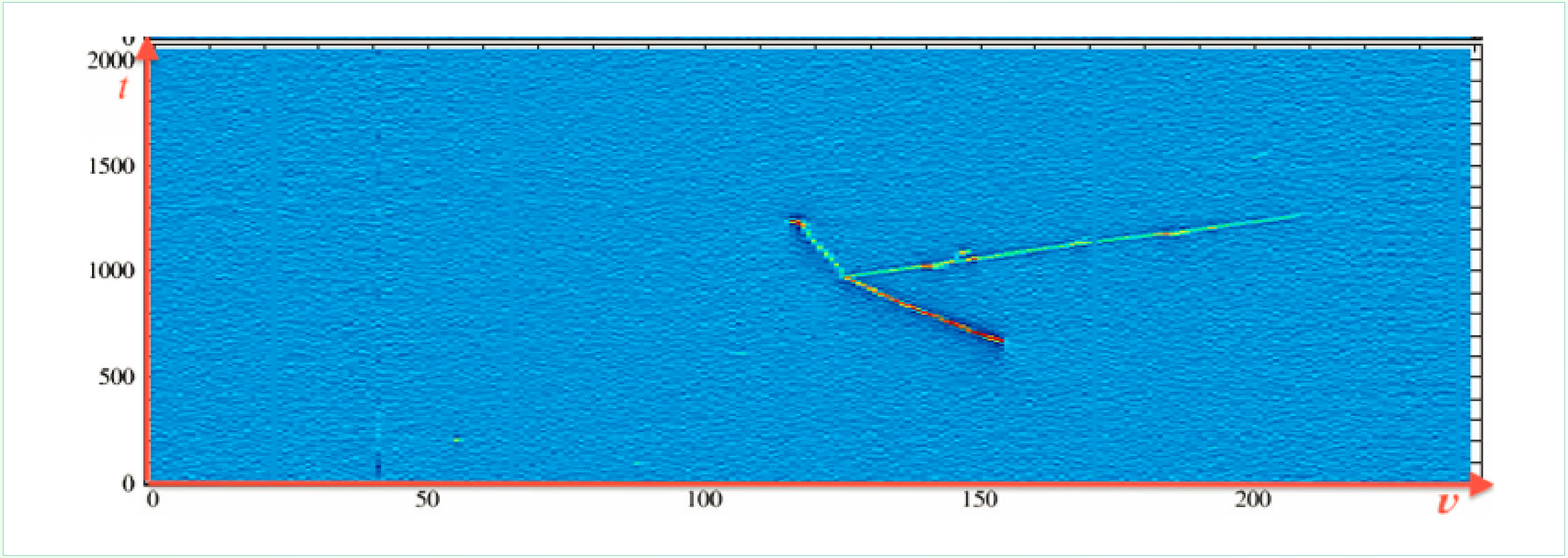
Short-range correlations

The main source of the depletion of the shell-model states are **short-range nucleon-nucleon correlations**.

Yielding NN pairs (typically pn pairs) with high relative momentum, they move ~20% of nucleons to the states of high removal energies.



Short-range correlations



Acciari *et al*. (ArgoNeuT), PRD 90, 012008 (2014)

Short-range correlations

The hole spectral function can be expressed as

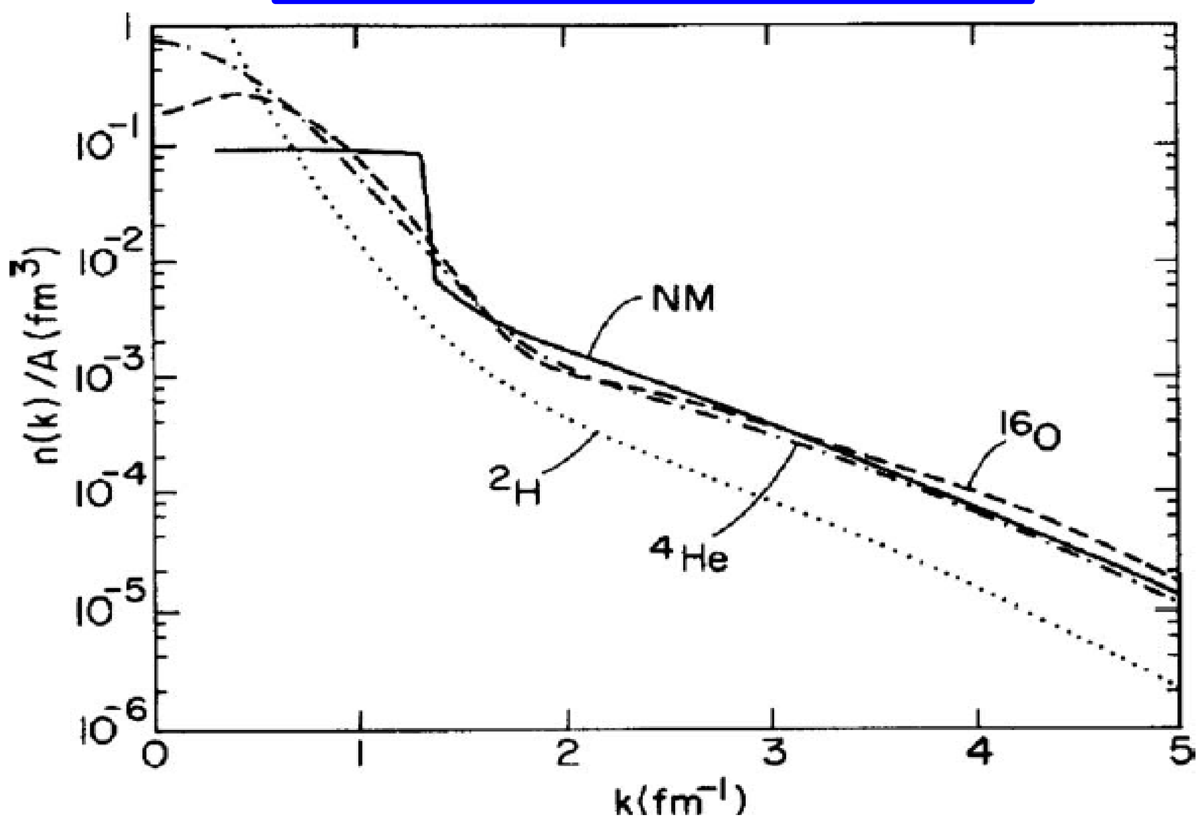
$$P_N(\mathbf{p}, E) = \underbrace{\sum_\alpha n_\alpha |\phi_\alpha|^2 f_\alpha(E - E_\alpha^N)} + \underbrace{P^N_{\rm corr}(\mathbf{p}, E)},$$

describes the contribution
of the shell-model states,
vanishes at high |p| or high *E*

relevant only
at high |p| **and** *E*

Short-range correlations

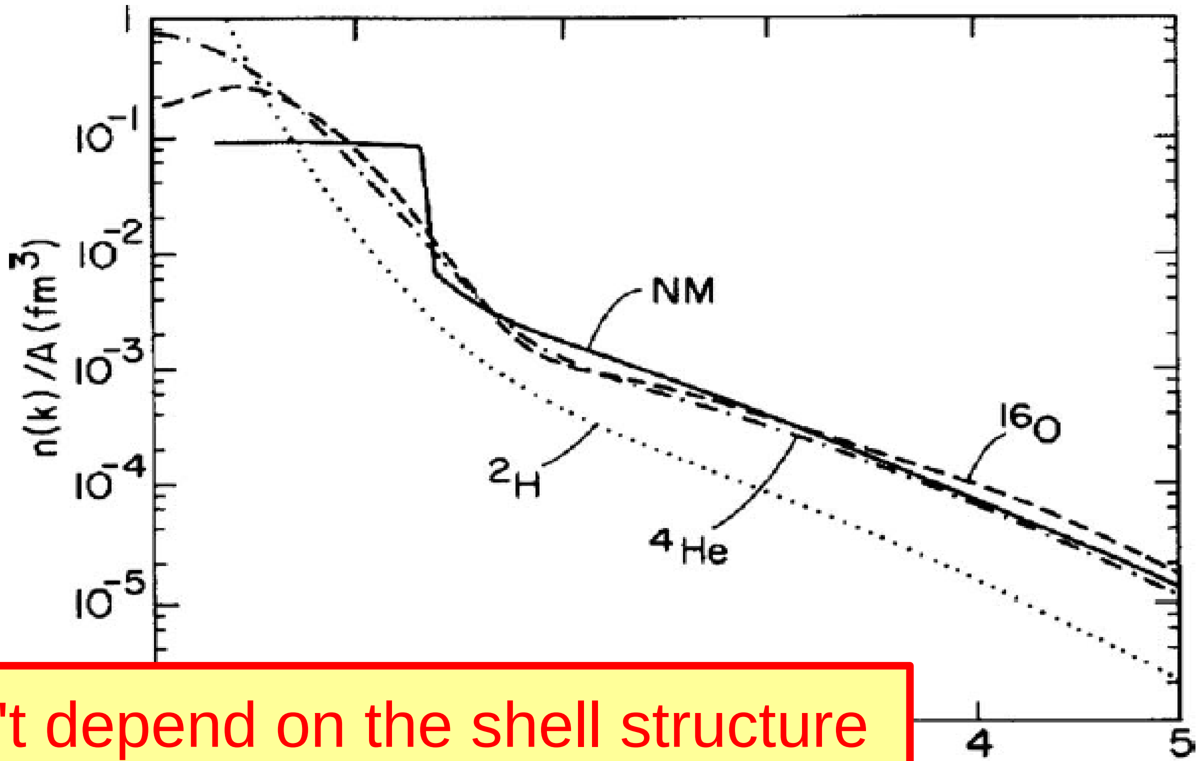
Momentum distributions



Benhar&Pandharipande, RMP 65, 817 (1993)

Short-range correlations

Momentum distributions

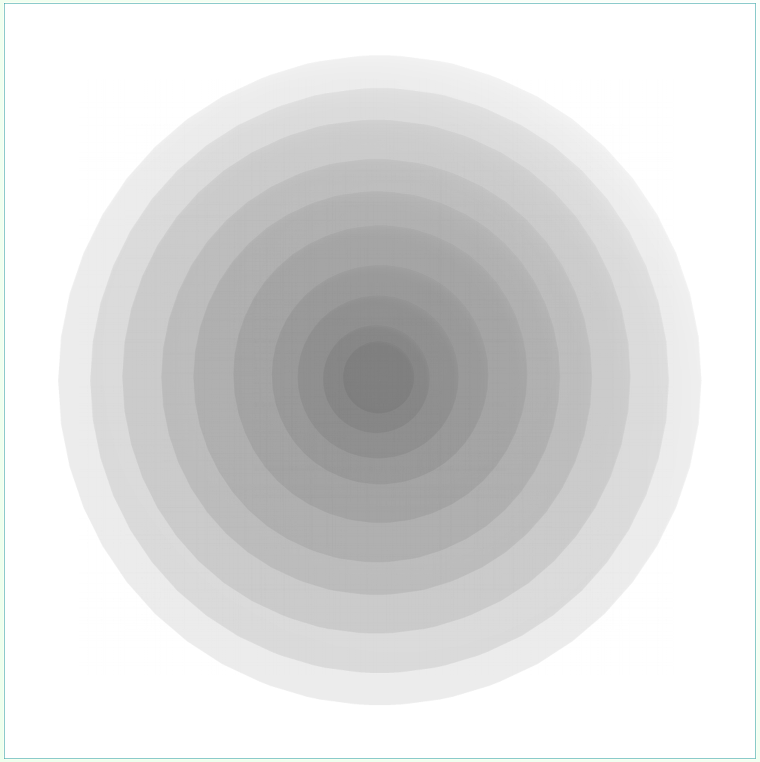


SRC don't depend on the shell structure
or finite-size effects, only on the density

Benhar&Pandharipande, RMP 65, 817 (1993)

Local-density approximation

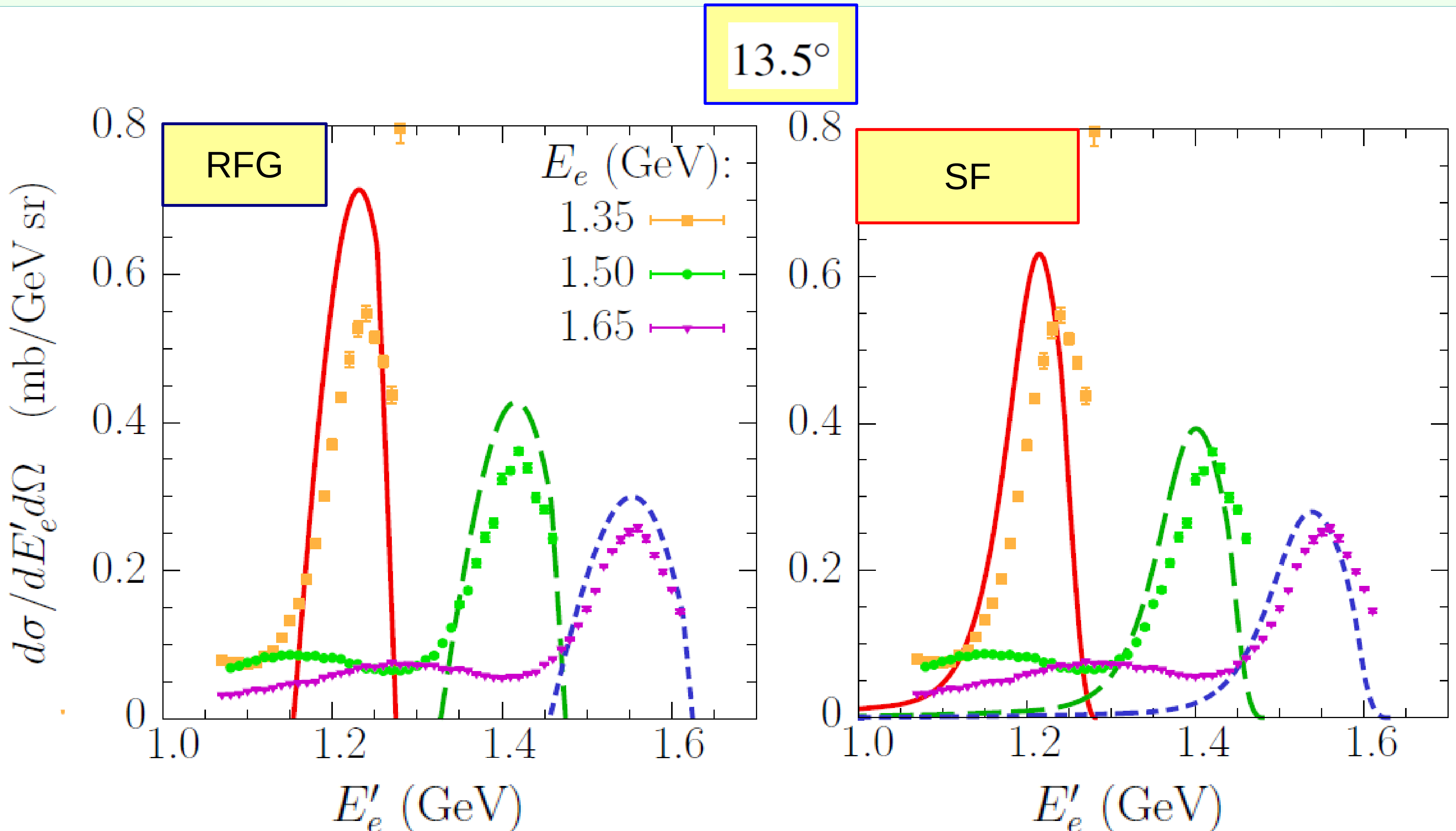
The correlation component in nuclei can be obtained combining the results for infinite nuclear matter obtained at different densities:



$$P^{N}_{\rm corr}(\mathbf{p}, E) = \int dR\, \rho(R) P^{NM,N}_{\rm corr}(\rho, \mathbf{p}, E).$$

Benhar *et al.*, NPA 579 493, (1994)

Comparison to C(*e*,*e*′) data



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

Final-state interactions

Their effect on the cross section is easy to understand in terms of the complex optical potential:

- the **real part** modifies the struck nucleon's energy spectrum: it differes from $\sqrt{M^2 + \boldsymbol{p}'^2}$
- the **imaginary part** reduces the single-nucleon final states and produces multinucleon final states

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

Horikawa *et al.*, PRC 22, 1680 (1980)

Energy conservation

$$E_{\mathbf{k}} + M_A = E_{\mathbf{k}'} + E_{A-1} + E_{\mathbf{p}'}$$

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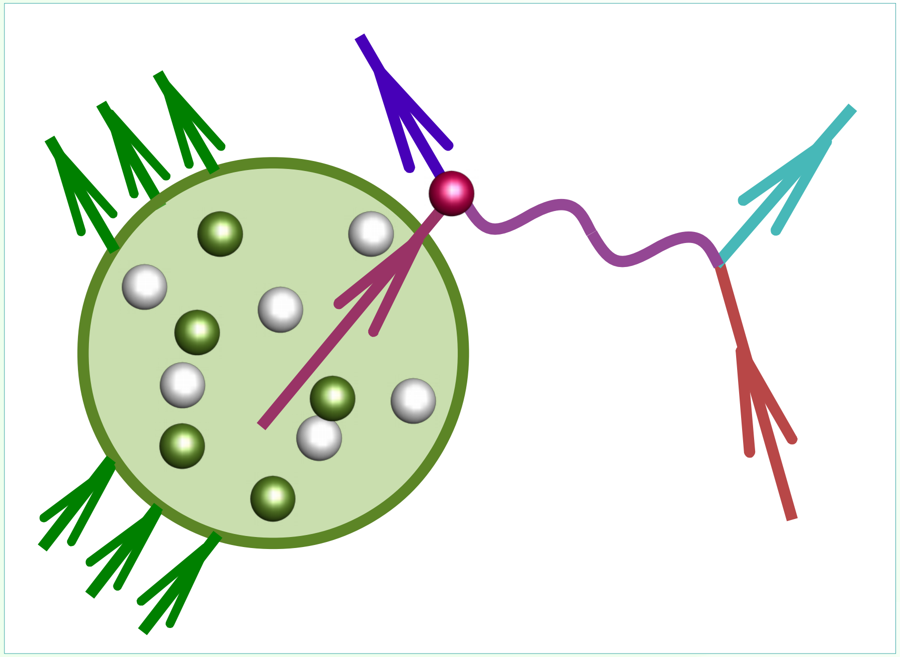

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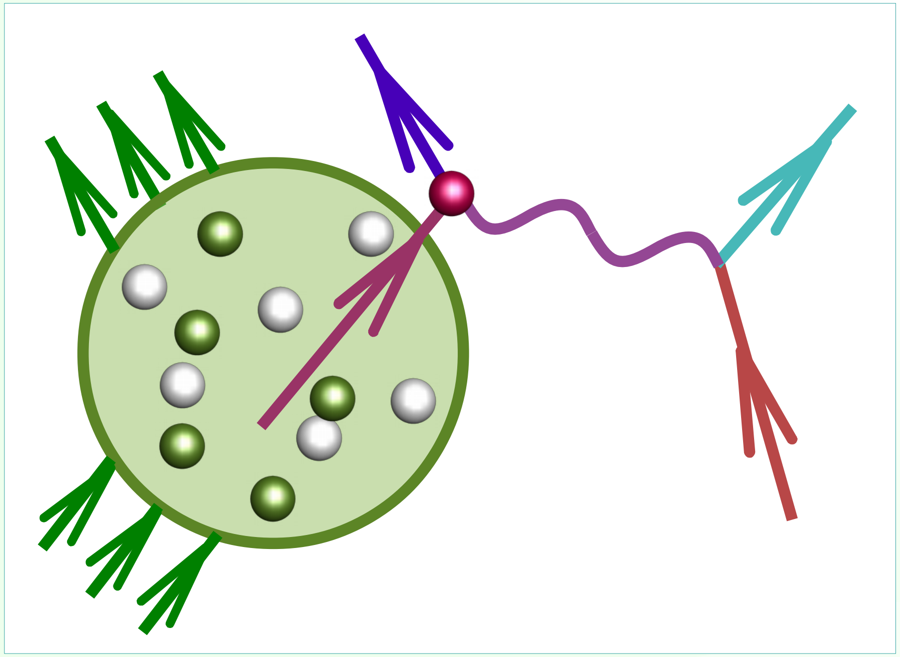
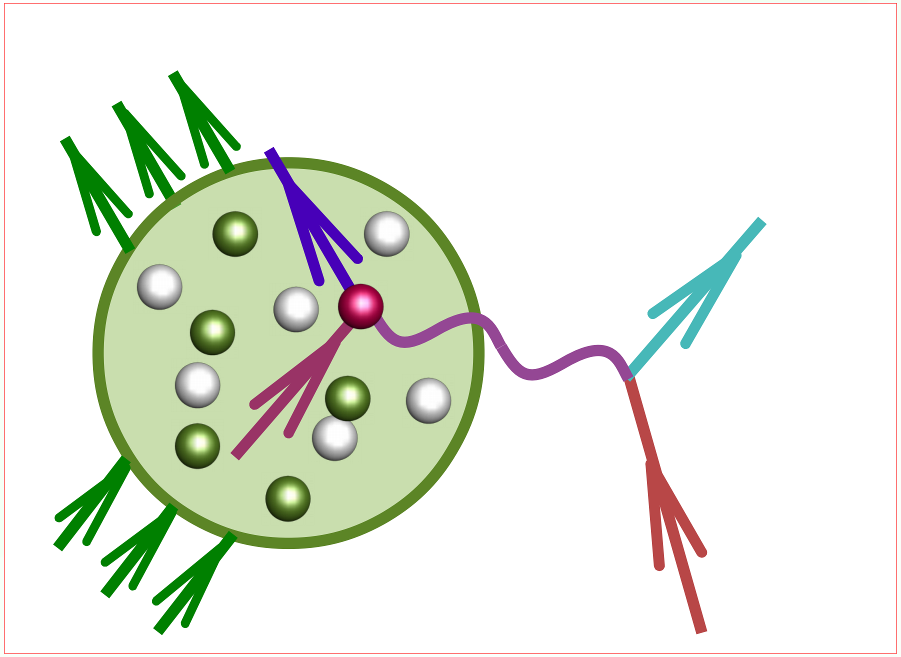
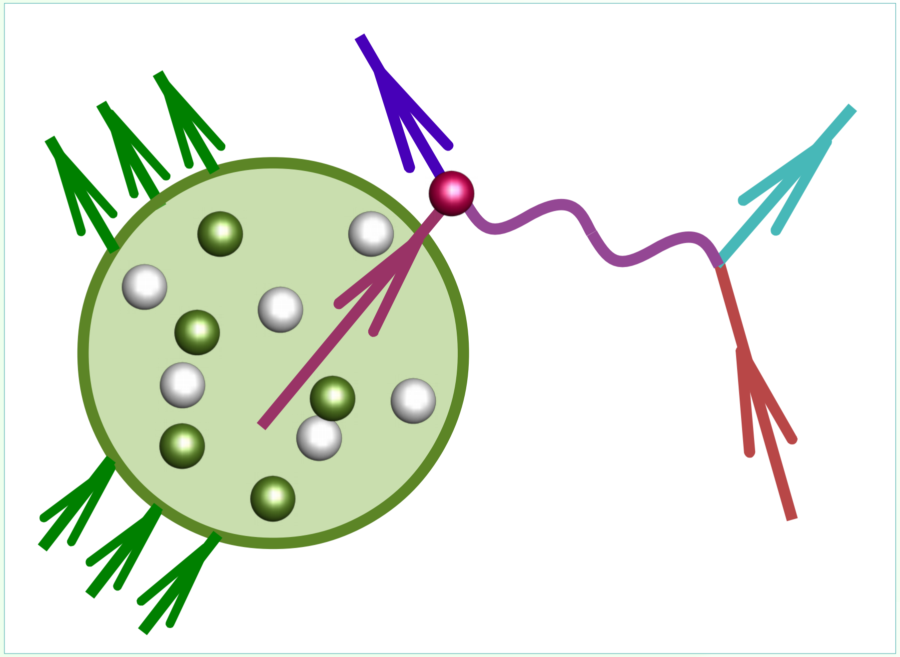


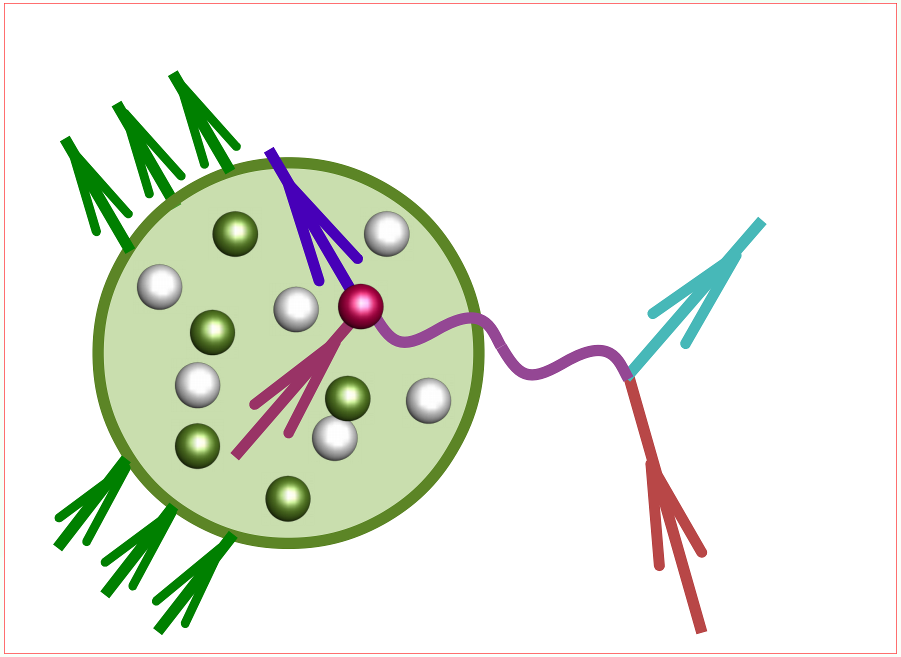


Energy conservation

$$E_{\mathbf{k}} + M_A = E_{\mathbf{k}'} + E_{A-1} + E_{\mathbf{p}'}$$

$$E_{\mathbf{k}} + M_A = E_{\mathbf{k}'} + E_{A-1} + E_{\mathbf{p}'} + U_V(\mathbf{p}')$$

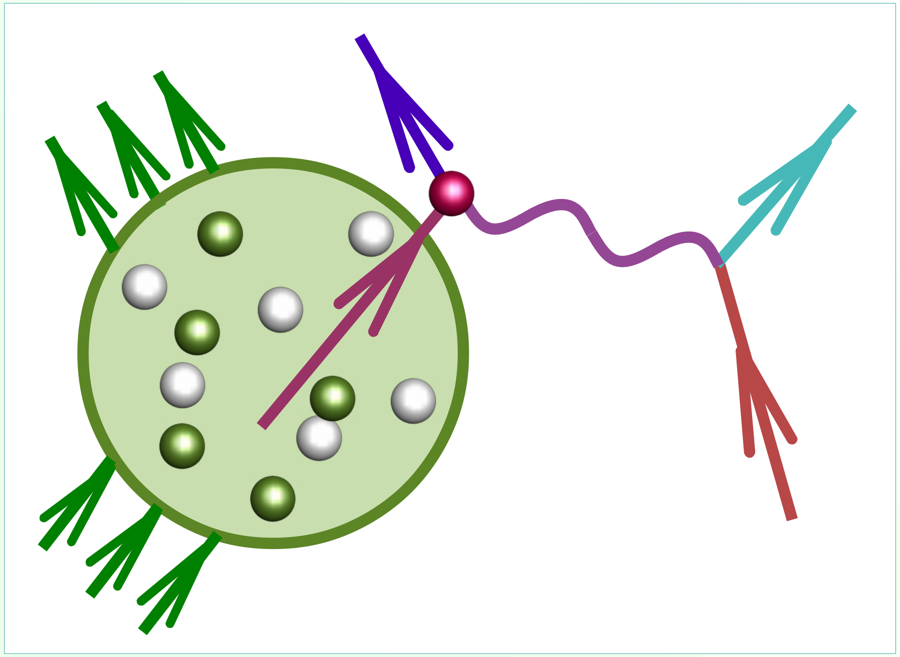


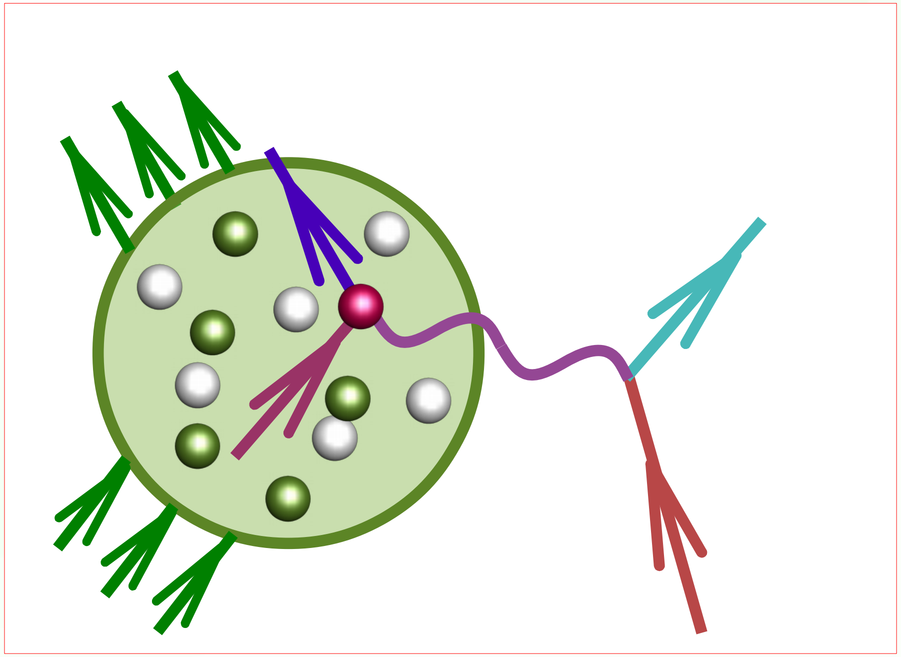


Energy conservation

$$E_{\mathbf{k}} + M_A = E_{\mathbf{k}'} + E_{A-1} + E_{\mathbf{p}'}$$

$$E_{\mathbf{k}} + M_A \boxed{\sim} E_{\mathbf{k}'} + E_{A-1} + E_{\mathbf{p}'} + U_V(\mathbf{p}')$$





Final-state interactions

In the convolution approach,

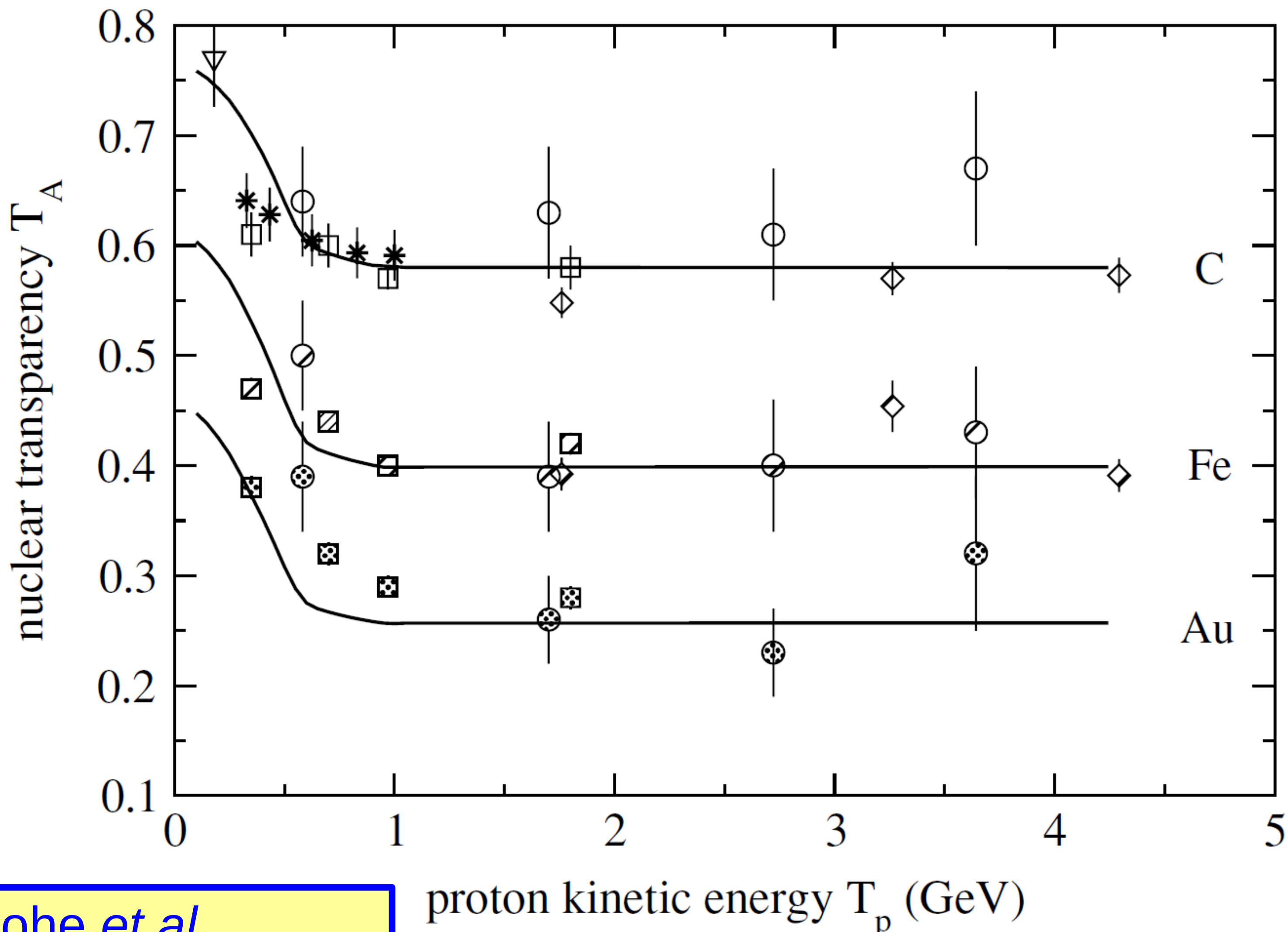
$$\frac{d\sigma^{\rm FSI}}{d\omega d\Omega} = \int d\omega' f_{\mathbf{q}}(\omega - \omega') \frac{d\sigma^{\rm IA}}{d\omega' d\Omega},$$

with the folding function

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

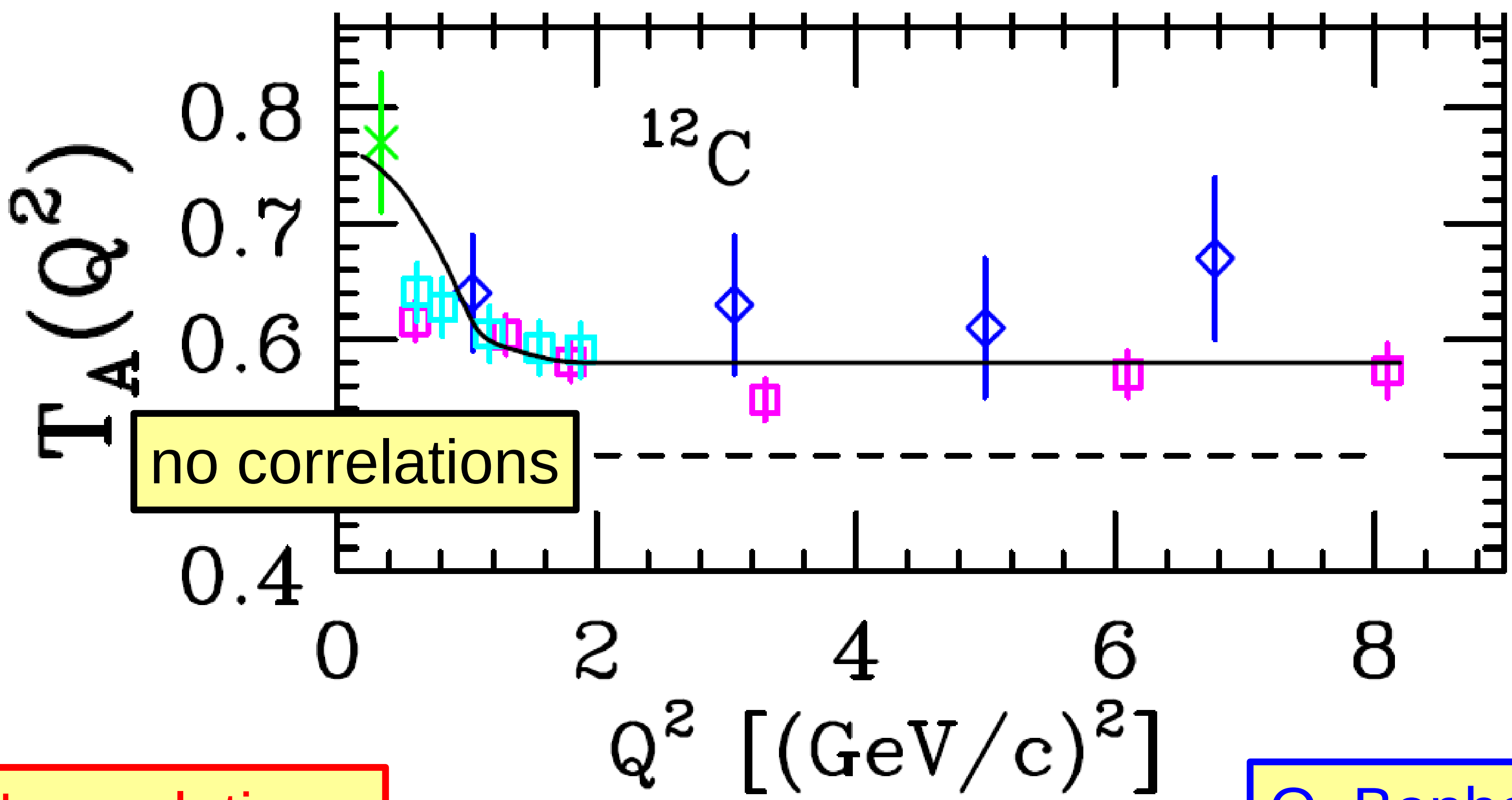
Nucl. transparency

Nuclear transparency



Rohe *et al.*,
PRC 72, 054602 (2005)

Nuclear transparency

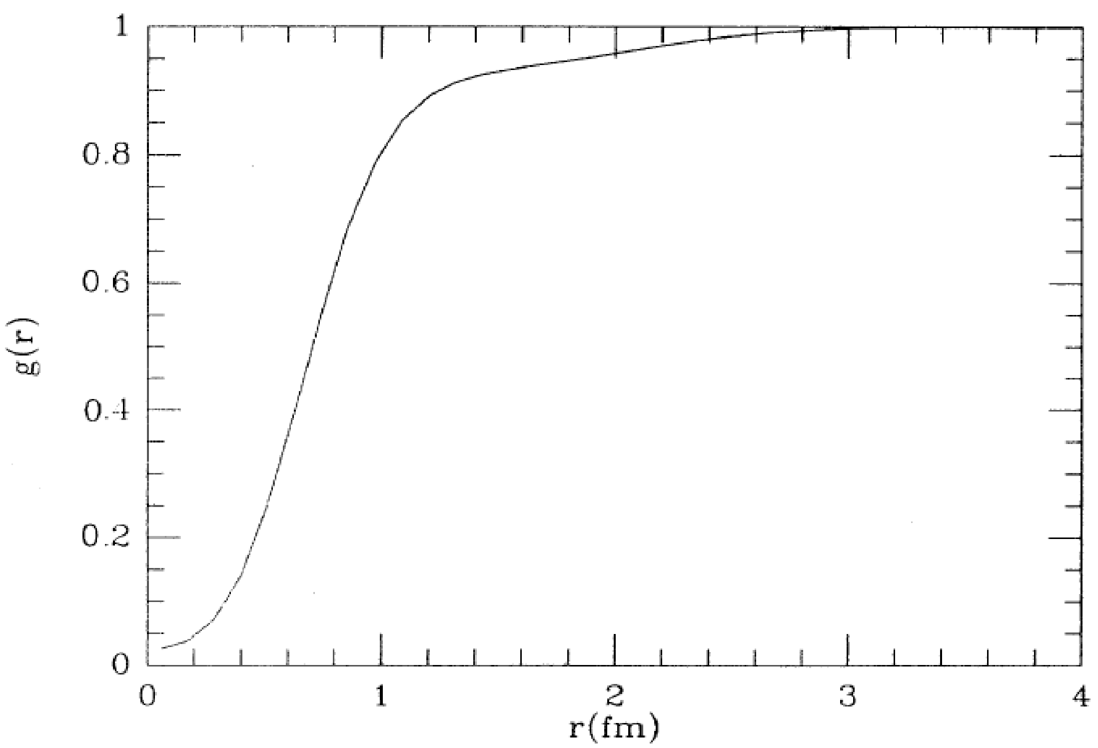


NN correlations
reduce FSI

O. Benhar
@ NuInt05

Short-range correlations

Pair distribution function of NM



Benhar *et al.*, PRC 44, 2328 (1991)

Real part of the optical potential

We account for the spectrum modification by

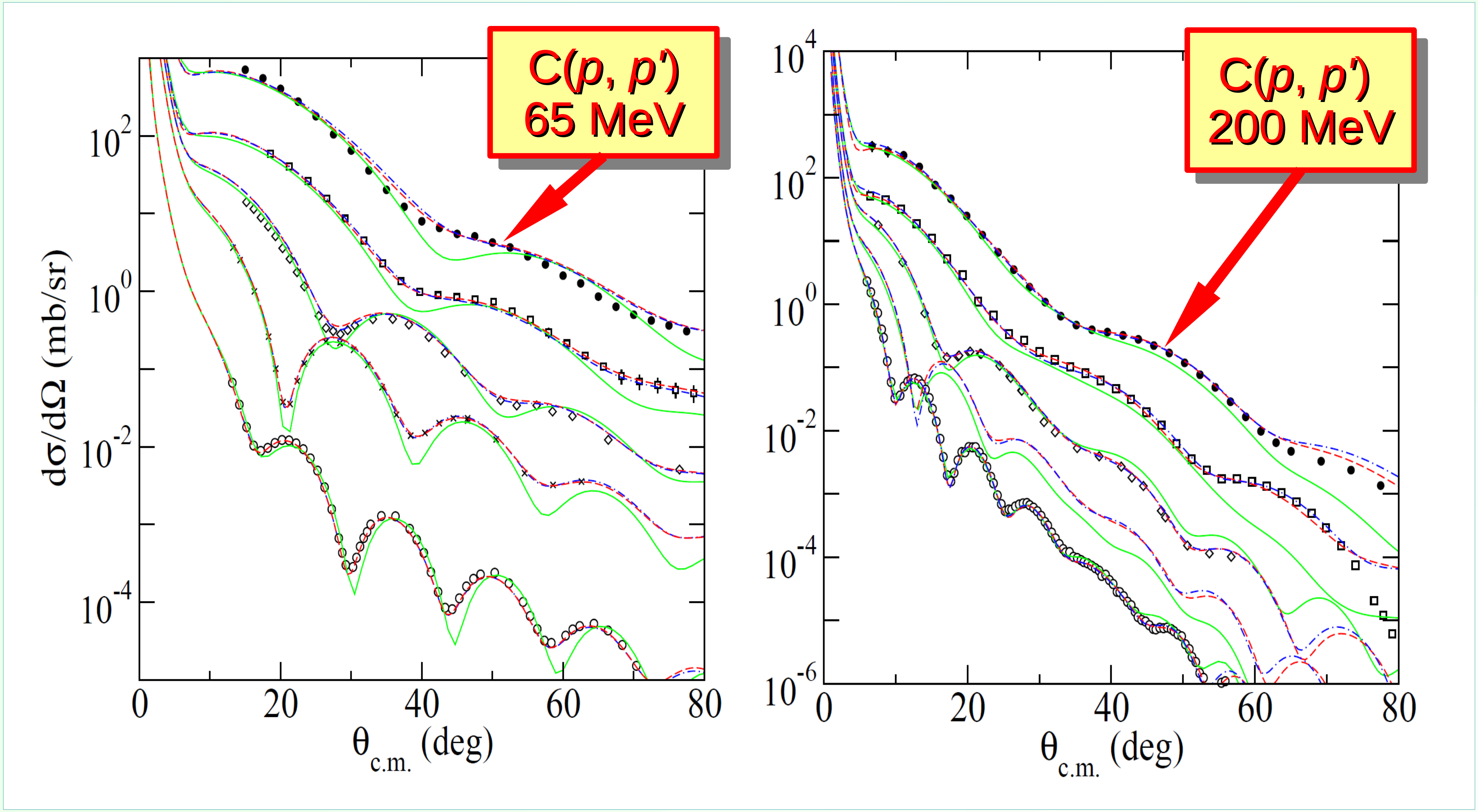
$$\boxed{f_{\mathbf{q}}(\omega - \omega') \to f_{\mathbf{q}}(\omega - \omega' - U_V).}$$

This procedure is similar to that from the Fermi gas model to introduce the binding energy in the argument of $\delta(...)$.

$$\boxed{U_V = U_V(t_{\mathrm{kin}})}$$

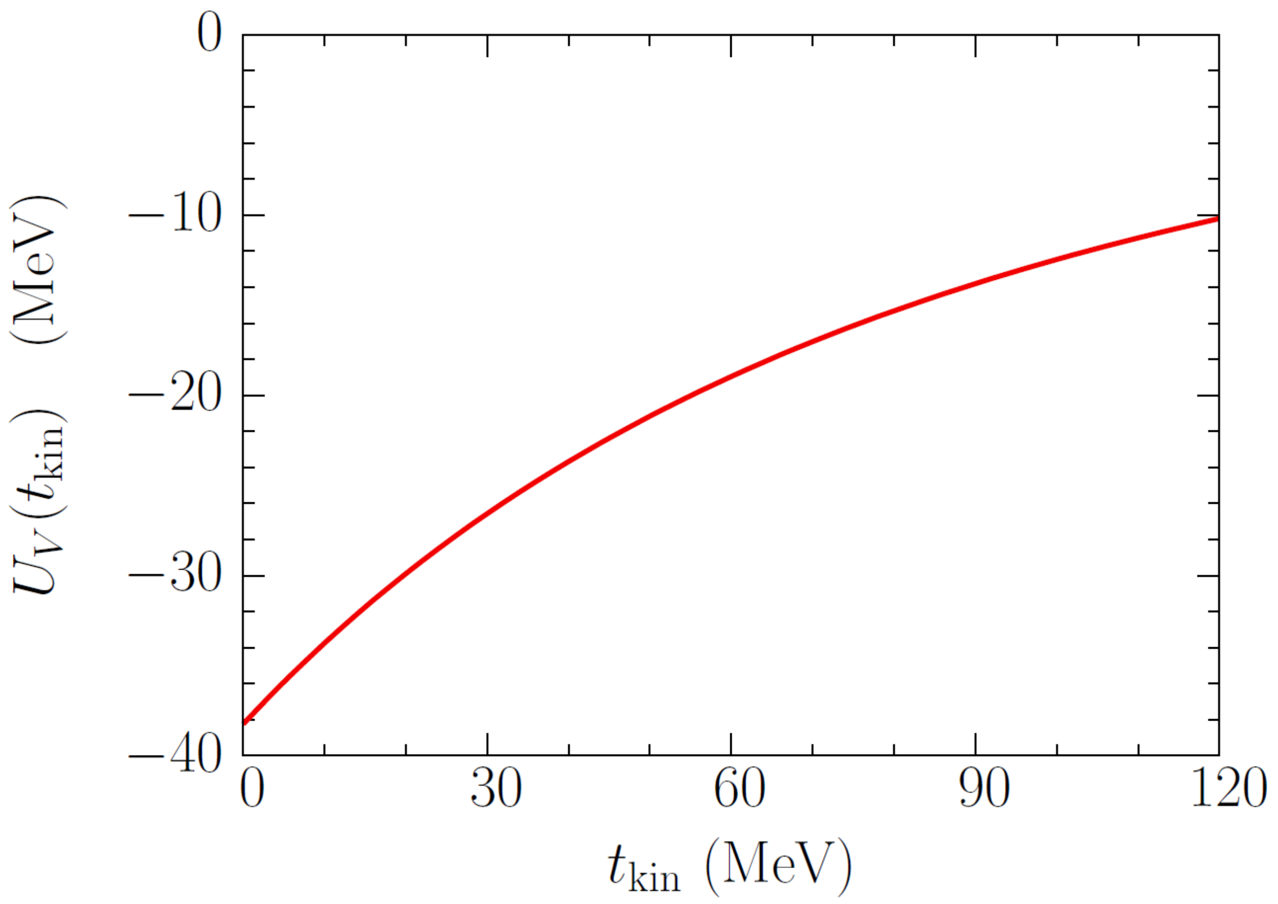
$$\boxed{t_{\mathrm{kin}} = \frac{E_{\mathbf{k}}^2(1-\cos\theta)}{M + E_{\mathbf{k}}(1-\cos\theta)}}$$

Optical potential by Cooper *et al.*



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

Optical potential by Cooper *et al.*



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

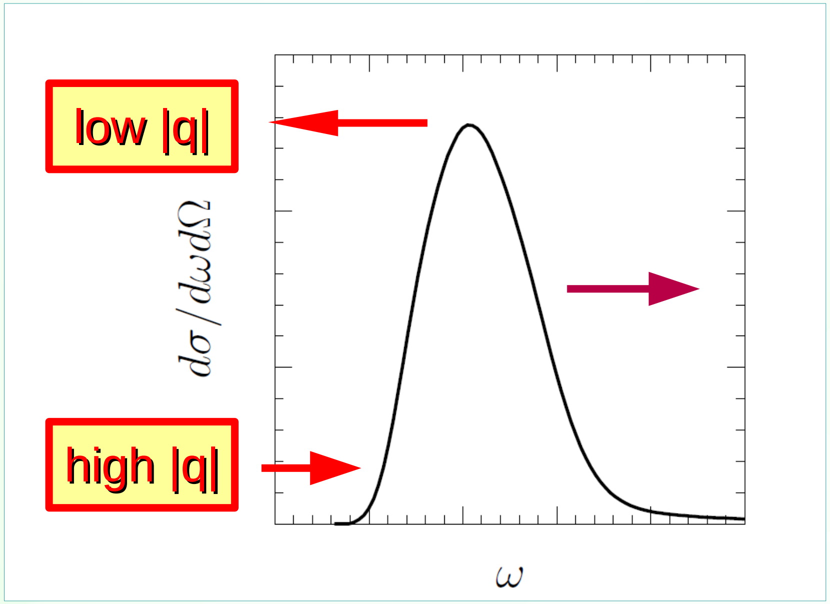
Simple comparison

Real part of the OP

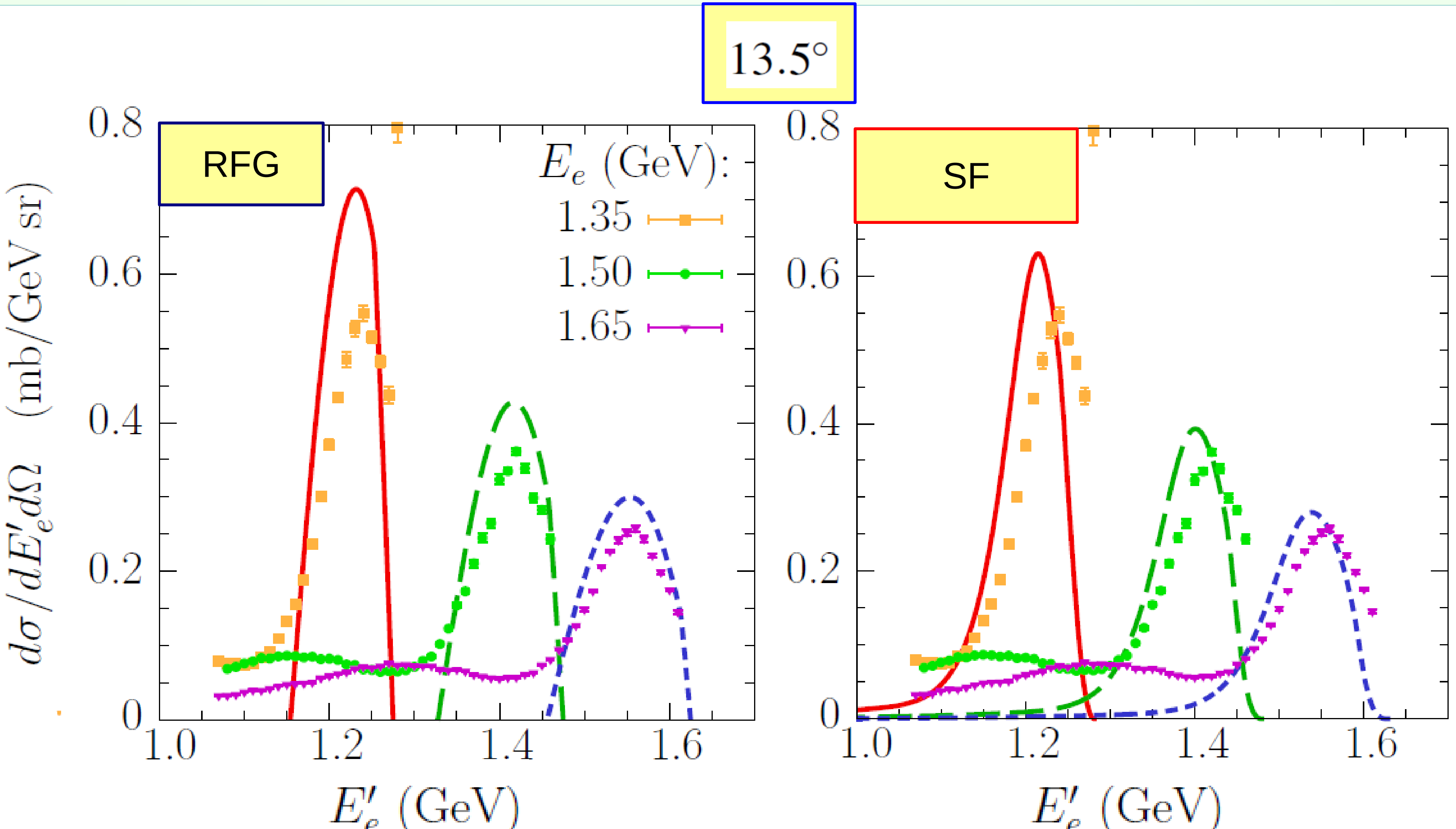
- acts in the final state
- shifts the QE peak
  to low ω at low $|\mathbf{q}|$
  (to high ω at high $|\mathbf{q}|$)

Binding energy in RFG

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

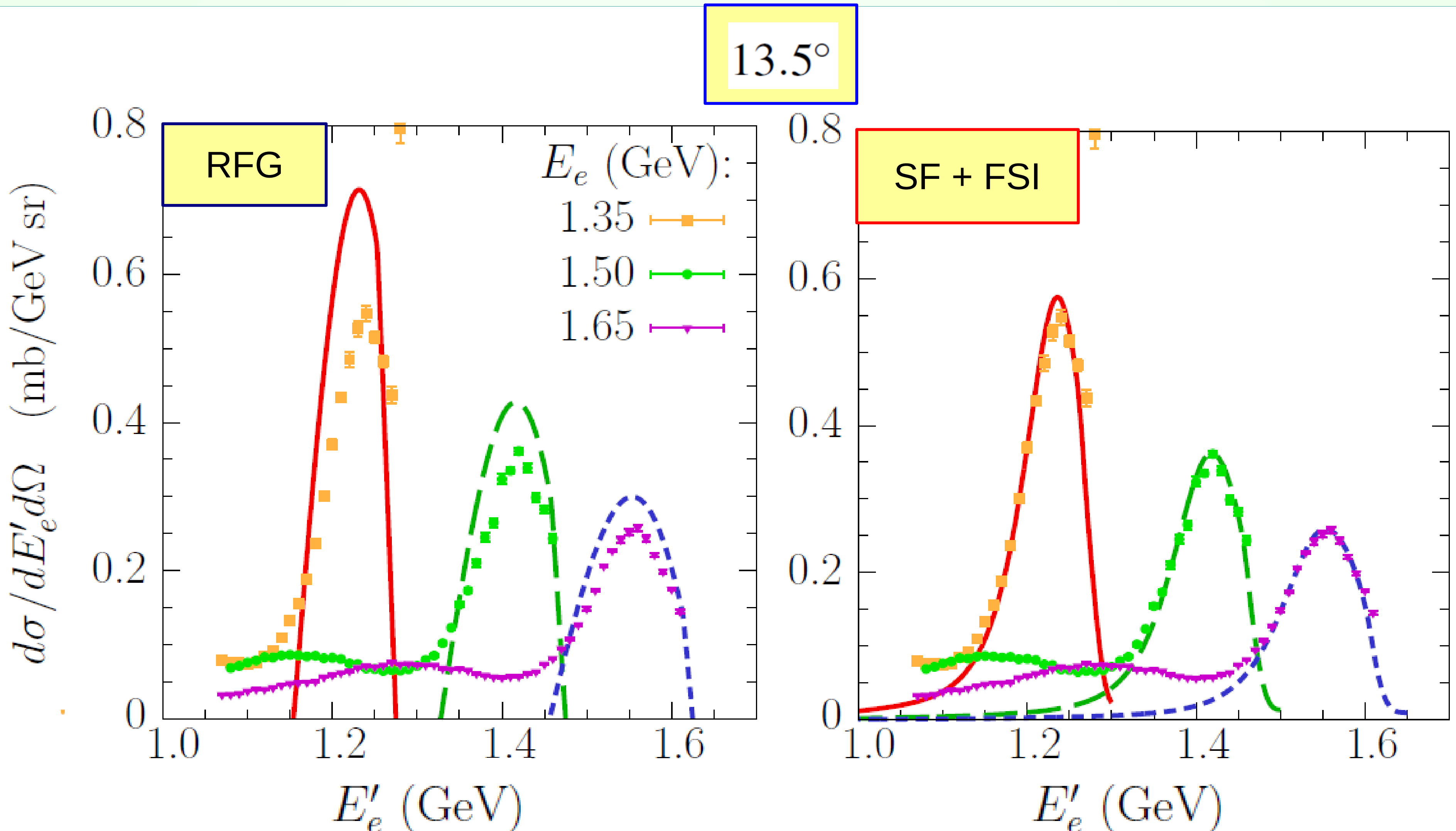


Comparison to C(e,e') data



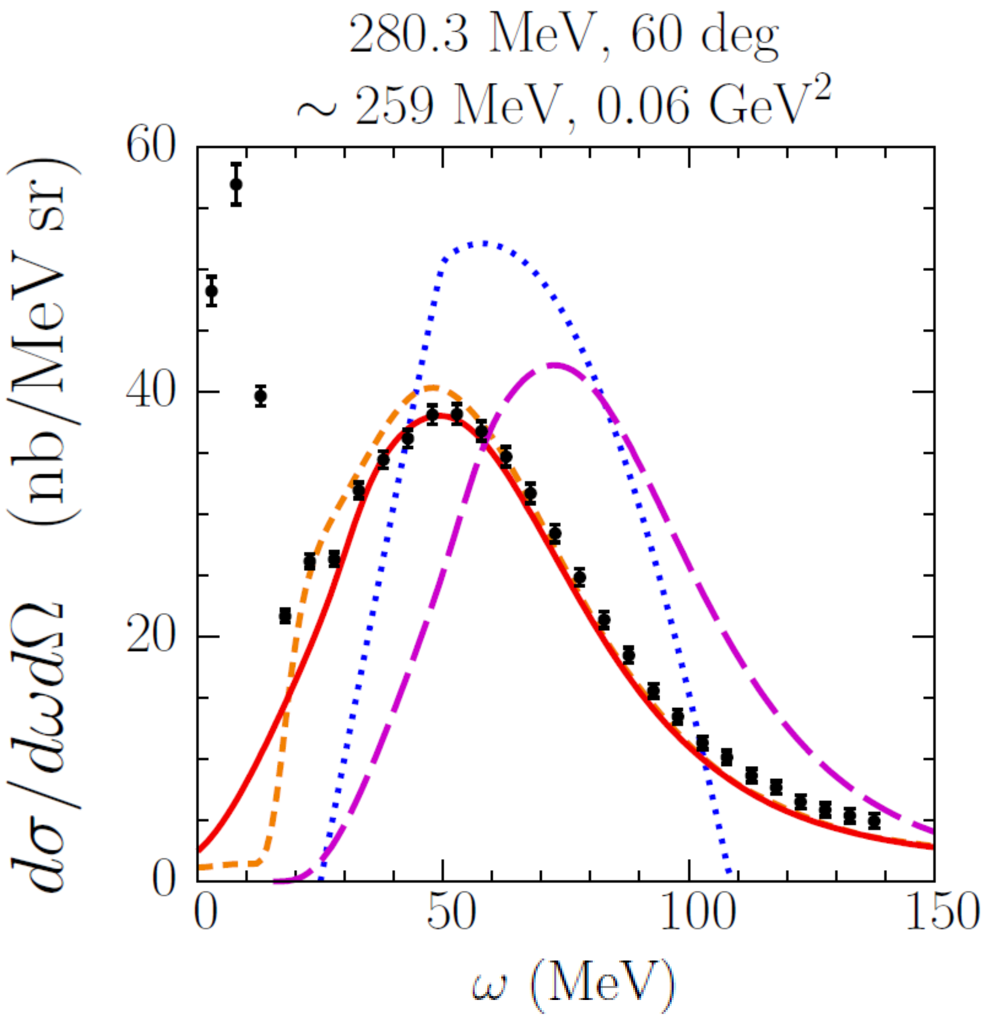
data: Baran *et al.*,
PRL 61, 400 (1988)

Comparison to C(*e*,*e*′) data



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

Compared calculations



RFG model
ε = 25 MeV
p_F = 221 MeV

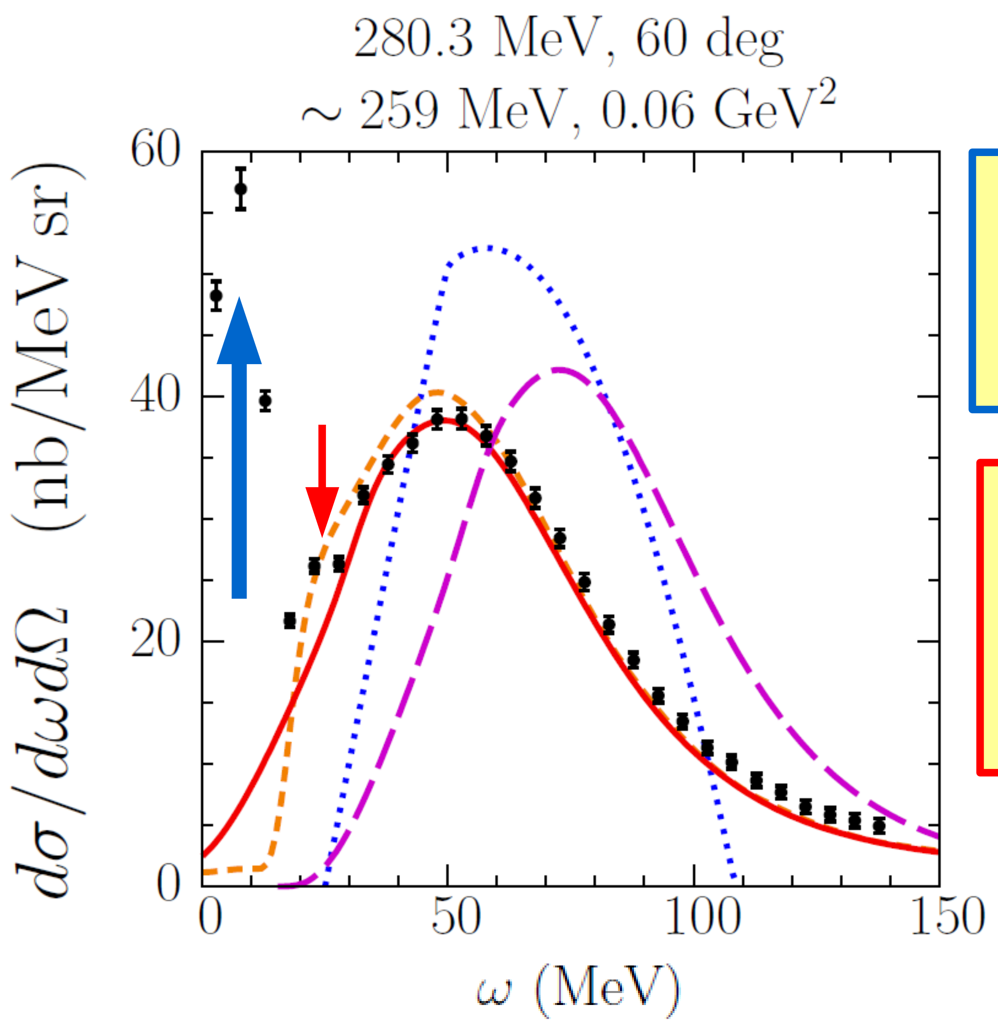
SF calculation without FSI

SF calculation, LDA treatment of Pauli blocking

SF calculation, step function

Low excitation-energy phenomena

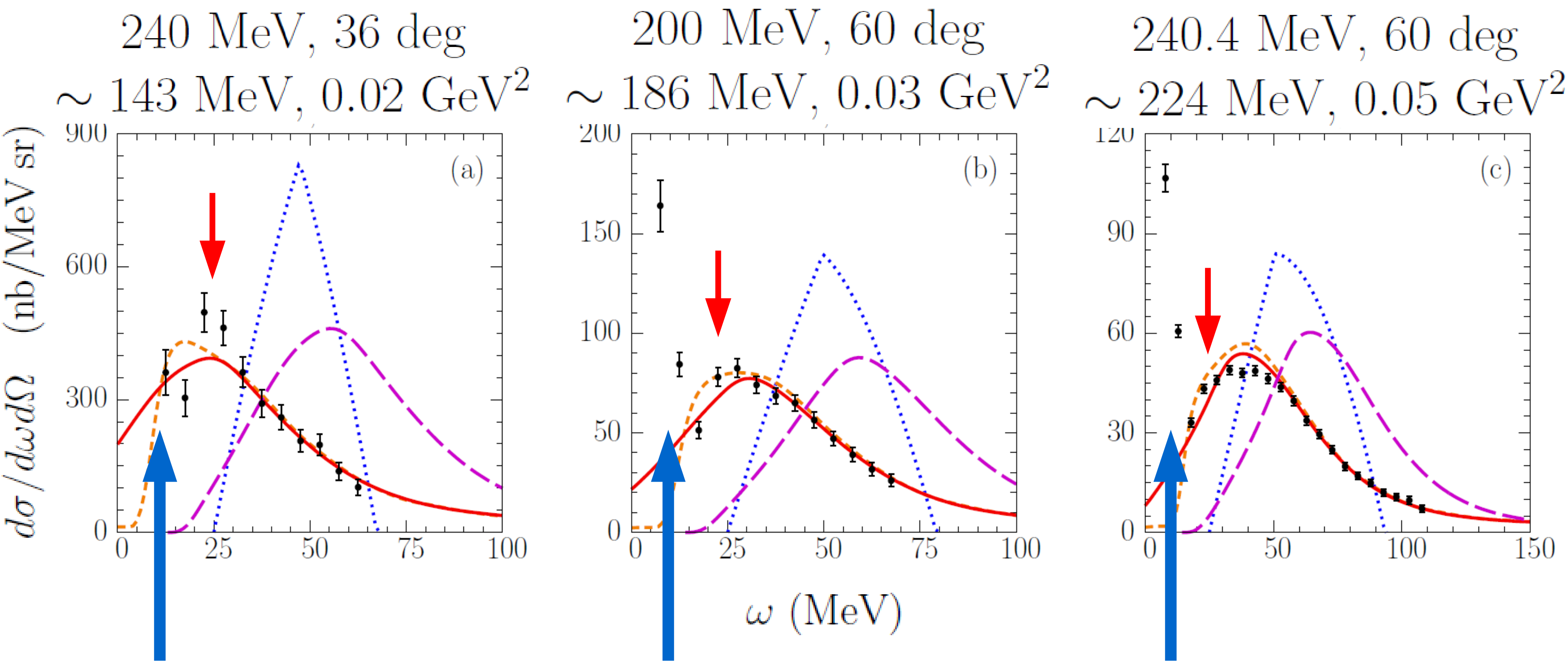
Calcs. include QE by 1-body current only



Elastic scattering and excitation of low-E_x levels

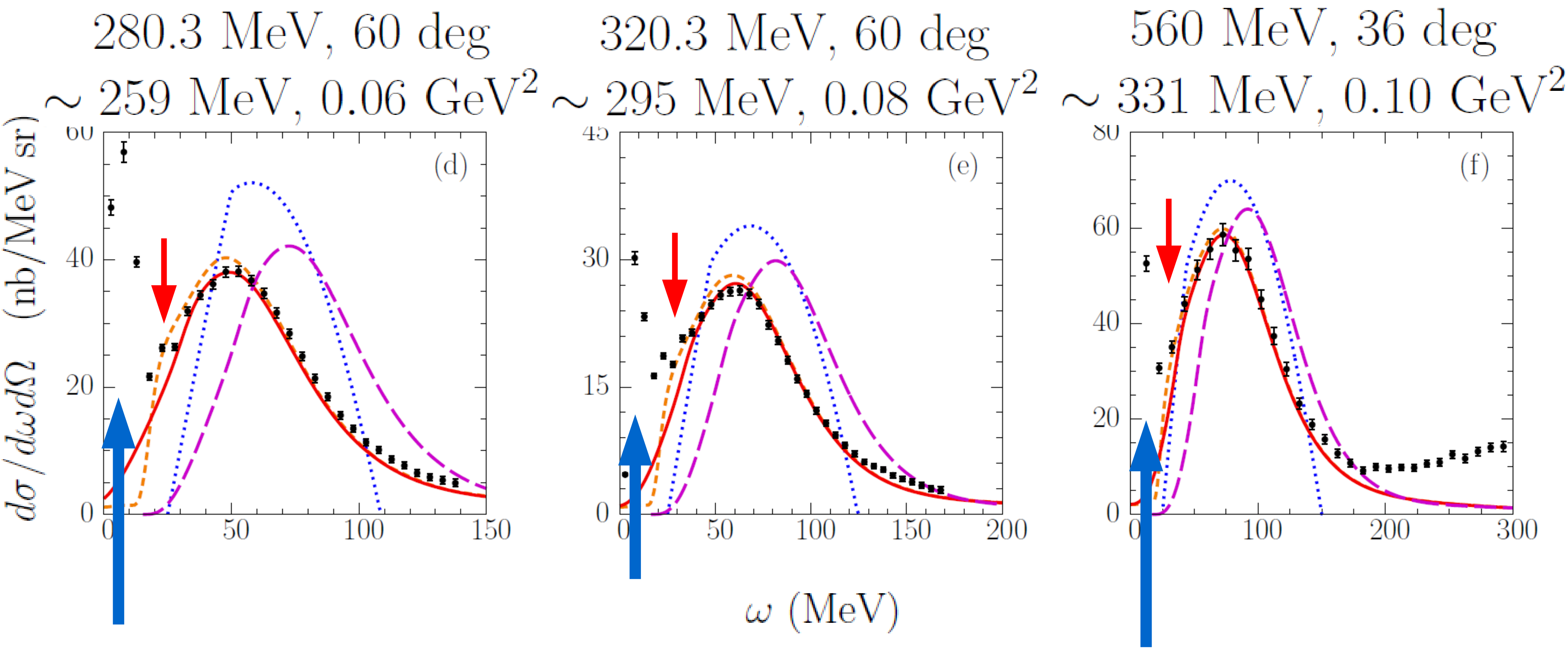
Giant resonance
E_x = 22.6 MeV,
Γ = 3.2 MeV

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



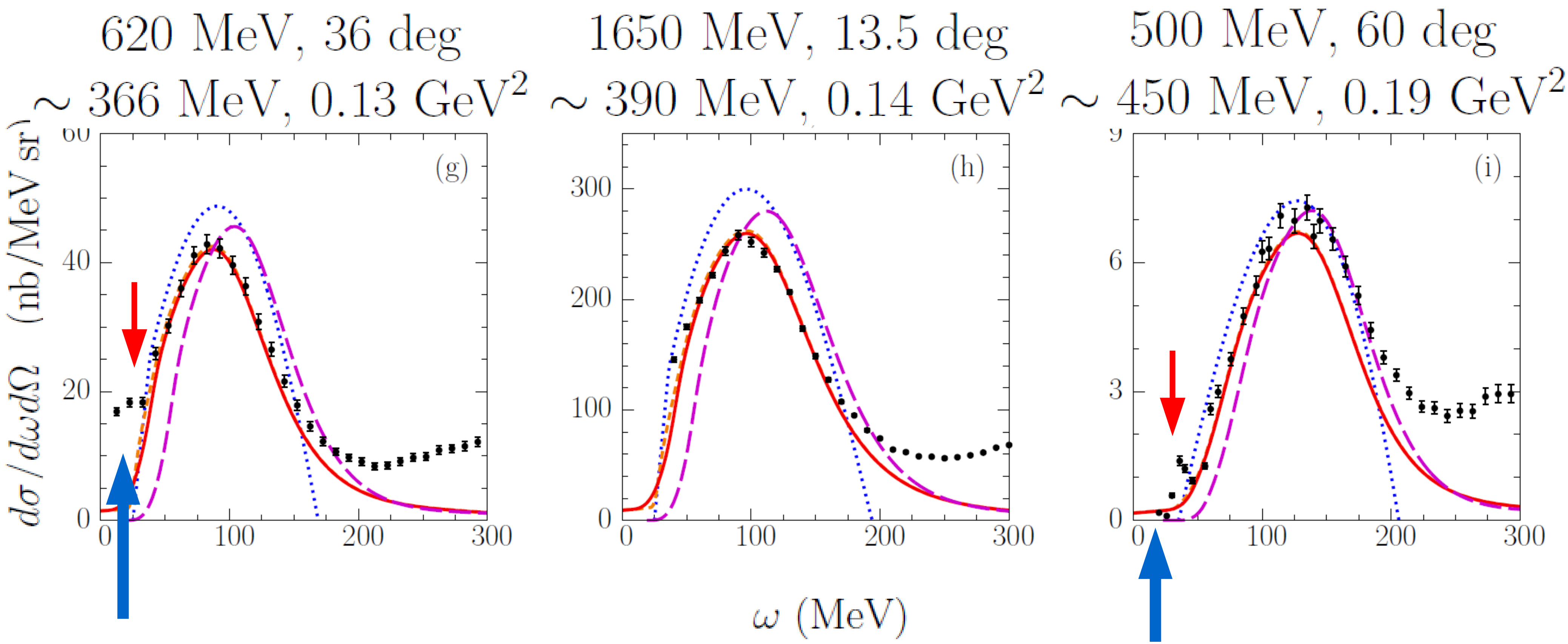
Barreau *et al.*,
NPA 402, 515 (1983)

Comparisons to C(e,e') data



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

Comparisons to C(*e*,*e*′) data



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

The supplemental material of PRD 91,033005 (2015) shows comparisons to the data sets collected at **54 kinematical setups**

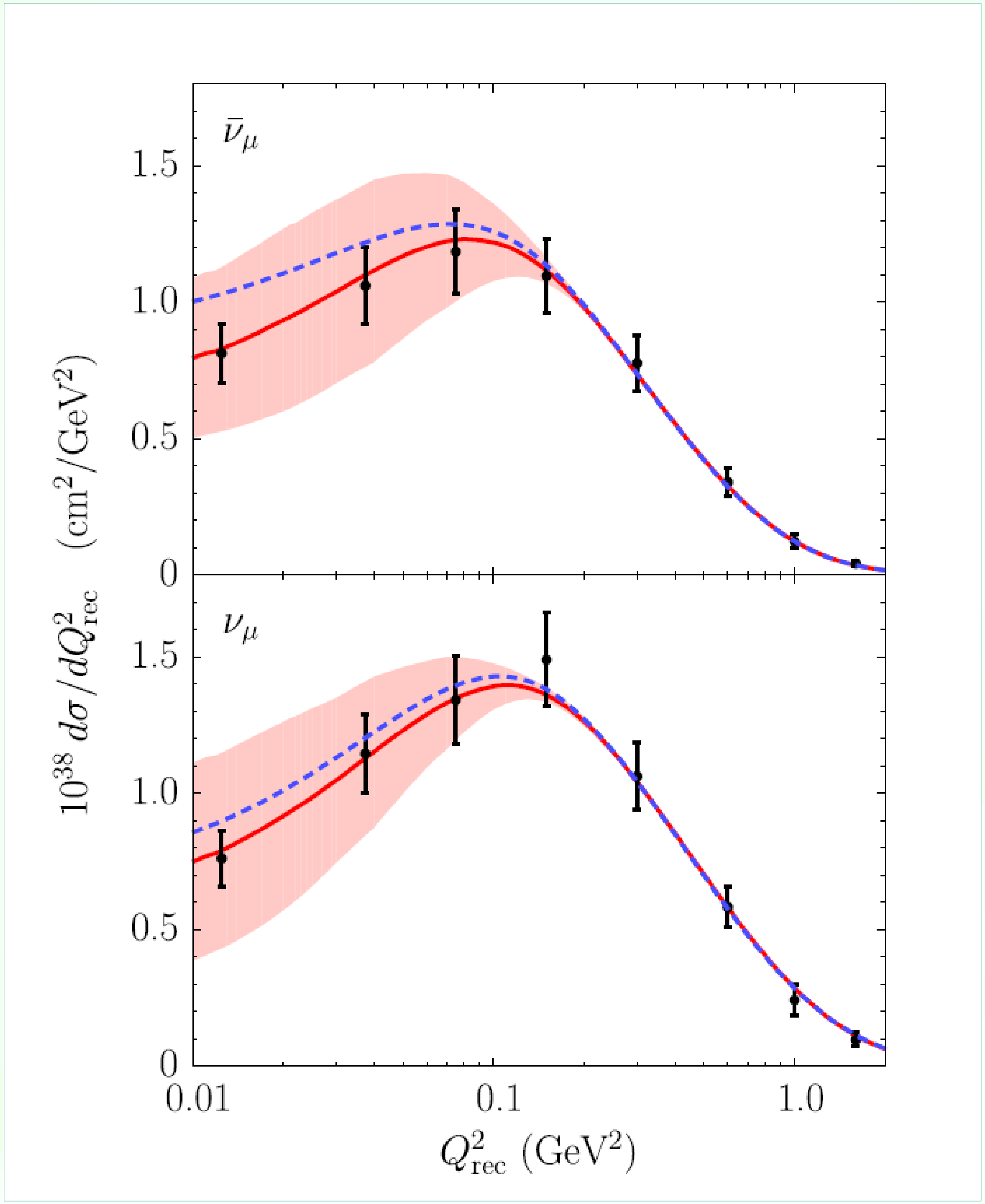
- energies from ~160 MeV to ~4 GeV,
- angles from 12 to 145 degrees,
- at the QE peak, the values of momentum transfer from ~145 to ~1060 MeV/c and $0.02 \leq Q^2 \leq 0.86$ (GeV/c)^2 .

CCQE MINERvA data

SF calculations with FSI

vs.

SF calculation without FSI



Fields *et al.*, PRL 111, 022501 (2013)

A.M. A, PRD 92, 013007 (2015)

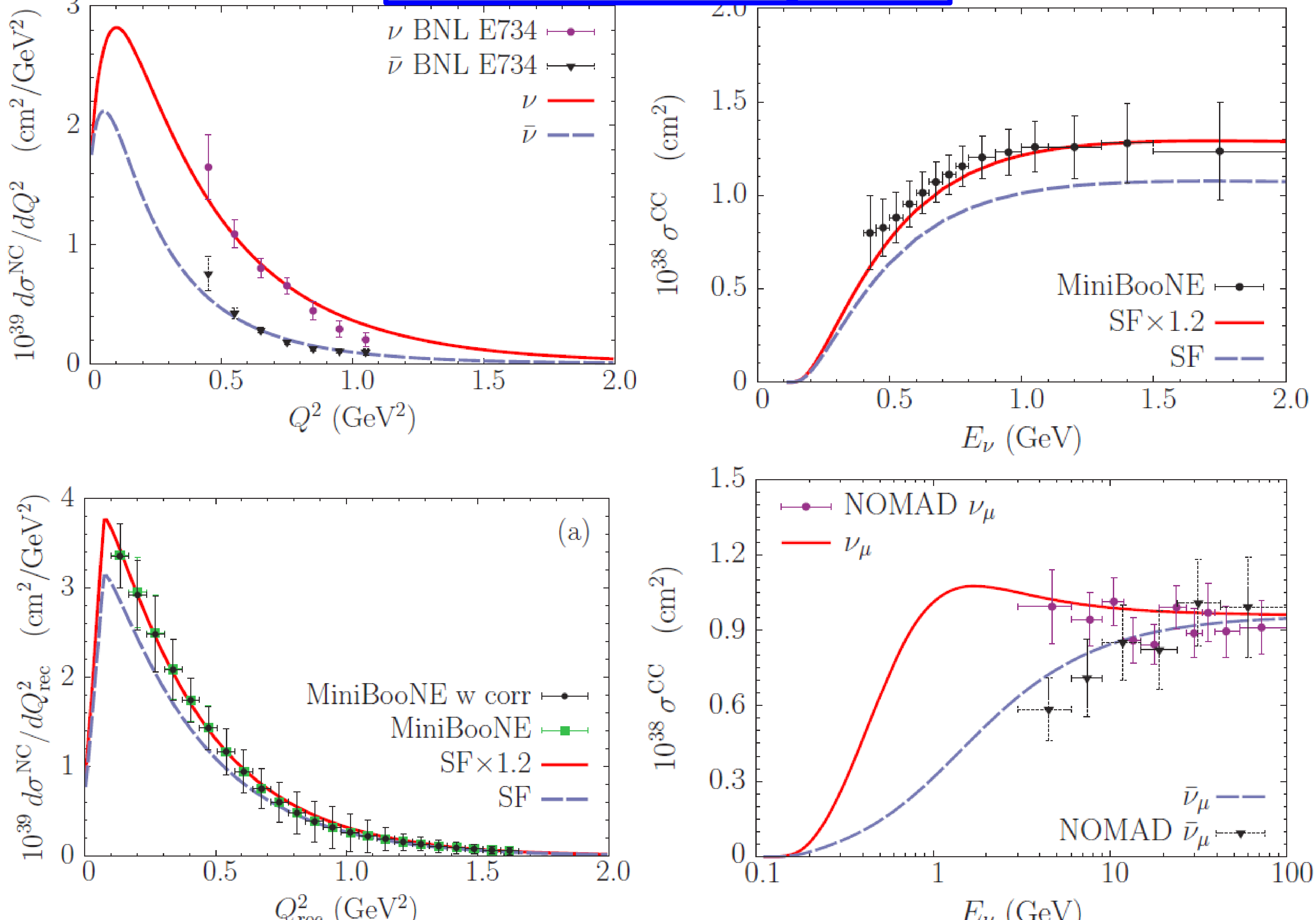
Fiorentini *et al.*, PRL 111, 022502 (2013)

CCQE MINERvA data

TABLE I. Fit results to the CC QE MINERvA data.

	antineutrino	neutrino	combined fit
	including theoretical uncertainties:		
M_A (GeV)	1.16 ± 0.06	1.17 ± 0.06	1.16 ± 0.06
χ^2/d.o.f.	0.38	1.33	0.93
	neglecting theoretical uncertainties:		
M_A (GeV)	1.15 ± 0.10	1.15 ± 0.07	1.13 ± 0.06
χ^2/d.o.f.	0.44	1.38	1.00
	neglecting FSI ($M_A = 1.16$ GeV):		
χ^2/d.o.f.	2.49	2.45	2.42

Other NC and CC QE data



A.M. A, PRC 86, 024616 (2012)

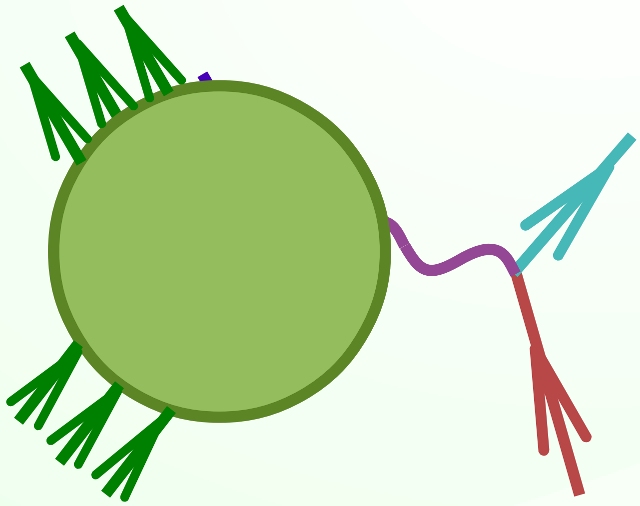
Kinematic energy reconstruction: simplest (unrealistic) case

Unknown monochromatic beam

Consider the simplest (unrealistic) case:

the beam is monochromatic but its energy is unknown

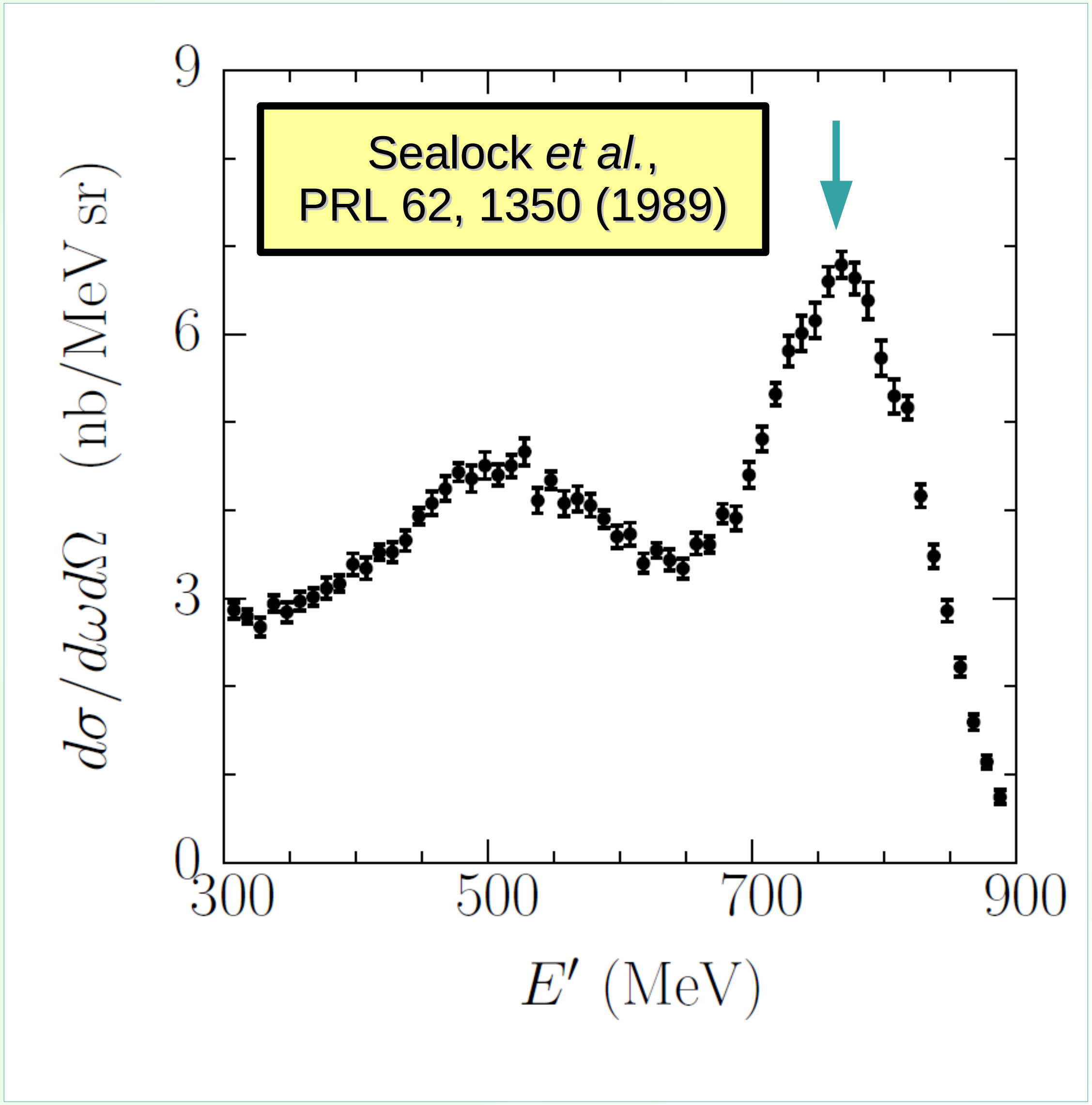
and has to be reconstructed



E' and θ known

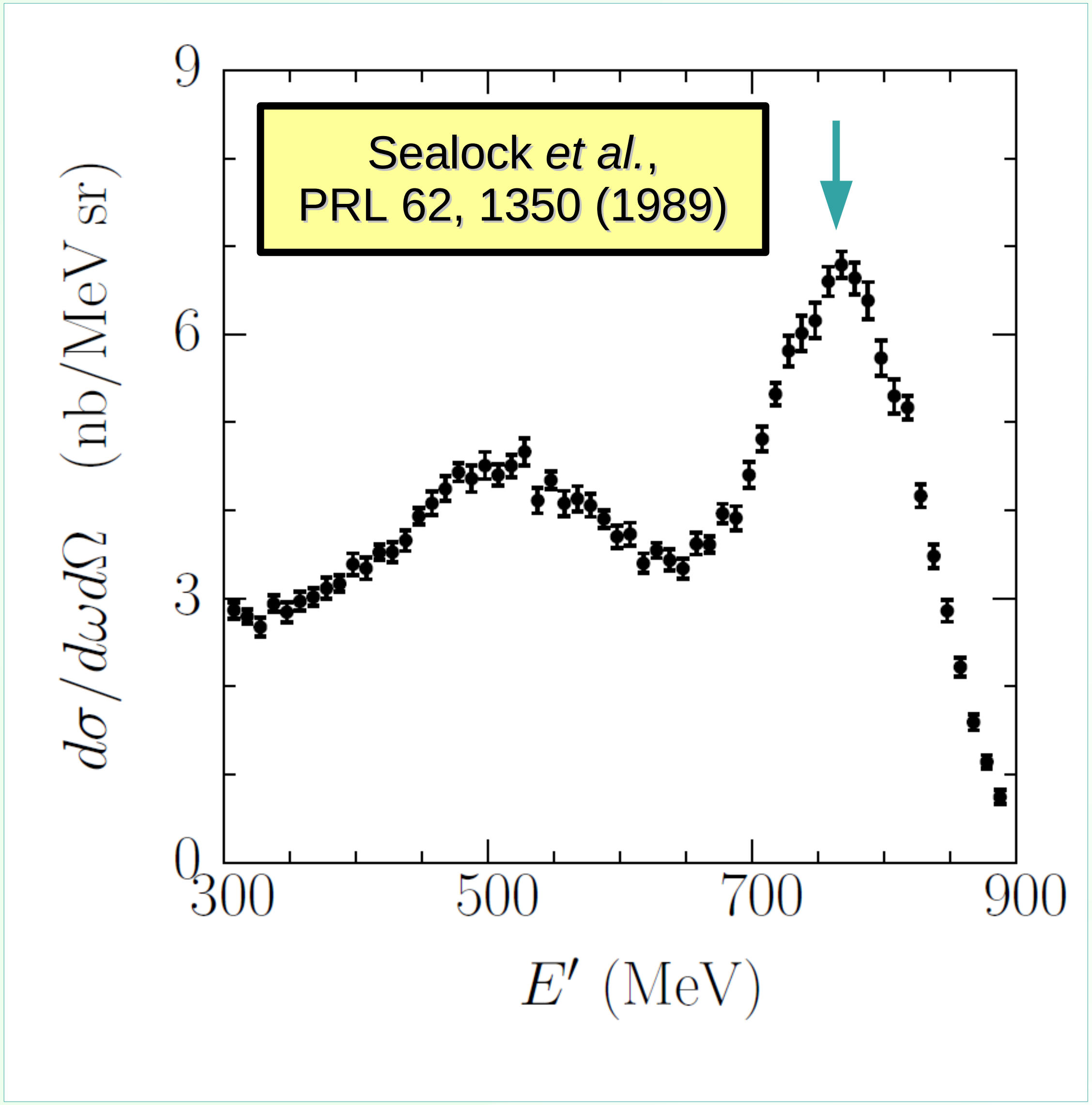
$E = ?$

“Unknown” monochromatic e− beam



$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 5$ MeV

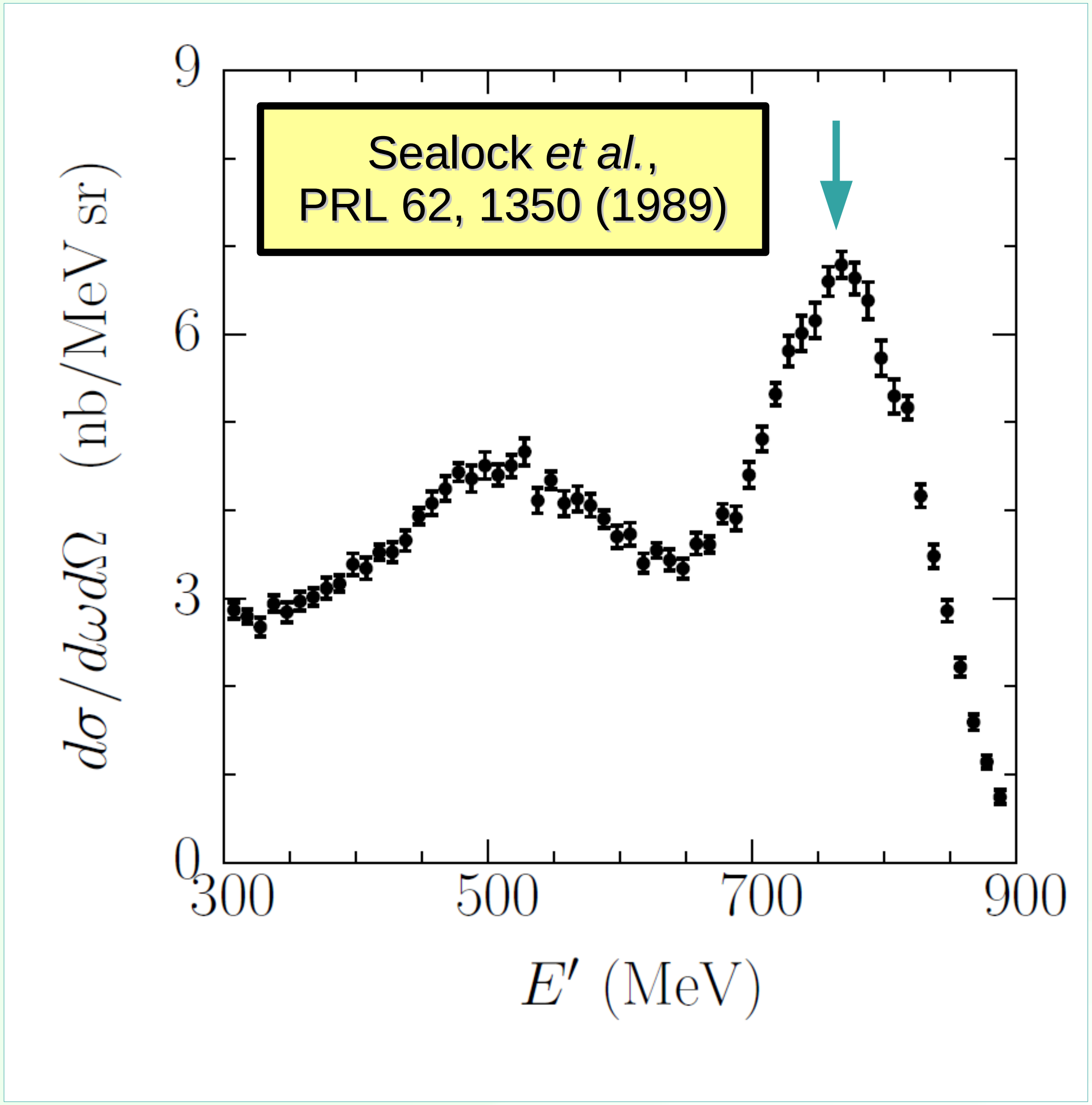
“Unknown” monochromatic e− beam



$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 5$ MeV

for $\epsilon = 25$ MeV
$E = 960$ MeV
$\Delta E = 7$ MeV

“Unknown” monochromatic e− beam



$E' = 768$ MeV
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for $\epsilon = 25$ MeV
$E = 960$ MeV
$\Delta E = 7$ MeV

true value
$E = 961$ MeV

“Unknown” monochromatic e− beam

θ (deg)	37.5	37.1	36	36
E' (MeV)	768.0	615.0	487.5	287.5
$\Delta E'$ (MeV)	5	5	5	2.5

$\epsilon = 25$ MeV

rec. *E*	**960 ± 7**	**741 ± 7**	**571 ± 6**	**333 ± 3**
true *E*	**961**	**730**	**560**	**320**

Sealock et al., PRL 62, 1350 (1989)

O'Connell *et al.*, PRC 35, 1063 (1987)

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

“Unknown” monochromatic e− beam

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ϵ	**26 ± 5**	**16 ± 5**	**16 ± 3**	**13 ± 3**

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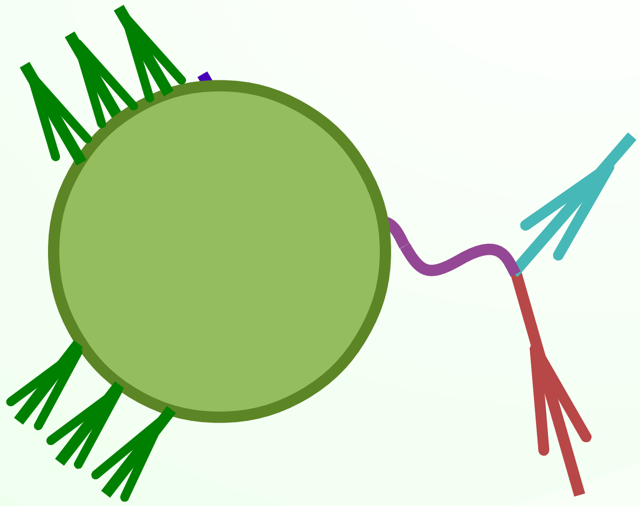
ϵ	**26 ± 5**	**16 ± 5**	**16 ± 3**	**13 ± 3**

different $E \equiv$ different $Q^2 \equiv$ different θ
$\rightarrow$ different ϵ

Kinematic energy reconstruction: realistic case

Polychromatic beam

In modern experiments, the neutrino beams are not monochromatic, and the energy must be reconstructed from the observables, typically E' and cos θ under the CCQE event hypothesis.



E' and θ known

$E = ?$

CCQE events

In practice, CCQE event candidates are defined as containing **no pions observed**.

CCQE ($1p1h$ and $2p2h$)

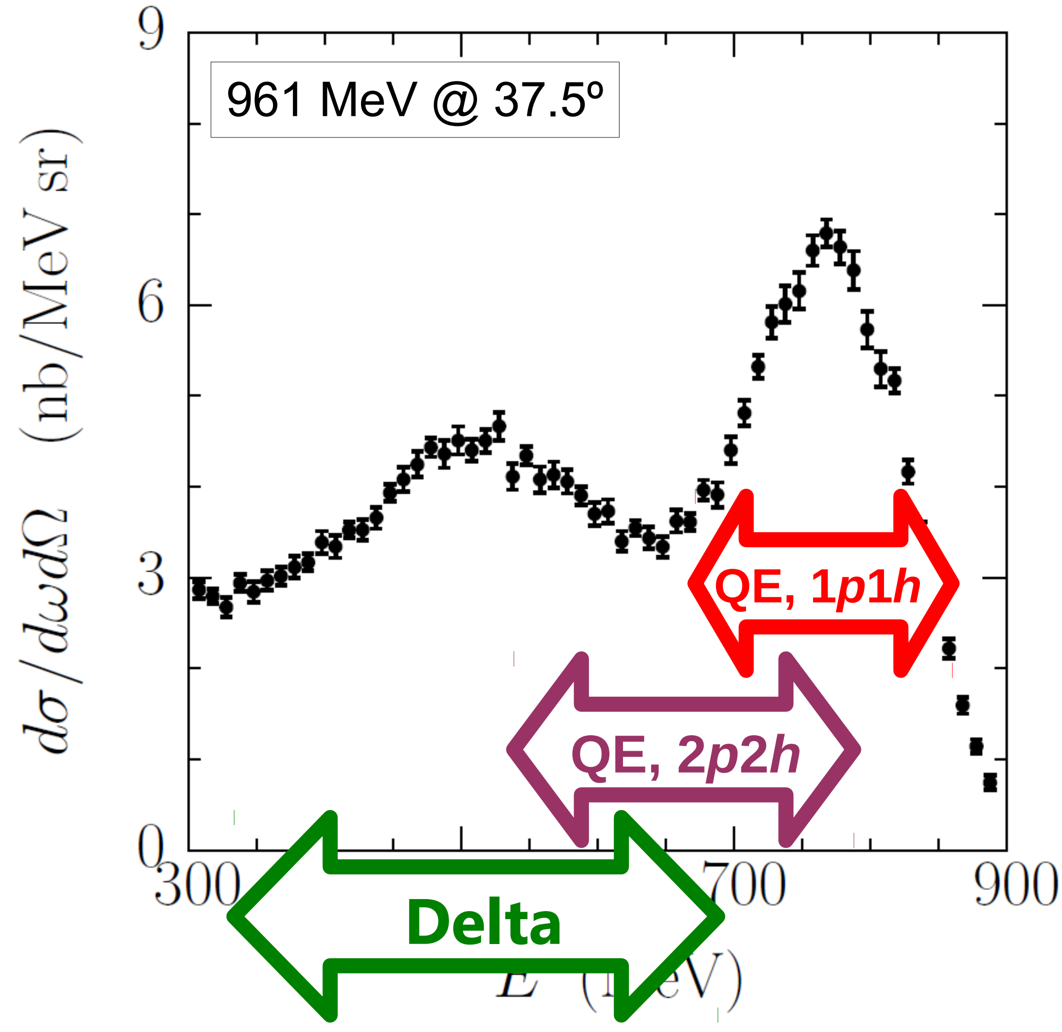
$+$ pion production and followed by absorption

undetected pions

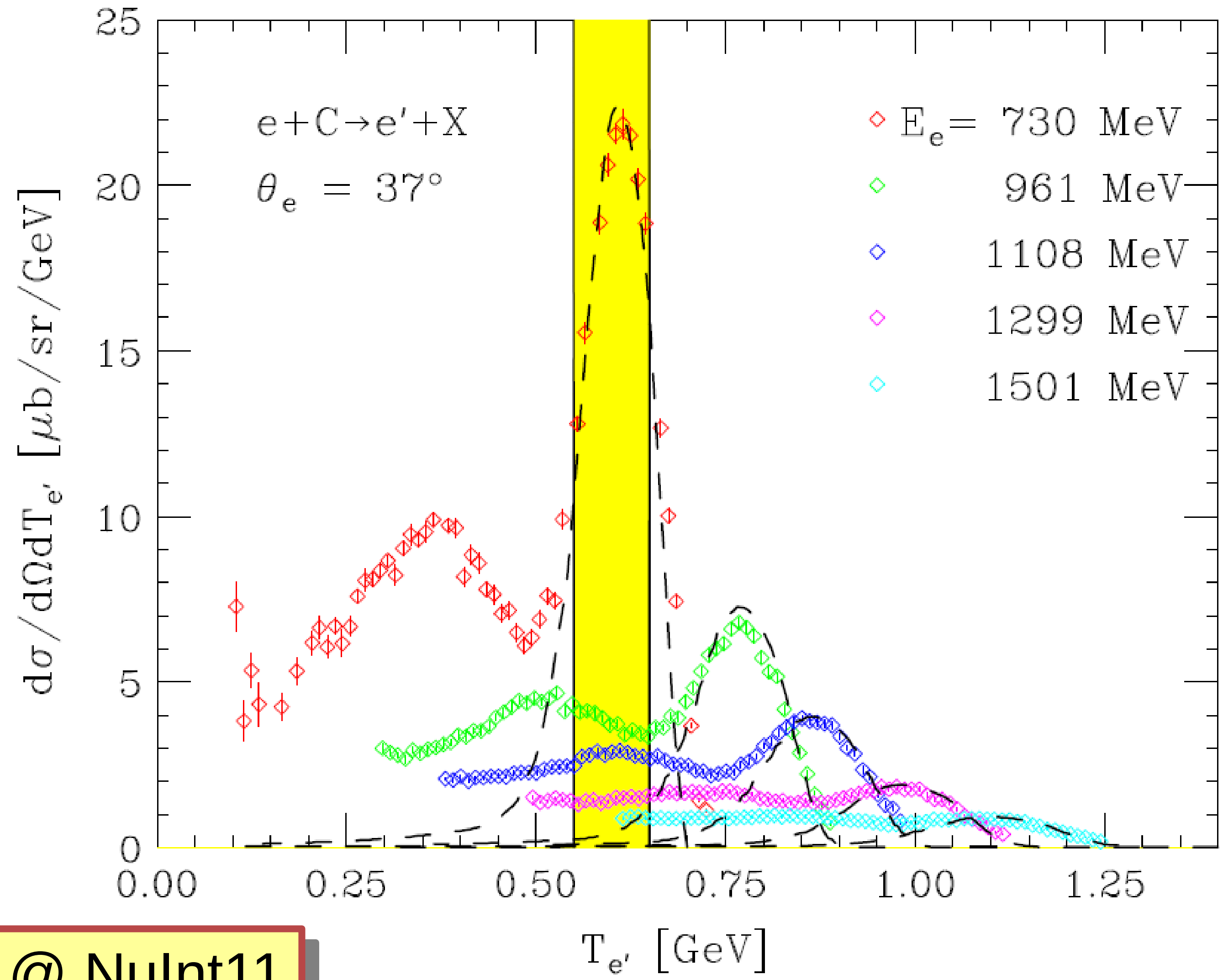
$-$ CCQE with pions from FSI

CCQE-like events

Recall the monochromatic-beam case



CCQE events of given $l^{\pm}$ kinematics



Omar Benhar @ NuInt11
PRL 105, 132301 (2010)

CCQE events of given $l^{\pm}$ kinematics

Very different **processes** and **neutrino energies** contribute to CCQE-like events of a given E' and $\cos\theta$.

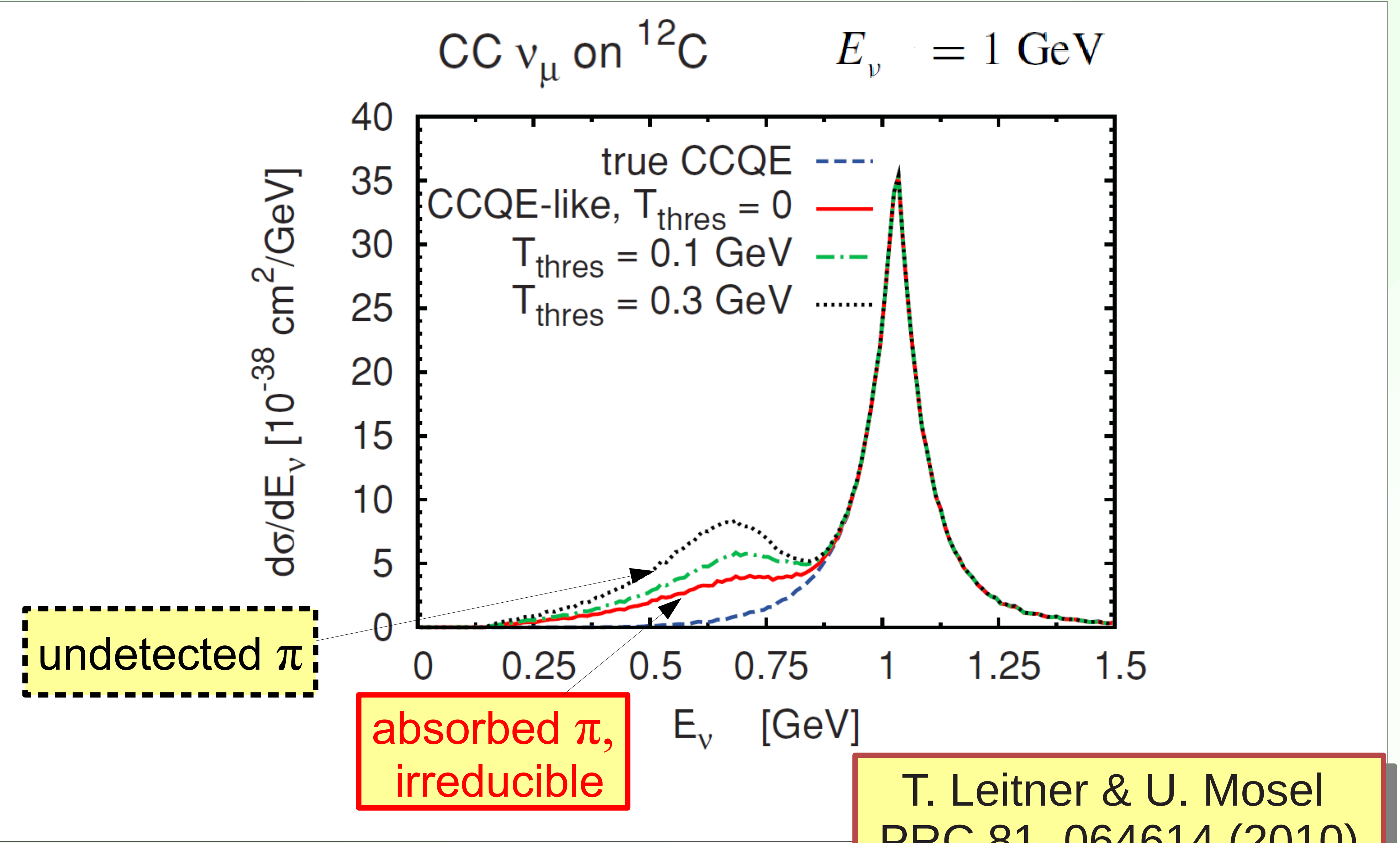
An undetected pion typically lowers the reconstructed energy by **~300–350 MeV**.

Note that in the reconstruction formula, $M_\Delta = 1232$ MeV would be more suitable than $M' = 939$ MeV.

$$\boxed{E_\nu^{\rm rec} = \frac{2(M-\varepsilon)E_\ell + M'^2 - (M-\varepsilon)^2 - m_\ell^2}{2(M-\varepsilon-E_\ell+|\mathbf{k}_\ell|\cos\theta)}.}$$

$$\boxed{\frac{M_\Delta^2 - M'^2}{2M} \approx 340\ \text{MeV}}$$

Absorbed or undetected pions



T. Leitner & U. Mosel
PRC 81, 064614 (2010)

Summary

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

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

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

- **Final-state interactions** can have an important effect on neutrino energy reconstruction, even at E ~ few GeV.

Question 1

Consider the process of quasielasic scattering on a free nucleon. Why is the antineutrino cross section lower than that for neutrino?

Question 2

At a given kinematics, the quasielastic cross sections $d\sigma_{IA}/d\omega d\Omega$ for neutrino and electron scattering off a nucleus are similar, barring the normalization. What is the total cross section for electrons? Why do neutrino and electron interactions differ qualitatively?

Question 3

At high neutrino energies, high scattering angles are strongly suppressed in quasielastic scattering. Can you explain it?

Problem 1

Consider charged-current scattering off a nuclear target leading to excitation of a resonance of the invariant mass W. How to reconstruct the neutrino energy from the charged-lepton's kinematics?

Problem 2

Assume a general case of charged-current interaction, with n nucleon and m meson tracks reconstructed in the detector. How to approximate the neutrino energy using the momentum conservation?

Problem 3

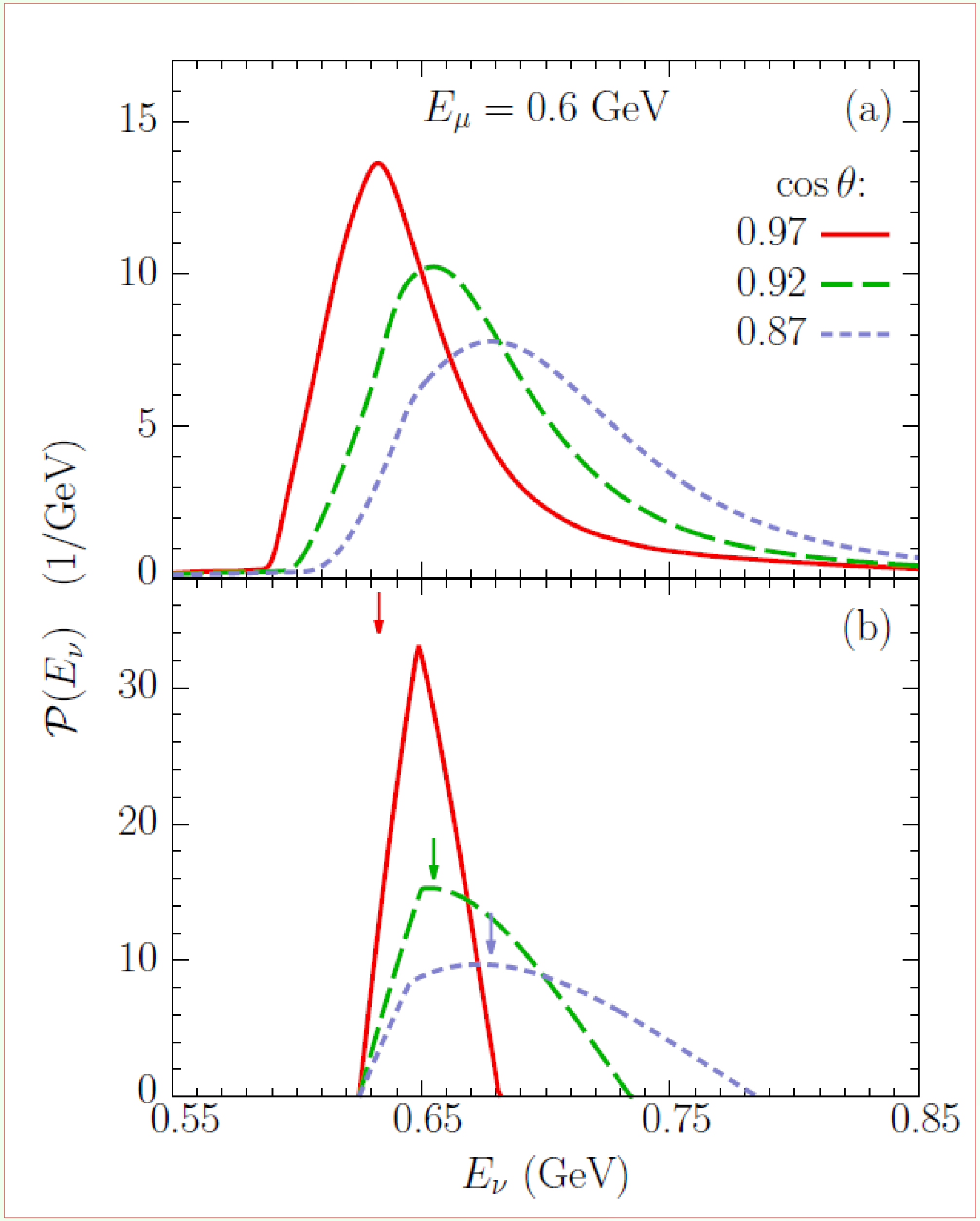
How to reconstruct the neutrino energy when a pion is produced in a single-nucleon knockout from a nucleus? Assume that the pion kinematics is known. Hint: use the relation between the energy and momentum of the knocked-out nucleon.

Backup slides

Energy reconstruction

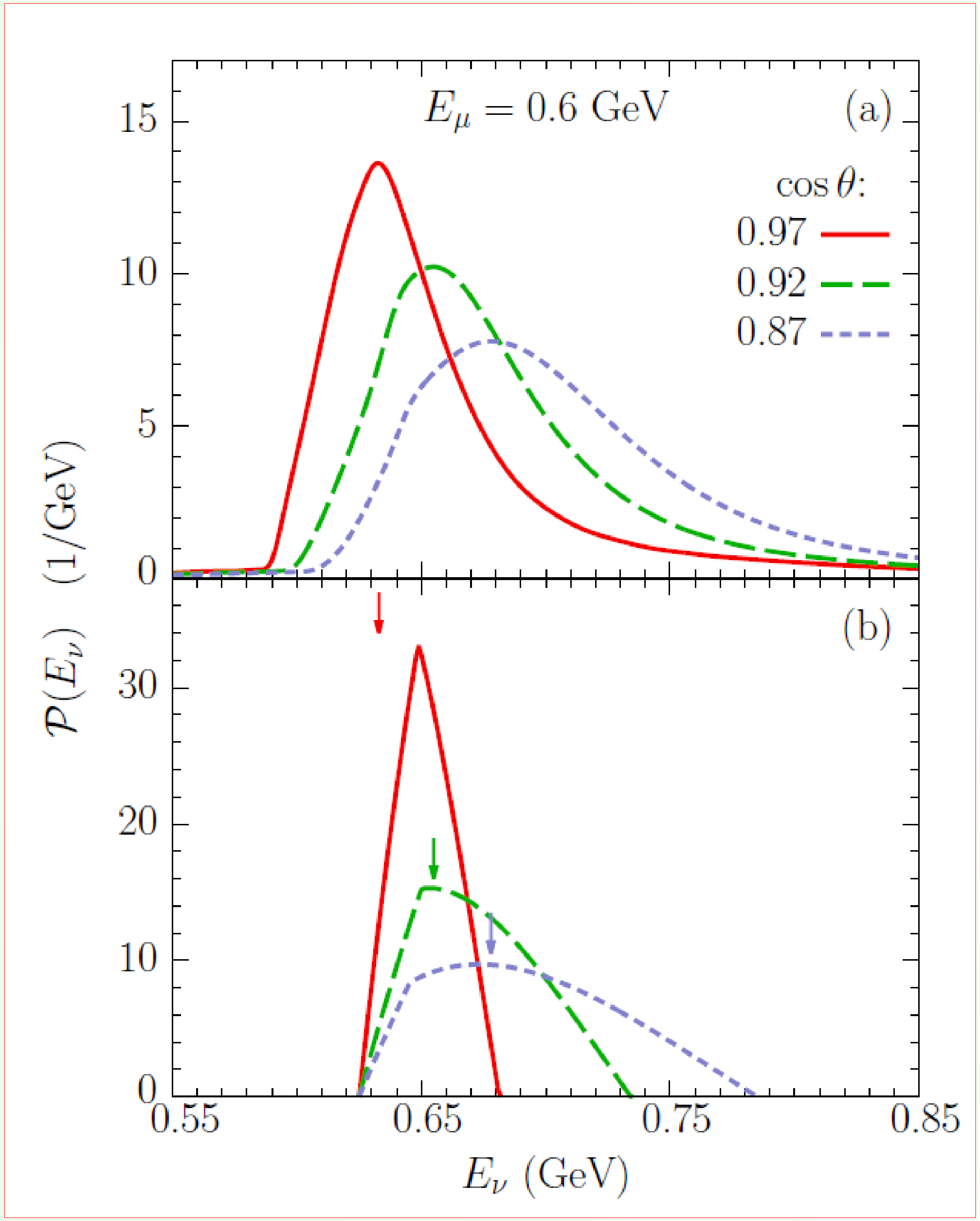
Consider the probability distribution that a muon of given energy and scattering angle is produced by a neutrino of energy E_ν

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



kinematics relevant to the T2K experiment

At cos = 0.97
the difference is ~16 MeV
for RFG with ε = 25 MeV



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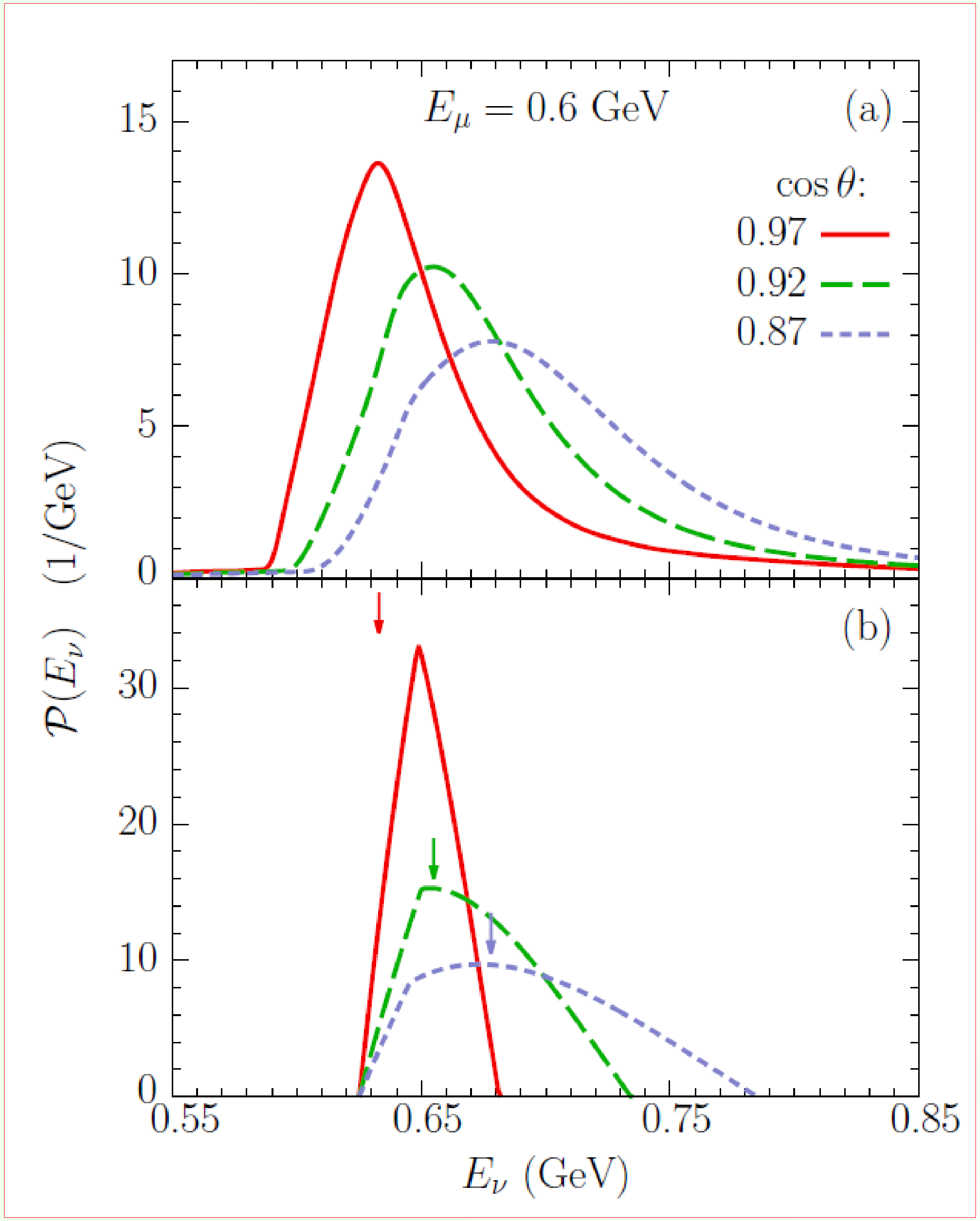
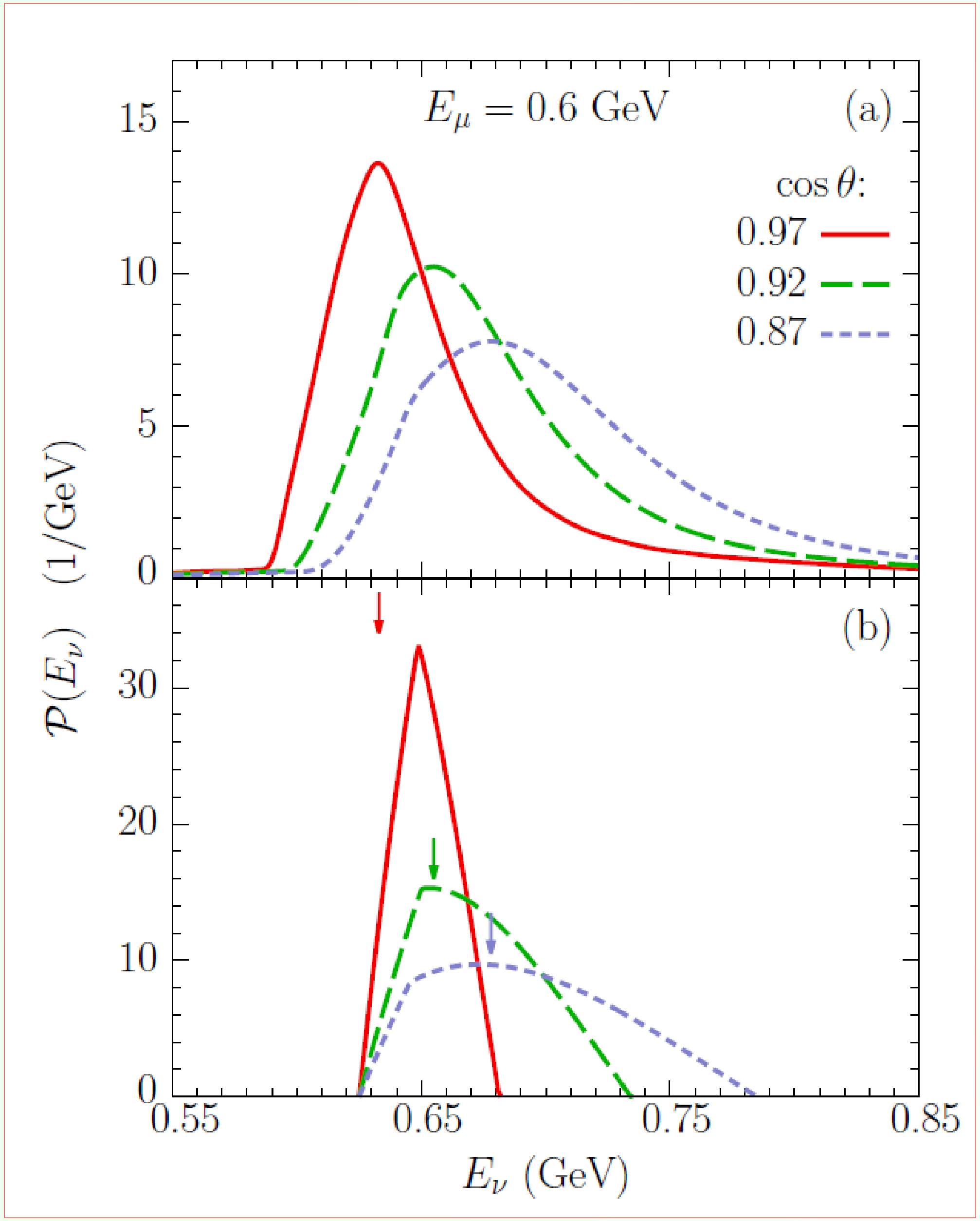


kinematics relevant to the T2K experiment

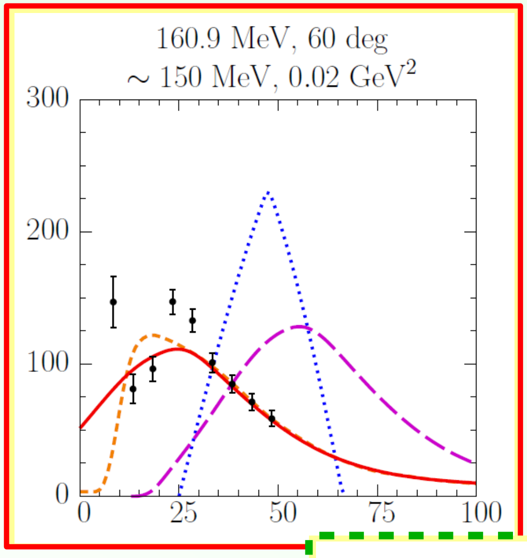
At cos = 0.97
the difference is ~16 MeV
for RFG with ε = 25 MeV

To get the maxima right

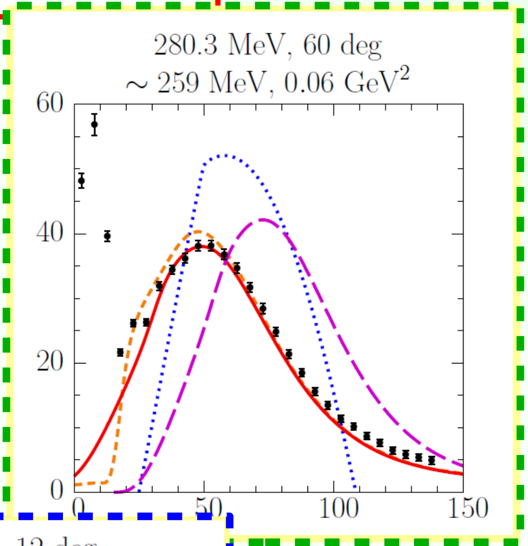
ε = 9 MeV @ cos = 0.97
ε =27 MeV @ cos = 0.92
ε =29 MeV @ cos = 0.87



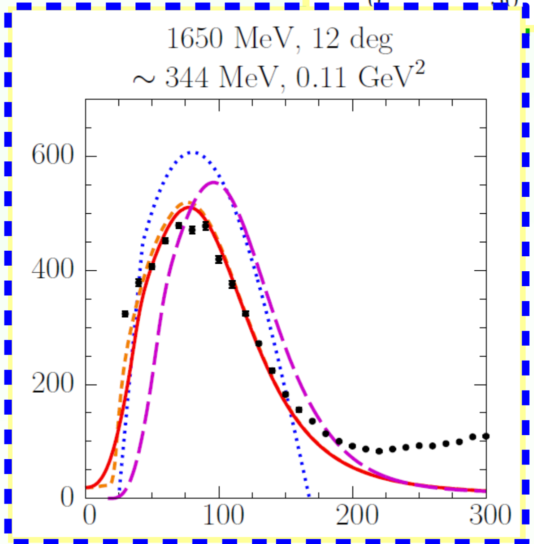
$E_\mu = 0.6$ GeV
(a)
(b)
cos θ:
0.97
0.92
0.87
$\mathcal{P}(E_\nu)$ (1/GeV)
E_ν (GeV)



160.9 MeV, 60 deg
~ 150 MeV, 0.02 GeV^2



280.3 MeV, 60 deg
~ 259 MeV, 0.06 GeV^2



1650 MeV, 12 deg
~ 344 MeV, 0.11 GeV^2