Primer on nuclear effects in neutrino interactions

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Fermilab, November 7, 2017

Outline

1) **Introduction**
- Neutrino interactions in a nutshell
- Accurate neutrino-energy reconstruction requires an accurate modeling of nuclear effects
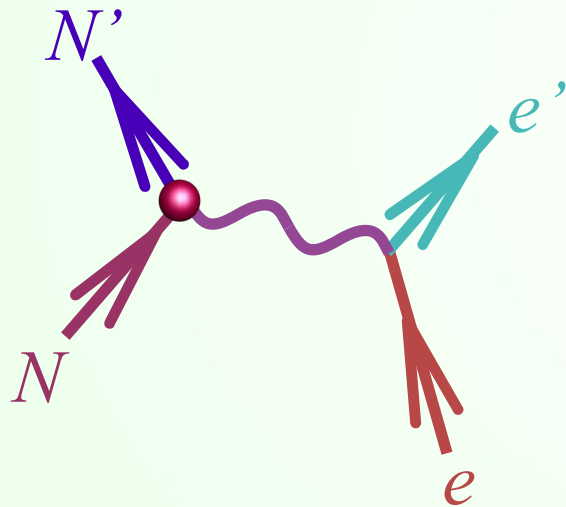
2) **Impulse approximation**
- Why to test nuclear models using electron scattering data
- Fermi gas model
- Shell model
- Spectral function approach
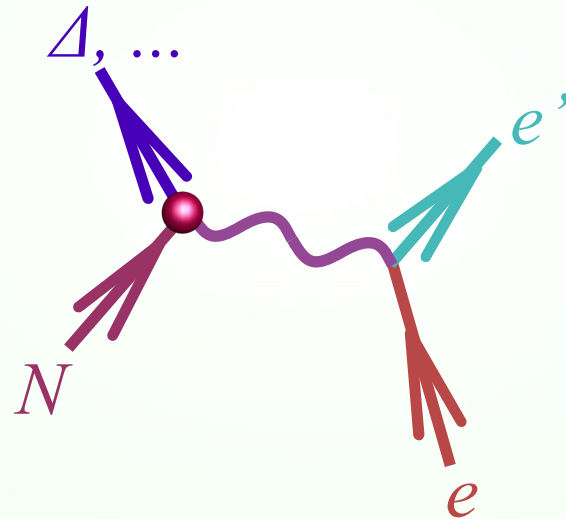- Final-state interactions in the spectral function approach

3) **Summary**

Electon scattering on a free nucleon
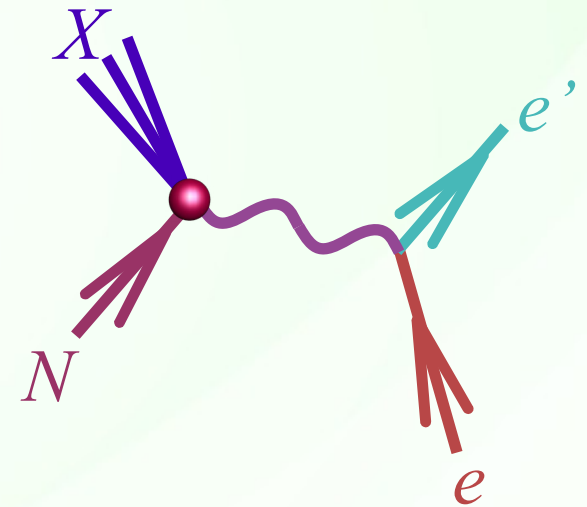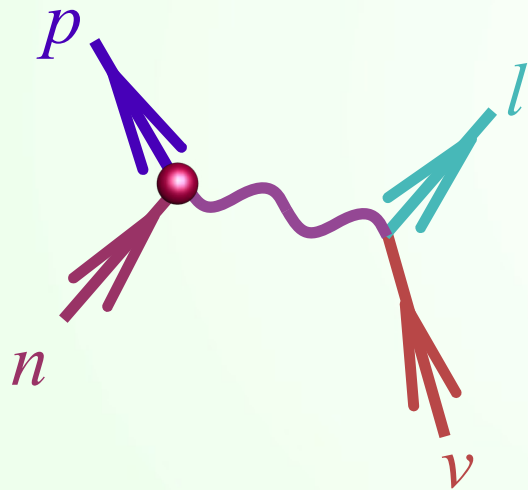

elastic scattering

resonance excitation

deep inelastic scattering

$x=1$

energy transfer ~300 MeV

$x \ll 1$

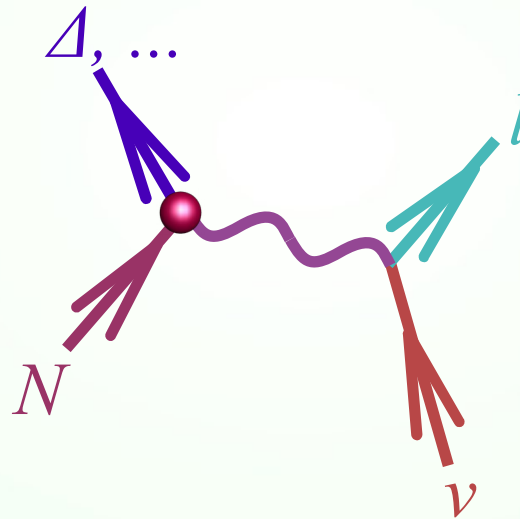# Neutrino CC scattering on a free nucleon

quasielastic scattering	resonance excitation	deep inelastic scattering
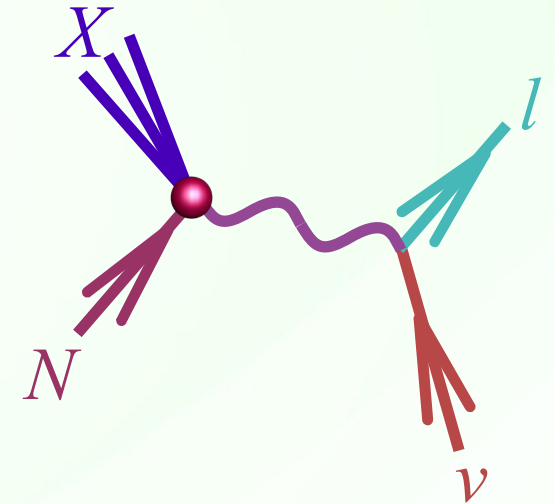
$x = 1$	energy transfer ~300 MeV	$x \ll 1$

Terminology difference

The processes $v + N \to v' + N'$ and $e + N \to e' + N'$

for bound nucleons are called
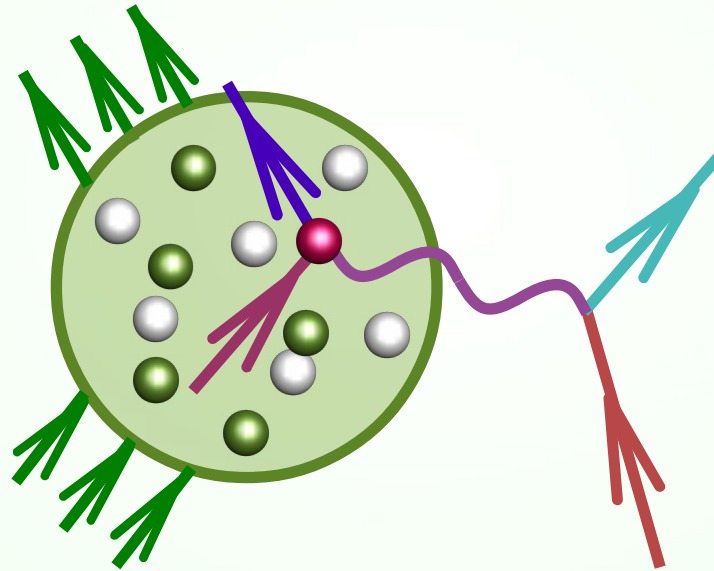
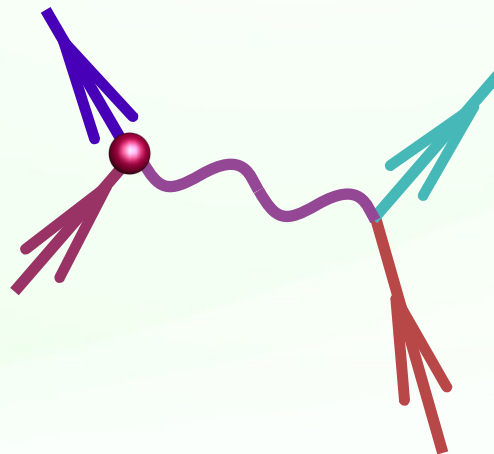| elastic scattering [neutrino physics] | quasielastic scattering [nuclear physics & (*e,e'*)] |

(Quasi)elastic scattering

In $e + N \rightarrow e + N'$ and $\nu + n \rightarrow l + p$ on free nucleons for a fixed beam energy, given scattering angle θ corresponds to a single value of energy transfer ω.
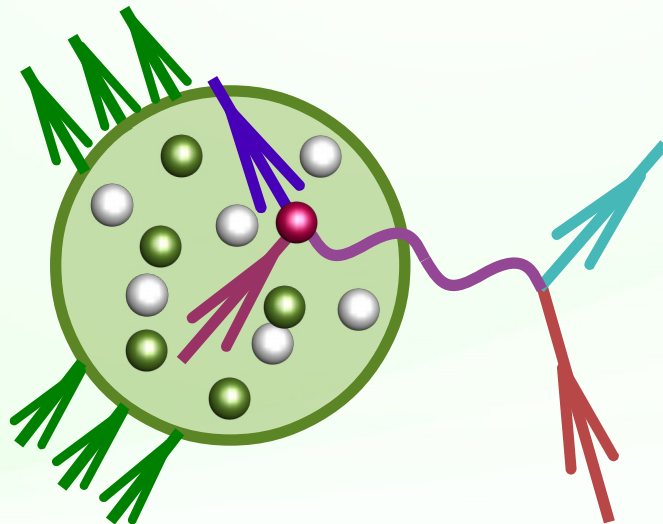
(Quasi)elastic condition
$$Q^2 = 2M\omega$$

Lepton kinematics ($m=0$)
$$Q^2 = 2E(E-\omega)(1-\cos\theta)$$

(Quasi)elastic scattering

In a **nucleus**, nucleons have an energy distribution and undergo Fermi motion. Even for a fixed beam energy, given scattering angle corresponds to a range of energy transfers.

- **Free nucleon**

$$E_p{'}^2 - \boldsymbol{p}{'}^2 = M^2$$

$$(M+\omega)^2 - \boldsymbol{q}^2 = M^2$$

$$2M\omega = Q^2$$

$$Q^2/(2M\omega) = 1$$

- **Bound nucleon**

$$E_p{'}^2 - \boldsymbol{p}{'}^2 = M^2$$

$$(M-E+\omega)^2 - (\boldsymbol{p}+\boldsymbol{q})^2 = M^2$$

$$2M\omega + E[E-2(\omega+M)] - \boldsymbol{p}(\boldsymbol{p}+2\boldsymbol{q}) = Q^2$$

$$Q^2/(2M\omega) = 1 + \frac{E}{M}(...) + \frac{\boldsymbol{p}}{M}(...)$$

Free nucleon vs. bound nucleon

NUCLEAR RESPONSE FUNCTION
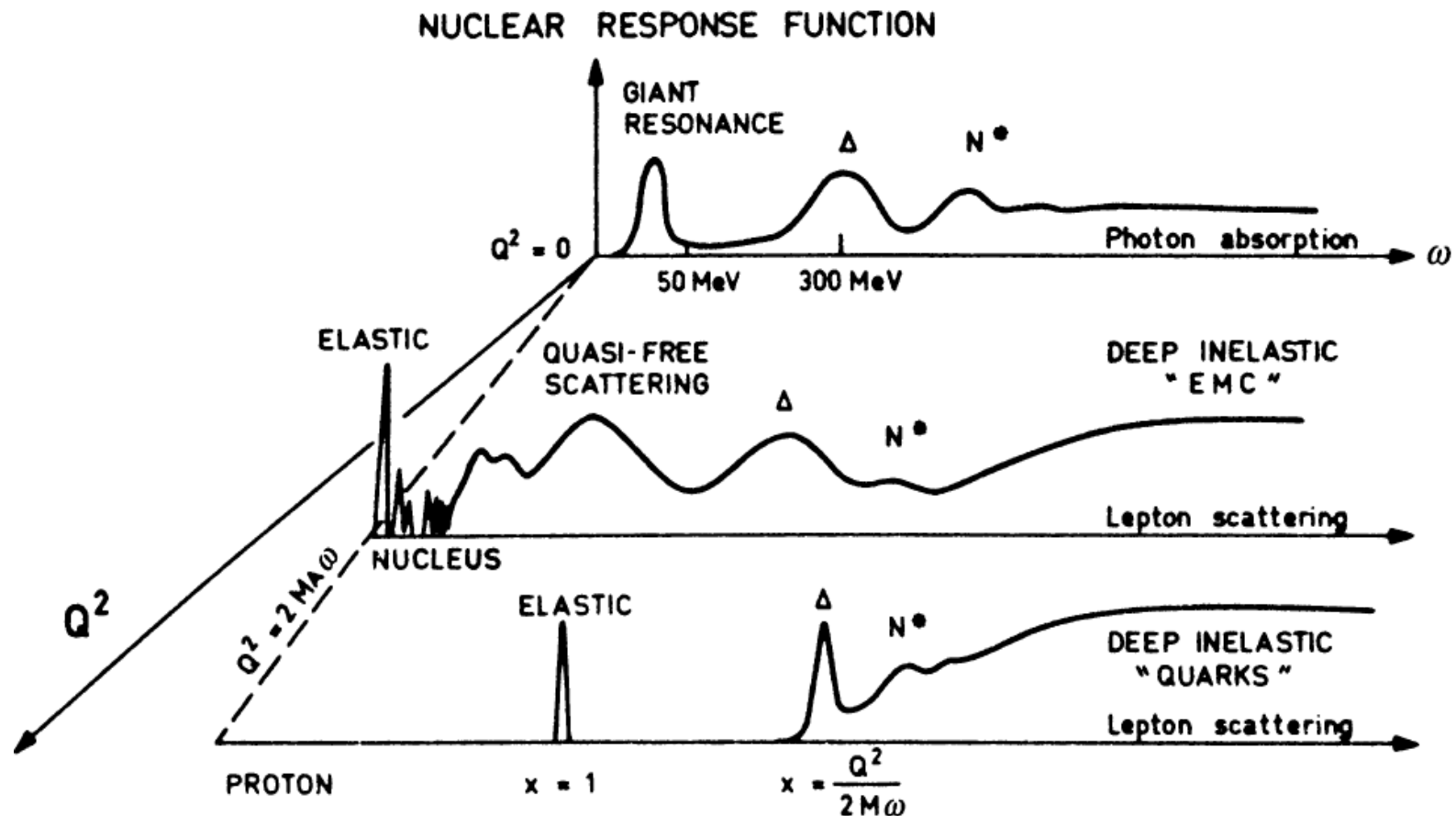
Target dependence

Neutrino oscillations in a nutshell

In the simplest case of 2 flavors

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

Example [K. Abe *et al.* (T2K Collaboration), PRD 91, 072010 (2015)]

Neutrino oscillations in a nutshell

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Example [K. Abe *et al.* (T2K Collaboration), PRD 91, 072010 (2015)]

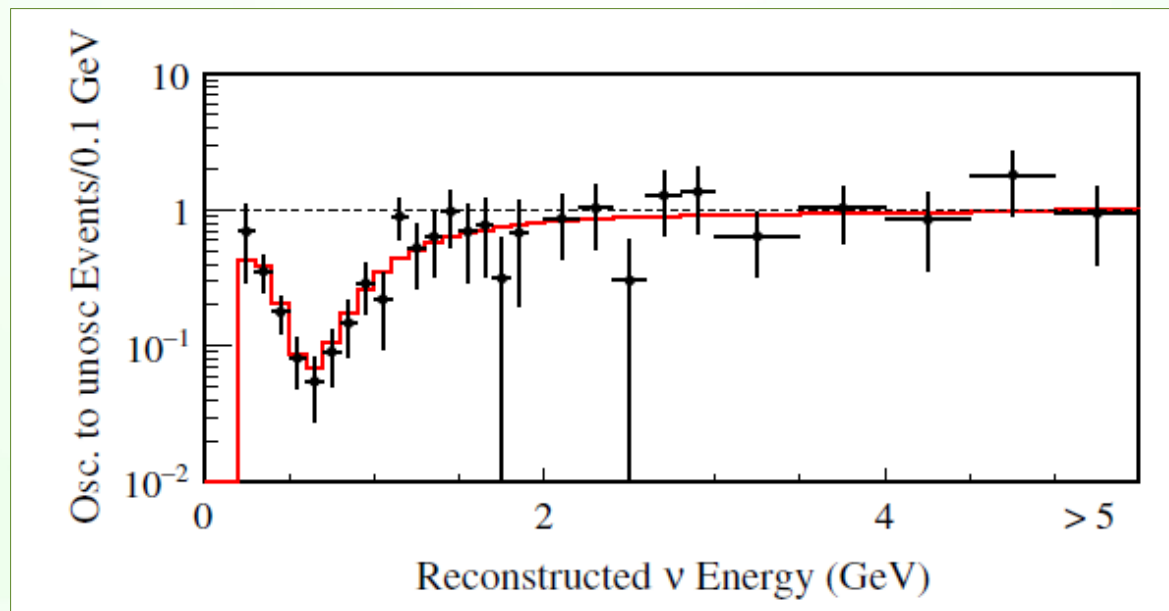# Neutrino oscillations in a nutshell

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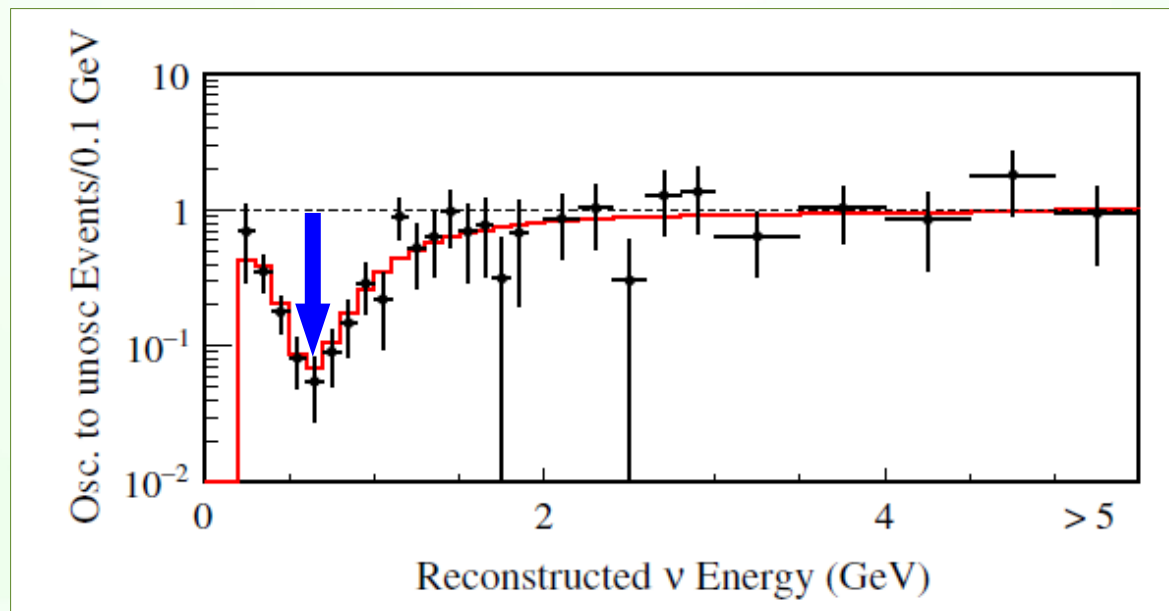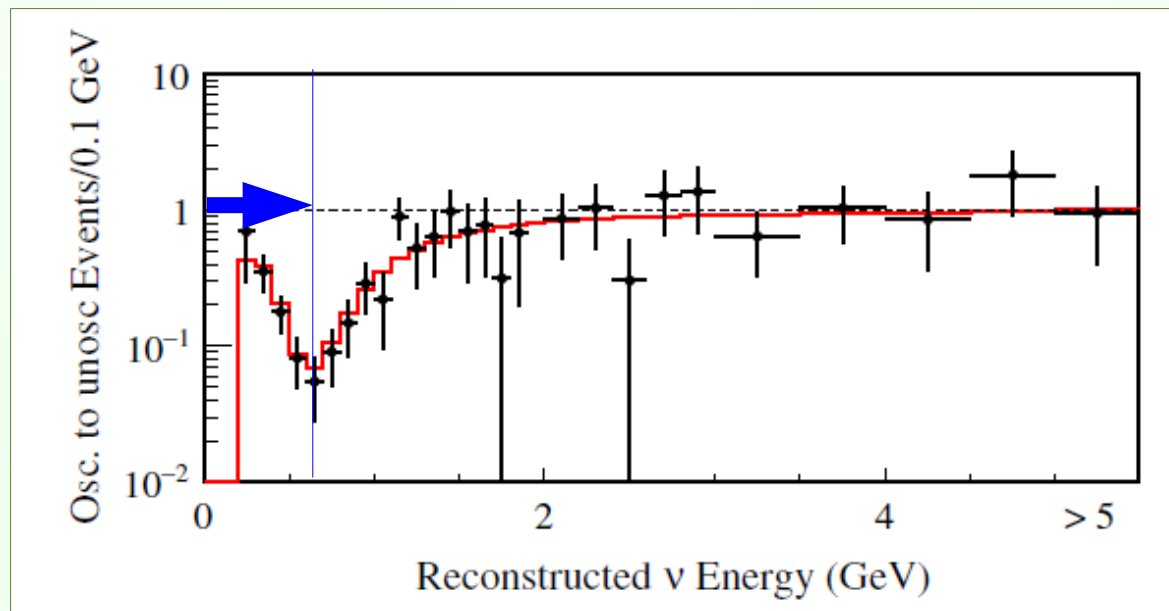Example [K. Abe *et al.* (T2K Collaboration), PRD 91, 072010 (2015)]

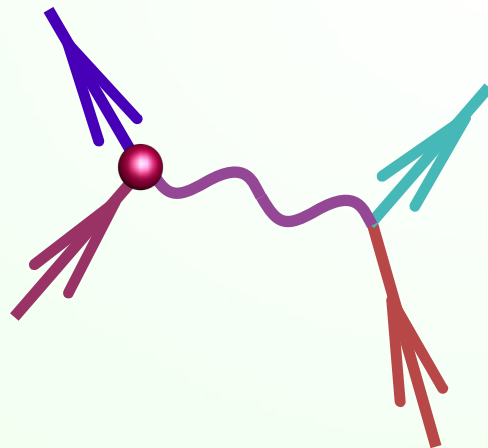**Energy reconstruction**

Kinematic reconstruction

In quasielastic scattering off free nucleons, $\bar{\nu} + p \rightarrow l + n$ and $\nu + n \rightarrow l + p$, we can deduce the neutrino energy from the charged lepton's kinematics.

No need to reconstruct the nucleon kinematics.

$$E' \text{ and } \theta \text{ known}$$
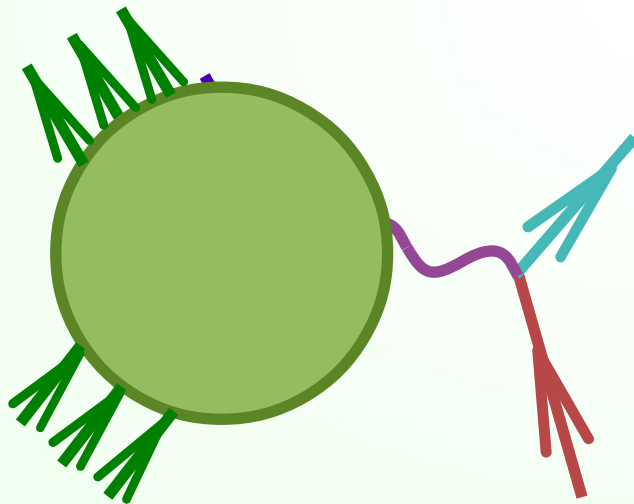
$$E = \frac{ME' + \text{const}}{M - E' + |\boldsymbol{k}'| \cos\theta}$$

Kinematic reconstruction

In nuclei the reconstruction becomes an approximation due to the binding energy, Fermi motion, final-state interactions, two-body interactions etc.
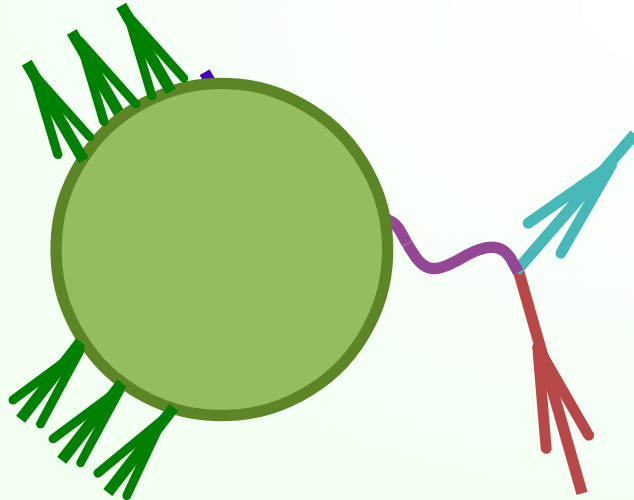
$$E' \text{ and } \theta \text{ known}$$

$$E \simeq \frac{(M-\epsilon)\,E'+\text{const}}{M-\epsilon-E'+|\boldsymbol{k}'|\cos\theta}$$

Unknown monochromatic beam

Consider the simplest (unrealistic) case:

the beam is monochromatic but its energy is unknown and has to be reconstructed

$$E' \text{ and } \theta \text{ known}$$

$$E = ?$$

PoS(NuFact2014)004

"Unknown" monochromatic e^- beam

Sealock *et al.*,
PRL 62, 1350 (1989)
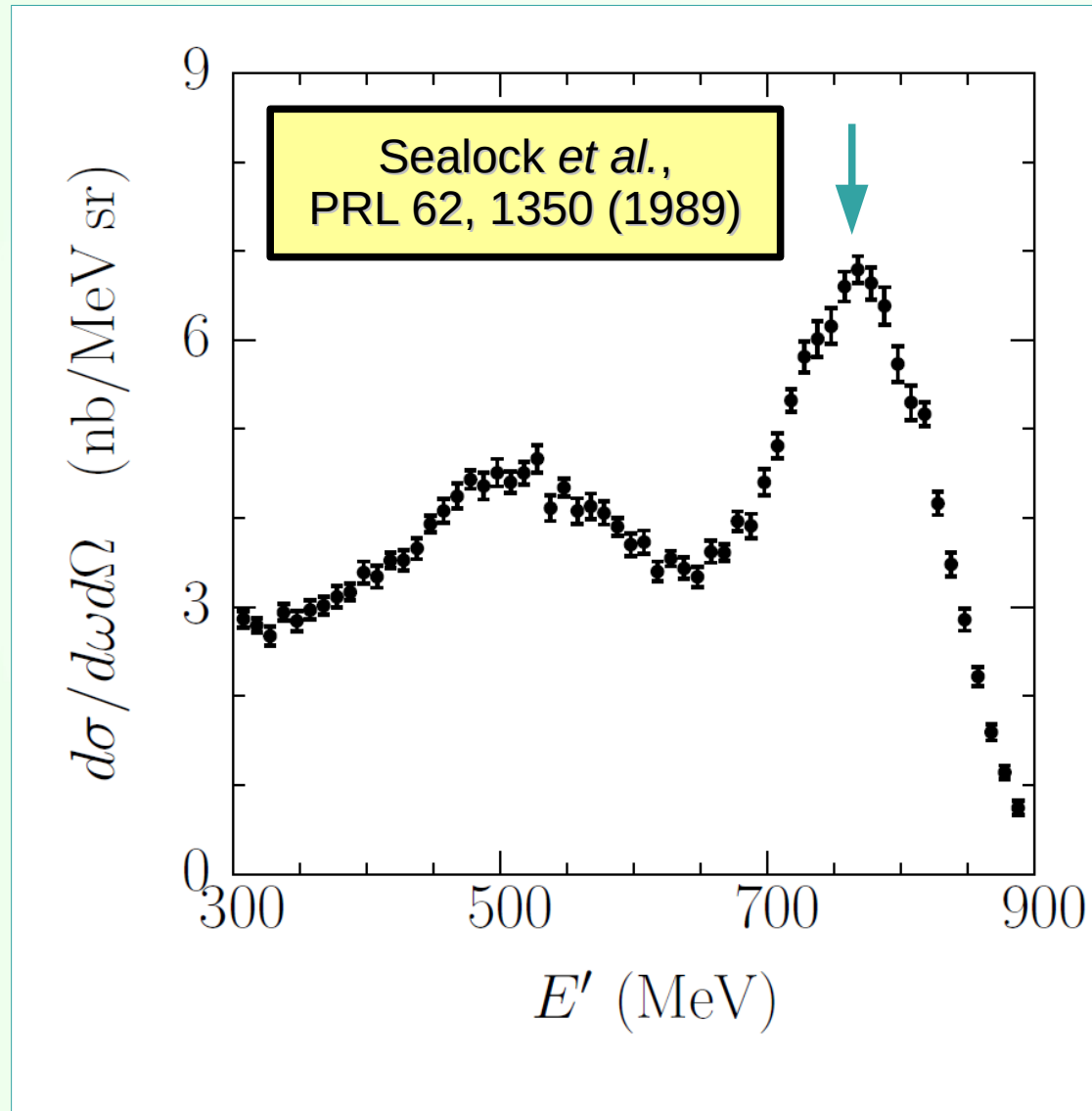
$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 5$ MeV

"Unknown" monochromatic e^- beam
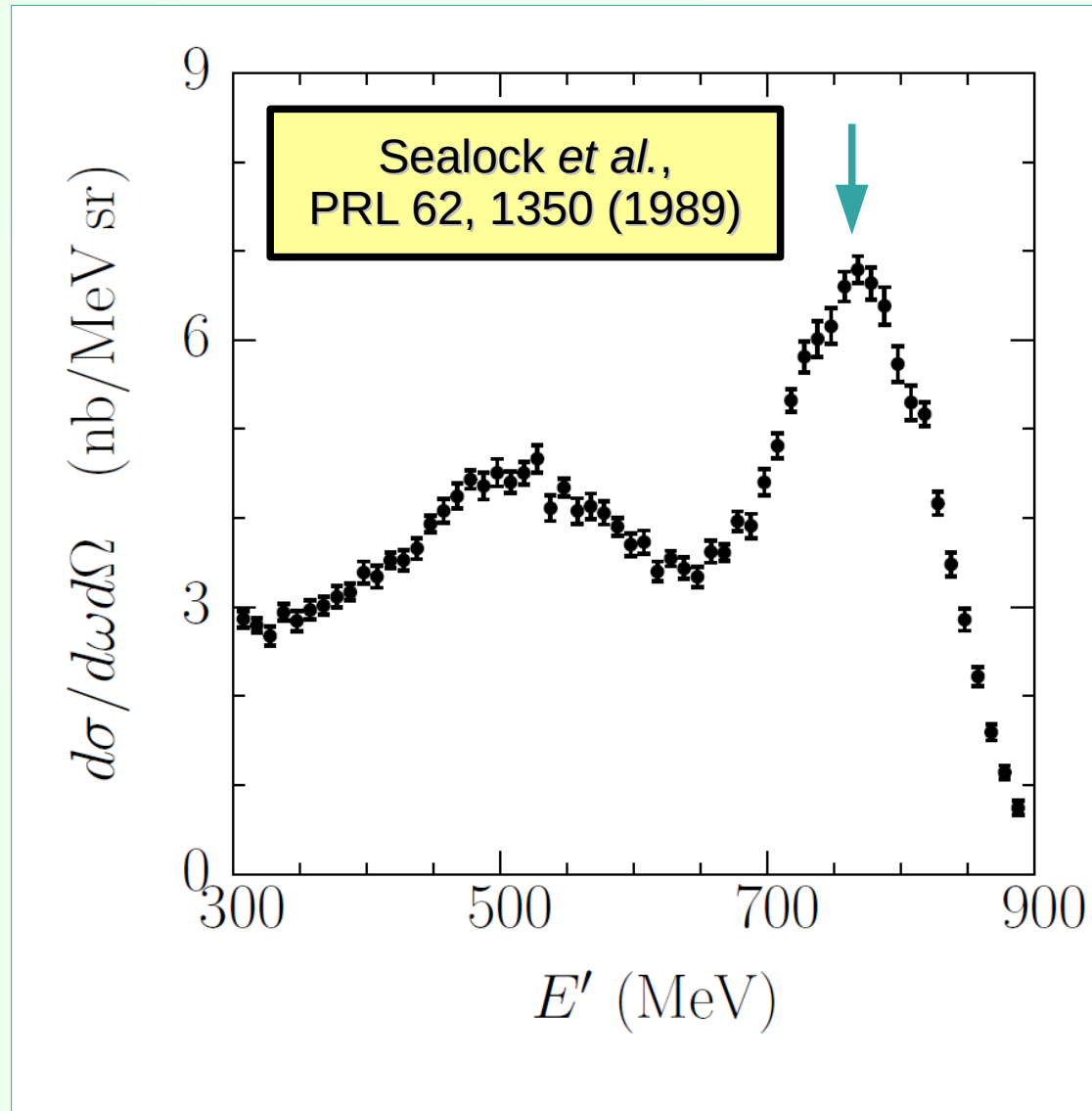
Sealock *et al.*,
PRL 62, 1350 (1989)

$E' = 768$ MeV
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$\Delta E' = 5$ MeV

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

"Unknown" monochromatic e^- beam

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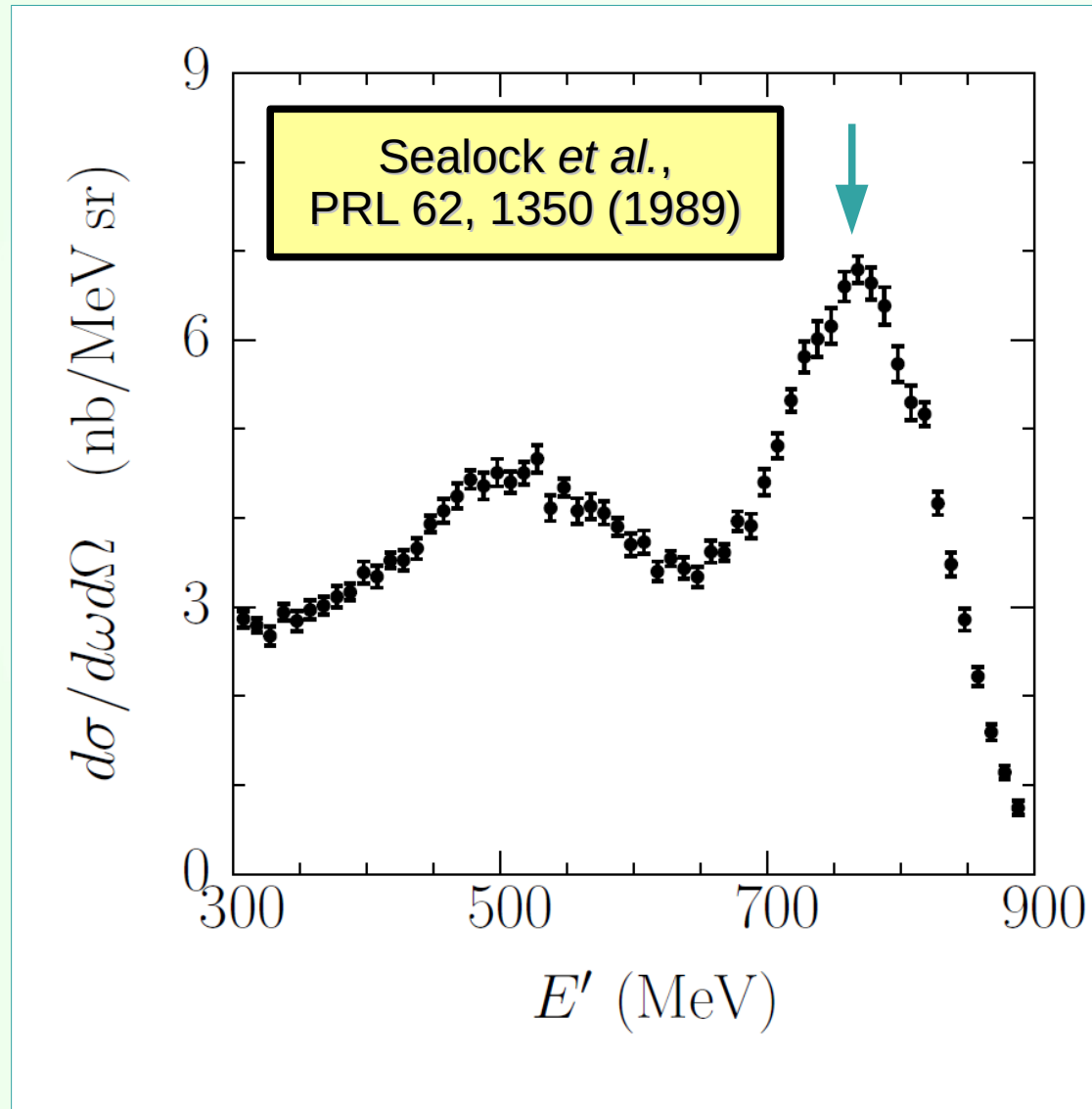
$E' = 768$ MeV
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true value
$E = 961$ MeV

"Unknown" monochromatic e^- beam

θ (deg)	37.5	37.5	37.1	36.0	36.0
E' (MeV)	976	768	615	487.5	287.5
$\Delta E'$ (MeV)	5	5	5	5	2.5

Assuming $\epsilon = 25$ MeV

rec. E	1285 ± 8	960 ± 7	741 ± 7	571 ± 6	333 ± 3
true E	1299	961	730	560	320

"Unknown" monochromatic e^- beam

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Appropriate ϵ value?

true E	1299	961	730	560	320
ϵ	33 ± 5	26 ± 5	16 ± 5	16 ± 3	13 ± 3

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

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

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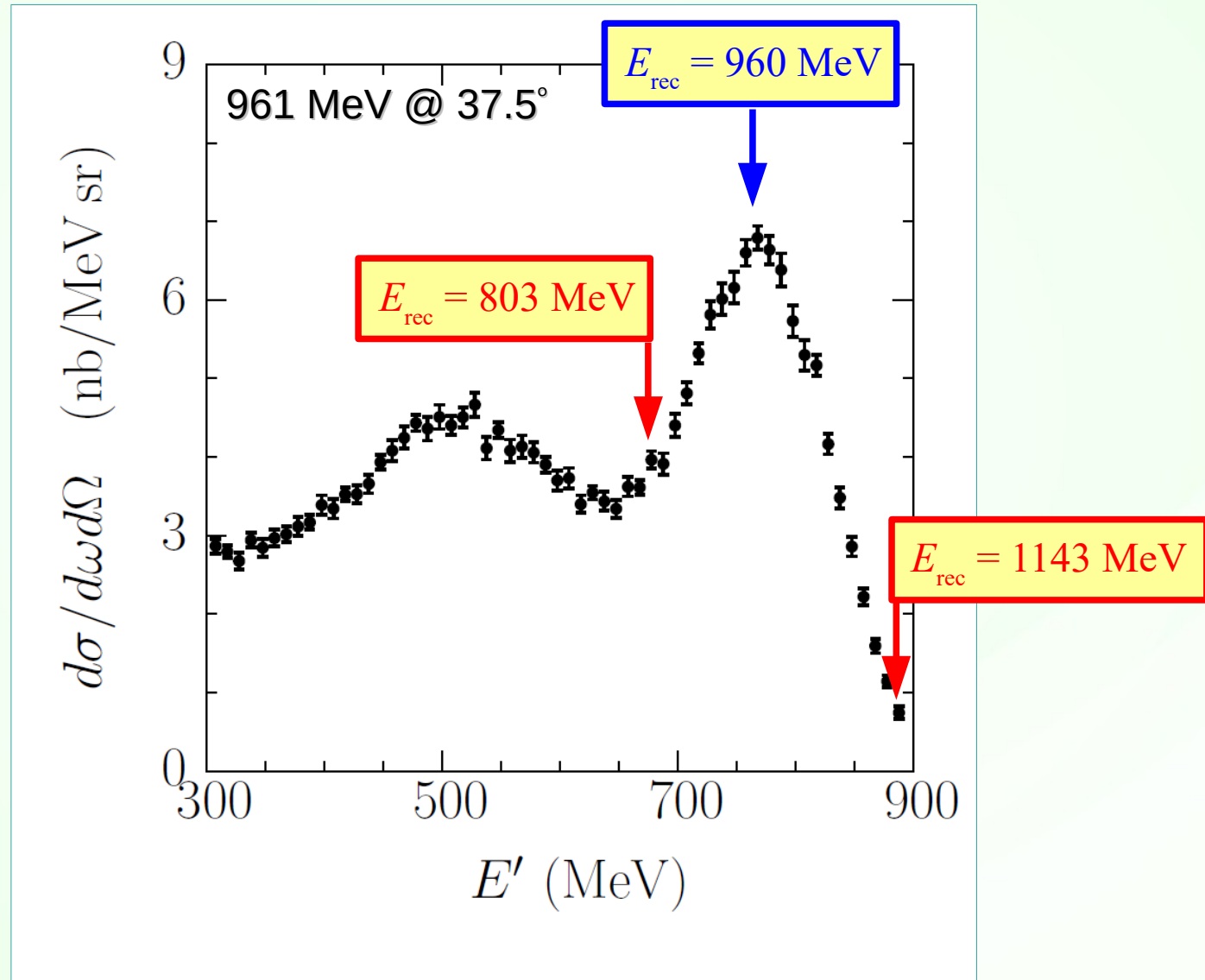(1983)

"Unknown" monochromatic e^- beam

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Appropriate ϵ value?

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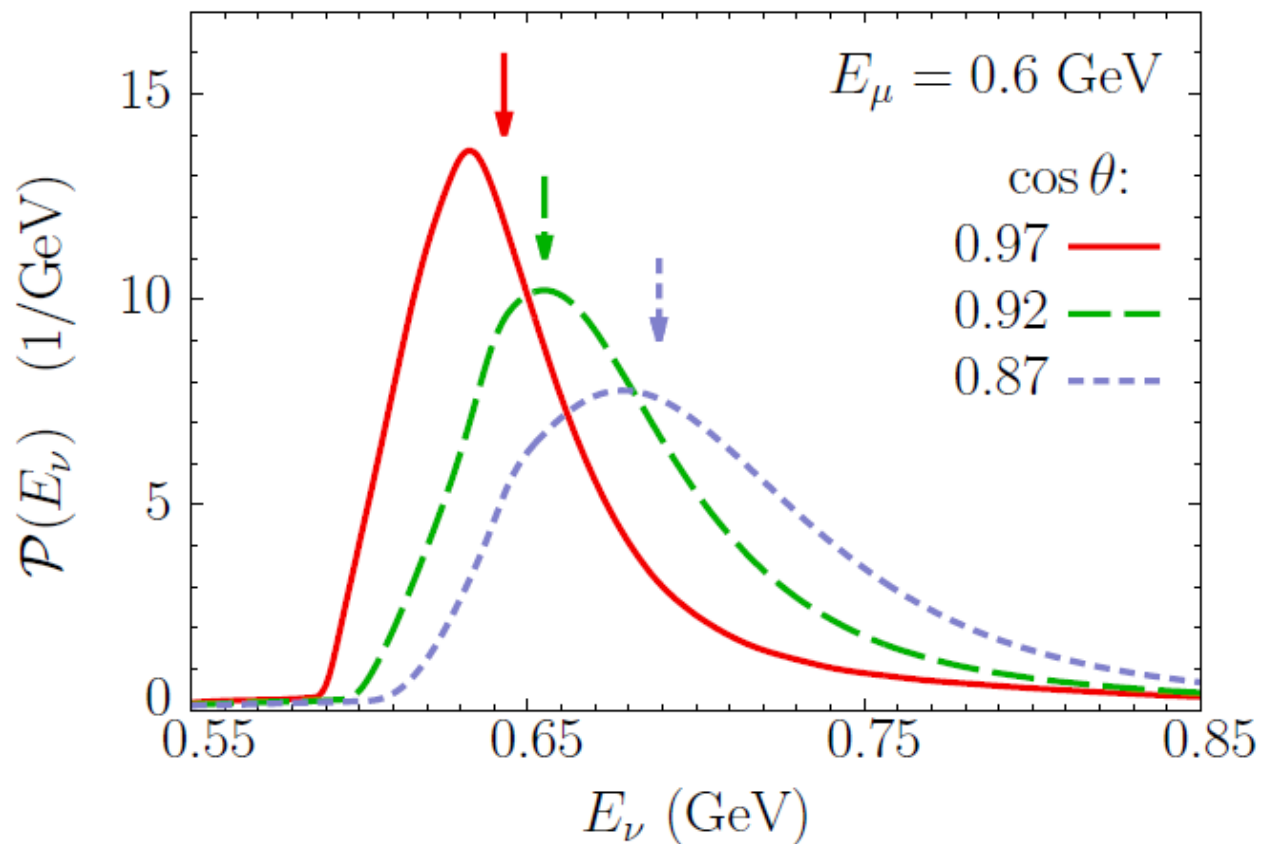$\rightarrow$ different ϵ

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"Unknown" monochromatic e^- beam

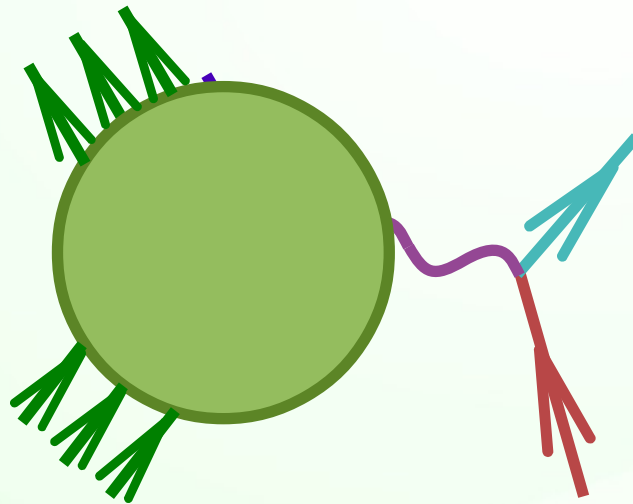# Realistic calculations vs E_{rec}
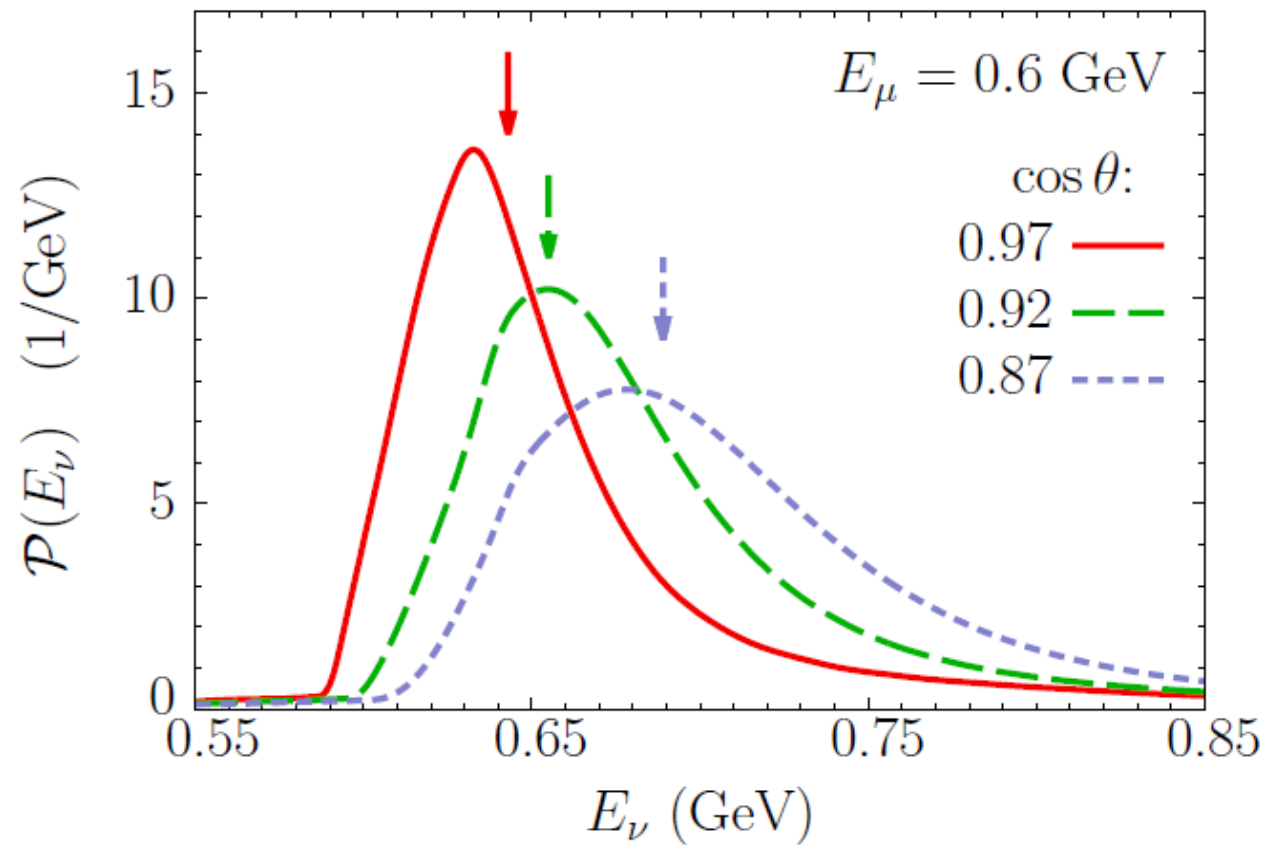
Realistic calculations vs E_{rec}

Same physics drives the QE peak position and relates the kinematics to neutrino energy

Polychromatic beam

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

E' and θ known
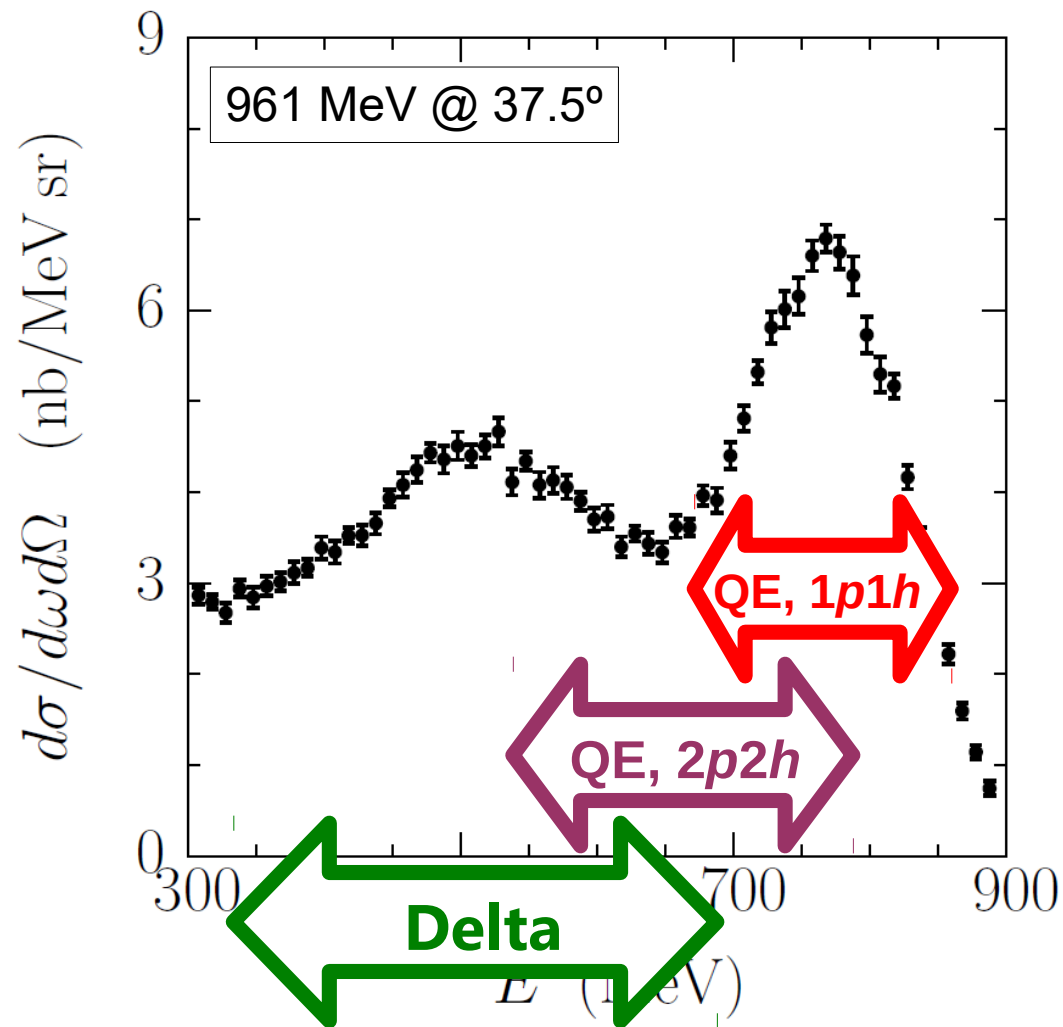
$E = ?$

CC0π events

In practice, CCQE energy reconstruction is applied to all events not containing **obseved pions**.

$+$
CCQE (any number of nucleons)
pion production and followed by absorption
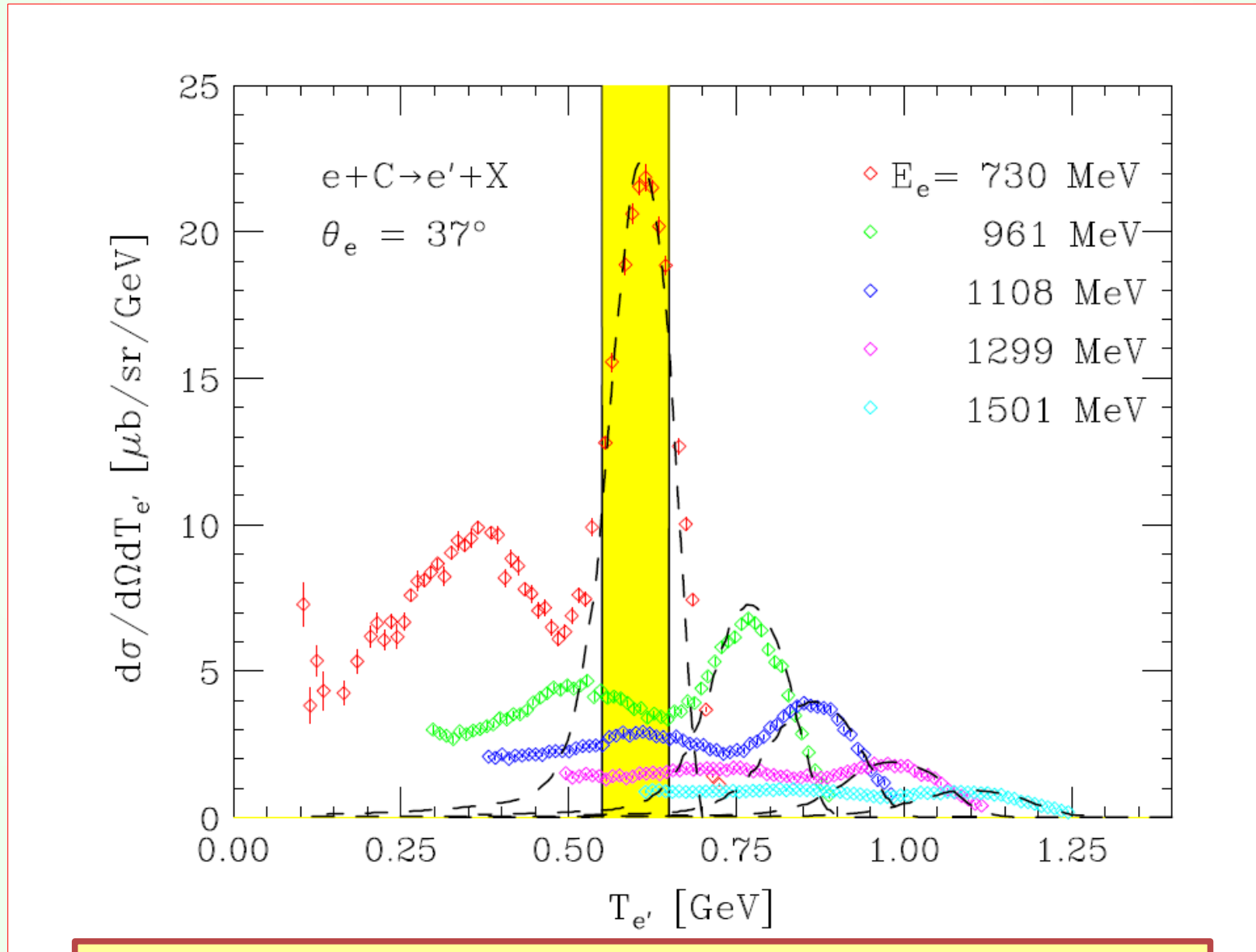undetected pions

$-$ CCQE with pions from FSI

0π events

Recall the monochromatic-beam case

CCQE events of given $l^\pm$ kinematics

Omar Benhar @ NuFact11, 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 $\cos\theta$.
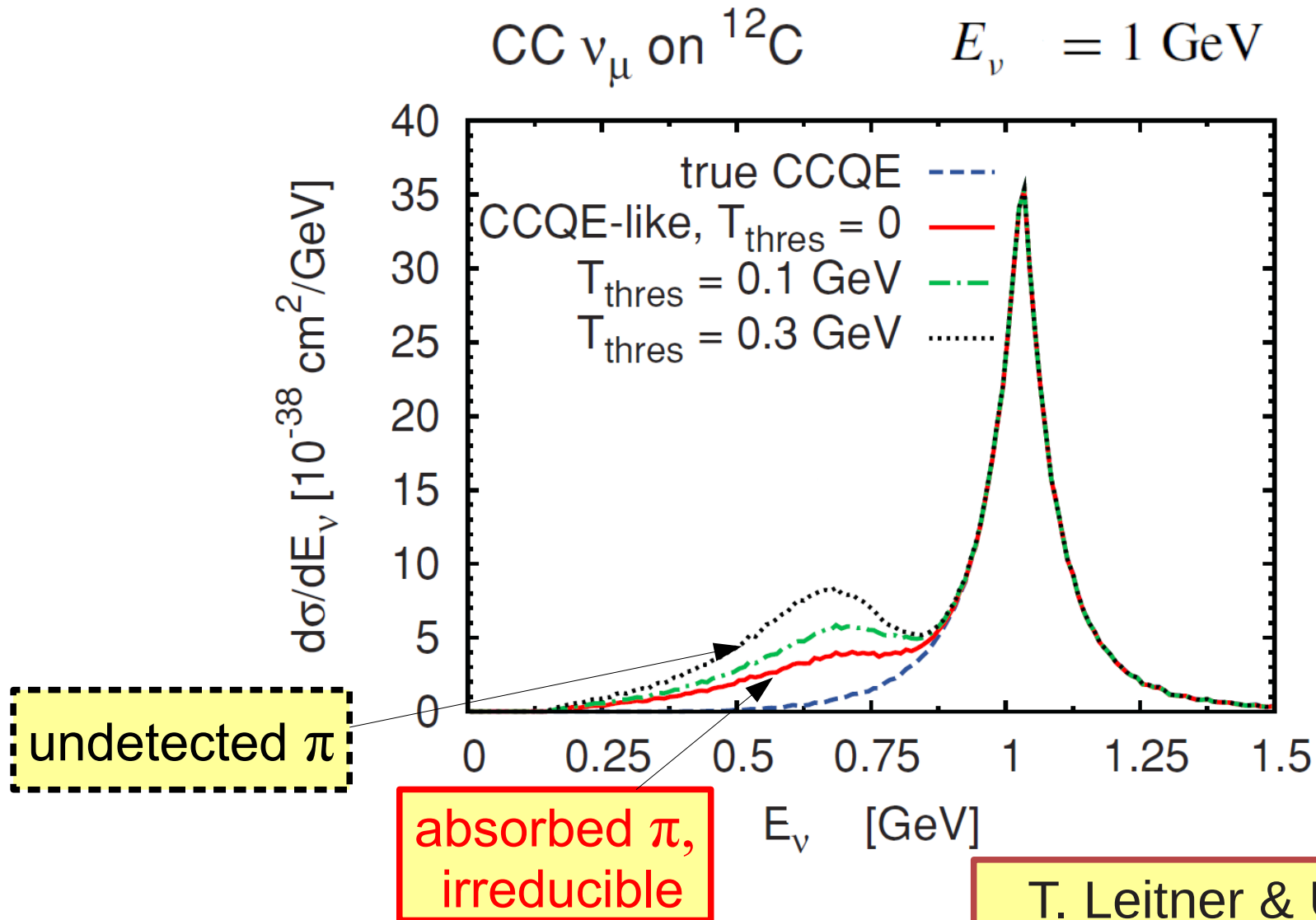
An undetected pion typically lowers the reconstructed energy by **~300–350 MeV**.

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

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

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

Absorbed or undetected pions

CC ν_μ on ^{12}C $E_\nu = 1$ GeV

true CCQE

CCQE-like, $T_{thres} = 0$

$T_{thres} = 0.1$ GeV

$T_{thres} = 0.3$ GeV

dσ/dE$_\nu$ [10^{-38} cm^2/GeV]

E_ν [GeV]

undetected π

absorbed π, irreducible

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

2*p*2*h* final states

Final states involving two (or more) nucleons may come from

- **initial-state correlations**: ~20% of nucleons in nucleus strongly interact, typically forming a deuteron-like *np* pair of high relative momentum

- **final-state interactions**

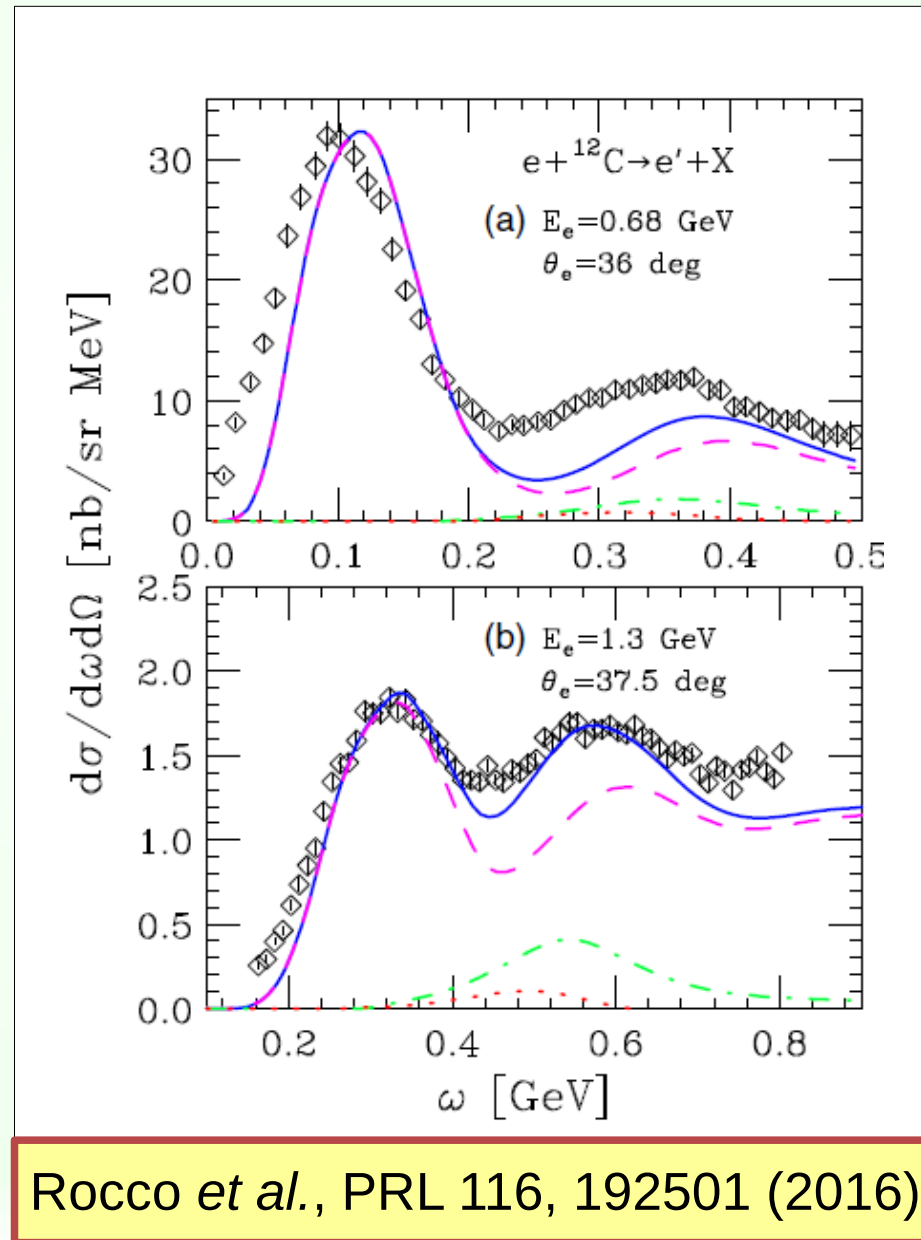- **2-body reaction mechanisms**, such as by meson-exchange currents

Alberico *et al.*
Ann. Phys. 154, 356 (1984)
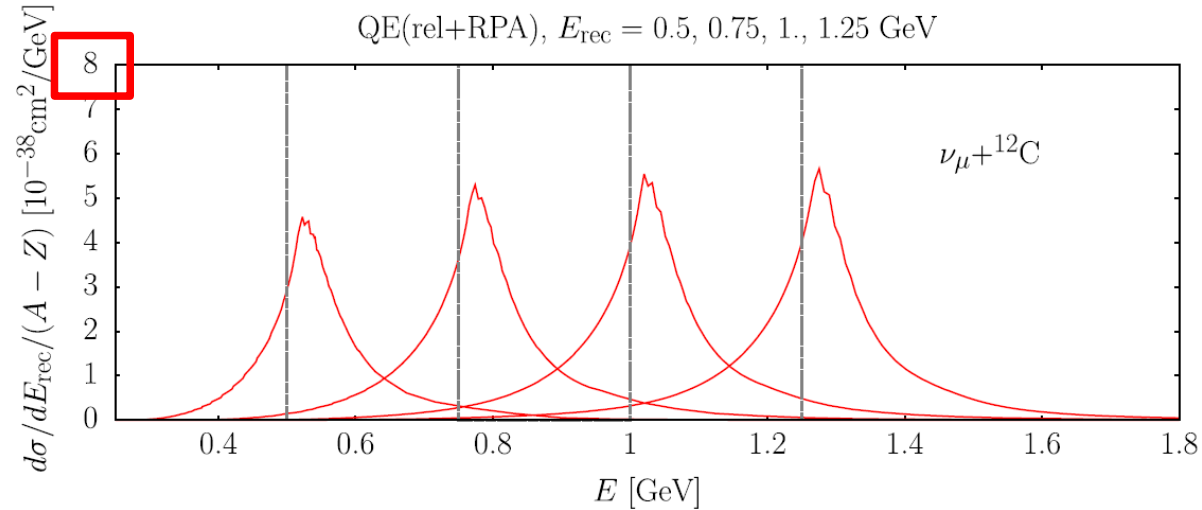
2-body reaction mechanisms
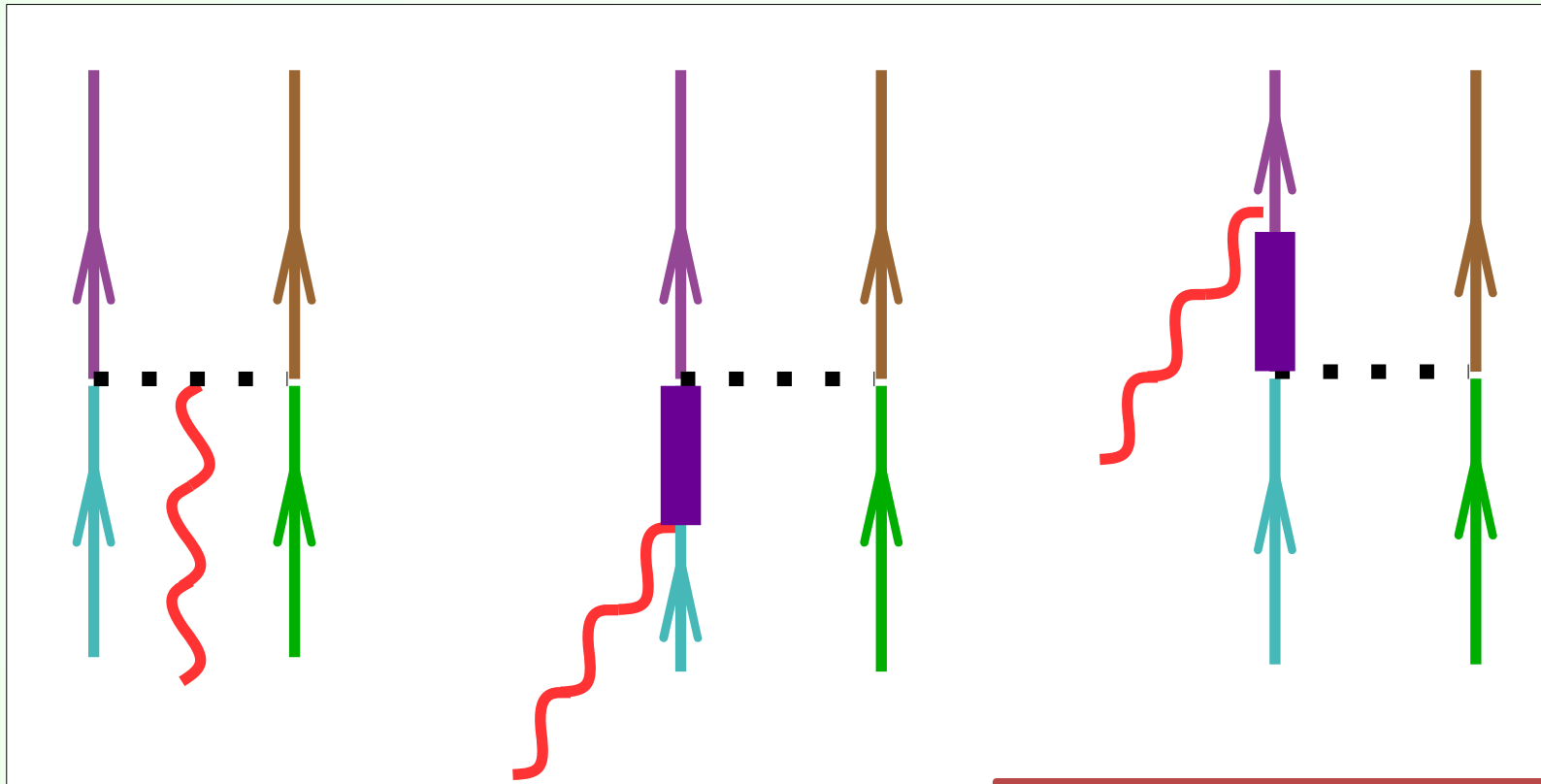
Donnelly *et al.*
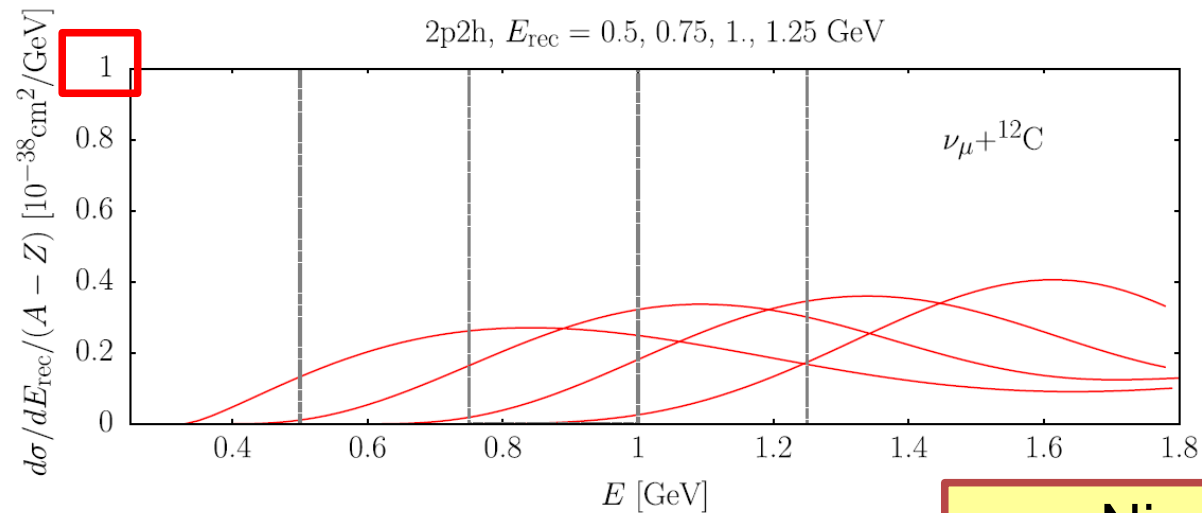PLB 76, 393 (1978)

2p2h contribution to the cross section

Rocco *et al.*, PRL 116, 192501 (2016)

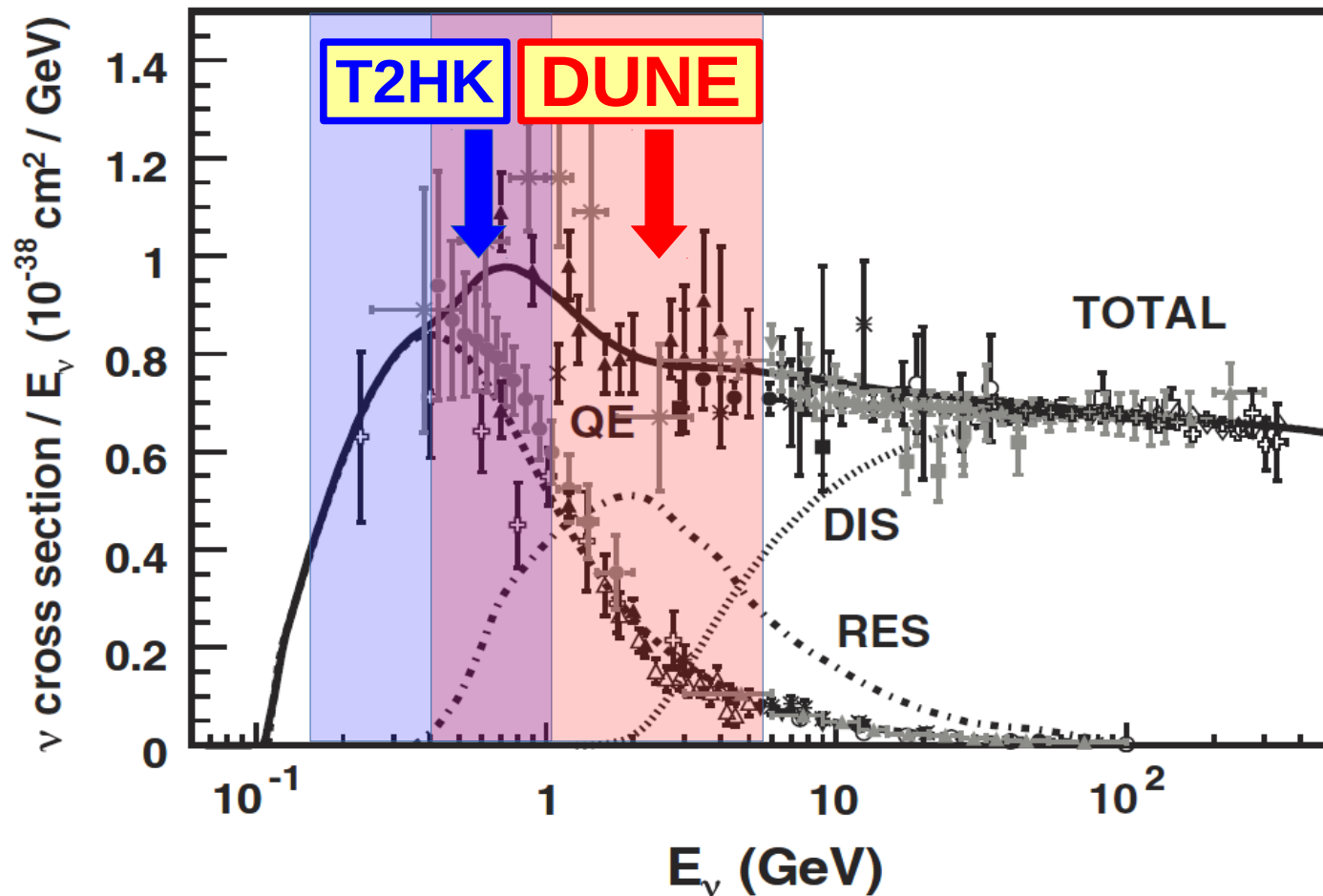# 2*p*2*h* effect on energy reconstruction

1*p*1*h*

2*p*2*h*

Nieves *et al.*,
PRD 85, 113008 (2012)

Neutrino scattering

adopted from
Formaggio & Zeller, RMP 84, 1307 (2013)

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Calorimetric energy reconstruction

- Seemingly simple procedure: add all energy depositions in the detector related to the neutrino event

- Advantages: (i) applicable to any final states, (ii) in an ideal detector, the reconstruction would be exact and insensitive to nuclear effects

π

neutrino

neutron

nuclear deexcitation
(γ, p, n, d, α)
possibly delayed

charged lepton
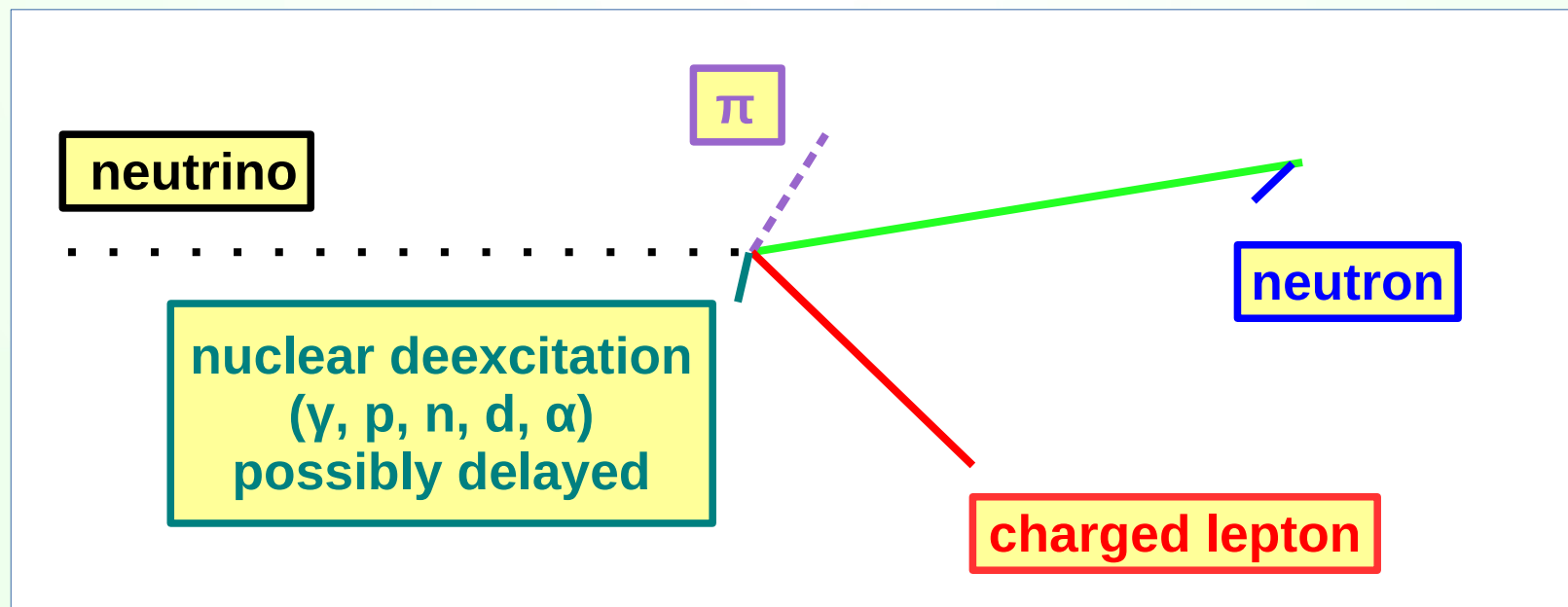
Calorimetric energy reconstruction

- In a real detector the method is only insensitive to nuclear effects when

  missing energy « neutrino energy

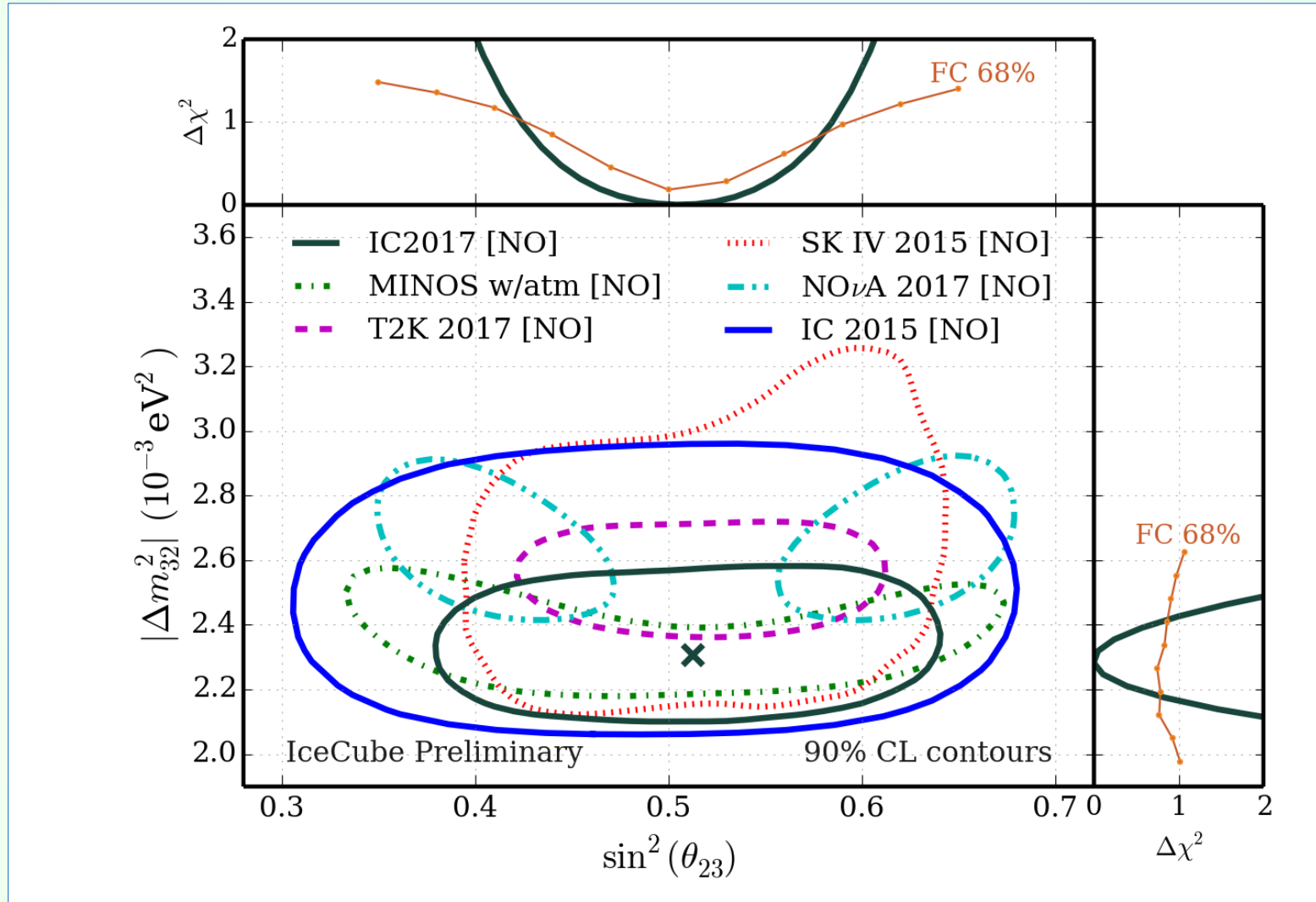- Otherwise, requires input from nuclear models

  <div style="border:1px solid; background:#ffffcc">A.M.A.,arXiv:
1704.07835</div>

- Correction for the missing energy **may be significant**:

  - undetected pion at least $m_\pi = 140$ MeV

  - neutrons are hard to associate with the event

To achieve ~25 MeV accuracy in DUNE, accurate predictions of exclusive cross sections are required.

What precision are we reaching?

J. Hignight (IceCube), APS April Meeting, 2017

What precision are we reaching?

At neutrino energy ~600 MeV (T2K kinematics),

- 10% uncertainty (current T2K), ~60 MeV
- 2% uncertainty (current global fits), ~10 MeV

At the NOvA and DUNE kinematics, values x4−5.

DUNE and **T2HK** aim at uncertainties < 1%, requiring ~**25 MeV** and ~**5 MeV** precision.

Effects considered to be "small" need to be accounted for accurately to avoid biases.

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.
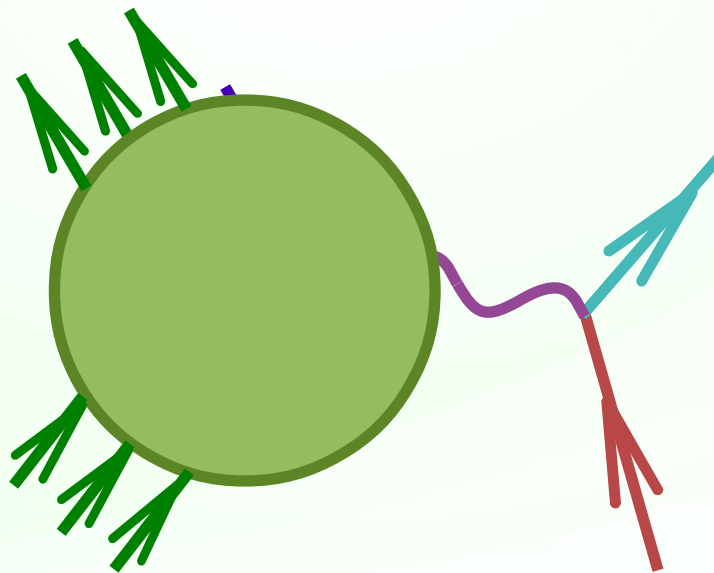
Impulse approximation

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 $|\mathbf{q}|$ is high enough, as the probe's spatial resolution is $\sim 1/|\mathbf{q}|$.
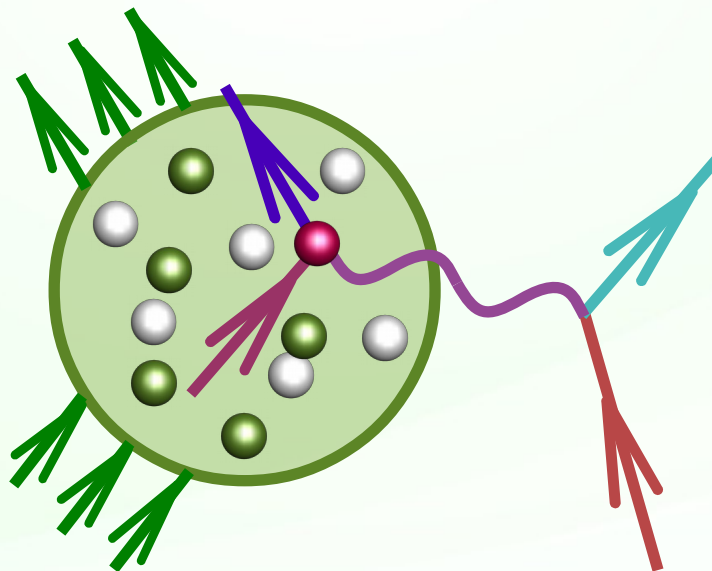
A(e, e') cross section

In Born approximation

$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \frac{\alpha^2}{Q^4}\frac{E_{e'}}{E_e}\,L_{\mu\nu}W^{\mu\nu}$$

with the lepton tensor

$$L_{\mu\nu} = 2\left[k_e^\mu k_{e'}^\nu + k_e^\nu k_{e'}^\mu - g^{\mu\nu}(k_e k_{e'})\right]$$

and the nuclear tensor

$$W^{\mu\nu} = \sum_X \langle 0|J^\mu|X\rangle\langle X|J^\nu|0\rangle\delta^{(4)}(p_0 + q - p_X)$$

$$W^{\mu\nu} = W_1\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + \frac{W_2}{m^2}\left(p_0^\mu - \frac{(p_0 q)}{q^2}q^\mu\right)\left(p_0^\nu - \frac{(p_0 q)}{q^2}q^\nu\right)$$

Benhar *et al.*, RMP 80, 189 (2008)

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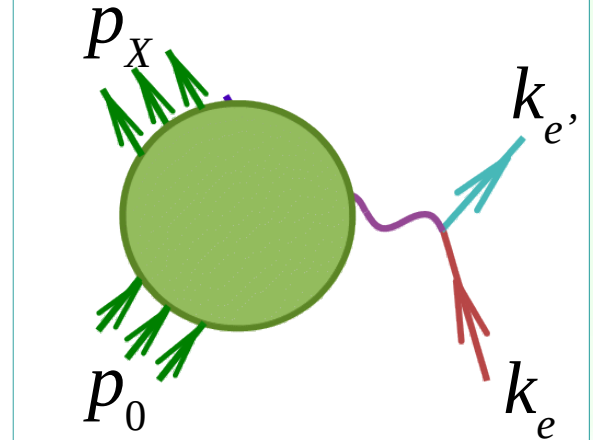
Impulse approximation

The current reduces to a sum of 1-body currents

$$J^\mu \to \sum_i j_i^\mu$$

and the final state separates to

$$|X\rangle \to |x, \mathbf{p}_x\rangle \otimes |\mathcal{R}, \mathbf{p}_\mathcal{R}\rangle$$

leading to the nuclear current

$$\langle 0|J^\mu|X\rangle = \left(\frac{M}{\sqrt{|\mathbf{p}_\mathcal{R}|^2 + M^2}}\right)^{1/2} \langle 0|\mathcal{R}, \mathbf{p}_\mathcal{R}; \mathrm{N}, -\mathbf{p}_\mathcal{R}\rangle \sum_i \langle -\mathbf{p}_\mathcal{R}, N|j_i^\mu|x, \mathbf{p}_x\rangle$$

Benhar *et al.*, RMP 80, 189 (2008)
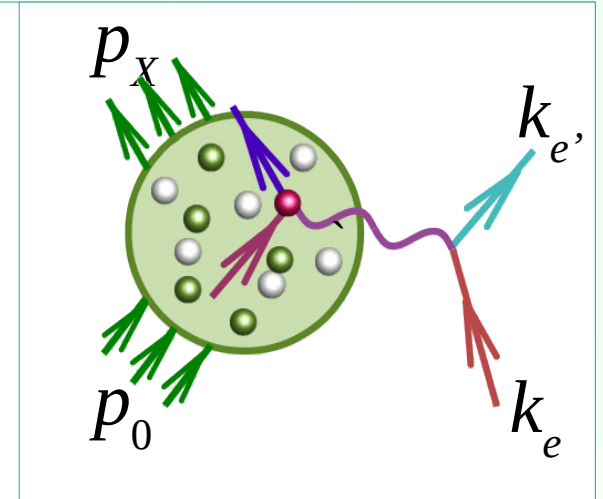
Impulse approximation

The nuclear tensor

$$W^{\mu\nu} = \sum_X \langle 0|J^\mu|X\rangle\langle X|J^\nu|0\rangle \delta^{(4)}(p_0 + q - p_X)$$

becomes in the impulse approximation

$$W^{\mu\nu} = \sum_{x,\mathcal{R}} \int d^3 p_\mathcal{R} \, d^3 p_x |\langle 0|\mathcal{R}, \mathbf{p}_\mathcal{R}; \mathrm{N}, -\mathbf{p}_\mathcal{R}\rangle|^2$$

$$\times \frac{M}{E_\mathcal{R}} \sum_i \langle -\mathbf{p}_\mathcal{R}, \mathrm{N}|j_i^\mu|x, \mathbf{p}_x\rangle\langle \mathbf{p}_x, x|j_i^\nu|\mathrm{N}, -\mathbf{p}_\mathcal{R}\rangle$$

$$\times \delta^{(3)}(\mathbf{q} - \mathbf{p}_\mathcal{R} - \mathbf{p}_x)\delta(\omega + E_0 - E_\mathcal{R} - E_x),$$

Benhar *et al.*, RMP 80, 189 (2008)

Impulse approximation

$$W^{\mu\nu}(\mathbf{q}, \omega) = \int d^3p \, dE \, \frac{M}{E_{\mathbf{p}}} \left[Z S_p(\mathbf{p}, E) w_p^{\mu\nu} + (A - Z) S_n(\mathbf{p}, E) w_n^{\mu\nu} \right]$$

where

$$S_N(\mathbf{p}, E) = \sum_{\mathcal{R}} |\langle 0 | \mathcal{R}, -\mathbf{p}; \mathrm{N}, \mathbf{p}\rangle|^2 \delta(E - M + E_0 - E_{\mathcal{R}})$$

$$w_N^{\mu\nu} = \sum_x \langle \mathbf{p}, \mathrm{N}|j_N^\mu|x, \mathbf{p} + \mathbf{q}\rangle \langle \mathbf{p} + \mathbf{q}, x|j_N^\nu|\mathrm{N}, \mathbf{p}\rangle \delta(\widetilde{\omega} + E_{\mathbf{p}} - E_x)$$

and

$$\widetilde{\omega} + E_{\mathbf{p}} = E_x = \omega + E_0 - E_{\mathcal{R}} = \omega + M - E$$

Benhar *et al.*, RMP 80, 189 (2008)

Importance of relativistic kinematics

A.M.A. & O. Benhar, PRC 83, 054616 (2011)
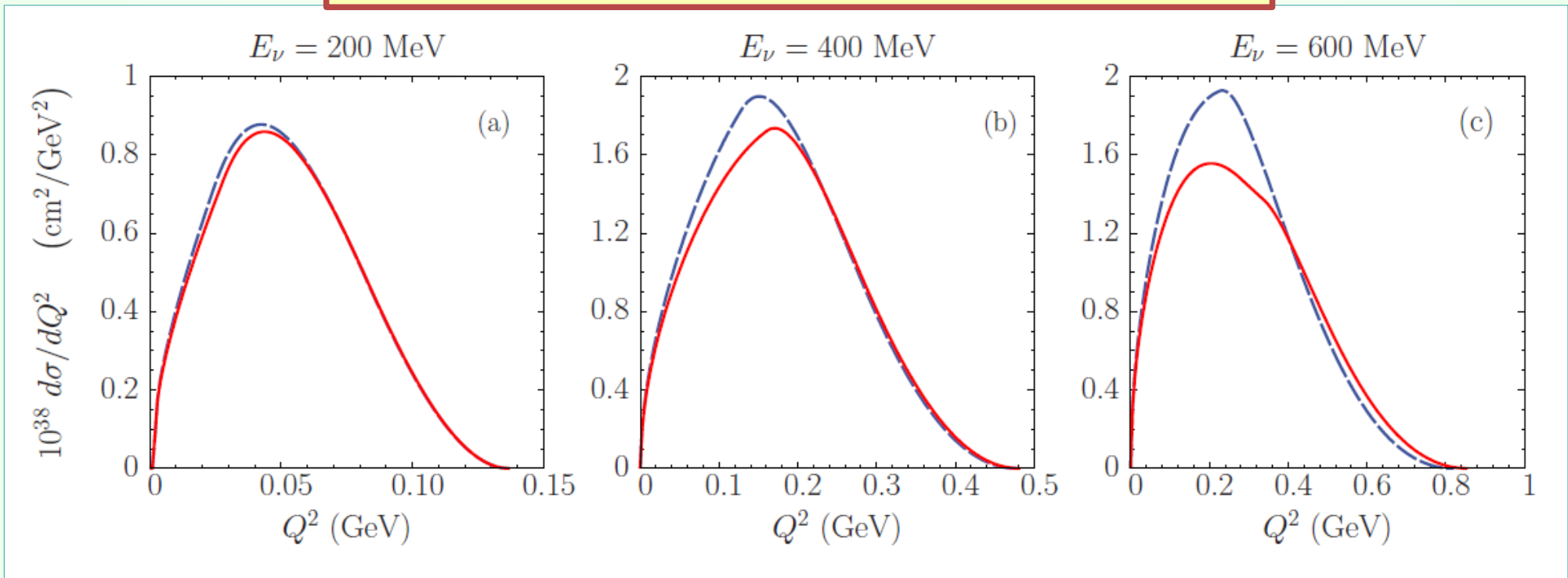
Sizable differences between the **relativistic** and **nonrelativistic** results at neutrino energies ~500 MeV.

Importance of relativistic kinematics
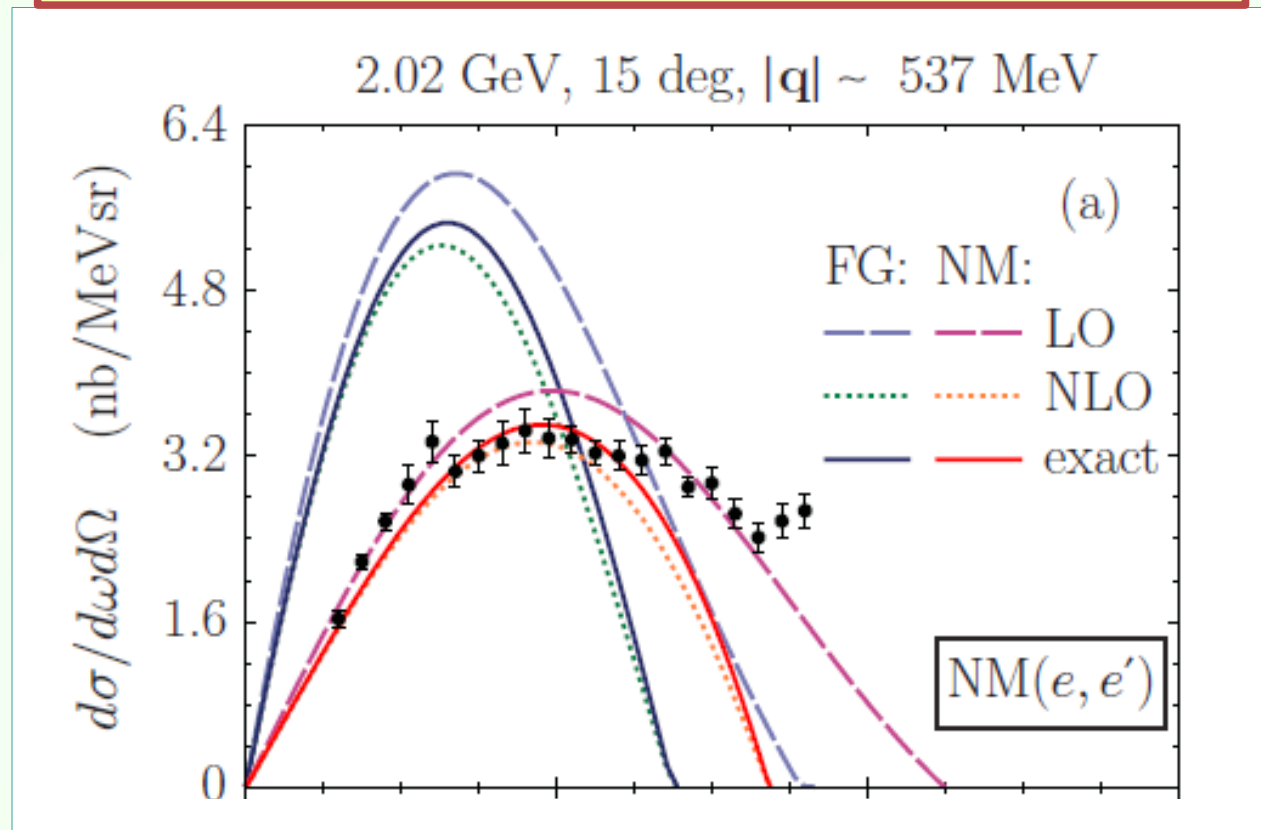
At |q|~540 MeV, semi-relativistic result is **5% lower** than the exact cross section.

Impulse approximation

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

Hole spectral function

Particle spectral function

Elementary cross section
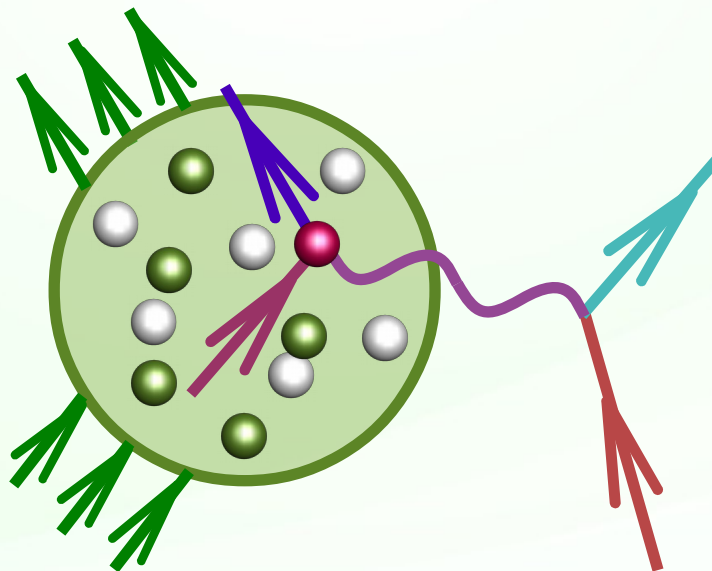
Impulse approximation

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.

Much more than the vector part...

electrons — 1650 MeV, 13.5 deg
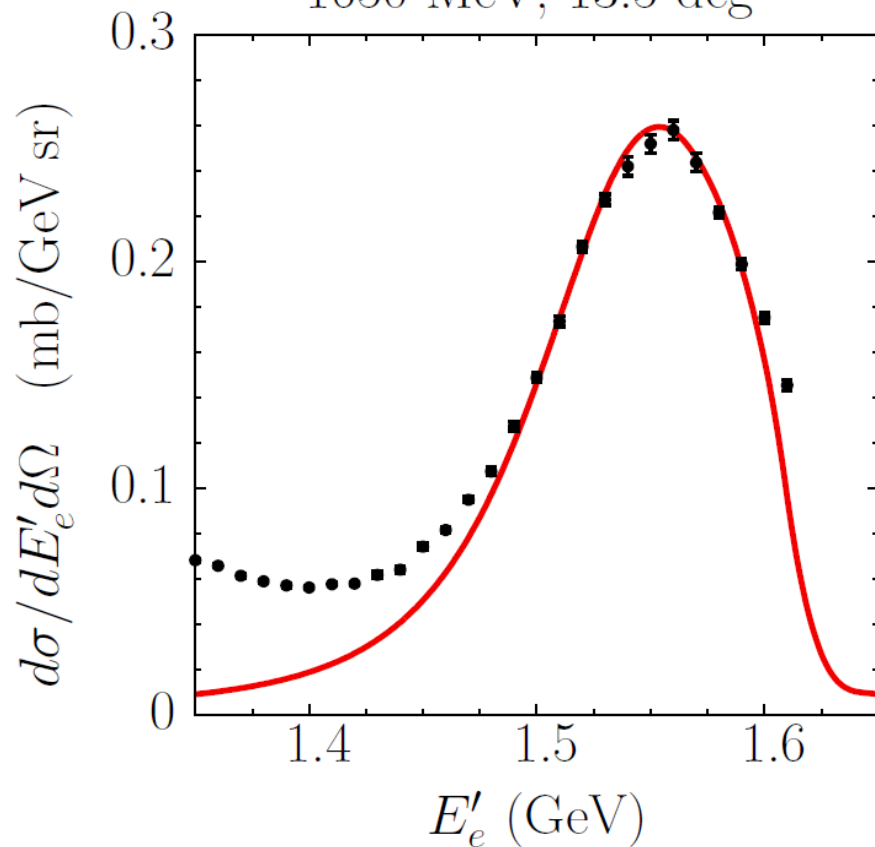
muon neutrinos — 1650 MeV, 13.5 deg

vector part
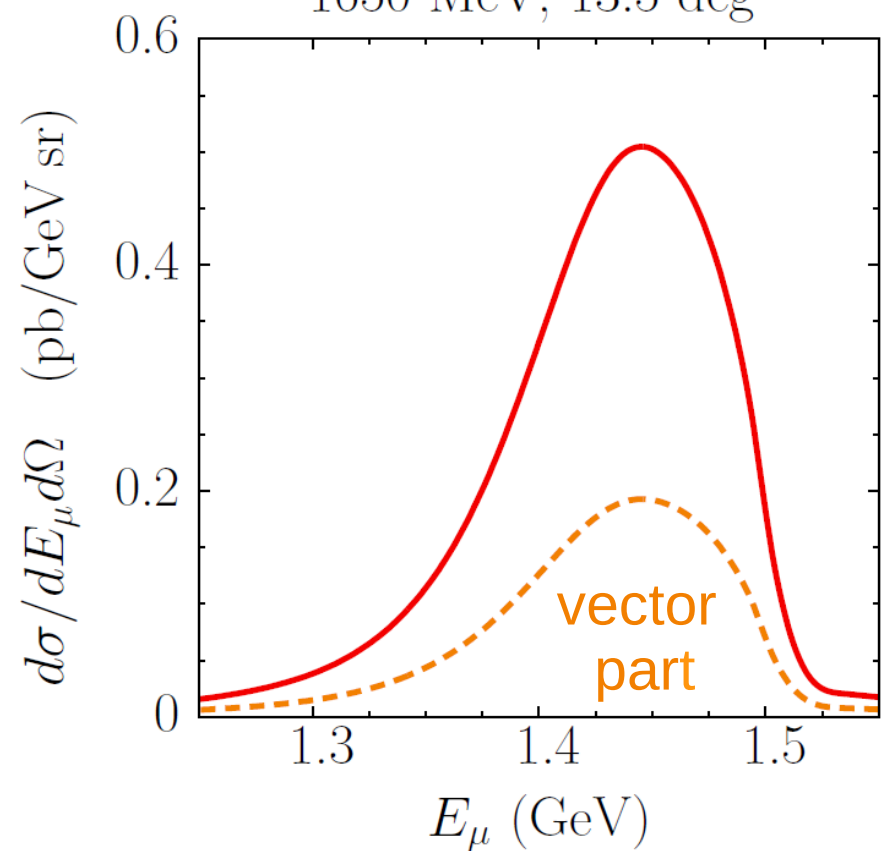
How relevant is the precision?

Expected sensitivity of DUNE to CP violation as a function of exposure for a ν_e signal normalization uncertainties between 5% + 1% and 5% + 3%.
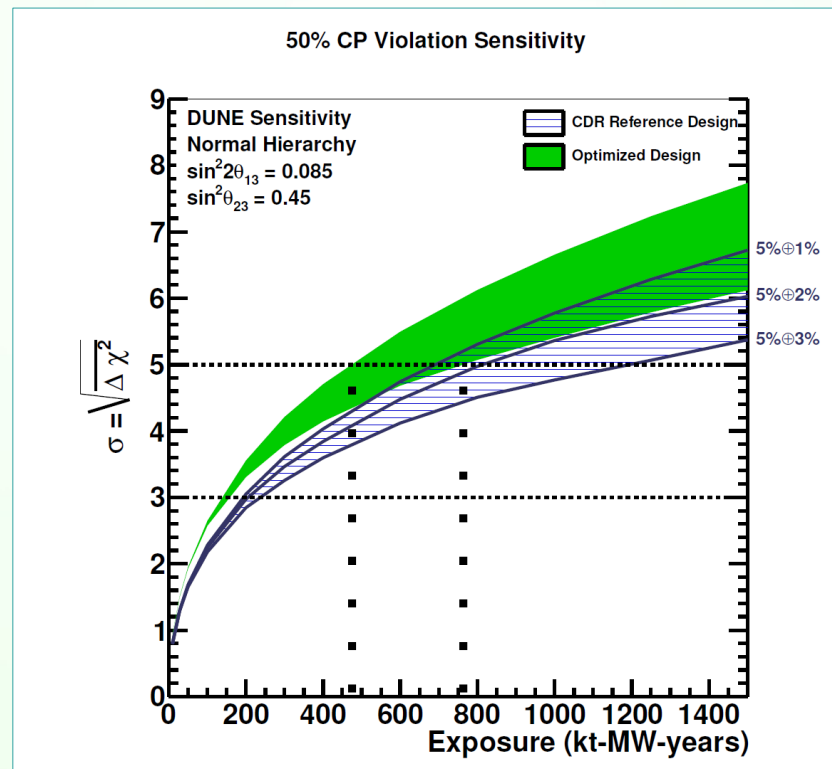
Acciari *et al.*, arXiv:1512.06148

Fermi gas model

Fermi gas model

Imagine an infinite space filled uniformly with nucleons
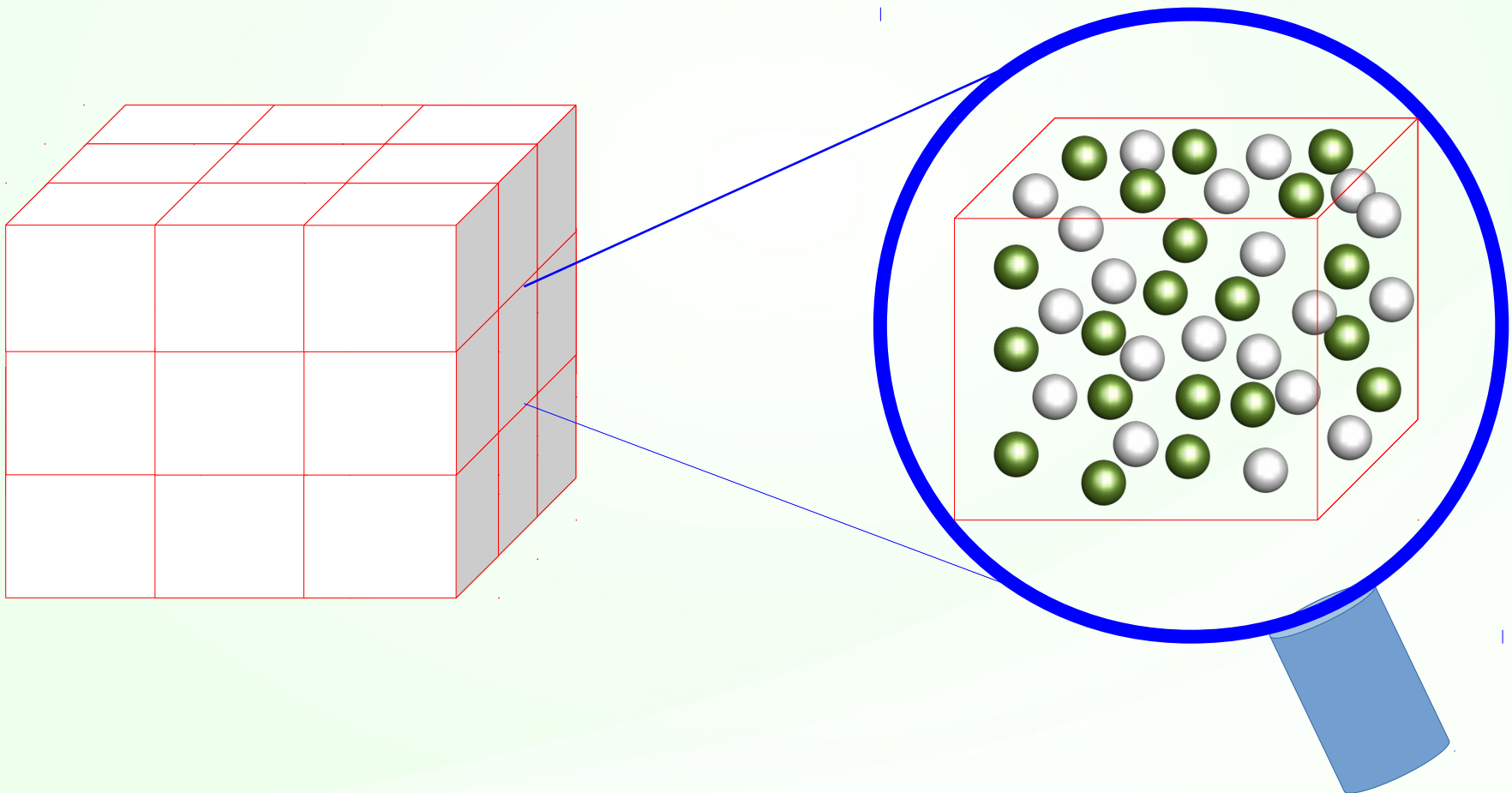
Fermi gas model

Due to the translational invariance, the eigenstates can be labeled using momentum, $\psi(x) = C e^{-i\boldsymbol{p}\boldsymbol{x}}$.
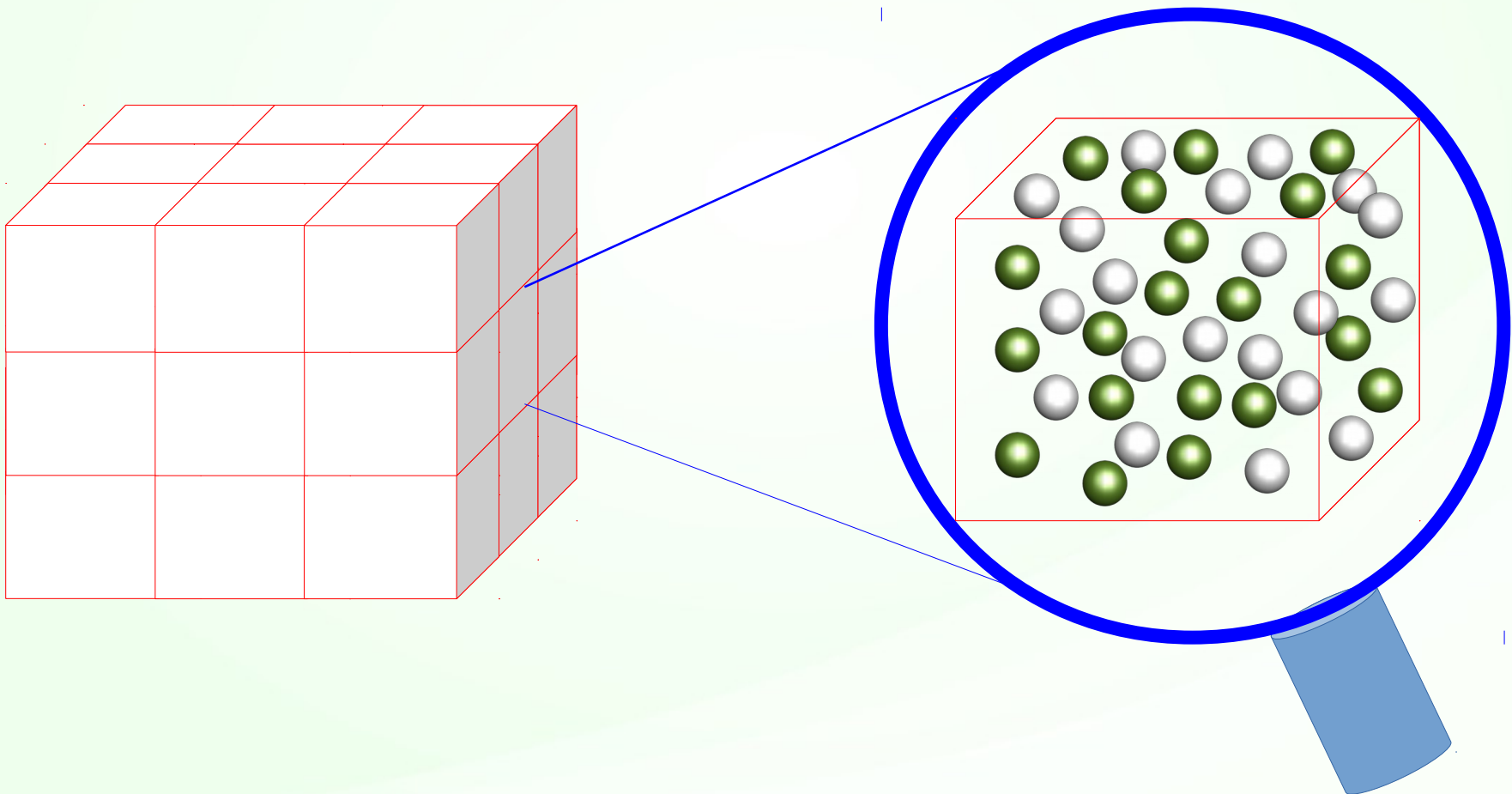
Fermi gas model

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

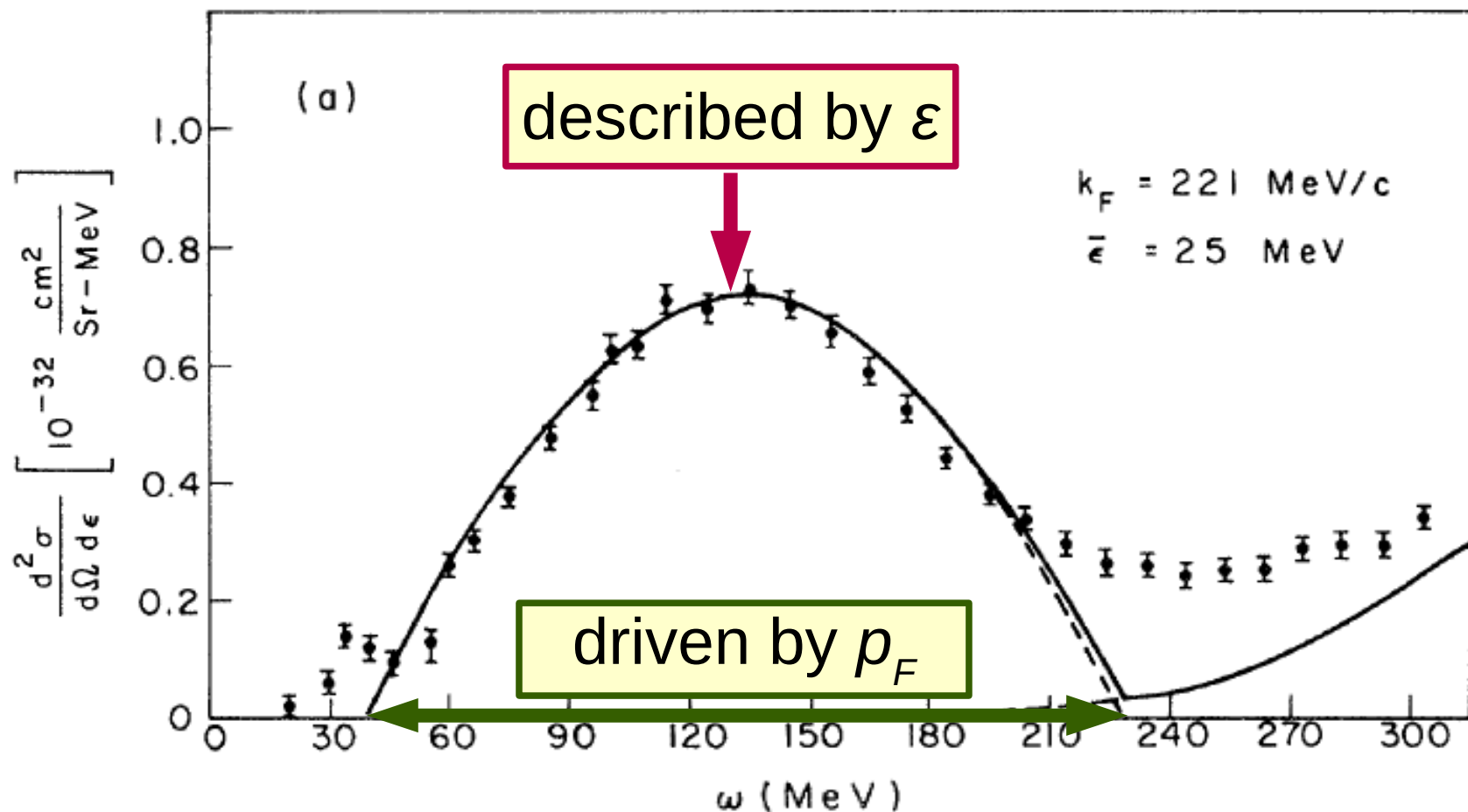every state occupies $(2\pi/L)^3$ in the momentum space
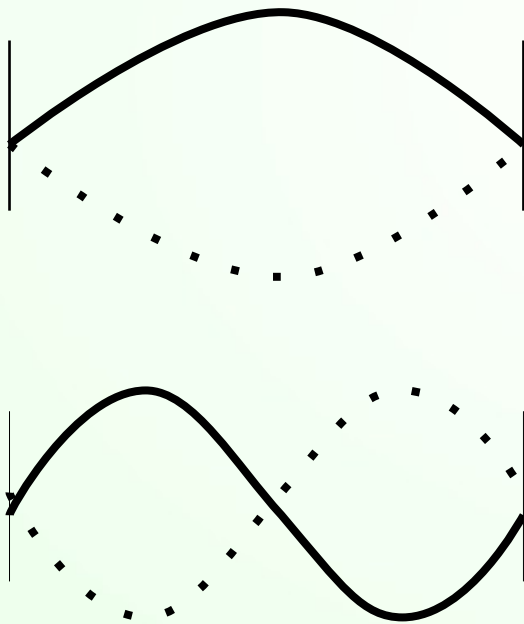
-L/2   +L/2
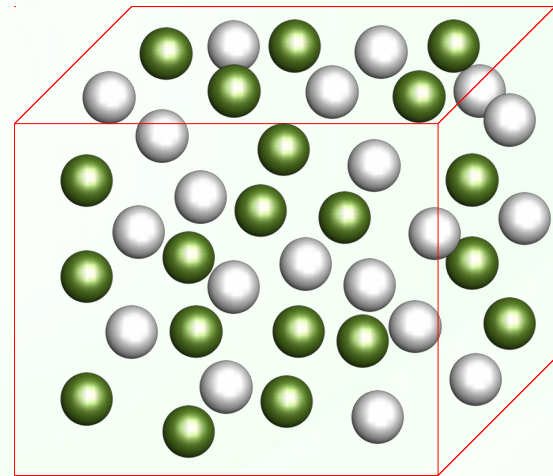
Fermi gas model

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

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

p_F
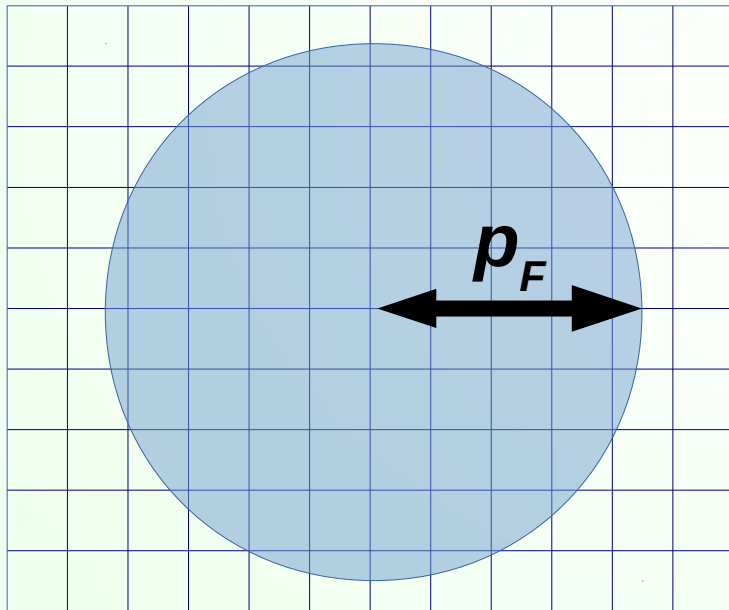
Momentum space
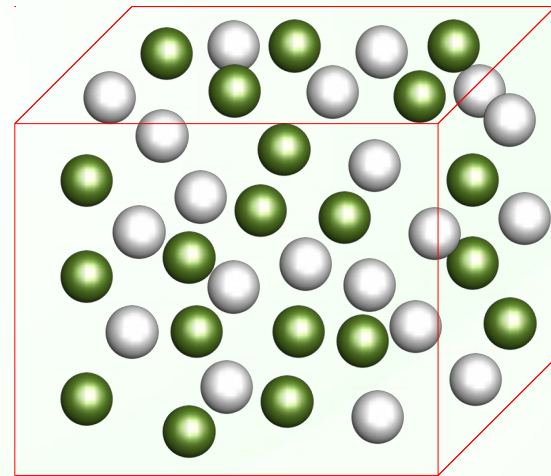
Coordinate space

Electron scattering off carbon, 500 MeV, 60 deg

$$\frac{d^2\sigma}{d\Omega\,d\epsilon}\left[10^{-32}\,\frac{cm^2}{Sr-MeV}\right]$$

(a)

$k_F = 221\ MeV/c$

$\bar{\epsilon} = 25\ MeV$

$\omega\ (MeV)$
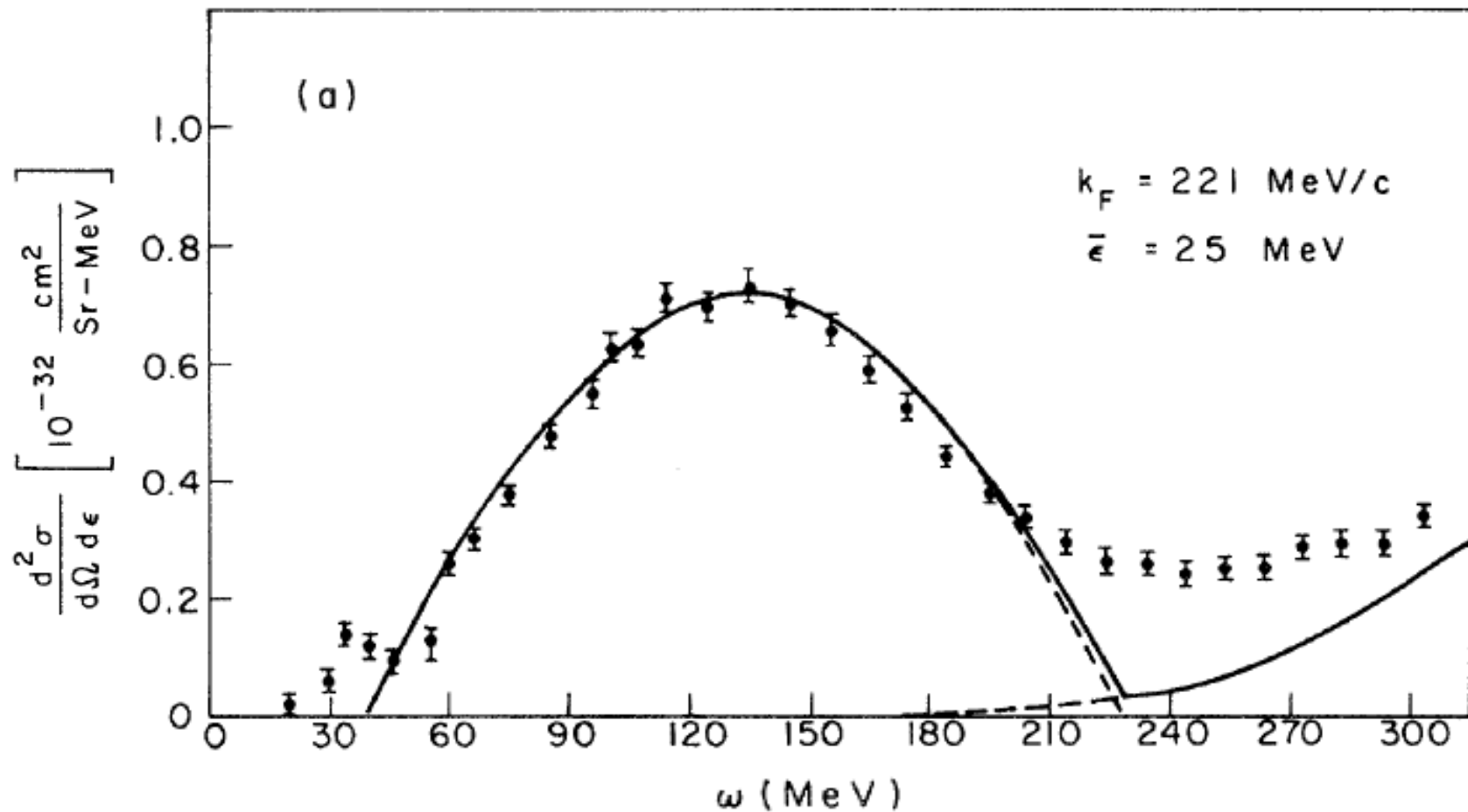
Moniz *et al.*, PRL 26, 445 (1971)

Electron scattering off carbon, 500 MeV, 60 deg

(a)

described by ε

driven by p_F

$k_F = 221$ MeV/c

$\bar{\varepsilon} = 25$ MeV

$\dfrac{d^2\sigma}{d\Omega\, d\epsilon}\ \left[\ 10^{-32}\ \dfrac{cm^2}{Sr-MeV}\ \right]$

ω (MeV)

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

Fermi gas model
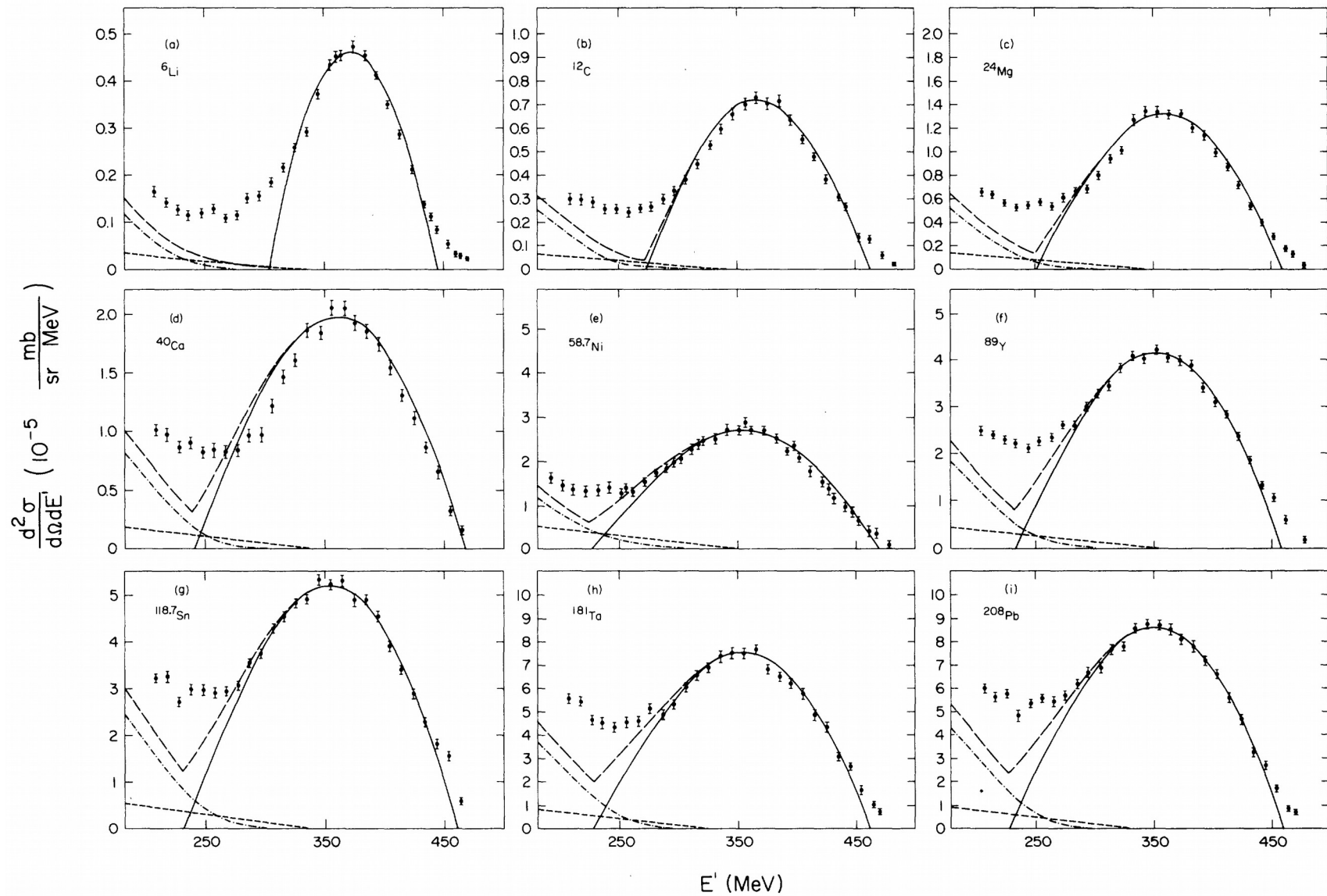
Fermi gas model

What happens at kinematics other than 500 MeV, 60 deg?
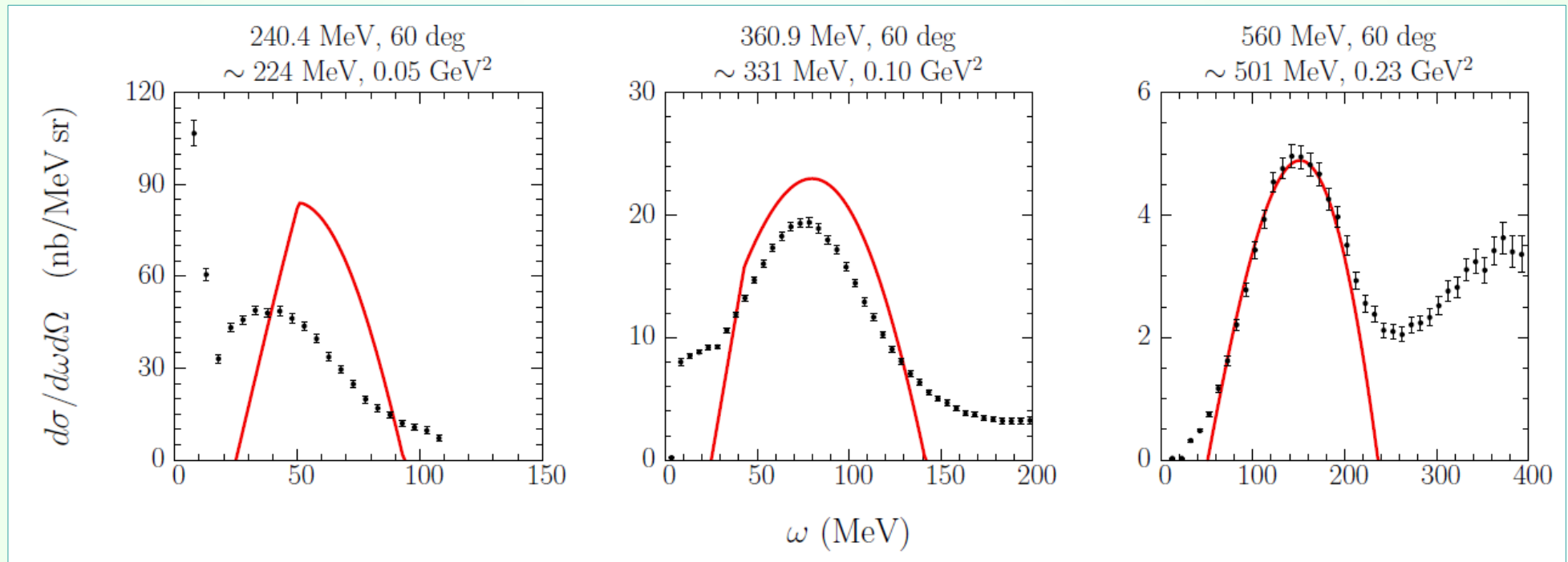
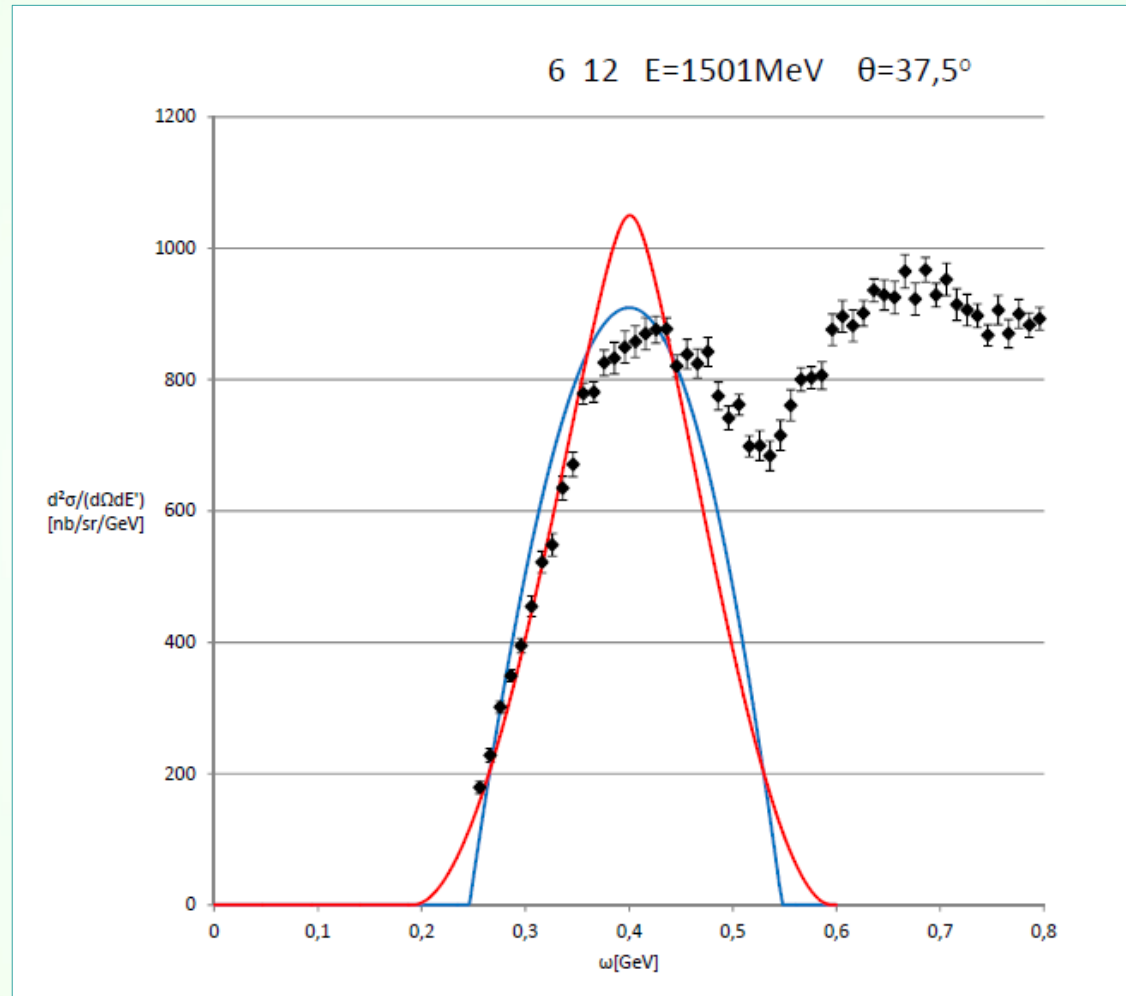Barreau *et al.*, NPA 402, 515 (1983)

Charge-density in nuclei
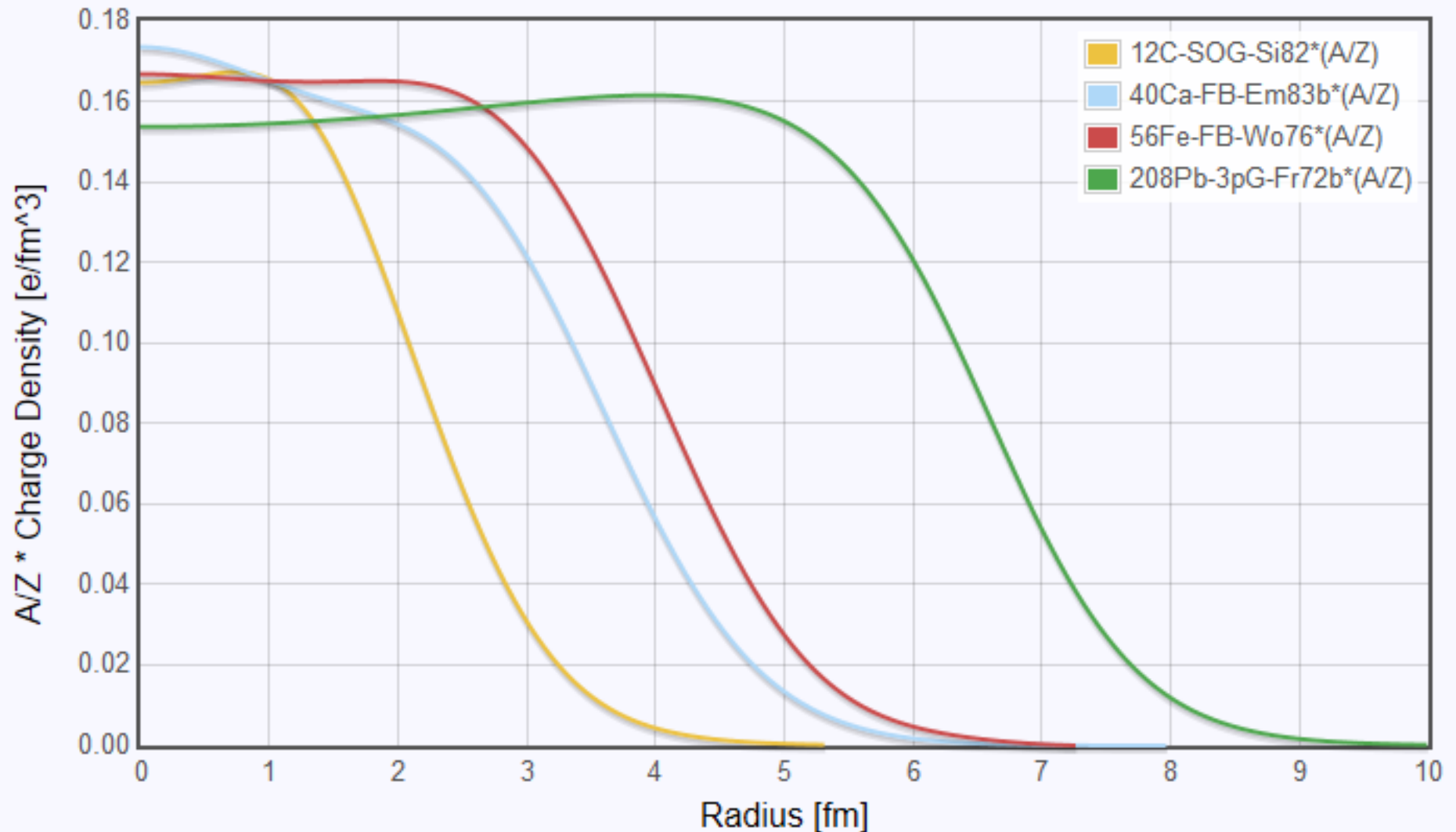
Local Fermi gas model

A spherically symmetric nucleus can be approximated by concentric spheres of a constant density.
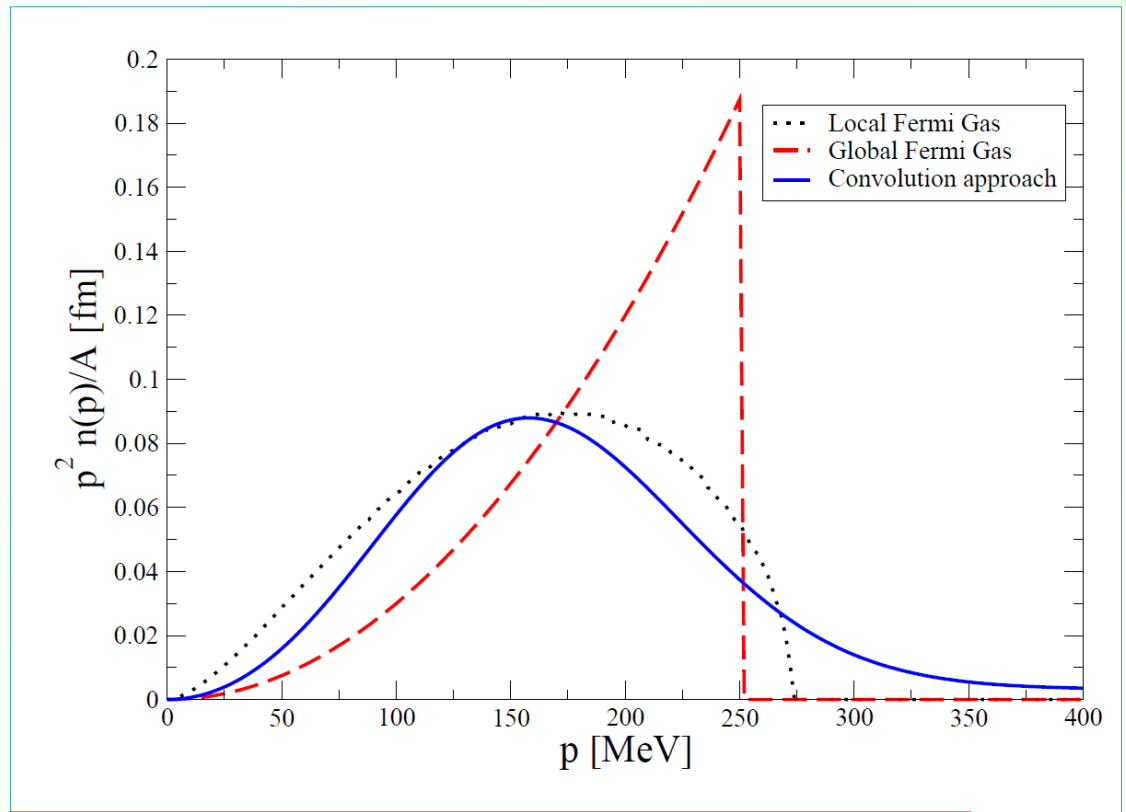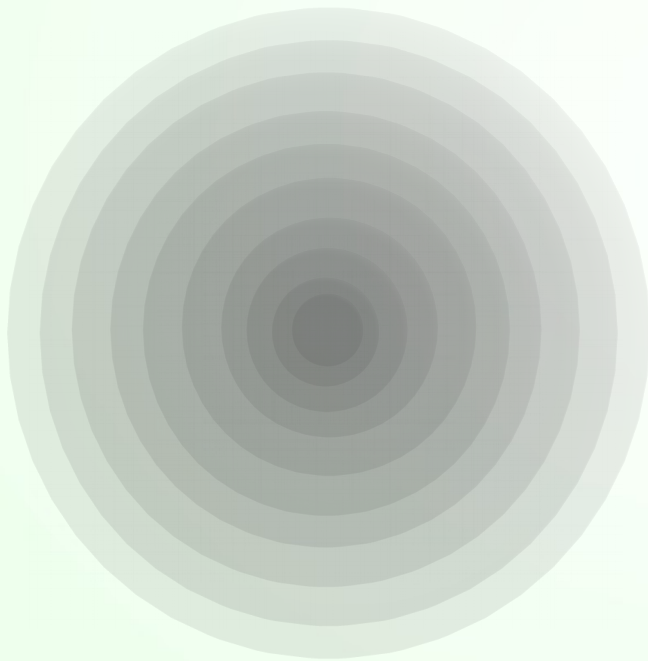
L. Alvarez-Ruso *et al.*,
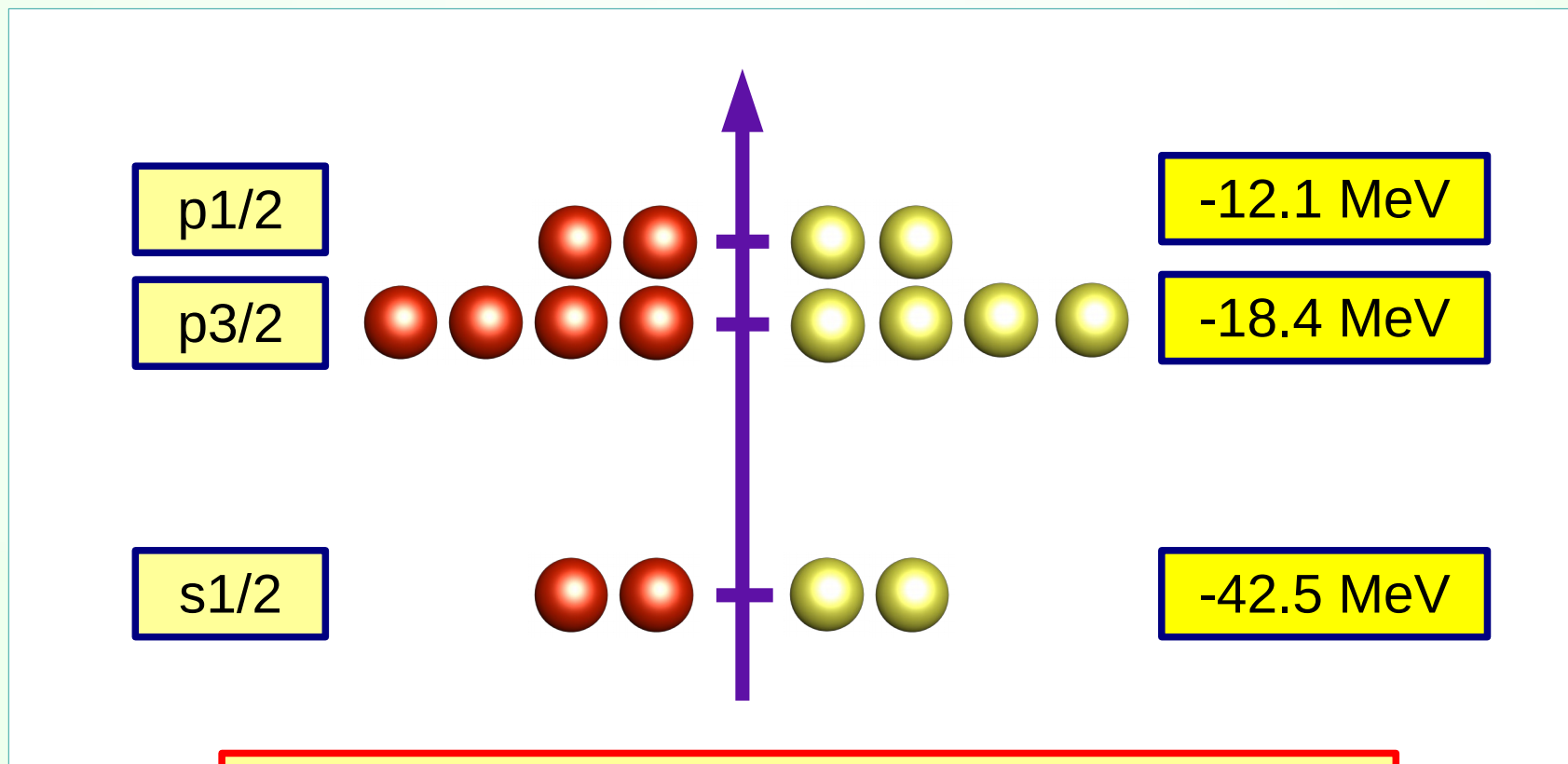New J.Phys. 16, 075015 (2014)

Local vs. global Fermi gas models

B. Kowal, M.Sc. thesis,
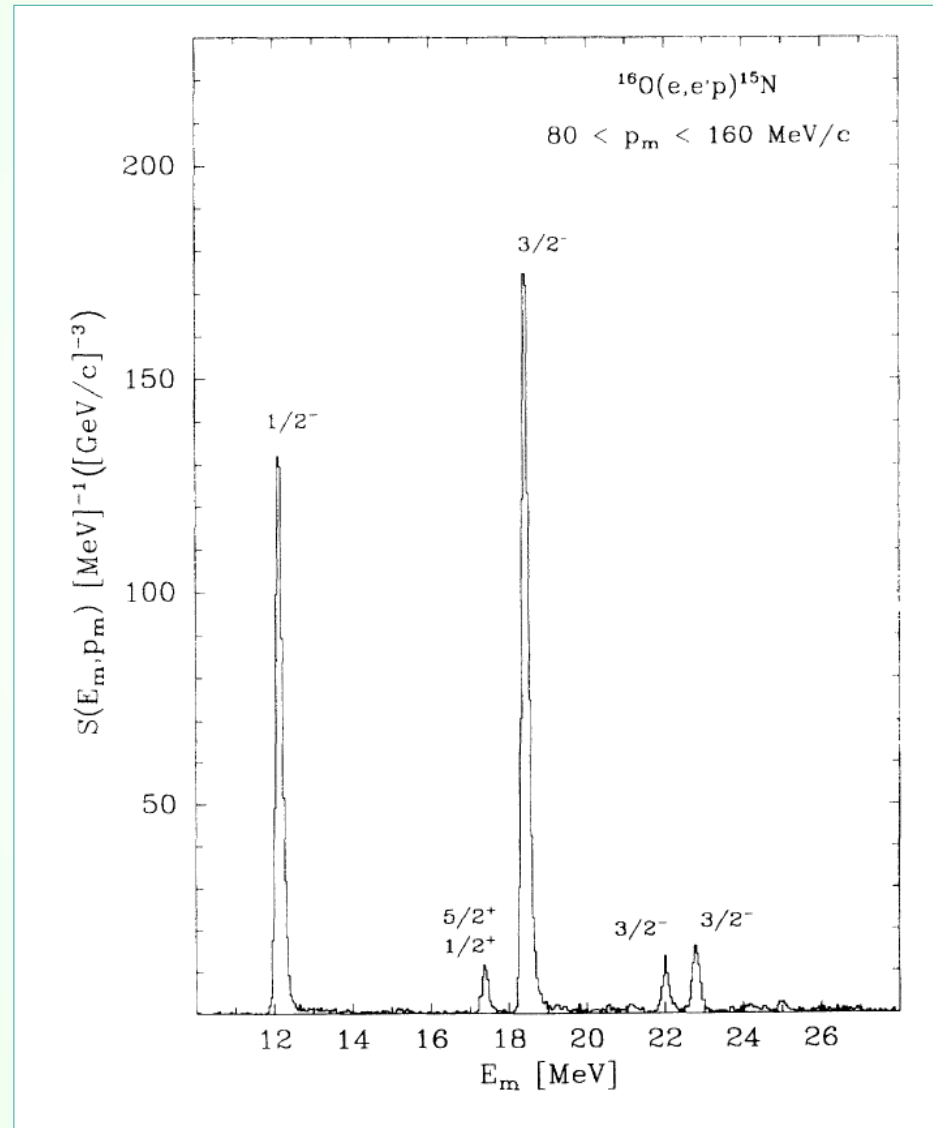University of Wrocław (2014)

Shell model

Shell model

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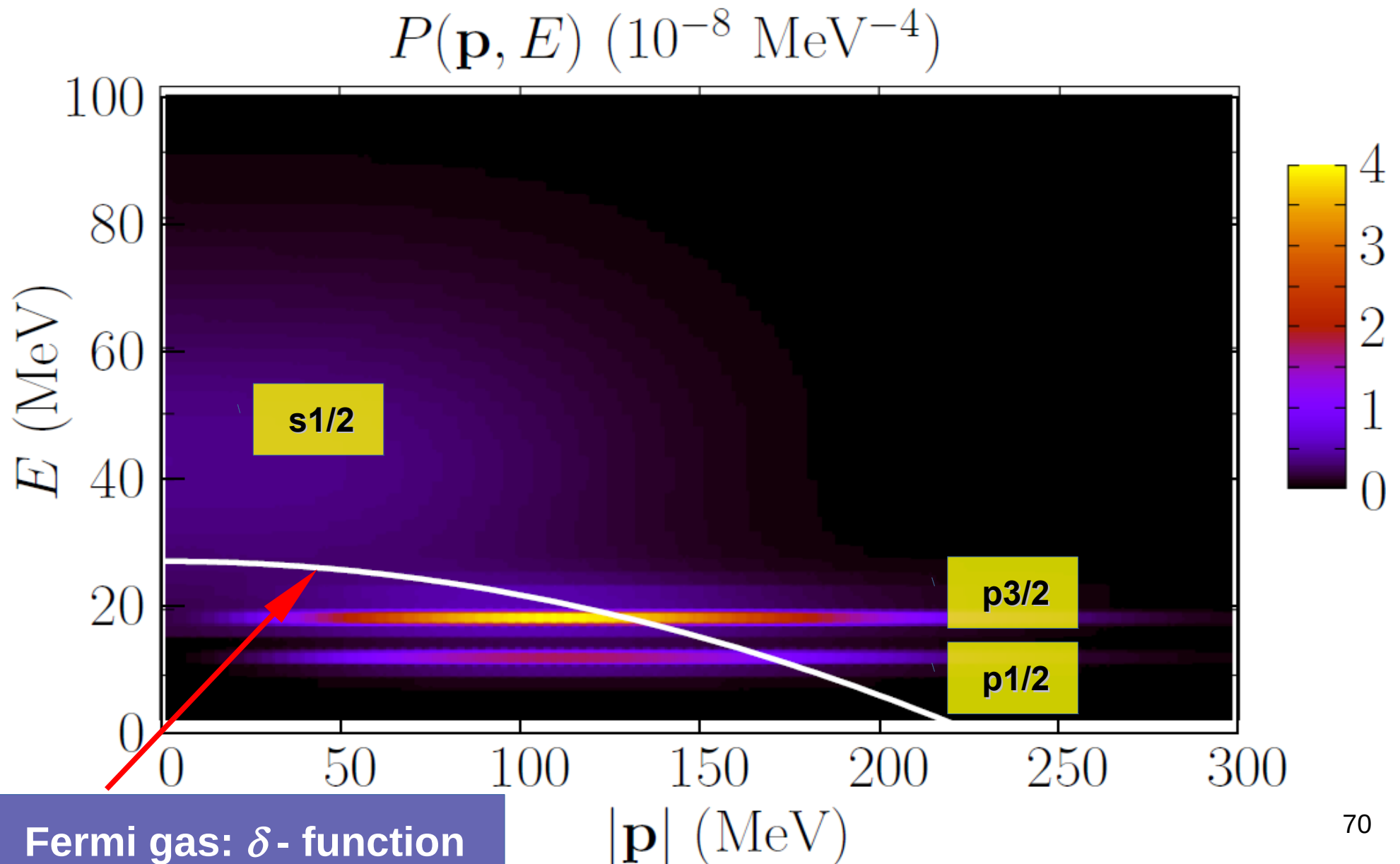

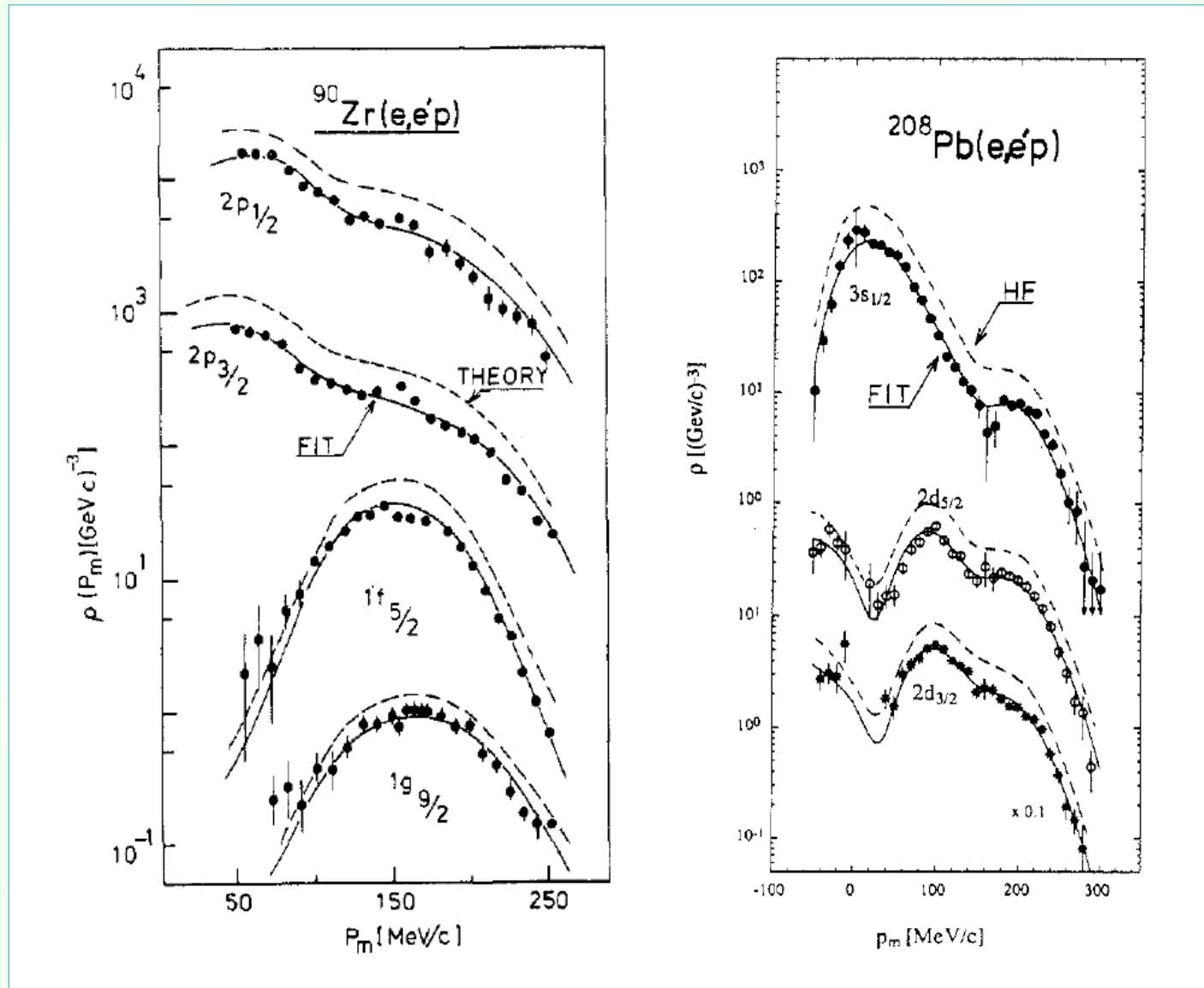See e.g. Cohen, Concepts of Nuclear Physics, McGraw-Hill, 1971

Example: oxygen nucleus

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

Example: oxygen spectral function

$P(\mathbf{p}, E)$ $(10^{-8}$ MeV$^{-4})$

s1/2

p3/2

p1/2

Fermi gas: δ - function

E (MeV)

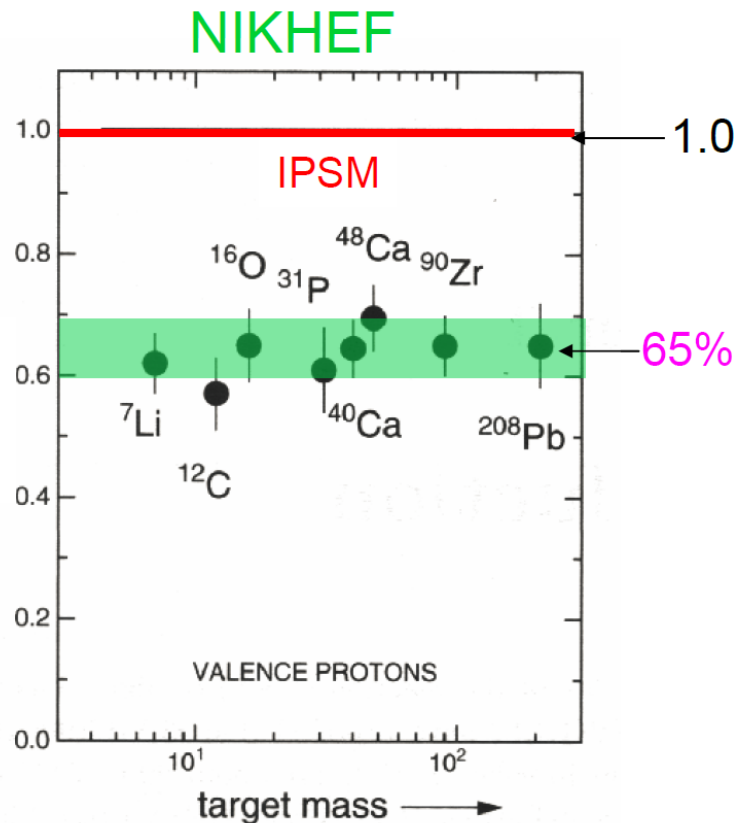$|\mathbf{p}|$ (MeV)

Depletion of the shell-model states
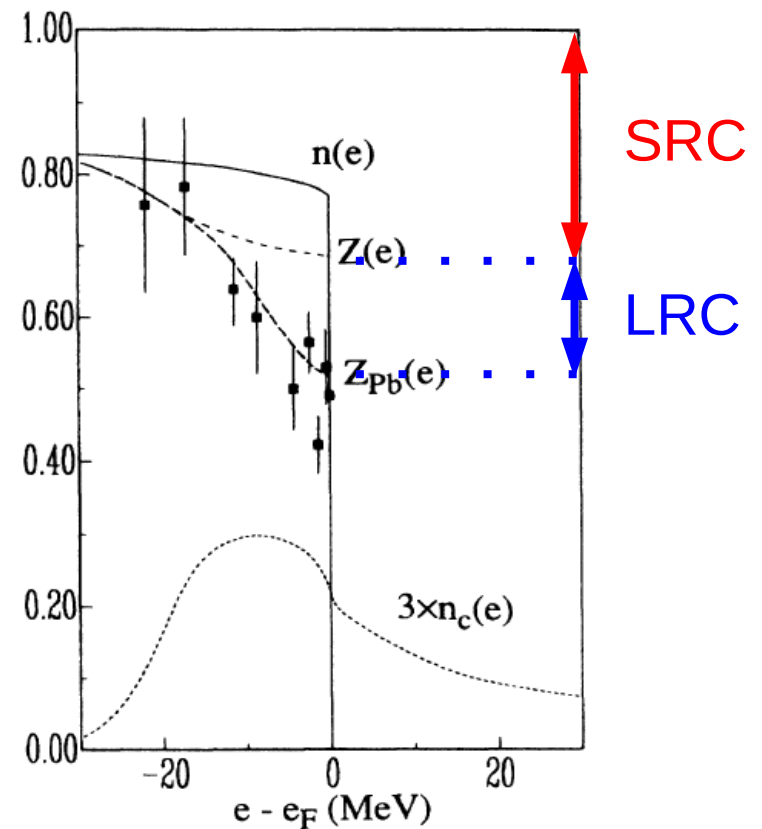

De Witt Huberts, JPG 16, 507 (1990)

Depletion of the shell-model states

The observed depletion is ~35% for the valence shells (LRC and SRC) and ~20% when higher missing energy is probed (SRC).

D. Rohe, NuInt05

NIKHEF: ^{208}Pb(e,e'p)^{207}Tl
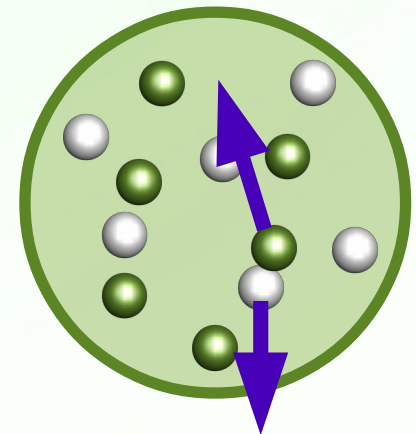
Benhar et al, PRC 41, R24 (1990)

Spectral function approach

Short-range correlations

The main source of the depletion of the shell-model states at high *E* 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

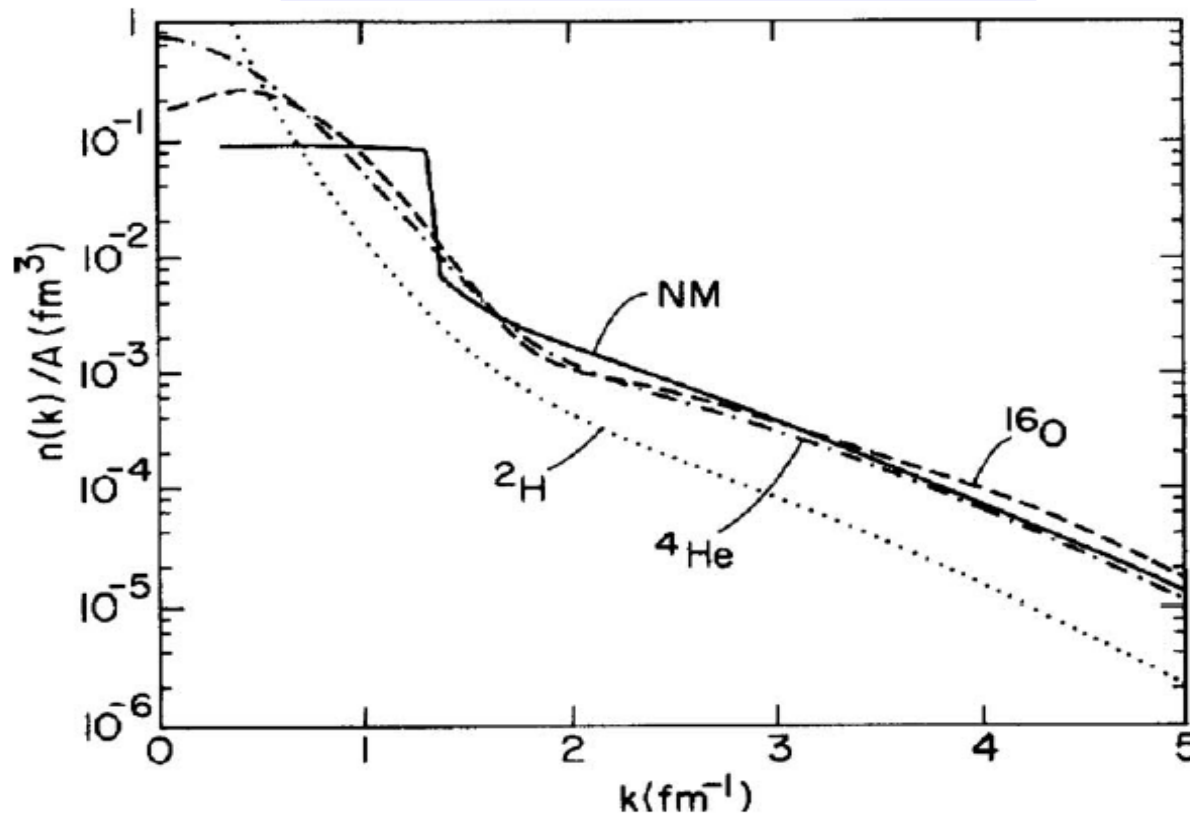The hole spectral function can be expressed as

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

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
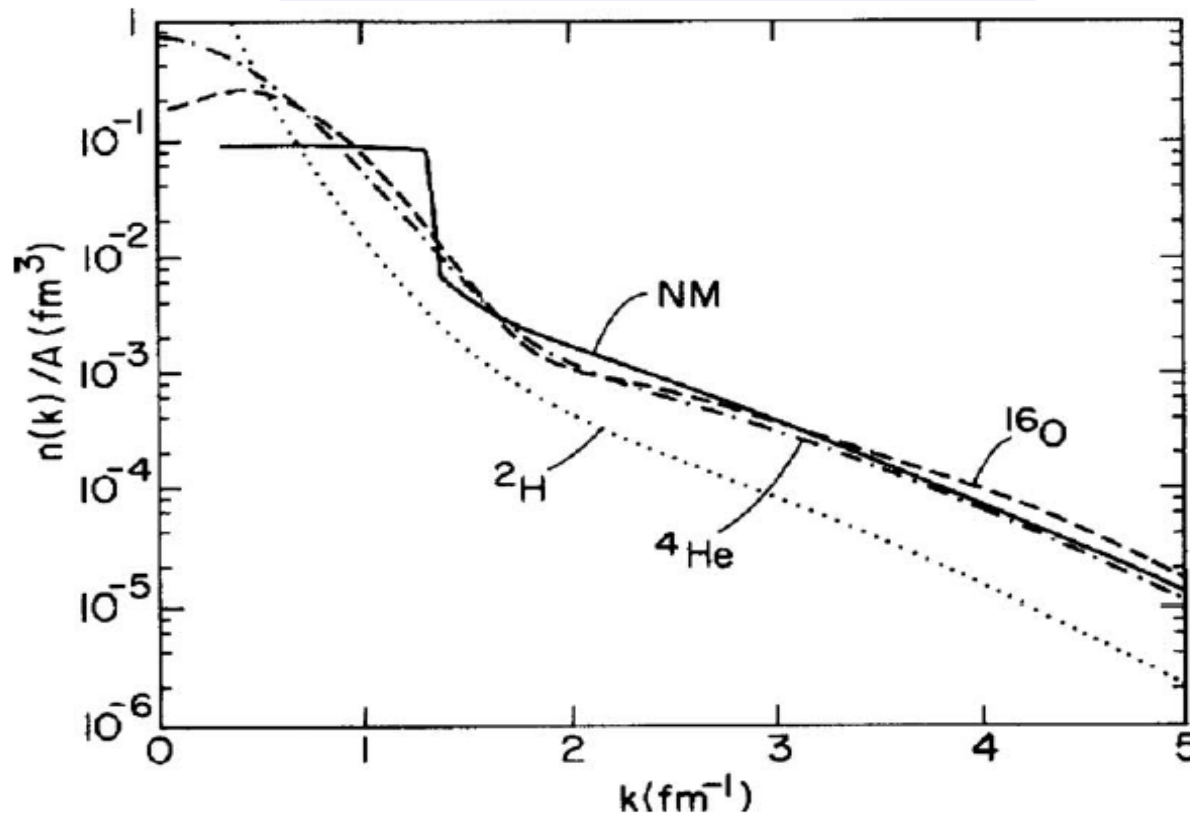
Benhar&Pandharipande, RMP 65, 817 (1993)
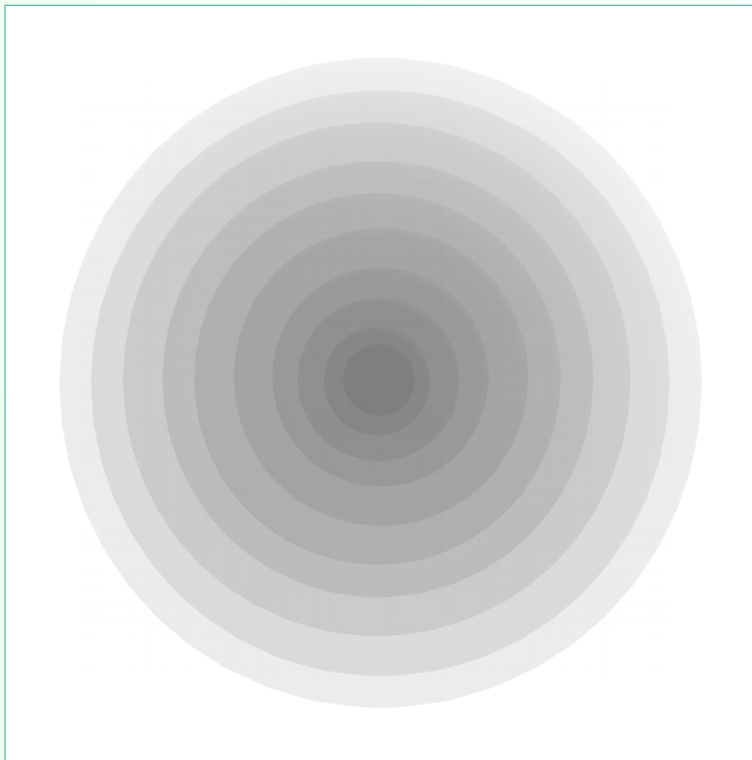
Short-range correlations

Momentum distributions

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

Local-density approximation

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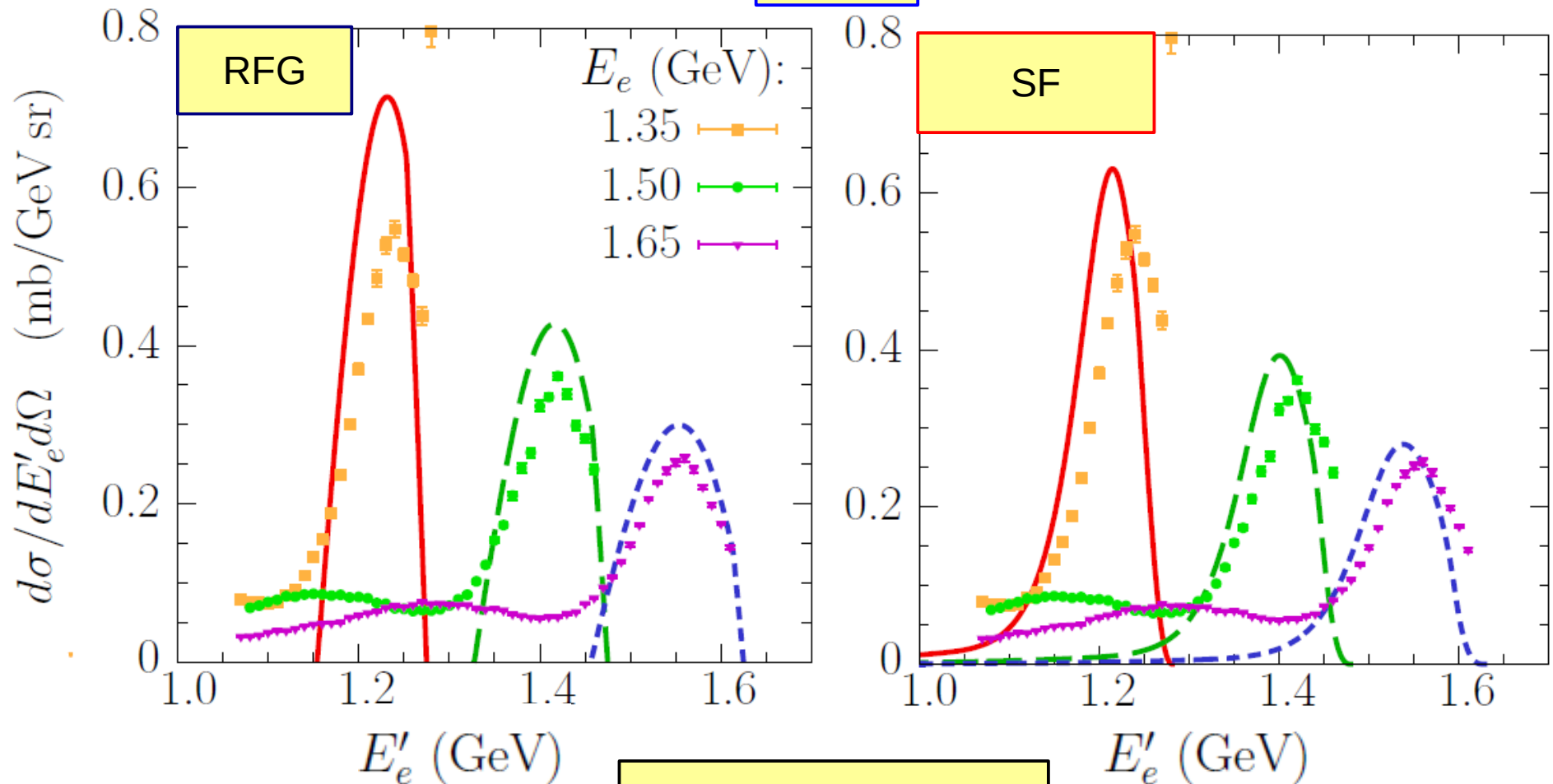

$$P_{\mathrm{corr}}^N(\mathbf{p}, E) = \int dR\, \rho(R) P_{\mathrm{corr}}^{NM,N}(\rho, \mathbf{p}, E).$$

Benhar *et al.*, NPA 579 493, (1994), included Urbana v_{14} NN interactions and 3N interactions [Lagaris & Pandharipande]

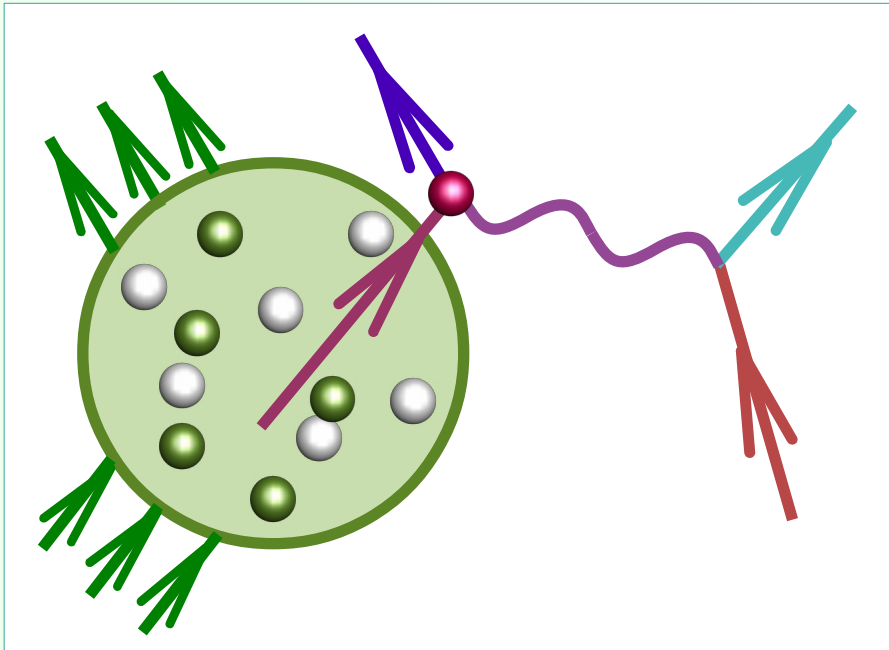# Comparison to C(*e*, *e'*) data

13.5°

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

Energy conservation

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

Energy conservation

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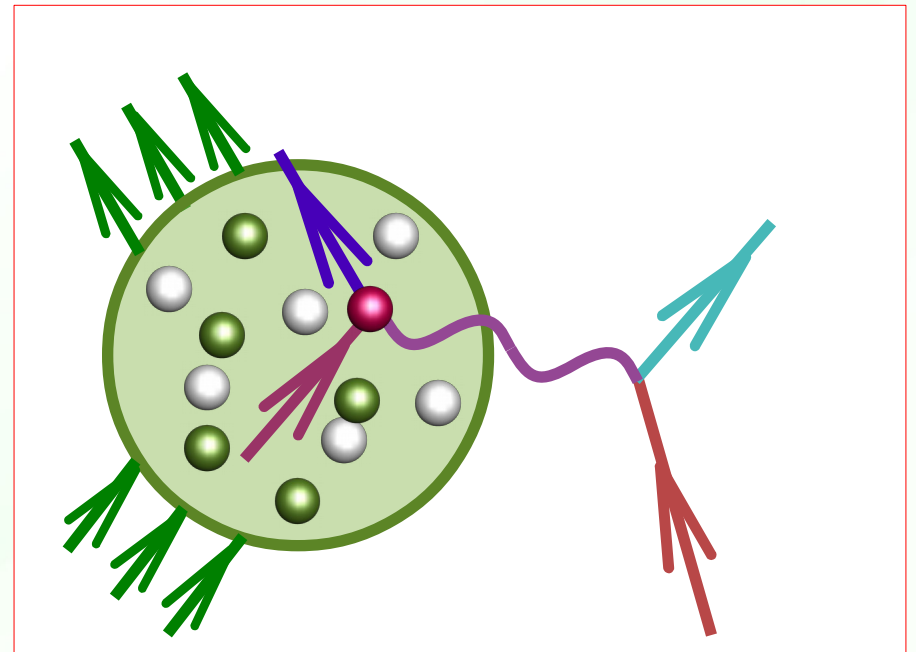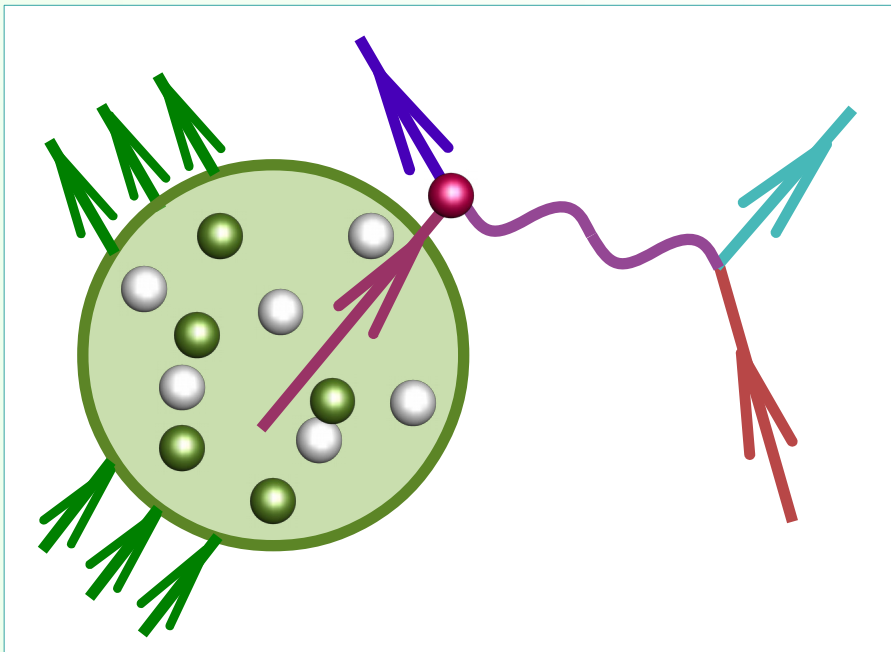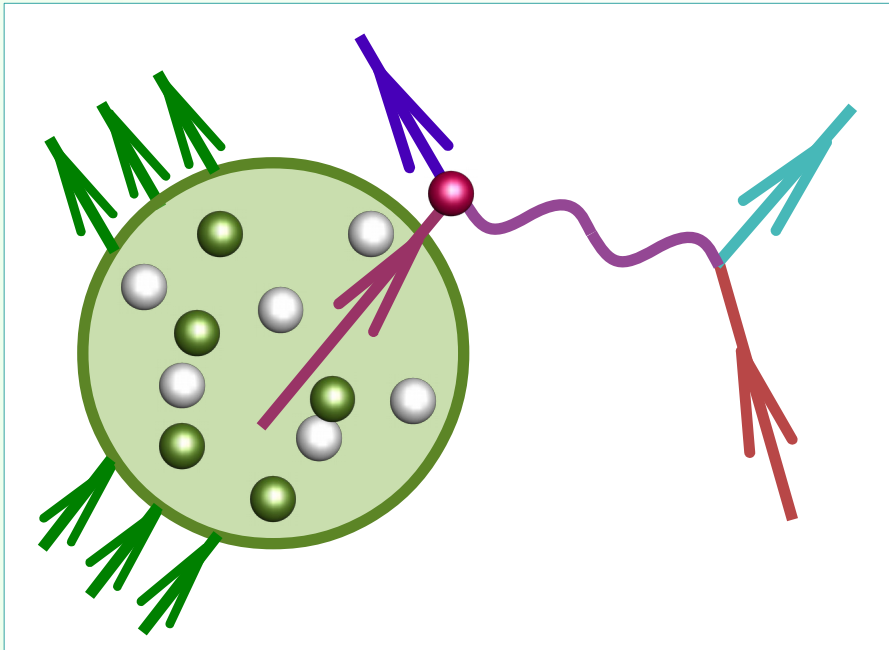
Energy conservation

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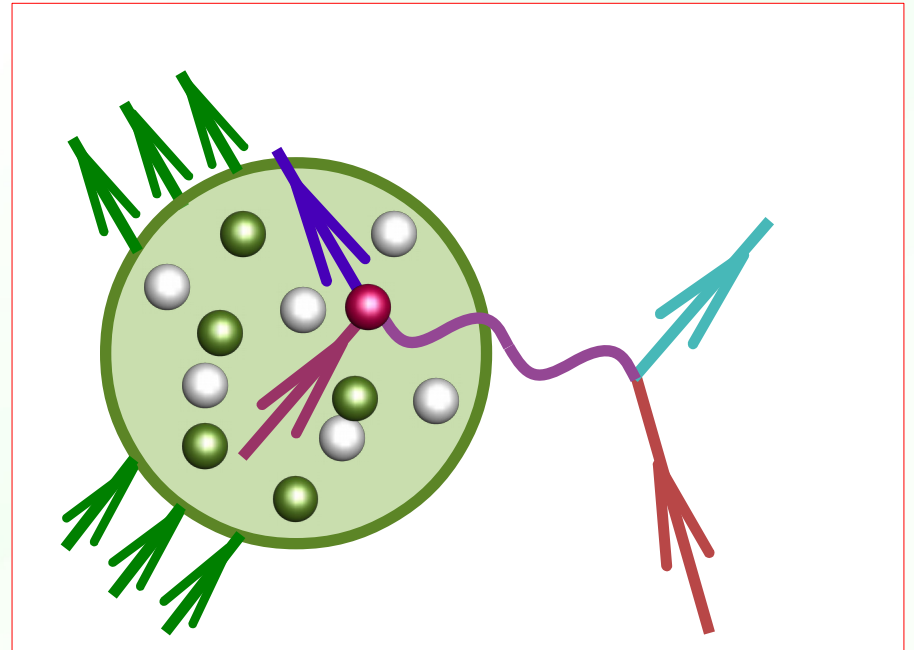
Energy conservation

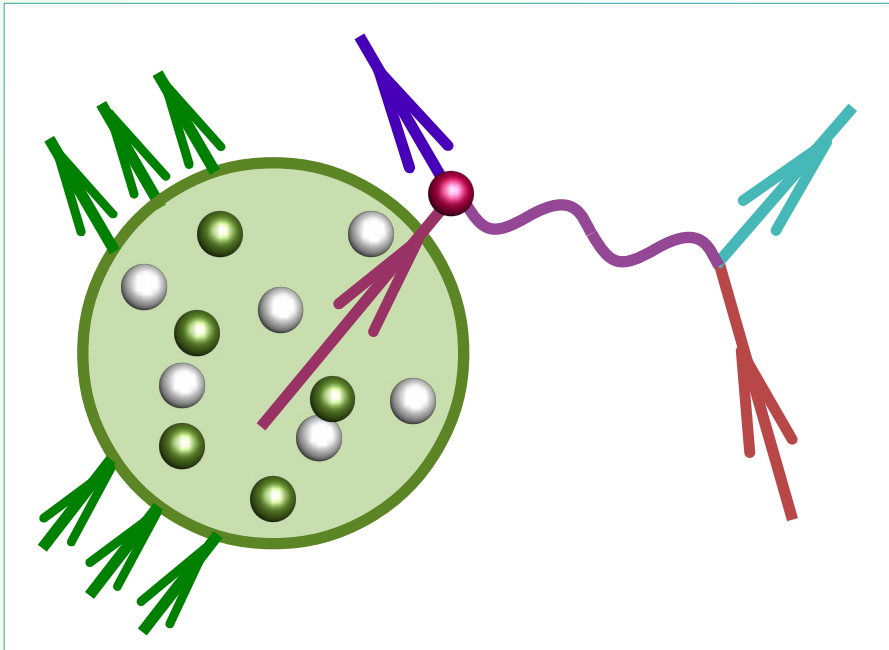$$E_{\mathbf{k}} + M_A = E_{\mathbf{k}'} + E_{A-1} + E_{\mathbf{p}'}$$

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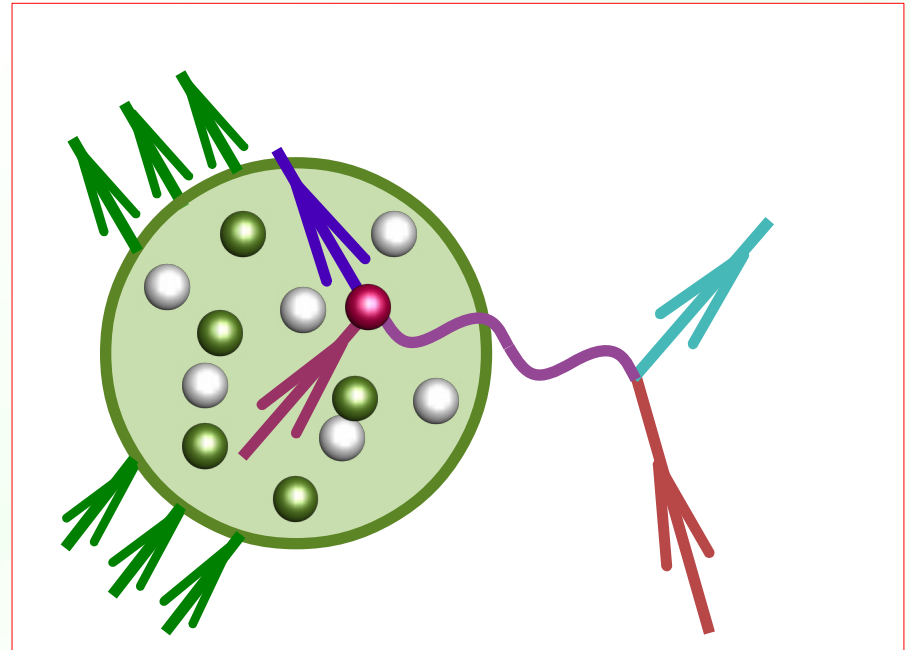
Energy conservation

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

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

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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

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

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

Final-state interactions
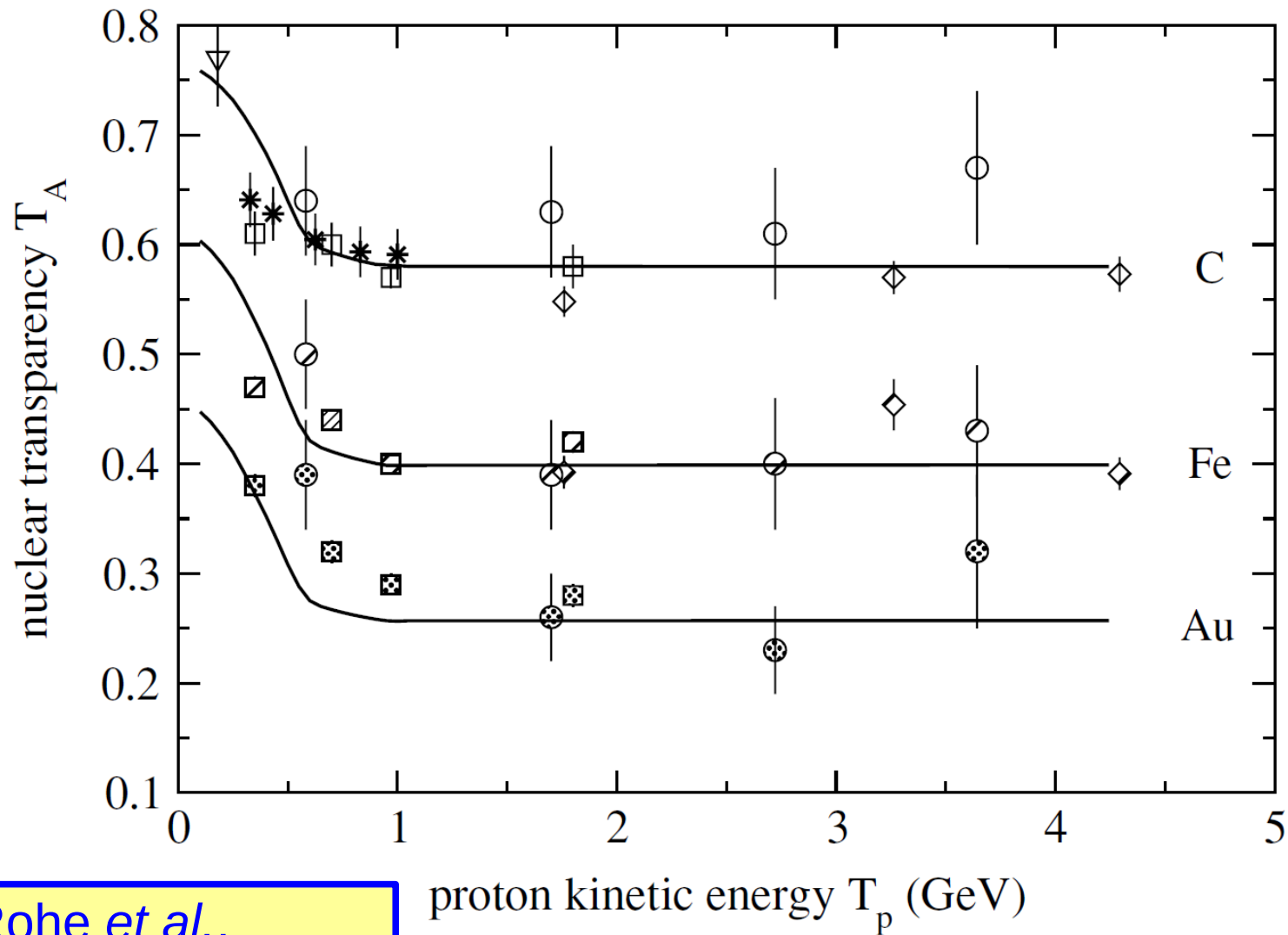
In the convolution approach,

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

with the folding function

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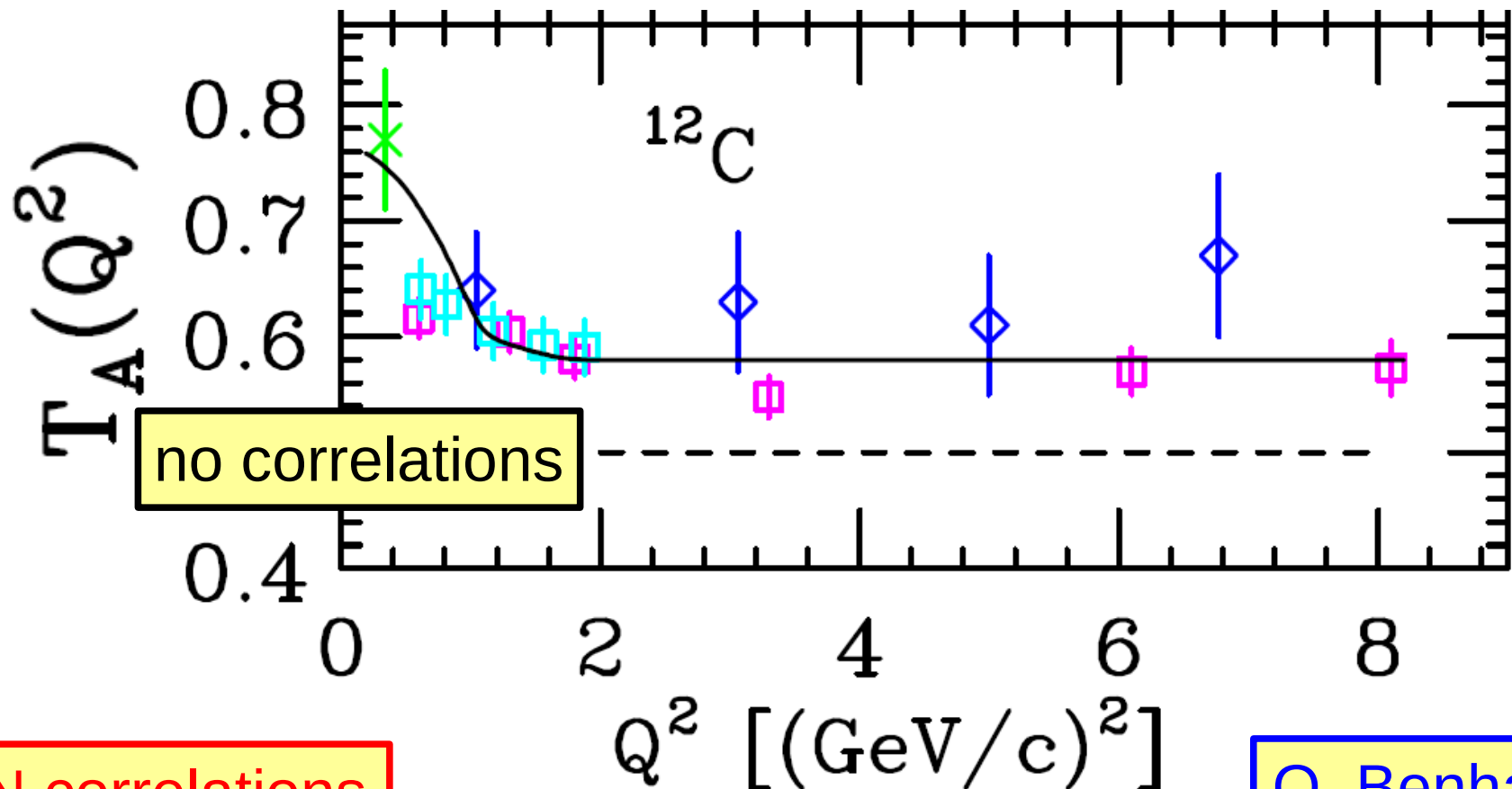
Nucl. transparency

86

Nuclear transparency

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

Nuclear transparency

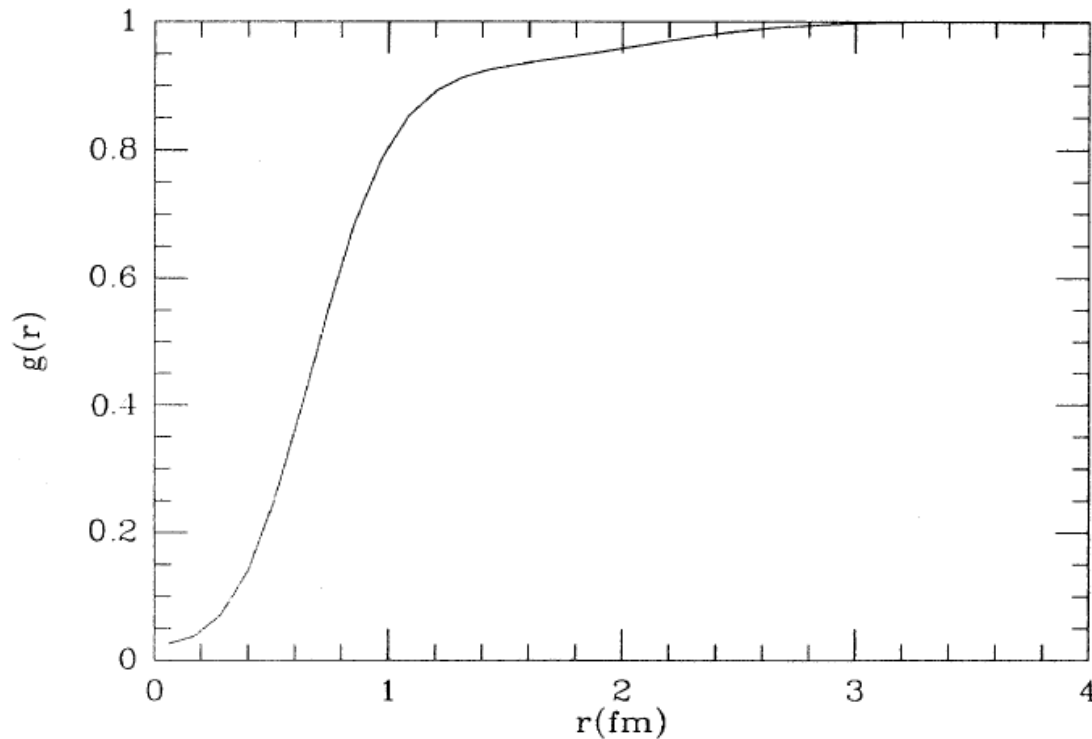no correlations

^{12}C

$T_A(Q^2)$

Q^2 [(GeV/c)^2]

NN correlations *reduce* FSI

O. Benhar @ NuInt05

Short-range correlations

Pair distribution function of NM

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

89

Real part of the optical potential

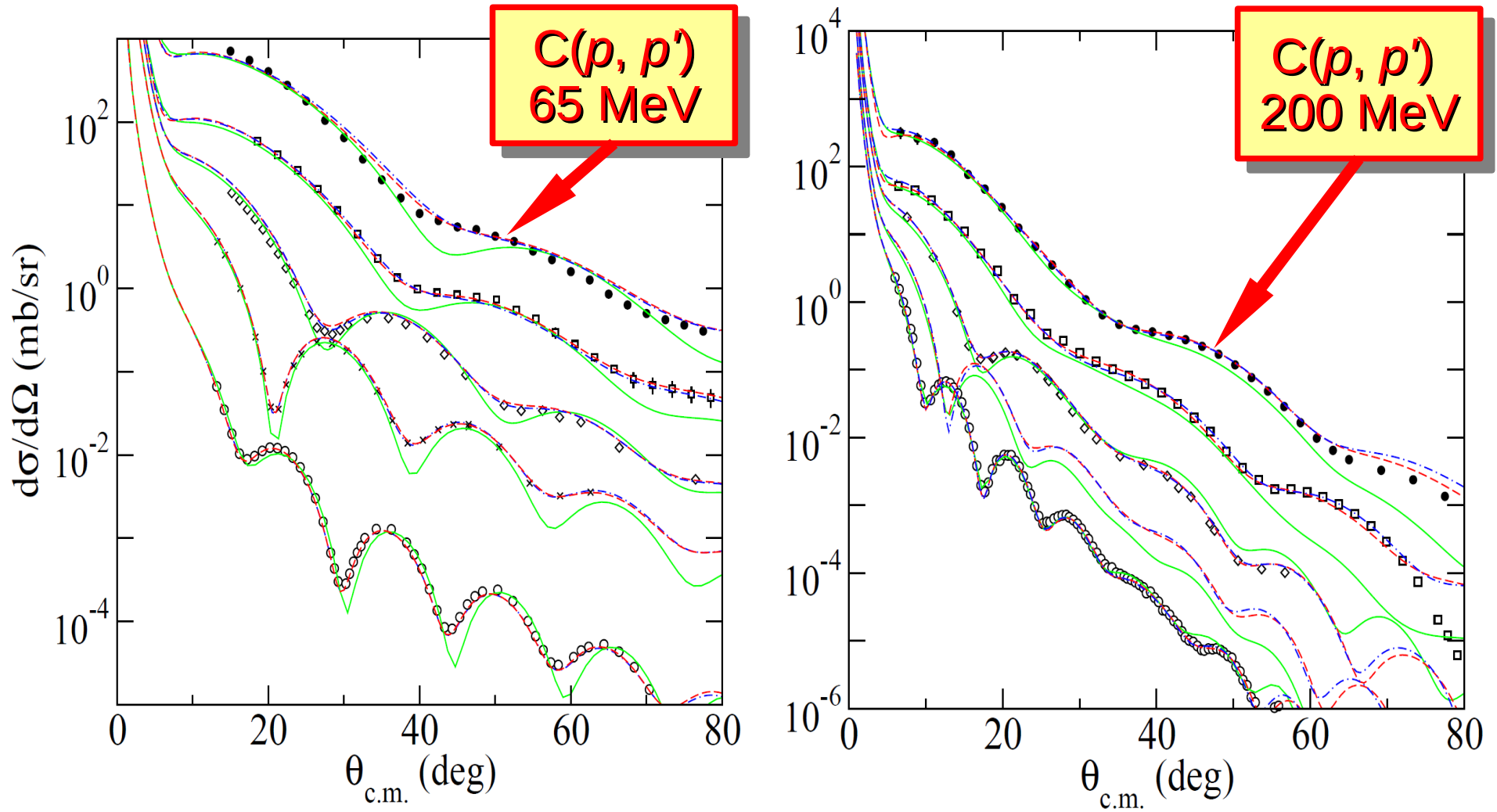We account for the spectrum modification by

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

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

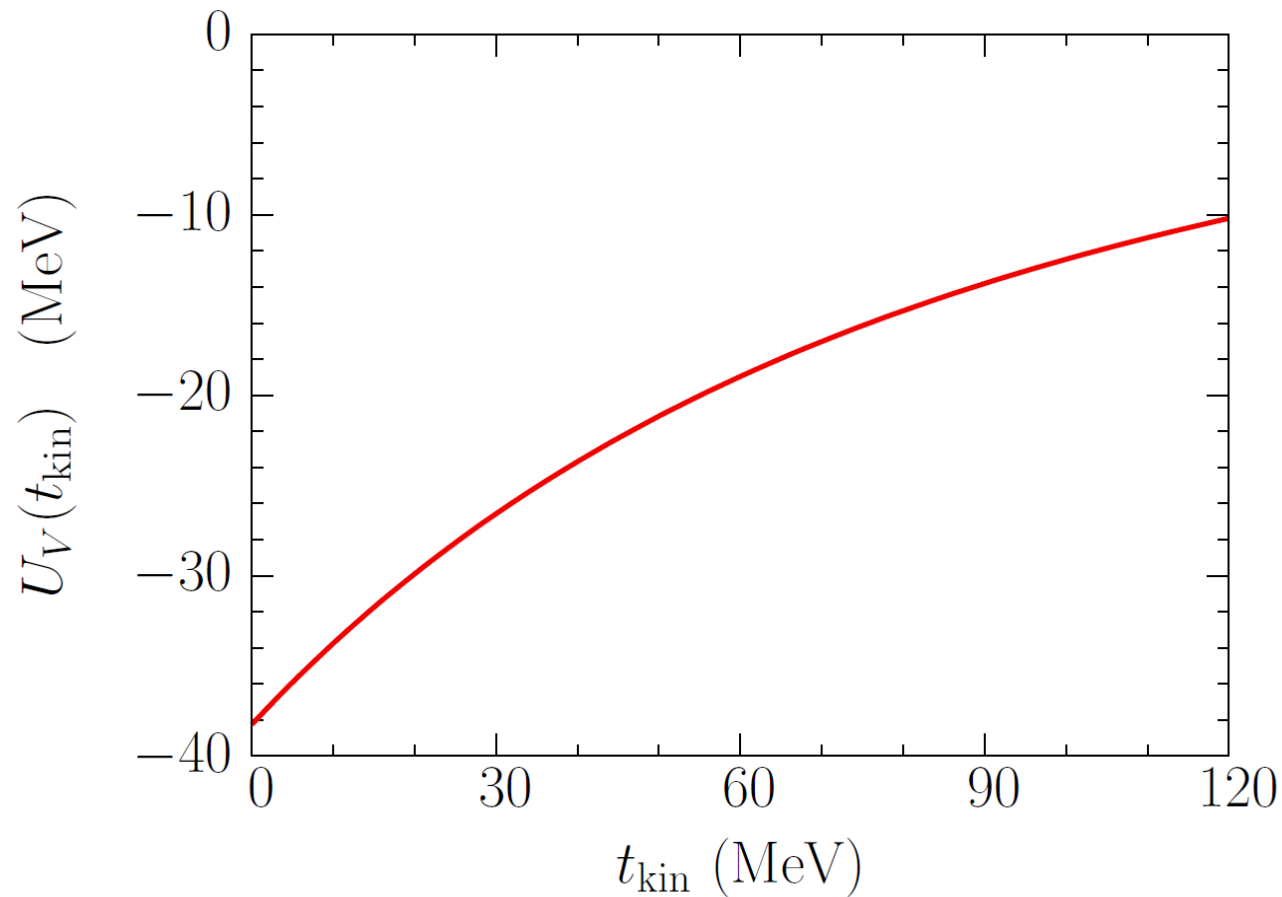$$U_V = U_V(t_{\mathrm{kin}})$$

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

Optical potential by Cooper *et al.*

C(*p, p'*)
65 MeV

C(*p, p'*)
200 MeV

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

Optical potential by Cooper *et al.*

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

Simple comparison
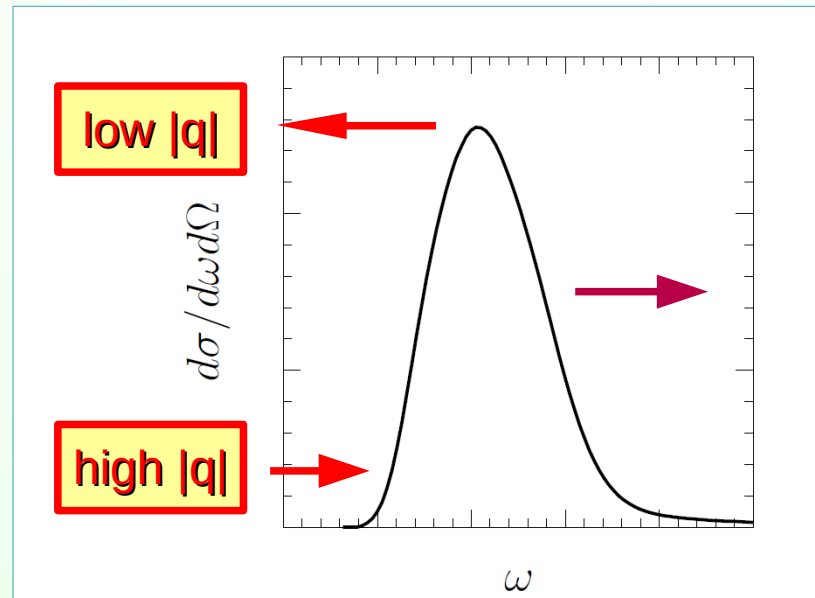
Real part of the OP

- acts in the final state

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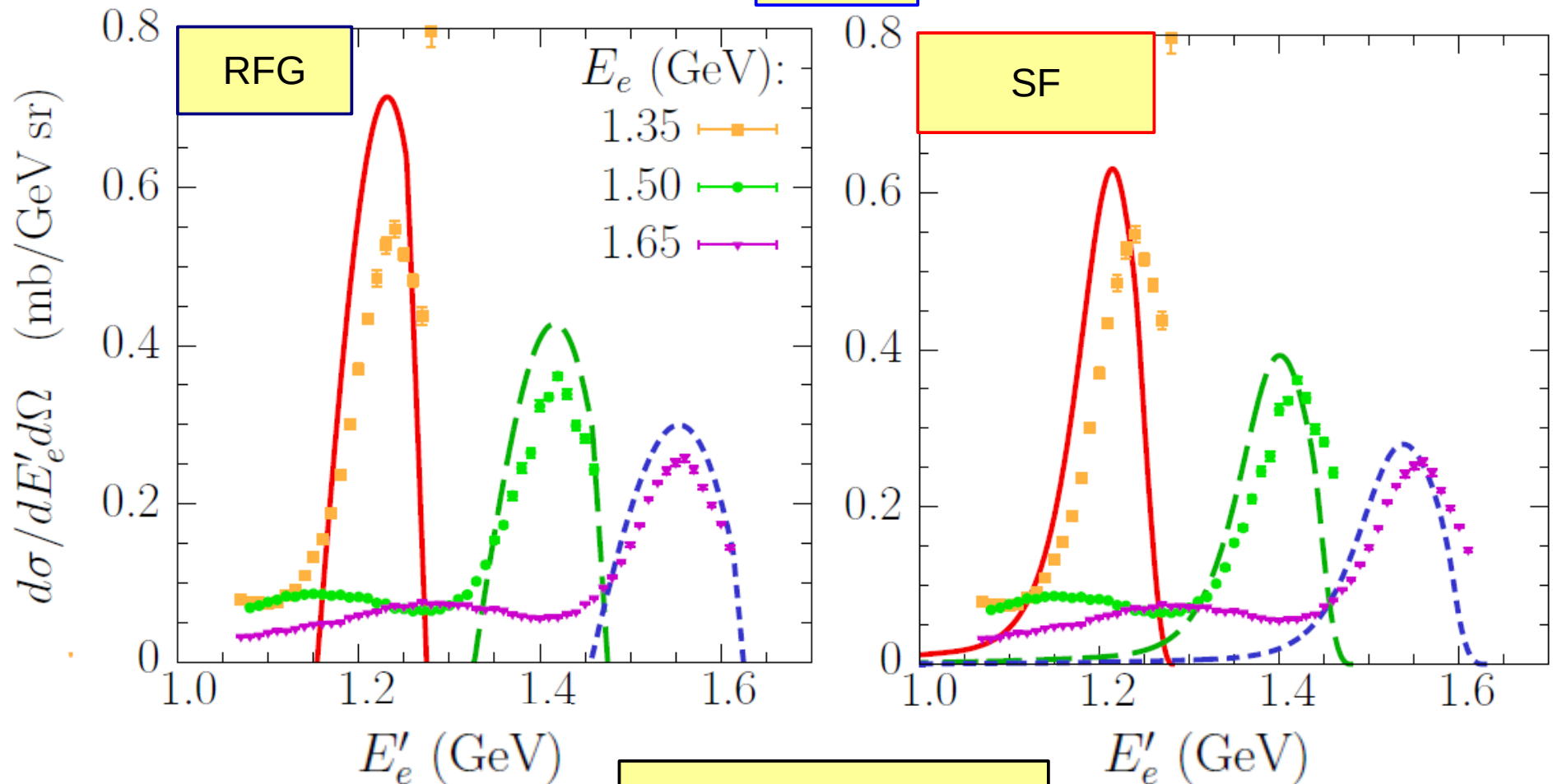 (to high ω at high $|\mathbf{q}|$)

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

13.5°

RFG

SF + FSI

E_e (GeV):
1.35
1.50
1.65

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

95
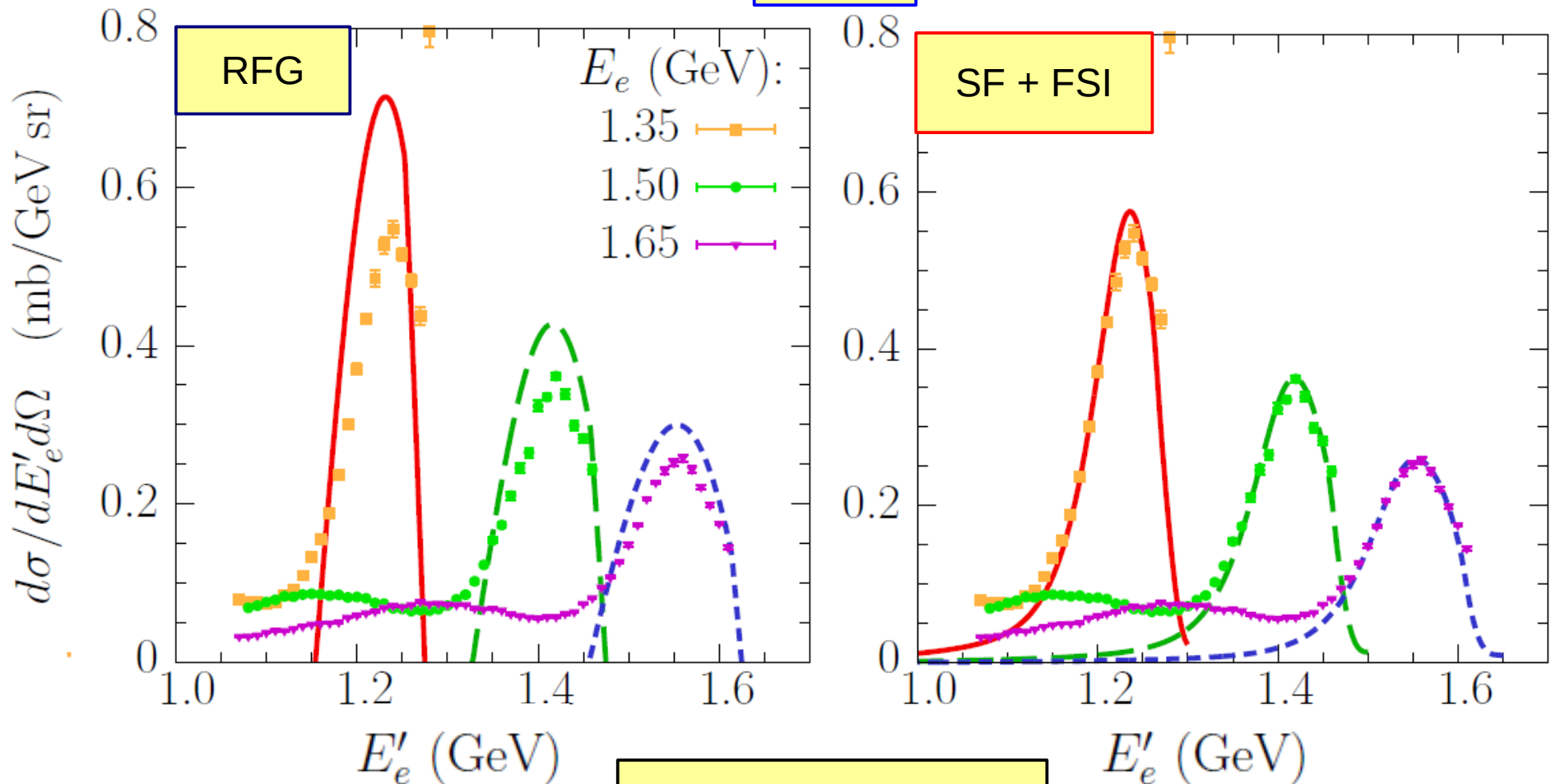
Importance of quasielastic scattering

Fixed beam energy and scattering angle
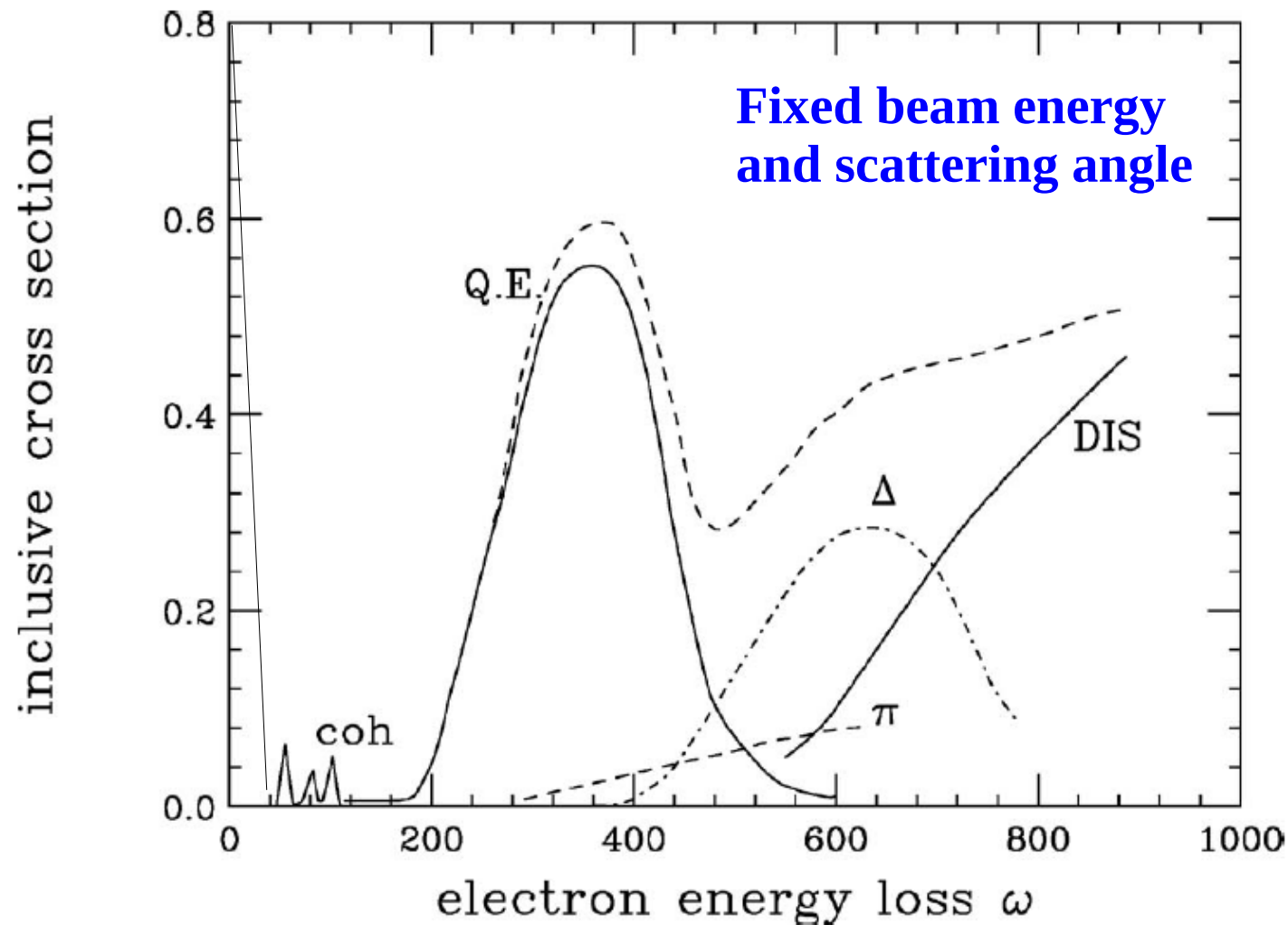
adopted from Benhar *et al.*, RMP 80, 189 (2008)

Compared calculations

280.3 MeV, 60 deg
~ 259 MeV, 0.06 GeV²

RFG model
ε = 25 MeV
p_F = 221 MeV

SF calculation
without FSI
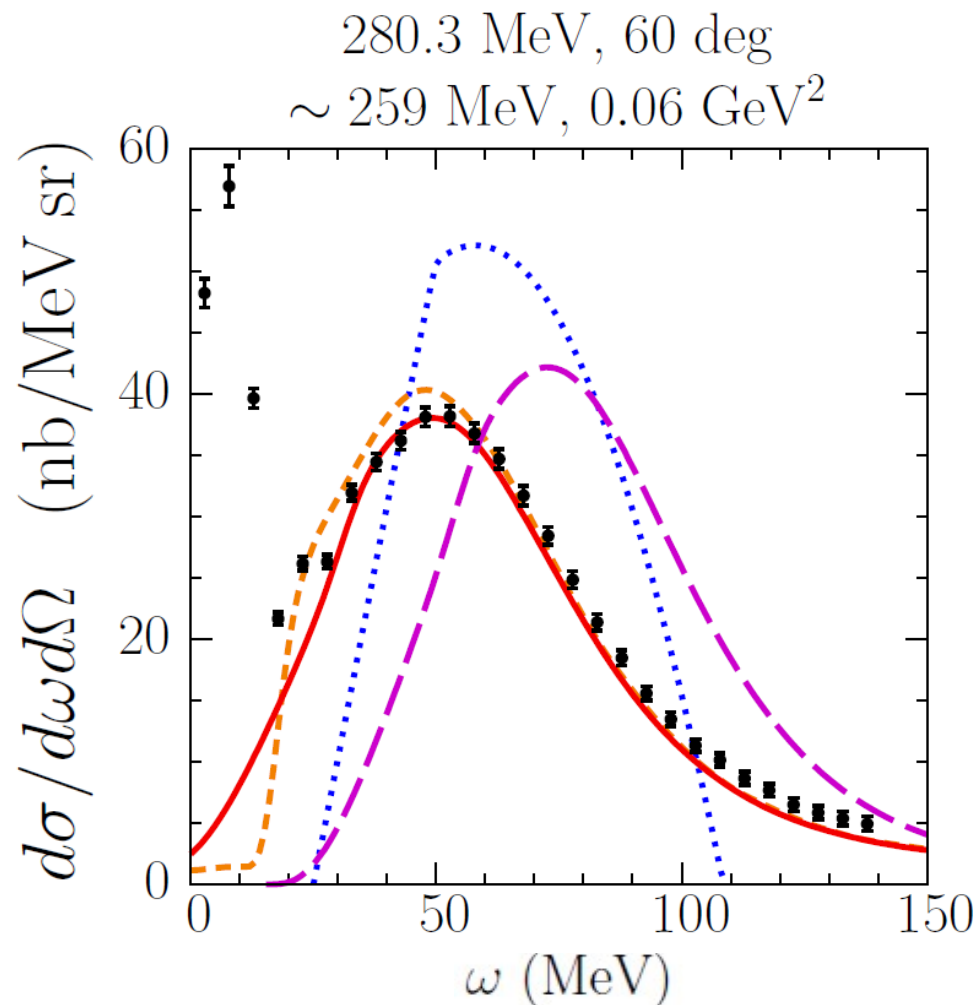
SF calculation,
LDA treatment
of Pauli blocking

SF calculation,
step function

97

Compared calculations
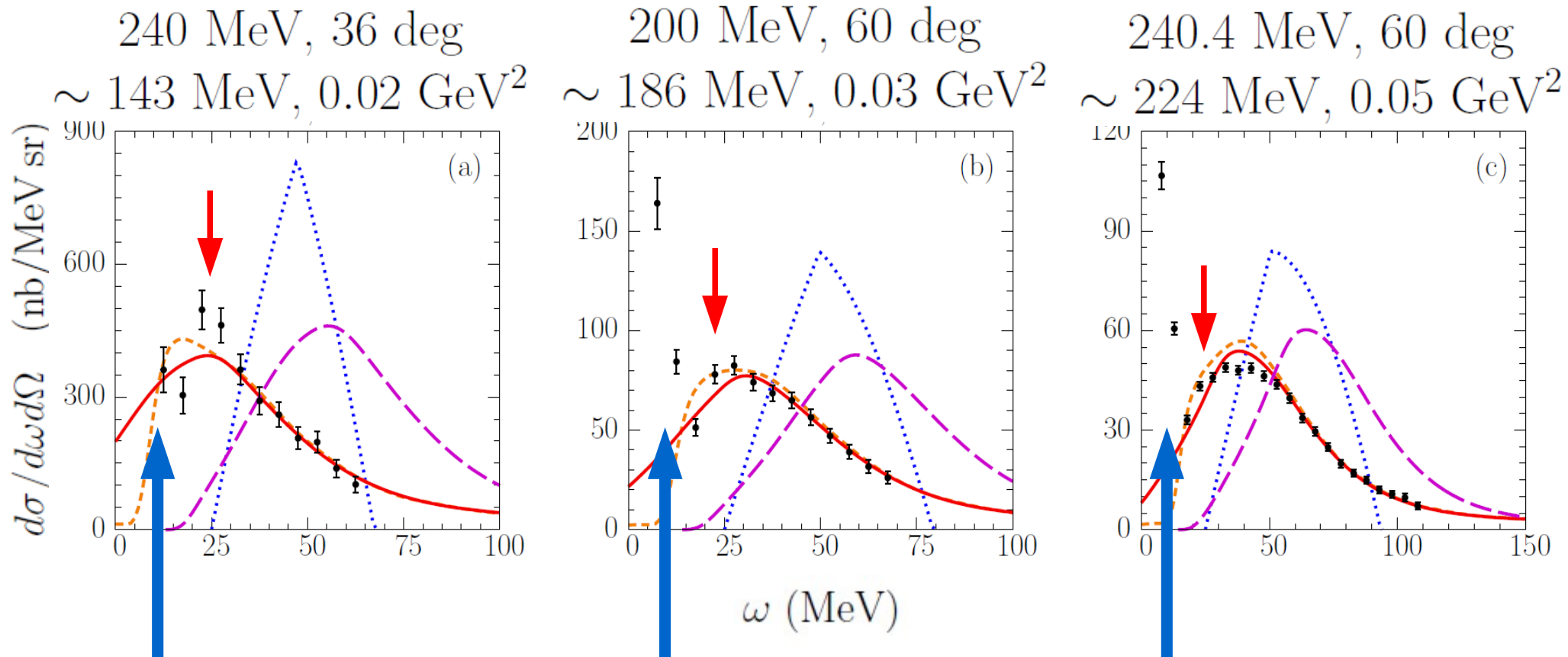

280.3 MeV, 60 deg
~ 259 MeV, 0.06 GeV^2
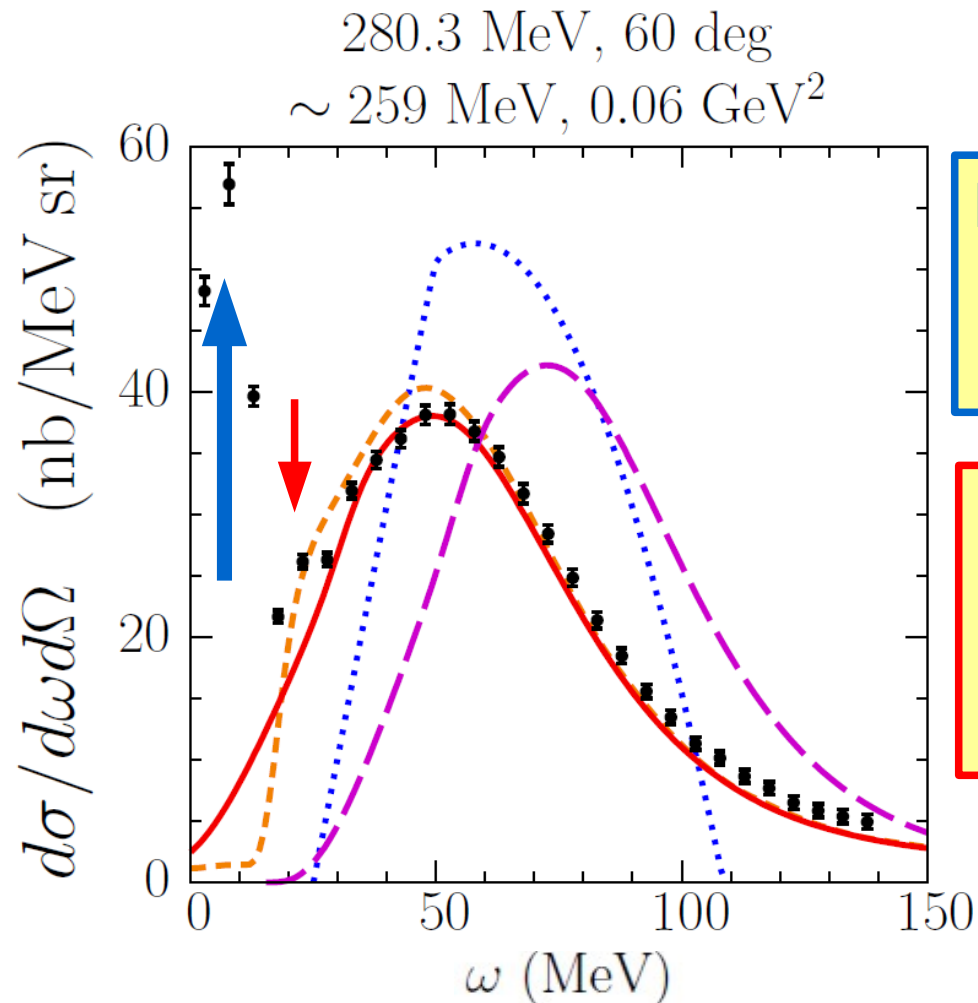
Calcs. include QE by 1-body current only

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
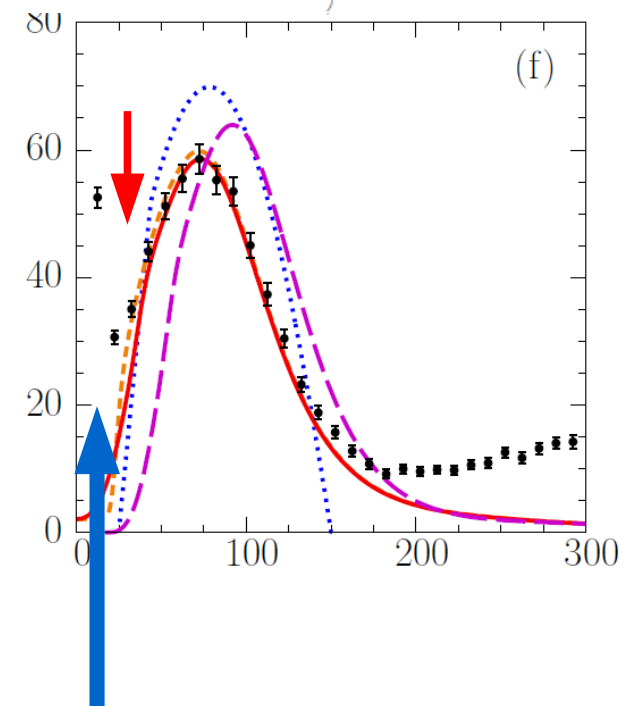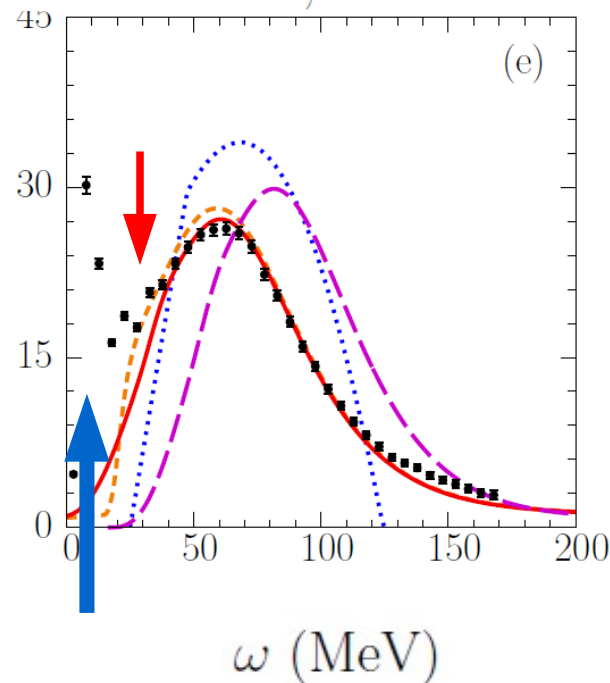

280.3 MeV, 60 deg $\sim$ 259 MeV, 0.06 GeV^2

320.3 MeV, 60 deg $\sim$ 295 MeV, 0.08 GeV^2

560 MeV, 36 deg $\sim$ 331 MeV, 0.10 GeV^2

$d\sigma/d\omega d\Omega$ (nb/MeV sr)

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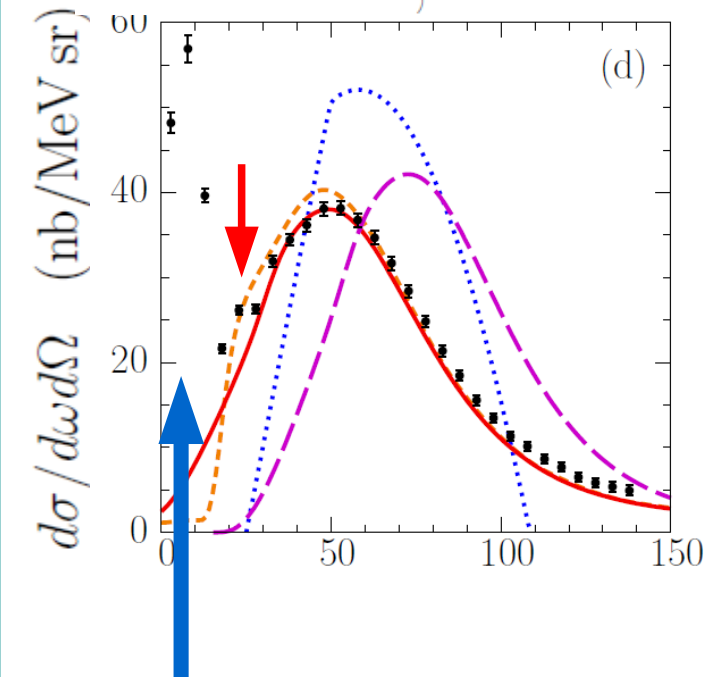
Barreau *et al.*,
NPA 402, 515 (1983)

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

620 MeV, 36 deg
$\sim$ 366 MeV, 0.13 GeV^2

1650 MeV, 13.5 deg
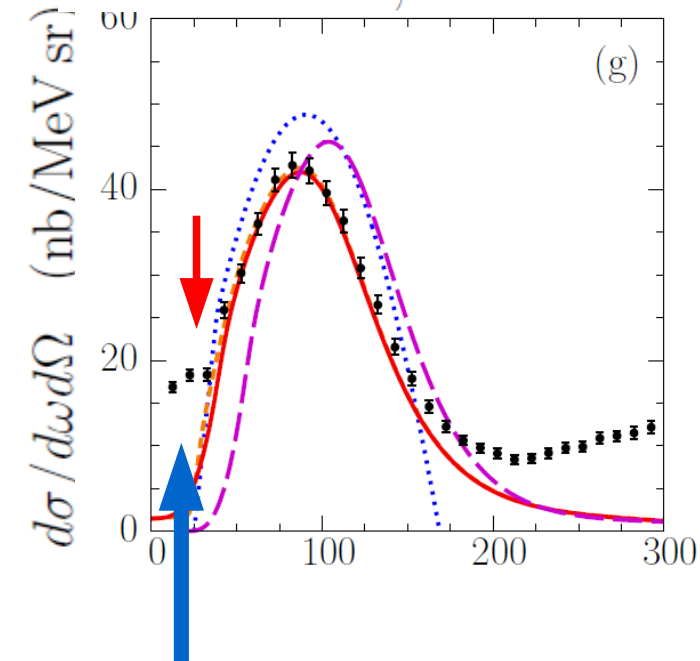$\sim$ 390 MeV, 0.14 GeV^2
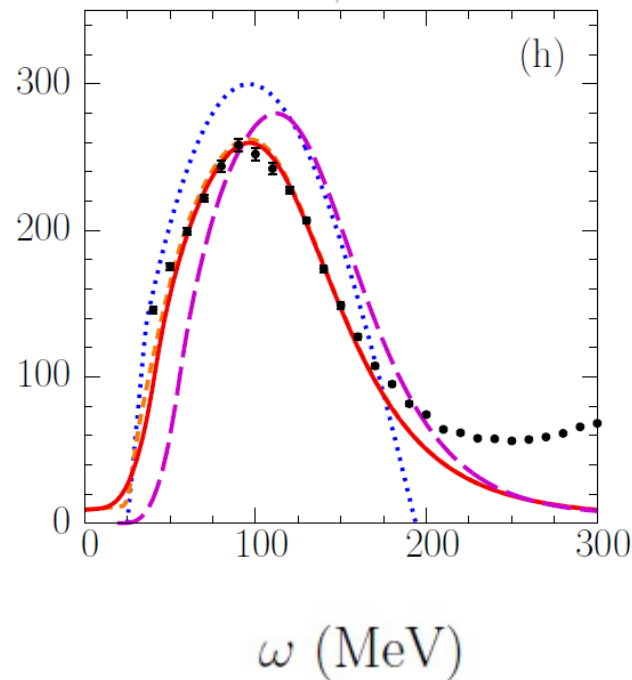
500 MeV, 60 deg
$\sim$ 450 MeV, 0.19 GeV^2

$d\sigma/d\omega d\Omega$ (nb/MeV sr)

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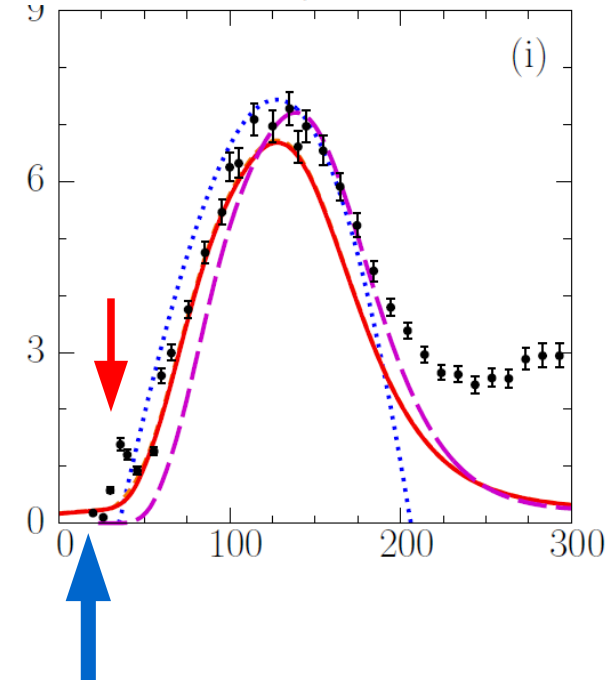
Barreau *et al.*,
NPA 402, 515 (1983)

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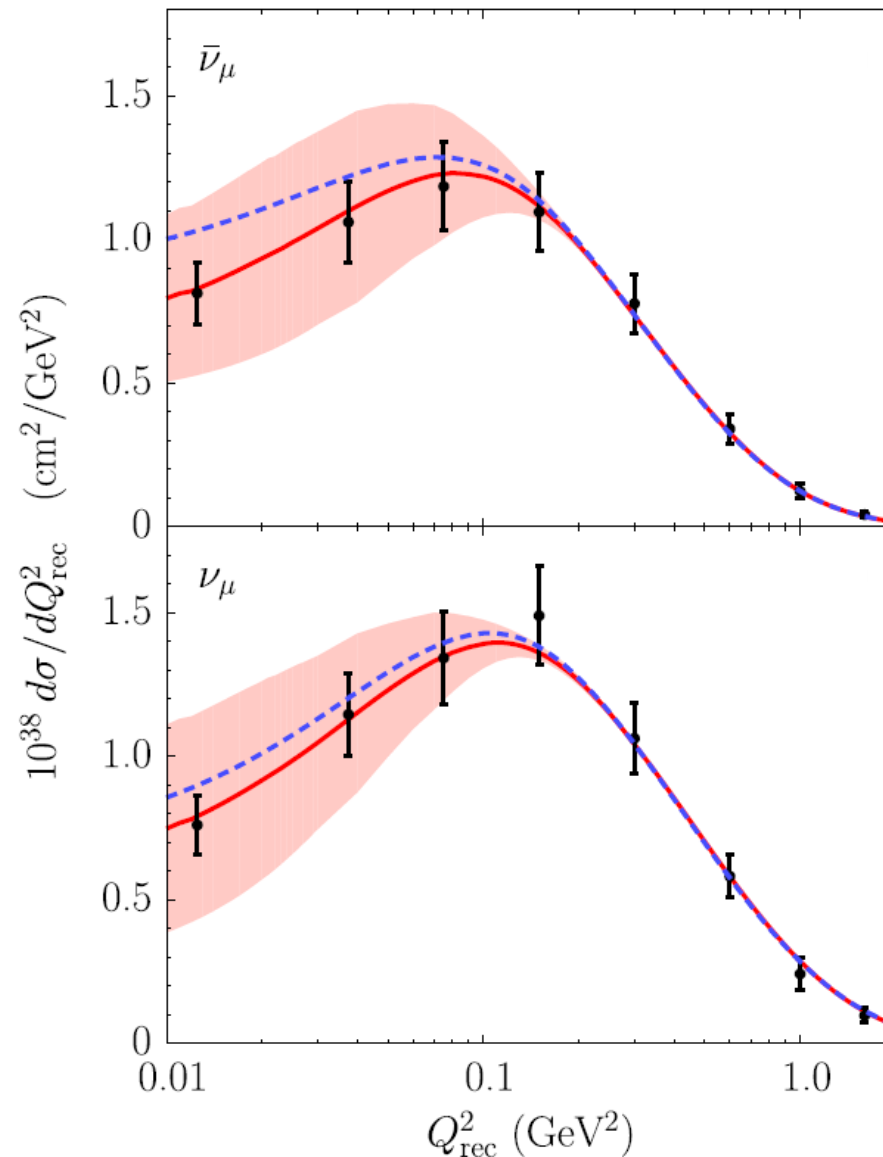
TABLE I. Fit results to the CC QE MINERvA data.

|	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

Summary

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

Measurement of the spectral function of argon in JLab

What do we know about Ar?

700 MeV @ 32 deg

□ oxygen
x argon

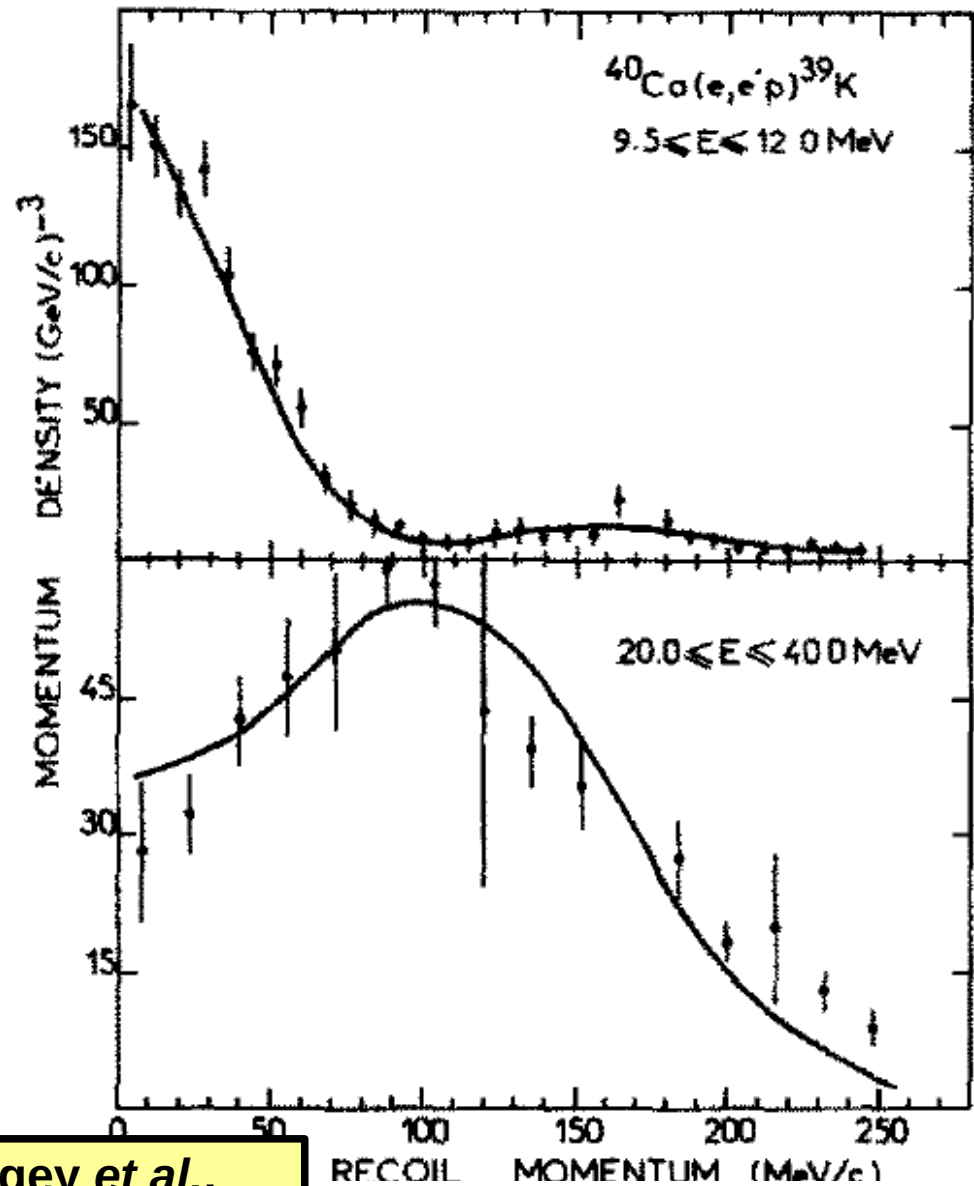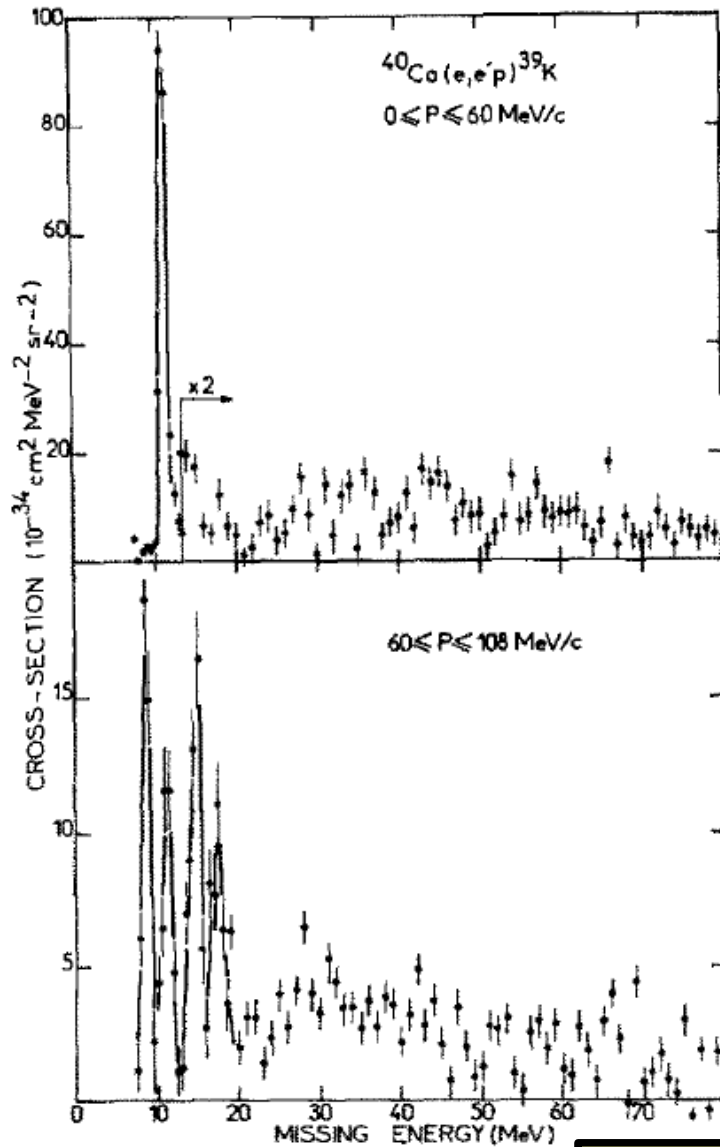**Anghinolfi *et al.*,
JPG 21, L9 (1995)**
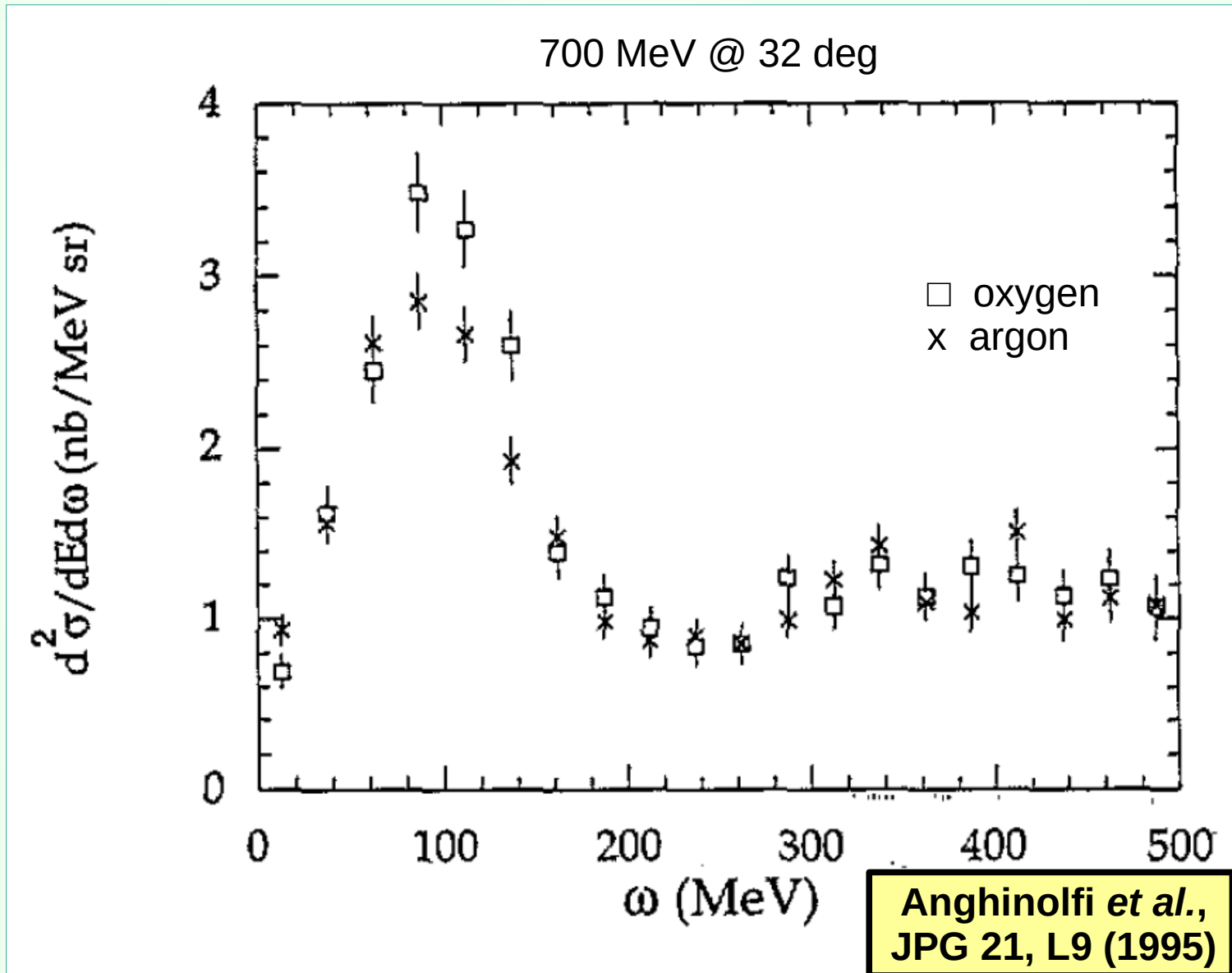
What do we know about Ar?

- nuclear excitations by up to ~11 MeV

  Cameron & Singh, Nucl. Data Sheets **102**, 293 (2004)

- angular distributions of ^{40}Ar(p, p') for a few excitation lvls.

  Fabrici *et al.*, PRC **21**, 830 & 844 (1980); De Leo *et al.*,

  PRC **31**, 362 (1985); Blanpied *et al.*, PRC **37**, 1304 (1988)

- angular distributions of ^{40}Ar(p ,d)^{39}Ar

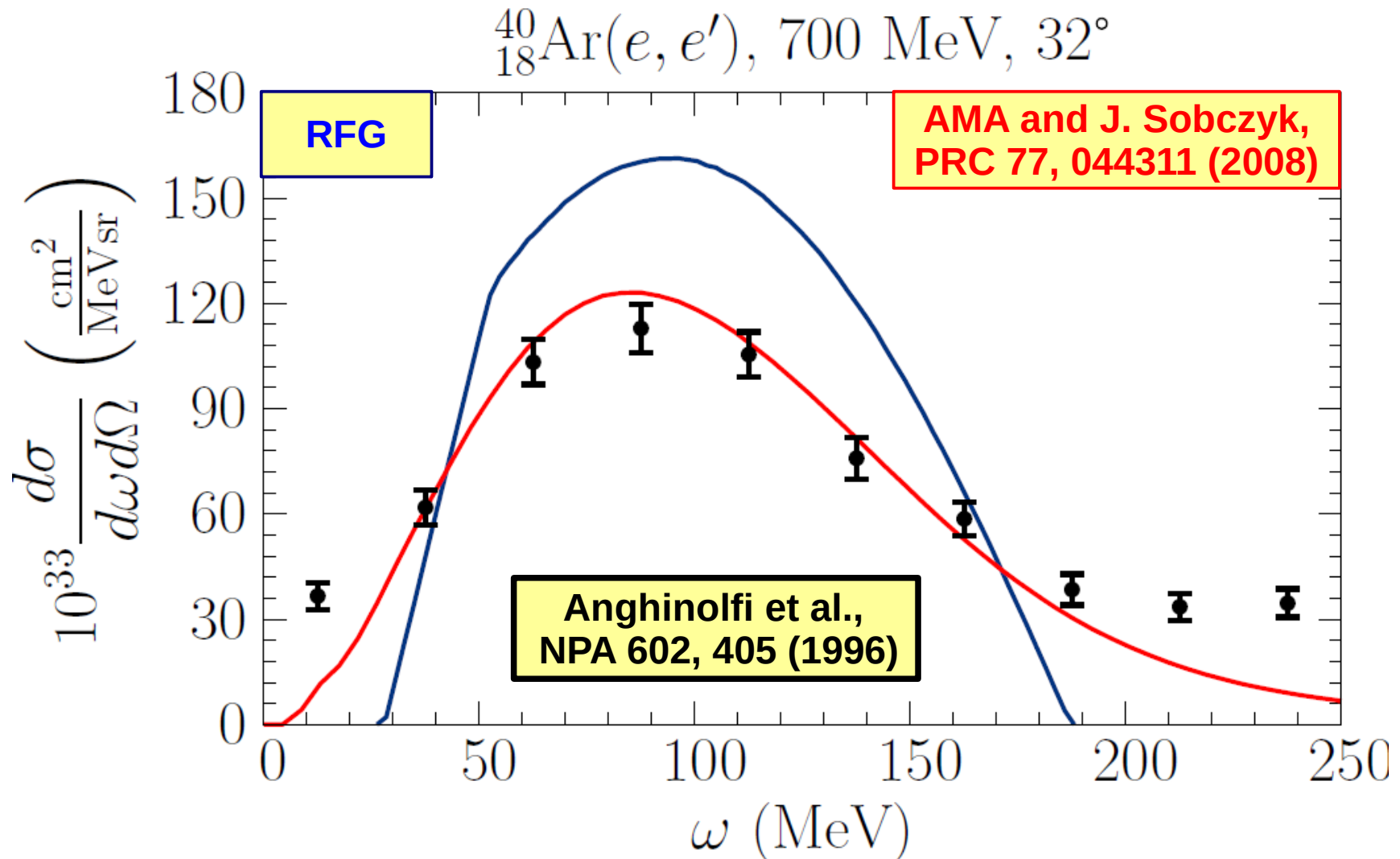 Tonn *et al.*, PRC **16**, 1357 (1977)

What do we know about Ar?

- *n*-Ar total cross section form energies < 50 MeV

  Winters *et al.*, PRC **43**, 492 (1991)

- ^{40}Ar(v_e ,*e*) cross section from the mirror ^{40}Ti$\rightarrow$^{40}Sc decay

  Bhattacharya *et al.*, PRC **58**, 3677 (1998)

- Gammov-Teller strength distrib. for ^{40}Ar$\rightarrow$^{40}K from 0°(*p, n*)

  Bhattacharya *et al.*, PRC **80**, 055501 (2009)

- ^{40}Ar(*n, p*)^{40}Cl cross section between 9 and 15 MeV

  Bhattacharya *et al.*, PRC **86**, 041602(R) (2012)

Spectral function of ^{40}Ca

Mougey *et al.*,
NPA 262, 461 (1976)

Approximated SF of ^{40}Ar

$^{40}_{18}\text{Ar}(e, e')$, 700 MeV, 32°

RFG

AMA and J. Sobczyk,
PRC 77, 044311 (2008)

Anghinolfi et al.,
NPA 602, 405 (1996)

$10^{33} \dfrac{d\sigma}{d\omega d\Omega} \left(\dfrac{\text{cm}^2}{\text{MeV sr}} \right)$

ω (MeV)

Experiment E12-14-012 at JLab

"We propose a measurement of the coincidence (e,e'p) cross section on argon. This data will provide the experimental input indis-pensable to construct the argon spectral function, thus paving the way for a reliable estimate of the neutrino cross sections."

Benhar *et al.*, arXiv:1406.4080

Experiment E12-14-012 at JLab

Primary goal: extraction of the proton shell structure of ^{40}Ar from ($e,e'p$) scattering

- spectroscopic factors,
- energy distributions,
- momentum distributions.

Secondary goal: improved description of final-state interactions in the argon nucleus.

Relevance for DUNE

- **Neutrino oscillations**
  Reduction of systematic uncertainties from nuclear effects, especially for the 2nd oscillation maximum.
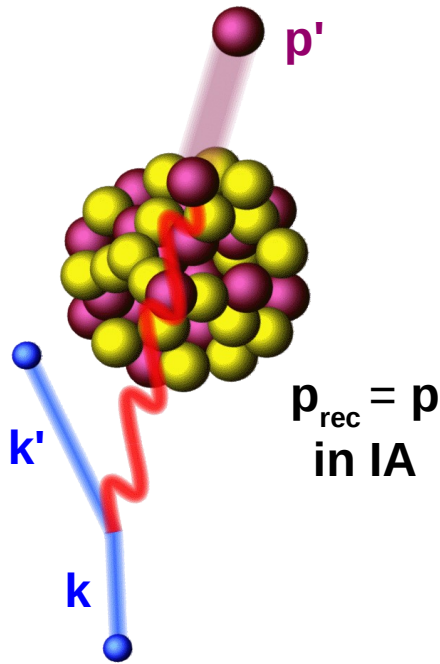
- **Proton decay**
  Probed lifetime affected by the partial depletion of the shell-model states.

- **Supernova neutrinos**
  Information on the valence shells essential for accurate simulations and detector design.
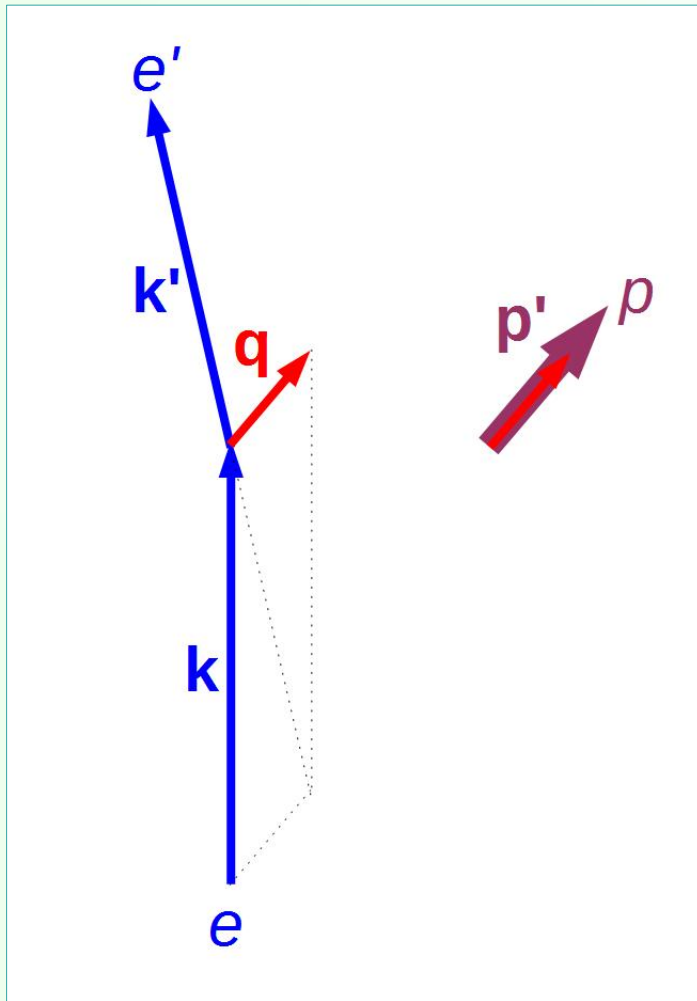
Impulse approximation

$$\frac{d^6\sigma_{\mathrm{IA}}}{d\Omega_{k'}\,dE_{k'}\,d\Omega_{p'}\,dE_{p'}} \propto \sigma_{ep}\, S(\mathbf{p}, E)\, T_A(E_{p'})$$

σ_{ep} elementary cross section

$S(\mathbf{p}, E)$ spectral function

$T_A(E_{p'})$ nuclear transparency

(Anti)parallel kinematics, p'∥q

Energy conservation

$$E_{\mathbf{k}} + M_A = E_{\mathbf{k}'} + E_{\mathbf{p}'} + \sqrt{(M_A - M + E)^2 + \mathbf{p}_{\text{rec}}^2}$$
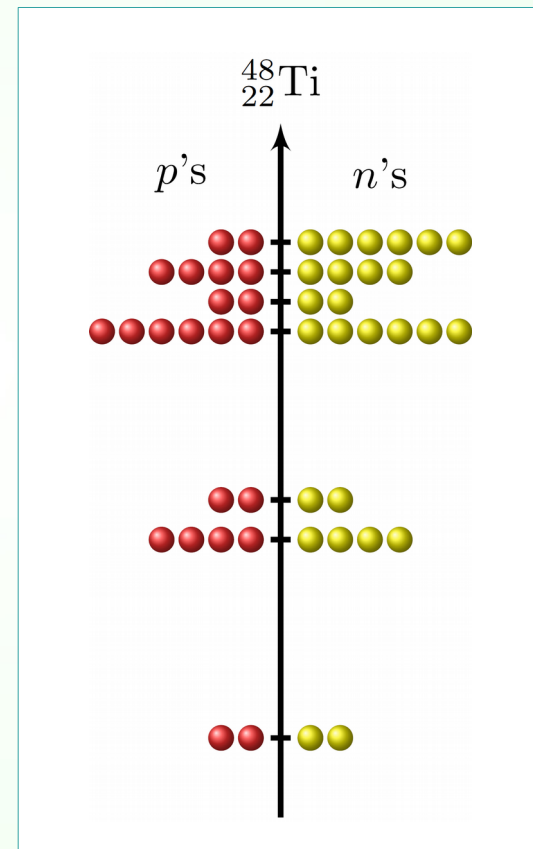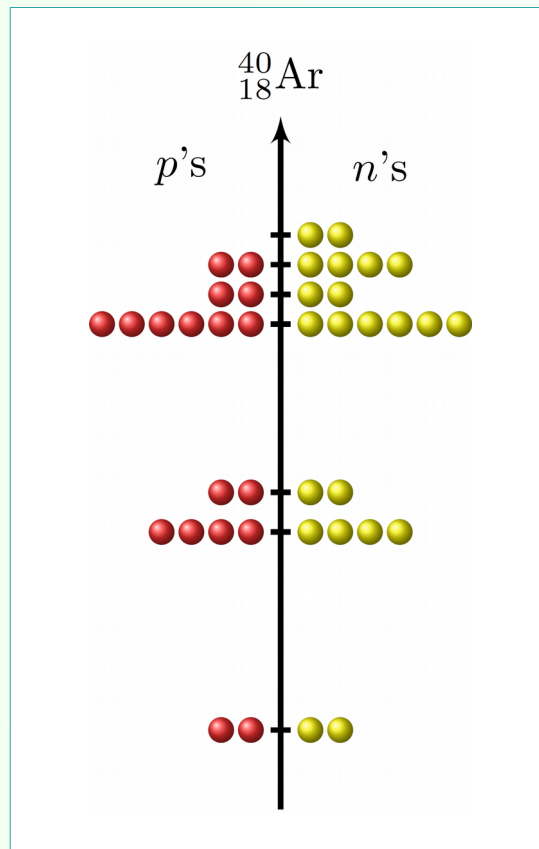
Momentum conservation

$$\mathbf{q} = \mathbf{p}' + \mathbf{p}_{\text{rec}} \rightarrow |\mathbf{q}| = |\mathbf{p}'| + |\mathbf{p}_{\text{rec}}|$$

$$\mathbf{q} = \mathbf{p}' + \mathbf{p}_{\text{rec}} \rightarrow |\mathbf{q}| = |\mathbf{p}'| - |\mathbf{p}_{\text{rec}}|$$

Impulse Approximation, $|p_{\text{rec}}| = |p|$
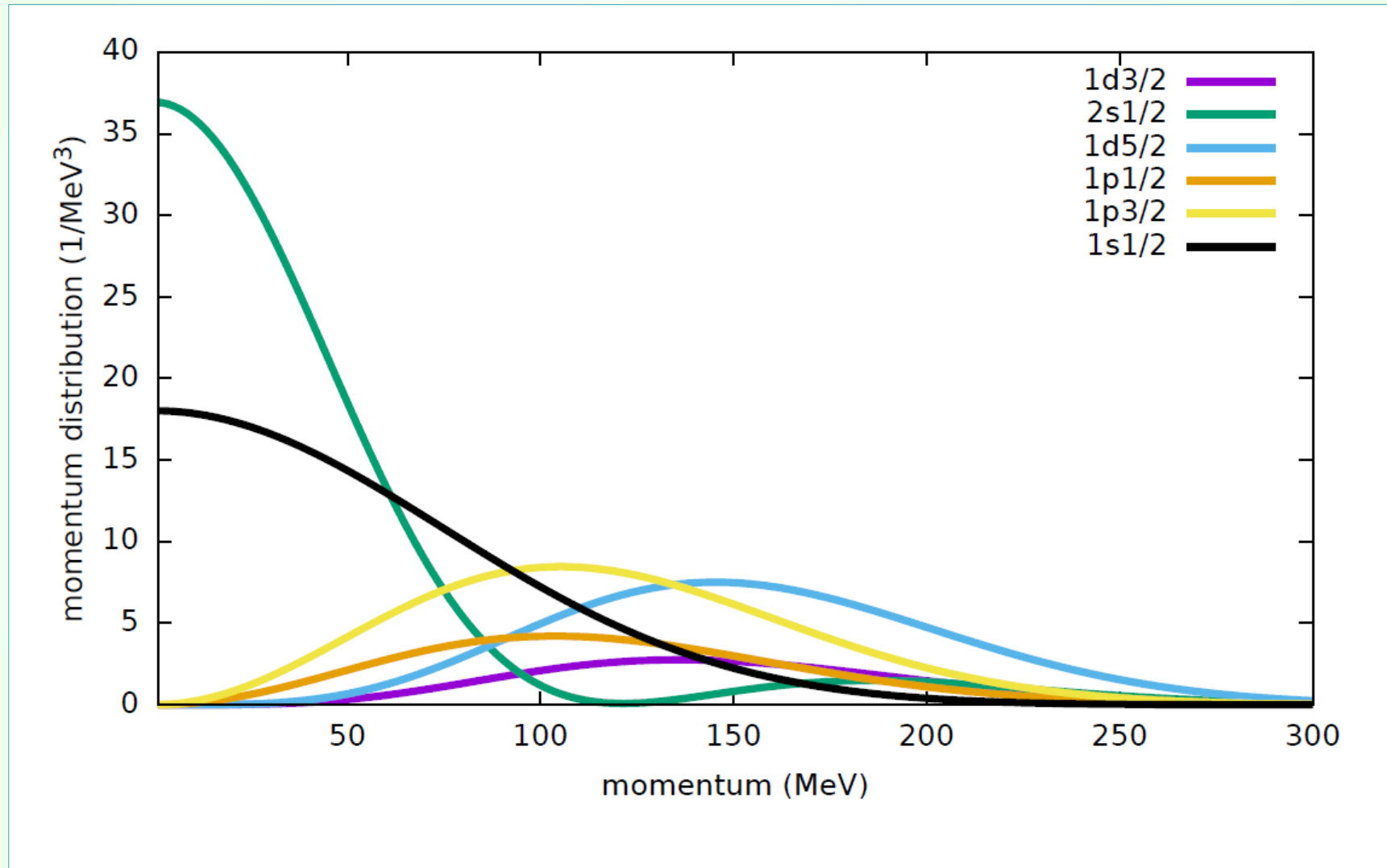
Neutron spectral function of ⁴⁰Ar

Kinematic settings

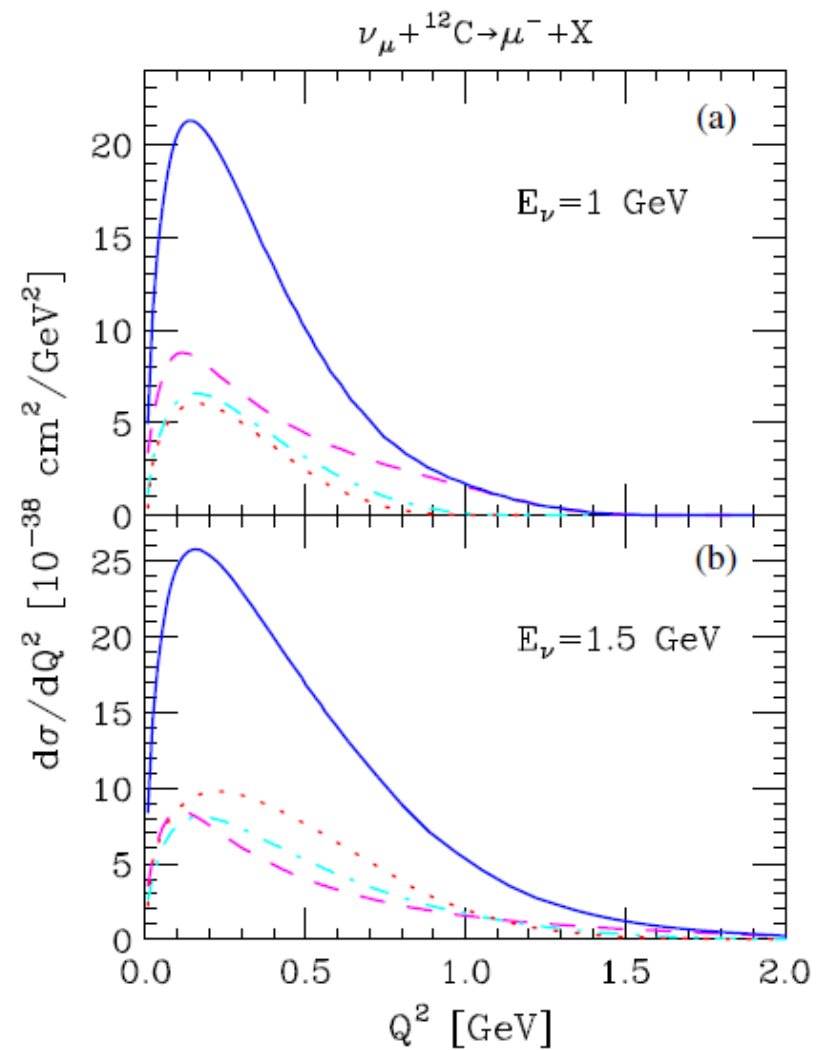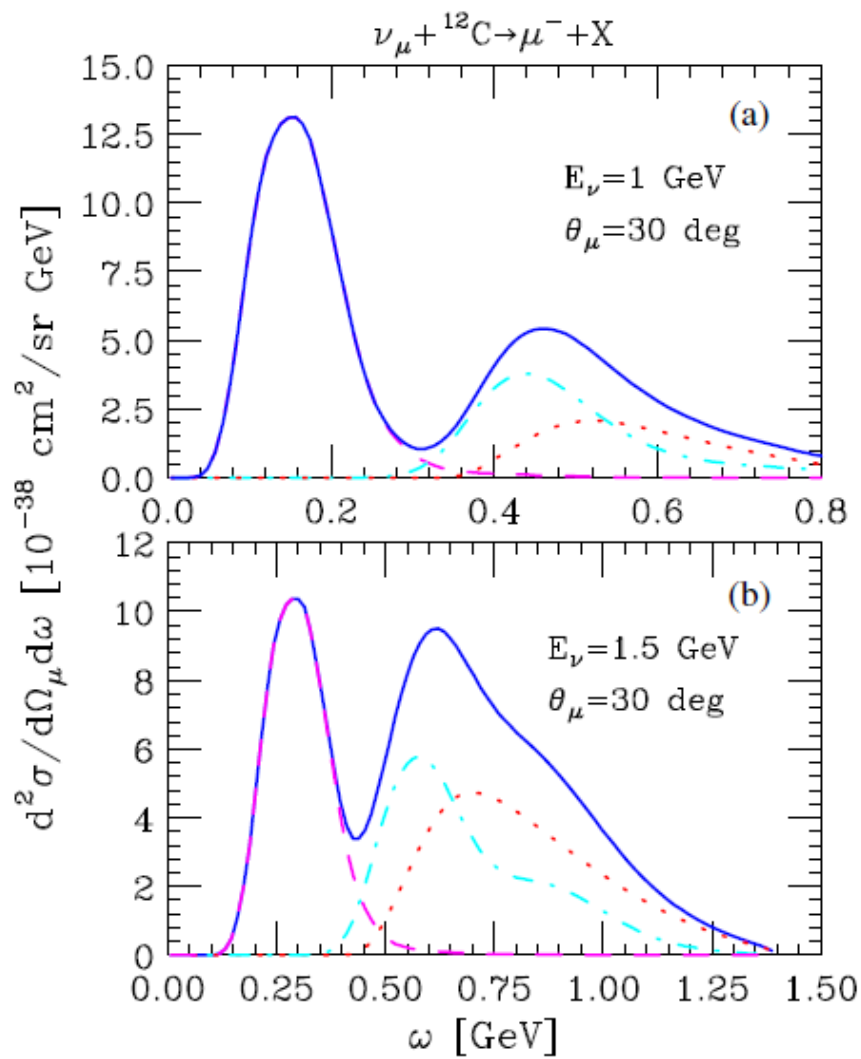|	E_e MeV	$E_{e'}$ MeV	θ_e deg	P_p MeV/c	θ_p deg	$|\mathbf{q}|$ MeV/c	p_m MeV/c	Ar events	Ti events
kin1	2222	1799	21.5	915	-50.0	857.5	57.7	44M	13M
kin2	2222	1716	20.0	1030	-44.0	846.1	183.9	63M	21M
kin3	2222	1799	17.5	915	-47.0	740.9	174.1	73M	28M
kin4	2222	1799	15.5	915	-44.5	658.5	229.7	159M	113M
kin5	2222	1716	15.5	1030	-39.0	730.3	299.7	45M	61k
(e, e')	2222		15.5					3M	3M

Data collected Feb - Mar 2017

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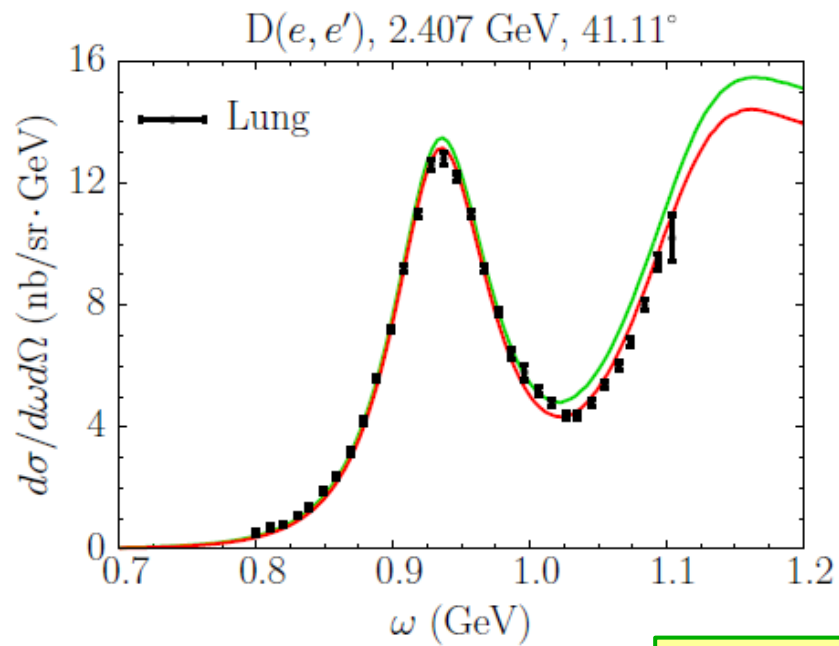# Expected energy distributions
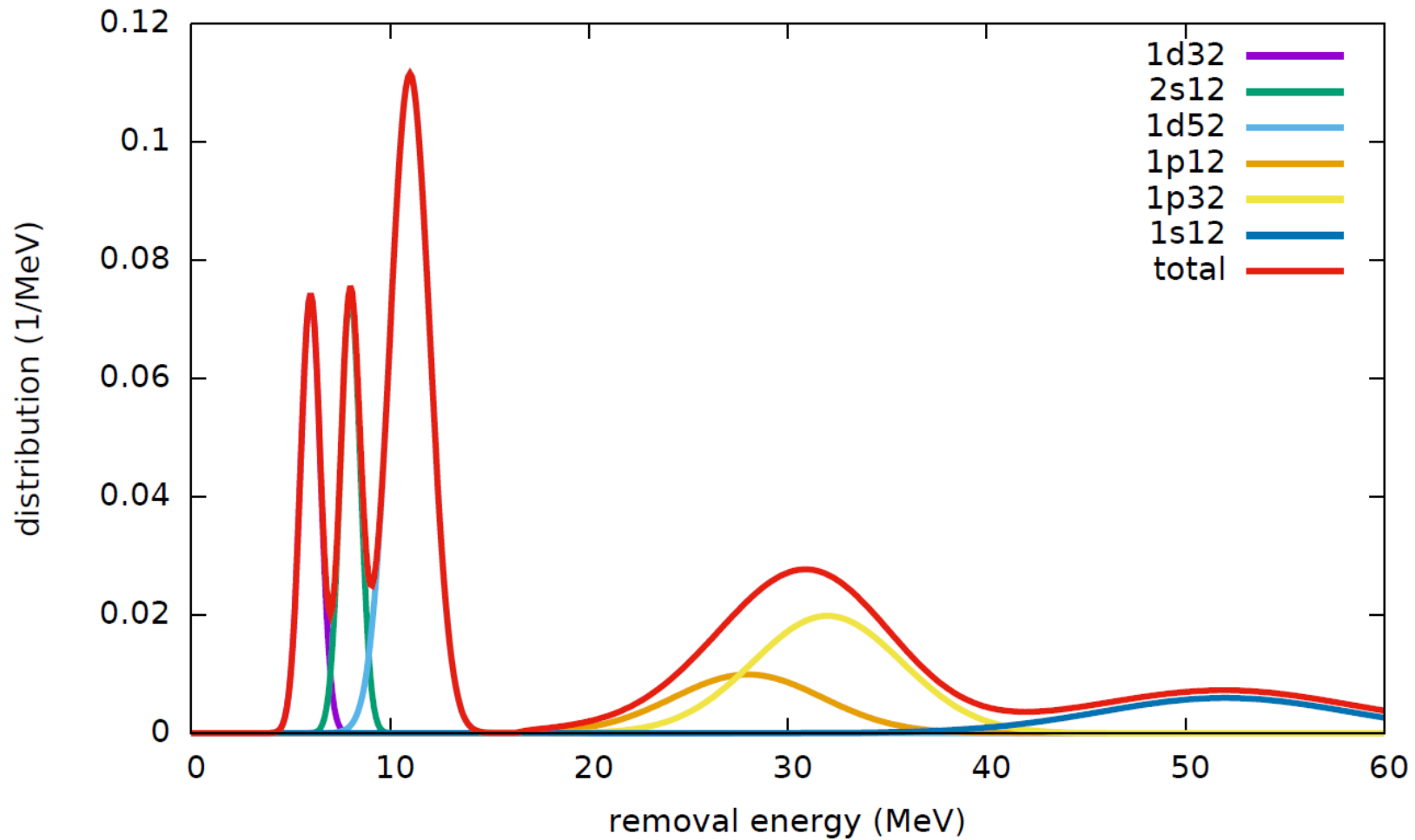
Momentum distributions

Backup slides

Vagnoni *et al.*, PRL 118, 142502 (2017)

D(e, e′), 2.407 GeV, 41.11°

O(e, e′), 880 MeV, 32°
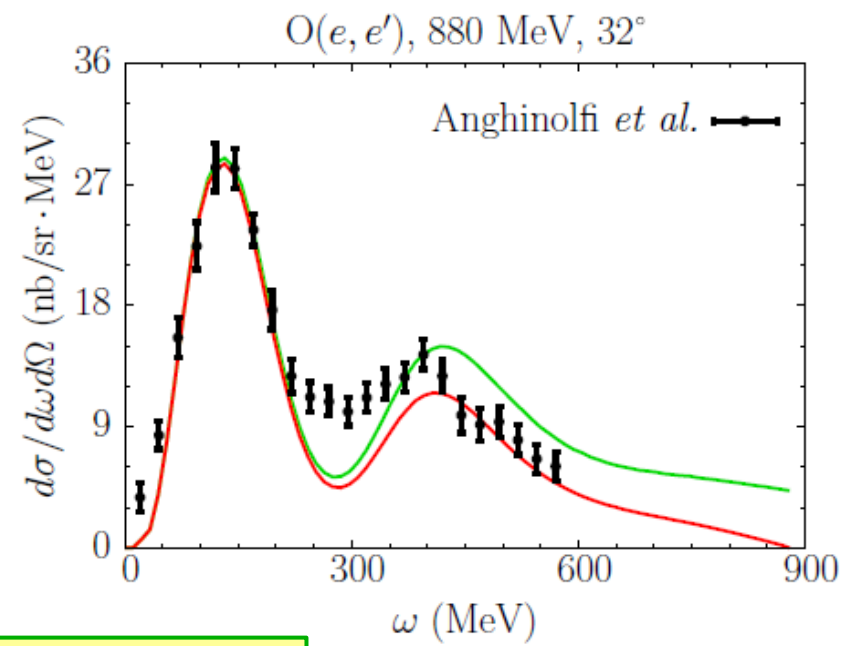
Conserved current

Conserved energy

Ca(e, e′), 681 MeV, 45.5°

Ca(e, e′), 782 MeV, 45.5°

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Other NC and CC QE data

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