FROM (e,e'p) TO NEUTRINO SCATTERING

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Università and INFN Pavia

Workshop on: Neutrino detection and interactions:
challenges and opportunities for ab-initio nuclear theory
INT Seattle March 4-8 2018

(e,e'p)

QE

$$e + A \Longrightarrow e' + p + (A-1)$$

(e,e'p)

QE

$$e + A \Longrightarrow e' + p + (A-1)$$

1pKO

both e' and p detected

(A-1) in a bound or unbound state

E_m missing energy (W^*_{A-1} - W_A)

discrete spectrum (low E_m) peaks

continuum spectrum (larger E_m)

for E_m corresponding to a peak (A-1) in a discrete eigenstate

(e,e'p) discrete low-lying states

(e,e'p) in the continuum

EXCLUSIVE

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all final states included

discrete and continuum spectrum

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proton-hole states

properties of bound protons

s.p. aspects of nuclear structure

validity and limitation of IPSM, MFA

nuclear correlations SRC

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short-range correlations

SRC

high E_m beyond threshold for the emission of a second N

two-nucleon knockout

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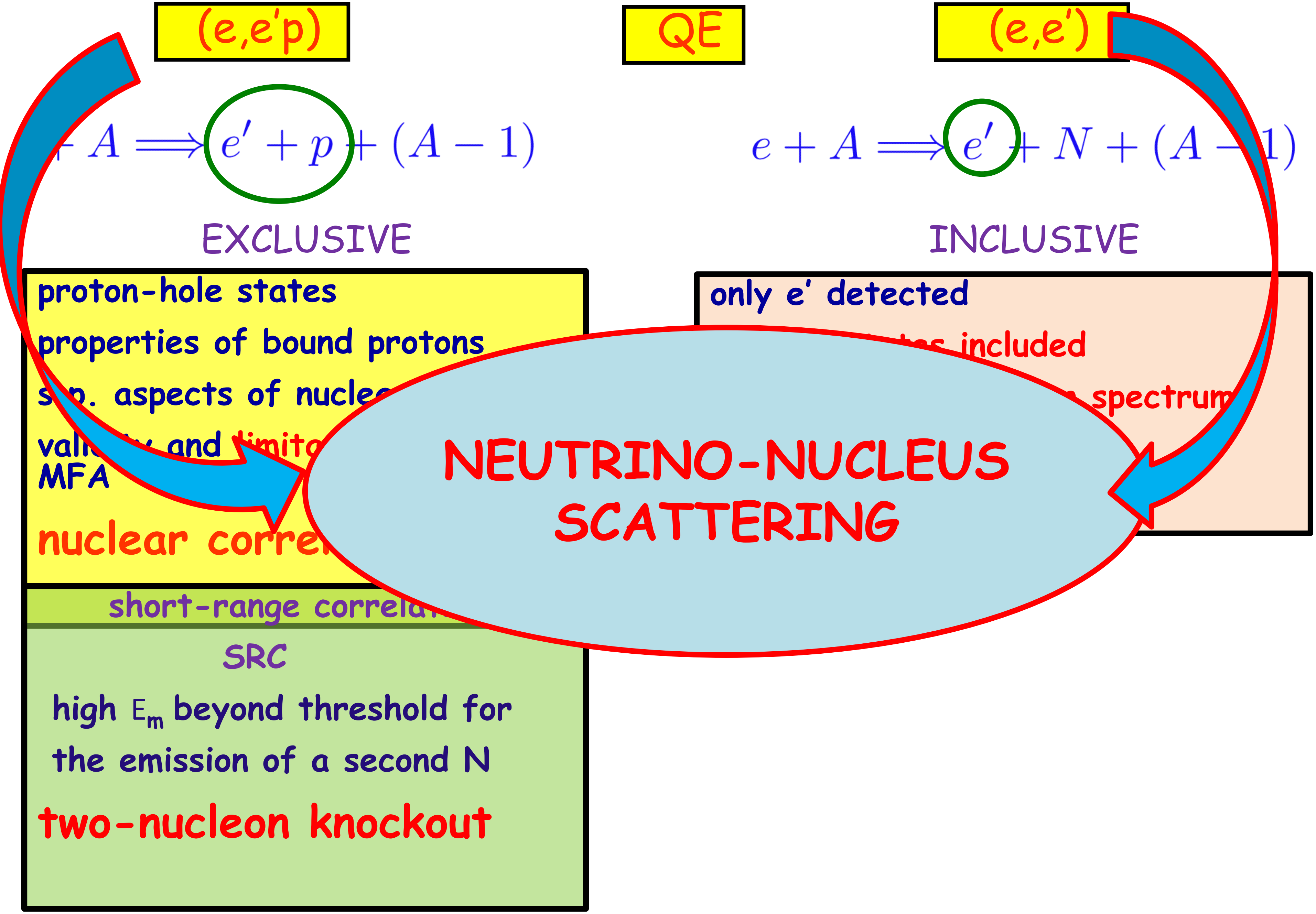

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NEUTRINO-NUCLEUS SCATTERING

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ectrum

If and how the work done for (e,e'p) can be useful for the analysis of neutrino experiments

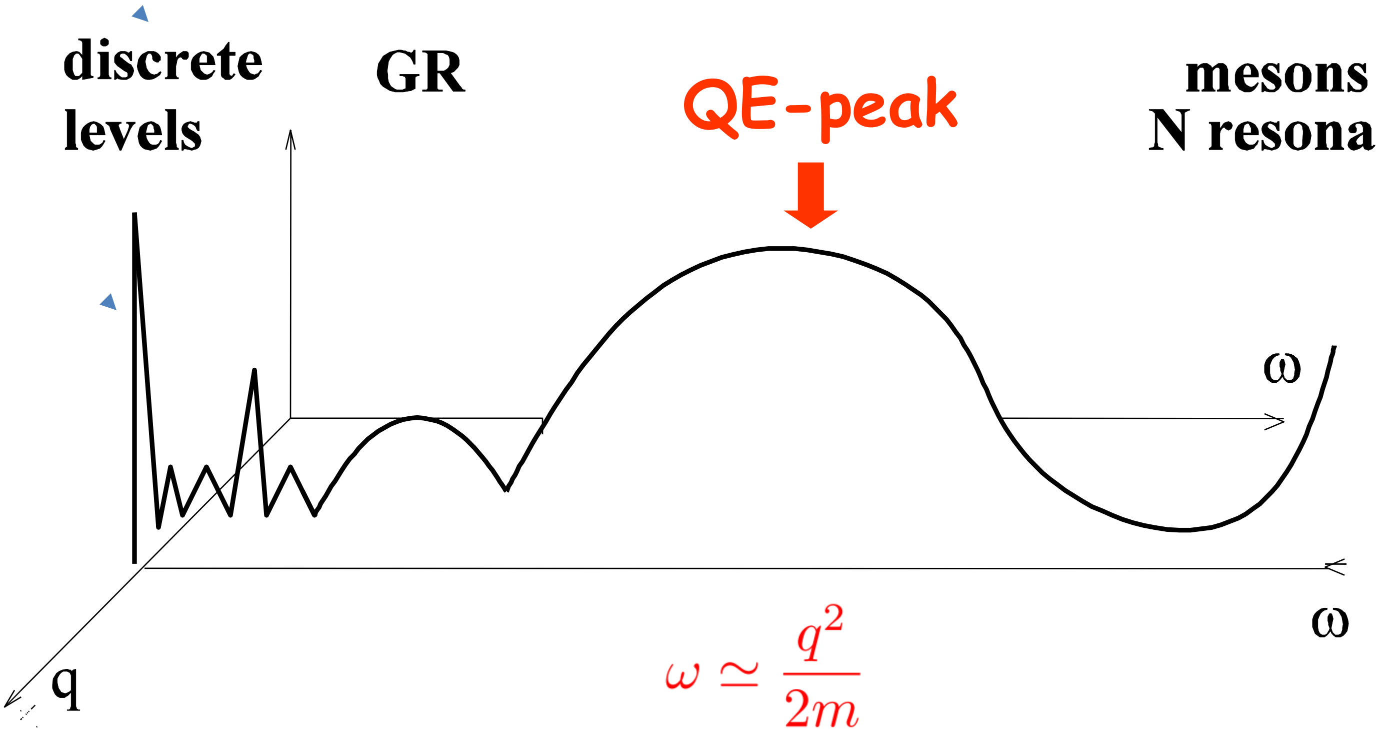
short-range correlations

SRC

high E_m beyond threshold for the emission of a second N

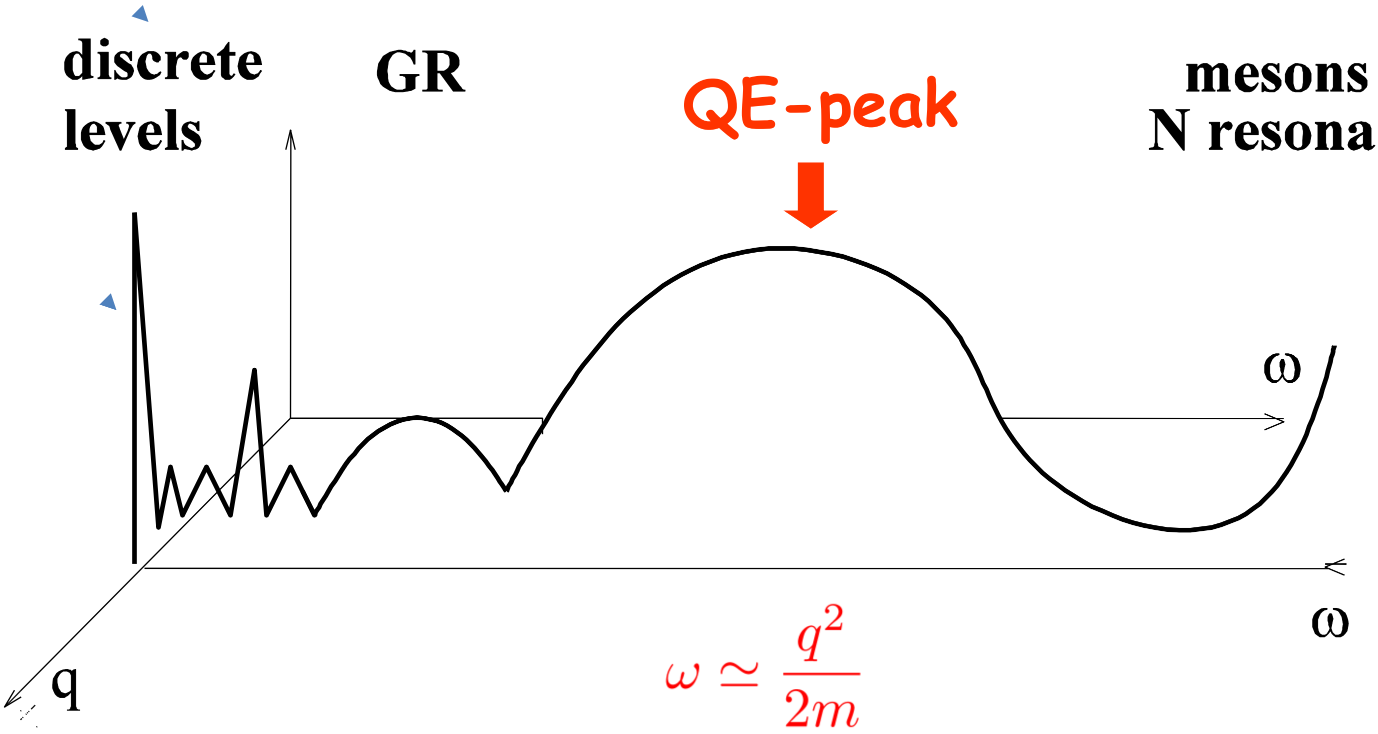
two-nucleon knockout

nuclear response to the electromagnetic probe



$$\omega \simeq \frac{q^2}{2m}$$

nuclear response to the electromagnetic probe



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QE-peak dominated by one-nucleon knockout

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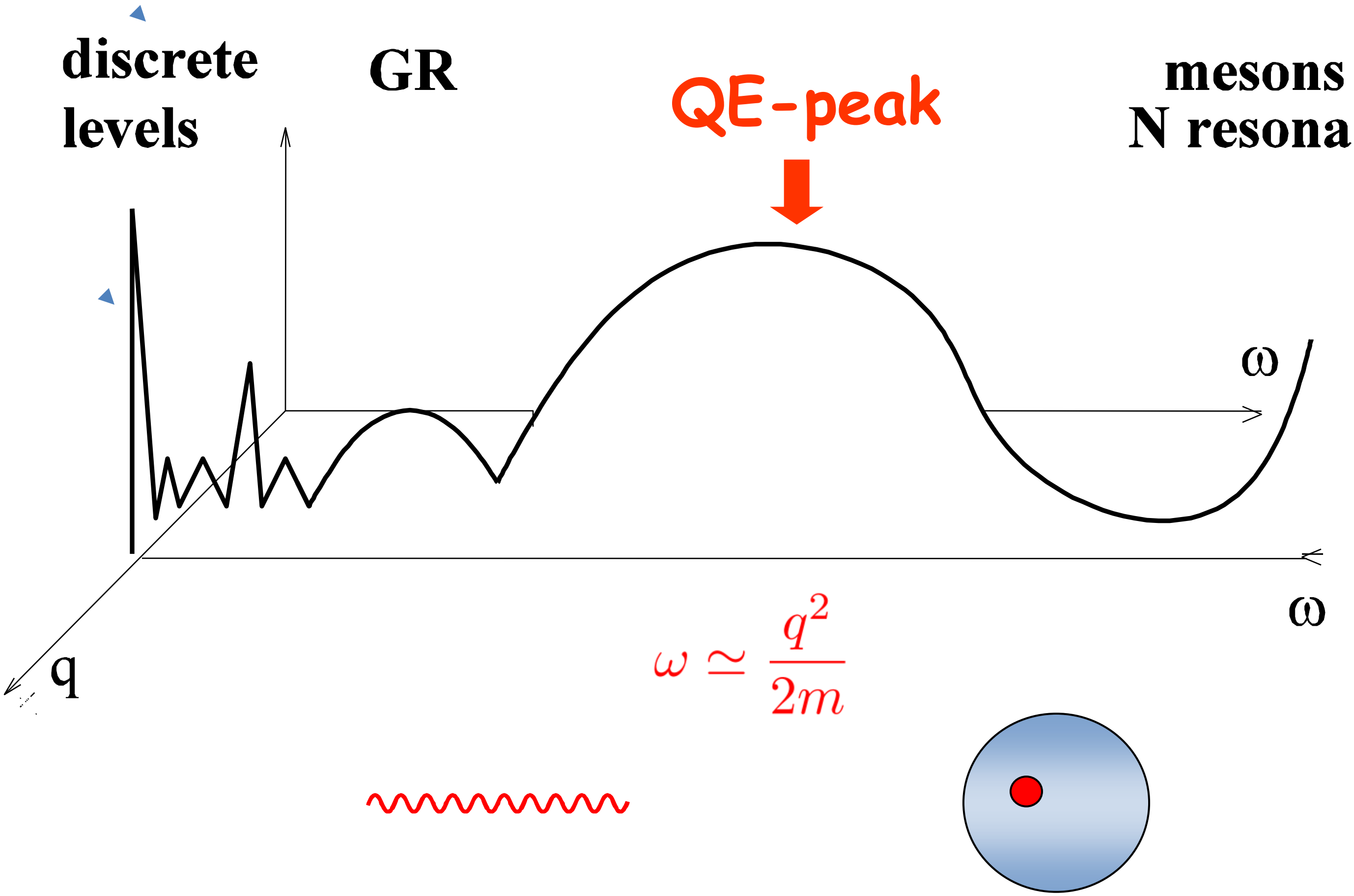

discrete levels

GR

QE-peak

mesons
N resonances

ω

q

ω

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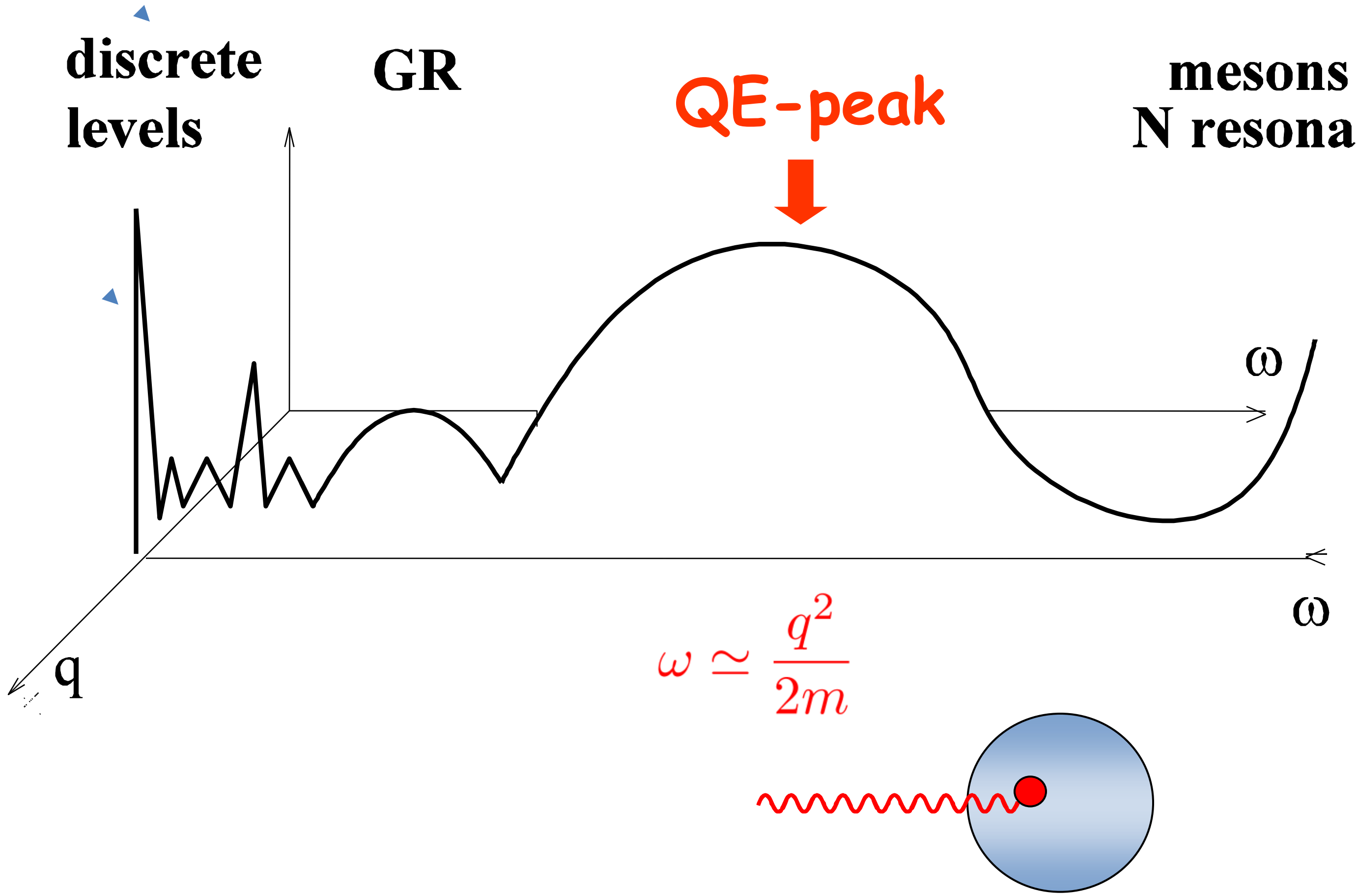

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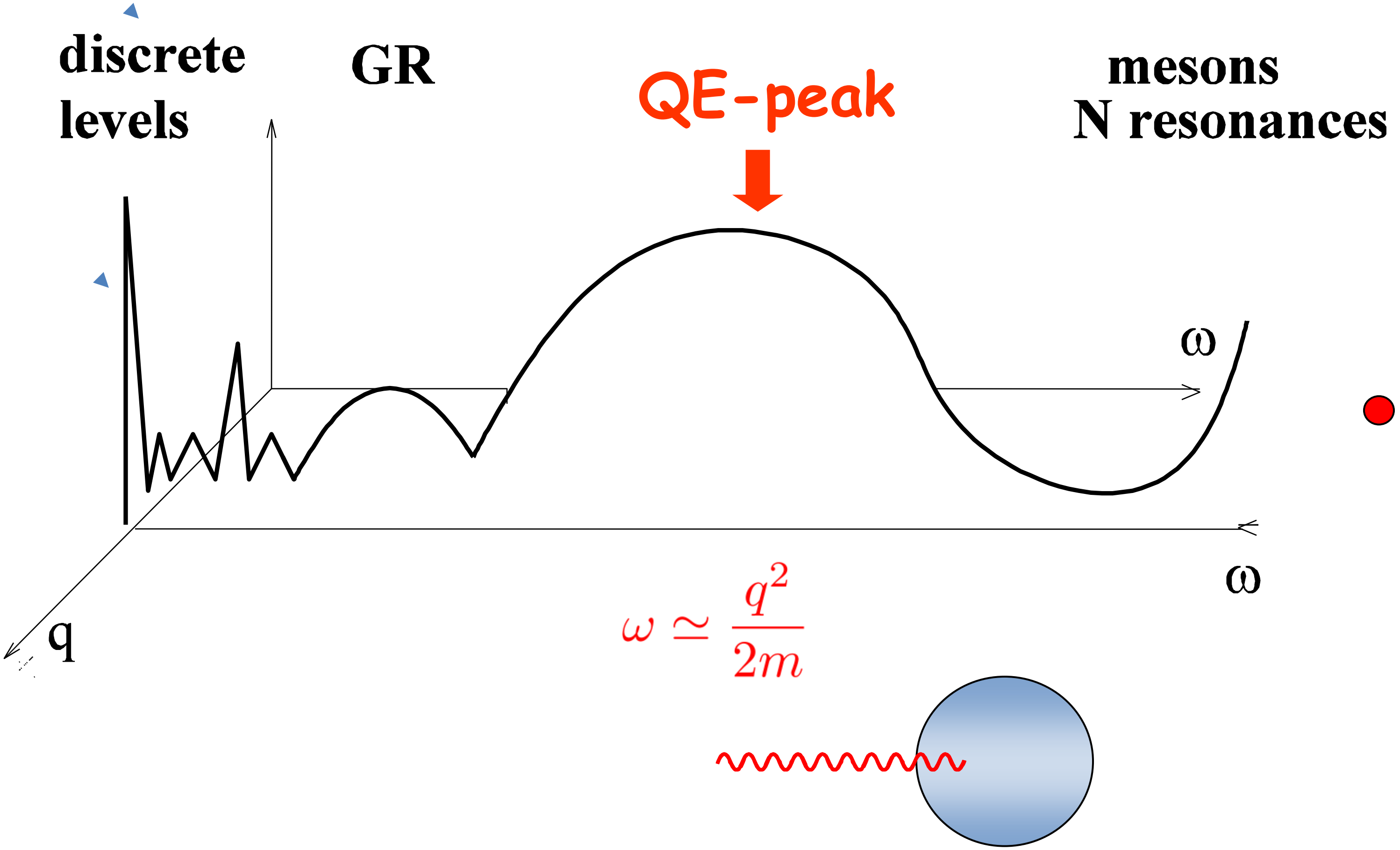

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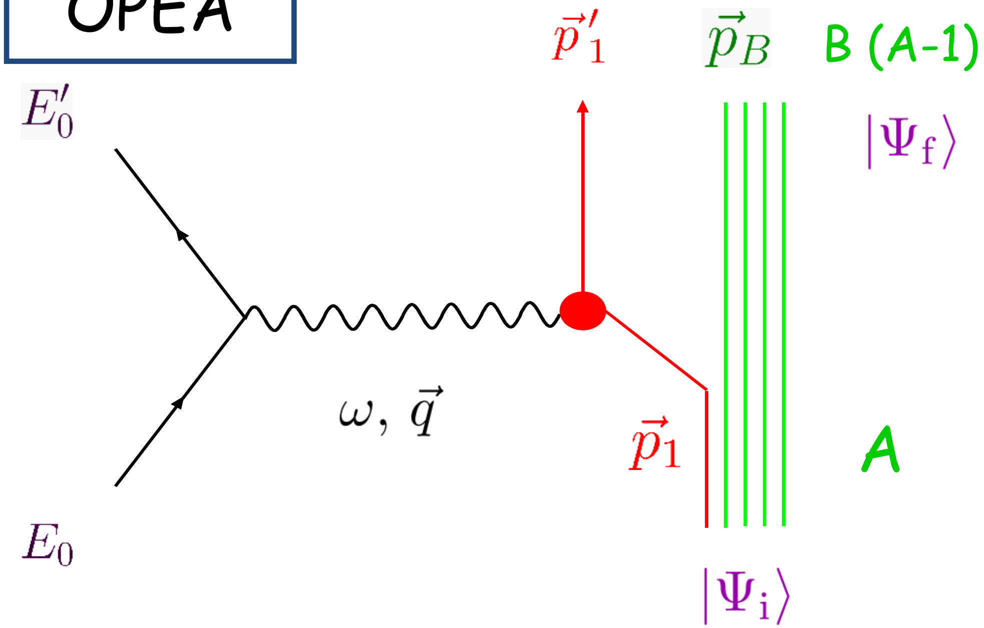
OPEA

(e,e'p)



$$E_\mathrm{m} = \omega - \frac{{p'_1}^2}{2m} - \frac{{p_B}^2}{2m(A-1)} = W_B^* - W_A$$

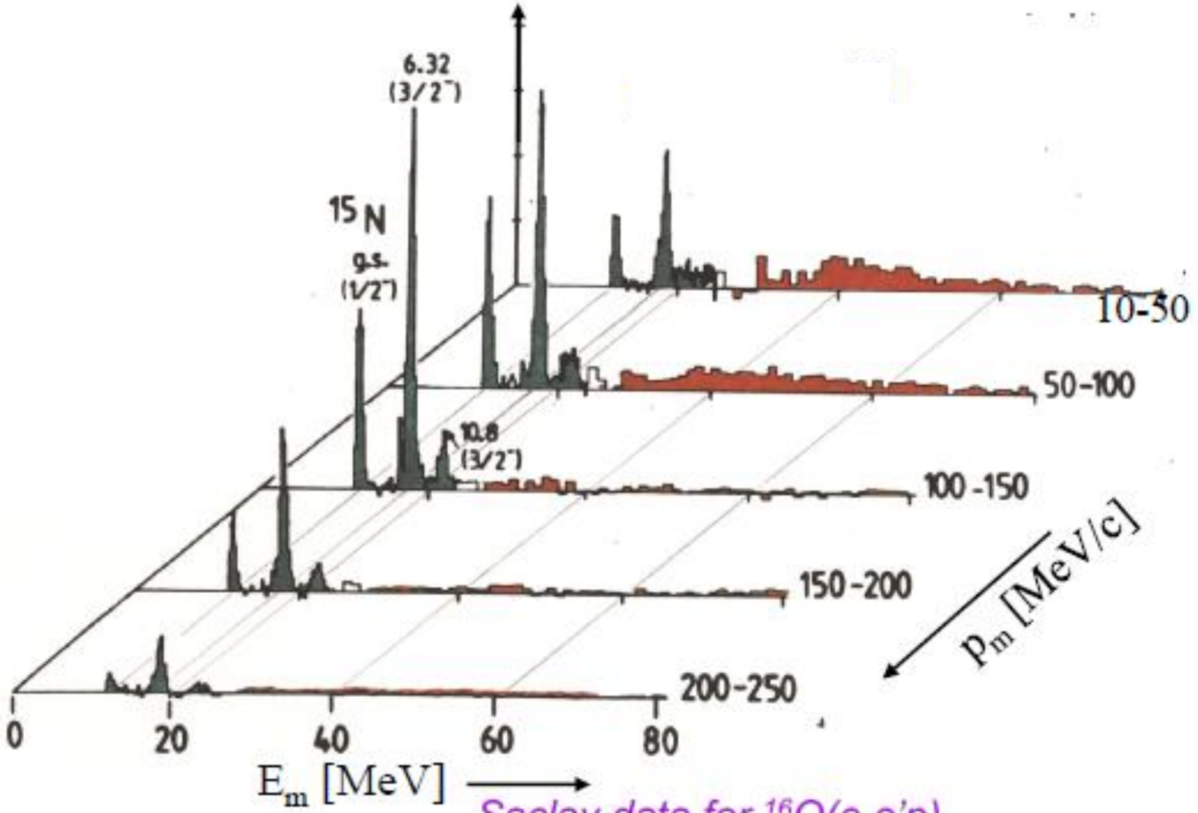
missing energy

$$\vec{p}_\mathrm{m} = \vec{q} - \vec{p'}_1 = -\vec{p}_1 = \vec{p}_B$$

missing momentum

Experimental data: E_m and p_m distributions

$^{16}\mathrm{O}(e,e'p)$



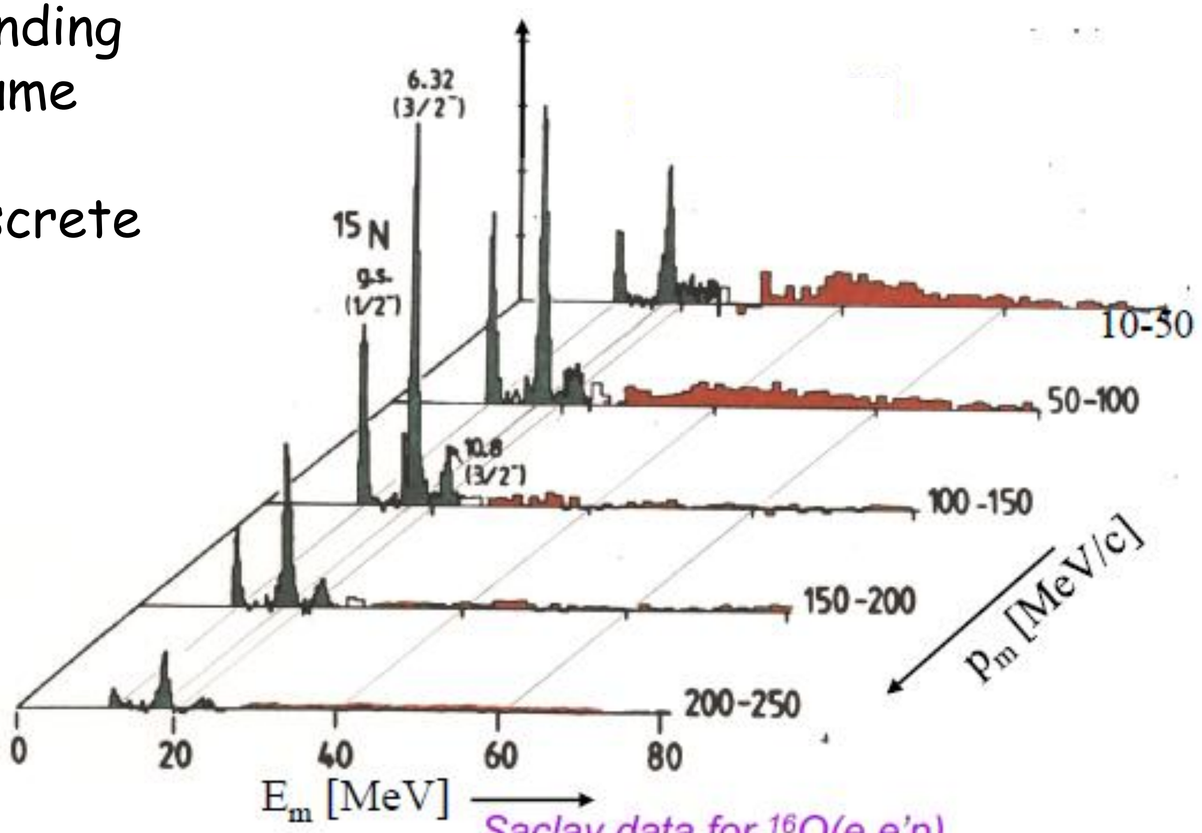
Saclay data for ^{16}O(e,e'p)

[Mougey et al., Nucl. Phys. A335, 35 (1980)]

Experimental data: E_m and p_m distributions

$^{16}\mathrm{O}(e,e'p)$

For E_m corresponding to a peak we assume that the residual nucleus is in a discrete eigenstate



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$$E_m$$

exclusive reaction

ONE-HOLE SPECTRAL FUNCTION

$$S(\vec{p_1}, \vec{\bar{p}_1}; E_m) = \langle \Psi_{\mathrm{i}} | a^{+}_{\vec{\bar{p}}_1} \delta(E_m - H) a_{\vec{p_1}} | \Psi_{\mathrm{i}} \rangle$$

$$\vec{p}_1 = \vec{\bar{p}}_1$$

joint probability of removing from the target a nucleon p_1 leaving the residual nucleus in a state with energy E_m

E_m

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joint probability of removing from the target a nucleon p_1
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$$\int S(\vec{p}_1,\vec{\bar{p}}_1;E_m)\mathrm{d}E_m = \boxed{\rho(\vec{p}_1,\vec{\bar{p}}_1)}$$

inclusive reaction : one-body density

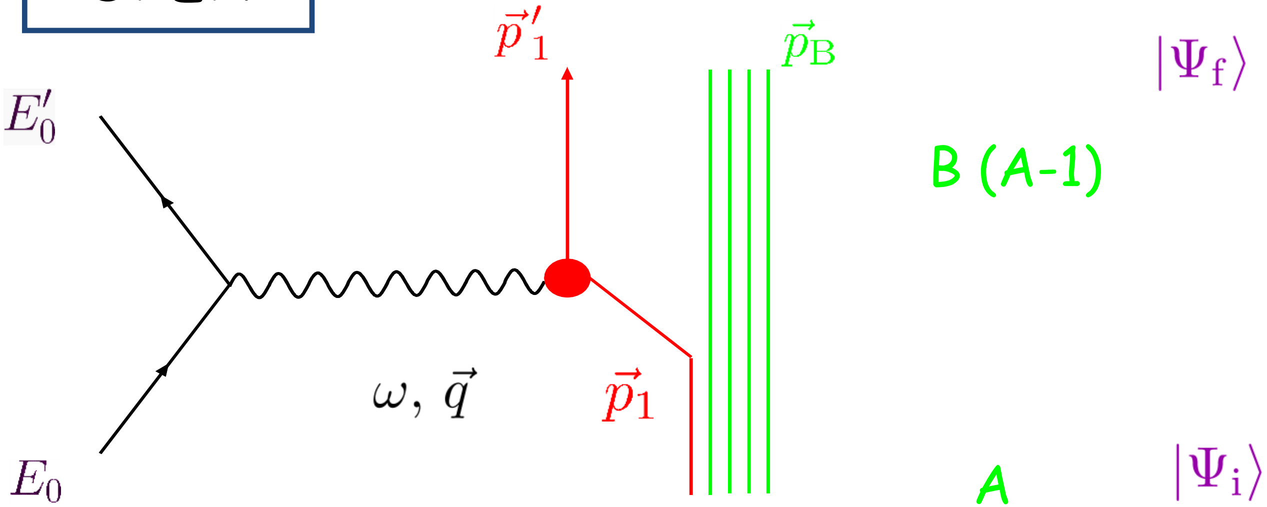
$\vec{p}_1 = \vec{\bar{p}}_1$ ⇨ $\rho(\vec{p}_1,\vec{\bar{p}}_1) = \boxed{F(\vec{p}_1)}$

MOMENTUM DISTRIBUTION

$$F(\vec{p}_1) = \int |\Psi_\mathrm{i}(\vec{p}_1,\vec{p}_2,....,\vec{p}_A|^2 \mathrm{d}\vec{p}_2....\mathrm{d}\vec{p}_A$$

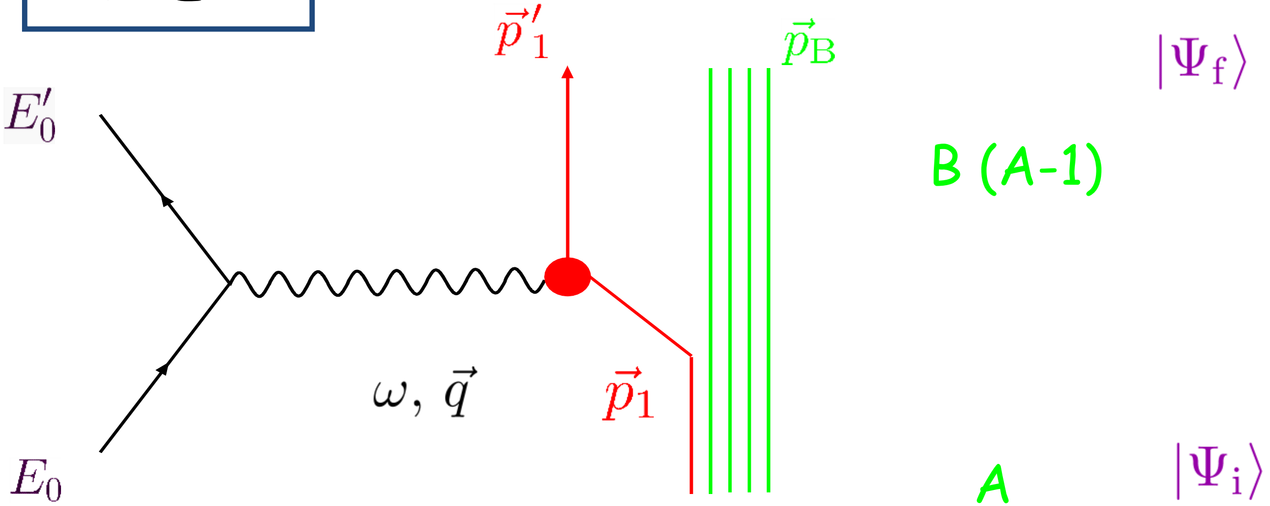
probability of finding in the target
a nucleon with momentum p_1

OPEA



$$\sigma = K L^{\mu\nu}\ W_{\mu\nu}$$

OPEA



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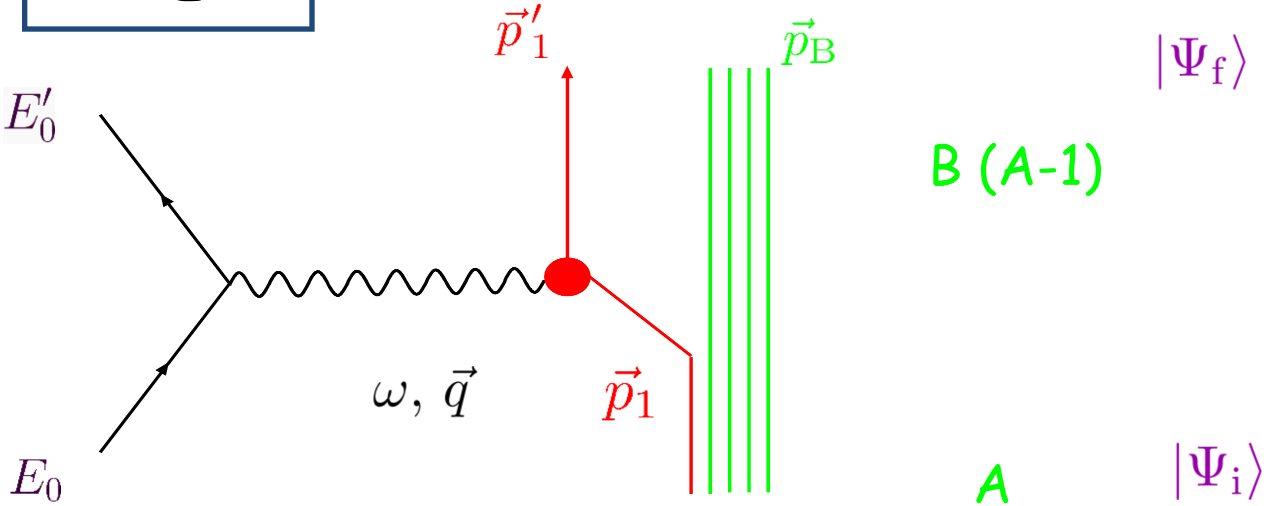
lepton tensor

OPEA



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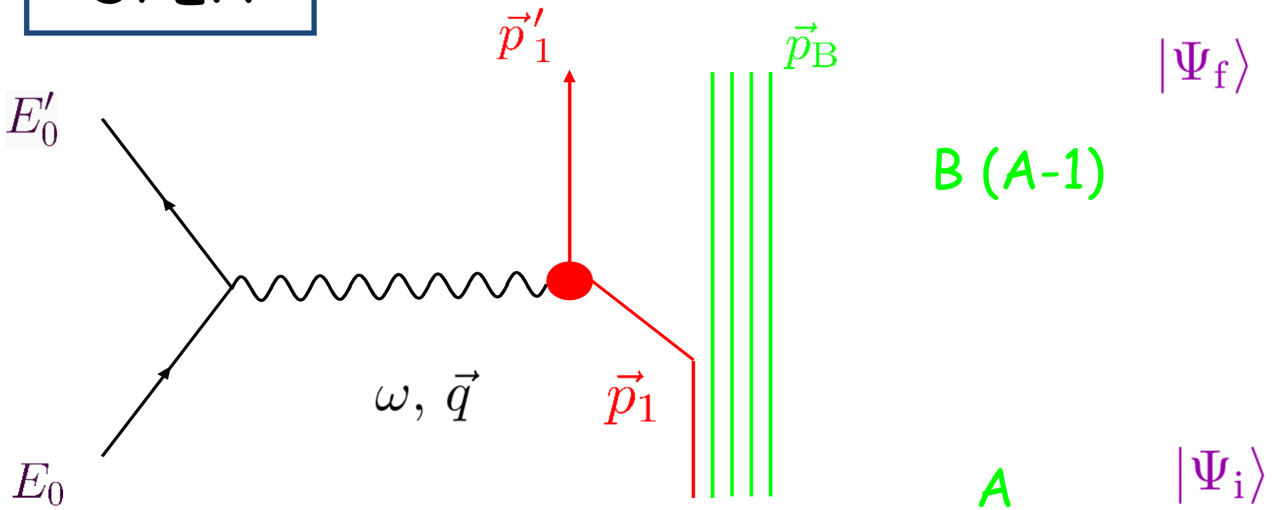
hadron tensor

OPEA



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hadron tensor

$$W^{\mu\nu} = \overline{\sum_{\mathrm{i,f}}} J^{\mu}(\vec{q}) J^{\nu *}(\vec{q}) \delta(E_{\mathrm{i}} - E_{\mathrm{f}})$$

$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \langle \Psi_{\mathrm{f}} \mid \hat{J}^{\mu}(\vec{r}) \mid \Psi_{\mathrm{i}} \rangle \mathrm{d}\vec{r}$$

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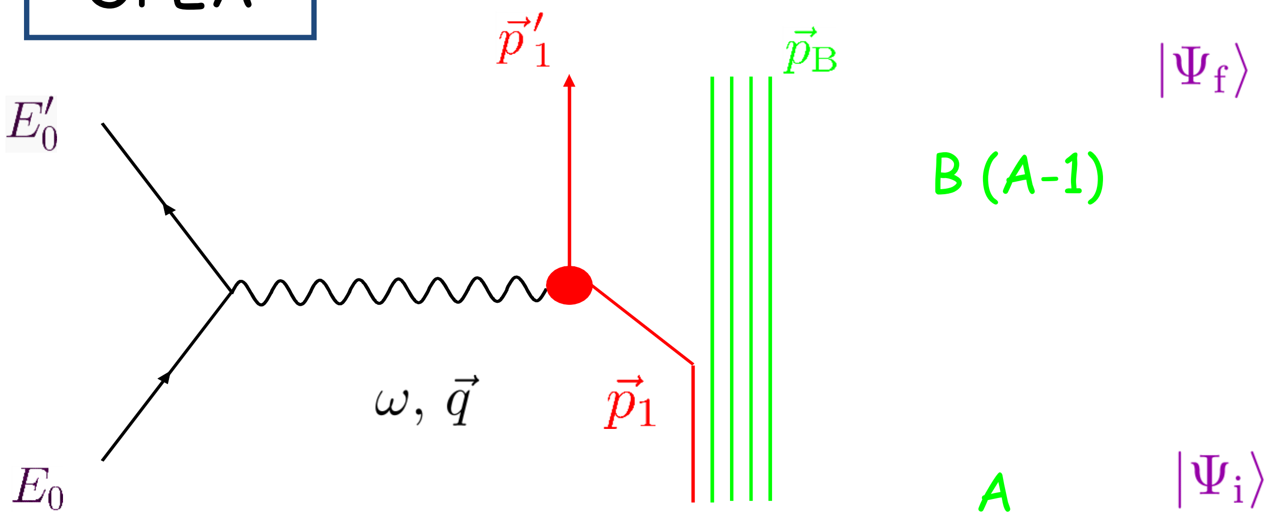

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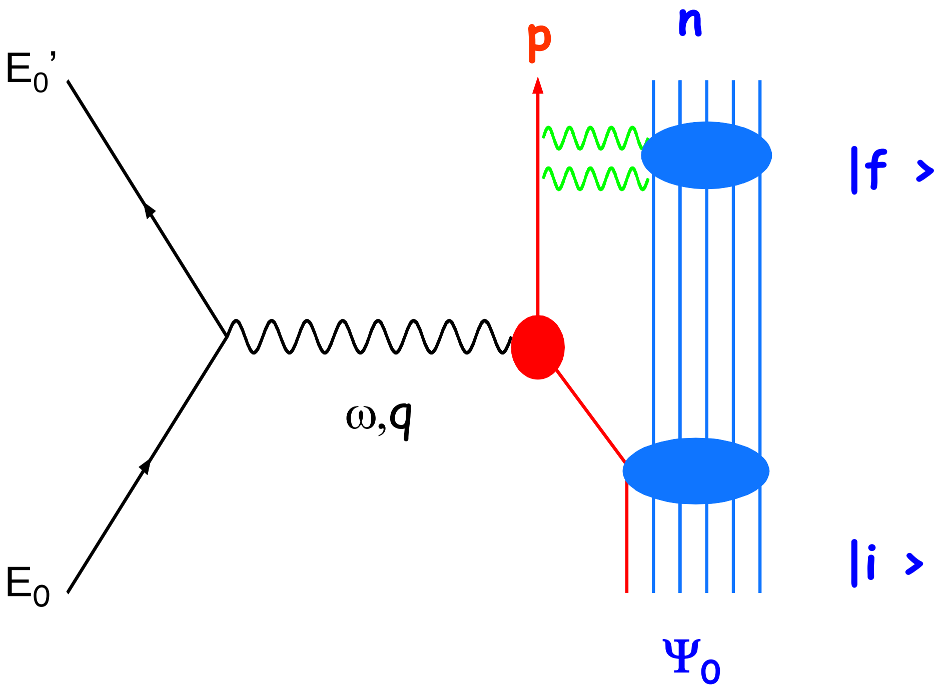
(e,e'p)

- exclusive reaction n
- DKO
- impulse approximation IA: the probe interacts through a one-body current only with the ejectile nucleon, the remaining nucleons are spectators



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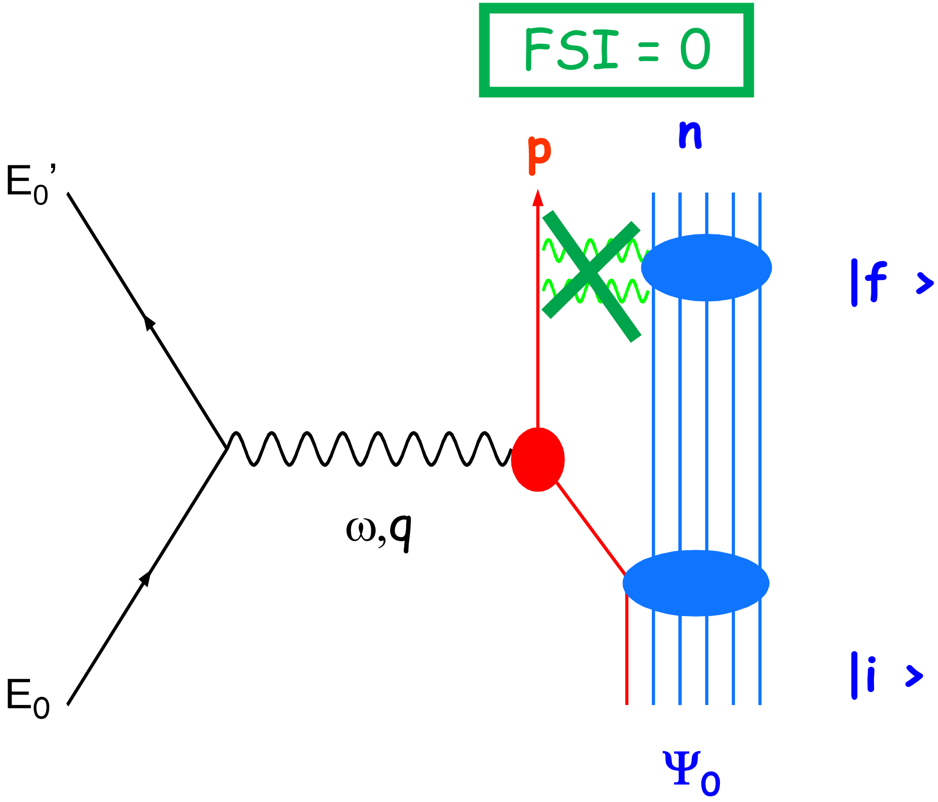
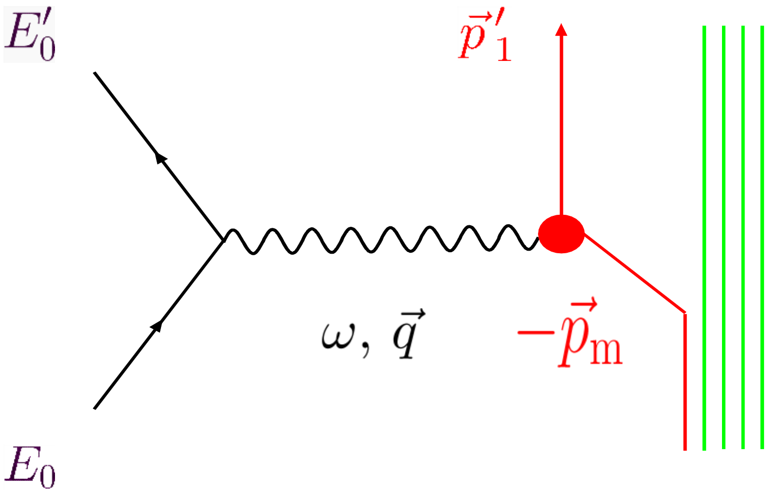


FSI=0

PW



PLANE-WAVE IMPULSE APPROXIMATION

PWIA

factorized cross section

$$\sigma = K \ \sigma_{\mathrm{ep}} \ S(E_{\mathrm{m}}, -\vec{p}_{\mathrm{m}})$$

spectral function

$$S(E_{\mathrm{m}}, -\vec{p}_{\mathrm{m}}) = \sum_n \ \lambda_n(E_{\mathrm{m}}) \ |\phi_n(-\vec{p}_{\mathrm{m}})|^2$$

spectroscopic factor

overlap function

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spectroscopic factor

overlap function

For each E_m the mom. dependence of the SF is given by the mom. distr. of the quasi-hole states n produced in the target nucleus at that energy and described by the normalized OVF

The norm of the OVF, the spectroscopic factor gives the probability that n is a pure hole state in the target.

IPSM

ϕ_n s.p. SM state

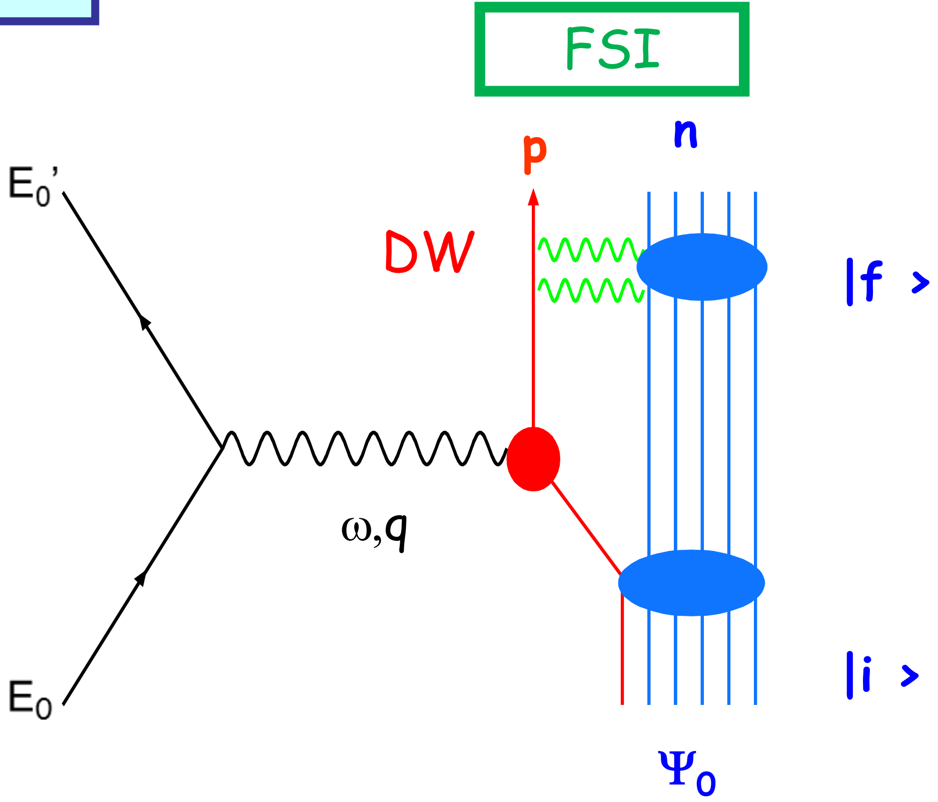
λ_n 1 occupied SM states

0 empty SM states

There are correlations and the strength of the quasi-hole state is fragmented over a set of s.p. states $0 \leq \lambda_n \leq 1$

DWIA (e,e'p)

- exclusive reaction n
- DKO IA
- FSI DWIA
- unfactorized c.s.
- non diagonal SF



$$\langle f \mid J^\mu(\boldsymbol{q}) \mid i\rangle \Rightarrow \lambda_n^{1/2}\ \langle \chi_{\boldsymbol{p}}^{(-)} \mid j^\mu(\boldsymbol{q}) \mid \phi_n\rangle$$

Direct knockout DWIA (e,e′p)

$$\lambda_n^{1/2}\ \langle\chi^{(-)}\mid j^{\mu}\mid\phi_n\rangle$$

- j^{μ} one-body nuclear current
- $\chi^{(-)}$ s.p. scattering w.f. $H^{+}(\omega+E_m)$
- ϕ_n s.p. bound state overlap function $H(-E_m)$
- λ_n spectroscopic factor
- $\chi^{(-)}$ and ϕ consistently derived as eigenfunctions of a Feshbach optical model Hamiltonian

DWIA-RDWIA calculations

- phenomenological ingredients usually adopted
- $\chi^{(-)}$ phenomenological optical potential
- ϕ_n phenomenological s.p. wave functions WS, HF MF (some calculations including correlations are available)
- λ_n extracted in comparison with data: reduction factor applied to the calculated c.s. to reproduce the magnitude of the experimental c.s.

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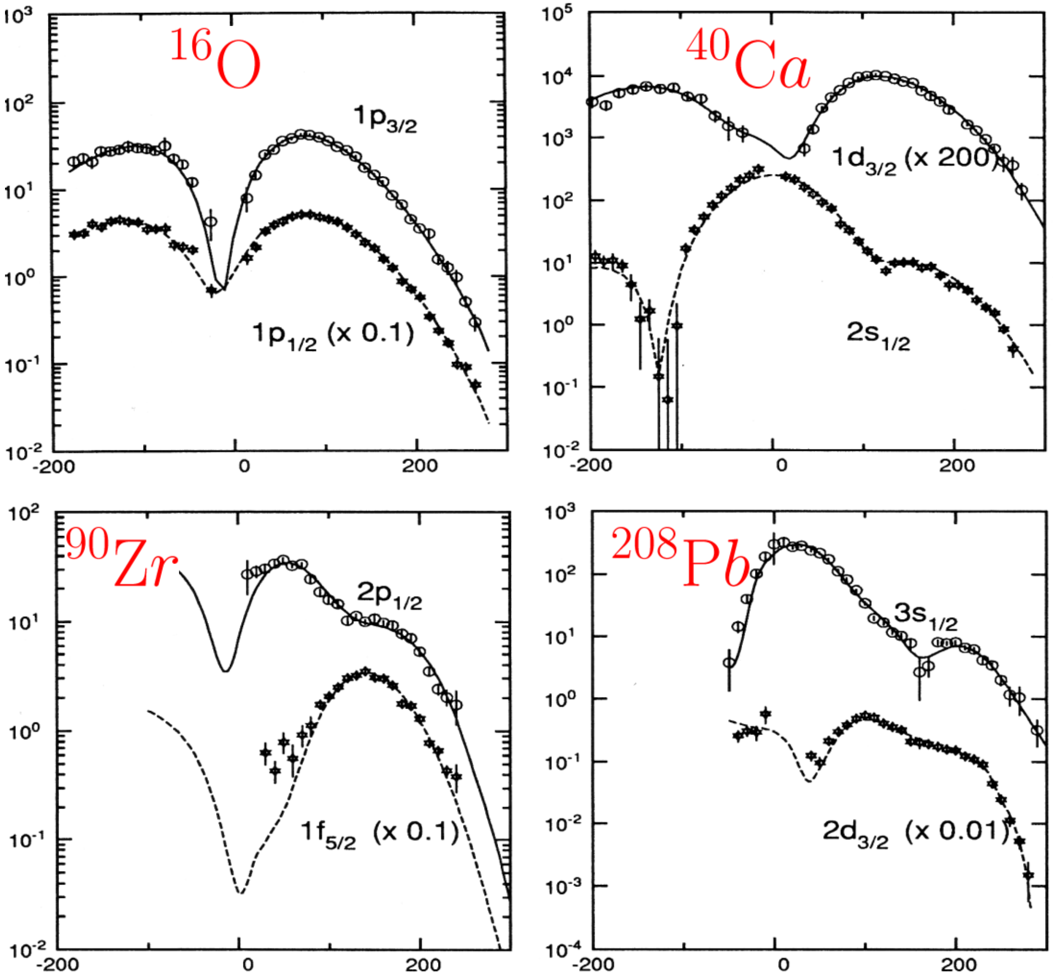
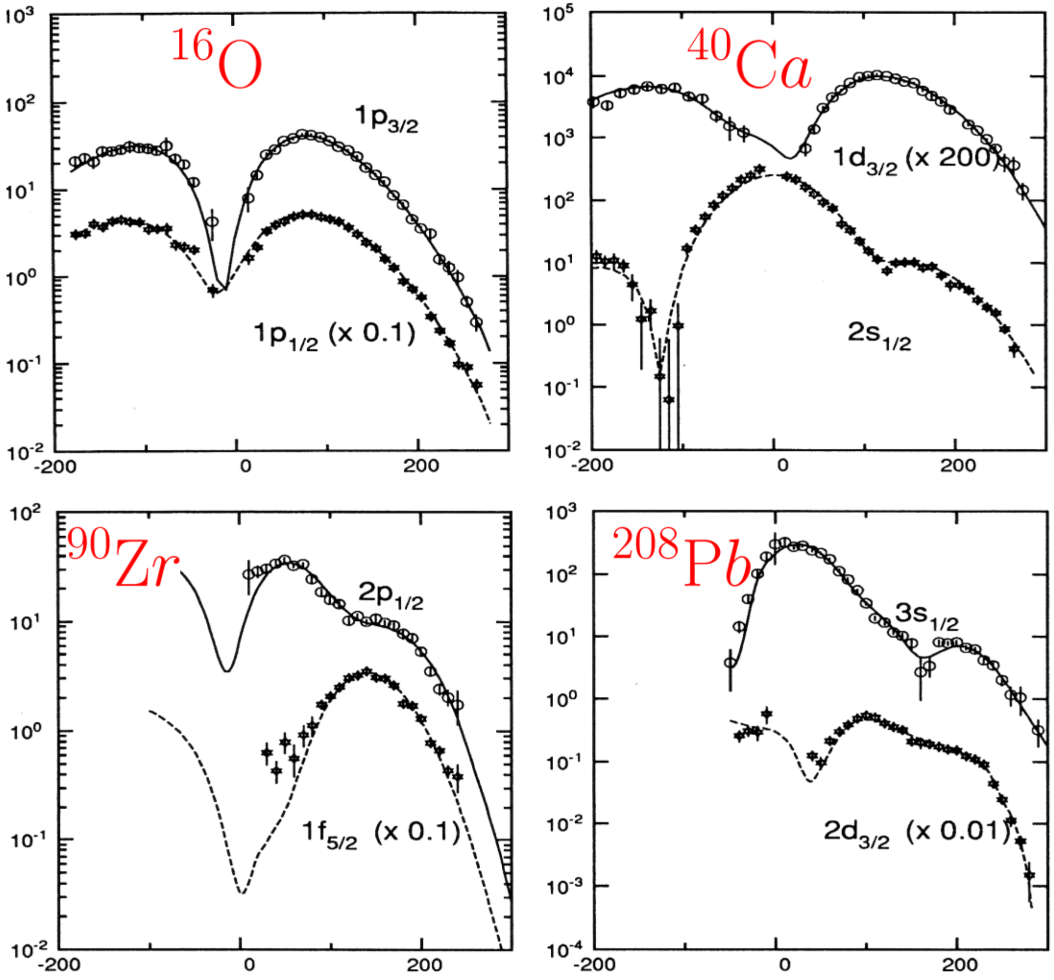
DWIA and RDWIA: excellent description of (e,e′p) data

Experimental data: p_m distribution



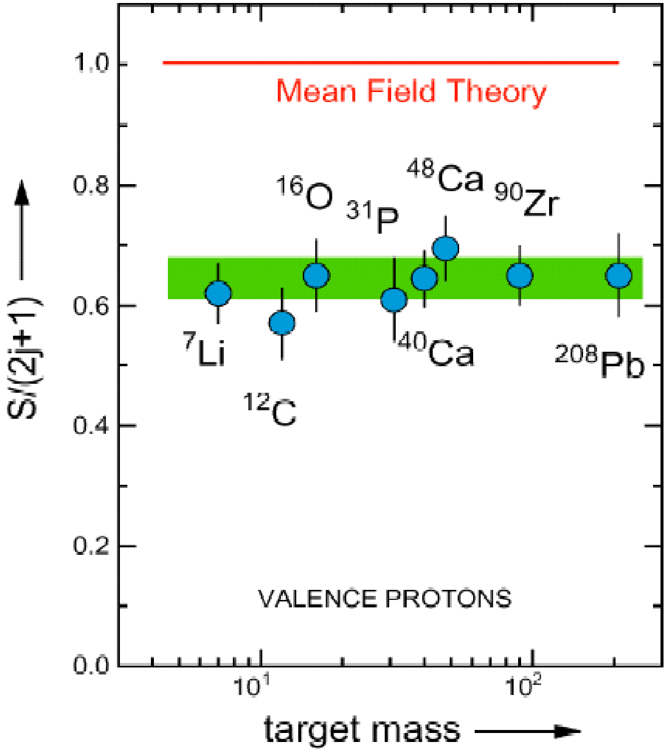
NIKHEF data & CDWIA calculations

Experimental data: p_m distribution



reduction factors applied: spectroscopic factors

0.6 - 0.7



NIKHEF data & CDWIA calculations

SPECTROSCOPIC FACTORS and NN CORRELATIONS

- depletion due to NN correlations
- different independent investigations:
- SRC (Short-Range Correlations) account for only a few % of the depletion, up to 10-15 % with TC
- LRC (Long-Range Correlations) main contribution to the depletion
- LRC collective excitations of nucleons at the nuclear surface

SRC

- account for only a small part of the depletion
- depletion due to SRC compensated by the admixture of high-momentum components in the s.p. w.f.
- SRC effects on (e,e'p) cross sections at high p_m are small for low-lying states
- calculations of the 1BDM and of the momentum distribution indicate that the missing strength due to SRC is found at large p_m and E_m, beyond the continuum threshold, where various processes involving more nucleons can be present

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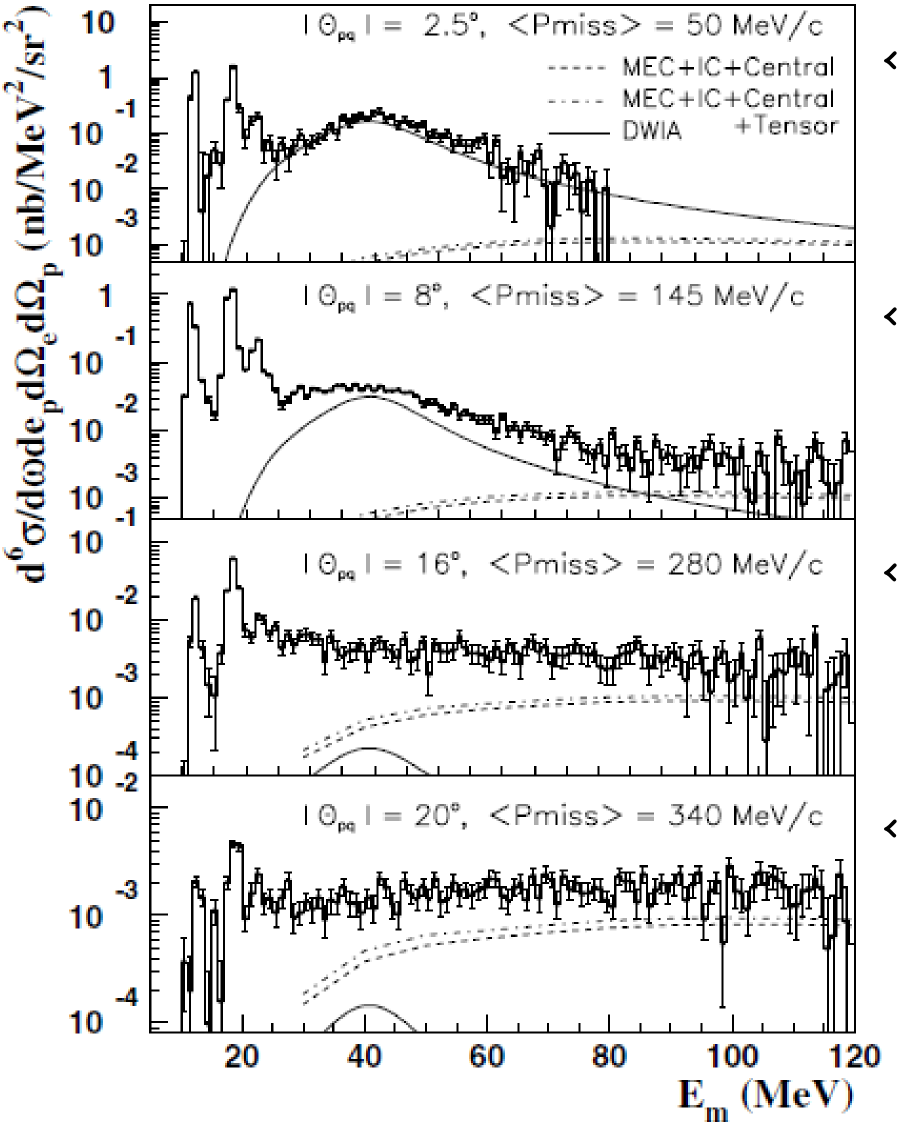
- (e,e′p) at high values of E_m ⇐

$^{16}O(e,e'p)$ at high E_m



$\langle p_m \rangle$ = 50 MeV/c

$\langle p_m \rangle$ = 145 MeV/c

$\langle p_m \rangle$ = 280 MeV/c

$\langle p_m \rangle$ = 340 MeV/c

N. Liyanage et al. PRL 86 (2001) 5670

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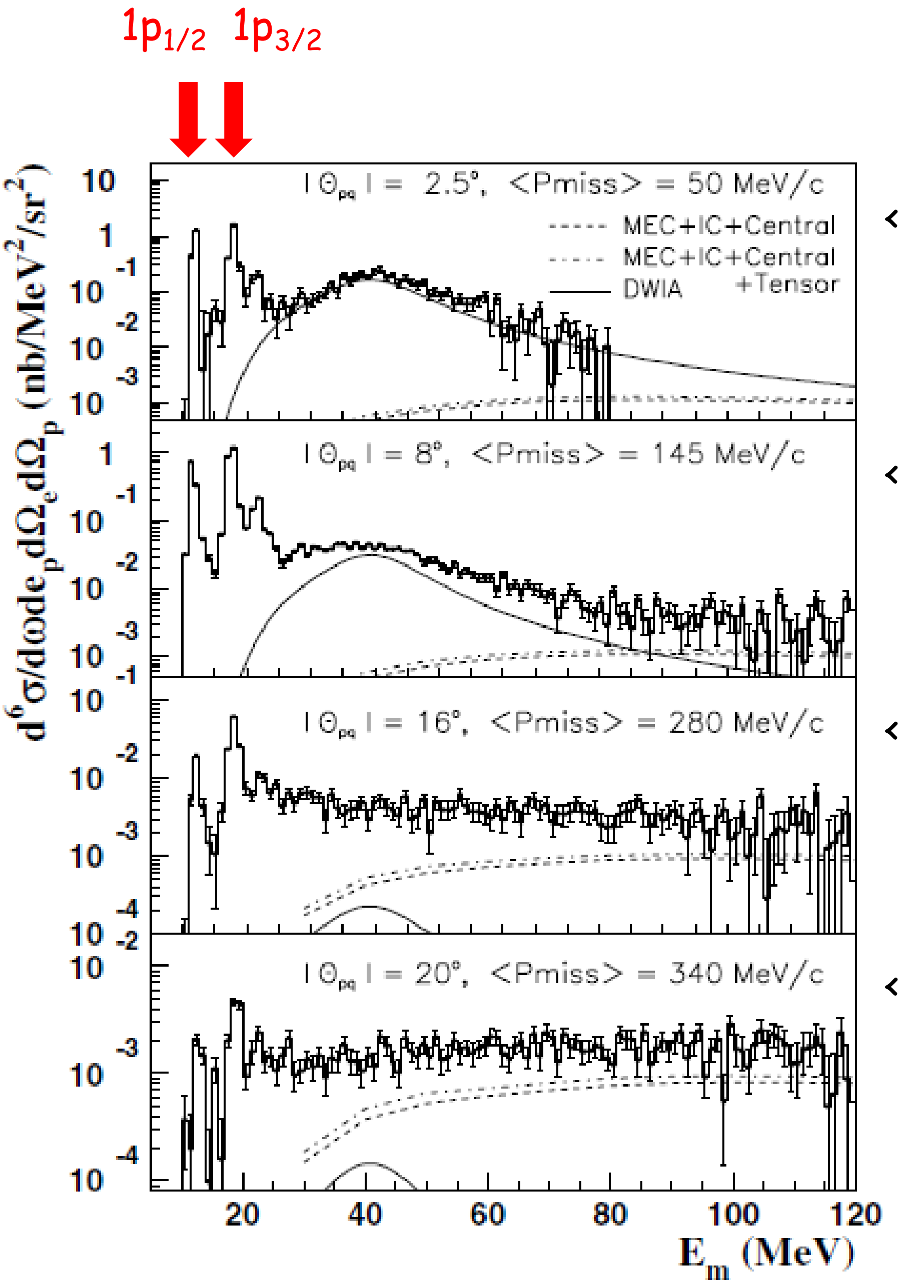

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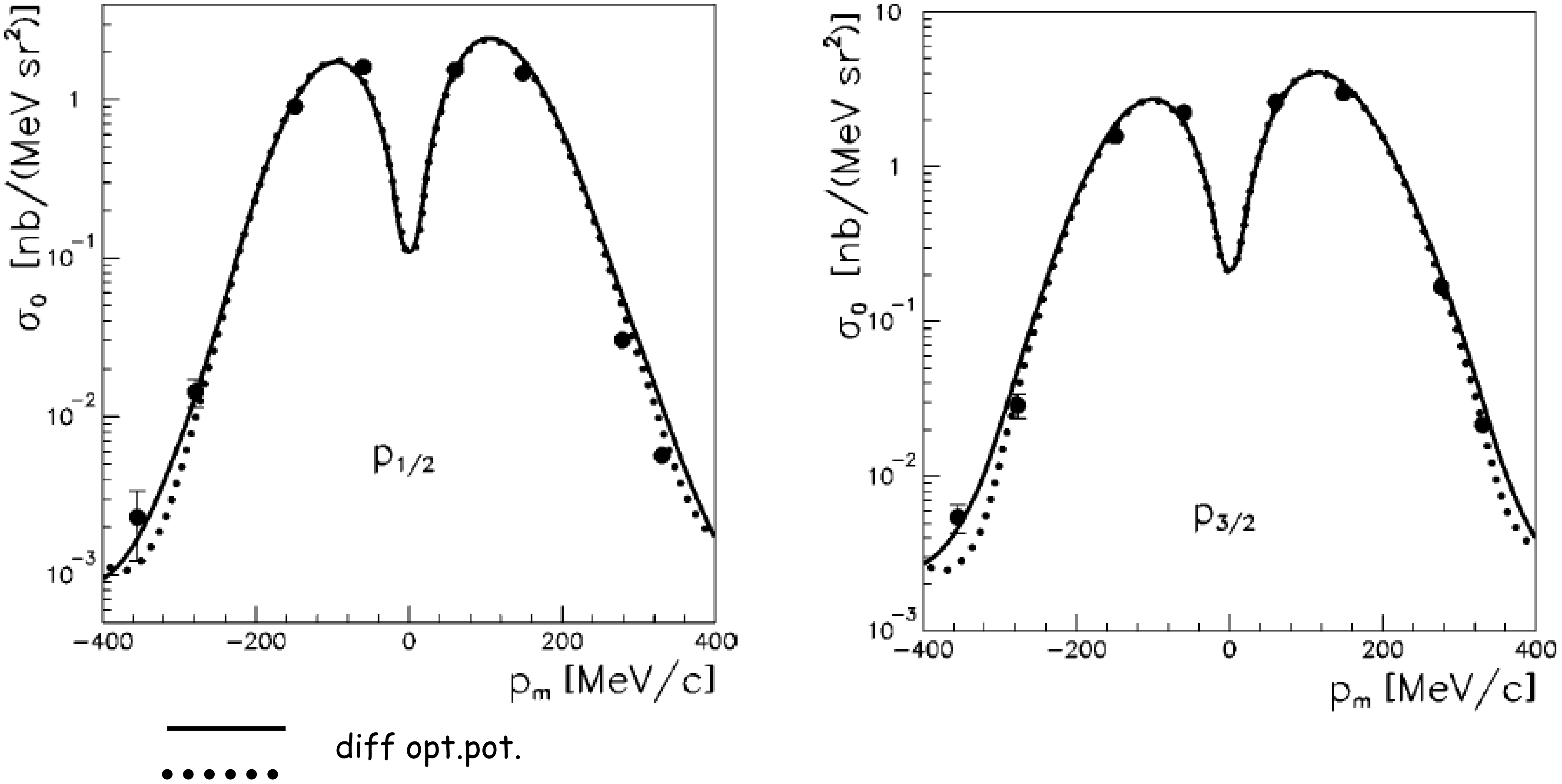
$^{16}O(e,e'p)$

RDWIA

JLab (ω,q) const kin E_0=2445 MeV ω =439 MeV T_p= 435 MeV



diff opt.pot.

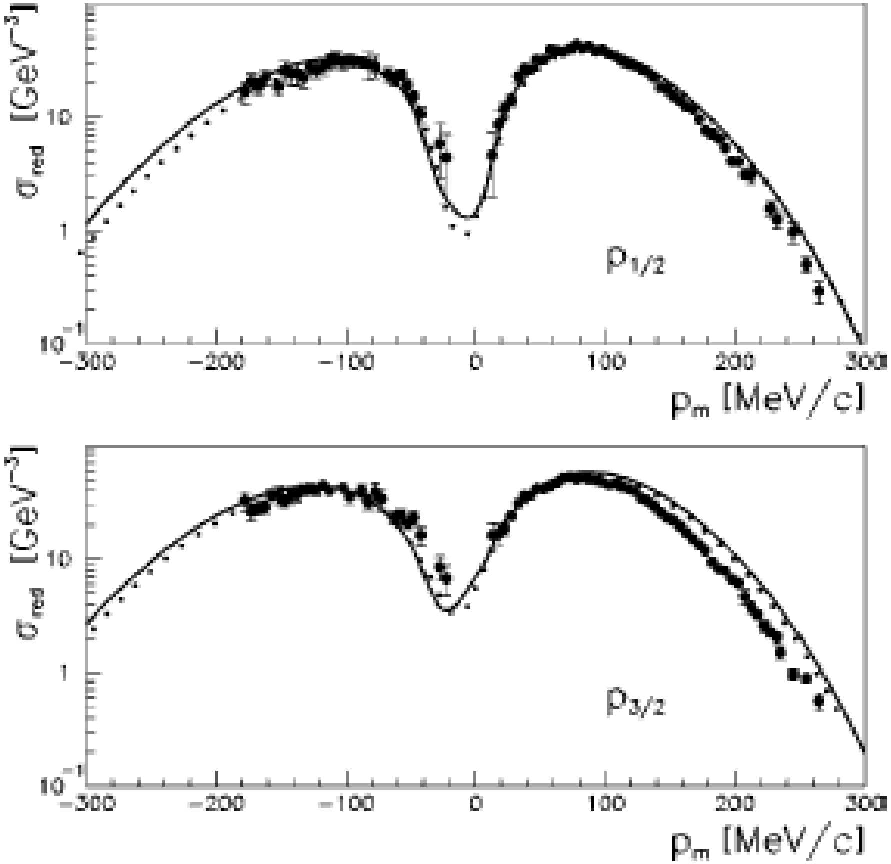
λ_n = 0.7

A. Meucci, C. Giusti, F.D. Pacati PRC 64 (2001) 014604

$^{16}O(e,e'p)$

DWIA - RDWIA

NIKHEF parallel kin $E_0 = 520$ MeV $T_p = 90$ MeV

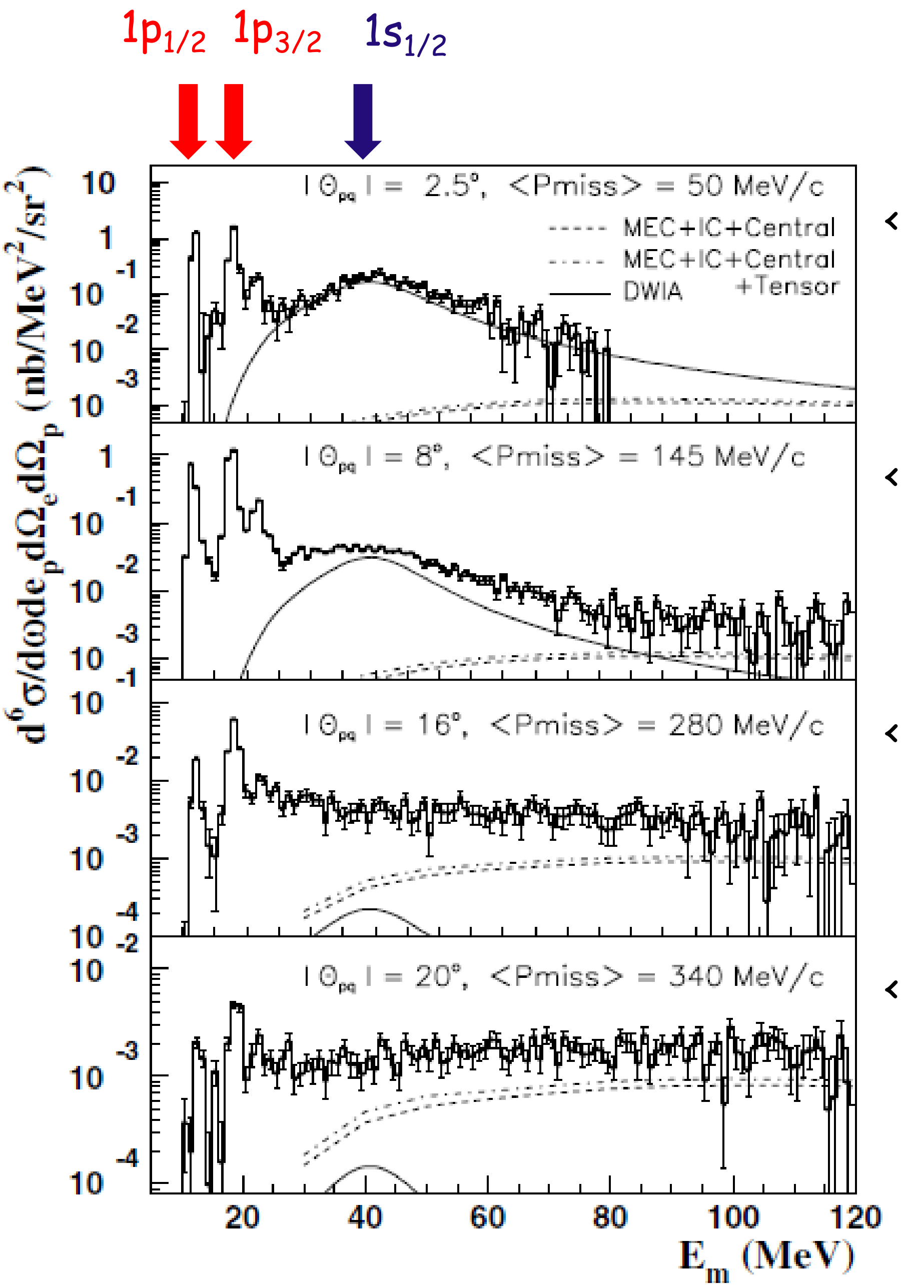


—— rel RDWIA $\lambda_n = 0.7$

••••••• nonrel DWIA $\lambda_n = 0.65$

A. Meucci, C. Giusti, F.D. Pacati PRC 64 (2001) 014604

^{16}O(e,e'p) at high E_m



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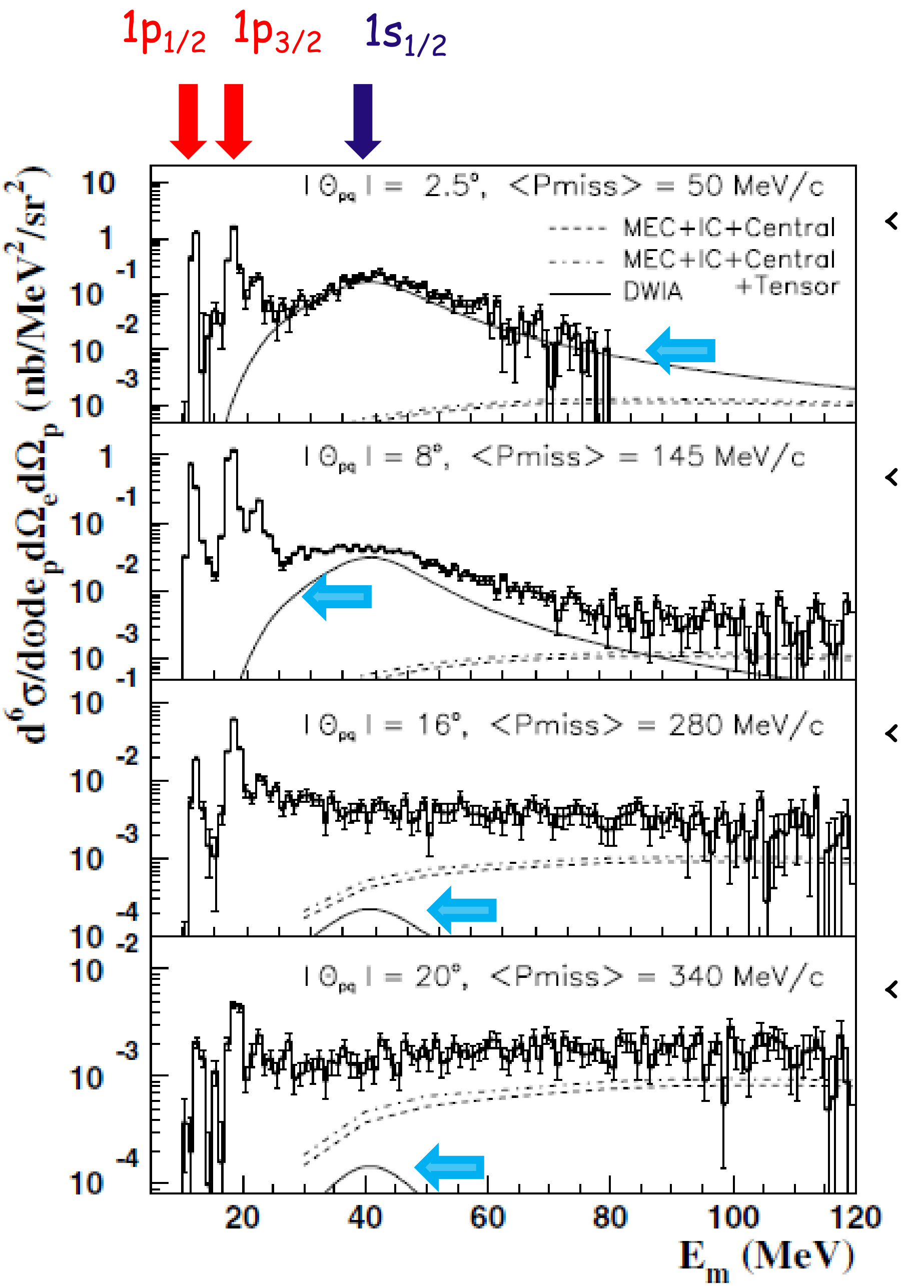

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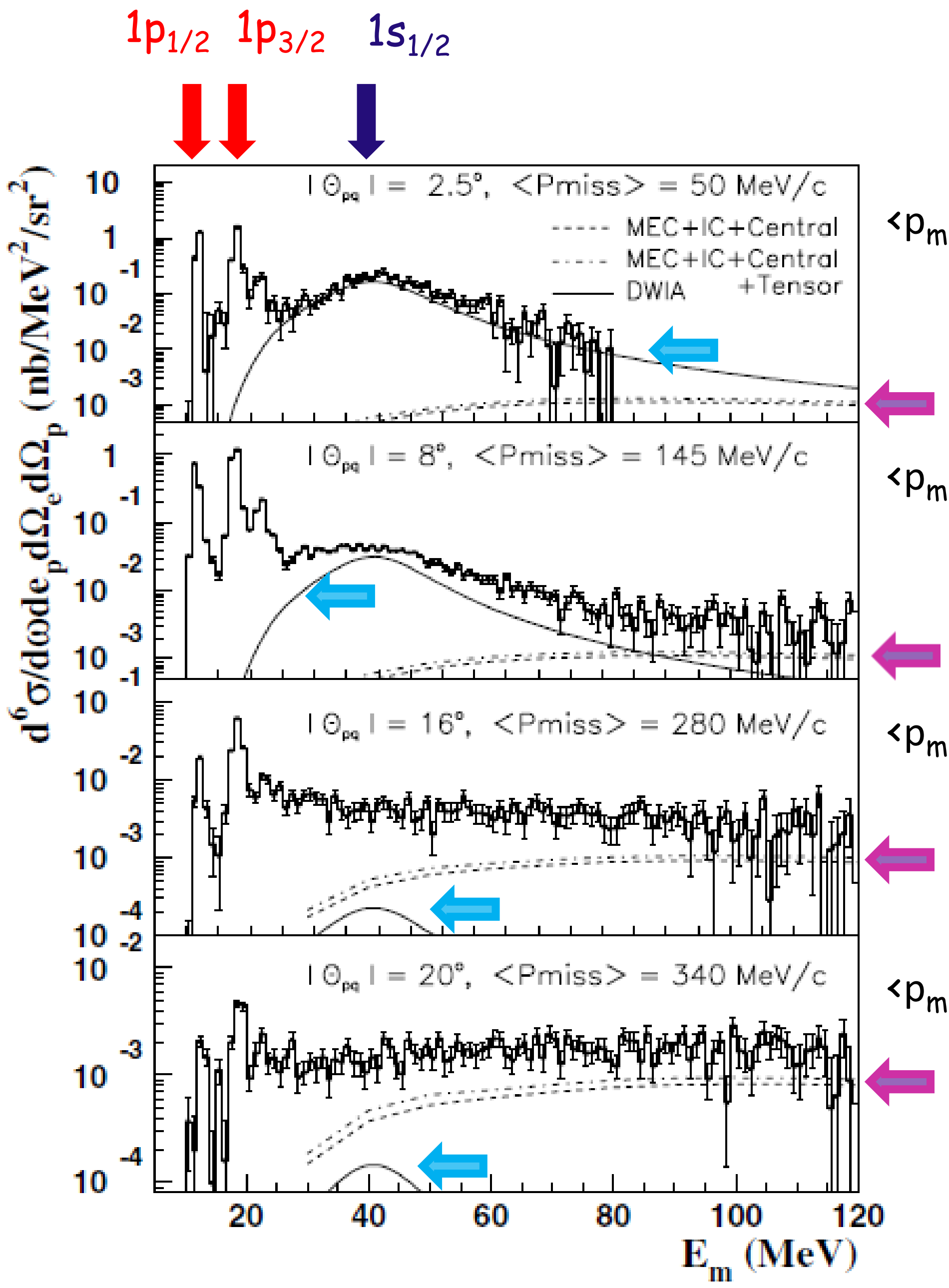

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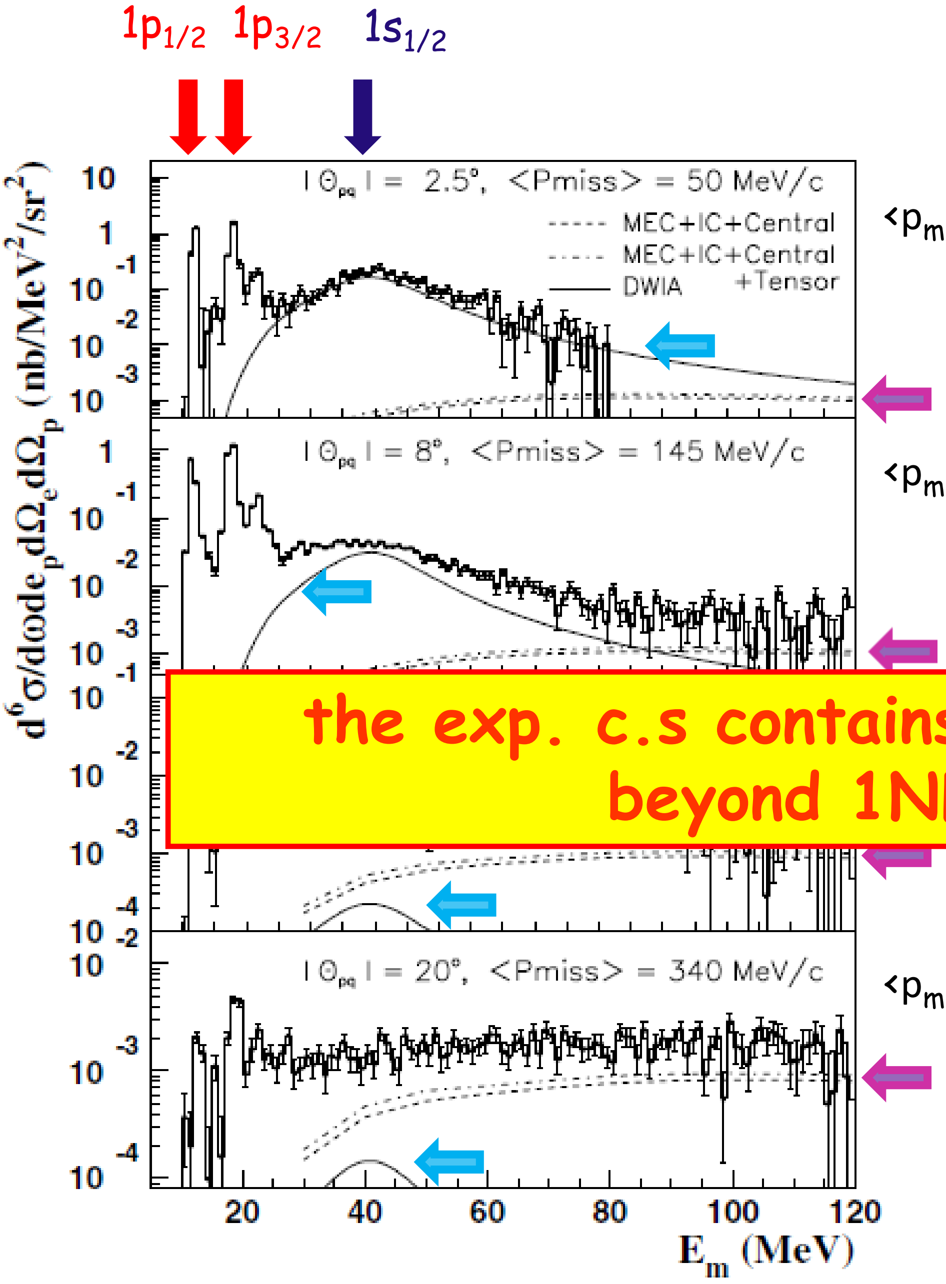

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the exp. c.s contains other contributions beyond 1NKO+2NKO.

N. Liyanage et al. PRL 86 (2001) 5670

FSI

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DWIA

FSI described by a complex OP, the imaginary part gives a reduction of the calculated c.s. which is essential to reproduce (e,e′p) data for low E_m (low-lying states)

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not suited to address the continuum

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DWIA

not suited to address the continuum

WHY?

FSI and OPTICAL POTENTIAL

- the OP describes elastic nucleon-nucleus scattering. The Im part accounts for the flux lost in the elastically scattered beam toward the inelastic channels that are open
- DWIA: the Im part removes the contribution of inelastic channels
- (e,e′p) at low E_m : only the final-state channel n is considered, it can be correct to account for the flux lost in the considered channel. The main contribution comes from the 1pKO process where the outgoing proton scatters elastically with the residual nucleus in the state n.
- inclusive (e,e′) all the final-state channels are included, the flux must be redistributed and conserved in the sum over all the channels. In every channel flux is lost toward the other channels and flux is gained due to the flux lost in the other channels toward the considered channel
- inclusive scattering: GREEN'S FUNCTION MODEL

GREEN'S FUNCTION MODEL

Based on the IA: one-body current interacts with a nucleon that is then emitted. Sum over all the nucleons of the target

FSI are accounted for by the complex energy dependent OP: the formalism translates the flux lost toward inelastic channels, represented by the Im part of the OP, into the strength observed in inclusive reactions.

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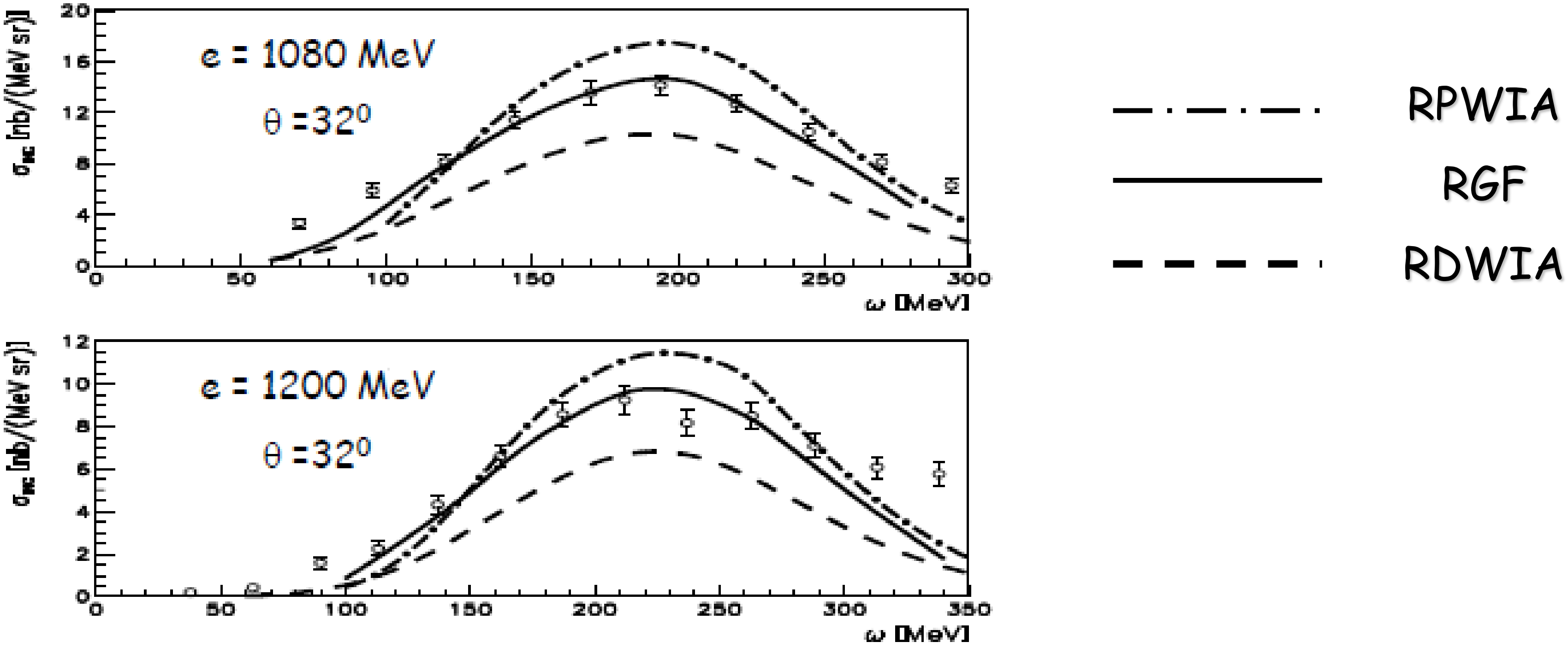
MODEL SUCCESSFULLY APPLIED TO QE (e,e') and CCQE NCE

$^{16}O(e,e')$

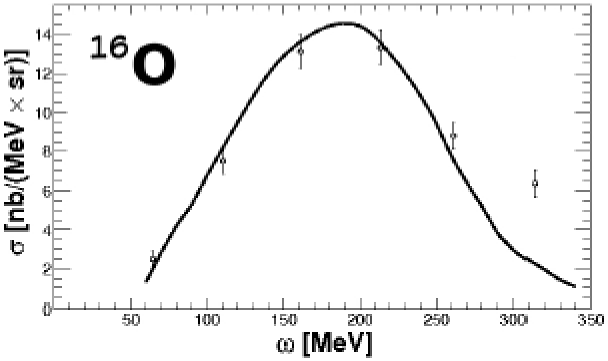


data from Frascati NPA 602 405 (1996)

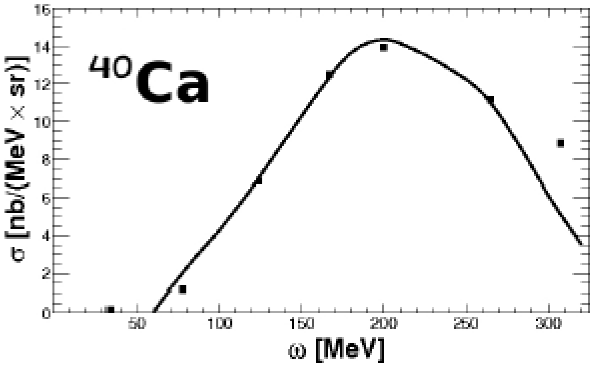
A. Meucci, F. Capuzzi, C. Giusti, F.D. Pacati PRC 67 (2003) 054601

(e,e')

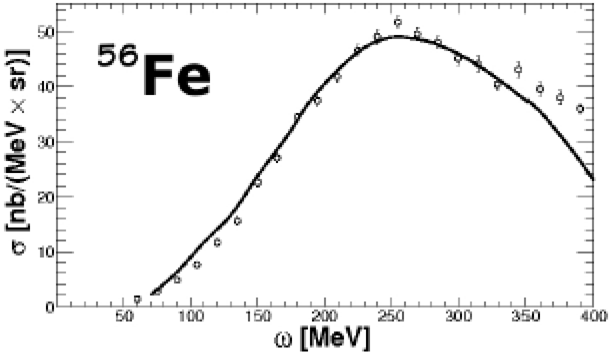
RGF



E_0 = 1080 MeV ϑ = 32°



E_0 = 841 MeV ϑ = 45.5°



E_0 = 2020 MeV ϑ = 20°

A. Meucci et al. PRC 87 (2013) 054620

FSI in (e,e'p)

DWIA not suited to address the continuum

at high E_m and p_m : contributions beyond 1pKO

removed in DWIA by the Im part of the OP and included by the Im part of the OP in the GF model

e.g. multi-scattering effects: the ejectile proton in its way through the nucleus undergoes secondary collisions where it can change direction and lose energy before being emitted and detected

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Multi-scattering effects in (e,e'p) knockout: P.Demetriou, S. Boffi, C. Giusti, F.D. Pacati, Nucl. Phys. A 625 (1997) 513

Multi-Scattering Effects in (e,e′p)

Improve the treatment of FSI

The method follows the lines of the multi-step direct (MSD) scattering theory of Feshbach. Kerman, and Koonin which allows one to trace the secondary collisions of the emitted nucleon.

The proton, following the initial elm int., is excited to the continuum and subsequently undergoes a series of 2-b interactions with the residual nucleus before being emitted.

Thus there are a series of collisions leading to the excitation of intermediate states of increasing complexity. At each step the proton loses energy and changes direction, a nucleon can be emitted.

The theory combines a QM treatment of multiple scattering with statistical assumptions that lead to the convolution nature of the multistep c.s. and enables the calculation of higher-order contributions (up to 6 steps) which would be otherwise impracticable

Multi-Scattering Effects in (e,e'p)

(e,e'p) c.s. = 1-step + n-step terms

$$\frac{d^4\sigma}{d\Omega_{k'}\, dE_{k'}\, d\Omega\, dE} = \underbrace{\frac{d^4\sigma^{(1)}}{d\Omega_{k'}\, dE_{k'}\, d\Omega\, dE}}_{\text{DWIA}} + \sum_{n=2}^{\infty} \frac{d^4\sigma^{(n)}}{d\Omega_{k'}\, dE_{k'}\, d\Omega\, dE}$$

n-step term convolution of 1NKO and 1-step MSD c.s. over all intermediate energies E_1, E_2 … and angles Ω_1, Ω_2…..

$$\frac{d^4\sigma^{(n)}}{d\Omega_{k'}\, dE_{k'}\, d\Omega\, dE} = \left(\frac{m}{4\pi^2}\right)^{n-1} \int d\Omega_{n-1} \int dE_{n-1}\, E_{n-1} \dots$$

$$\times \int d\Omega_1 \int dE_1\, E_1 \underbrace{\frac{d^2\sigma^{(1)}}{d\Omega\, dE}(E, \Omega \leftarrow E_{n-1}, \Omega_{n-1})}_{} \dots$$

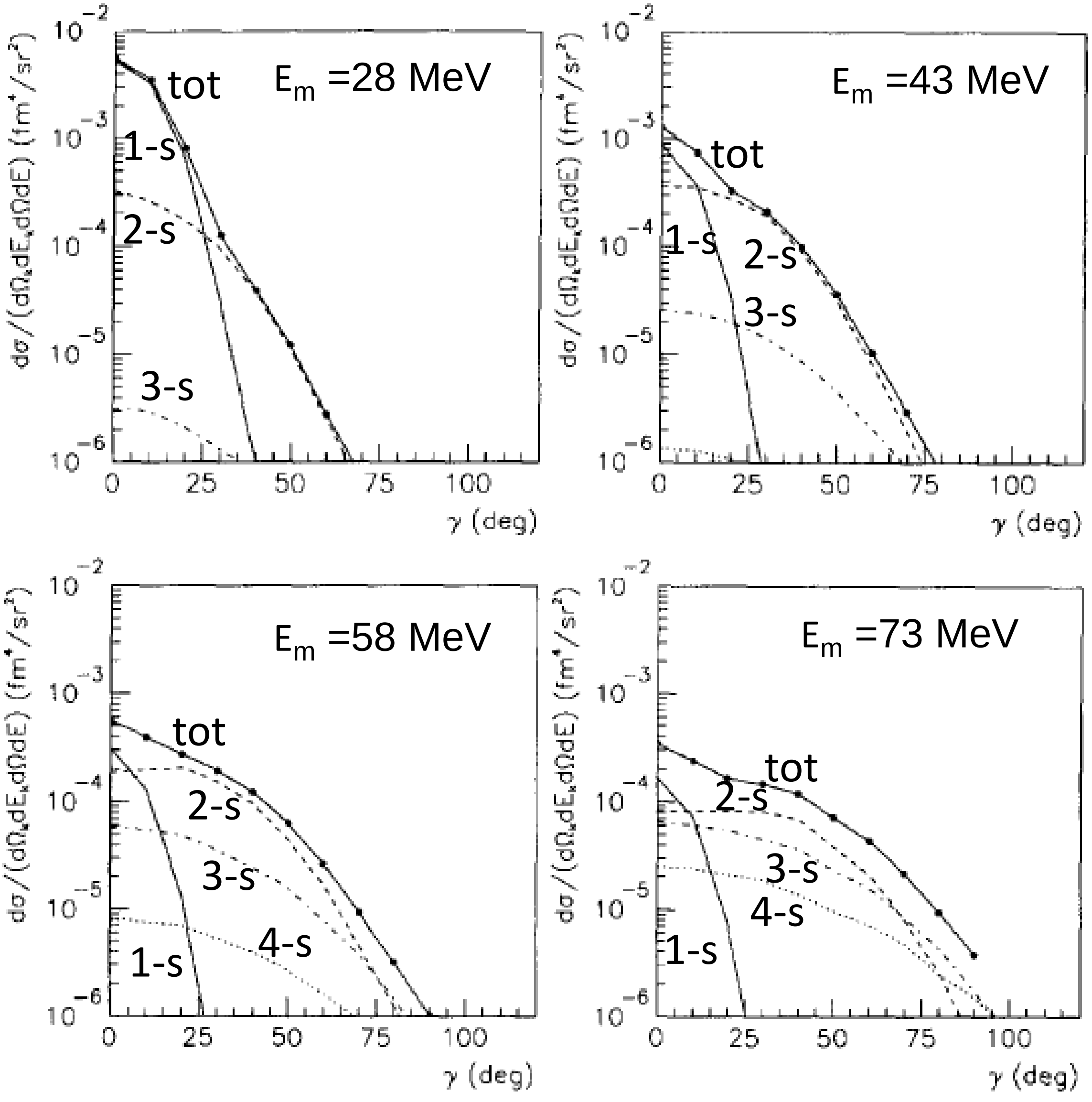
$$\times \underbrace{\frac{d^2\sigma^{(1)}}{d\Omega_2\, dE_2}(E_2, \Omega_2 \leftarrow E_1, \Omega_1)}_{\text{DWBA}} \underbrace{\frac{d^4\sigma}{d\Omega_{k'}\, dE_{k'}\, d\Omega_1\, dE_1}}_{\text{DWIA}} .$$

Multi-Scattering Effects in (e,e′p)

- The method follows the trace of the fast emitted proton but does not follow the fate of secondary nucleons
- 2NKO not included
- Pion contribution and reabsorption not included
- Suited to study the continuum spectrum with not too high E_m

$^{40}Ca(e,e'p)$

E_0=497 MeV, θ=52.9°, ω= 140 MeV , T_p= 87 10 MeV



P . Demetriou et al Nucl. Pys. A 625 (1997) 513

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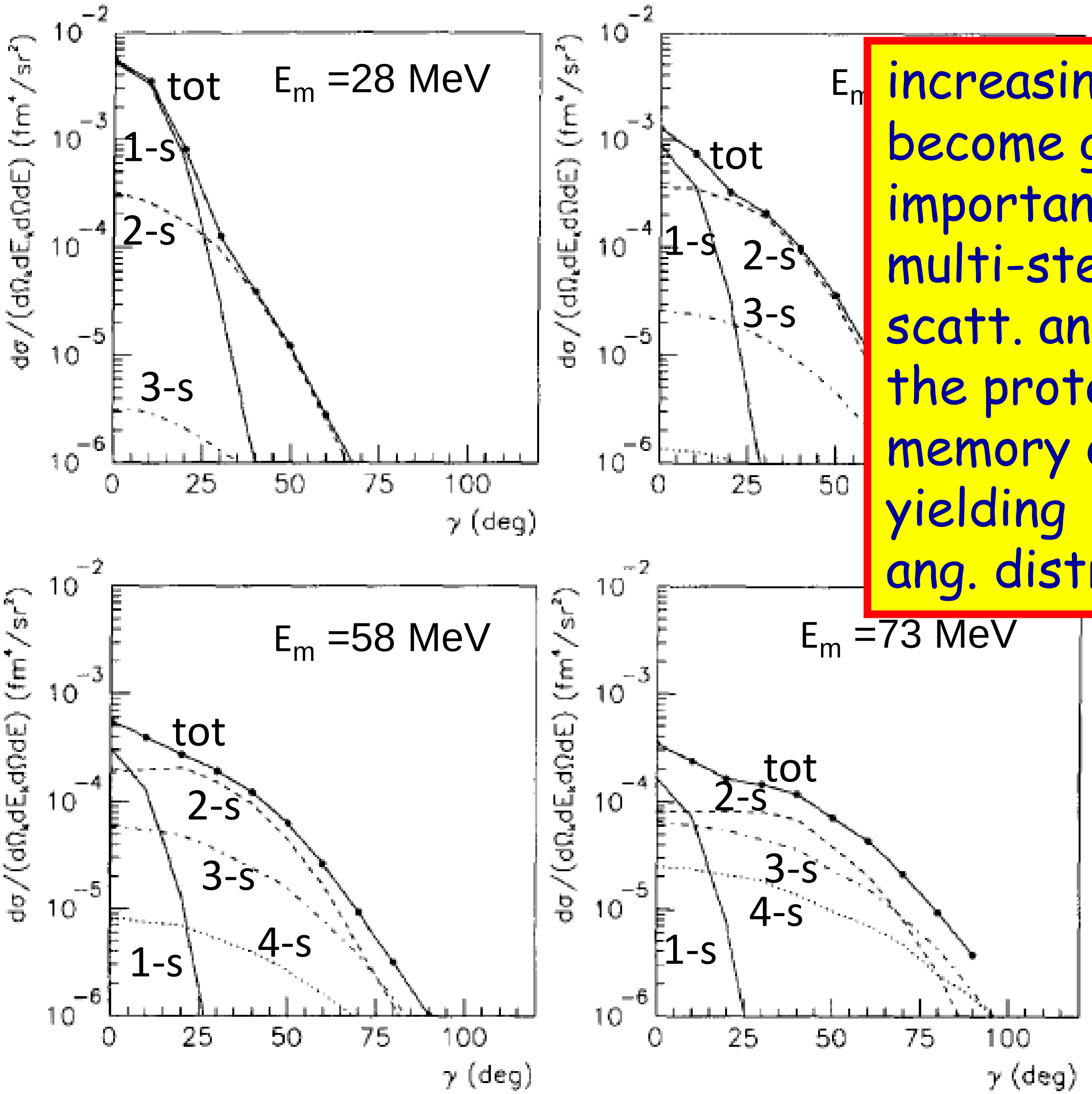

increasing E_m 2-s and 3-s become gradually more important. The domination of multi-step processes at large scatt. angles is expected since the proton gradually loses memory of its initial direction yielding thus increasingly symm. ang. distribution

P . Demetriou et al Nucl. Phys. A 625 (1997) 513

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Strong sensitivity to kinematic conditions.

In electron scattering suitable kinematic conditions can be selected able to minimize or emphasize and therefore study specific contributions

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from e-nucleus to ν-nucleus scattering

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CCQE

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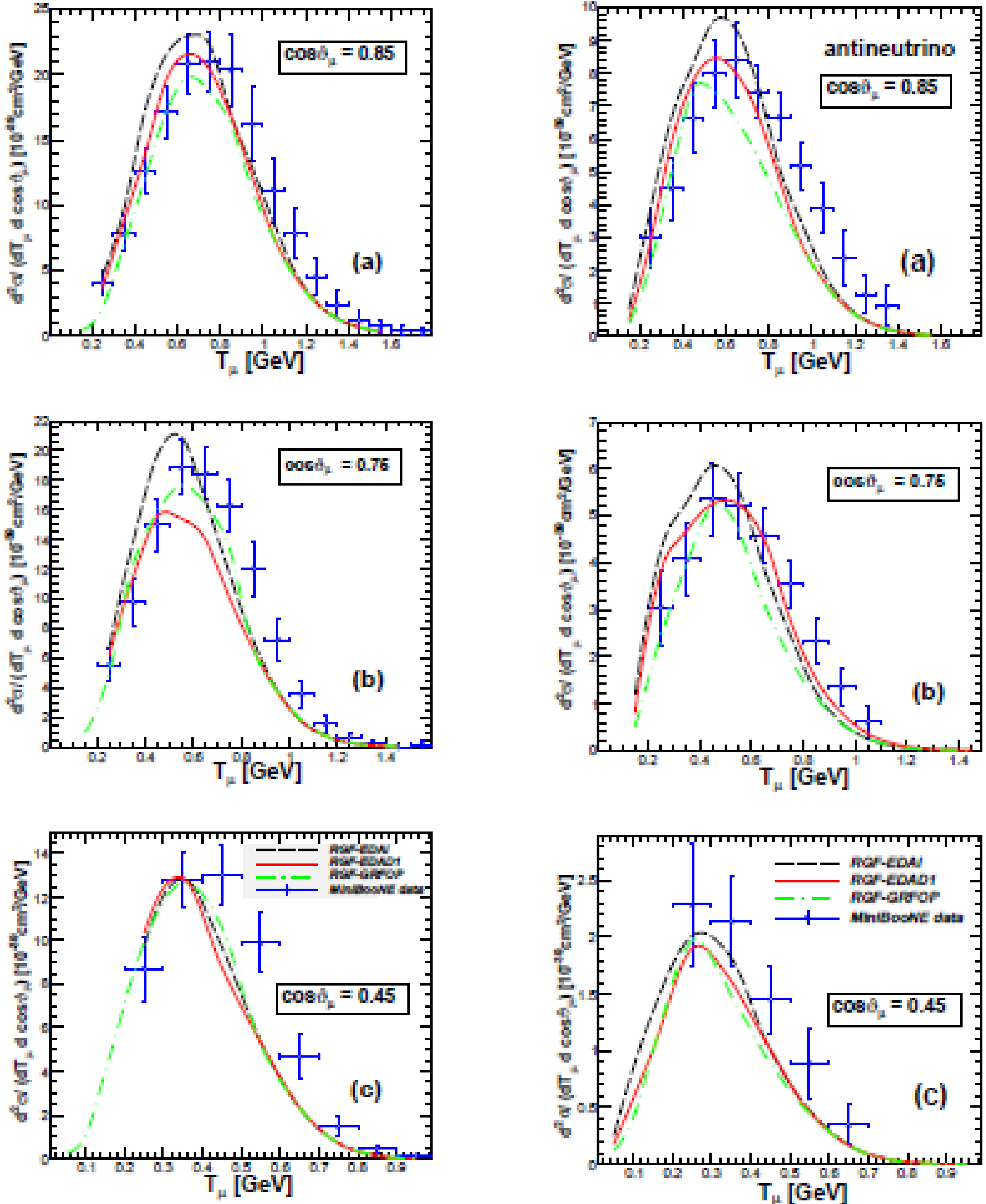
RGF

the flux-average procedure picks up contributions from different kinematic regions, not only QE, contributions other than direct 1-nucleon emission are more important than in (e,e')

MiniBooNe CCQE data

$^{12}C(\nu_\mu, \mu^-)$ $^{12}C(\bar{\nu}_\mu, \mu^+)$



- - - - RGF-EDAI

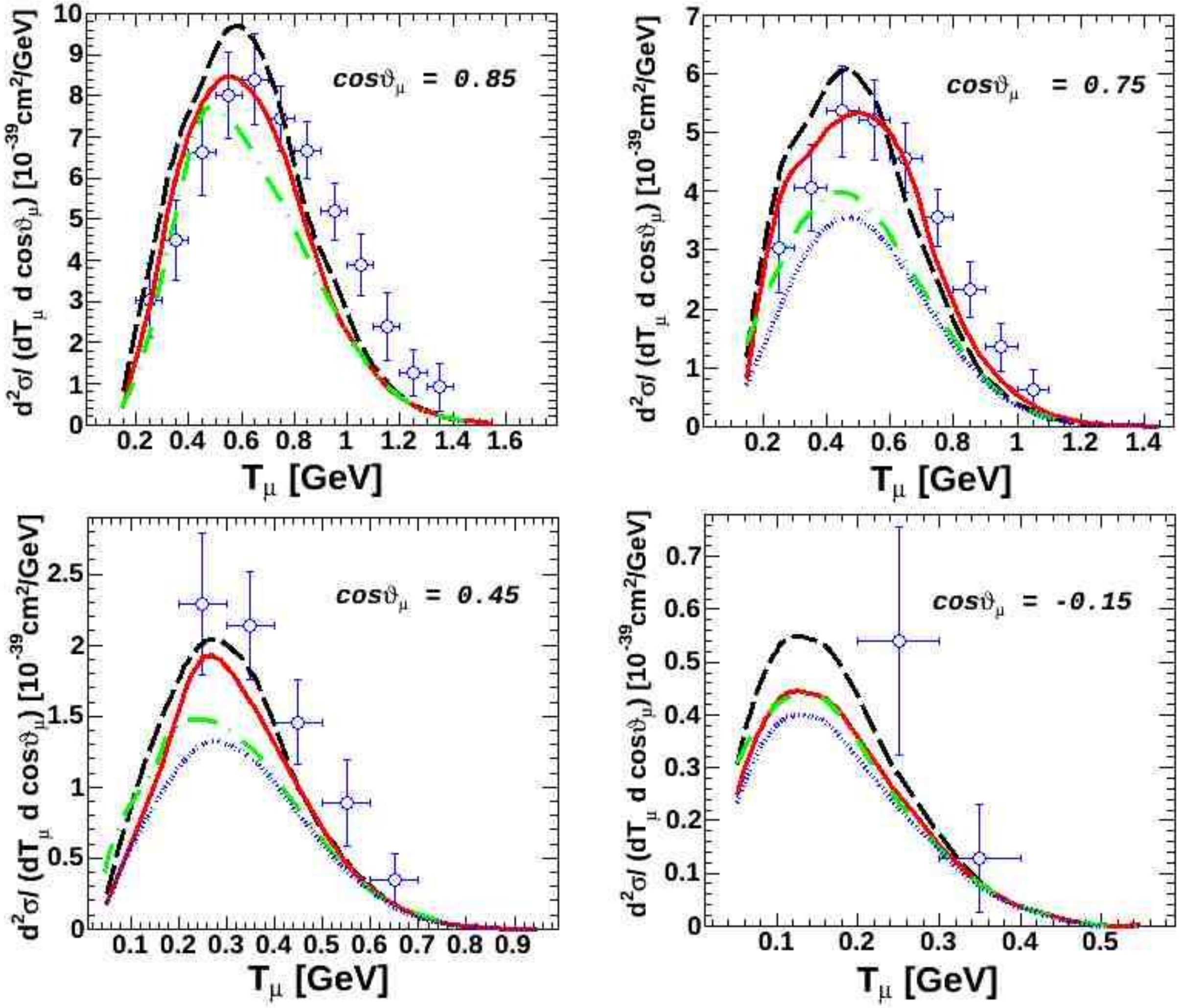
—— RGF-EDAD1

— · — · RGF-GRFOP

M.V. Ivanov et al. PRC 94 014608 (2016)

Comparison with MiniBooNe CCQE data

$^{12}C(\bar{\nu}_\mu, \mu^+)$



- - - RPWIA
----- rROP
— — RGF EDAI
—— RGF-EDAD1

A. Meucci and C. Giusti PRD 85 (2012) 093002

from e-nucleus to ν-nucleus scattering

$$\nu_l(\bar{\nu}_l) + A \Longrightarrow l^-(l^+) + N + (A-1)$$

CCQE

- both final lepton and nucleon …. (e,e′p) where the incident electron energy is not know
- calculations for different values of E_ν , ω, and E_m

from e-nucleus to ν-nucleus scattering

- Experimental and theoretical work already done and that can be done for electron scattering extremely useful to provide reliable ν-nucleus cross sections

- Comparison with electron-scattering data test of the validity and predictive power of a nuclear model

- Electron scattering experiments in suitable kinematics can give information on the relevant reaction mechanisms, nuclear dynamics FSI, nuclear current (1-body, 2-body)....

- Information on nuclear structure and correlations, contained in the spectral function, can be obtained from dedicated (e,e′p) experiments (e.g. Jefferson Lab experiment on ^{40}Ar)