DE LA RECHERCHE À L'INDUSTRIE

cea

ESNT

Espace de Structure Nucléaire Théorique
DSM - DAM

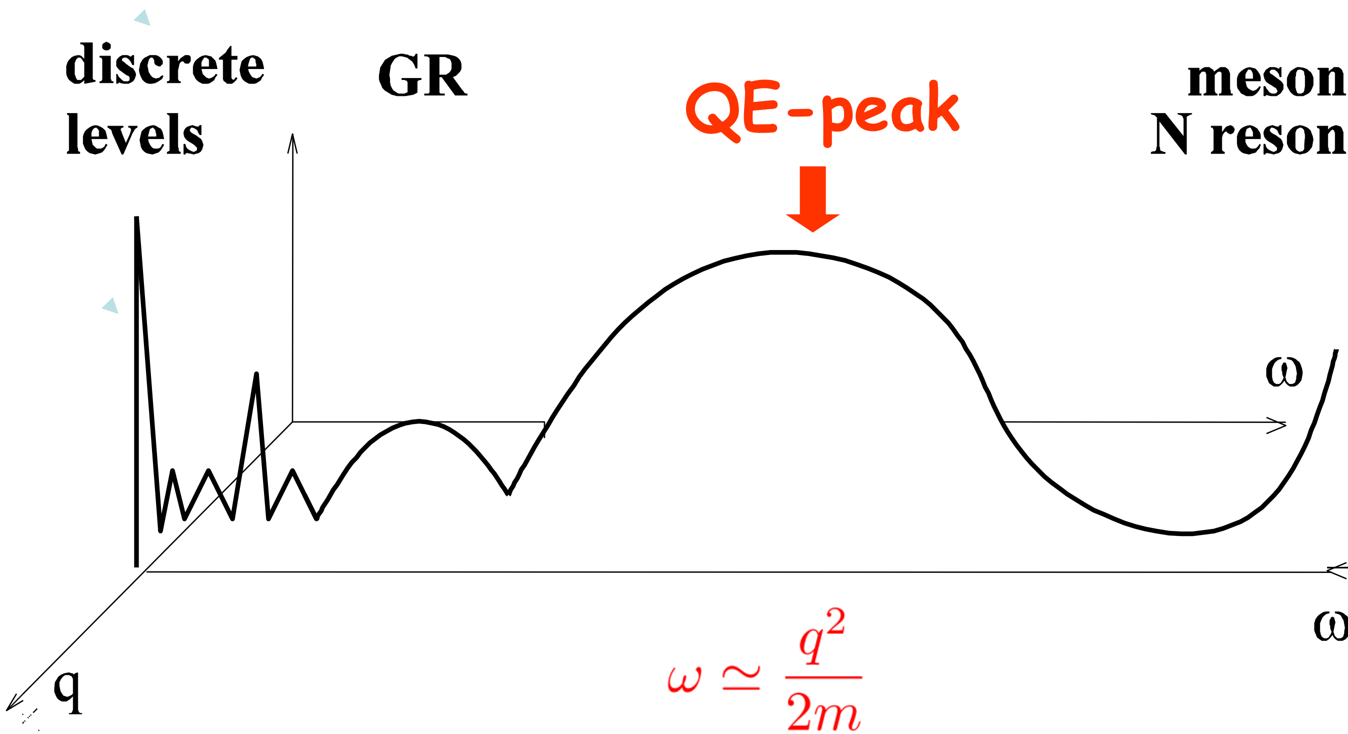
NN CORRELATIONS IN EXCLUSIVE (e,e'p) AND (e,e'NN) REACTIONS

Carlotta Giusti

Università and INFN Pavia

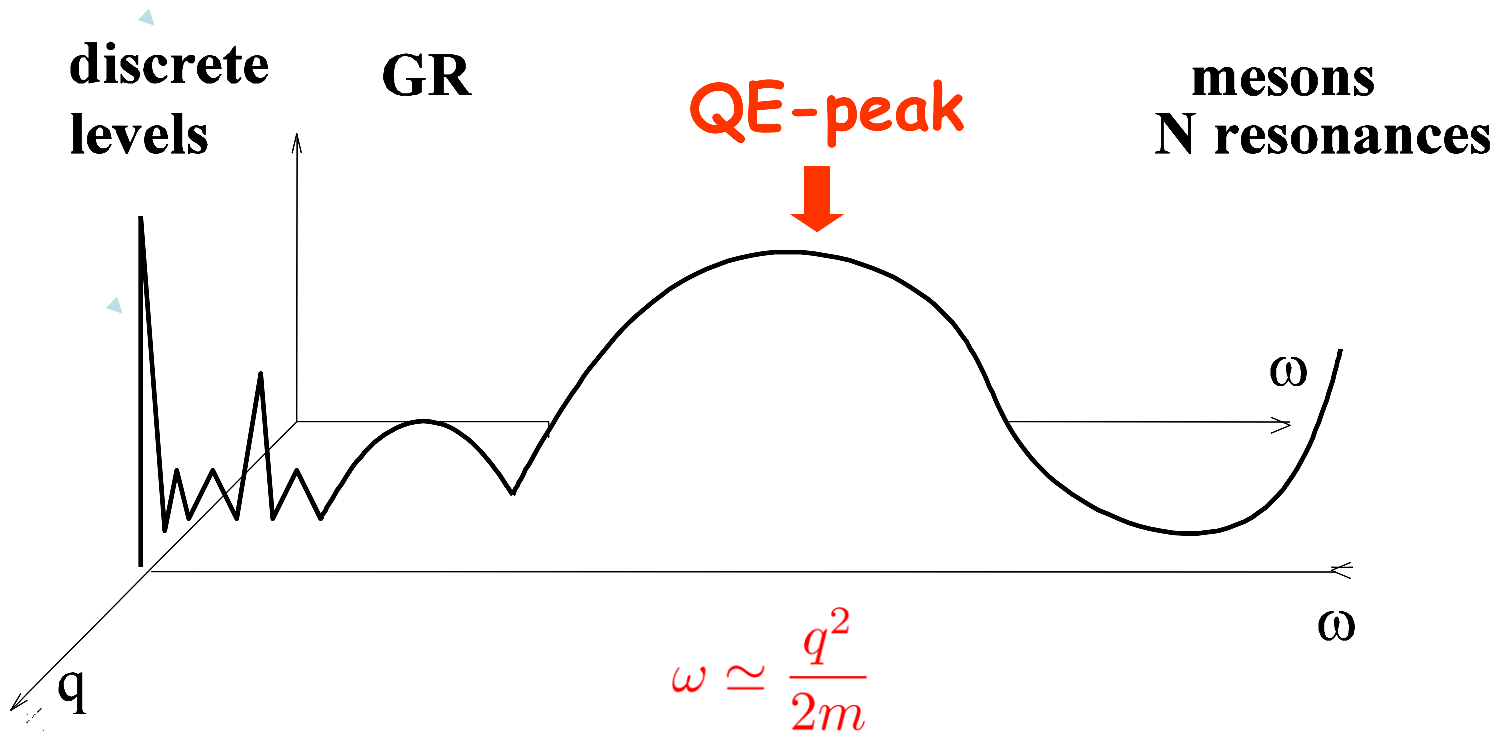
Electron-radioactive ion collisions: theoretical and experimental challenges, Saclay 25-27 April 2016

nuclear response to the electromagnetic probe



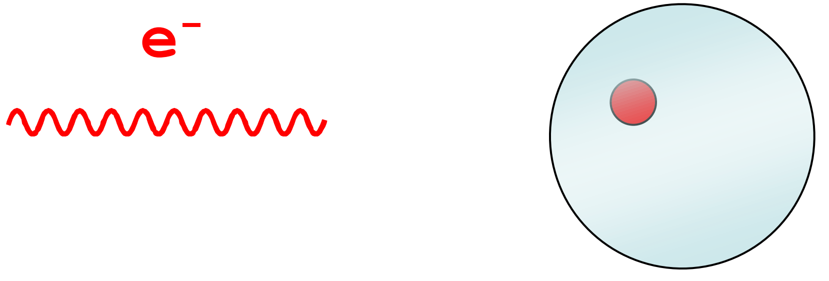
$$\omega \simeq \frac{q^2}{2m}$$

nuclear response to the electromagnetic probe

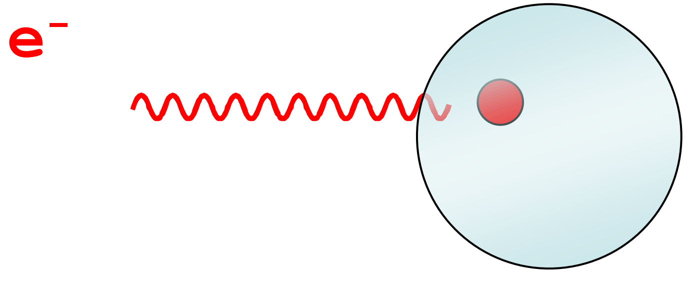


QE-peak dominated by one-nucleon knockout

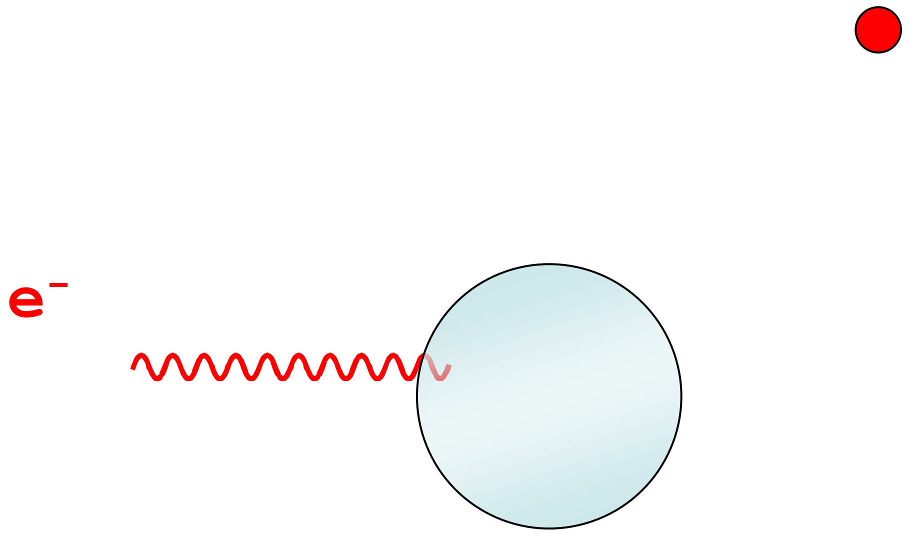
(e,e'p) one-nucleon knockout



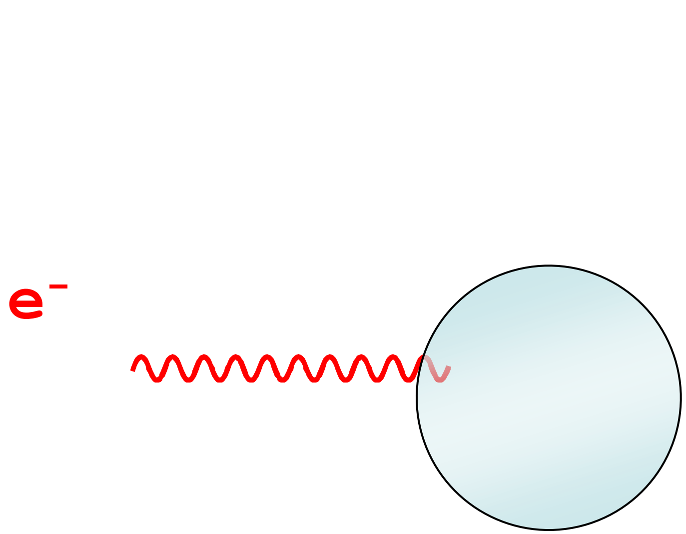
(e,e'p) one-nucleon knockout



(e,e'p) one-nucleon knockout



(e,e′p) one-nucleon knockout

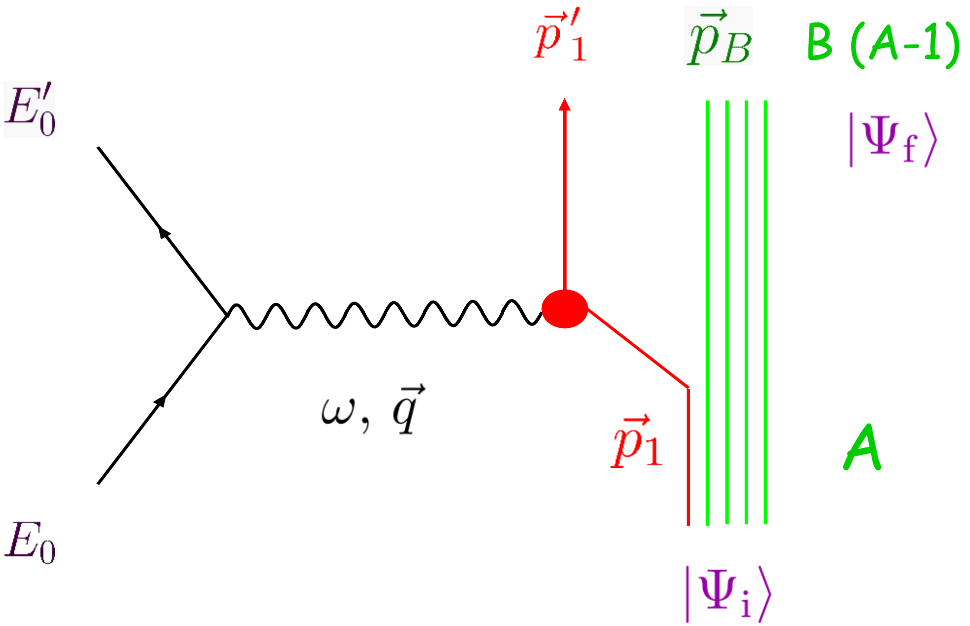


proton-hole states

properties of bound protons

validity and limit of a MF description

nuclear correlations



(e,e'p)

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

$$\vec{p}_m = \vec{q} - \vec{p}'_1 = -\vec{p}_1 = \vec{p}_B$$ missing momentum

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

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

$$\int S(\vec{p}_1,\vec{\bar{p}}_1;E_m)\mathrm{d}E_m = \rho(\vec{p}_1,\vec{\bar{p}}_1)$$

inclusive reaction : one-body density

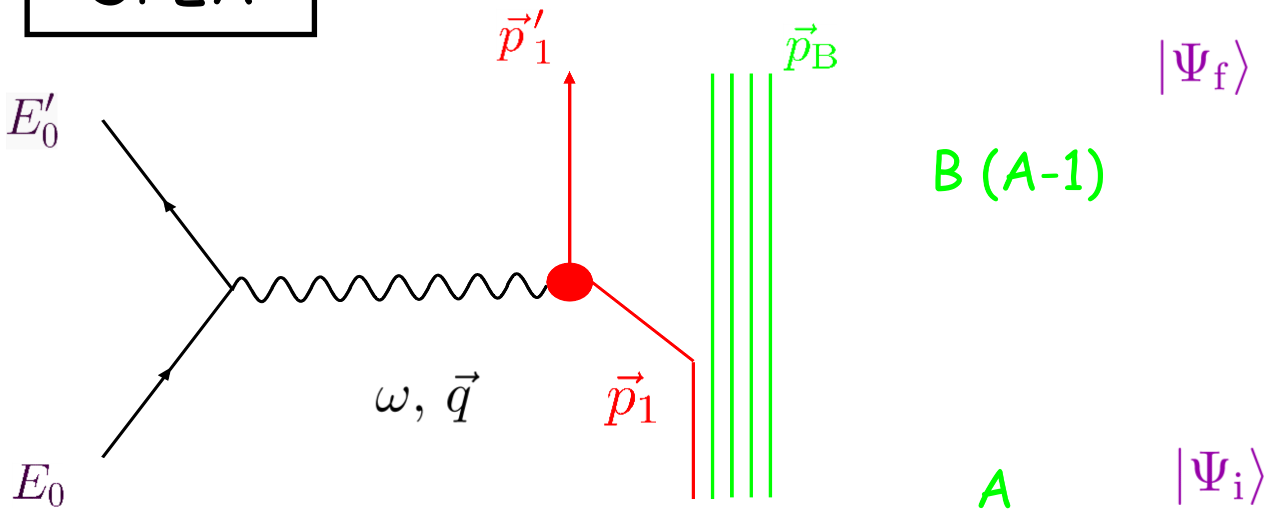
$\vec{p}_1 = \vec{\bar{p}}_1$ ⇒ $\rho(\vec{p}_1,\vec{\bar{p}}_1) = F(\vec{p}_1)$

MOMENTUM DISTRIBUTION

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

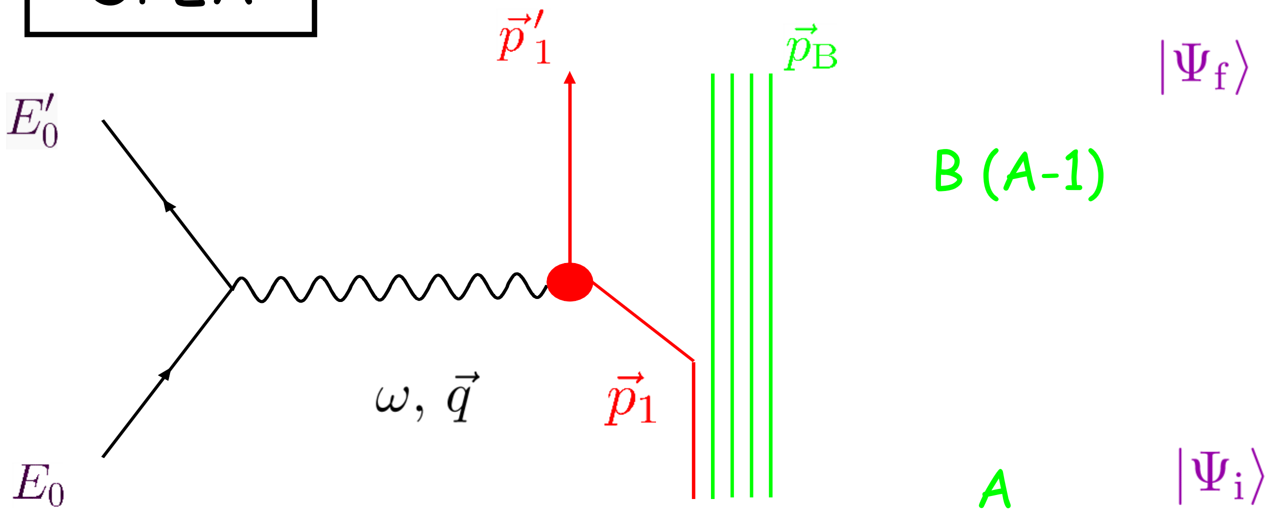
probability of finding in the target a nucleon with momentum p_1

OPEA



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

OPEA

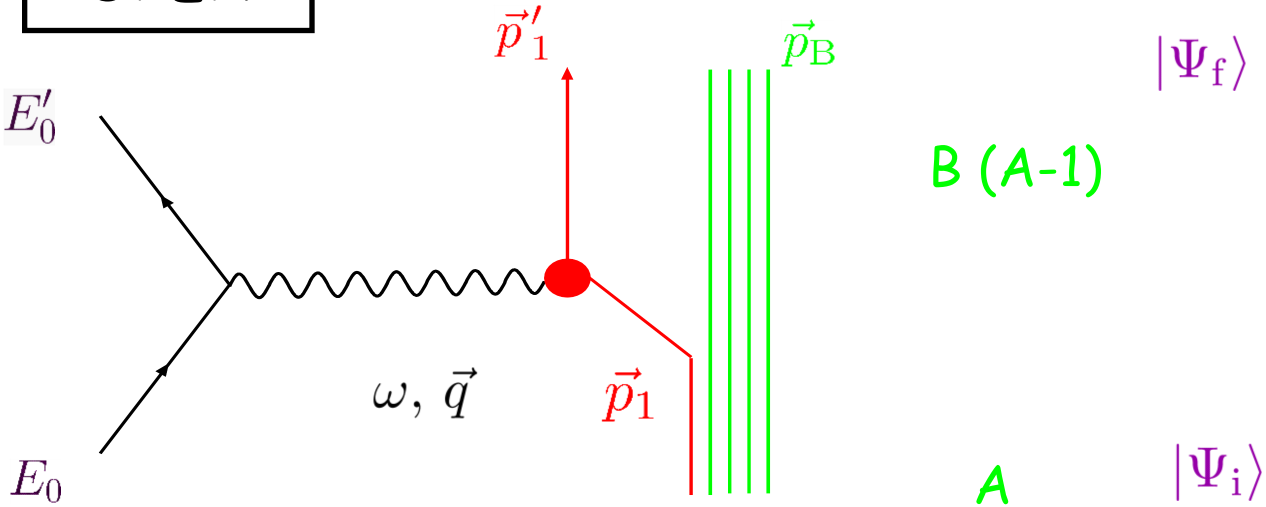


$$\sigma = K L^{\mu\nu} \; W_{\mu\nu}$$

↓

lepton tensor

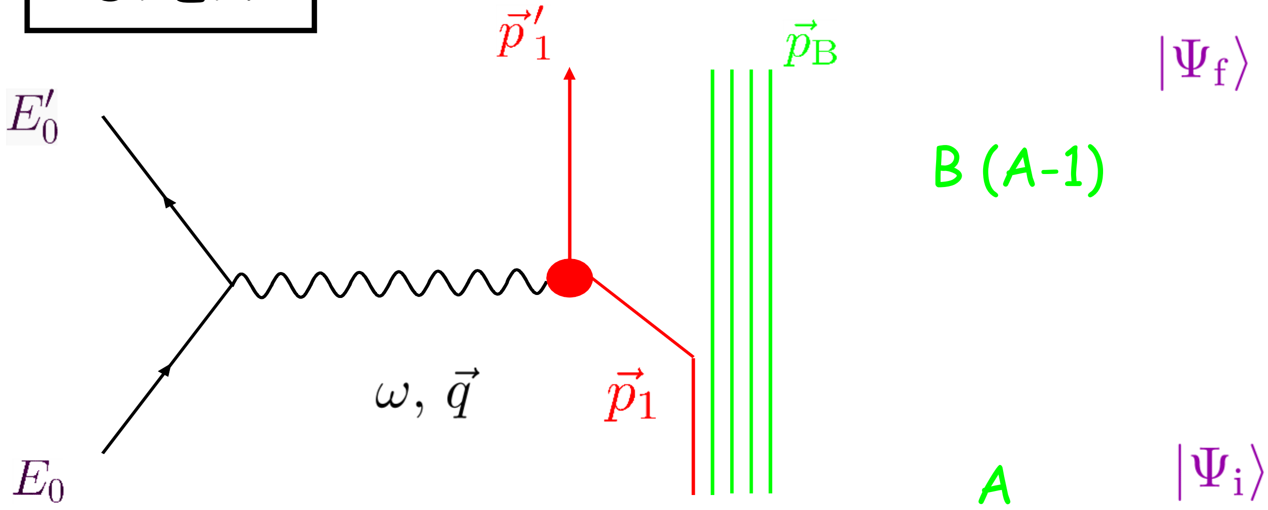
OPEA



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

hadron tensor

OPEA



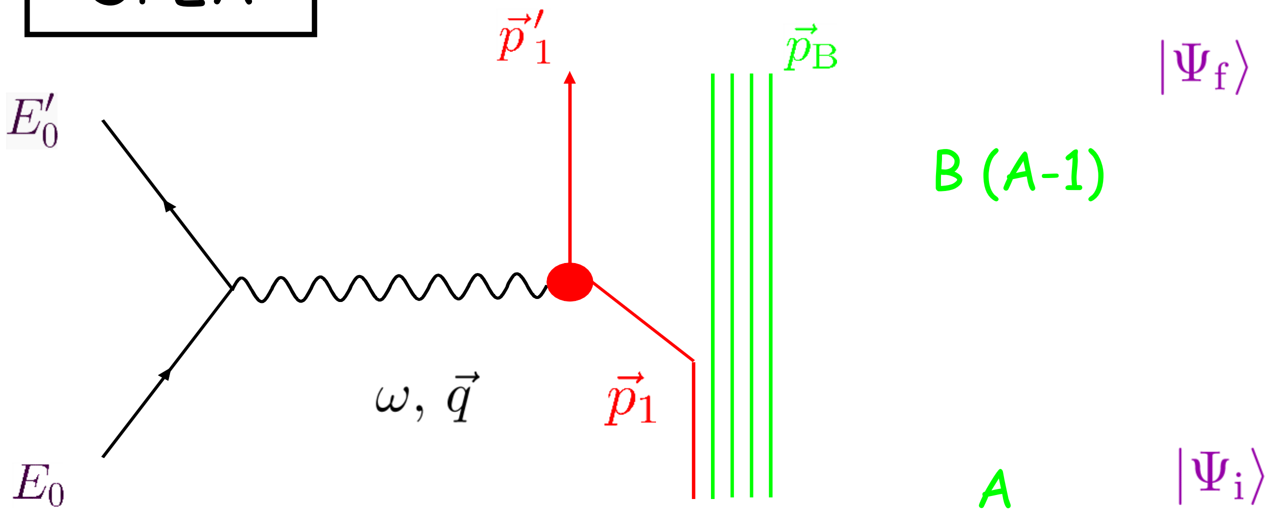
$$\sigma = K L^{\mu\nu} \; W_{\mu\nu}$$

hadron tensor

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

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

OPEA



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

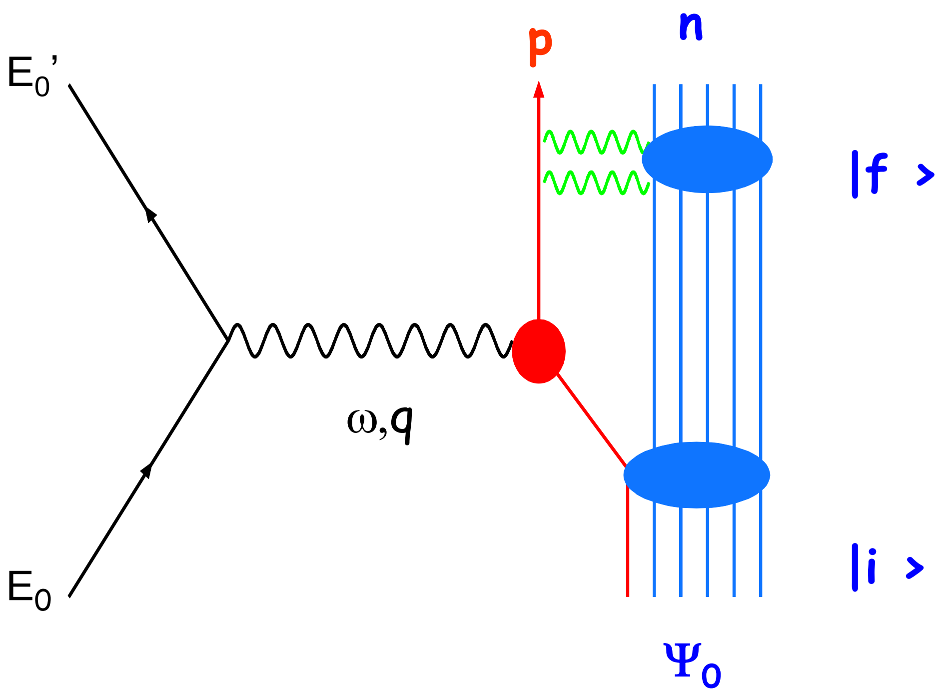
hadron tensor

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

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

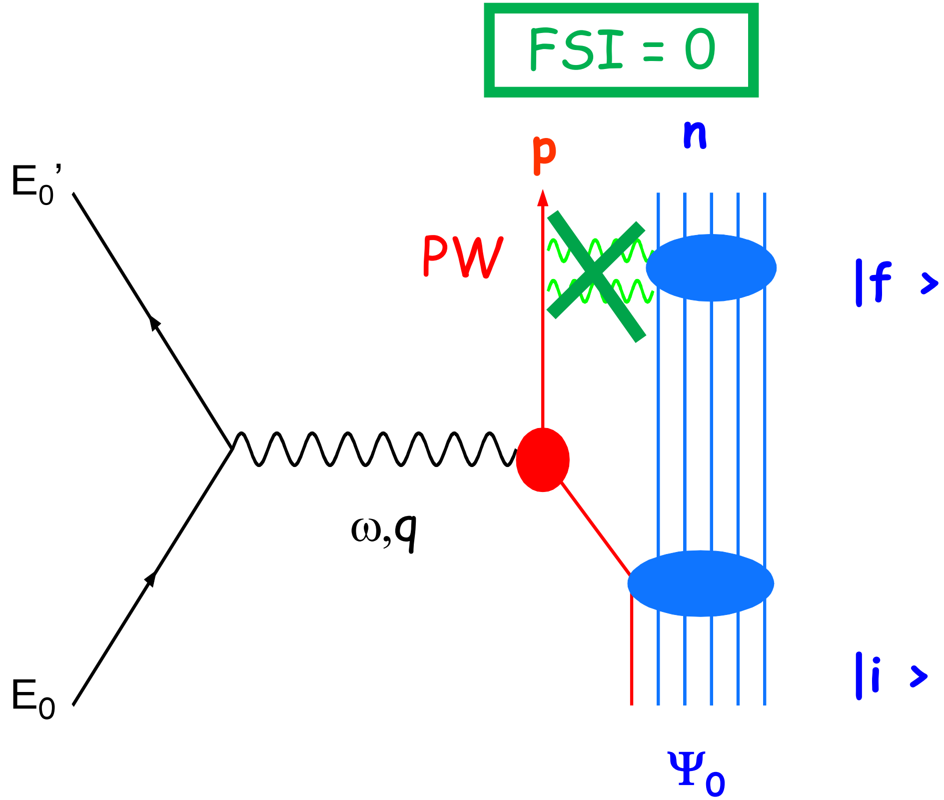
(e,e'p)

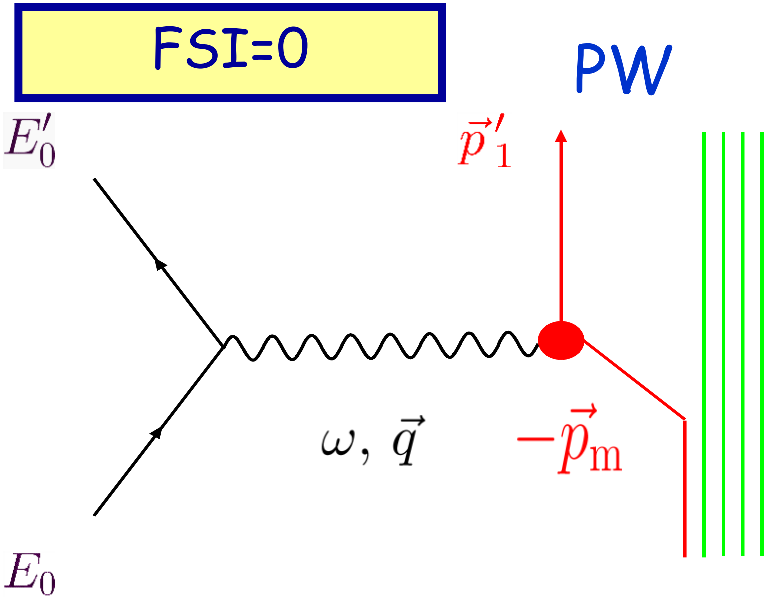
- exclusive reaction n
- DKO mechanism: the probe interacts through a one-body current with one nucleon which is then emitted the remaining nucleons are spectators
- impulse approximation IA



(e,e'p)

- exclusive reaction n
- DKO mechanism: the probe interacts through a one-body current with one nucleon which is then emitted the remaining nucleons are spectators
- impulse approximation IA





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

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

spectroscopic factor ($\lambda_n(E_\mathrm{m})$) — overlap function ($\phi_n(-\vec{p}_\mathrm{m})$)

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 spectroscopic factor gives the probability that n is a pure hole state in the target.

IPSM

ϕ_n s.p. SM state

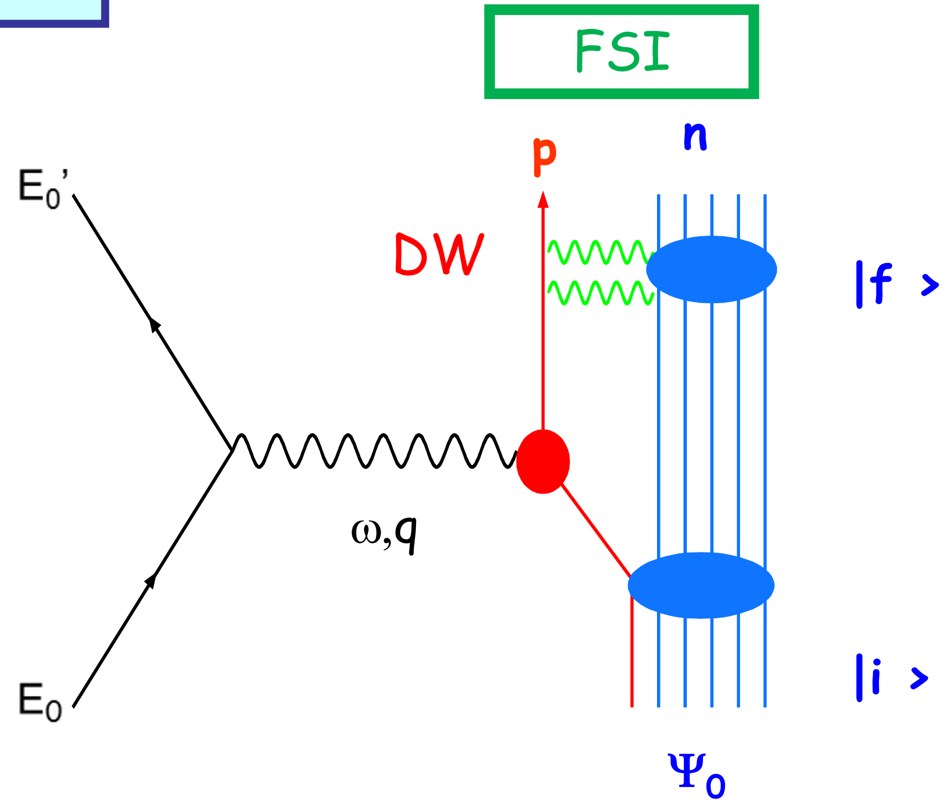
λ_n 1 occupied SM states

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)

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

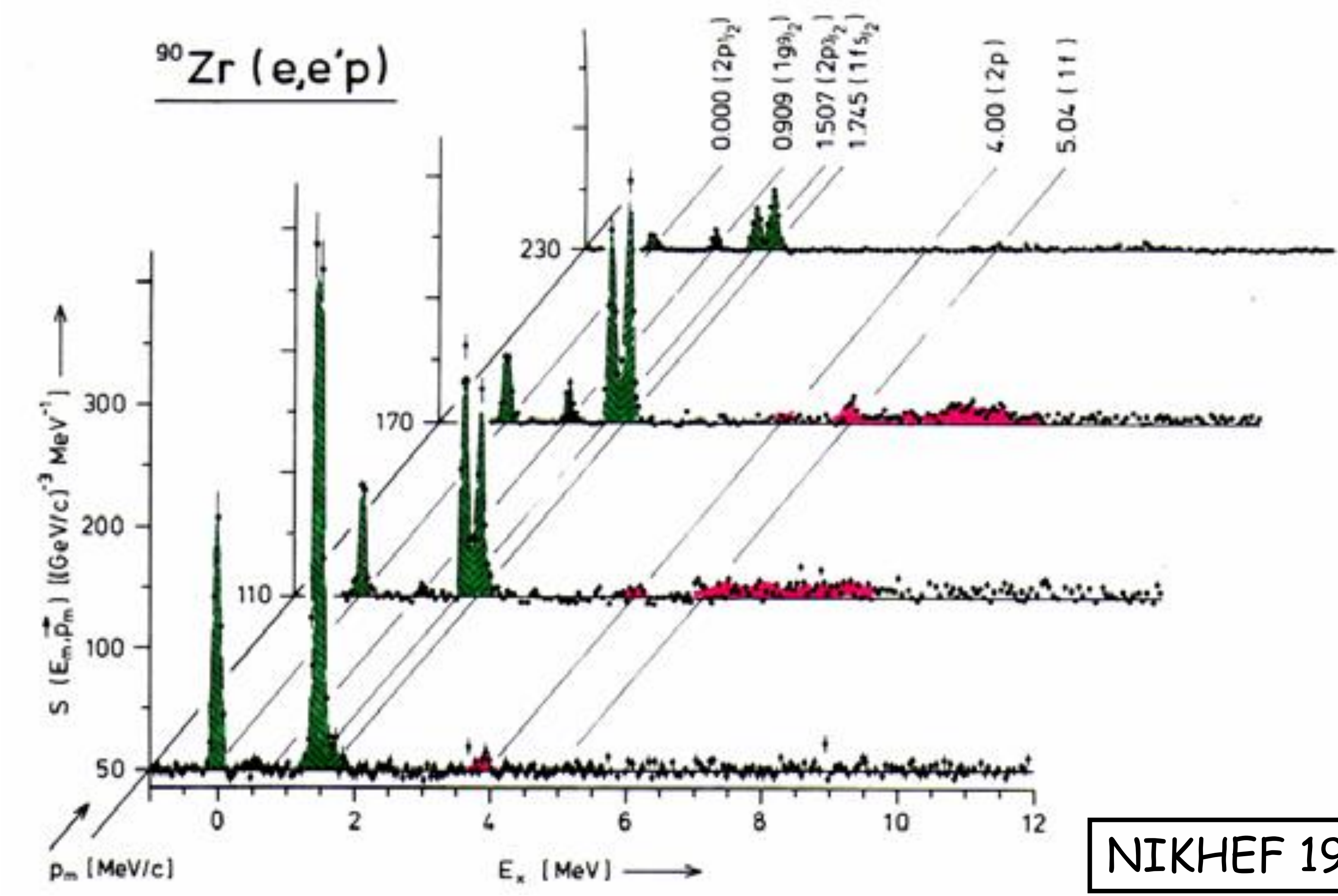
- j^μ one-body nuclear current
- $\chi^{(-)}$ s.p. scattering w.f. $H^+(\omega+E_m)$
- ϕ_n s.p. bound state overlap function $H(-E_m)$
- λ_n spectroscopic factor
- $\chi^{(-)}$ and ϕ consistently derived as eigenfunctions of a Feshbach optical model Hamiltonian

DWIA calculations

- phenomenological ingredients usually adopted
- $\chi^{(-)}$ phenomenological optical potential
- ϕ_n phenomenological s.p. wave functions WS, HF (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.
- DWIA RDWIA calculations with Coulomb distortion excellent description of (e,e′p) data

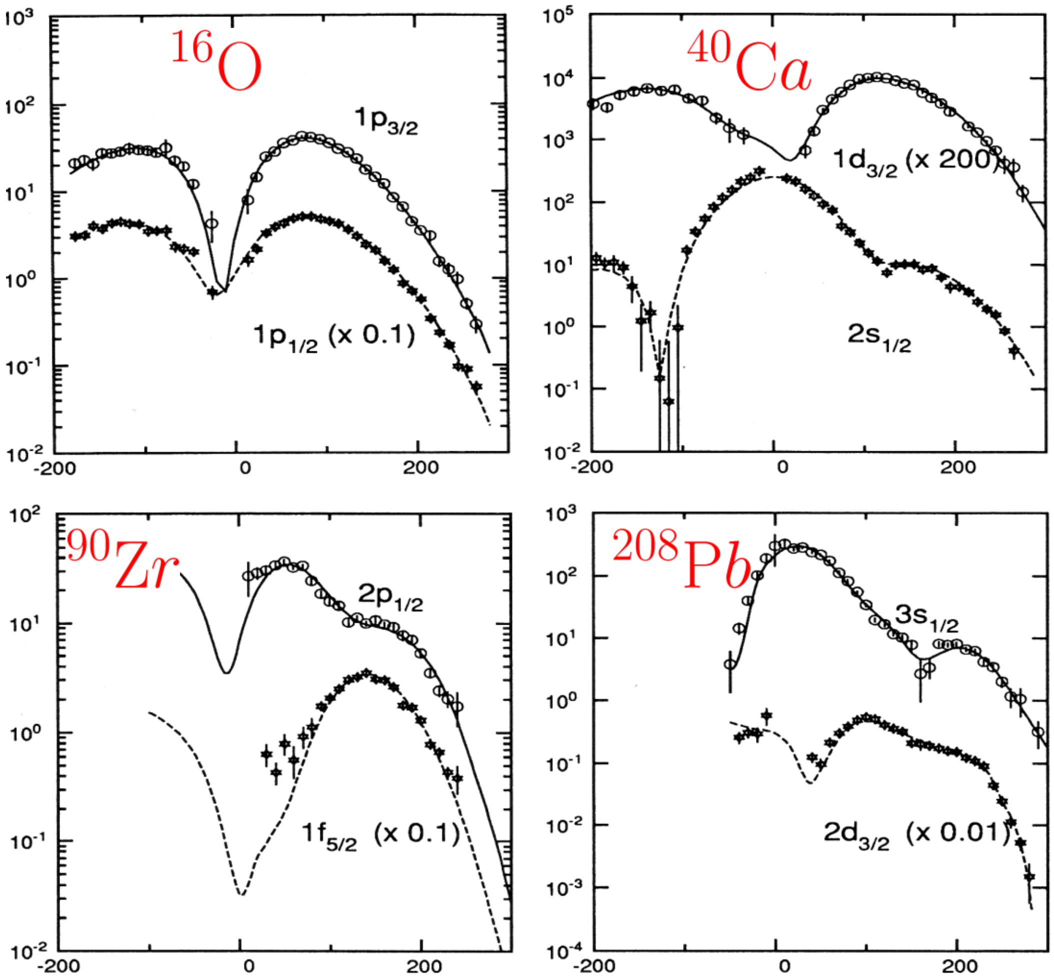
Experimental data E_m and p_m distributions

Experimental data: E_m and p_m distributions



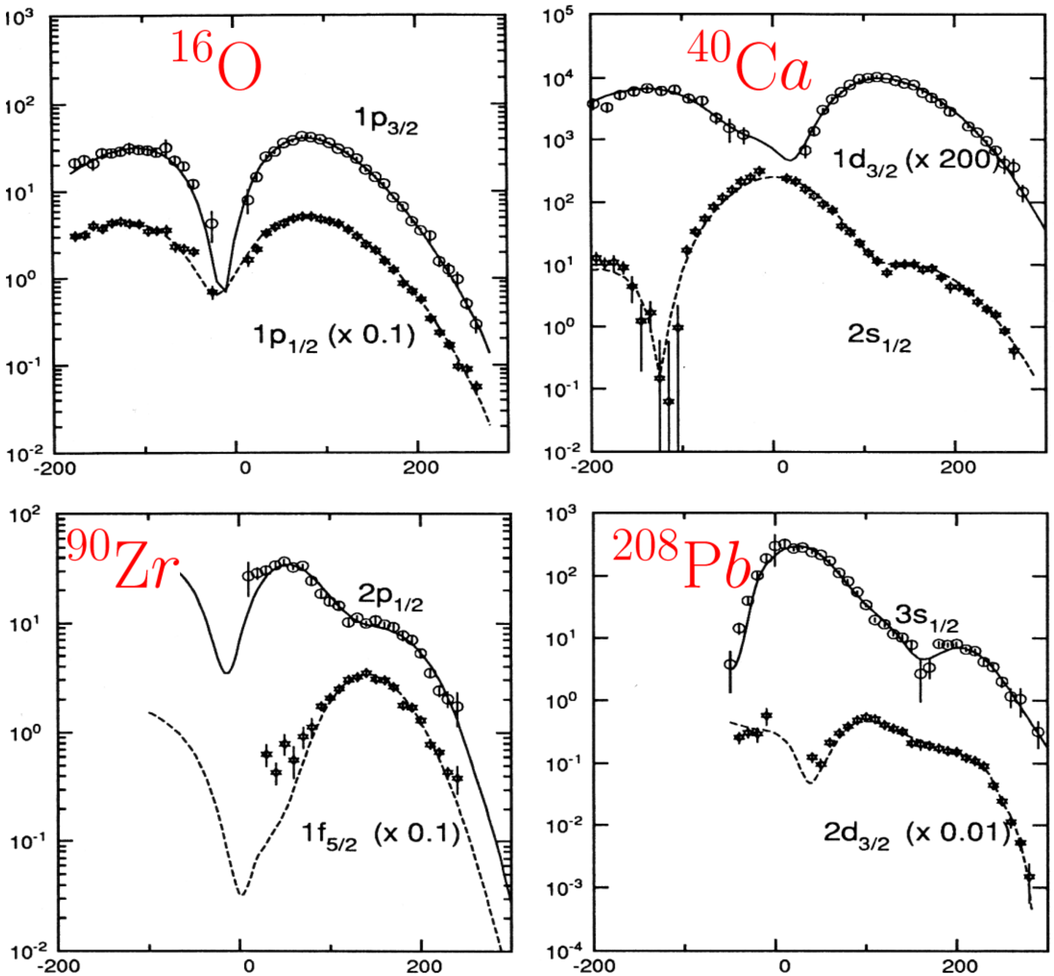
NIKHEF 1990

Experimental data: p_m distribution



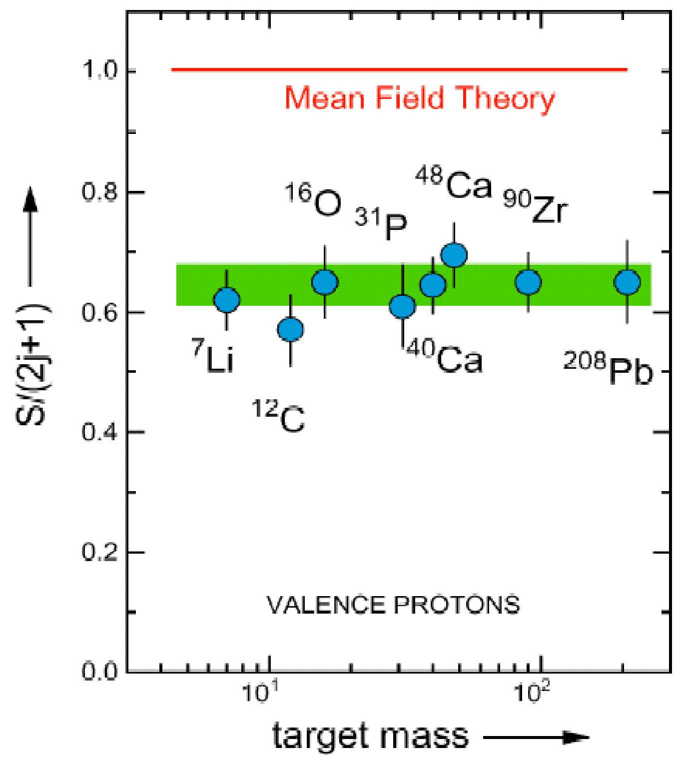
NIKHEF data & CDWIA calculations 1993

Experimental data: p_m distribution



reduction factors applied:
spectroscopic factors

0.6 - 0.7



NIKHEF data & CDWIA calculations
1993

SPECTROSCOPIC FACTORS and NN CORRELATIONS

- depletion due to **NN correlations**
- SRC Short-Range Correlations:

  short-range repulsion of NN interaction pp pairs
- TC Tensor Correlations:

  tensor component of NN interaction pn pairs
- LRC Long-Range Correlations:

  long-range part of NN interaction

  collective excitations of nucleons at the nuclear surface

SPECTROSCOPIC FACTORS and NN CORRELATIONS

- from different independent investigations our calculations with correlated w.f. + C. Barbieri PRL 103 202502 (2009)
- SRC account for only a few % of the depletion, up to 10-15 % with TC
- LRC give the main contribution to the depletion

SRC

- account for only a small part of the depletion
- depletion compensated by the admixture of high-momentum components of 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 many processes are present and a clear-cut identification of SRC appears very difficult
- in exclusive (e,e′p) one does not measure the mom. distrib. but only the SF at specific (low) values of E_m

SRC

- (e,e′p) at high E_m

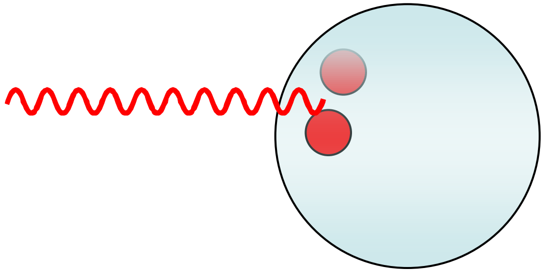
- TWO-NUCLEON KNOCKOUT

SRC

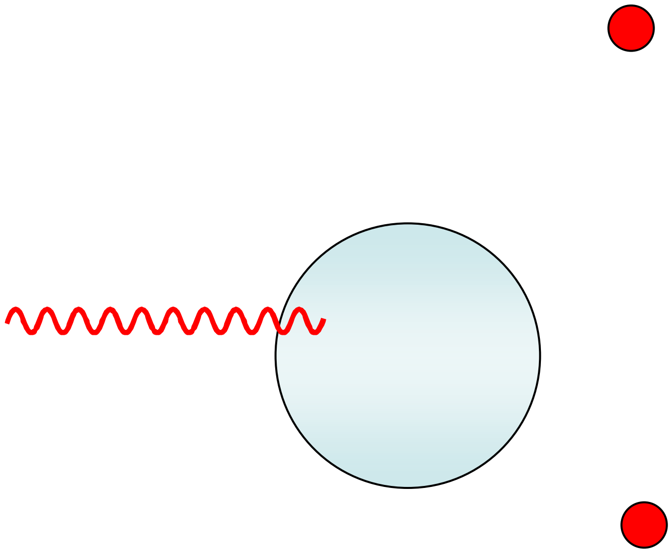
- (e,e'p) at high E_m
- TWO-NUCLEON KNOCKOUT

TWO-NUCLEON KNOCKOUT

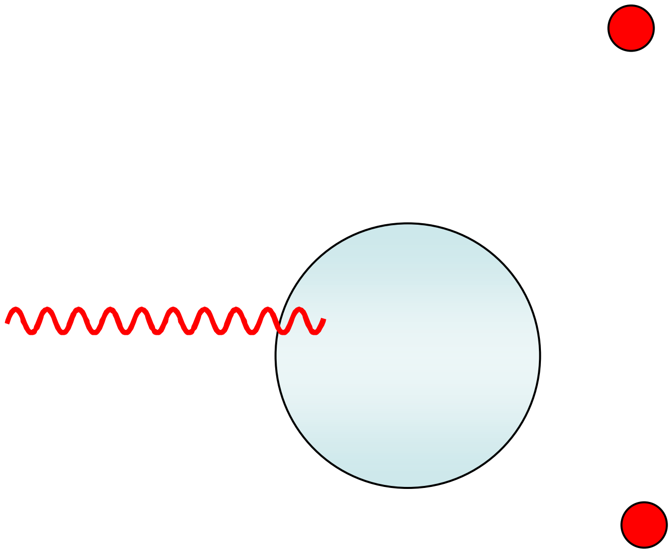
TWO-NUCLEON KNOCKOUT



TWO-NUCLEON KNOCKOUT



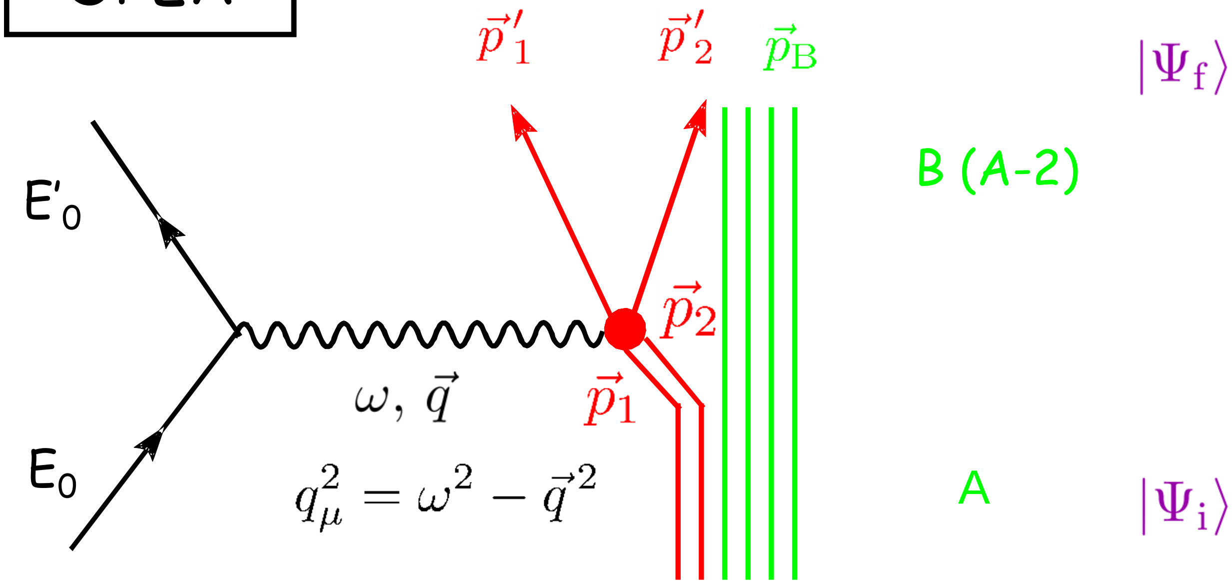
TWO-NUCLEON KNOCKOUT



DKO:
restricted kinematic conditions
between the QE and Δ peak
back to back kinematics
exclusive reactions low values of E_x

OPEA

(e,e'NN)



$$E_m = \omega - \frac{{p'_1}^2}{2m} - \frac{{p'_2}^2}{2m} - \frac{{p_B}^2}{2m(A-1)} = W_B^* - W_A$$ missing energy

$$\vec{p}_m = \vec{q} - \vec{p'}_1 - \vec{p'}_2 = -\vec{P} = -(\vec{p}_1 + \vec{p}_2) = \vec{p}_B$$ missing momentum

E_m

exclusive reaction

TWO-HOLE SPECTRAL FUNCTION

$$S(p_1, p_2, \bar{p}_1, \bar{p}_2; E_m) = \langle \Psi_\mathrm{i} | a^+_{\bar{p}_2} a^+_{\bar{p}_1} \delta(E_m - H) a_{\bar{p}_1} a_{\bar{p}_2} | \Psi_\mathrm{i} \rangle$$

$\bar{p}_1 = p_1, \bar{p}_2 = p_2$

joint probability of removing from the target a pair of nucleons p_1 p_2 leaving the residual nucleus in a state with energy E_m

inclusive reaction :

TWO-BODY DENSITY

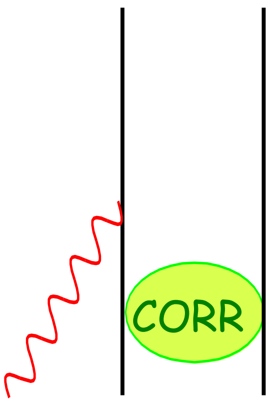
$$\int S(p_1, p_2, \bar{p}_1, \bar{p}_1; E_m) \mathrm{d}E_m = \rho_2(p_1, p_2; \bar{p}_1, \bar{p}_2)$$

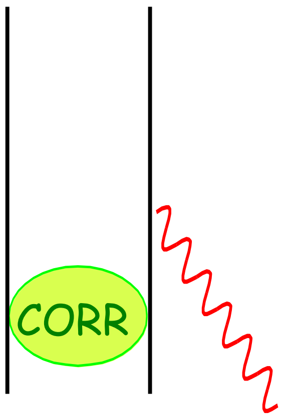
$$\rho_2(r_1, r_2, r_1, r_2) = \int |\Psi_\mathrm{i}(r_1, r_2, r_3, ...r_\mathrm{A})|^2 \mathrm{d}r_3....\mathrm{d}r_\mathrm{A} = C(r_1, r_2)$$

PAIR CORRELATION FUNCTION

probability of finding in the target a nucleon at r_1 if another nucleon is known to be at r_2

TWO-NUCLEON KNOCKOUT

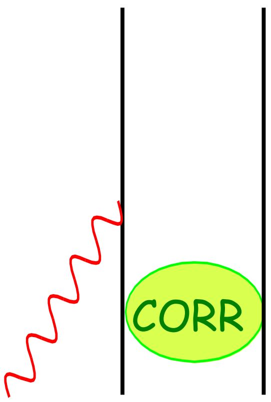


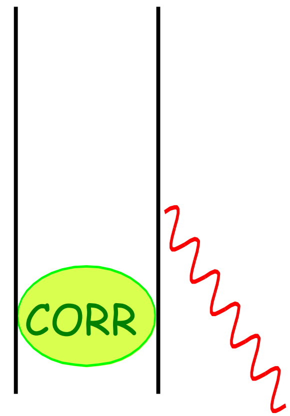


1-body current OB

NN correlations

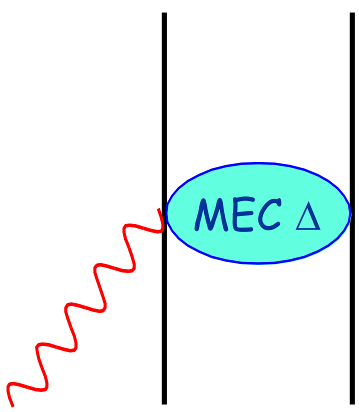
TWO-NUCLEON KNOCKOUT





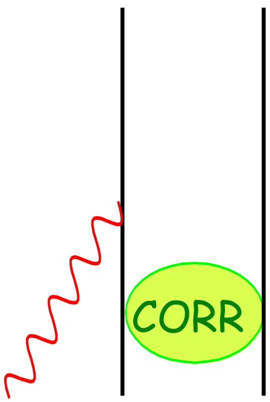
1-body current OB

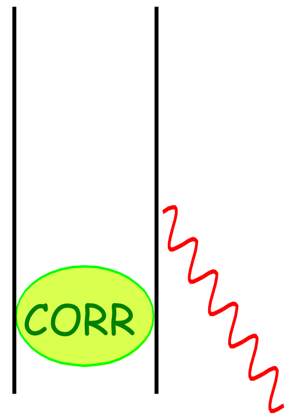
NN correlations



2-body currents TB

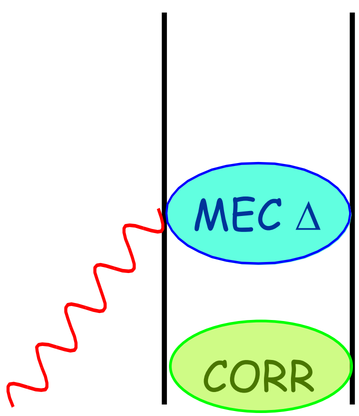
TWO-NUCLEON KNOCKOUT





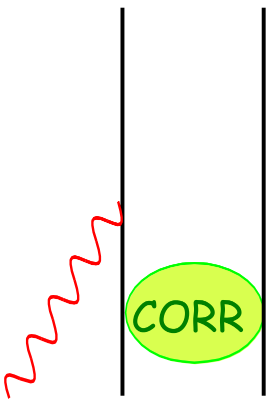
1-body current OB

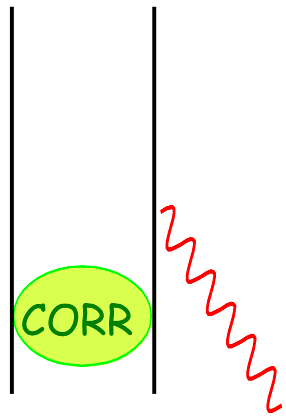
NN correlations



correlations affect also the reaction process due to TB currents

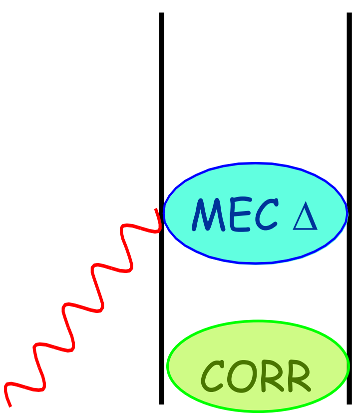
TWO-NUCLEON KNOCKOUT





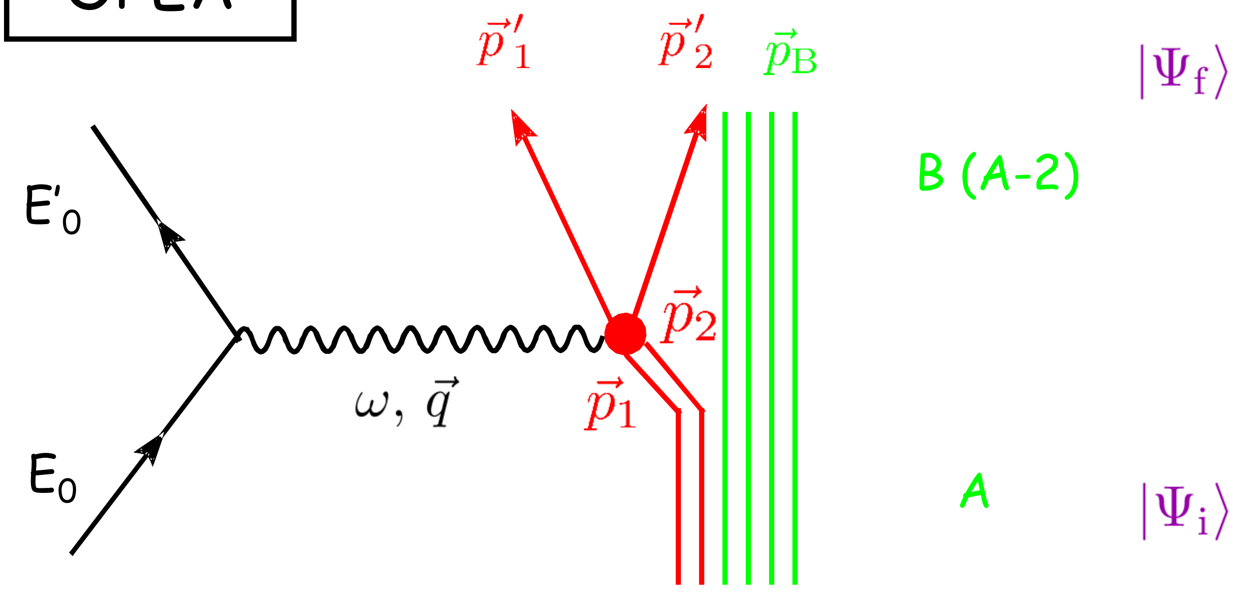
1-body current OB

NN correlations



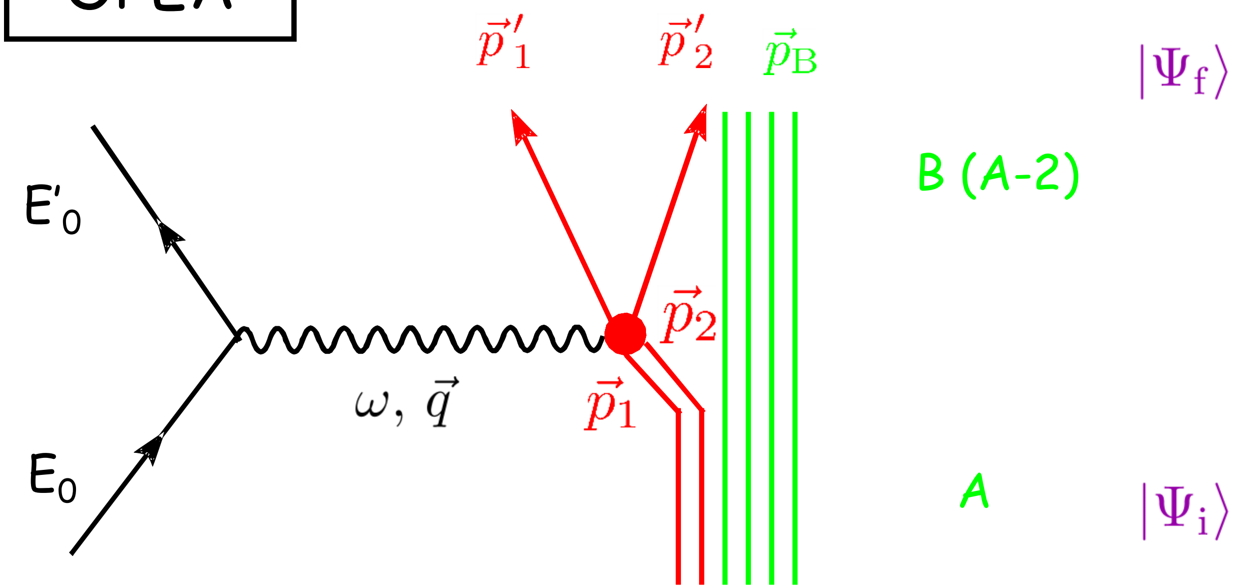
correlations affect also the reaction process due to TB currents

OPEA



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

OPEA



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

hadron tensor

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

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

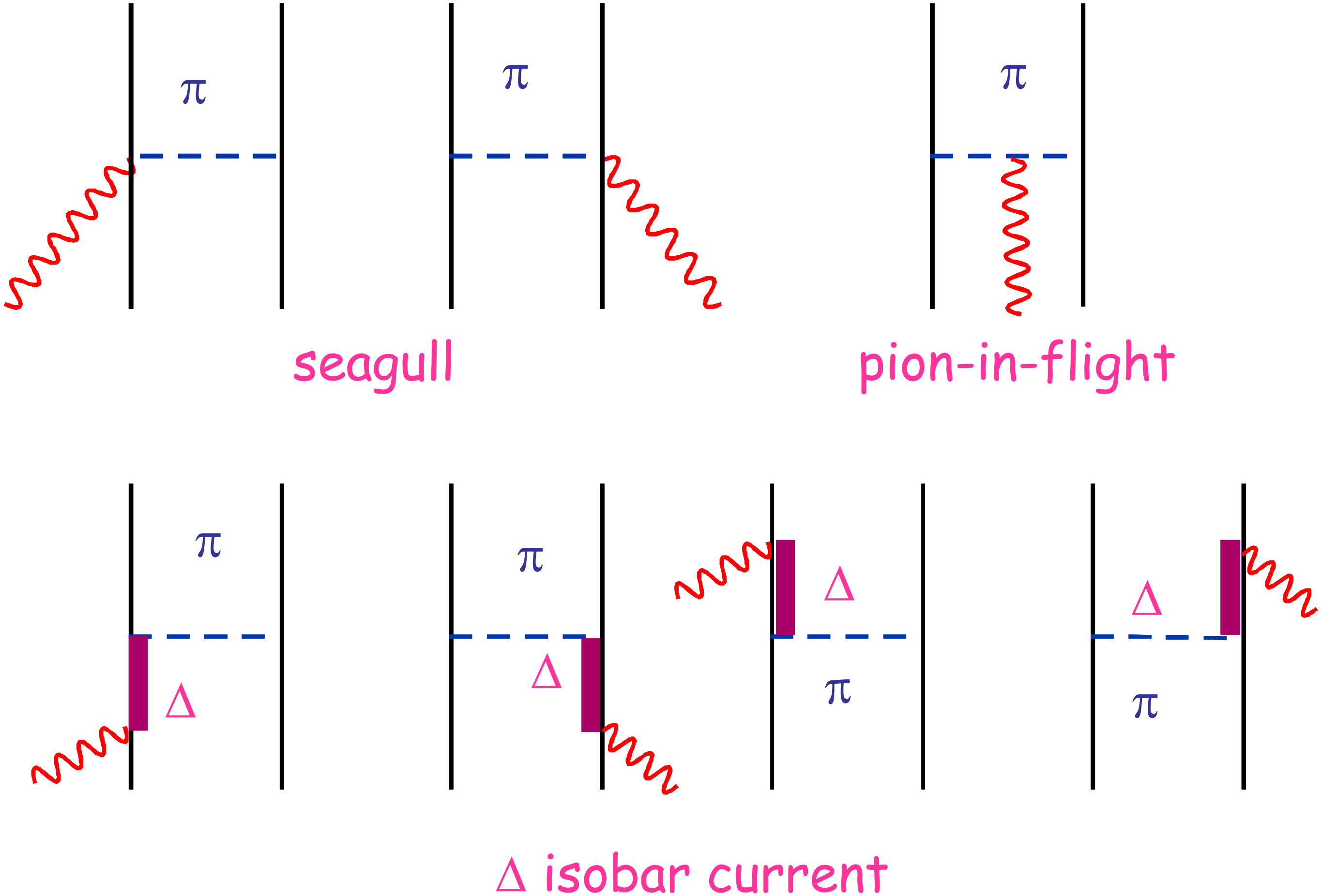
$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \langle \Psi_{\mathrm{f}} \mid \hat{J}^{\mu}(\vec{r}) \mid \Psi_{\mathrm{i}} \rangle \mathrm{d}\vec{r}$$

- **exclusive reaction**
- **DKO mechanism**

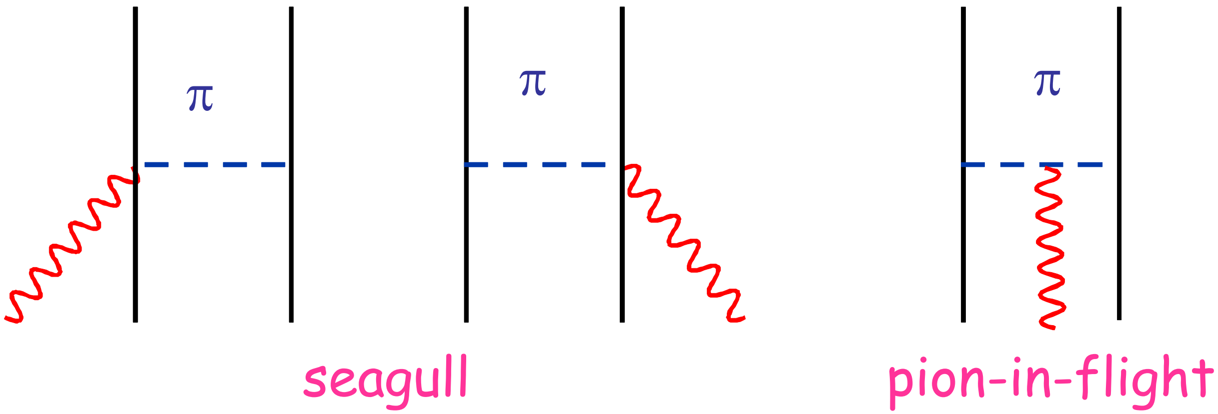
$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^{\mu}(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

- $J^{\mu} = J^{(1)\mu} + J^{(2)\mu}$ nuclear current
- $\chi^{(-)}(r_1, r_2) = \langle \Phi_B\, r_1\, r_2 | \Psi_f \rangle$ two nucleon scattering w.f. $H^{+}(\omega + Em)$
- $\phi(r_1, r_2) = \langle \Phi_B\, r_1\, r_2 | \Psi_i \rangle$ two-nucleon overlap function $H(-Em)$
- $\chi^{(-)}$ and ϕ consistently derived as eigenfunctions of a Feshbach-type optical model Hamiltonian

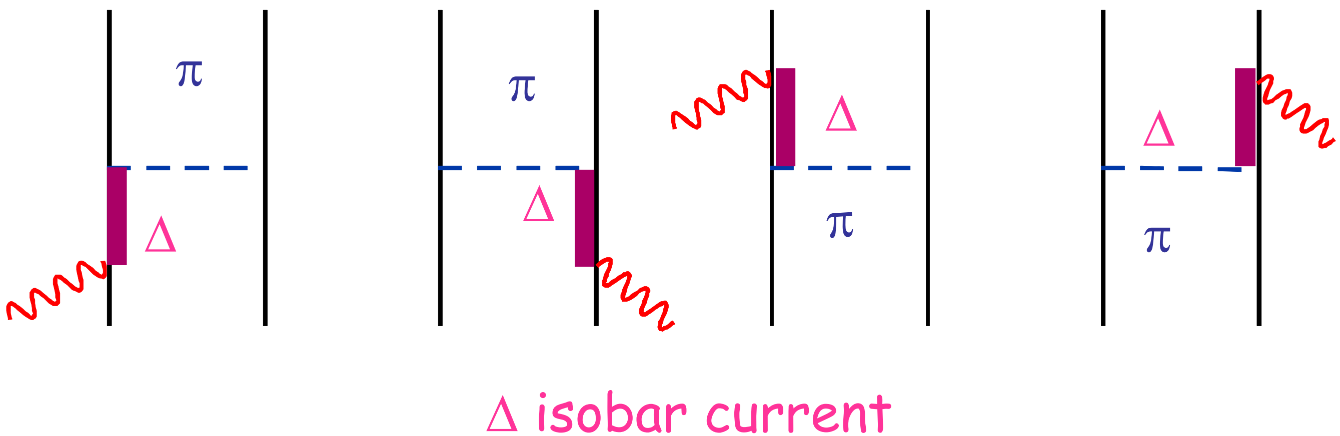
TWO-BODY CURRENTS



TWO-BODY CURRENTS



pn knockout



pn and pp knockout

FINAL-STATE INTERACTION

$$J^\mu(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^\mu(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

2N and residual nucleus : 3-body problem

FINAL-STATE INTERACTION

$$J^{\mu}(\vec{q}) = \int e^{i\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^{\mu}(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) d\vec{r} d\vec{r}_1 d\vec{r}_2$$

2N and residual nucleus : 3-body problem

$V = V_{1B} + V_{2B} + V_{12}$

FINAL-STATE INTERACTION

$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^{\mu}(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

2N and residual nucleus : 3-body problem

$V = V_{1B} + V_{2B} + V_{12}$

DW

phenomenological optical potential $\chi^{(-)}(r_1,r_2)=\chi^{(-)}(r_1)\ \chi^{(-)}(r_2)$ DW

FINAL-STATE INTERACTION

$$J^{\mu}(\vec{q}) = \int e^{i\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1,\vec{r}_2) J^{\mu}(\vec{r}_1,\vec{r}_2,\vec{r}) \phi(\vec{r}_1,\vec{r}_2) d\vec{r} d\vec{r}_1 d\vec{r}_2$$

2N and residual nucleus : 3-body problem

$V = V_{1B} + V_{2B} + V_{12}$ NN-FSI

DW

phenomenological optical potential $\chi^{(-)}(r_1,r_2)=\chi^{(-)}(r_1)\,\chi^{(-)}(r_2)$ DW

NN-FSI perturbative approach based on 3-body scattering theory

M. Schwamb, S. Boffi, C. Giusti, F.D. Pacati Eur. Phys. J. A17 (2003) 7; A20 (2004) 233

FINAL-STATE INTERACTION

$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}}\chi^{(-)*}(\vec{r}_1,\vec{r}_2)J^{\mu}(\vec{r}_1,\vec{r}_2,\vec{r})\phi(\vec{r}_1,\vec{r}_2)\mathrm{d}\vec{r}\mathrm{d}\vec{r}_1\mathrm{d}\vec{r}_2$$

2N and residual nucleus : 3-body problem

$V = V_{1B} + V_{2B} + V_{12}$ NN-FSI

DW

phenomenological optical potential $\chi^{(-)}(r_1,r_2)=\chi^{(-)}(r_1)\,\chi^{(-)}(r_2)$ DW

NN-FSI perturbative approach based on 3-body scattering theory

M. Schwamb, S. Boffi, C. Giusti, F.D. Pacati Eur. Phys. J. A17 (2003) 7; A20 (2004) 233

→ $\chi^{(-)}(r_1,r_2)=\chi^{(-)}(r_1)\,\chi^{(-)}(r_2)\,F(r_1,r_2)$ DW-NN

TWO-NUCLEON OVERLAP

$$J^\mu(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^\mu(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

TWO-NUCLEON OVERLAP

$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^{\mu}(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

IPSM correlations neglected:

Φ_B 2h state in the SM $\quad J^{\pi} \; (n_1\, l_1\, j_1, n_2, l_2, j_2)^{-1}$

TWO-NUCLEON OVERLAP

$$J^\mu(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1,\vec{r}_2) J^\mu(\vec{r}_1,\vec{r}_2,\vec{r}) \phi(\vec{r}_1,\vec{r}_2) \mathrm{d}\vec{r}\mathrm{d}\vec{r}_1\mathrm{d}\vec{r}_2$$

IPSM correlations neglected:

Φ_B 2h state in the SM J^π $(n_1\, l_1\, j_1, n_2, l_2, j_2)^{-1}$

$\phi_{JMT}{}^{SM}(r_1\, \sigma_1\, \tau_1,\, r_2\, \sigma_2\, \tau_2)$ SM pair function

TWO-NUCLEON OVERLAP

$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^{\mu}(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

IPSM correlations neglected:

Φ_B 2h state in the SM J^{π} $(n_1\, l_1\, j_1, n_2, l_2, j_2)^{-1}$

$\phi_{JMT}{}^{SM}(r_1\, \sigma_1\, \tau_1, r_2\, \sigma_2\, \tau_2)$ SM pair function

$\phi_{JMT}{}^{SM}(r_1\, \sigma_1\, \tau_1, r_2\, \sigma_2\, \tau_2)\, F^{SRC}(|r_1 - r_2|)$ SM-SRC

$F^{SRC}(|r_1 - r_2|)$ Jastrow corr. function central state-independent SRC

TWO-NUCLEON OVERLAP

$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^{\mu}(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

IPSM correlations neglected:

Φ_B 2h state in the SM J^{π} $(n_1\, l_1\, j_1, n_2, l_2, j_2)^{-1}$

$\phi_{JMT}{}^{SM}(r_1\, \sigma_1\, \tau_1, r_2\, \sigma_2\, \tau_2)$ SM pair function

$\phi_{JMT}{}^{SM}(r_1\, \sigma_1\, \tau_1, r_2\, \sigma_2\, \tau_2)\, F^{SRC}(|r_1 - r_2|)$ SM-SRC

$F^{SRC}(|r_1 - r_2|)$ Jastrow corr. function central state-independent SRC

TWO-NUCLEON OVERLAP

$$J^{\mu}(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^{\mu}(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

more complete and sophisticated approach:

ϕ obtained from microscopic calculations of the NN spectral function of ^{16}O include consistently different types of correlations SRC, TC, LRC

C. Giusti, F.D. Pacati, K. Allaart, W. Geurts, H . Muether, W.H. Dickhoff, PRC 54 (1996) 1144

C. Barbieri, C. Giusti, F.D. Pacati, W.H. Dickhoff PRC 70 (2004) 014606

TWO-NUCLEON OVERLAP

$$J^\mu(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^\mu(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

more complete and sophisticated approach:

ϕ obtained from microscopic calculations of the NN spectral function of ^{16}O include consistently different types of correlations SRC, TC, LRC

C. Giusti, F.D. Pacati, K. Allaart, W. Geurts, H . Muether, W.H. Dickhoff, PRC 54 (1996) 1144

C. Barbieri, C. Giusti, F.D. Pacati, W.H. Dickhoff PRC 70 (2004) 014606

^{16}O suitable target due to the presence of discrete final states in the E_x spectrum of ^{14}C and ^{14}N well separated in energy

experimental data available for pp and pn knockout off ^{16}O

TWO-NUCLEON OVERLAP

$$J^\mu(\vec{q}) = \int \mathrm{e}^{\mathrm{i}\vec{q}\cdot\vec{r}} \chi^{(-)*}(\vec{r}_1, \vec{r}_2) J^\mu(\vec{r}_1, \vec{r}_2, \vec{r}) \phi(\vec{r}_1, \vec{r}_2) \mathrm{d}\vec{r} \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2$$

more complete and sophisticated approach:

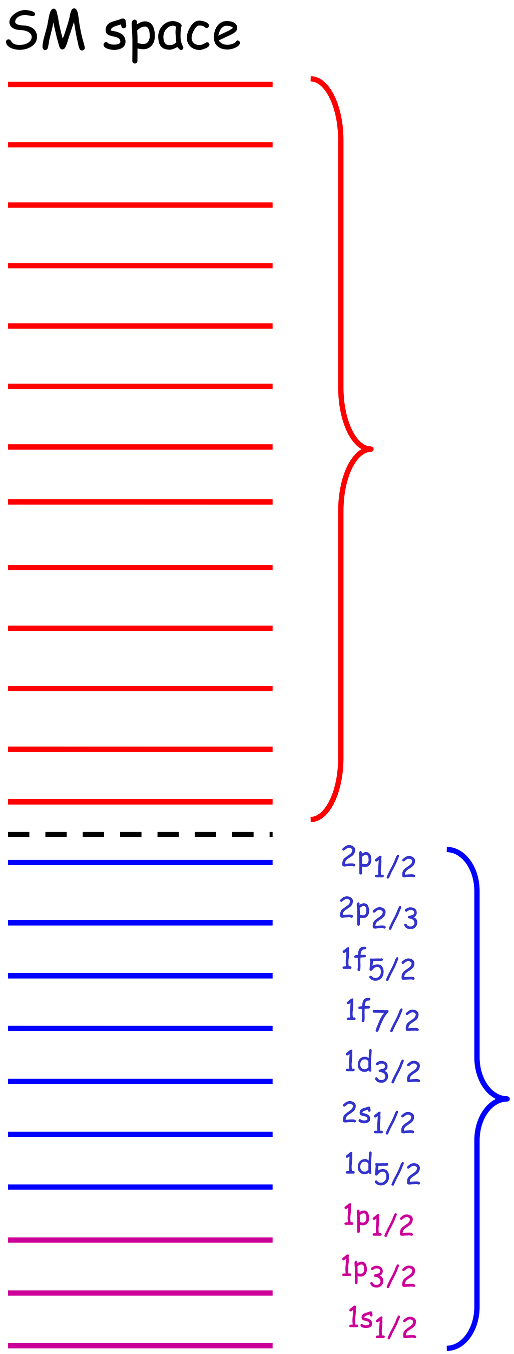
ϕ obtained from microscopic calculations of the NN spectral function of ^{16}O include consistently different types of correlations SRC, TC, LRC

C. Giusti, F.D. Pacati, K. Allaart, W. Geurts, H . Muether, W.H. Dickhoff, PRC 54 (1996) 1144

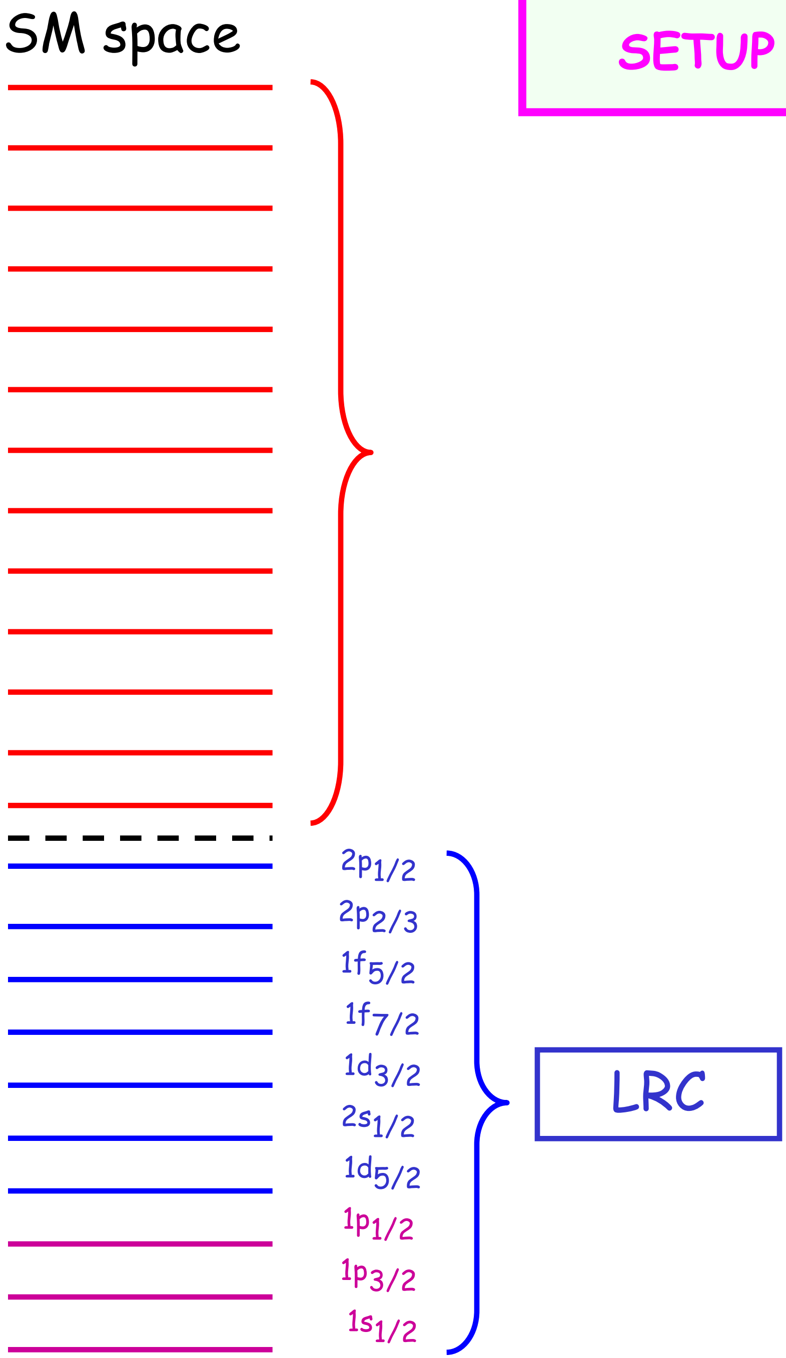
C. Barbieri, C. Giusti, F.D. Pacati, W.H. Dickhoff PRC 70 (2004) 014606 ⟵

The two-nucleon overlap is obtained from a self-consistent calculation of the 2hGF, where the coupling of nucleons and collective excitations of the system is calculated with realistic NN forces employing the Faddeev RPA method

SETUP TO INCLUDE SRC AND LRC

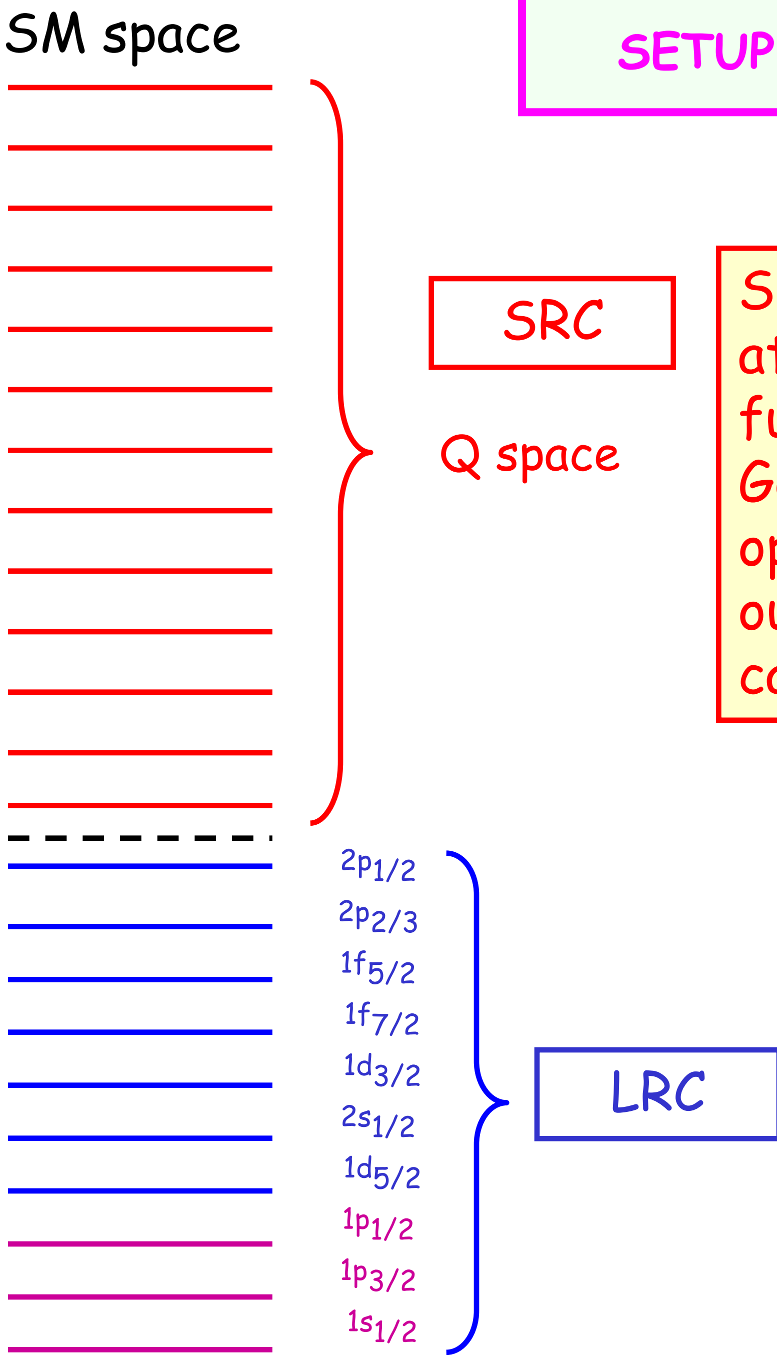


SETUP TO INCLUDE SRC AND LRC



LRC and the LR part of TC computed using the self-consistent Green's function formalism in a 10 shell h.o. basis large enough to account for the main collective features that influence the pair removal amplitudes

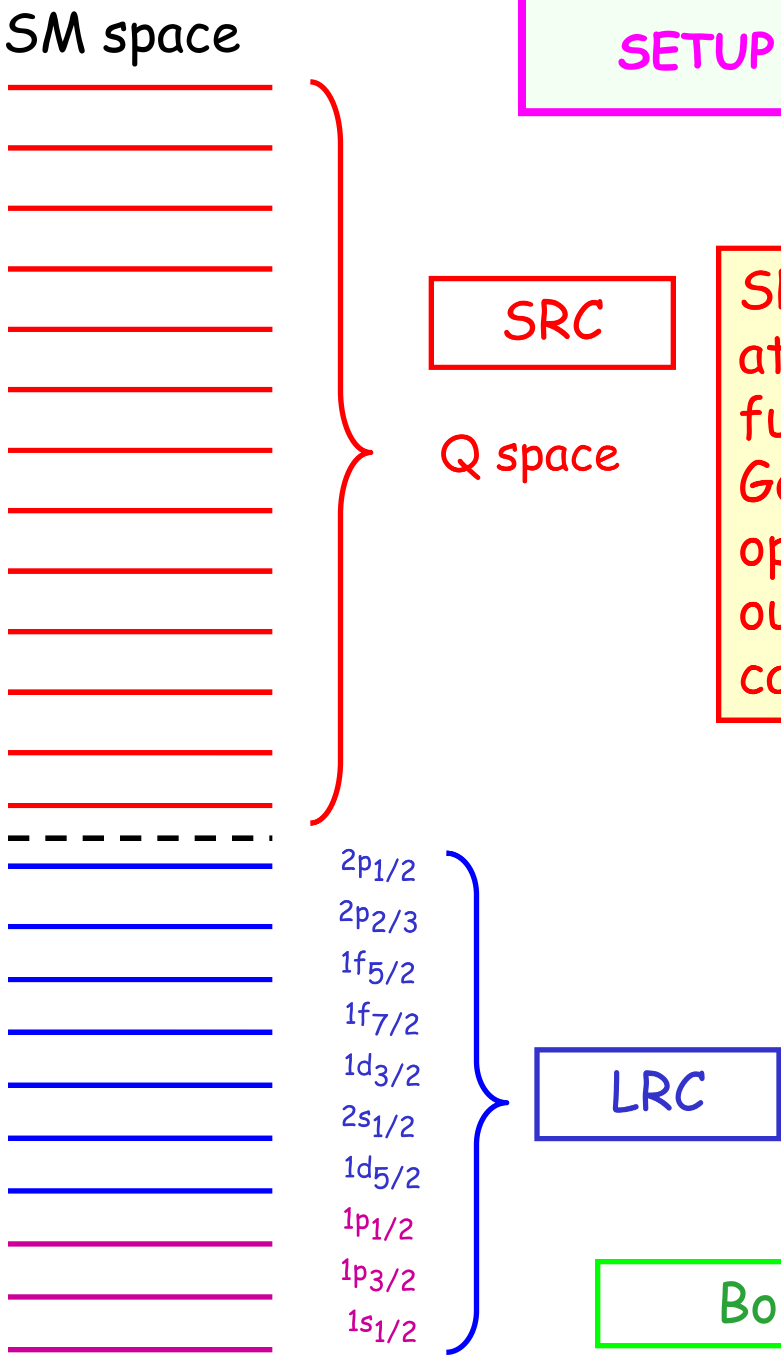
SETUP TO INCLUDE SRC AND LRC



SRC due to the central and tensor part at high momenta added by defect functions obtained from the Bethe-Goldstone equation where the Pauli operator considers only configurations outside the model space where LRC are calculated

LRC and the LR part of TC computed using the self-consistent Green's function formalism in a 10 shell h.o. basis large enough to account for the main collective features that influence the pair removal amplitudes

SETUP TO INCLUDE SRC AND LRC

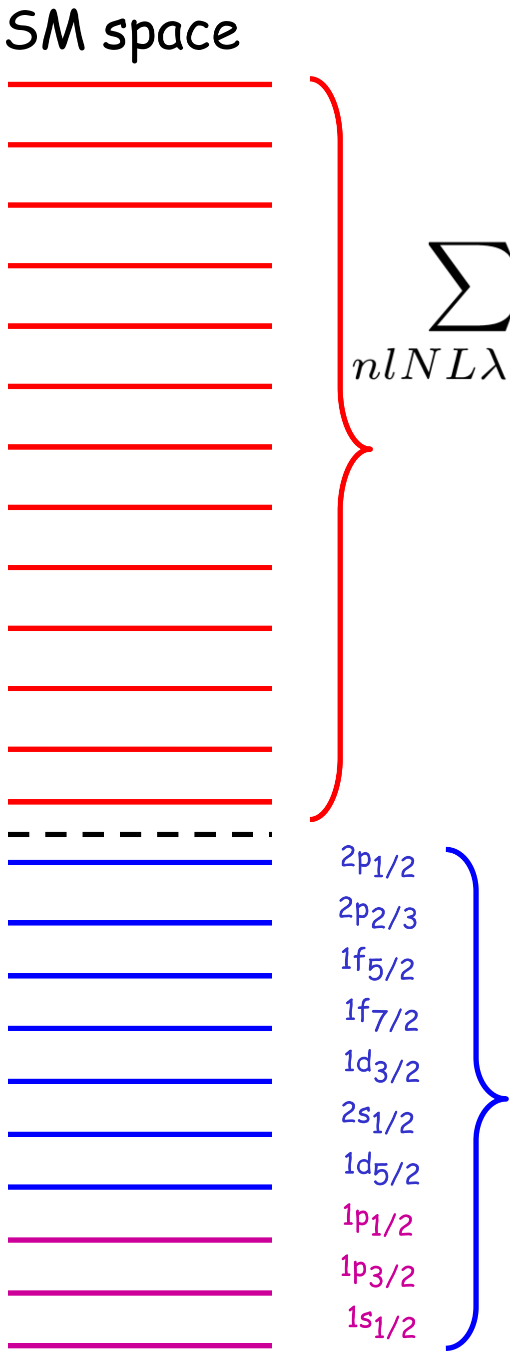


SRC due to the central and tensor part at high momenta added by defect functions obtained from the Bethe-Goldstone equation where the Pauli operator considers only configurations outside the model space where LRC are calculated

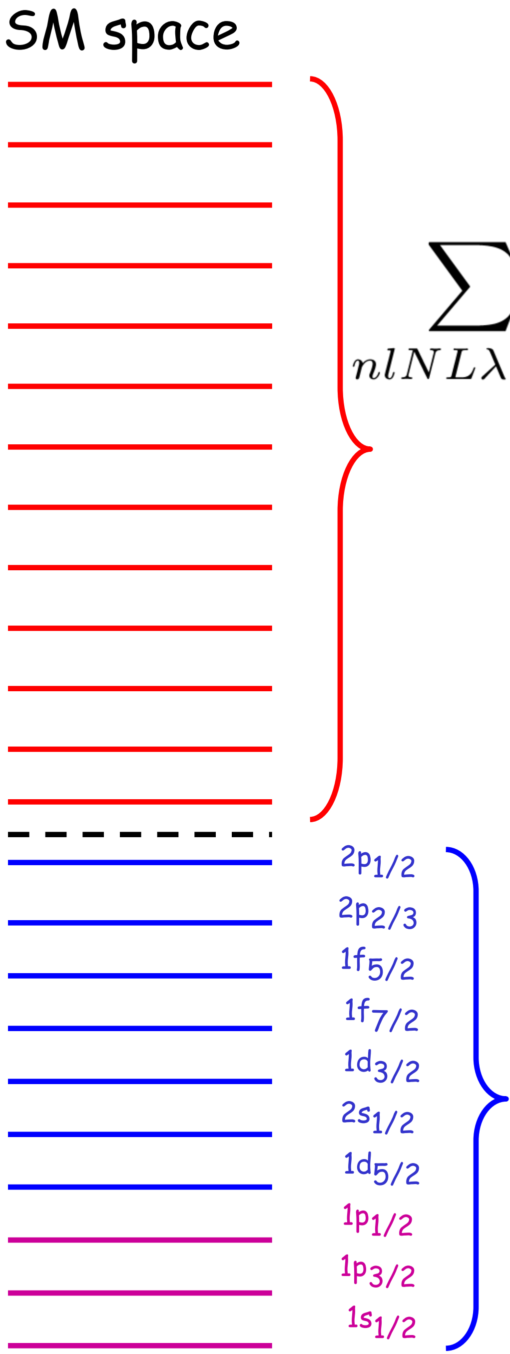
LRC and the LR part of TC computed using the self-consistent Green's function formalism in a 10 shell h.o. basis large enough to account for the main collective features that influence the pair removal amplitudes

Bonn-C NN interaction

$$\langle {}^{14}\mathrm{C}(J^\pi)\vec{r}\vec{R}\,|^{16}\,O_{\mathrm{g.s.}}\rangle \quad \langle {}^{14}\mathrm{N}(J^\pi)\vec{r}\vec{R}\,|^{16}\,O_{\mathrm{g.s.}}\rangle$$

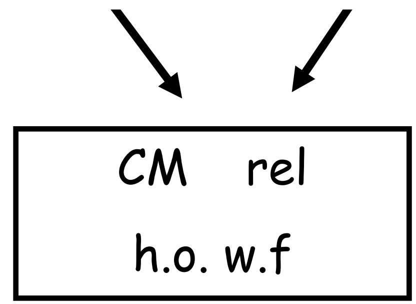


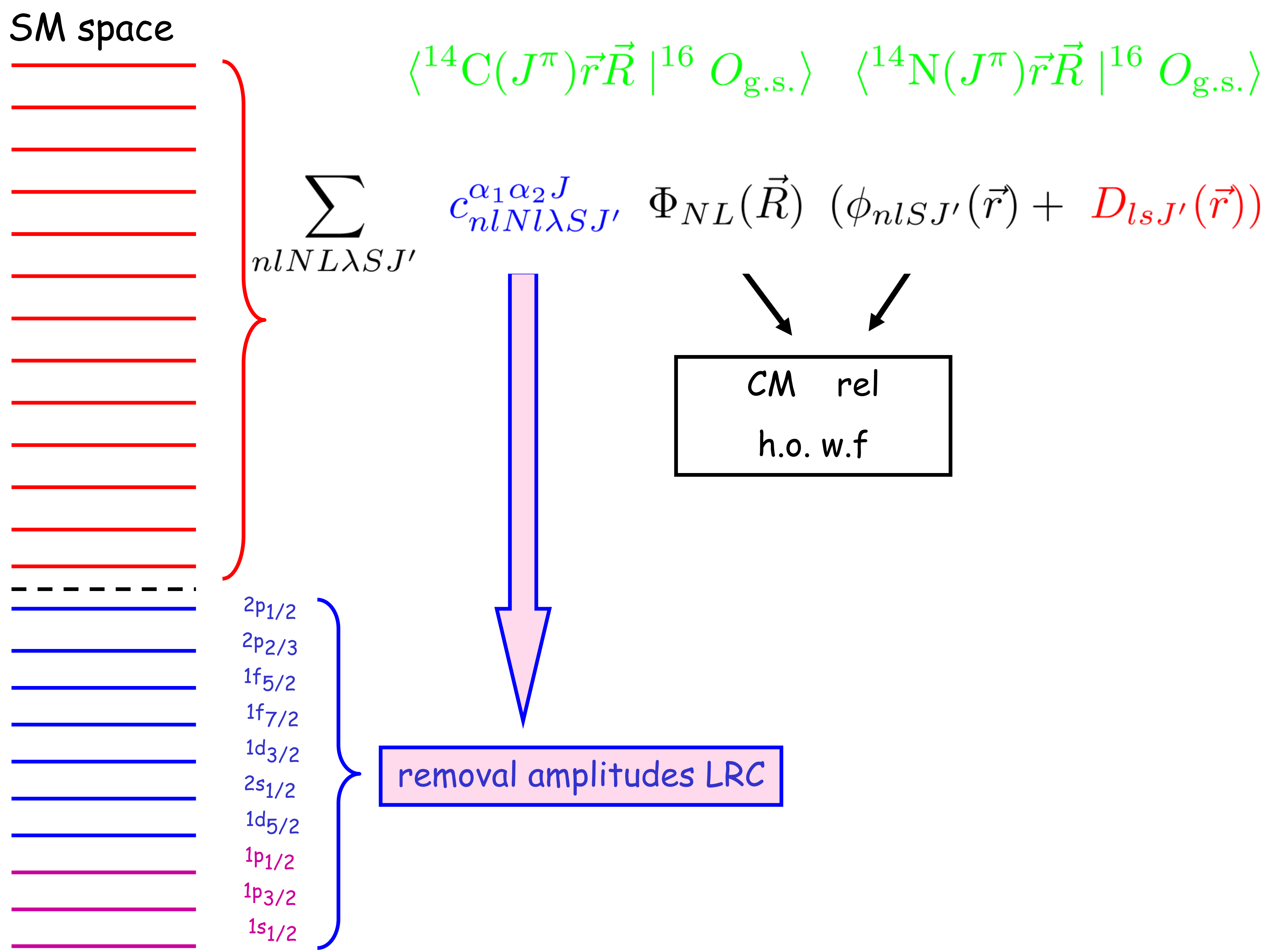
$$\sum_{nlNL\lambda SJ'} c^{\alpha_1\alpha_2 J}_{nlNl\lambda SJ'}\;\Phi_{NL}(\vec{R})\;\left(\phi_{nlSJ'}(\vec{r}) + D_{lsJ'}(\vec{r})\right)$$

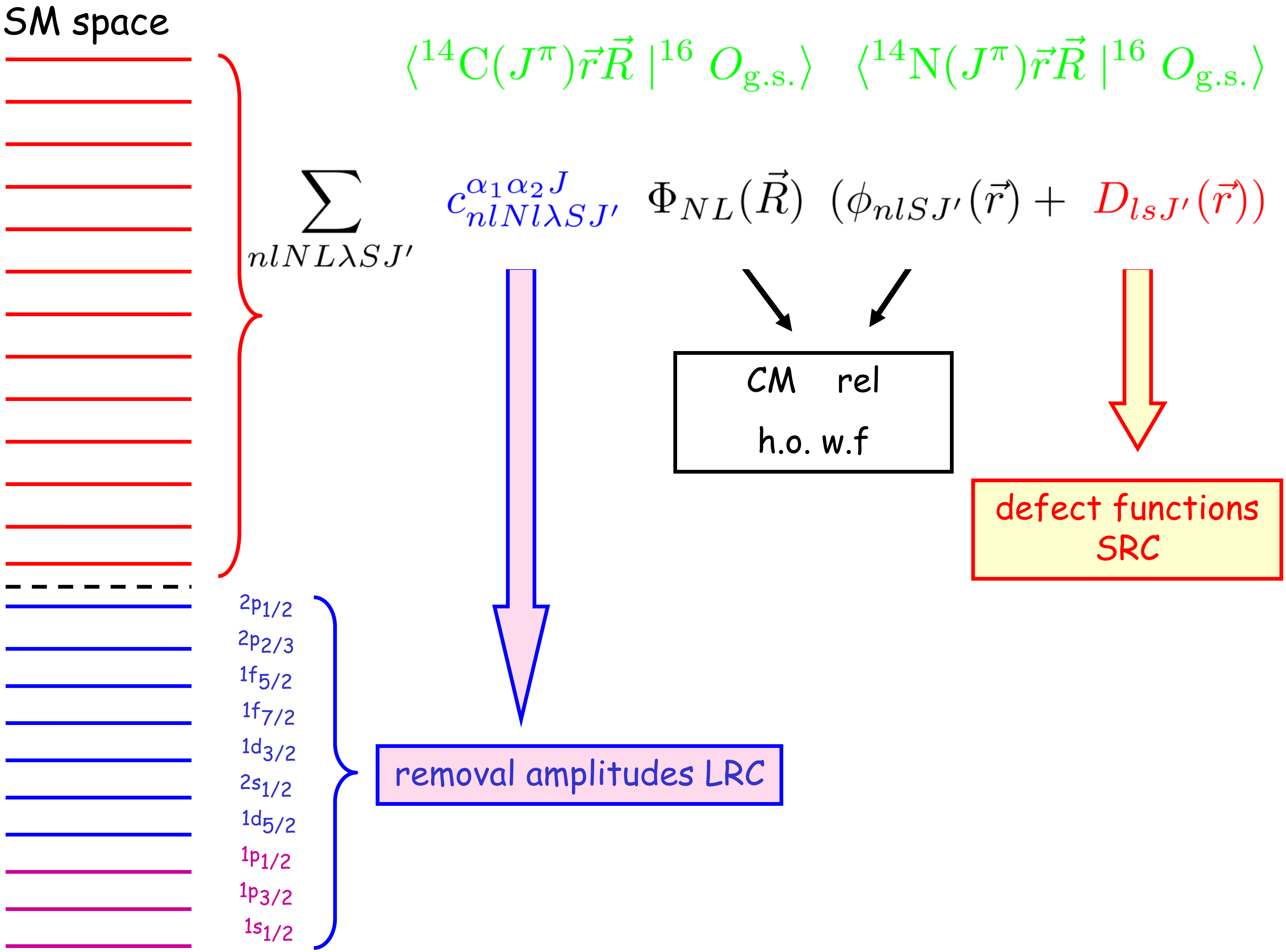


$$\langle {}^{14}\mathrm{C}(J^\pi)\vec{r}\vec{R}\,|^{16}\,O_{\mathrm{g.s.}}\rangle \quad \langle {}^{14}\mathrm{N}(J^\pi)\vec{r}\vec{R}\,|^{16}\,O_{\mathrm{g.s.}}\rangle$$

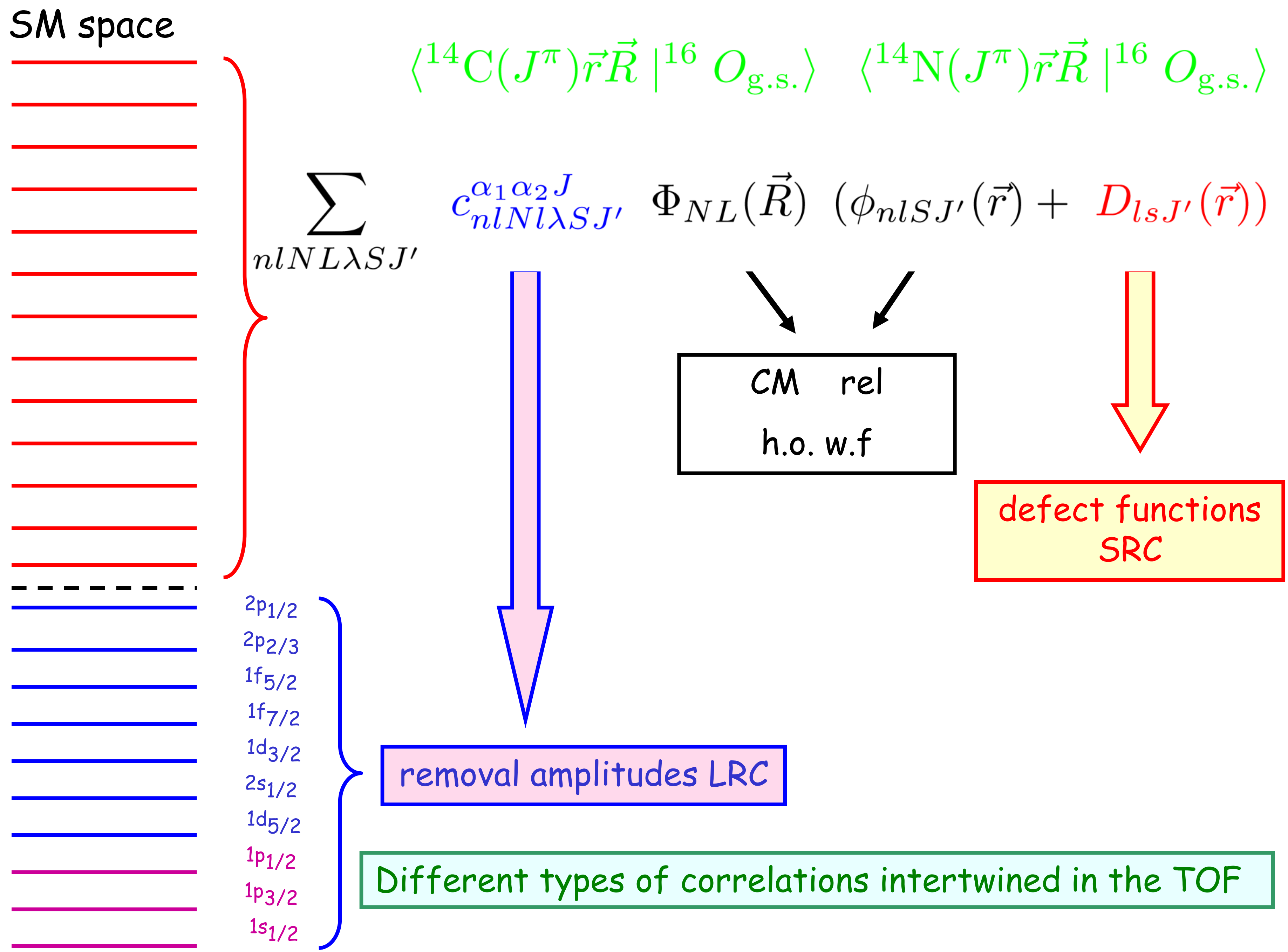
$$\sum_{nlNL\lambda SJ'} c^{\alpha_1\alpha_2 J}_{nlNl\lambda SJ'}\ \Phi_{NL}(\vec{R})\ \left(\phi_{nlSJ'}(\vec{r}) + D_{lsJ'}(\vec{r})\right)$$




SM space
$\langle {}^{14}\mathrm{C}(J^\pi)\vec{r}\vec{R}\,|^{16}\,O_{\mathrm{g.s.}}\rangle$
$\langle {}^{14}\mathrm{N}(J^\pi)\vec{r}\vec{R}\,|^{16}\,O_{\mathrm{g.s.}}\rangle$
$\sum_{nlNL\lambda SJ'} c^{\alpha_1\alpha_2 J}_{nlNl\lambda SJ'}\ \Phi_{NL}(\vec{R})\ (\phi_{nlSJ'}(\vec{r}) +\ D_{lsJ'}(\vec{r}))$
CM rel
h.o. w.f
$2p_{1/2}$
$2p_{2/3}$
$1f_{5/2}$
$1f_{7/2}$
$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
removal amplitudes LRC

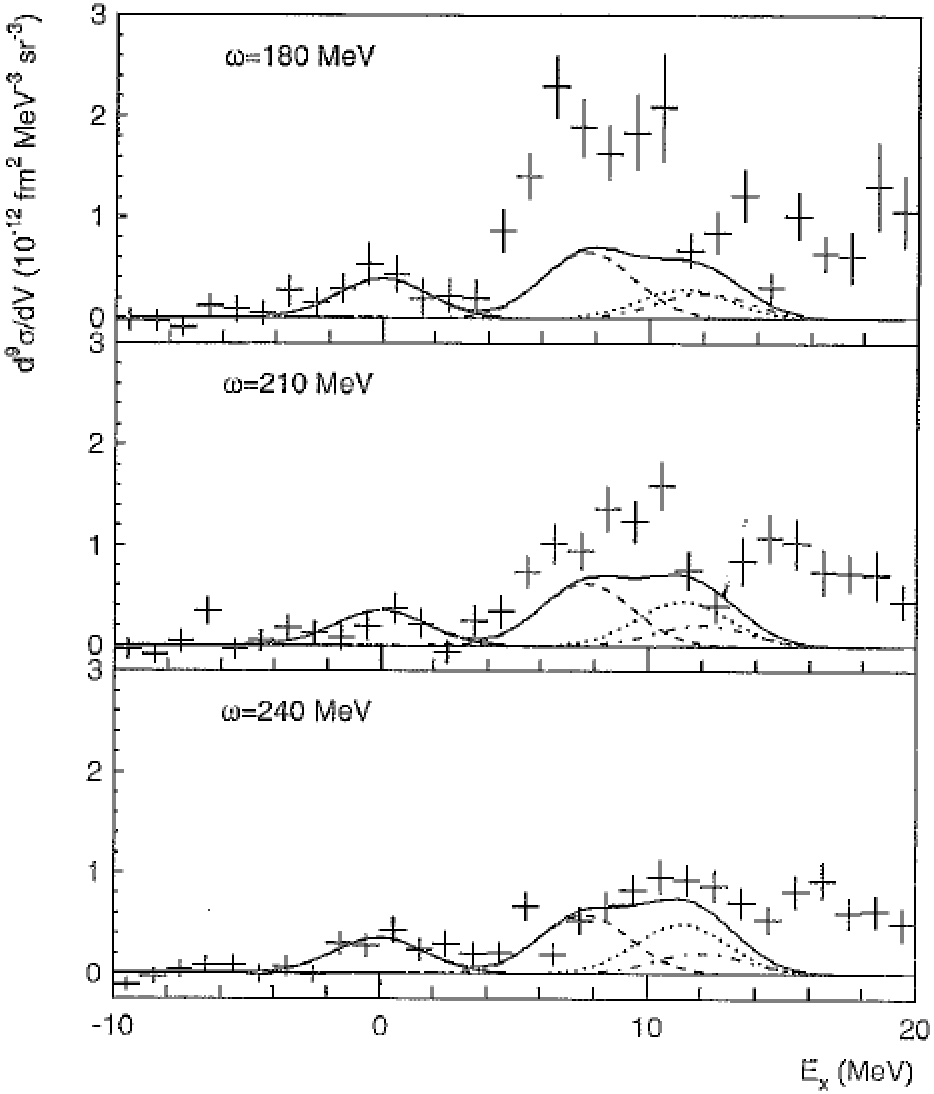


SM space
$\langle {}^{14}\mathrm{C}(J^\pi)\vec{r}\vec{R}\,|{}^{16}O_{\mathrm{g.s.}}\rangle$
$\langle {}^{14}\mathrm{N}(J^\pi)\vec{r}\vec{R}\,|{}^{16}O_{\mathrm{g.s.}}\rangle$
$\sum_{nlNL\lambda SJ'} c^{\alpha_1\alpha_2 J}_{nlNl\lambda SJ'}\ \Phi_{NL}(\vec{R})\ \left(\phi_{nlSJ'}(\vec{r}) + D_{lsJ'}(\vec{r})\right)$
CM rel
h.o. w.f
defect functions
SRC
$2p_{1/2}$
$2p_{2/3}$
$1f_{5/2}$
$1f_{7/2}$
$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
removal amplitudes LRC



SM space
$\langle {}^{14}\mathrm{C}(J^\pi)\vec{r}\vec{R}\,|{}^{16}\,O_{\mathrm{g.s.}}\rangle$ $\langle {}^{14}\mathrm{N}(J^\pi)\vec{r}\vec{R}\,|{}^{16}\,O_{\mathrm{g.s.}}\rangle$
$\sum_{nlNL\lambda SJ'} c^{\alpha_1\alpha_2 J}_{nlNl\lambda SJ'}\ \Phi_{NL}(\vec{R})\ (\phi_{nlSJ'}(\vec{r}) + D_{lsJ'}(\vec{r}))$
CM rel
h.o. w.f
defect functions
SRC
2p1/2
2p2/3
1f5/2
1f7/2
1d3/2
2s1/2
1d5/2
1p1/2
1p3/2
1s1/2
removal amplitudes LRC
Different types of correlations intertwined in the TOF

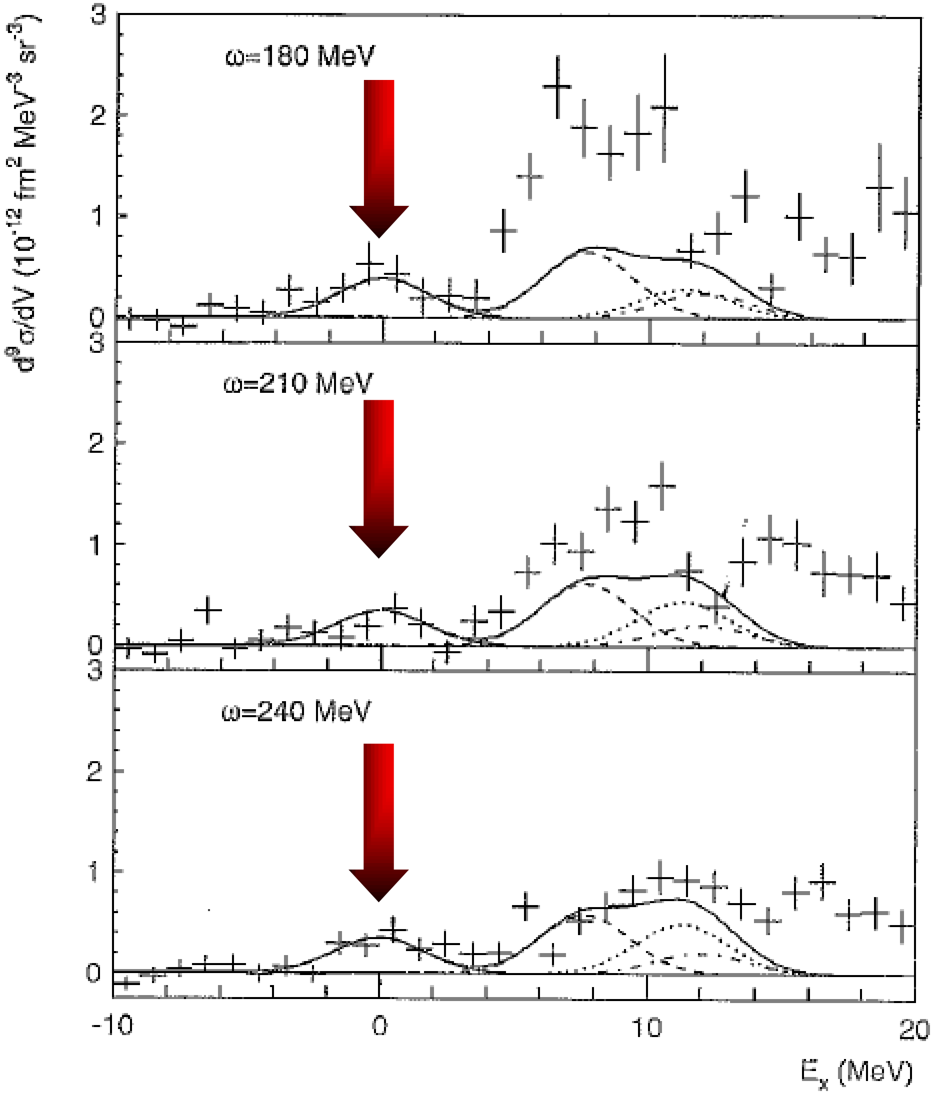
$^{16}O(e,e'pp)^{14}C$: NIKHEF data



R. Starink, Ph.D thesis 1999

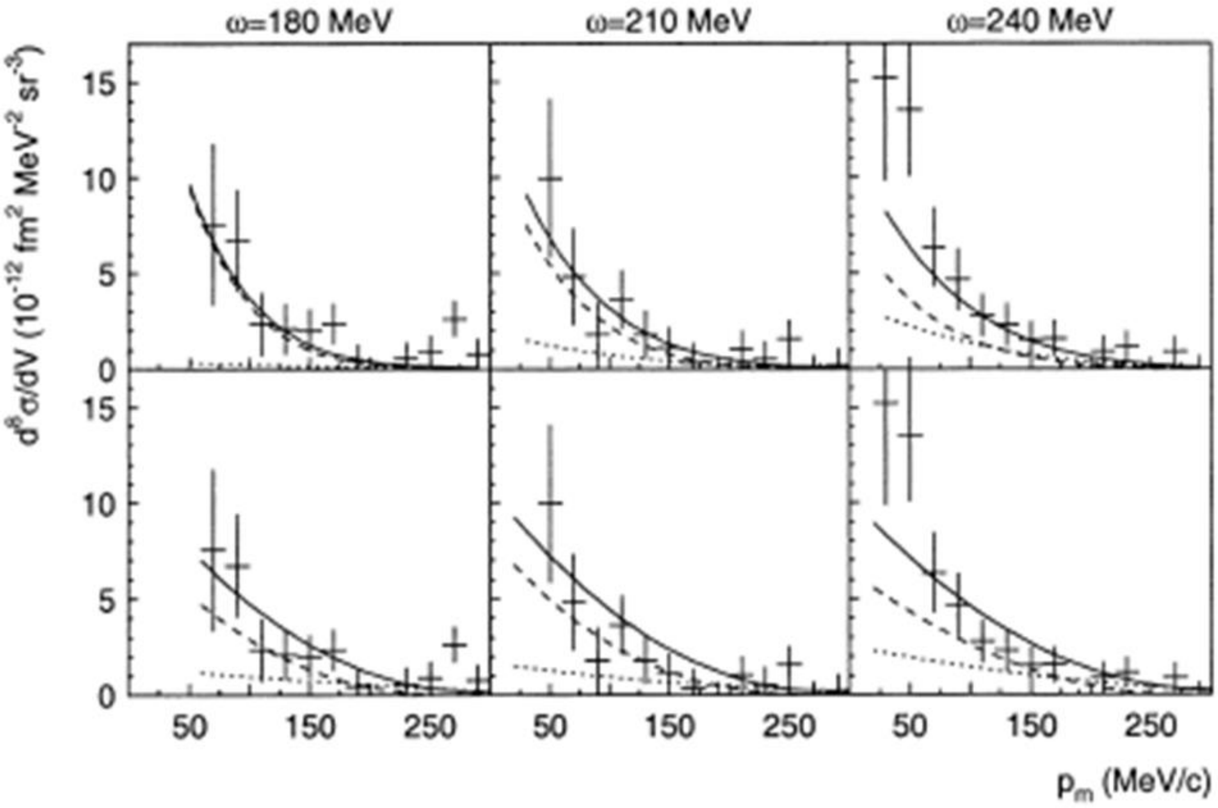
$^{16}O(e,e'pp)^{14}C$: NIKHEF data

g.s. 0^+



R. Starink, Ph.D thesis 1999

$^{16}O(e,e'pp)^{14}C_{g.s.}$ NIKHEF data



Pavia

Gent

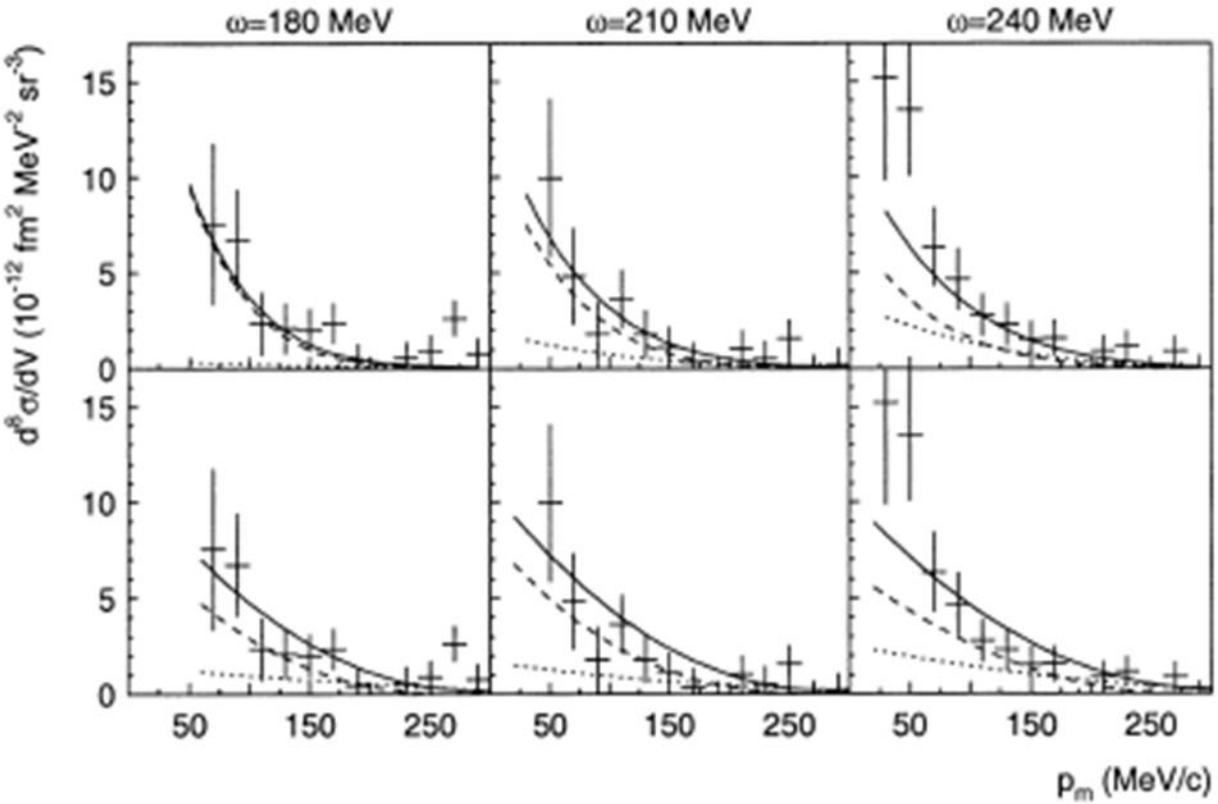
1-b +Δ

1-b

Δ

R. Starink et al. PLB 474 33 (2000)

$^{16}O(e,e'pp)^{14}C_{g.s.}$ NIKHEF data



Pavia

Gent

——— 1-b +Δ

- - - - - - 1-b

·········· Δ

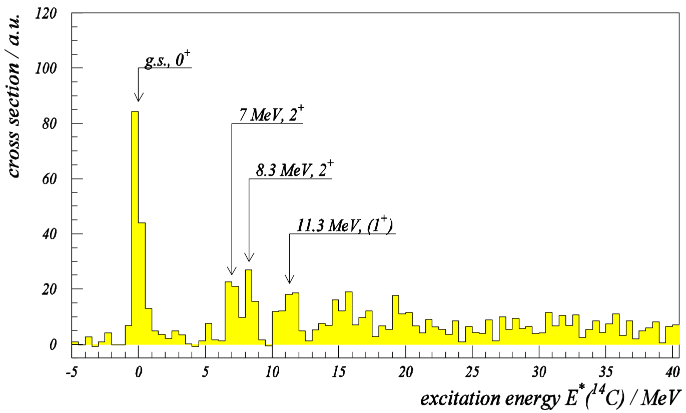
EVIDENCE FOR SRC !

R. Starink et al. PLB 474 33 (2000)

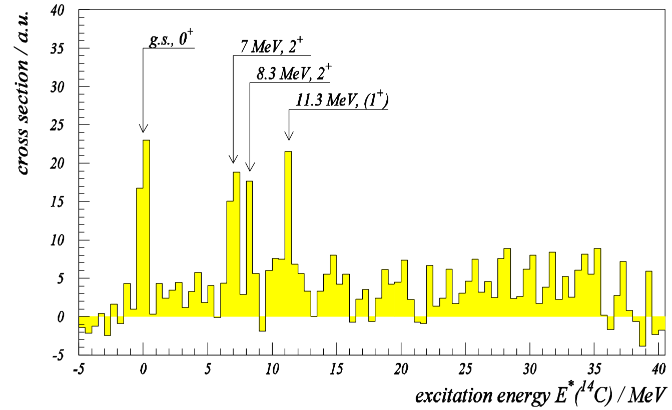
$^{16}O(e,e'pp)^{14}C$: MAMI data

super-parallel kinematics

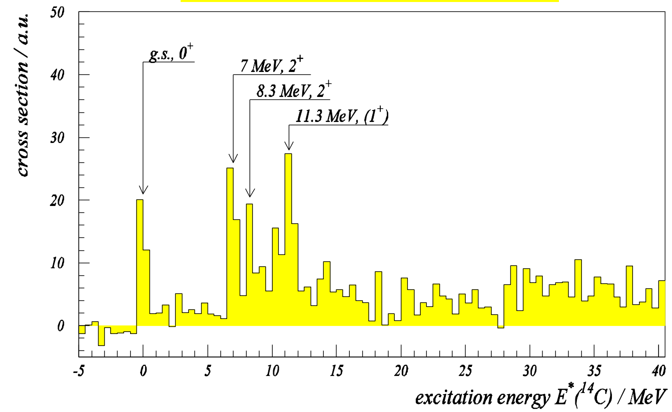
$\langle p_m \rangle$ =0 Mev/c



$\langle p_m \rangle$ =70 Mev/c

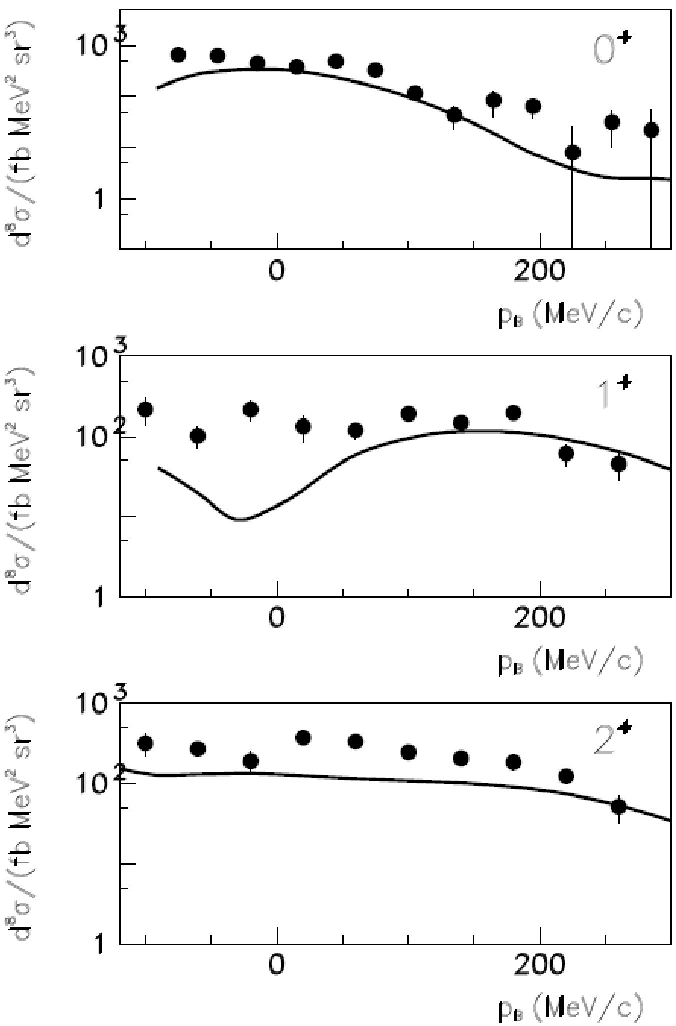


$\langle p_m \rangle$ =125 Mev/c



G. Rosner, Prog. Part. Nucl. Phys. 44 (2000) 99

$^{16}O(e,e'pp)^{14}C$: comparison to MAMI data



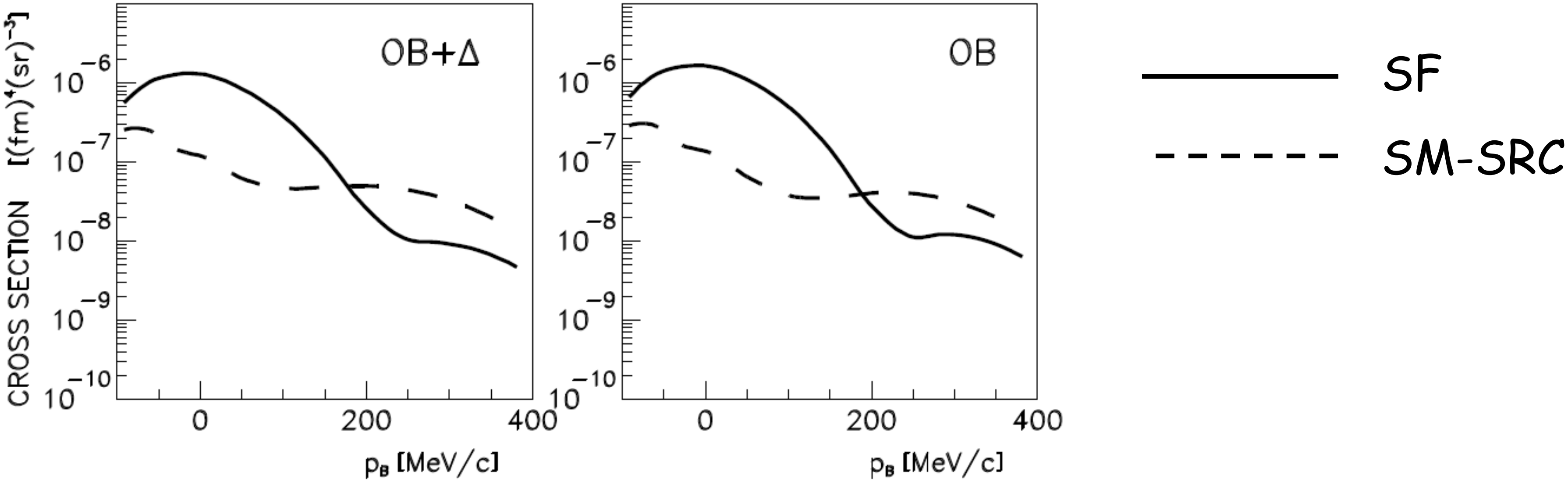
0^+

1^+

2^+

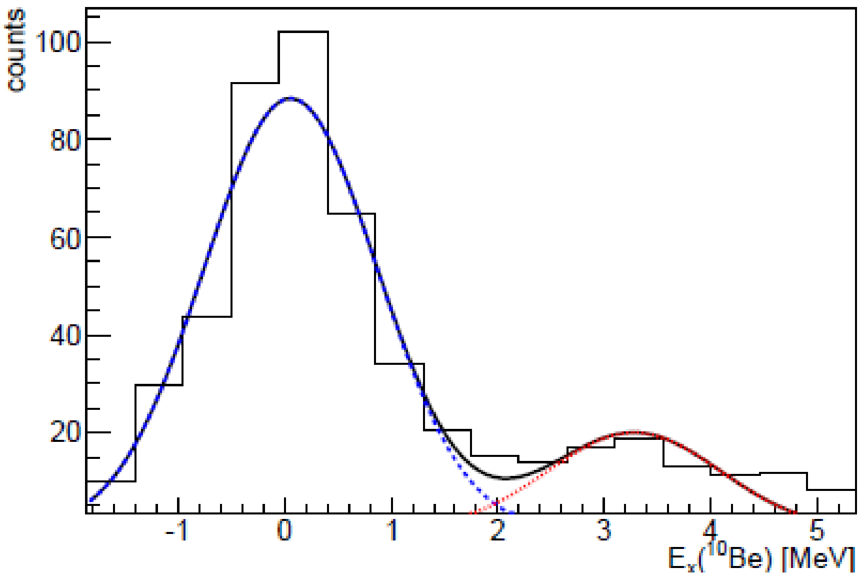
exp. data : G. Rosner, Prog. Part. Nucl. Phys. 44 (2000) 99

super-parallel kinematics $^{16}O(e,e'pp)^{14}C_{g.s.}$ 0^+



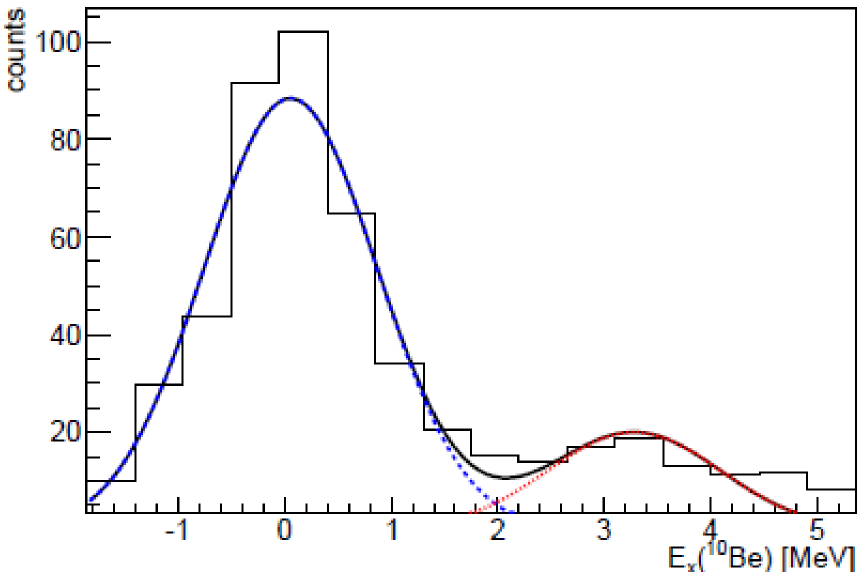
results very sensitive to correlations and to their treatment

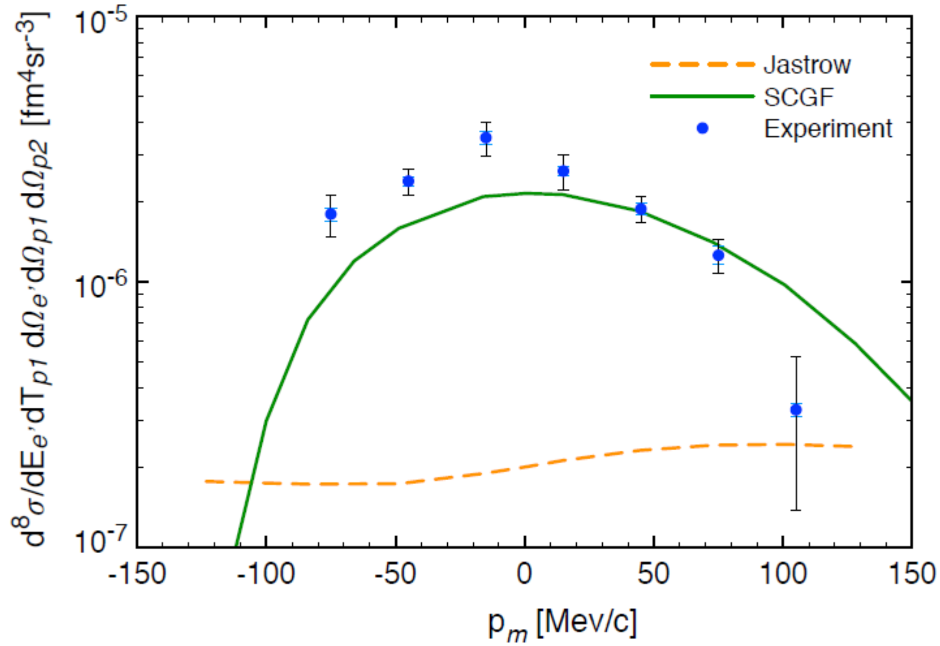
super-parallel kinematics $^{12}C(e,e'pp)^{10}Be_{g.s.}$ 0^+



M Makek et al. 2016 (MAMI)

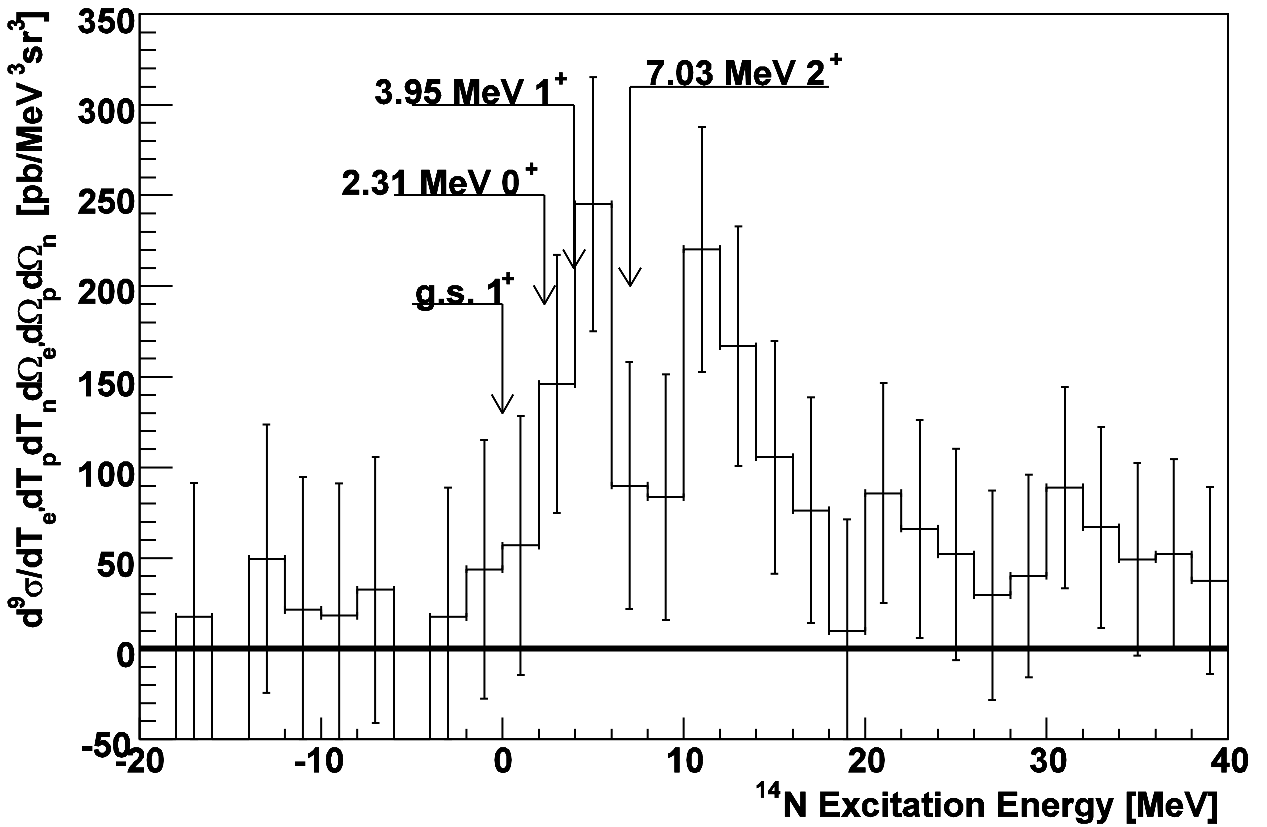
super-parallel kinematics $^{12}C(e,e'pp)^{10}Be_{g.s.}\ 0^+$





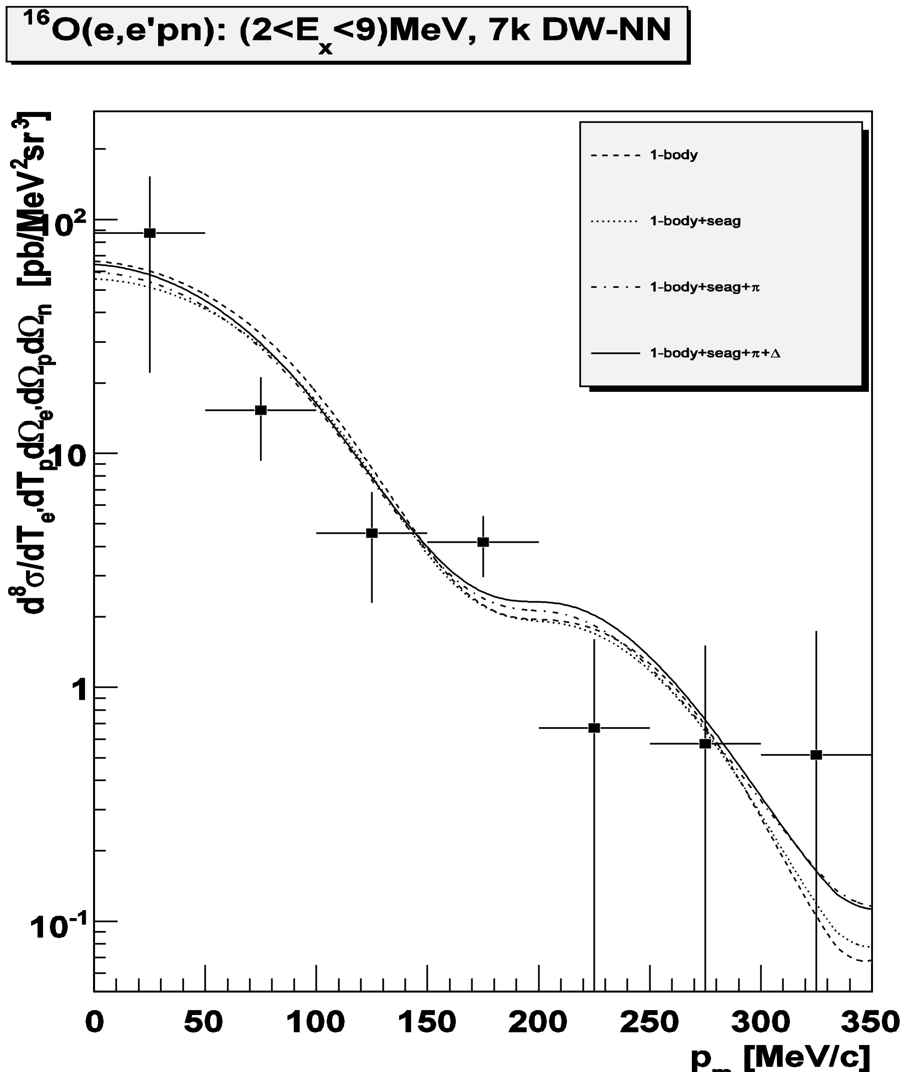
M Makek et al. 2016 (MAMI)

$^{16}O(e,e'pn)^{14}N$: MAMI data



D. Middleton et al., EPJA 29 (2006) 261

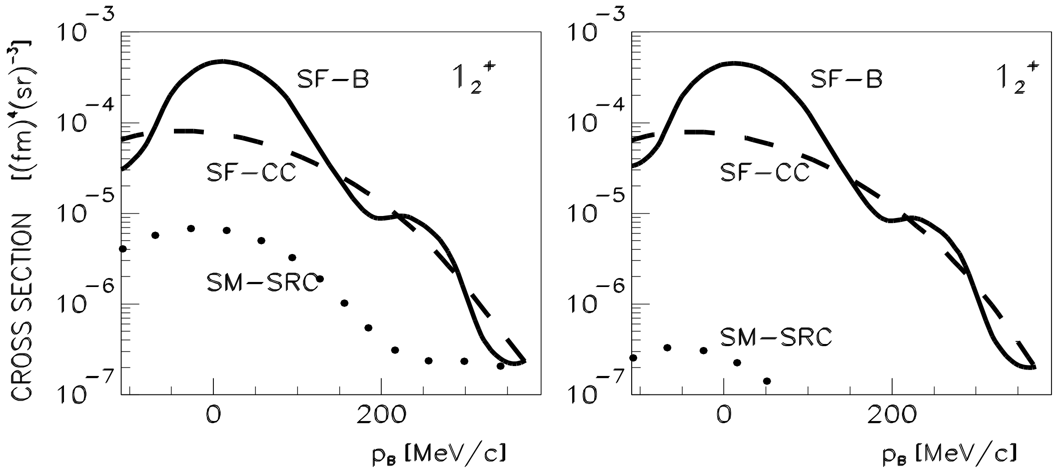
$^{16}O(e,e'pn)^{14}N$: comparison to MAMI data



D. Middleton et al., EPJA 43 (2010) 137

super-parallel kinematics $^{16}O(e,e'pn)^{14}N$

OB+TB OB



SF-B

SF-CC

SM-SRC

results very sensitive to correlations and to their treatment

- several decades of experimental and theoretical work on electron scattering have provided a wealth of information on the properties of stable nuclei
- the advantages of the electron probe can be extended to unstable nuclei

ELECTRON SCATTERING ON EXOTIC NUCLEI

- Quasifree (e,e′p) Reactions on Nuclei with Neutron Excess: C. G., A. Meucci, F.D. Pacati, G. Co′, V. De Donno, PRC 84 (2011) 024615
- Elastic and Quasi-Elastic Electron Scattering off Nuclei with Neutron Excess: A. Meucci, M. Vorabbi, C. G., P. Finelli, F.D. Pacati PRC 87 (2013) 054620
- Elastic and Quasi-Elastic Electron Scattering on the N = 14, 20, and 28 Isotonic Chains: A. Meucci, M. Vorabbi, C. G., P. Finelli, F.D. Pacati PRC 89 (2014) 034604
- Elastic and Quasi-Elastic Electron Scattering off Isotopic and Isotonic Chains: M. Vorabbi, A, Meucci, C. G., F.D. Pacati, P. Finelli, J. Phys. Conf. Ser. 527 (2014) 012024

ELECTRON SCATTERING ON EXOTIC NUCLEI

- Quasifree (e,e′p) Reactions on Nuclei with Neutron Excess: C. G., A. Meucci, F.D. Pacati, G. Co′, V. De Donno, PRC 84 (2011) 024615
- Elastic and Quasi-Elastic Electron Scattering off Nuclei with Neutron Excess: A. Meucci, M. Vorabbi, C. G., P. Finelli, F.D. Pacati PRC 87 (2013) 054620
- Elastic and Quasi-Elastic Electron Scattering on the N = 14, 20, and 28 Isotonic Chains: A. Meucci, M. Vorabbi, C. G., P. Finelli, F.D. Pacati PRC 89 (2014) 034604
- Elastic and Quasi-Elastic Electron Scattering off Isotopic and Isotonic Chains: M. Vorabbi, A, Meucci, C. G., F.D. Pacati, P. Finelli, J. Phys. Conf. Ser. 527 (2014) 012024

MOTIVATION: STUDY THE EVOLUTION OF NUCLEAR PROPERTIES AS A FUNCTION OF N/Z

ELECTRON SCATTERING ON EXOTIC NUCLEI

- Quasifree (e,e′p) Reactions on Nuclei with Neutron Excess: C. G., A. Meucci, F.D. Pacati, G. Co′, V. De Donno, PRC 84 (2011) 024615
- Elastic and Quasi-Elastic Electron Scattering off Nuclei with Neutron Excess: A. Meucci, M. Vorabbi, C. G., P. Finelli, F.D. Pacati PRC 87 (2013) 054620
- Elastic and Quasi-Elastic Electron Scattering on the N = 14, 20, and 28 Isotonic Chains: A. Meucci, M. Vorabbi, C. G., P. Finelli, F.D. Pacati PRC 89 (2014) 034604
- Elastic and Quasi-Elastic Electron Scattering off Isotopic and Isotonic Chains: M. Vorabbi, A, Meucci, C. G., F.D. Pacati, P. Finelli, J. Phys. Conf. Ser. 527 (2014) 012024

Matteo Vorabbi's talk

ELECTRON SCATTERING ON EXOTIC NUCLEI

- Quasifree (e,e′p) Reactions on Nuclei with Neutron Excess: C. G., A. Meucci, F.D. Pacati, G. Co′, V. De Donno, PRC 84 (2011) 024615
- Elastic and Quasi-Elastic Electron Scattering off Nuclei with Neutron Excess: A. Meucci, M. Vorabbi, C. G., P. Finelli, F.D. Pacati PRC 87 (2013) 054620
- Elastic and Quasi-Elastic Electron Scattering on the N = 14, 20, and 28 Isotonic Chains: A. Meucci, M. Vorabbi, C. G., P. Finelli, F.D. Pacati PRC 89 (2014) 034604
- Elastic and Quasi-Elastic Electron Scattering off Isotopic and Isotonic Chains: M. Vorabbi, A, Meucci, C. G., F.D. Pacati, P. Finelli, J. Phys. Conf. Ser. 527 (2014) 012024

(e,e'p) on isotopic chains

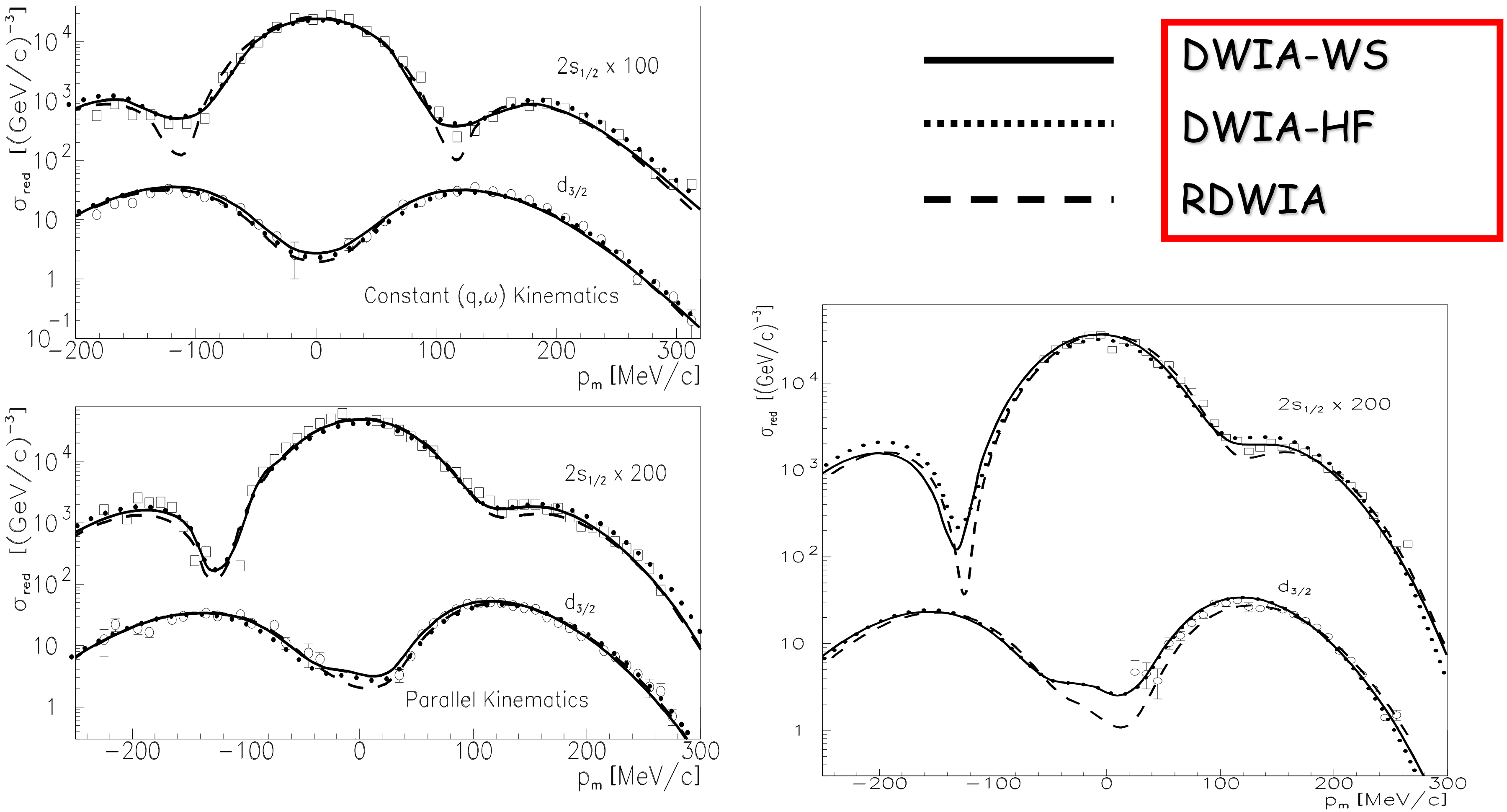
- DWIA model for (e,e'p)
- NIKHEF data ^{40}Ca ^{48}Ca
- original analysis DWIA
- comparison of different models DWIA, RDWIA, different s.p. wave functions
- calculations performed for Ca and O isotopes
- evolution of nuclear properties with models of proven reliability in stable isotopes will test the ability of the established nuclear theory in the domain of exotic nuclei

Comparison of different models

- DWIA with phenomenological WS wave functions (DWIA-WS)
- DWIA with HF wave functions from two different parametrizations of the finite-range Gogny interactions D1S and D1M. Results presented for the D1M force (DWIA-HF)
- RDWIA relativistic model, ROP for the scattering state, the bound states are obtained in the context of the RMF approach solving the Dirac-Hartree equations. The nucleon interaction is derived from a relativistic Lagrangian containing σ, ω, ρ meson fields and also the photon field
- E- and A-dependent optical potentials contain central, spin-orbit, Coulomb terms and a term dependent on the (N-Z)/A asymmetry
- comparison with NIKHEF data on ^{40}Ca ^{48}Ca

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

^{48}Ca(e,e'p)



(ω,q) const: E_0=483.2 MeV θ =61.52 deg. q=450 MeV/c T_p=100 MeV

parallel kin: E_0=483.2 MeV T_p=100 MeV

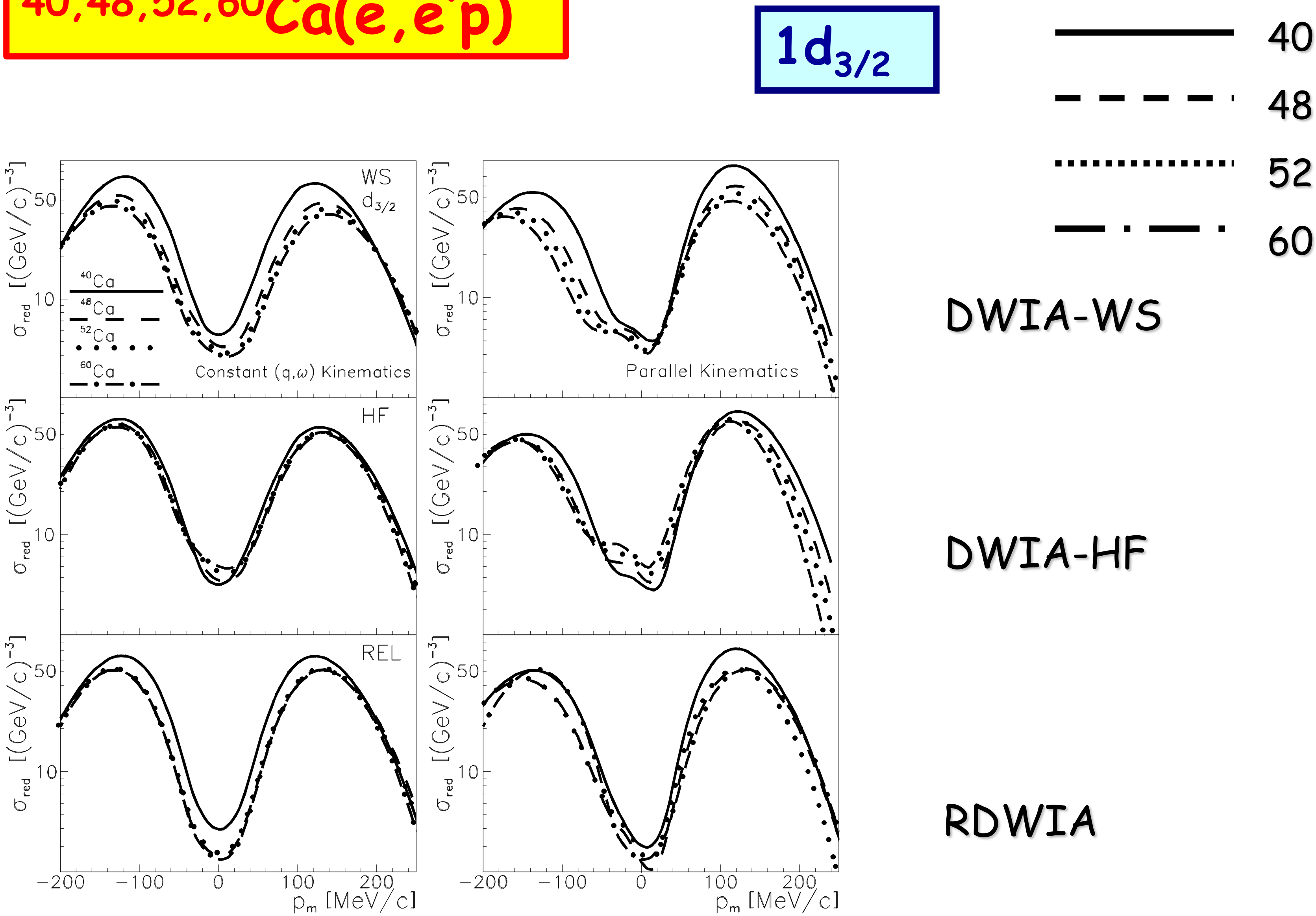
$^{40}Ca(e,e'p)$	parallel kin	$^{48}Ca(e,e'p)$
λ_n = 0.65 DWIA-WS	$1d_{3/2}$	λ_n = 0.56 DWIA-WS
0.64 DWIA-HF		0.55 DWIA-HF
0.69 RDWIA		0.52 RDWIA
λ_n = 0.52 DWIA-WS	$2s_{1/2}$	λ_n = 0.54 DWIA-WS
0.57 DWIA-HF		0.58 DWIA-HF
0.51 RDWIA		0.55 RDWIA

$^{40,48,52,60}Ca(e,e'p)$

- DWIA-WS DWIA-HF and RDWIA for Ca isotopes
- even-even isotopes, spherical nuclei where the s.p. levels are fully occupied and pairing effects should be minimized

$^{40,48,52,60}Ca(e,e'p)$

$1d_{3/2}$



constant (q,ω)

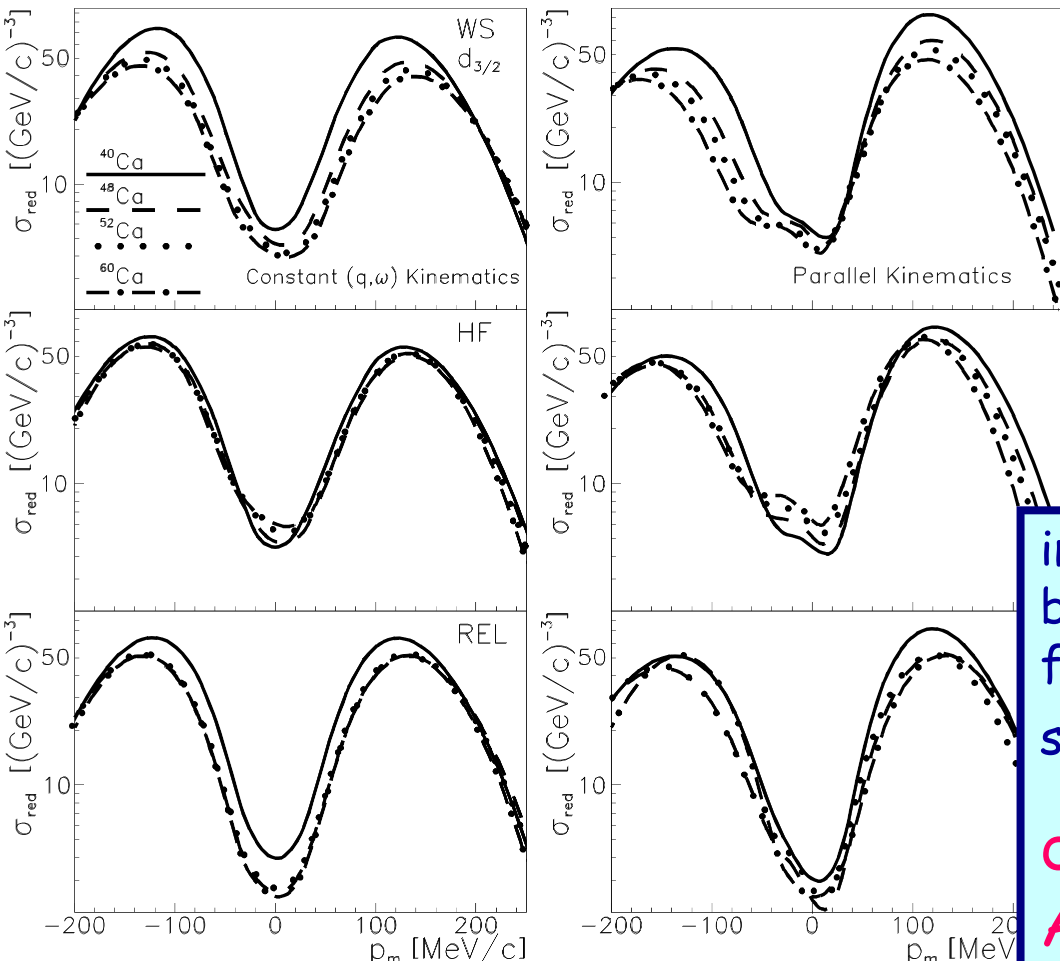
parallel

$^{40,48,52,60}Ca(e,e'p)$

$1d_{3/2}$

— 40
- - - 48
······ 52
— · — 60

DWIA-WS



DWIA-HF

constant (q,ω)

parallel

increasing N/Z different behavior for the wave functions and the cross sections: FSI

difference due to the A- dependence of the optical potential

- general behavior of the cross sections with respect to the increasing N/Z asymmetry is analogous for all the three models: evolve by lowering and widening increasing N
- the behavior of the s.p. b.s w.f. shows different trends for the different models
- the dependence of the w.f. on N/Z is responsible for only a part of the differences in the cross sections, crucial contribution given by FSI which are described by phenomenological optical potentials
- the optical potential affects the size and the shape of the cross section in a way that strongly depends on kinematics. Its dependence on N/Z deserves careful investigation
- spectroscopic factors and correlations: recent studies indicate that the s.f. depend on N/Z, in general the quenching of the quasi-hole states becomes stronger increasing the separation energy (increasing N)
- (e,e′p) on nuclei with neutron excess would offer a unique opportunity for studying the dependence of the properties of bound protons on N/Z
- comparison with data can confirm or invalidate the predictions of the models and will test the ability of the established nuclear theory in the domain of exotic nuclei