(e,e'p) and Nuclear Structure

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A. Saha

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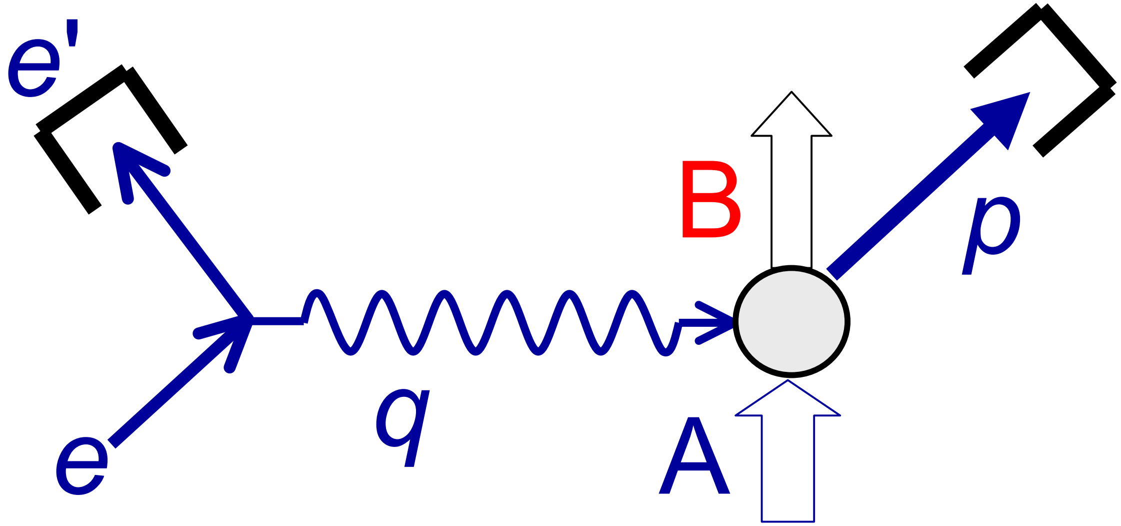
Outline

- Introduction
- Background
  - Experimental
  - Theoretical
- Nuclear Structure
- Medium-modified nucleons
  - Cross sections
  - Polarization transfer
- Studies of the reaction mechanism
- Few-body nuclei
  - The deuteron
  - ^{3,4}He

A(e,e'p)B

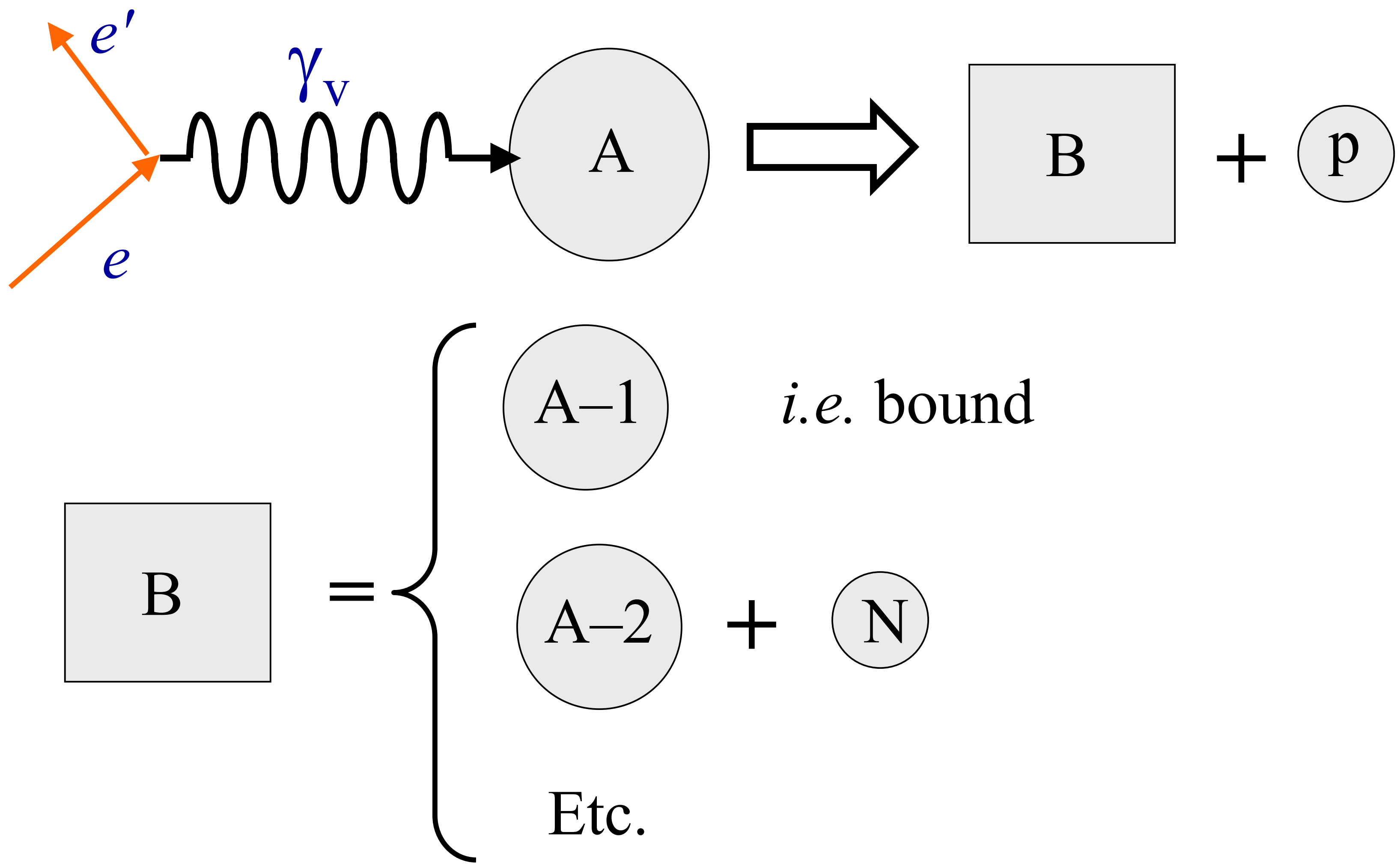


Known: e and A

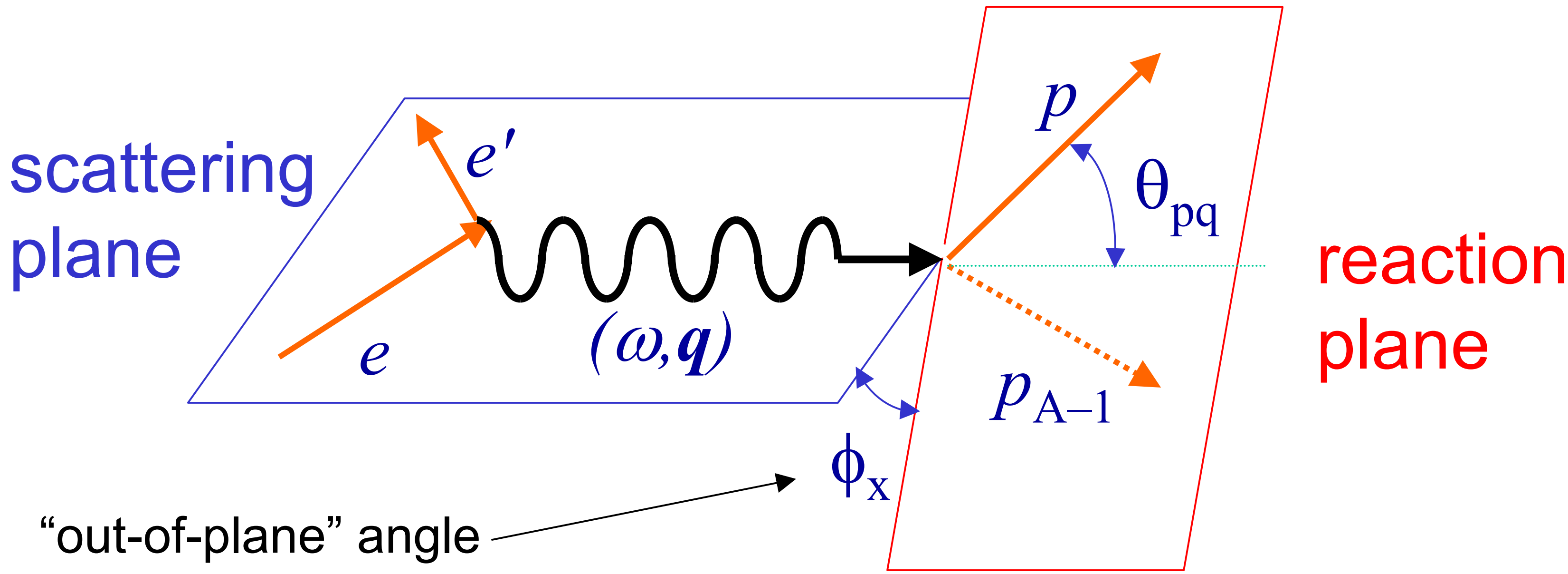
Detect: e' and p

Infer: $\boldsymbol{p}_{\mathrm{m}} = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{\mathrm{B}}$

(e,e'p) - Schematically



Kinematics

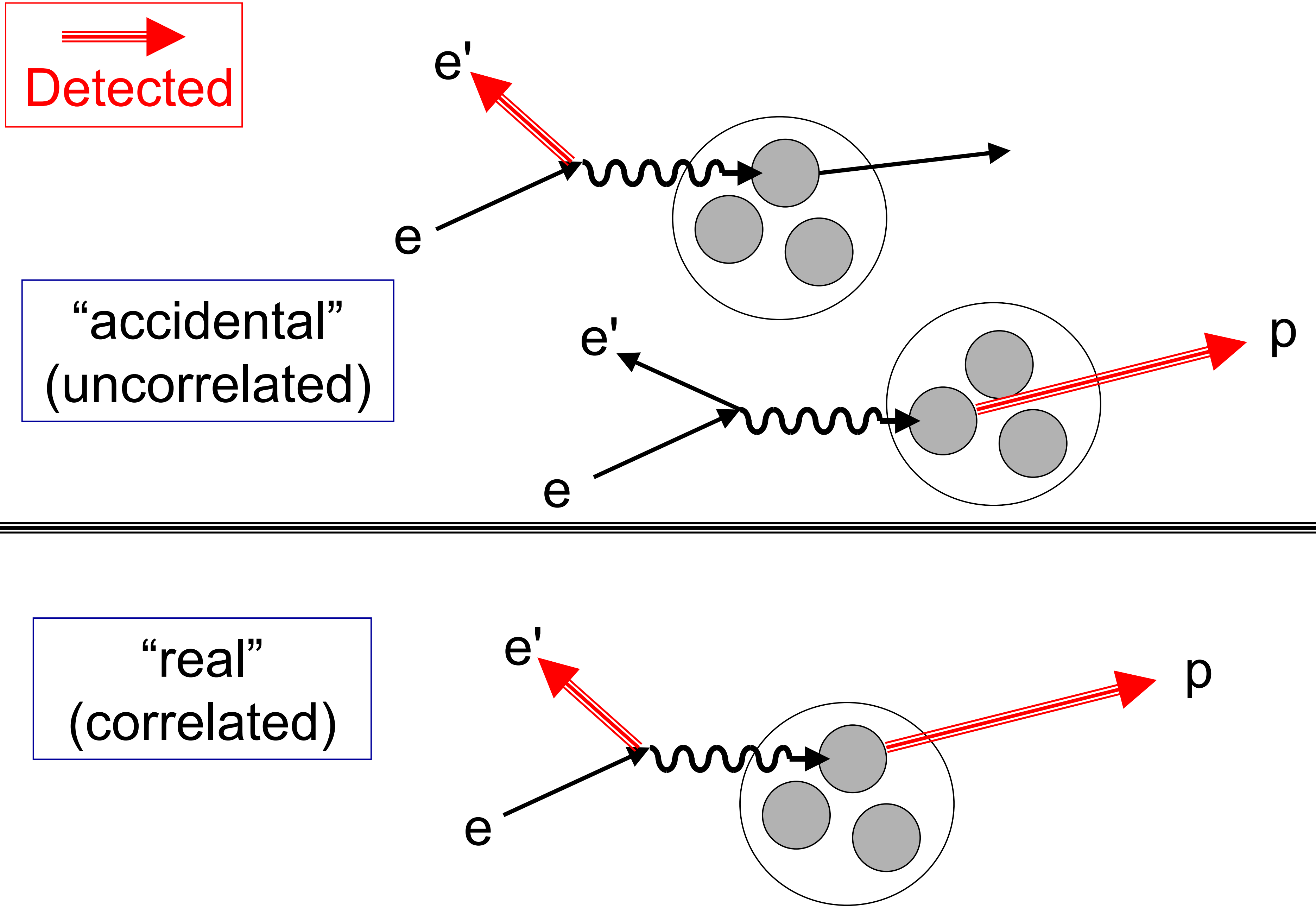


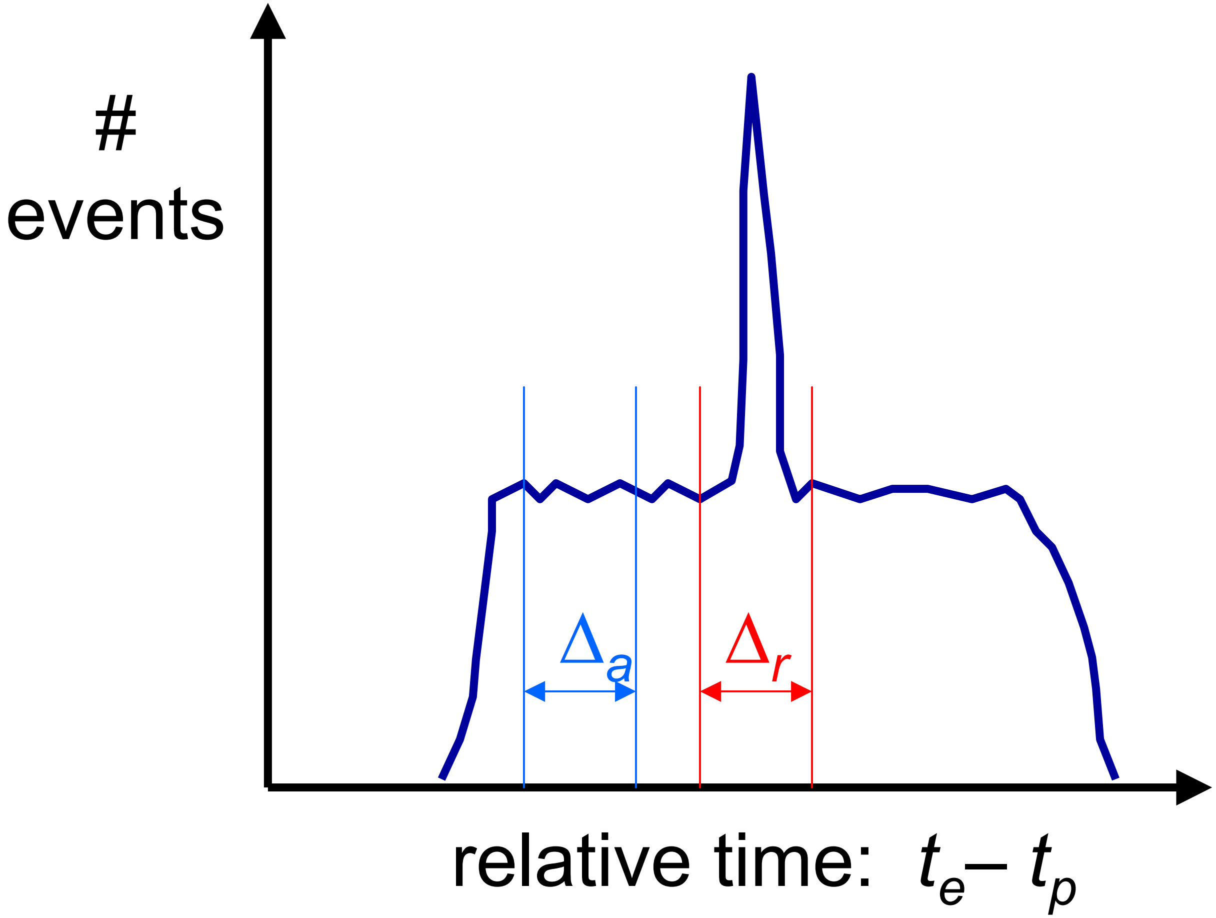
In ERL$_e$: $Q^2 \equiv -q_\mu q^\mu = \boldsymbol{q}^2 - \omega^2 = 4ee' \sin^2\theta/2$

Missing momentum: $\boldsymbol{p}_m = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{A-1}$

Missing mass: $\varepsilon_m = \omega - T_p - T_{A-1}$

Some (Very Few) Experimental Details …


Detected
“accidental”
(uncorrelated)
e'
e
e'
p
e
“real”
(correlated)
e'
p
e



$$C(x) = \left[C(x) \cap \mathrm{Real}\right] - \frac{\Delta_r}{\Delta_a} \times \left[C(x) \cap \mathrm{Accidental}\right]$$

Accidentals Rate = $\boldsymbol{R_e} \times \boldsymbol{R_p} \times \Delta\tau/\mathbf{DF}$

$\propto \boldsymbol{I}^{\,2}\,\Delta\tau/\mathbf{DF}$

Reals Rate = $\boldsymbol{R_{eep}}$

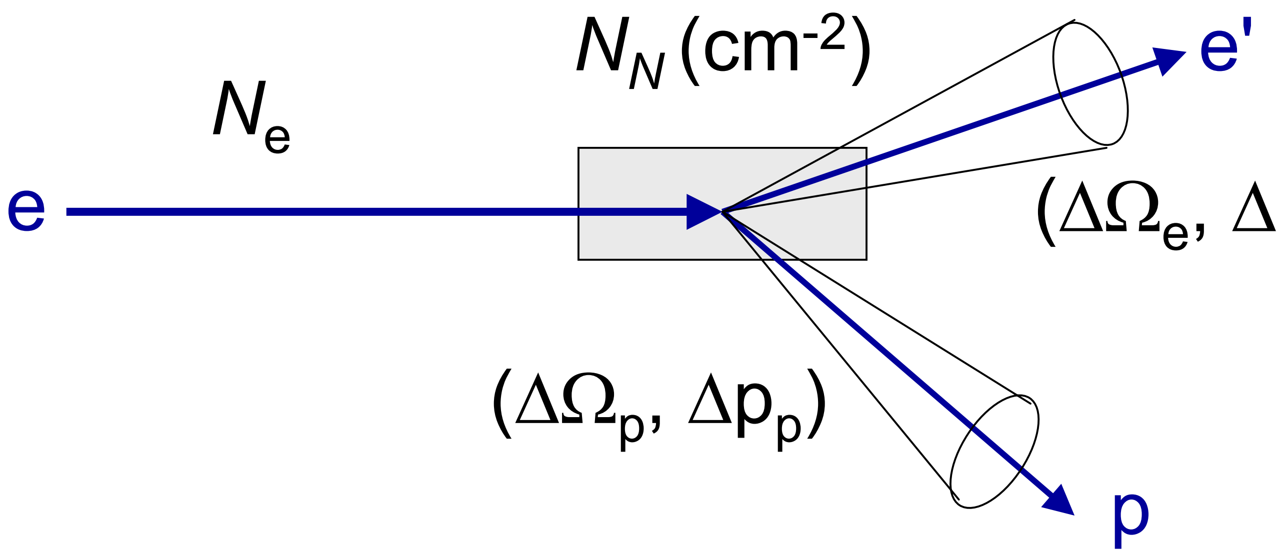
$\propto \boldsymbol{I}$

S:N = Reals/Accidentals $\propto$ $\mathbf{DF}\ /(\Delta\tau * \boldsymbol{I})$

Compromise:

Optimize ***S:N*** and $\boldsymbol{R_{eep}}$

Extracting the cross section



$$\left\langle \frac{\mathrm{d}^6\sigma}{\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_\mathrm{p}\mathrm{d}p_e\,\mathrm{d}p_p} \right\rangle = \frac{\text{Counts}}{N_e N_N \Delta\Omega_e \Delta\Omega_p \Delta p_e \Delta p_p}$$

Some Theory …

Cross Section for A(e,e'p)B in OPEA

"A-1"

$$d\sigma_{\text{lab}} = \frac{1}{\beta}\frac{m_e}{e}\overline{\sum_{if}}\left|M_{fi}\right|^2\left[\frac{m_e}{e'}\frac{d^3k'}{(2\pi)^3}\right]\left[\frac{m}{E}\frac{d^3p}{(2\pi)^3}\right]$$

$$\times(2\pi)^4\delta^4(P+P_{A-1}-Q-P_A)$$

where

$$M_{fi} = \frac{4\pi\alpha}{Q^2}\left\langle k'\,\lambda'\middle|j_\mu\middle|k\,\lambda\right\rangle\left\langle Bp\middle|J^\mu\middle|A\right\rangle$$

Current-Current Interaction

Square of Matrix Element

$$\overline{\sum_{if}}\left|M_{fi}\right|^2 = \left(\frac{4\pi\alpha}{Q^2}\right)^2 \overbrace{\overline{\sum_{if}}\left\langle k'\lambda'\middle|j_\mu\middle|k\lambda\right\rangle^*\left\langle k'\lambda'\middle|j_\nu\middle|k\lambda\right\rangle}^{\eta_{\mu\nu}}$$

$$\times \underbrace{\overline{\sum_{if}}\left\langle Bp\middle|J^\mu\middle|A\right\rangle^*\left\langle Bp\middle|J^\nu\middle|A\right\rangle}_{W^{\mu\nu}}$$

Cross Section in terms of Tensors

$$\frac{d^6\sigma}{d\Omega_e d\Omega_p dp\, d\omega} = \sigma_M \eta_{\mu\nu} W^{\mu\nu}$$

Mott cross section

Electron tensor

Nuclear tensor

Consider Unpolarized Case

Lorentz Vectors/Scalars

3 indep. momenta: $Q\,,\ P_i\,,\ P\ \ (P_{A-1} = Q + P_i - P)$

target nucleus

ejectile

6 indep. scalars: $\cancel{P_i^2},\ \cancel{P^2},\ Q^2,\ Q\bullet P_i\,,\ Q\bullet P\,,\ P\bullet P_i$

$= m^2$

$= M_A^{\,2}$

Nuclear Response Tensor

$$
\begin{aligned}
W^{\mu\nu} = {} & X_1 g_{\mu\nu} + X_2 q^\mu q^\nu + X_3 p_i^\mu p_i^\nu \\
& + X_4 p^\mu p^\nu + X_5 q^\mu p_i^\nu + X_6 p_i^\mu q^\nu \\
& + X_7 q^\mu p^\nu + X_8 p^\mu q^\nu + X_9 p^\mu p_i^\nu \\
& + X_{10} p_i^\mu p^\nu \\
& + (\text{PV terms like } \varepsilon_{\mu\nu\rho\sigma} q_\rho p_\sigma)
\end{aligned}
$$

X_i are the response functions

Impose Current Conservation

$$S^{\nu} \equiv q_{\mu} W^{\mu\nu} = 0$$

$$T^{\mu} \equiv q_{\nu} W^{\mu\nu} = 0$$

Then $\quad q_{\nu} S^{\nu} = 0, \quad p_{\nu} S^{\nu} = 0, \quad p_{i\nu} S^{\nu} = 0$

$$q_{\mu} T^{\mu} = 0, \quad p_{\mu} T^{\mu} = 0, \quad p_{i\mu} T^{\mu} = 0$$

Get 6 equations in 10 unknowns

$\Downarrow$

4 independent response functions

Putting it all together …

$$\left(\frac{\mathrm{d}^6\sigma}{\mathrm{d}\Omega_e \mathrm{d}\Omega_p \mathrm{d}p\, \mathrm{d}\omega}\right)_{LAB} = \frac{pE}{(2\pi)^3}\sigma_M [v_L R_L + v_T R_T$$

$$+ v_{LT} R_{LT} \cos\varphi_x + v_{TT} R_{TT} \cos 2\varphi_x]$$

with

$$\sigma_M = \frac{\alpha^2 \cos^2\theta/2}{4e^2 \sin^4\theta/2}$$

$$v_L = \left(\frac{Q^2}{q^2}\right)^2 \qquad v_T = \frac{Q^2}{2q^2} + \tan^2\theta/2$$

$$v_{TT} = \frac{Q^2}{2q^2} \qquad v_{LT} = \frac{Q^2}{q^2}\sqrt{\frac{Q^2}{q^2} + \tan^2\theta/2}$$

The Response Functions

Use spherical basis with *z*-axis along ***q*:**

Nuclear 4-current
$$
\begin{cases}
J_{fi}^{0} \equiv J_{fi}^{z} = \dfrac{\omega}{q}\rho_{\mathrm{fi}} \\[2ex]
J_{fi}^{\pm 1} \equiv \mp \dfrac{1}{\sqrt{2}}\left(J_{fi}^{x} \pm iJ_{fi}^{y}\right)
\end{cases}
$$

$$
\boxed{
\begin{aligned}
R_{L} &= \left|\rho_{fi}(\vec{q})\right|^{2} = \left(\frac{\vec{q}}{\omega}\right)^{2}\left|J_{fi}^{0}(\vec{q})\right|^{2} \\
R_{T} &= \left|J_{fi}^{+1}(\vec{q})\right|^{2} + \left|J_{fi}^{-1}(\vec{q})\right|^{2} \\
R_{TT} &= 2\,\mathrm{Re}\left\{J_{fi}^{+1}(\vec{q})J_{fi}^{-1}(\vec{q})\right\} \\
R_{LT} &= -2\,\mathrm{Re}\left\{\rho_{\mathrm{fi}}(\vec{q})\left(J_{fi}^{+1}(\vec{q}) - J_{fi}^{-1}(\vec{q})\right)\right\}
\end{aligned}
}
$$

Response functions depend on scalar quantities

In lab:
$$\left\{ \begin{array}{l} Q \bullet P_i = \omega M_A \\ P \bullet P_i = E M_A \\ Q \bullet P = \omega E - q\, p \cos \theta_{pq} \end{array} \right.$$

Can choose: $\boxed{Q^2,\ \omega\ ,\ \varepsilon_m\ ,\ p_m}$

Note: no ϕ_x dependence in response functions

Including electron and recoil proton polarizations

$$\left(\frac{d^6\sigma}{d\Omega_e d\Omega_p dp\, d\omega}\right)_{LAB} = \frac{pE}{(2\pi)^3}\sigma_M\{v_L(R_L + R_L^n S_n) + v_T(R_T + R_T^n S_n)$$

$$+ v_{LT}[(R_{LT} + R_{LT}^n S_n)\cos\varphi_x + (R_{LT}^l S_l + R_{LT}^t S_t)\sin\varphi_x]$$

$$+ v_{TT}[(R_{TT} + R_{TT}^n S_n)\cos 2\varphi_x + (R_{TT}^l S_l + R_{TT}^t S_t)\sin 2\varphi_x]$$

$$+ hv_{LT'}[(R_{LT'} + R_{LT'}^n S_n)\sin\varphi_x + (R_{LT'}^l S_l + R_{LT'}^t S_t)\cos\varphi_x]$$

$$+ hv_{TT'}(R_{TT'}^l S_l + R_{TT'}^t S_t)\}$$

with $\quad v_{LT'} = \frac{Q^2}{q^2}\tan\theta/2 \qquad v_{TT'} = \tan\theta/2\sqrt{\frac{Q^2}{q^2} + \tan^2\theta/2}$

and other v's defined as before

Extracting Response Functions

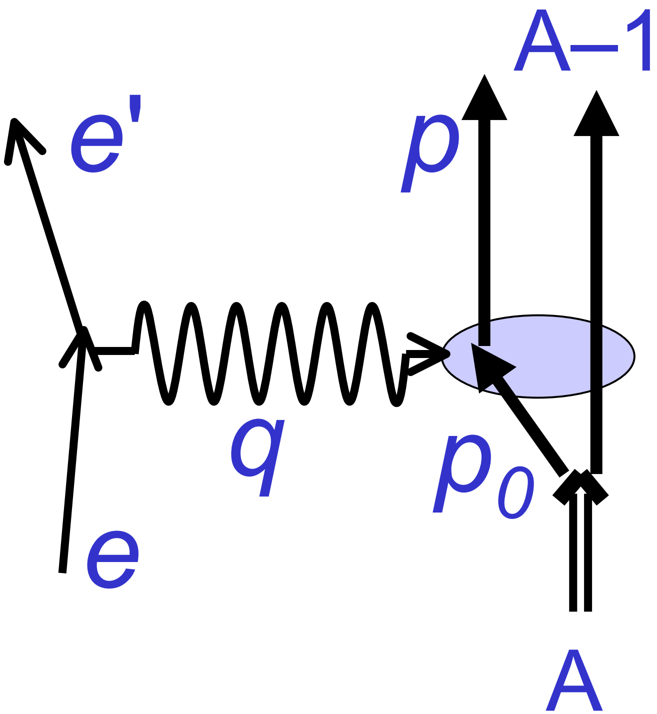
For instance: R_{LT} and A_ϕ (=A_{LT})

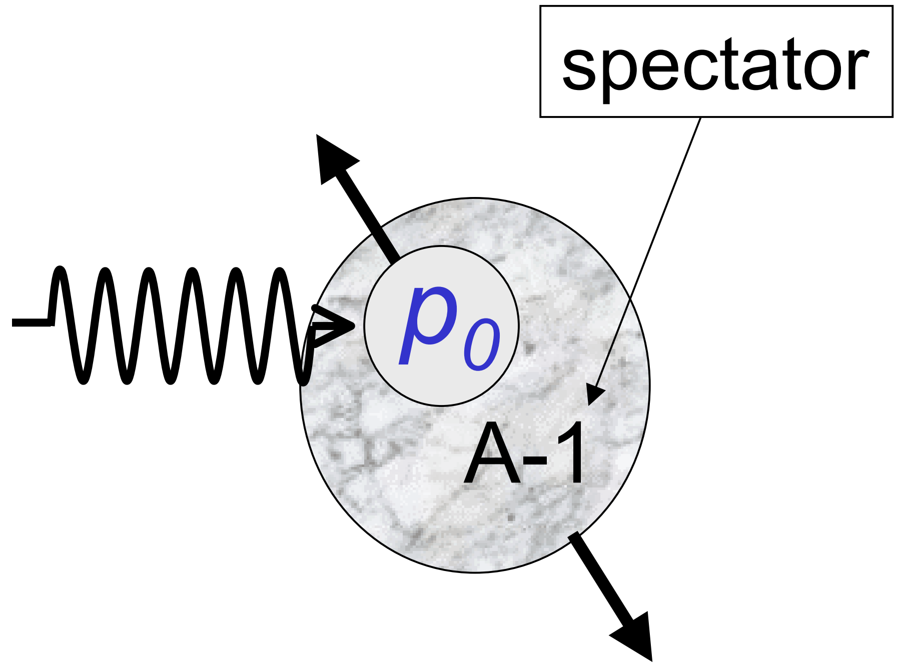
$$\boxed{\sigma_{\mathrm{eep}} = K\sigma_{\mathrm{M}}[v_L R_L + v_T R_T + v_{LT} R_{LT}\cos\varphi_{\mathrm{x}} + v_{TT} R_{TT}\cos 2\varphi_{\mathrm{x}}]}$$

$$R_{LT} = \frac{\sigma_{\mathrm{eep}}(\varphi_x = 0) - \sigma_{\mathrm{eep}}(\varphi_x = \pi)}{2K\sigma_M v_{LT}}$$

$$A_\varphi = \frac{\sigma_{\mathrm{eep}}(\varphi_x = 0) - \sigma_{\mathrm{eep}}(\varphi_x = \pi)}{\sigma_{\mathrm{eep}}(\varphi_x = 0) + \sigma_{\mathrm{eep}}(\varphi_x = \pi)}$$

Plane Wave Impulse Approximation (PWIA)





$$\boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{\mathrm{A-1}} = \boldsymbol{p}_{\mathrm{m}} = -\,\boldsymbol{p}_{0}$$

The Spectral Function

In nonrelativistic PWIA:

$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K \boxed{\sigma_{ep}} \boxed{S(p_m, \varepsilon_m)}$$

e-p cross section

nuclear spectral function

For bound state of recoil system:

proton momentum distribution

$$\rightarrow \frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = K'\sigma_{ep} \boxed{\left|\Phi(p_m)\right|^2}$$

The Spectral Function, cont'd.

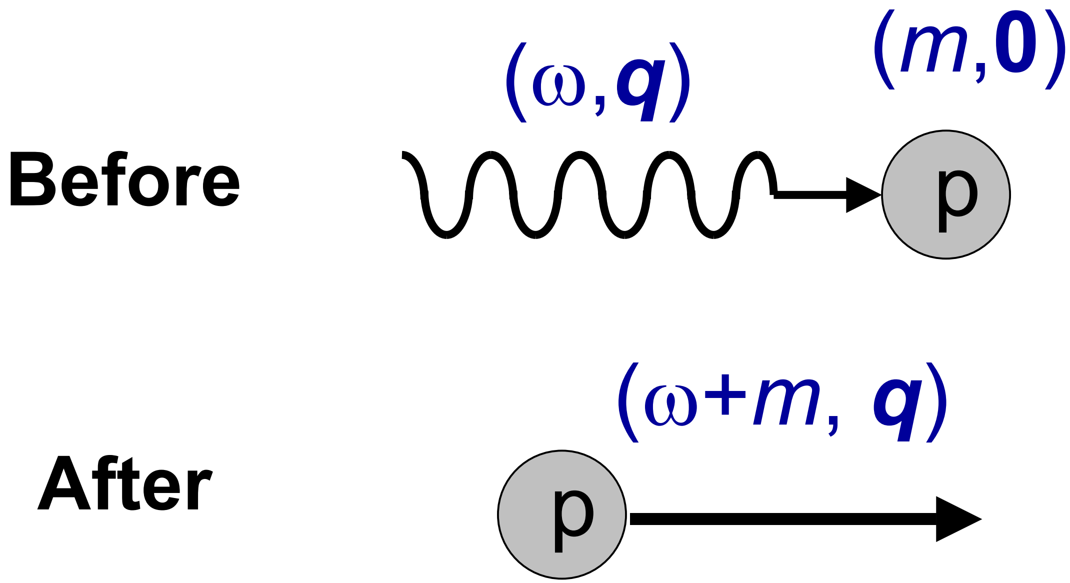
$$S(\vec{p}_0, \mathrm{E}_0) = \sum_f \left| \left\langle B_f \middle| a(\vec{p}_0) \middle| A \right\rangle \right|^2 \delta(\mathrm{E}_0 - \varepsilon_\mathrm{m})$$

where $\vec{p}_0 = -\vec{p}_m = $ initial momentum

$E_0 = E - \omega = $ initial energy

Note: *S* is not an observable!

Elastic Scattering from a Proton at Rest



Proton is on-shell $\Rightarrow$ $(\omega + m)^2 - \boldsymbol{q}^2 = m^2$

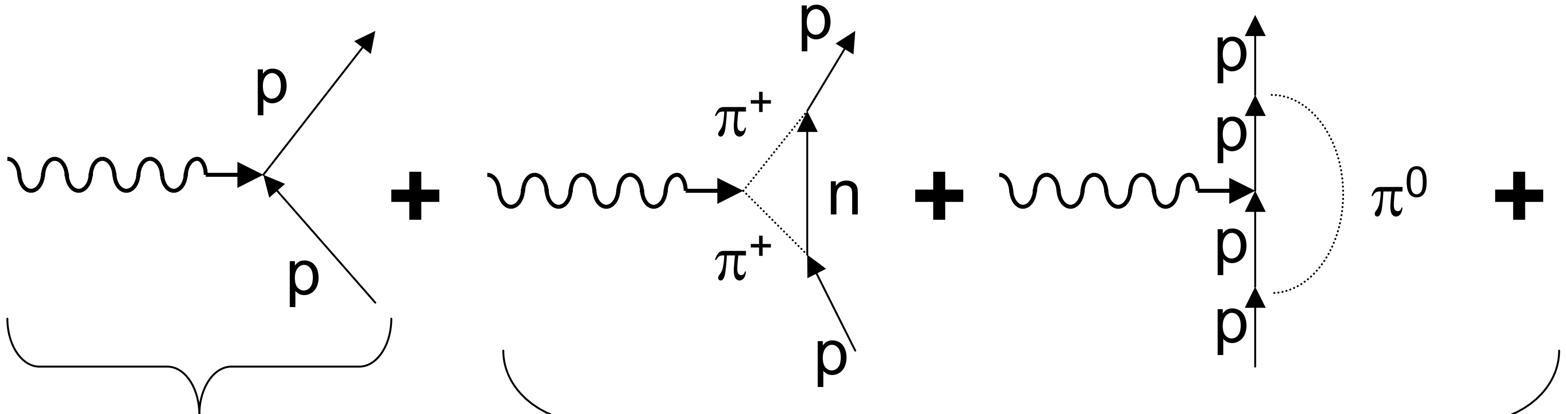
$$\omega^2 + 2m\omega + m^2 - \boldsymbol{q}^2 = m^2$$

$$\omega = Q^2 / 2m$$

Scattering from a Proton , cont'd.

$$\left\langle p, s_f \middle| J^\mu \middle| p-q, s_i \right\rangle = \overline{U}_f \Gamma^\mu U_i$$

Vertex fcn



$$\Gamma^\mu = \gamma^\mu$$

point proton

structure/anomalous moment

Scattering from a Proton , cont'd.

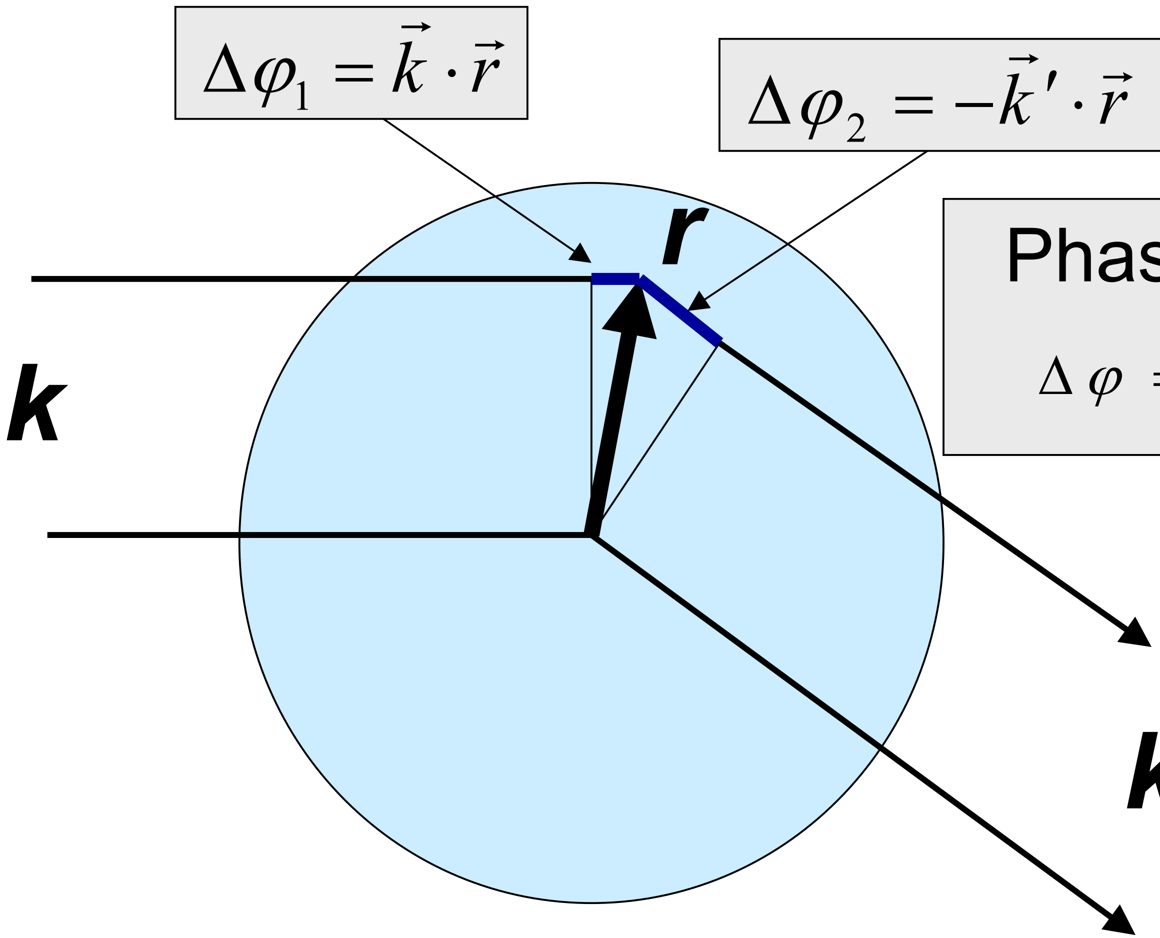
Vertex fcn: $$\Gamma^{\mu} = \gamma^{\mu} F_1(Q^2) + i\sigma^{\mu\nu} \frac{q_{\nu}}{2m} \kappa F_2(Q^2)$$

Dirac FF (F_1) Pauli FF (F_2)

Sachs FF's
$$\begin{cases} G_E(Q^2) = F_1(Q^2) - \tau\kappa\, F_2(Q^2) \\ G_M(Q^2) = F_1(Q^2) + \kappa\, F_2(Q^2) \\ \text{with} \quad \tau = \dfrac{Q^2}{4m^2} \end{cases}$$

G_E and G_M are the Fourier transforms of the charge and magnetization densities in the Breit frame.

Form Factor



Phase difference:

$$\Delta\varphi = \left(\vec{k} - \vec{k}'\right)\cdot\vec{r} = \vec{q}\cdot\vec{r}$$

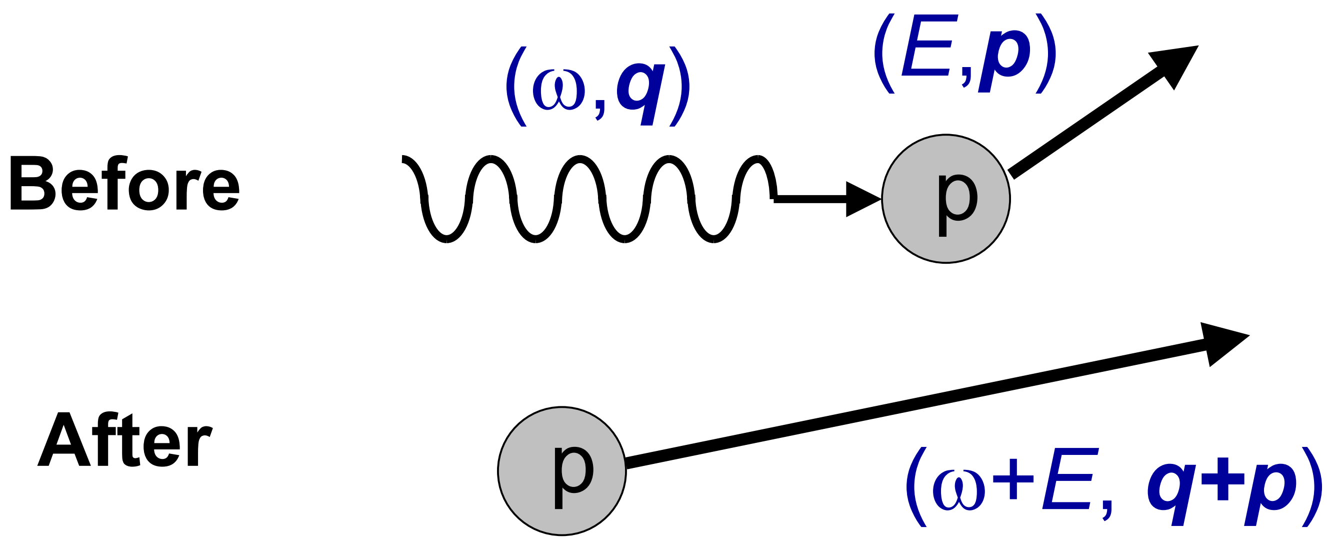
Amplitude at q: $F(q) = \int d\vec{r}\, A(\vec{r})\, e^{i\vec{q}\cdot\vec{r}}$

Cross section for *ep* elastic

$$\frac{d\sigma}{d\Omega} = f_{rec}\sigma_{\mathrm{M}}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau\tan^2\frac{\theta}{2}G_M^2\right]$$

However, (e,e'p) on a **nucleus** involves scattering from **moving** protons, *i.e.* Fermi motion.

Elastic Scattering from a Moving Proton



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

$$\omega^2 + 2E\omega + E^2 - \boldsymbol{q}^2 - 2\boldsymbol{p}\bullet\boldsymbol{q} - \boldsymbol{p}^2 = m^2$$

$$Q^2 = 2E\omega - 2\boldsymbol{p}\bullet\boldsymbol{q}$$

$$\omega\,(E/m) = (Q^2/\,2m) + \boldsymbol{p}\bullet\boldsymbol{q}\,/\,m$$

Cross section for ep elastic scattering off moving protons

Follow same procedure as for unpolarized (e,e'p) from nucleus

We get same form for cross section, with 4 response functions …

Response functions for ep elastic scattering off moving protons

$$R_L = \left[\frac{(E_0 + E)}{2m}\right]^2 W_1 - \frac{\vec{q}^{\,2}}{4m^2} W_2$$

$$R_T = 2\tau W_2 + \frac{\vec{p}^{\,2} \sin^2\theta_{pq}}{m^2} W_1$$

$$R_{LT} = -\frac{(E_0 + E)\left|\vec{p}\right| \sin\theta_{pq}}{m^2} W_1$$

$$R_{TT} = \frac{\vec{p}^{\,2} \sin^2\theta_{pq}}{m^2} W_1$$

with

$$W_1 = F_1^2 + \tau(\kappa F_2)^2 \qquad W_2 = (F_1 + \kappa F_2)^2$$

Quasielastic Scattering

For $E \approx m$:

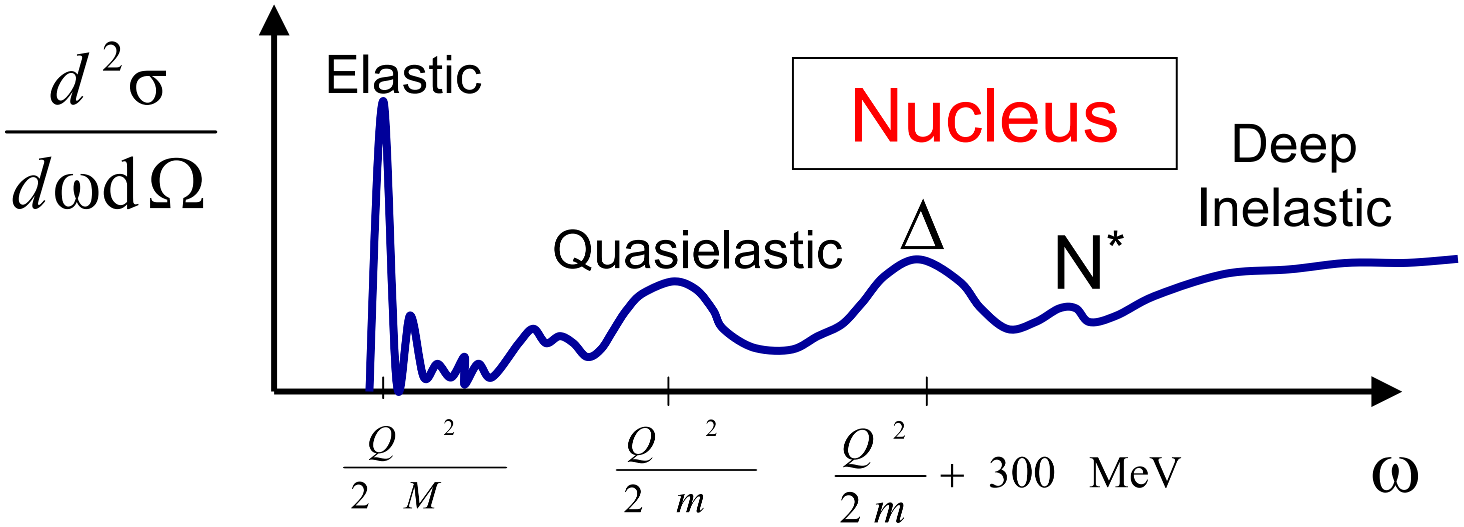
$$\omega \approx (Q^2 / 2m) + \mathbf{p} \cdot \mathbf{q} / m$$

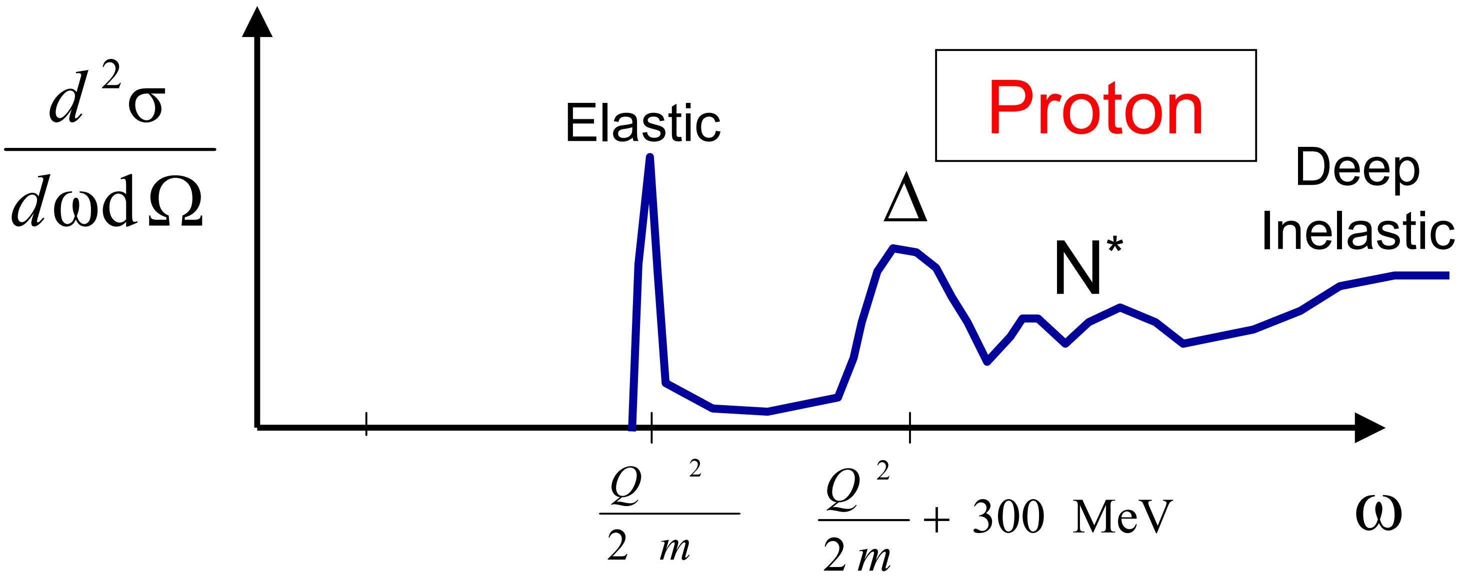
If we "quasielastically" scatter from nucleons within nucleus:

Expect peak at: $\omega \approx (Q^2 / 2m)$

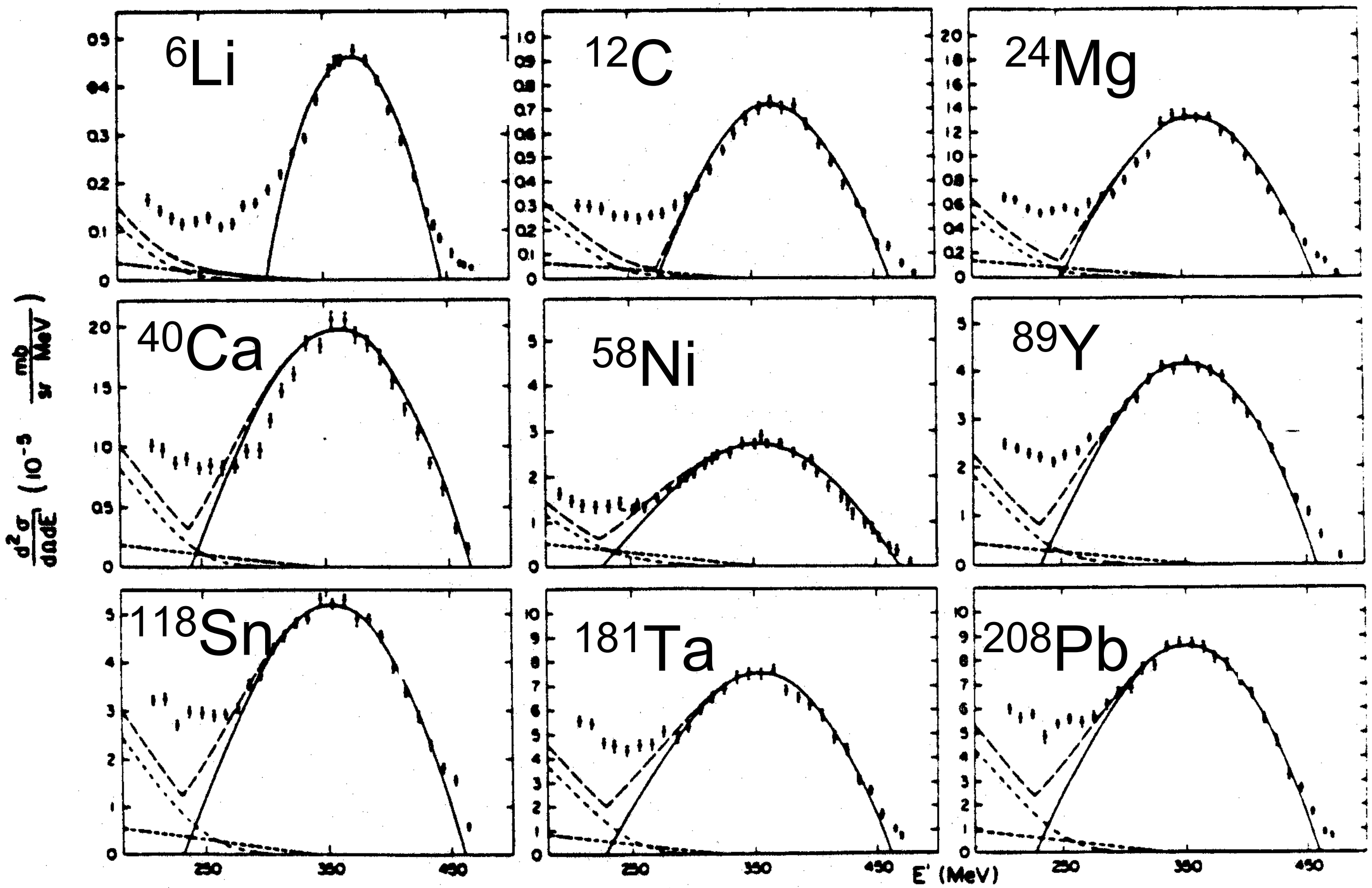
Broadened by Fermi motion: $\mathbf{p} \cdot \mathbf{q} / m$

Electron Scattering at Fixed Q^2

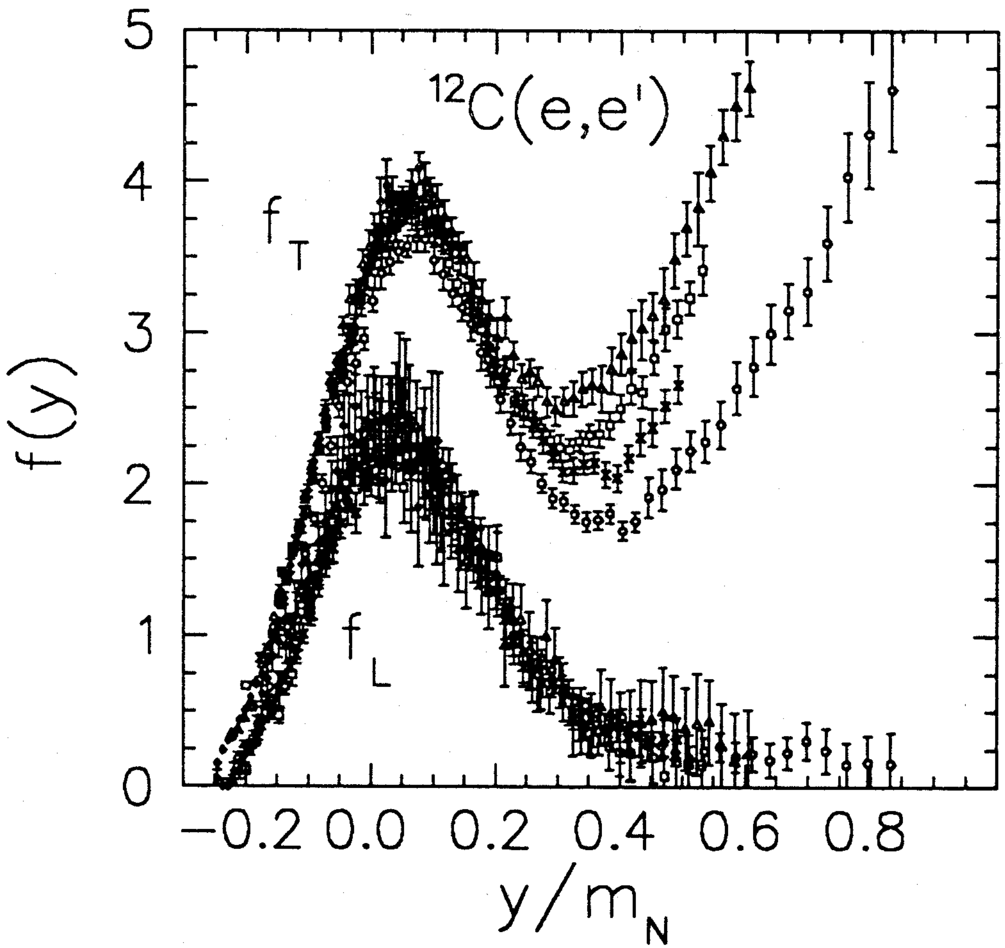




Quasielastic Electron Scattering



R.R. Whitney *et al.*, Phys. Rev. C **9**, 2230 (1974).



Data: P. Barreau *et al.,* Nucl. Phys. **A402**, 515 (1983).

y-scaling analysis: J.M. Finn, R.W. Lourie and B.H. Cottman, Phys. Rev. C **29**, 2230 (1984).

Nuclear Structure

First, a bit of history:
The first (e,e'p) measurement

$^{12}C(e,e'p)$

$^{27}Al(e,e'p)$

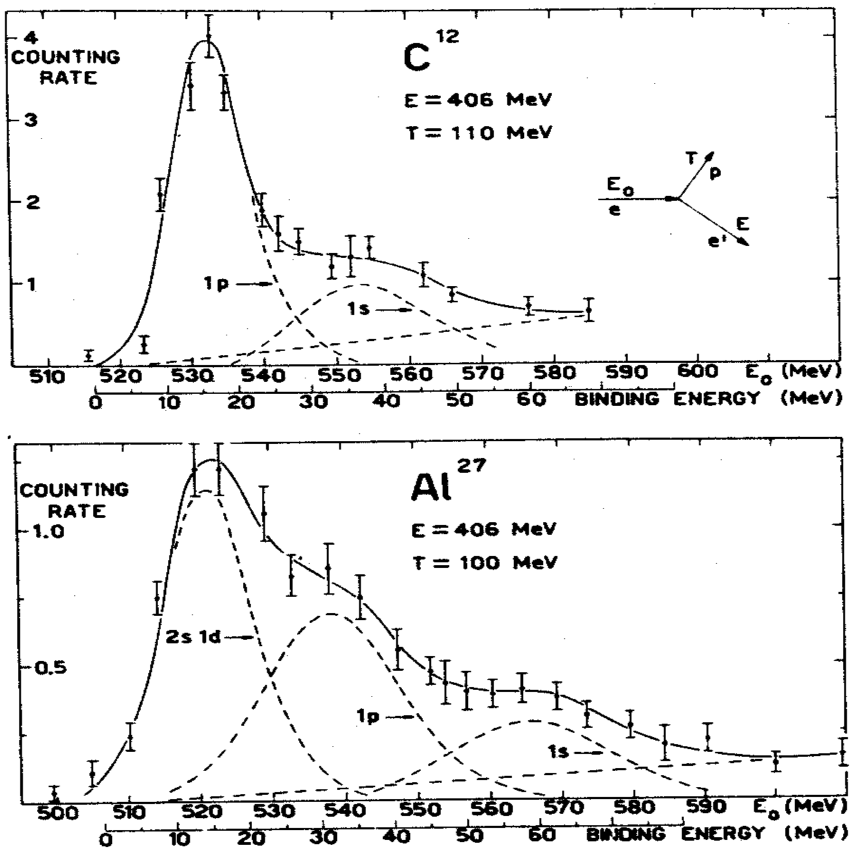


FIG. 2. Electron-proton coincidence counting rate per 10^{11} equivalent quanta at 550 MeV as a function of the incident energy. The dashed lines indicate the contributions of the various shells and the background as explained in the text.

Frascati Synchrotron, Italy

U. Amaldi, Jr. *et al.*, Phys. Rev. Lett. **13**, 341 (1964).

(e,e'p) advantages over (p,2p)

- Electron interaction relatively weak: OPEA is reasonably accurate.
- Nucleus is very transparent to electrons: Can probe deeply bound orbits.

However: ejected proton is strongly interacting. The “cleanness” of the electron probe is somewhat sacrificed.

FSI must be taken into account.

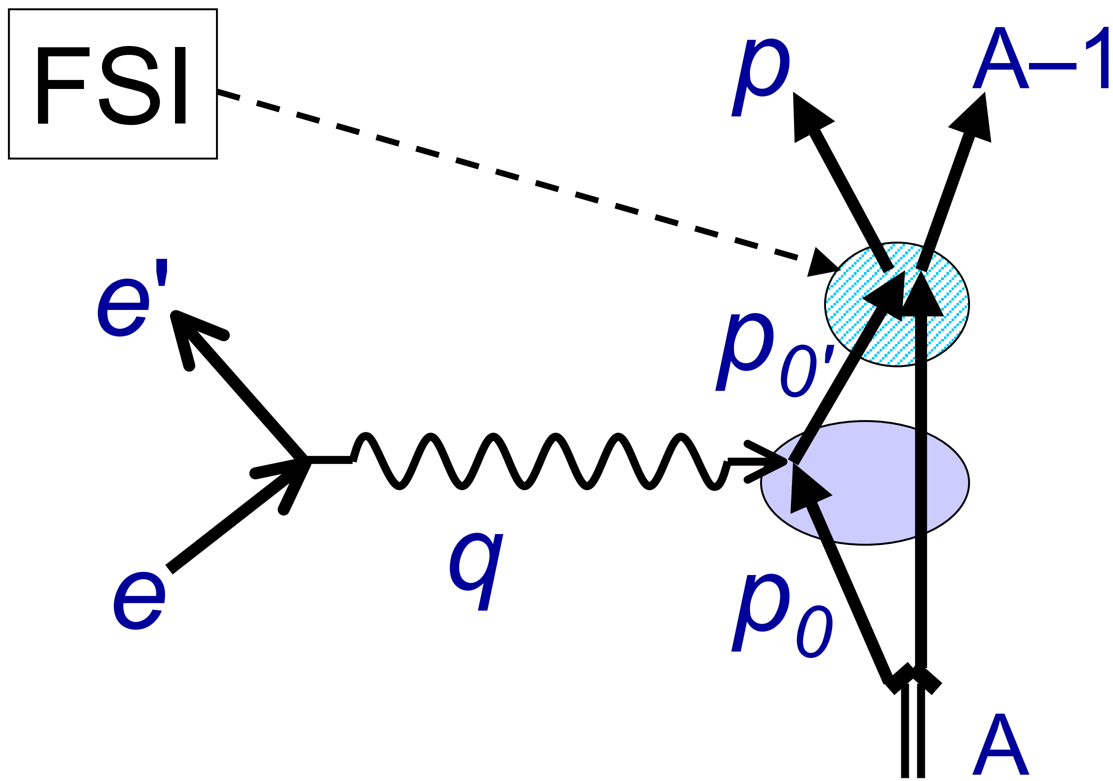
Recall, in nonrelativistic PWIA:

$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K\,\sigma_{ep}\,S(p_m,\varepsilon_m)$$

where $\boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{\mathrm{m}} = -\,\boldsymbol{p_0}$

FSI destroys simple connection between the measured $\boldsymbol{p_m}$ and the proton initial momentum (not an observable).

Final State Interactions (FSI)



$$\vec{q} - \vec{p} = \vec{p}_{A-1} \neq \vec{p}_0$$

Distorted Wave Impulse Approximation (DWIA)

Treat outgoing proton distorted waves in presence of potential produced by residual nucleus (*optical potential*).

$$\frac{d^6\sigma}{d\omega d\Omega_e dp d\Omega_p} = K\,\sigma_{ep}\,\boxed{S^D(p_m, \varepsilon_m, p)}$$

"Distorted" spectral function

Optical potential is constrained by proton elastic scattering data.

Problems with this approach:

- Residual nucleus contains hole state, unlike the target in p+A scattering.
- Proton scattering data is surface dominated, whereas ejected protons in (e,e'p) are produced within entire nuclear volume.

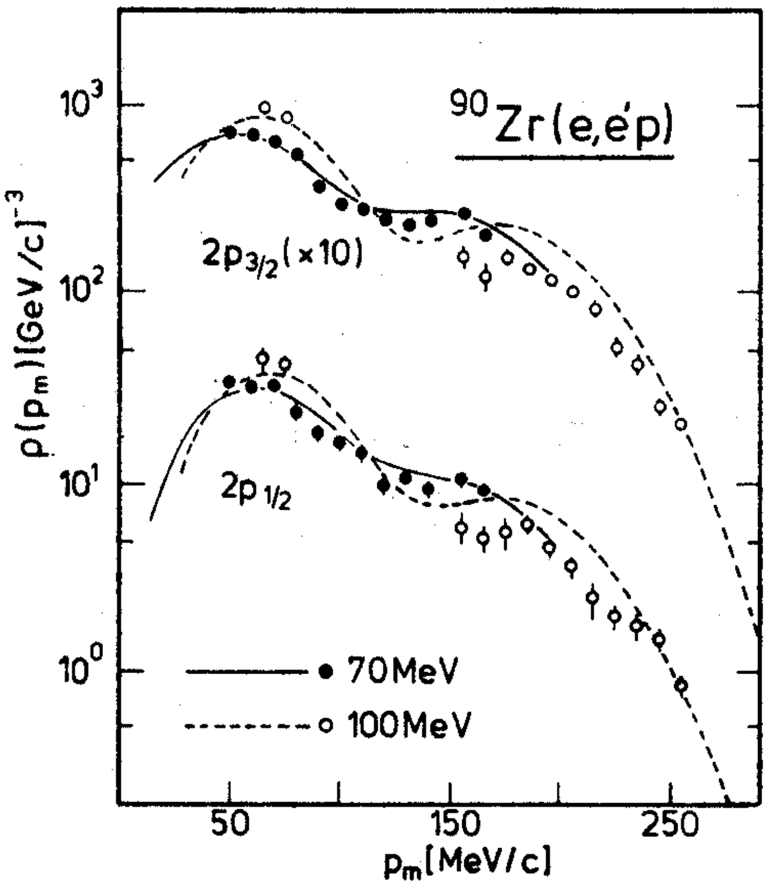


Fig. 1. Experimental momentum distributions for the $2p_{3/2}$ and $2p_{1/2}$ transitions in the $^{90}Zr(e,e'p)^{89}Y$ reaction. The curves correspond to DWIA calculations for the two proton energies (set I in table 1).

100 MeV data is significantly overestimated by DWIA near 2nd maximum.

NIKHEF-K Amsterdam

J.W.A. den Herder, *et al.,* Phys. Lett. B **184**, 11 (1987).

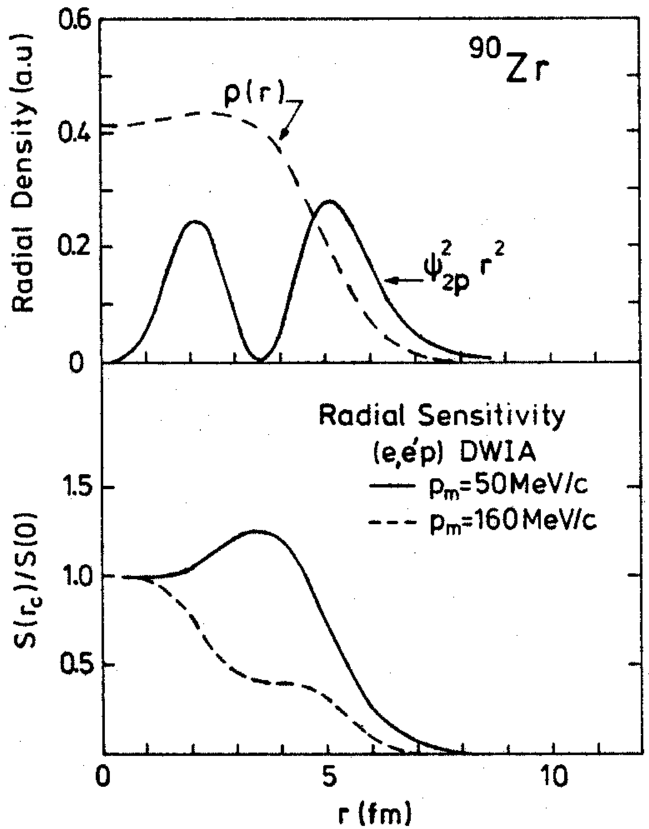


Fig. 2. Radial sensitivity, $S(r_c)$, as a function of the lower integration limit r_c (see text). For reference the radial dependence of the charge density (ρ) and of the 2p wave functions (ψ_{2p}) are indicated as well (not to scale).

$$\rho_\alpha^{\mathrm{th}}(p_m,\vec{p}) = S_\alpha \left| \int_{r_c=0}^{\infty} \chi^{(-)*}(\vec{r}_p,\vec{p}) \times \exp(i\vec{q}\cdot\vec{r}_p)\psi_\alpha(\vec{r}_p)\mathrm{d}\vec{r}_p \right|^2$$

At p_m≈160 MeV/c, wf is probed in nuclear interior.

J.W.A. den Herder, *et al.,* Phys. Lett. B **184**, 11 (1987).

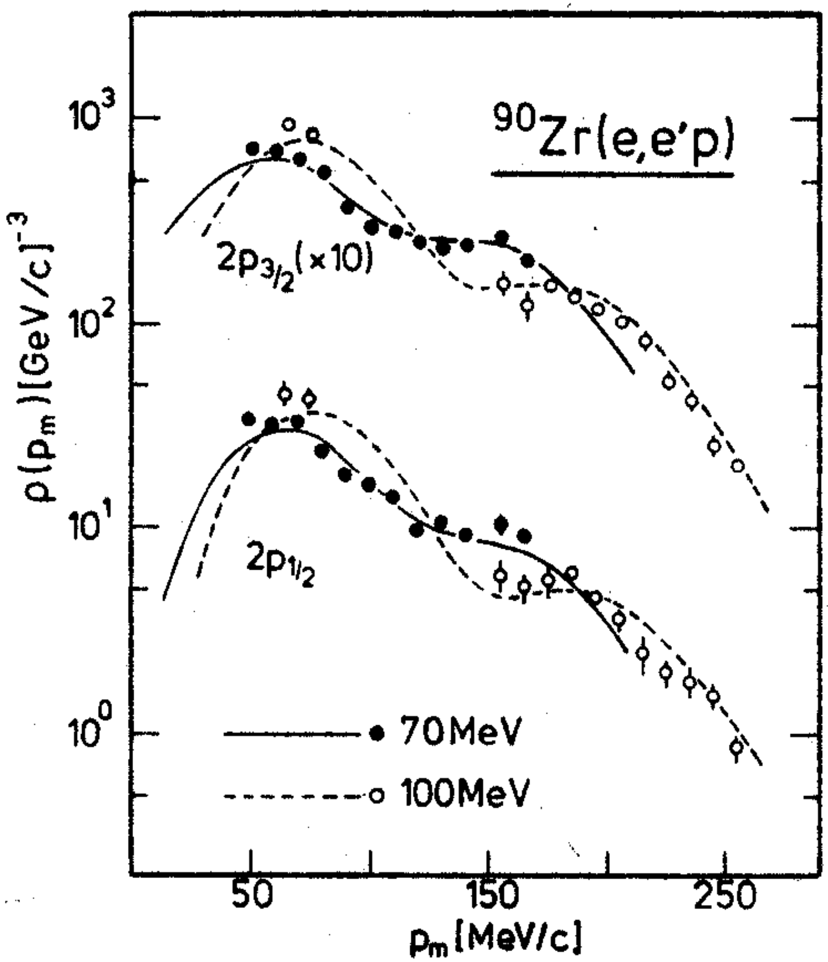


Fig. 3. Same as fig. 1, but for the modified optical potential (set II in table 1).

Adjusting optical potential renders good agreement while maintaining agreement with p+A elastic.

J.W.A. den Herder, *et al.*, Phys. Lett. B **184**, 11 (1987).

$^{12}C(e,e'p)^{11}B$

Saclay Linac, France

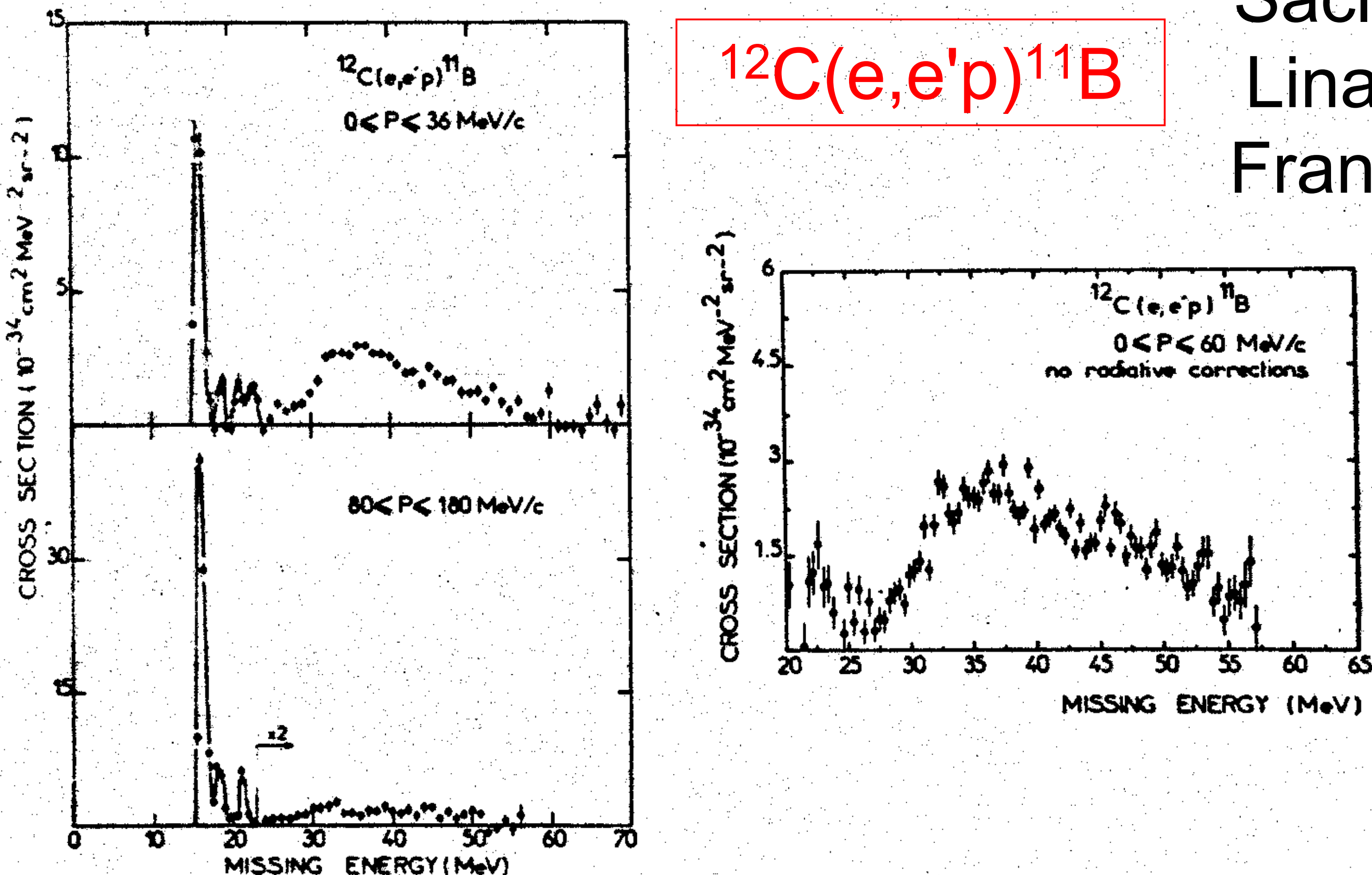


Fig. 9. Missing energy spectra from ^{12}C(e, e′p), (a) $0 \leqq P \leqq 36$ MeV/c, (b) $80 \leqq P \leqq 180$ MeV/c and (c) $0 \leqq P \leqq 60$ MeV/c for $20 \leqq E \leqq 60$ MeV.

J. Mougey *et al.*, Nucl. Phys. **A262**, 461 (1976).

p-shell
l=1

s-shell
l=0

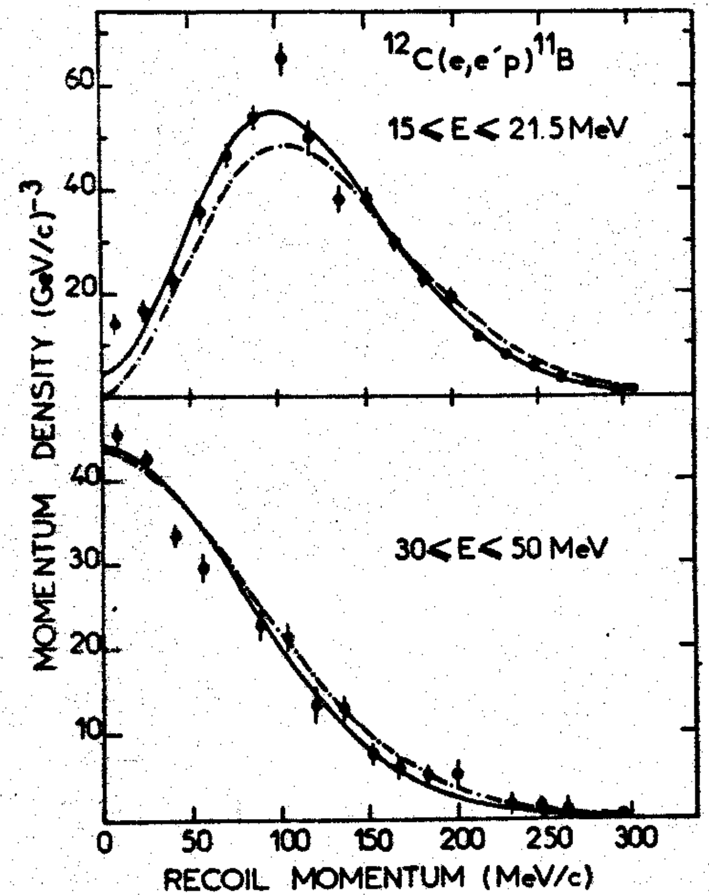


Fig. 10. Momentum distribution from $^{12}C(e, e'p)$; (a) $15 \leq E \leq 21.5$ MeV and (b) $30 \leq E \leq 50$ MeV. The solid and dashed lines represent DWIA and PWIA calculations respectively, with normalization obtained by a fit to the data.

$^{12}C(e,e'p)^{11}B$

Saclay
Linac,
France

J. Mougey *et al.,* Nucl. Phys. **A262**, 461 (1976).

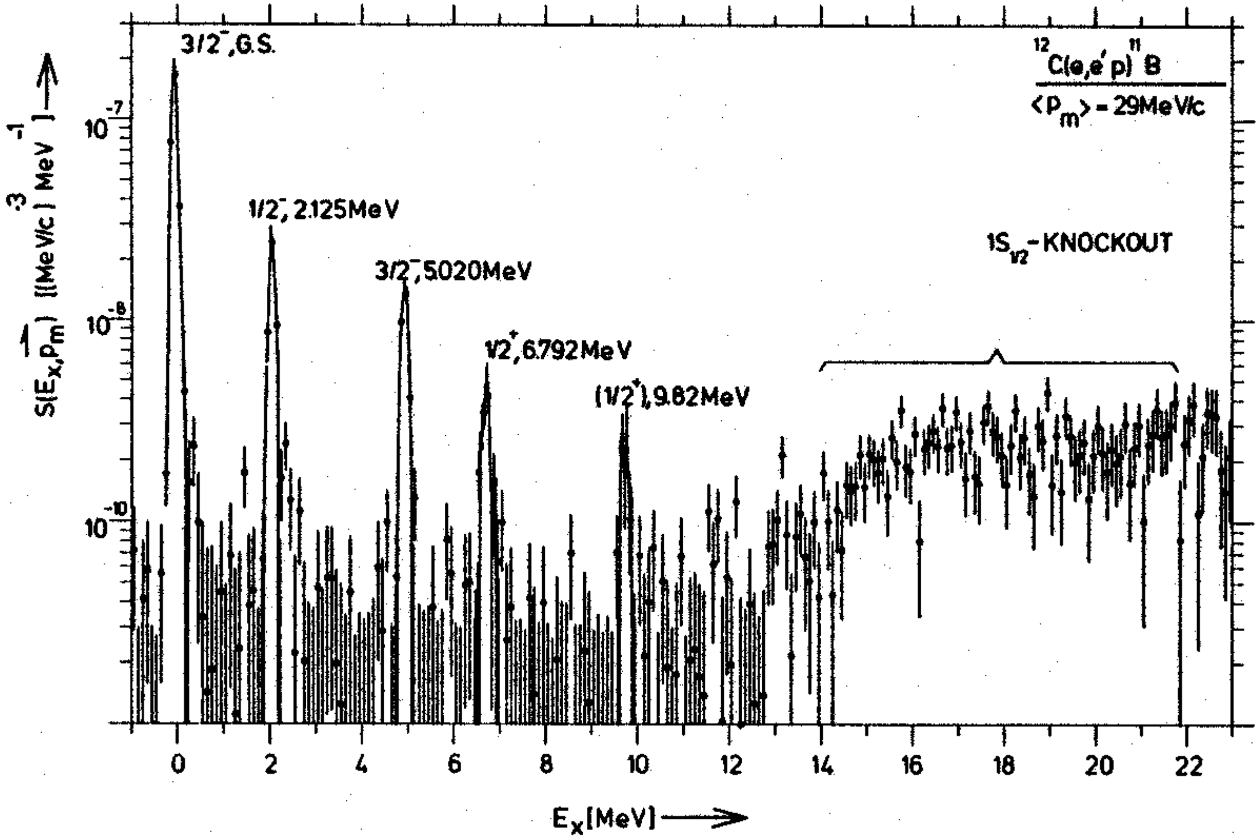


Fig. 1. Excitation-energy spectrum of the reaction $^{12}C(e,e'p)^{11}B$ at a central value of the missing momentum $p_m = 29$ MeV/c. The spectrum has been sorted in 100 keV bins.

$^{12}C(e,e'p)^{11}B$

NIKHEF-K
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G. van der Steenhoven *et al.,* Nucl. Phys. **A484**, 445 (1988).

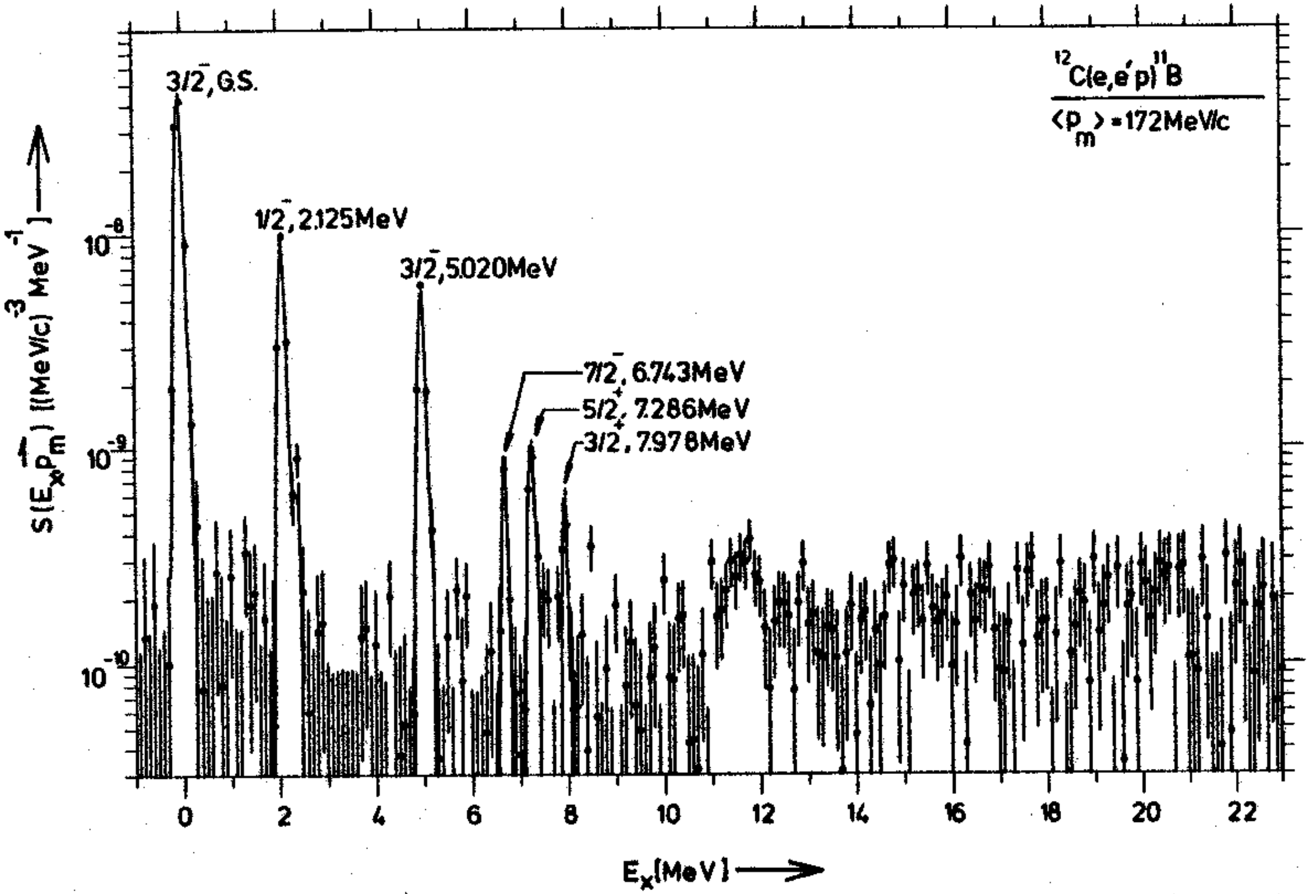


Fig. 2. Same as fig. 1 but for $p_m = 172$ MeV/c.

$^{12}C(e,e'p)^{11}B$

NIKHEF-K
Amsterdam

G. van der Steenhoven *et al.,* Nucl. Phys. **A484**, 445 (1988).

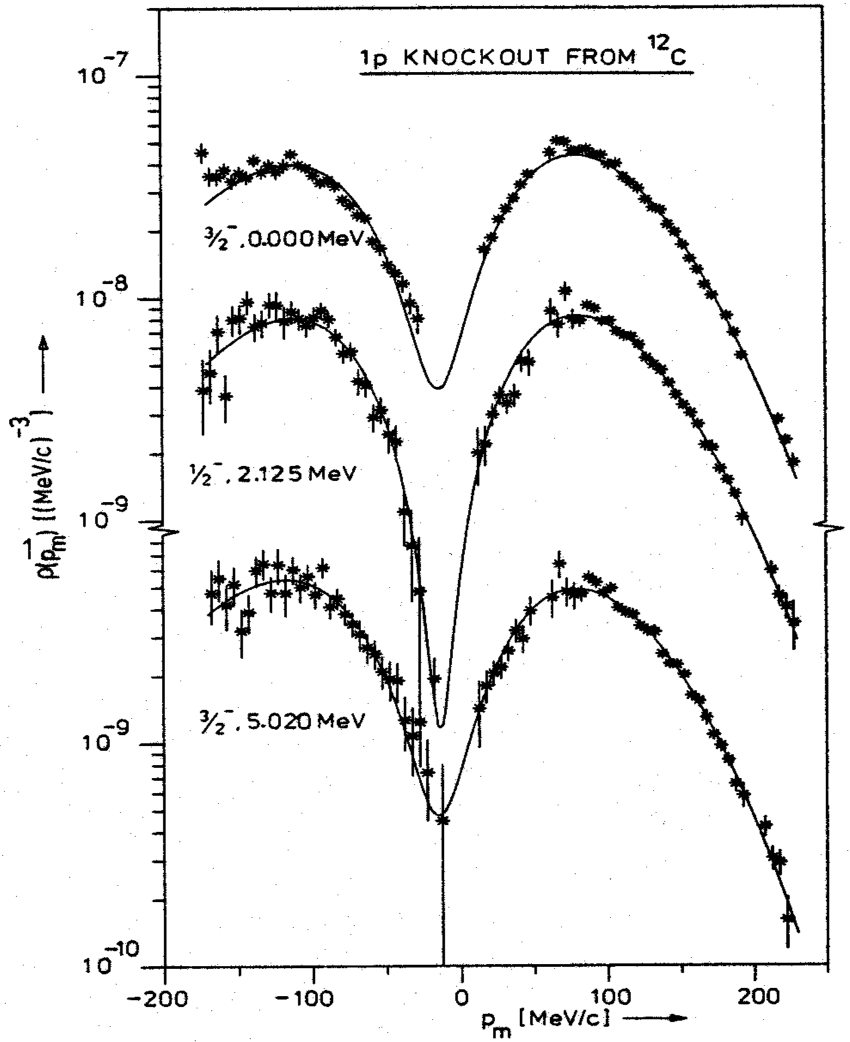


Fig. 11. Momentum distributions for 1p knockout from ^{12}C leading to the $\frac{3}{2}^-$ ground state, the $\frac{1}{2}^-$ state at 2.125 MeV and the $\frac{3}{2}^-$ state at 5.020 MeV in ^{11}B. The curves represent DWIA calculations employing the MCO potential. The fitted parameters are listed in table 6 (after a correction for the omitted couplings using table 5).

$^{12}C(e,e'p)^{11}B$

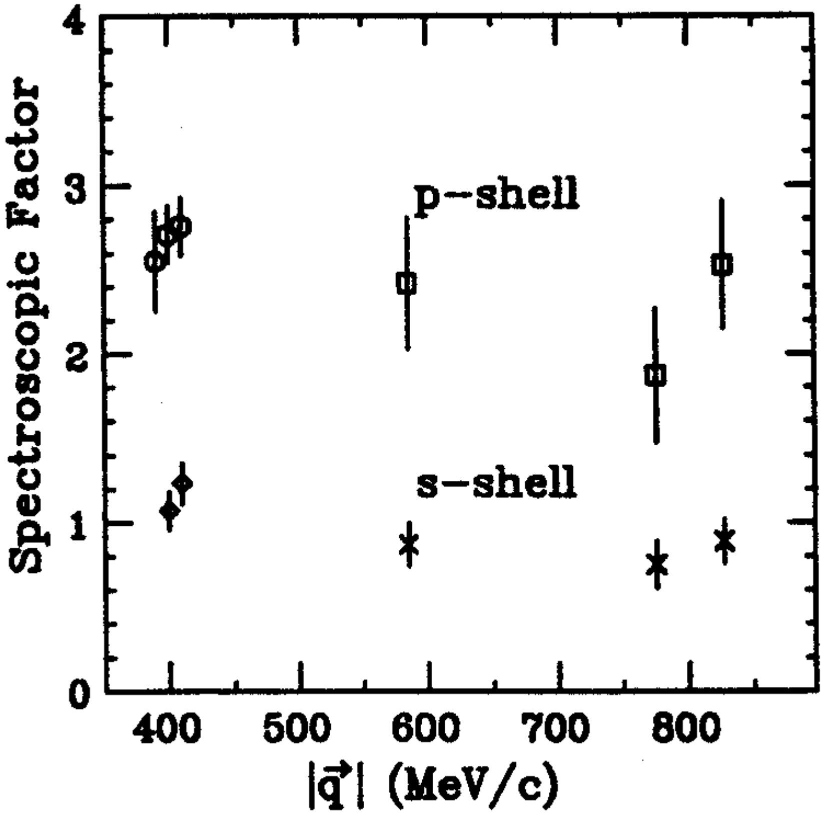
NIKHEF-K
Amsterdam

DWIA calculations fit data reasonably well.

Missing strength observed however.

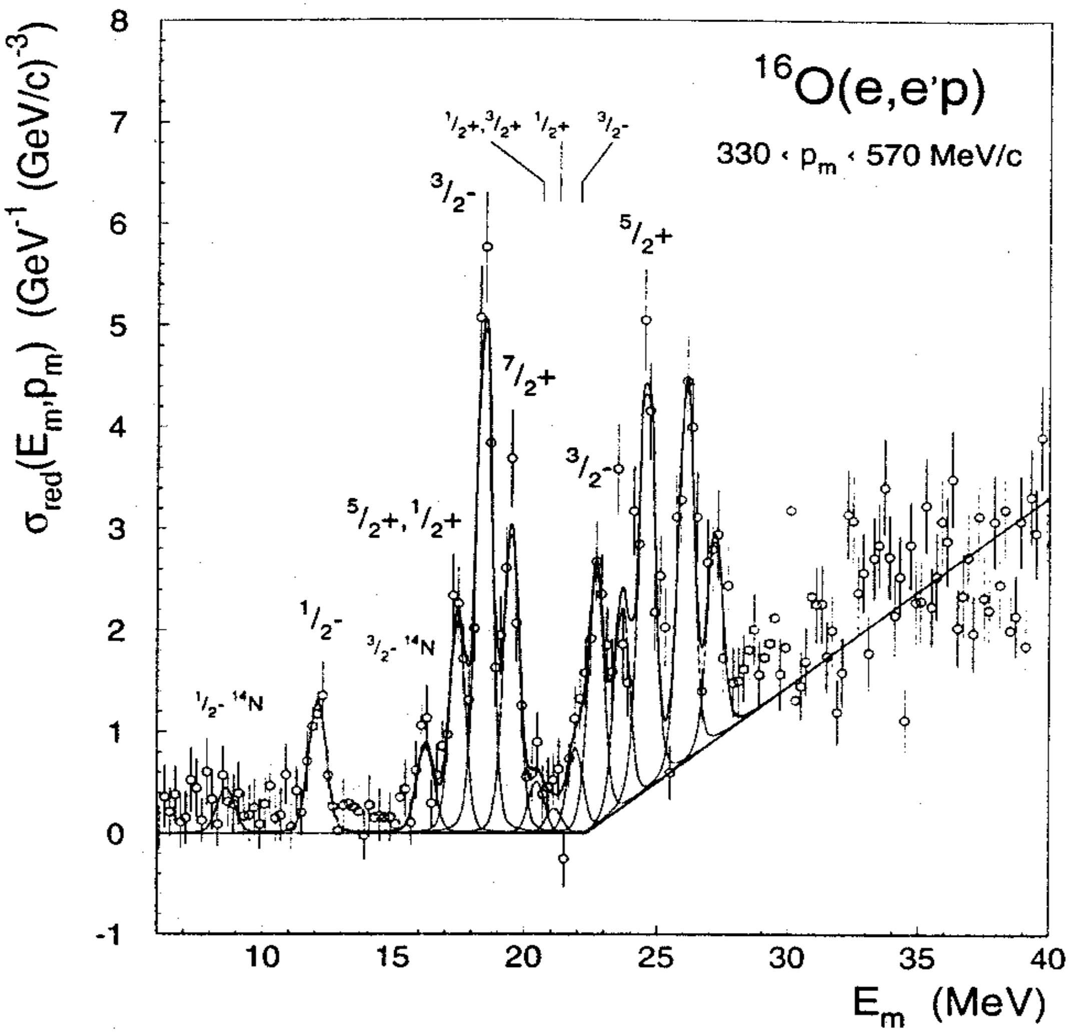
G. van der Steenhoven, *et al.,* Nucl. Phys. **A480**, 547 (1988).

$^{12}C(e,e'p)$



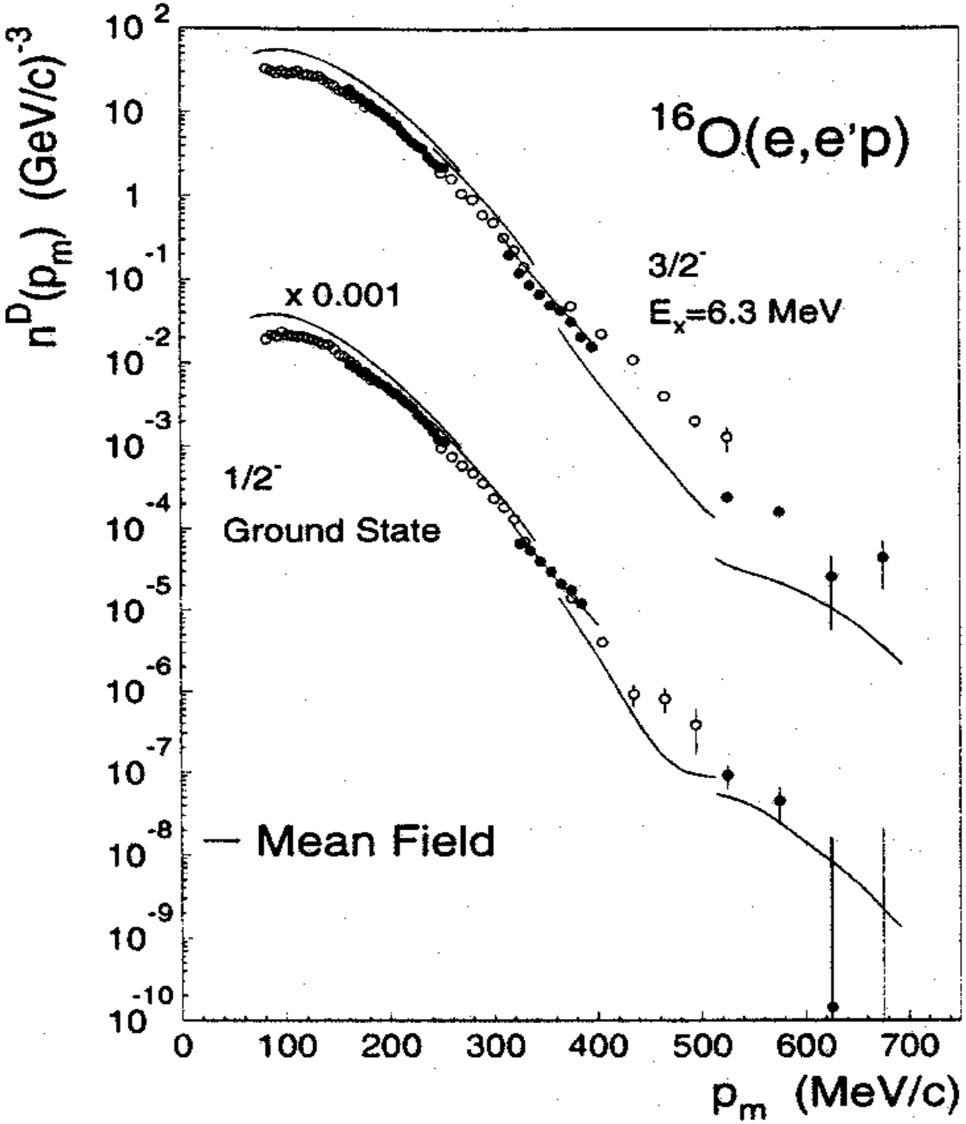
Bates Linear Accelerator

L.B. Weinstein *et al*., Phys. Rev. Lett. **64**, 1646 (1990).



MAMI
Mainz,
Germany

K.I. Blomqvist *et al.,* Phys. Lett. B **344**, 85 (1995).



MAMI Mainz, Germany

Factorization violated.

DWIA calculations underpredict at high $p_{m.}$

Neglected MEC's & relativistic effects. Offshell effects uncertain at high $p_{m.}$

K.I. Blomqvist *et al.,* Phys. Lett. B **344**, 85 (1995).

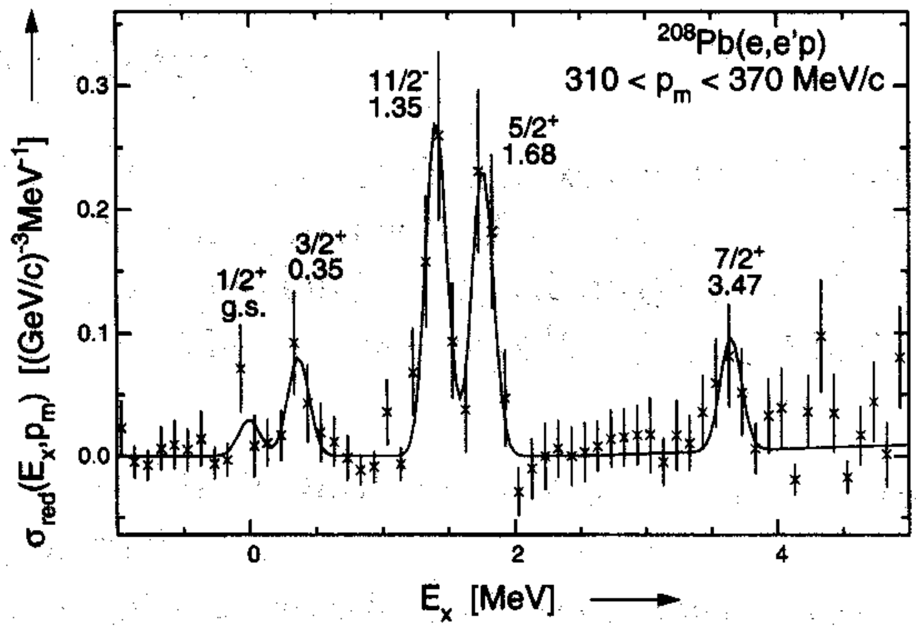


FIG. 1. The reduced cross section of the reaction ^{208}Pb$(e, e'p)$ at an average missing momentum of 340 MeV/c, showing the knock out of valence protons to discrete states in ^{207}Tl, labeled by their spin, parity, and excitation energy. The solid curve is the result of a fit to the spectrum.

^{208}Pb(e,e'p)

AmPS NIKHEF-K
Amsterdam

I. Bobeldijk *et al.,* Phys. Rev. Lett. **73**, 2684 (1994).

^{208}Pb(e,e'p)

AmPS NIKHEF-K
Amsterdam

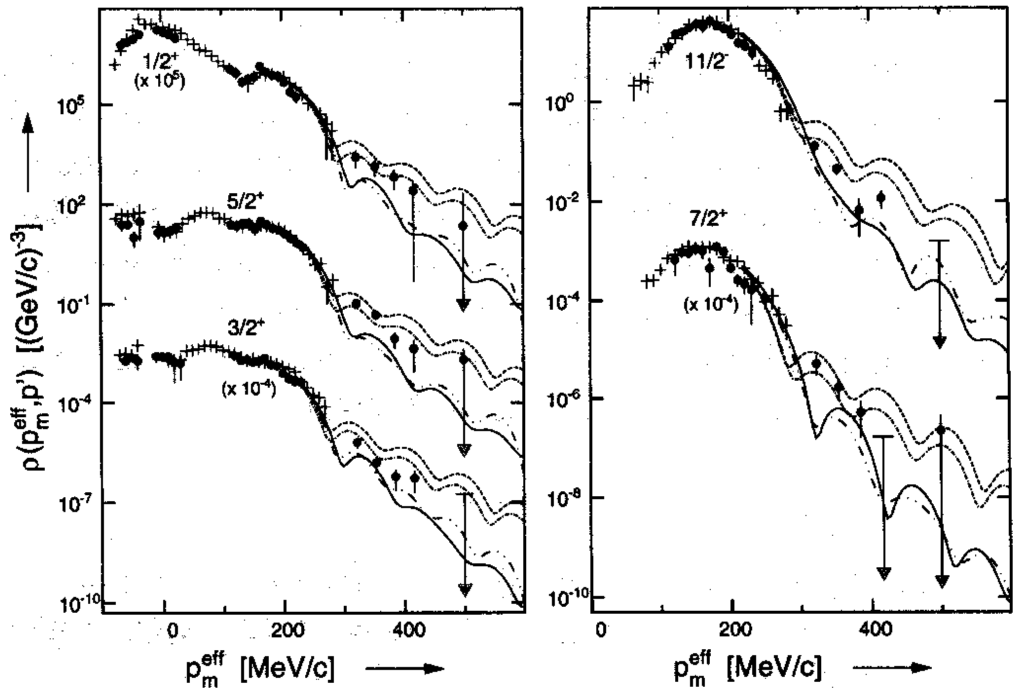


FIG. 2. Missing-momentum distributions for the transitions to the $\frac{1}{2}+$, $\frac{3}{2}+$, $\frac{11}{2}-$, $\frac{5}{2}+$, and $\frac{7}{2}+$ states in the reaction ^{208}Pb(e, $e'p$) at excitation energies of 0.00, 0.35, 1.35, 1.68, and 3.47 MeV, respectively. The present data are represented by solid circles, the plus marks have been measured by Quint [16]. The solid curves are knockout calculations in the distorted-wave impulse approximation. The calculations including correlations as proposed by Pandharipande [8], Ma and Wambach [10], and Mahaux and Sartor [12] are represented by dash–double-dotted, dashed, and dot-dashed curves, respectively.

Long-range correlations important.

SRC and TC less so, but expected to grow with ε_m.

I. Bobeldijk *et al.,* Phys. Rev. Lett. **73**, 2684 (1994).

Some of the lessons learned:

• (e,e'p) sensitive probe of single-particle orbits.

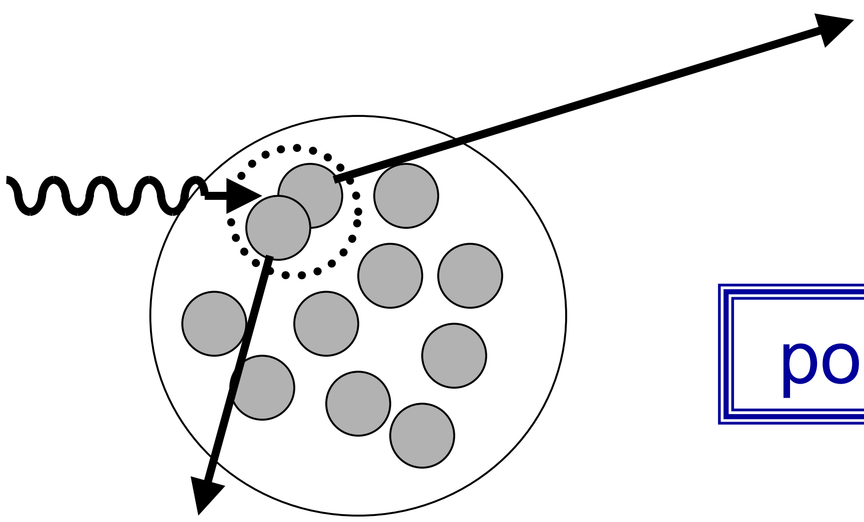
• Proton distortions (FSI) must be accounted for to reproduce shape of spectral function. Energy dependence of FSI breaks factorization.

• Missing strength in valence orbits, even after accounting for FSI

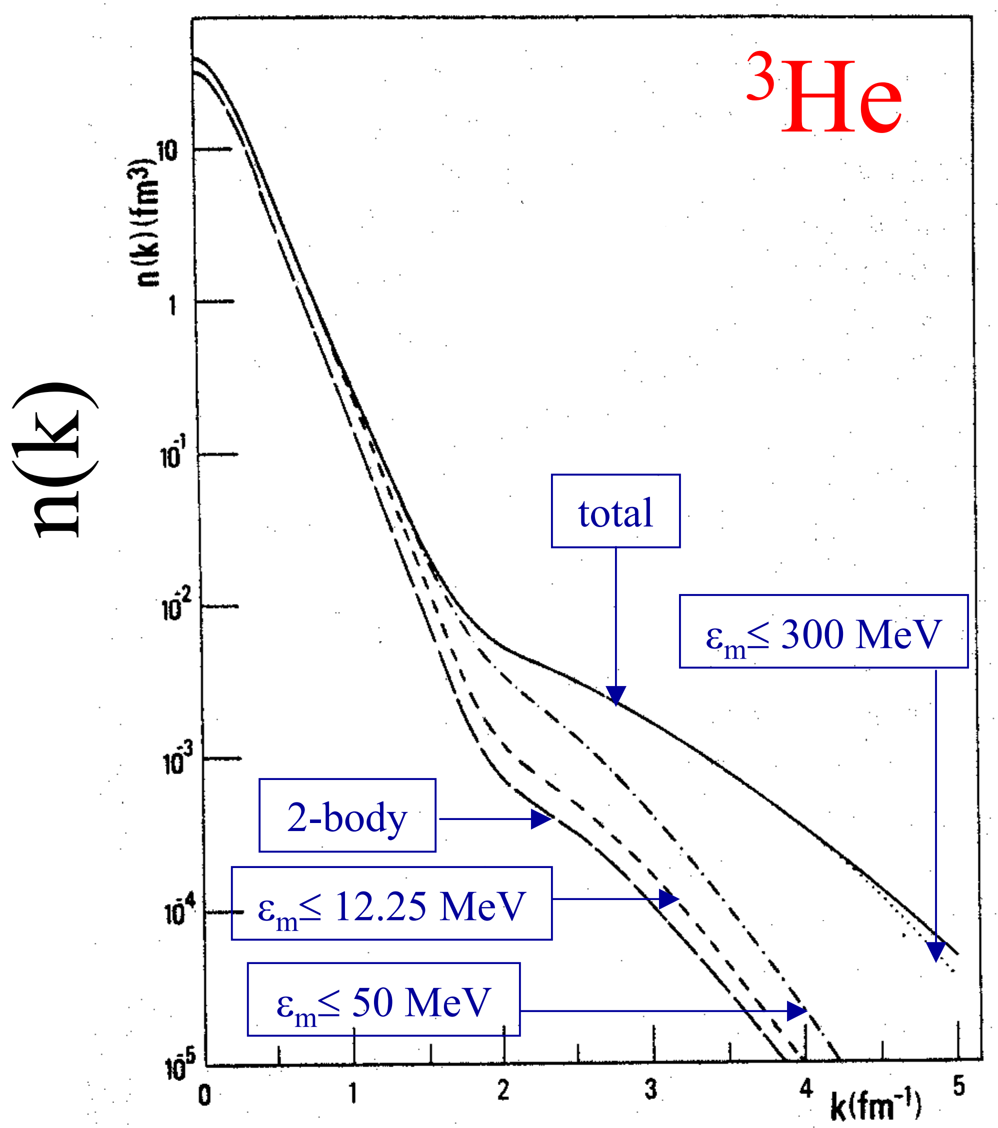
• At high P_m significant discrepancies found relative to calculations.

Where does the "missing" strength go?

One possibility:

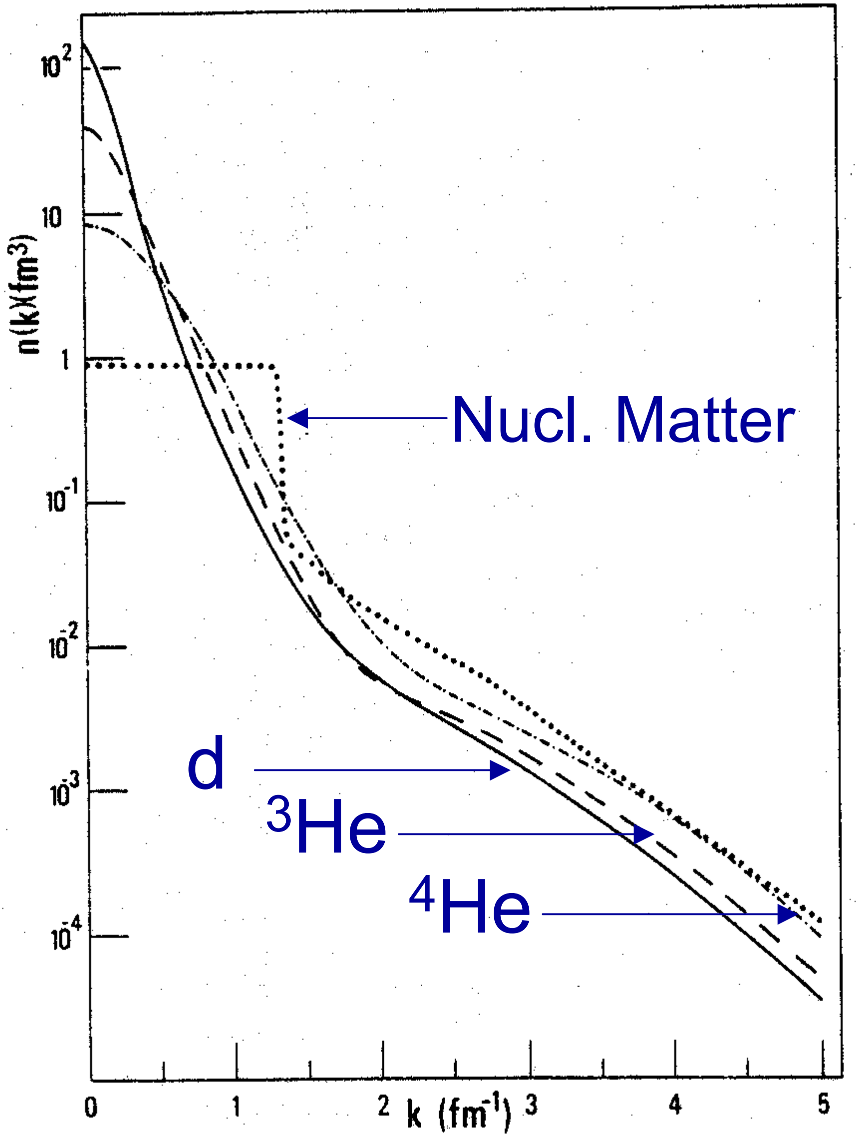


populates high ε_m



SRC dominate high k (=p_m) and are related to large values of ε_m.

C. Ciofi degli Atti, E. Pace and G. Salmè, Phys. Lett. **141B**, 14 (1984).



C. Ciofi degli Atti, E. Pace and G. Salmè, Phys. Lett. **141B**, 14 (1984).

Similar shapes for few-body nuclei and nuclear matter at high k (=p_m).

Medium-Modified Nucleons

Searching for Medium Effects on the Nucleon …

In parallel kinematics:

$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_\mathrm{p}\mathrm{d}p\,\mathrm{d}\omega} = \frac{pE}{(2\pi)^3}\sigma_\mathrm{M}[v_L R_L + v_T R_T]$$

Can write *ep* elastic cross section as:

$$\frac{d\sigma}{d\Omega} = f_{rec}\sigma_\mathrm{M}\left[v_L k_L G_E^2 + v_T k_T G_M^2\right]$$

$$\text{with} \quad k_L = \frac{|\vec{q}|^2}{Q^2} \quad \text{and} \quad k_T = \frac{Q^2}{2m^2}$$

Relate R_T/R_L to in-medium proton FF's

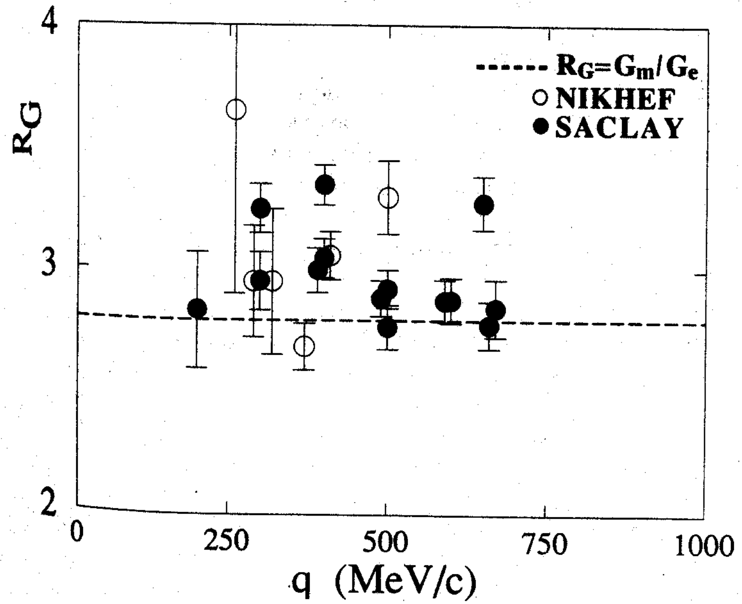
$$R_G \equiv \frac{m|\vec{q}|}{Q^2}\sqrt{\frac{2R_T}{R_L}} \rightarrow \frac{\tilde{G}_M}{\tilde{G}_E}$$

PWIA

This relies on (unrealistic) model assumptions!

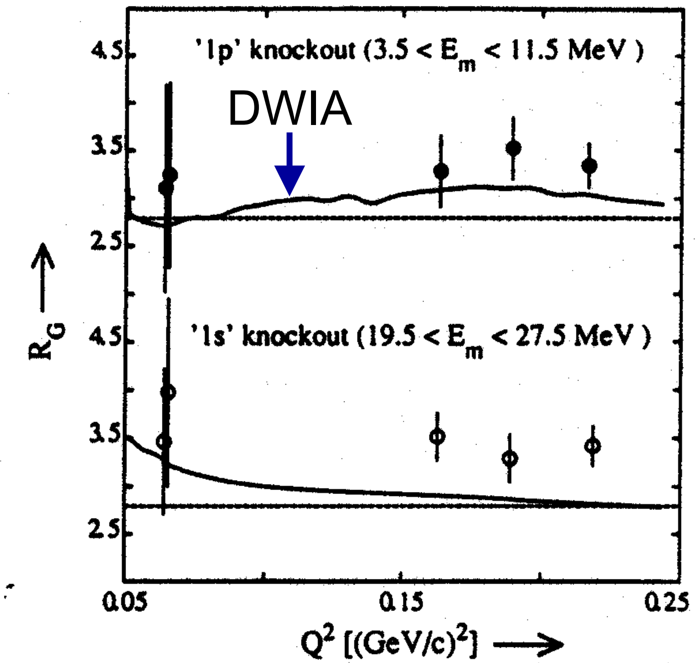
Nonetheless …

$^2H(e,e'p)n$



J.E. Ducret *et al.*,
Phys. Rev. C **49**, 1783 (1994).

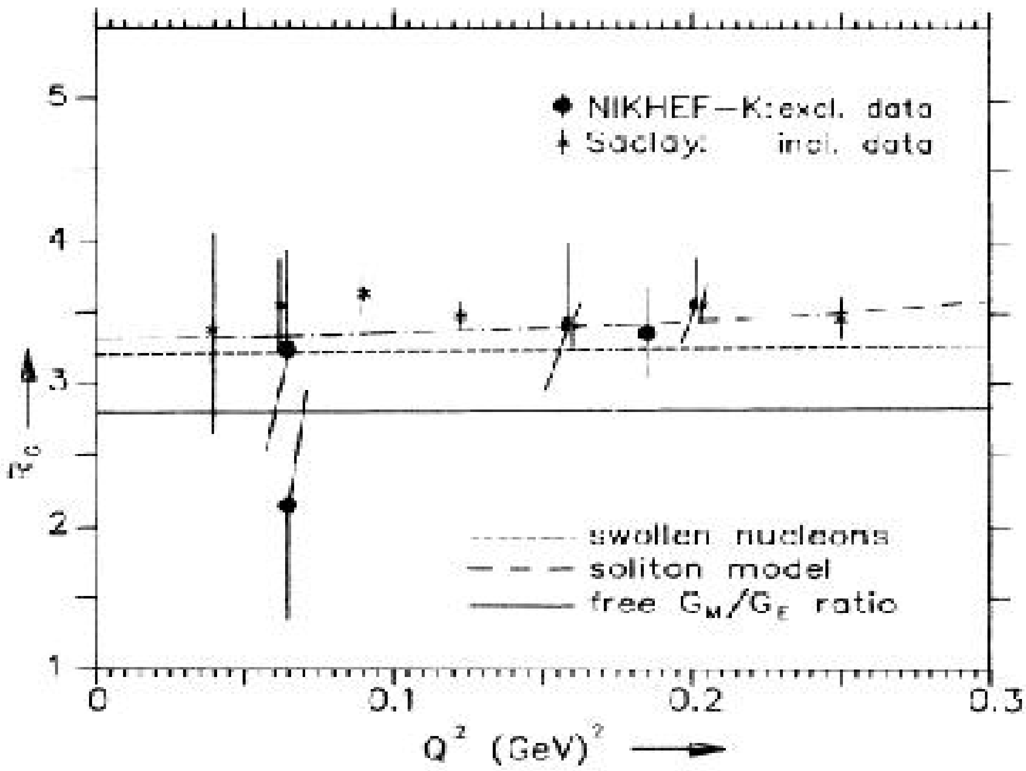
$^6Li(e,e'p)$



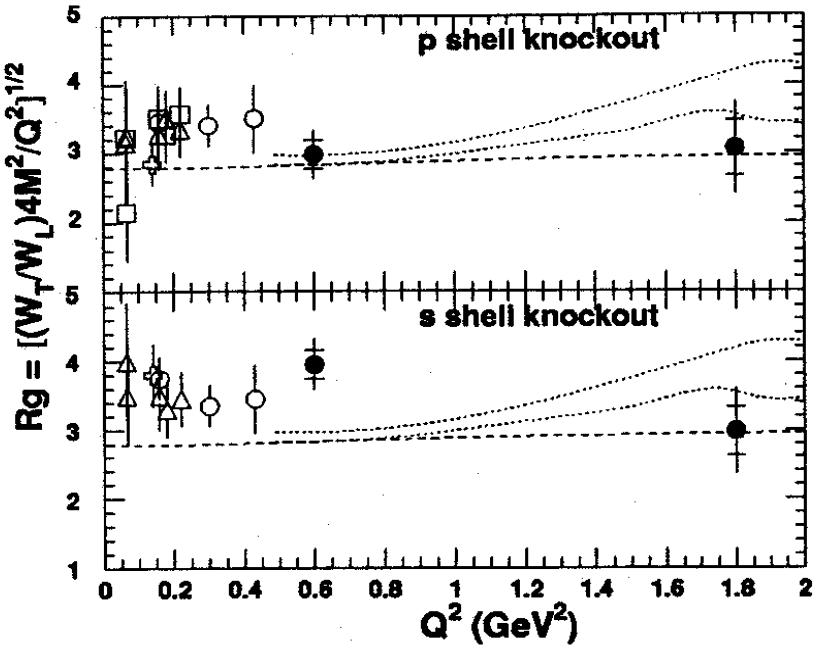
J.B.J.M. Lanen *et al.*,
Phys. Rev. Lett. **64**, 2250 (1990).

NIKHEF-K
Amsterdam

$^{12}C(e,e'p)$ and $^{12}C(e,e')$



G. Van der Steenhoven *et al.*,
Phys. Rev. Lett. **57**, 182 (1986)



JLab
Hall C

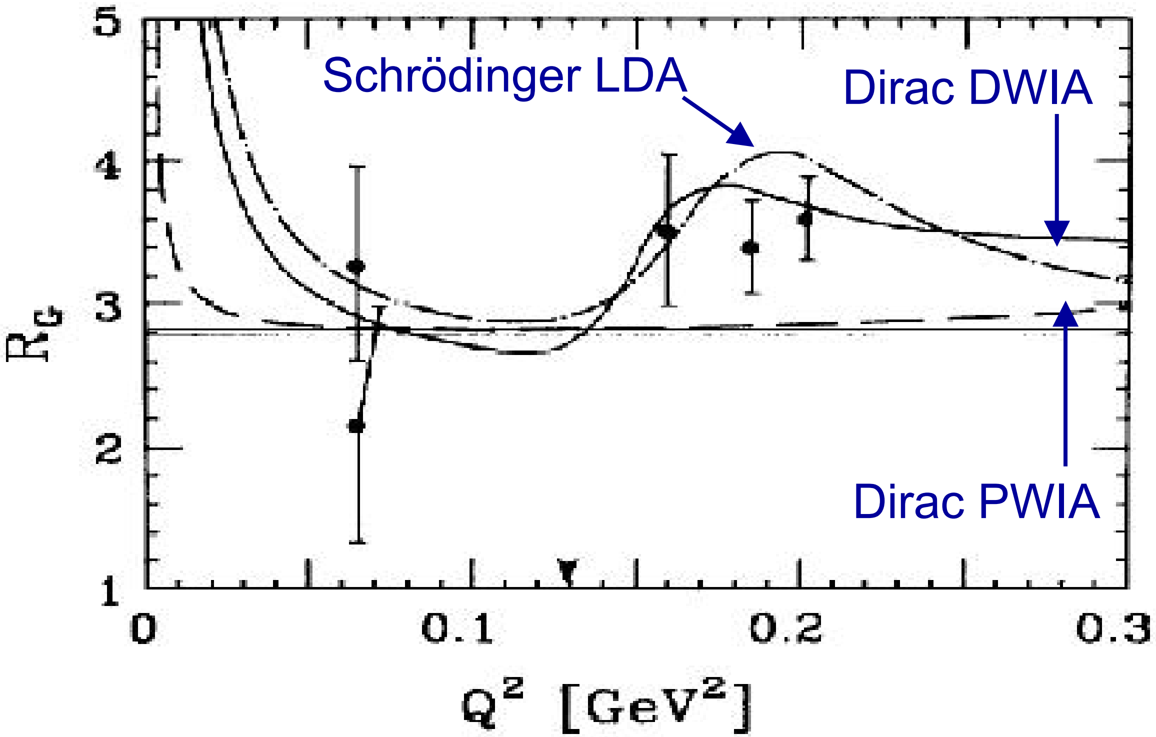
FIG. 3. $R_G = \sqrt{W_T 4M_p^2 / W_L Q^2}$ for ^{12}C (solid) from the measurements of this experiment with ^{6}Li (p shell: open squares [3], open circles [25], and s shell: open triangles [3], open circles [25]) and ^{12}C (p shell: open cross [1], open triangles [15], and s shell: open cross [1]). The top panel is for the p shell region and bottom panel is for the s shell region. The inner error bar represents that statistical error and the outer error bar includes the systematic error. The dashed line represents R_G for the free proton with the dipole electric and Ref. [18] magnetic form factor while the dotted lines represent the one sigma error band of the recent proton results of Ref. [27].

D. Dutta *et al.,* Phys. Rev. C **61**, 061602 (2000).

However, large FSI effects can mimic this behavior …

FSI calculations for ^{16}O $1p_{3/2}$

Data for ^{12}C $1p_{3/2}$



T.D. Cohen, J.W. Van Orden, A. Picklesimer, Phys. Rev. Lett. **59**, 1267 (1987)

Another, less model-dependent, method …

Polarization Transfer

Proton Polarization and Form Factors

Free $\vec{e}\, p$ scattering

$$I_0 P'_x = -2\sqrt{\tau(1+\tau)}\, G_E G_M \tan\left(\frac{\theta_e}{2}\right)$$

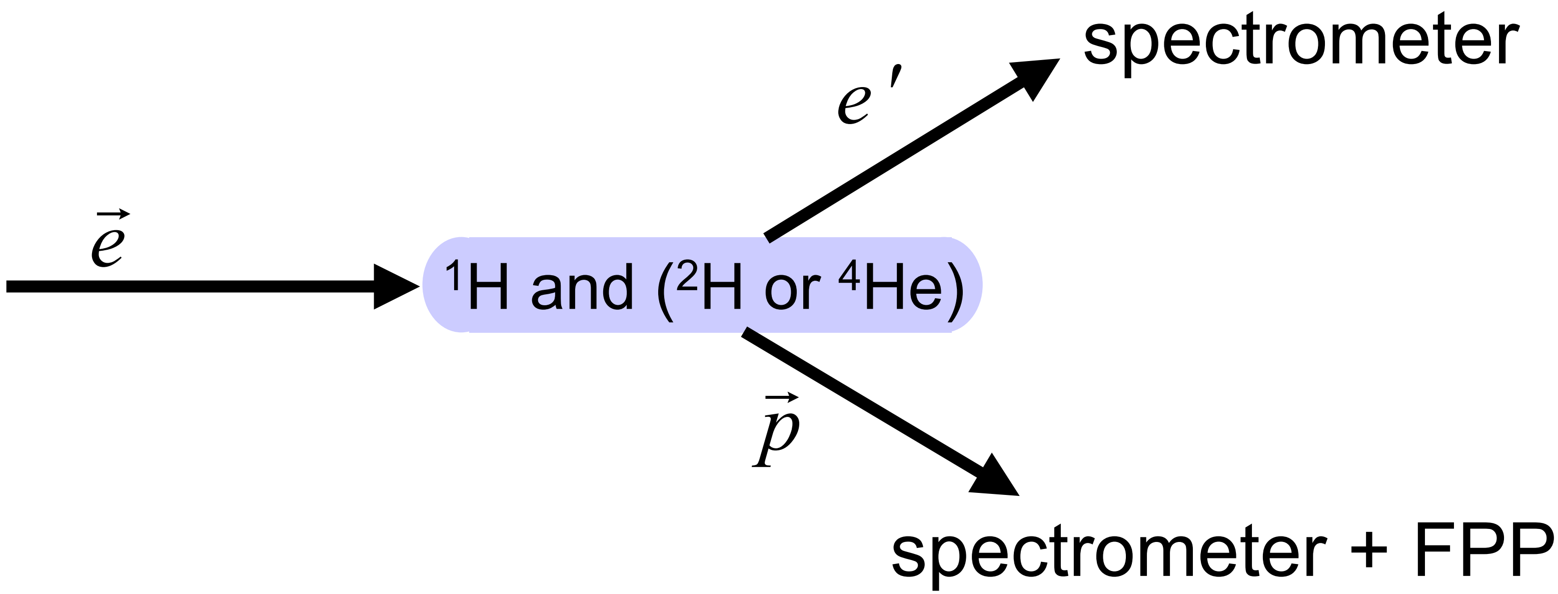
$$I_0 P'_z = \frac{e+e'}{m}\sqrt{\tau(1+\tau)}\, G_M^2 \tan^2\left(\frac{\theta_e}{2}\right)$$

$$I_0 = G_E^2 + \tau G_M^2 \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]$$

$$\boxed{\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\cdot\frac{e+e'}{2m}\tan\left(\frac{\theta_e}{2}\right)}$$

R. Arnold, C. Carlson and F. Gross, Phys. Rev. C **23**, 363 (1981)

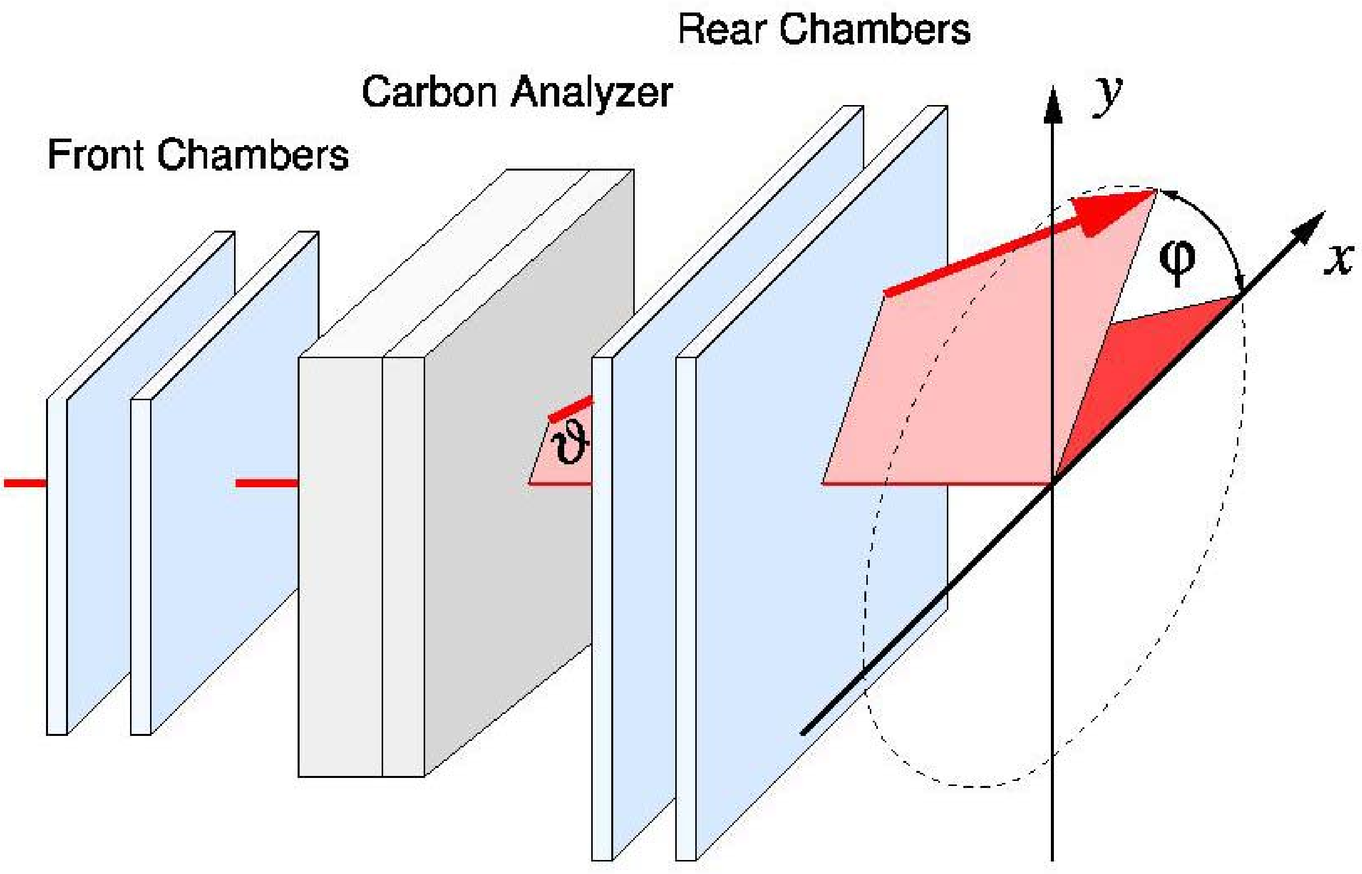
Polarization Transfer in Hall A



$$^{2}\mathrm{H}(\vec{e},e'\vec{p})n \qquad {}^{4}\mathrm{He}(\vec{e},e'\vec{p})^{3}\mathrm{H}$$

$$^{1}\mathrm{H}(\vec{e},e'\vec{p})$$

Measuring the Proton Polarization: FPP



Density Dependent Form Factors

Quark-Meson Coupling Model (QMC):

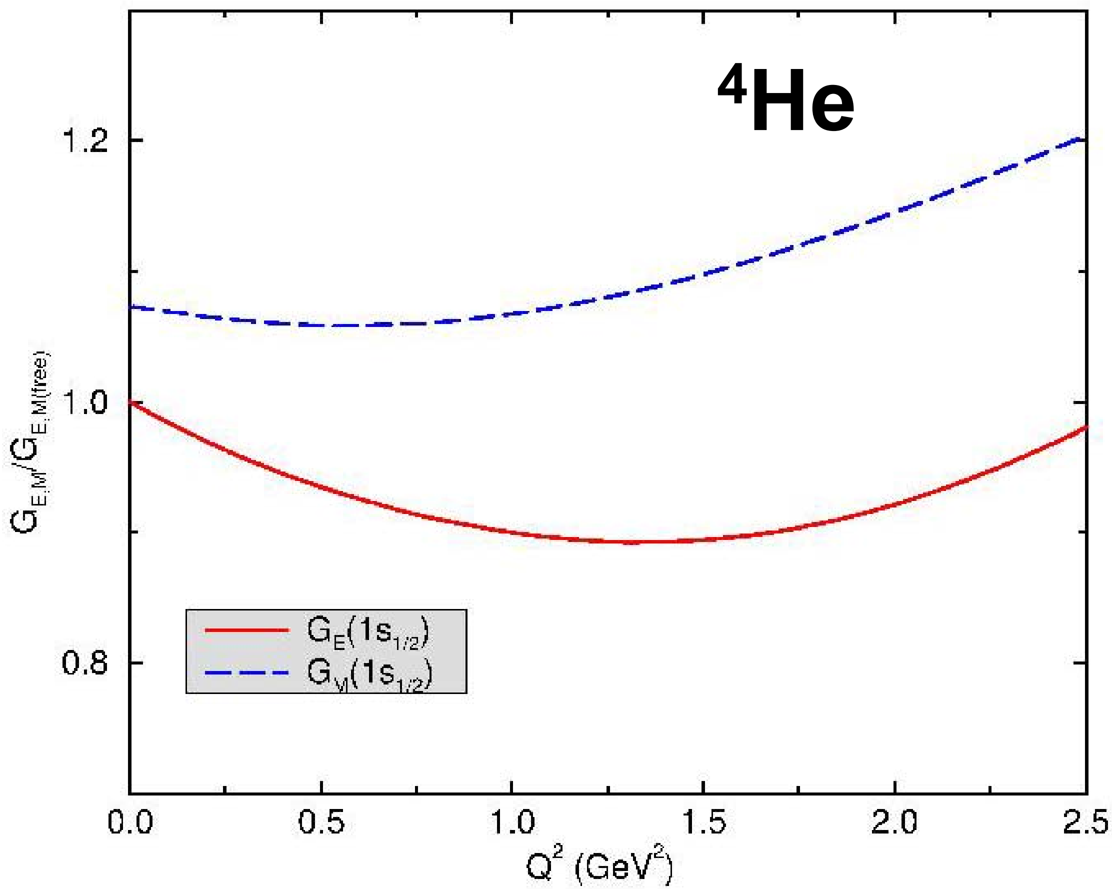
$$\overline{G}_\alpha(Q^2) = \frac{\int d^3 r w_\alpha(r) \boxed{G(Q^2, \rho_B(r))}}{\int d^3 r w_\alpha(r)}$$

For (e,e'p)

$$w_\alpha = \exp(i\vec{q}\cdot\vec{r})\chi^{(-)}(\vec{p}\,',\vec{r})^* \phi_\alpha(r)$$

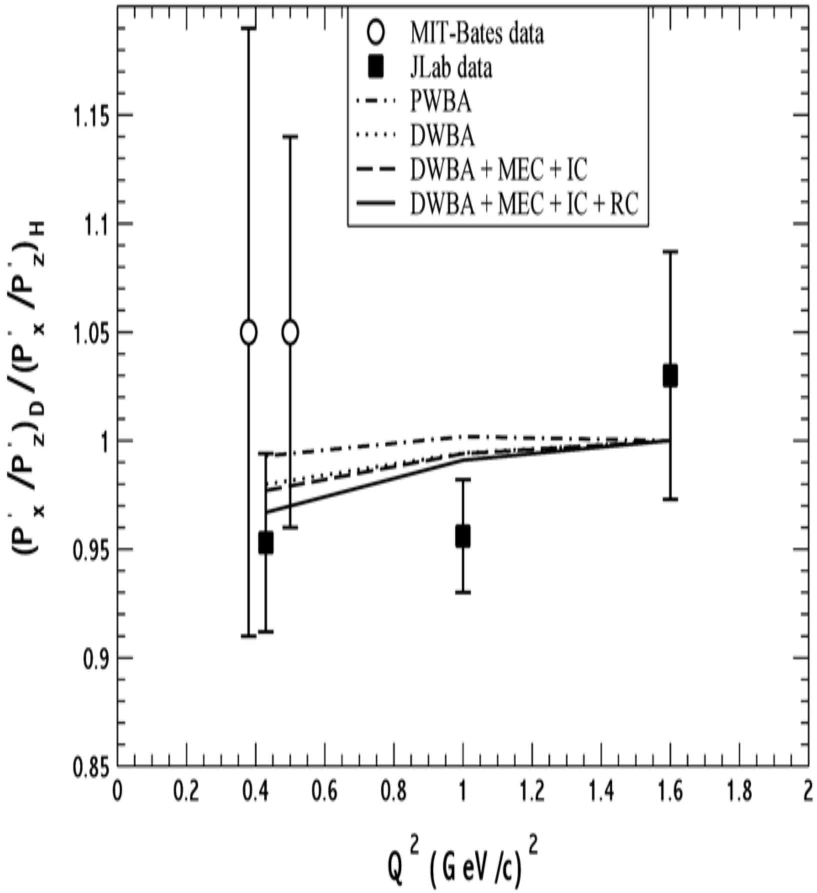
D.H. Lu, , A.W. Thomas, K. Tsushima, A.G. Williams, K. Saito, Phys. Lett. **B** 417, 217 (1998).

Quark-Meson Coupling Model



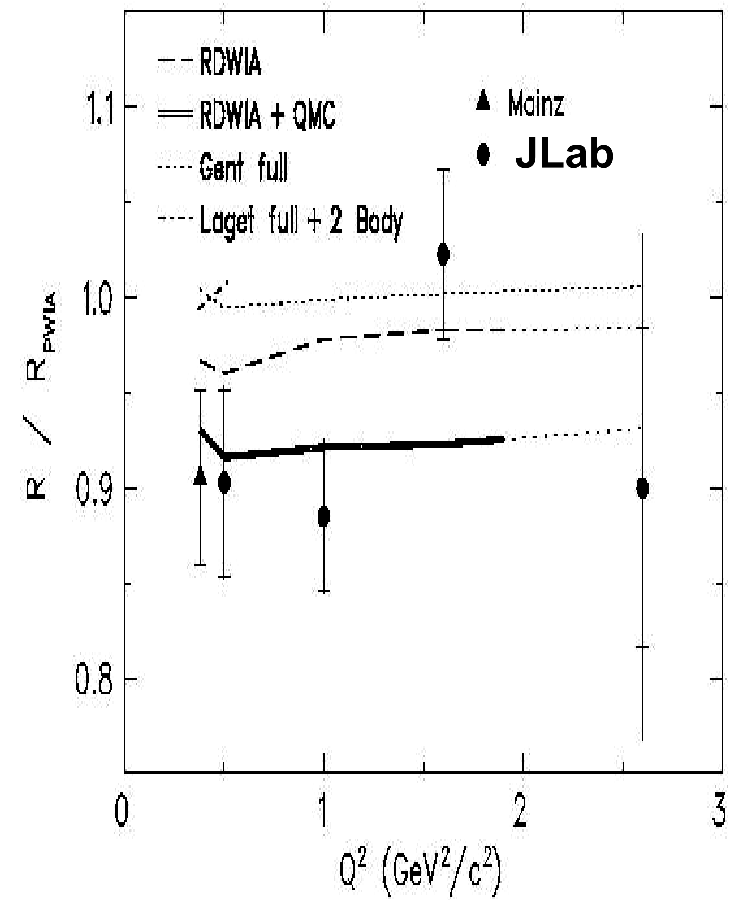
D.H. Lu, K. Tsushima, A.W. Thomas, A.G. Williams and K. Saito, Phys. Lett. **B417**, 217 (1998) and Phys. Rev. C **60**, 068201 (1999).

$^{2}\mathrm{H}(\vec{e},e'\vec{p})n$



Calculations by Arenhövel

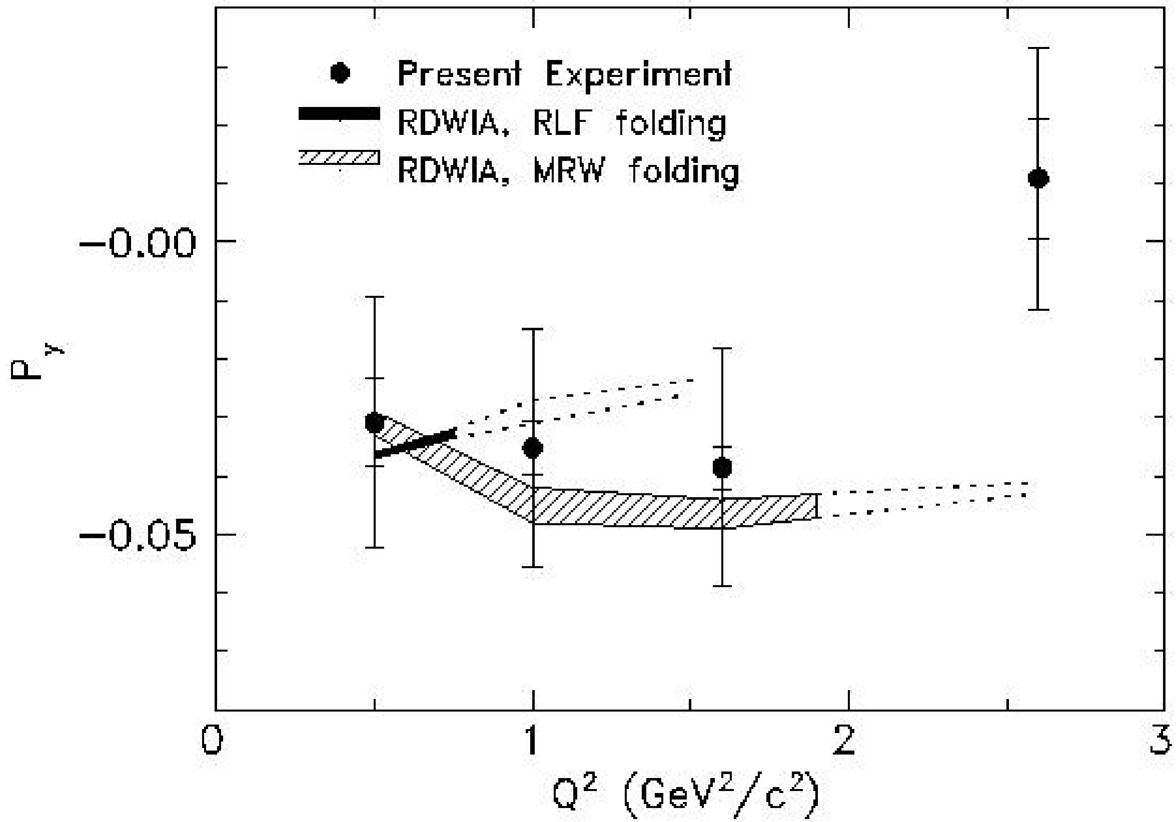
$^{4}\mathrm{He}(\vec{e},e'\vec{p})^{3}\mathrm{H}$



RDWIA calculations by Udias *et al.*

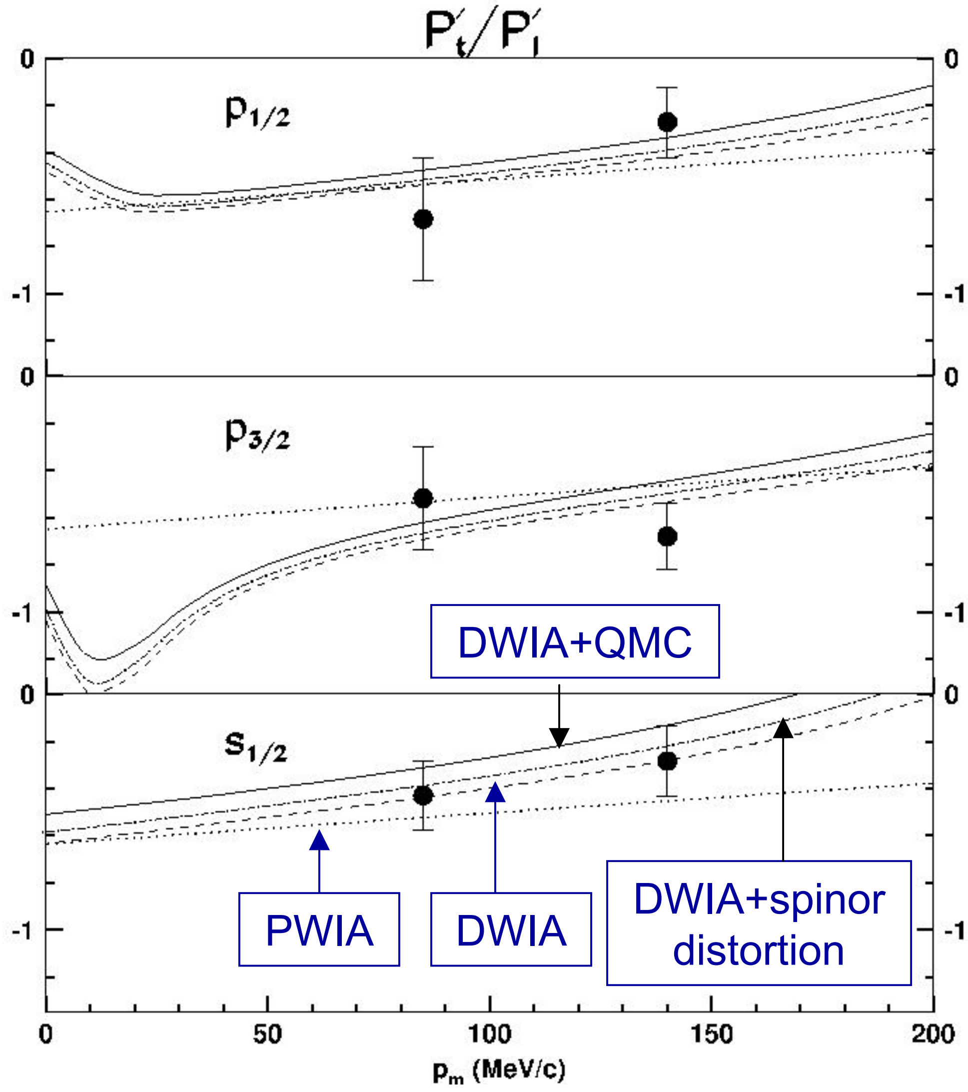
Induced Polarization – ^{4}He

JLab E93-049



P_y=0 in PWIA: test of FSI

$$^{16}\mathrm{O}(\vec{e},e'\vec{p})^{15}\mathrm{N} \text{ at } Q^2 = 0.8\,(\mathrm{GeV/c})^2$$

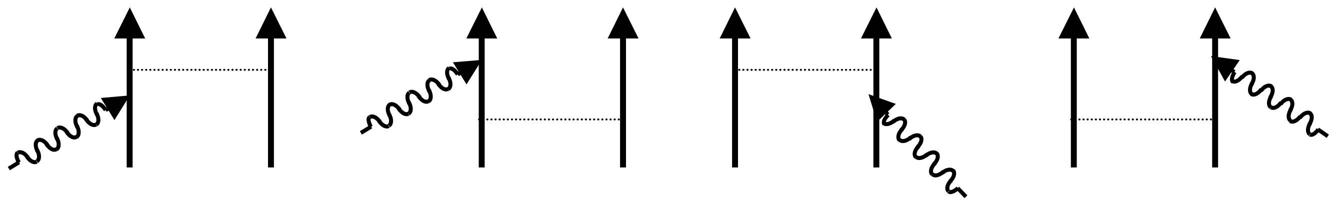


S. Malov *et al*., Phys. Rev. C **62**, 057302 (2000).

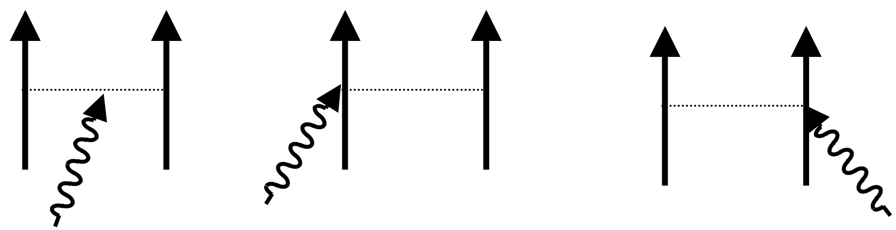
Studies of the Reaction Mechanism

Correlations and Interaction Currents

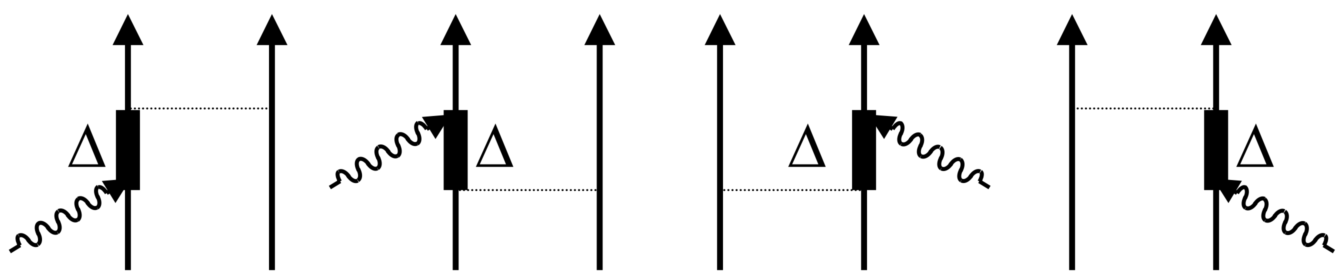
Correlations



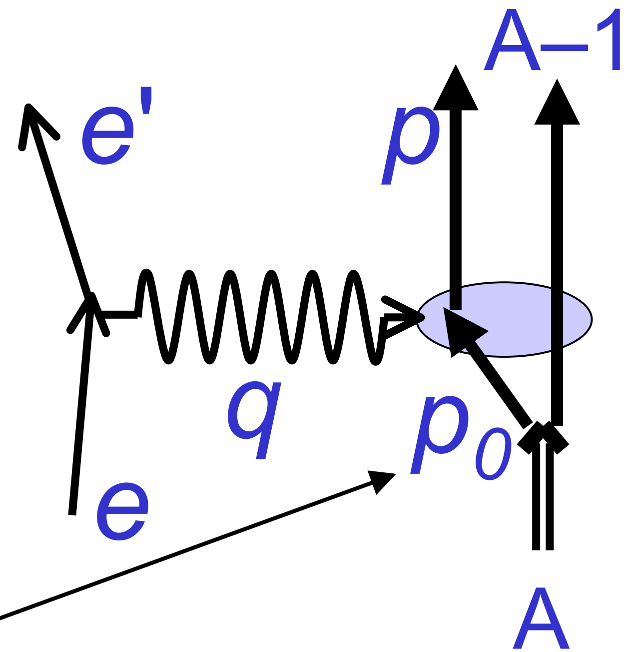
MEC's



IC's



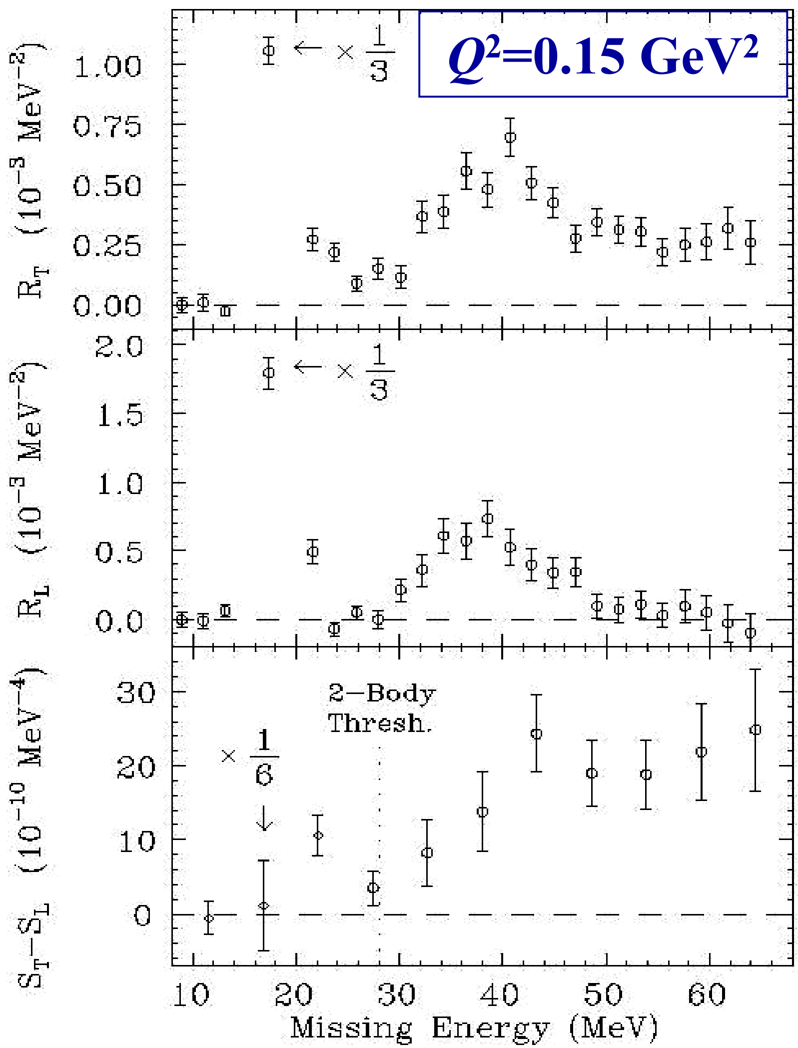
Off-shell Effects



initial proton is bound

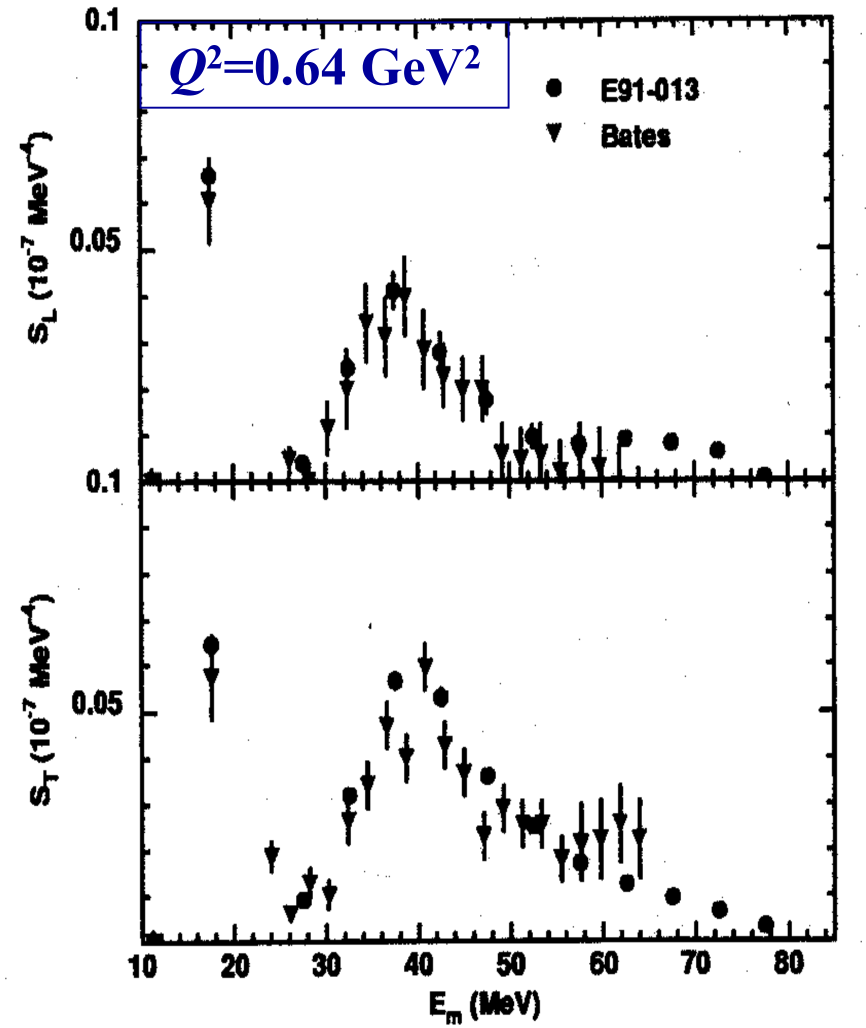
Vertex function is not well defined. The "Gordon identity" leads to alternative forms, equivalent only when proton is on-shell.

$^{12}C(e,e'p)$ L/T Separations



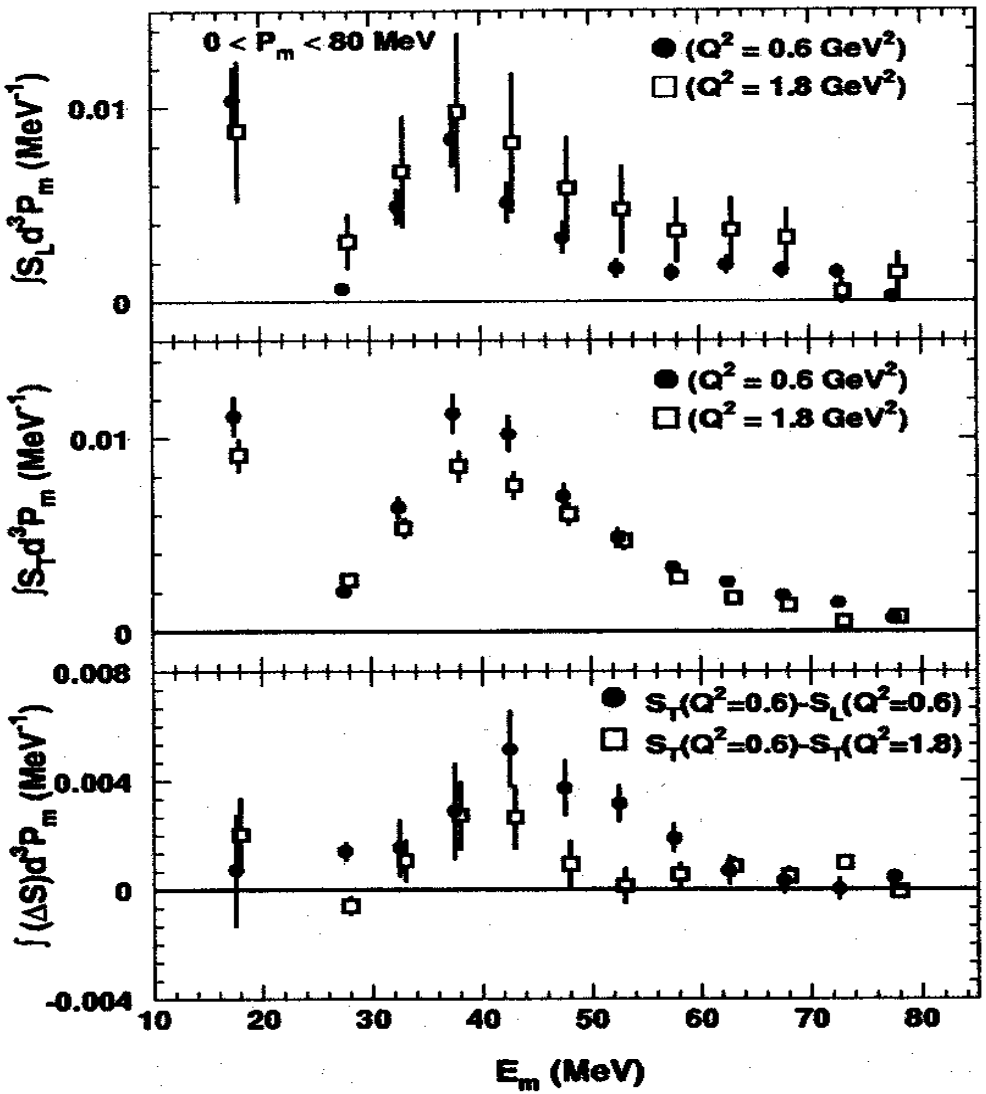
P.E. Ulmer *et al.*, Phys. Rev. Lett. **59**, 2259 (1987).

Bates Linear Accelerator



D. Dutta *et al.,* Phys. Rev. C **61**, 061602 (2000).

JLab Hall C



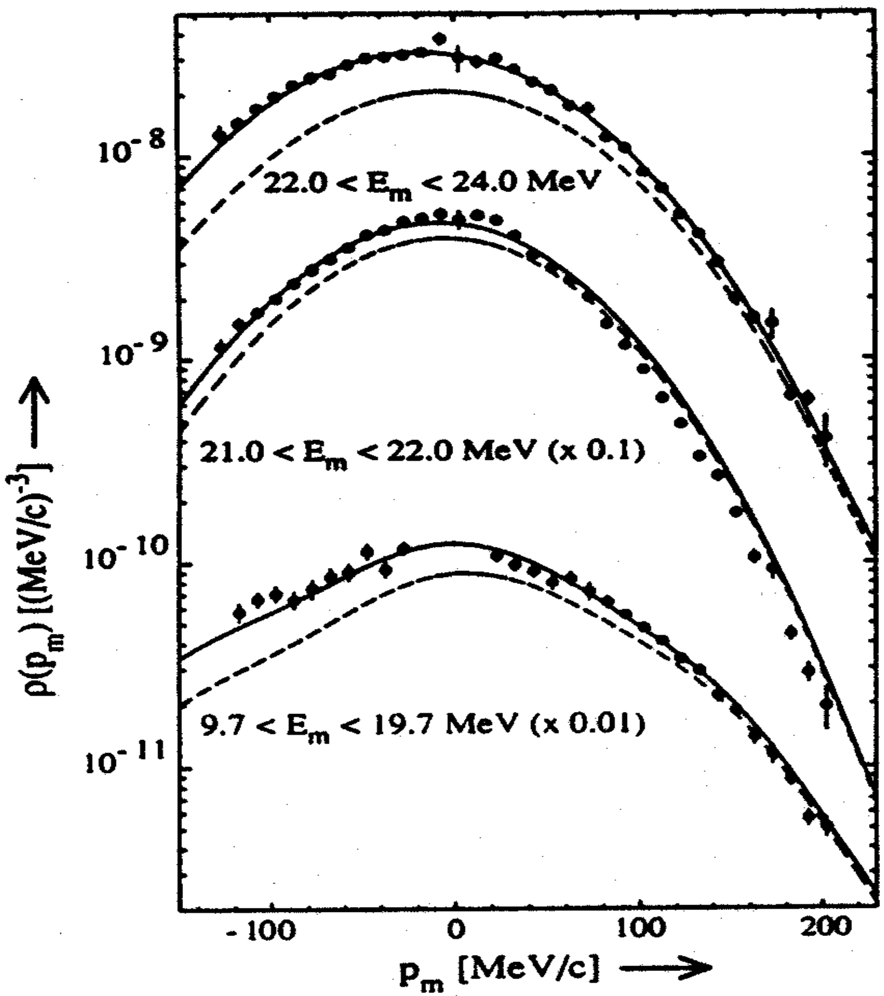
Excess transverse strength at high ε_m.

Persists, though perhaps declines, at higher Q^2.

JLab Hall C

D. Dutta *et al.*, Phys. Rev. C **61**, 061602 (2000).

^{6}Li(e,e'p) T/L Ratio



DWIA (dashed) fails to describe overall strength.

Scaling transverse amplitude in DWIA (solid) gives good agreement → deduce scale factor, η.

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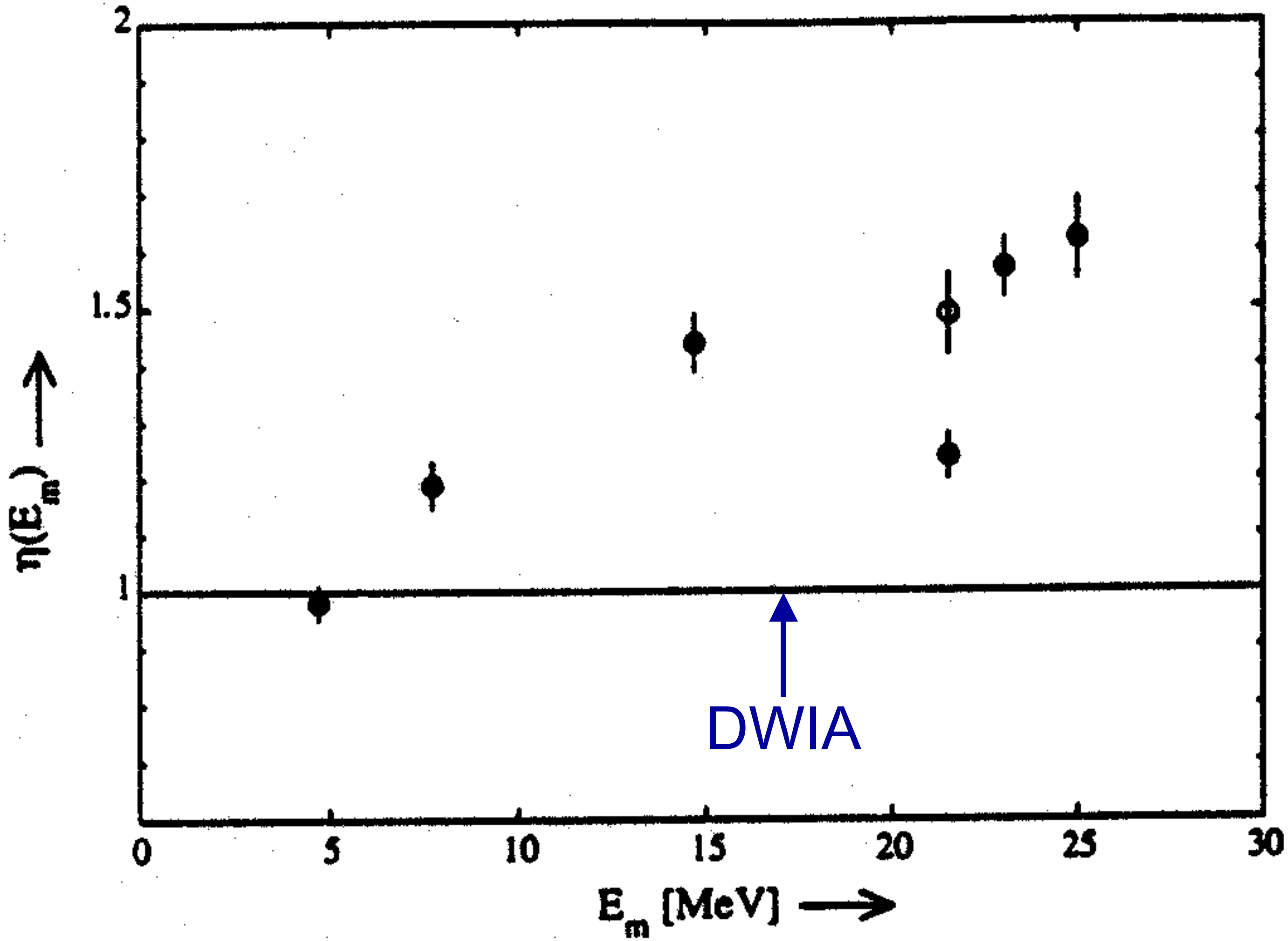
Amsterdam

J.B.J.M. Lanen *et al.,* Phys. Rev. Lett. **64**, 2250 (1990).

^{6}Li(e,e'p) T/L Ratio



J.B.J.M. Lanen *et al.*, Phys. Rev. Lett. **64**, 2250 (1990).

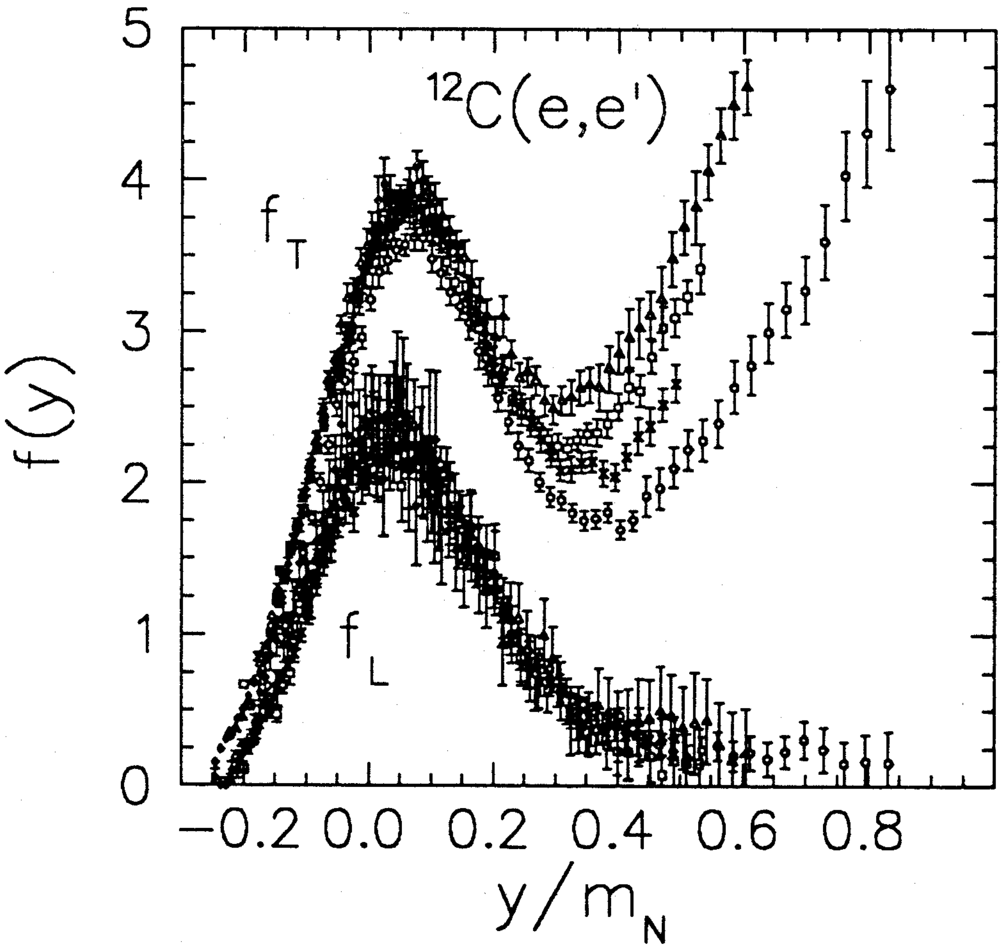
NIKHEF-K Amsterdam

The L/T separations suggest

- Additional transverse reaction mechanism above 2-nucleon emission threshold.
- MEC's primarily transverse in character. Suggestive of two-body current.

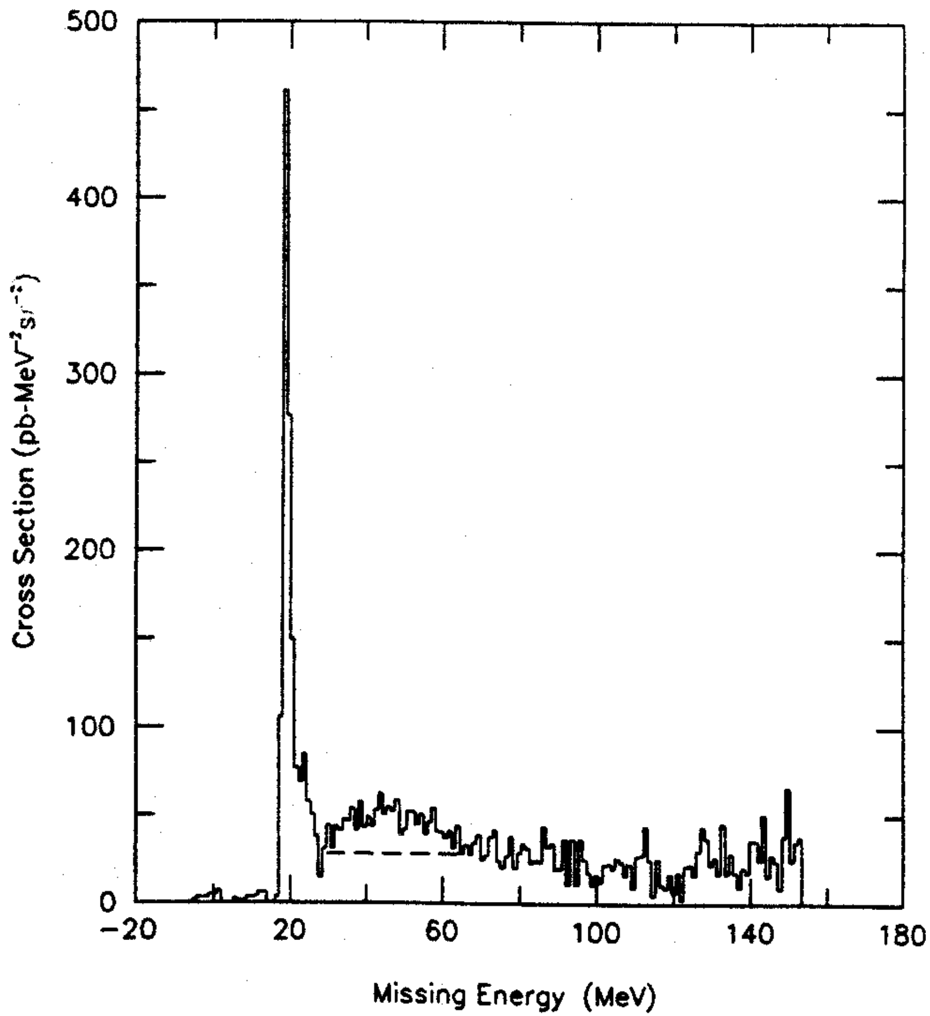
Reminiscent of …

T/L anomaly in inclusive (e,e'):



J.M. Finn, R.W. Lourie and B.H. Cottman, Phys. Rev. C **29**, 2230 (1984).

$^{12}C(e,e'p)$ in “Dip Region”



Bates
Linear
Accelerator

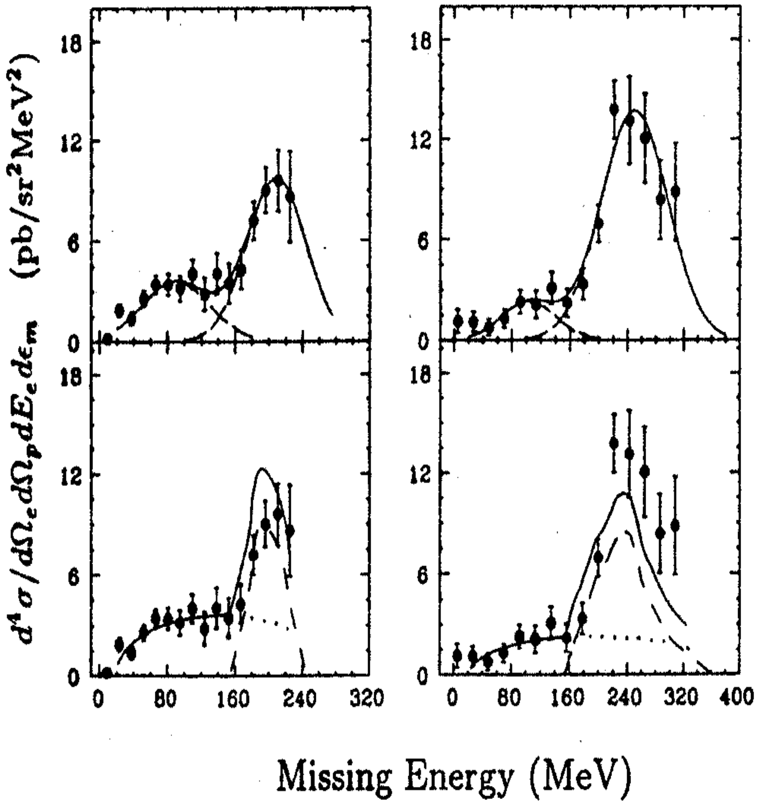
R.W. Lourie *et al.*, Phys. Rev. Lett. **56**, 2364 (1986).

Data from: Bates Linear Accelerator

$^{12}C(e,e'p)$

"Delta"

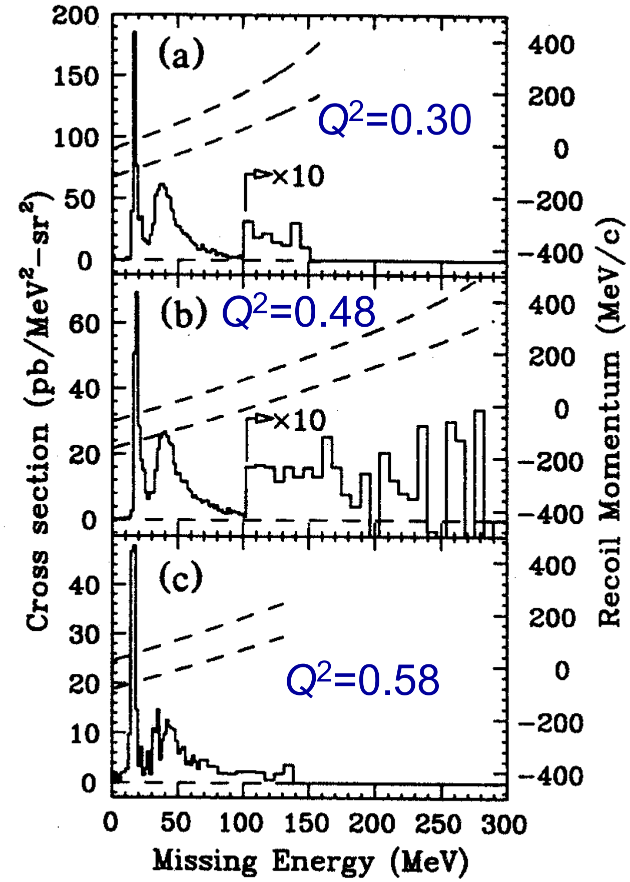
Between dip and Δ   Peak of Δ



H. Baghaei *et al.*,
Phys. Rev. C **39**, 177 (1989).

Bates Linear Accelerator

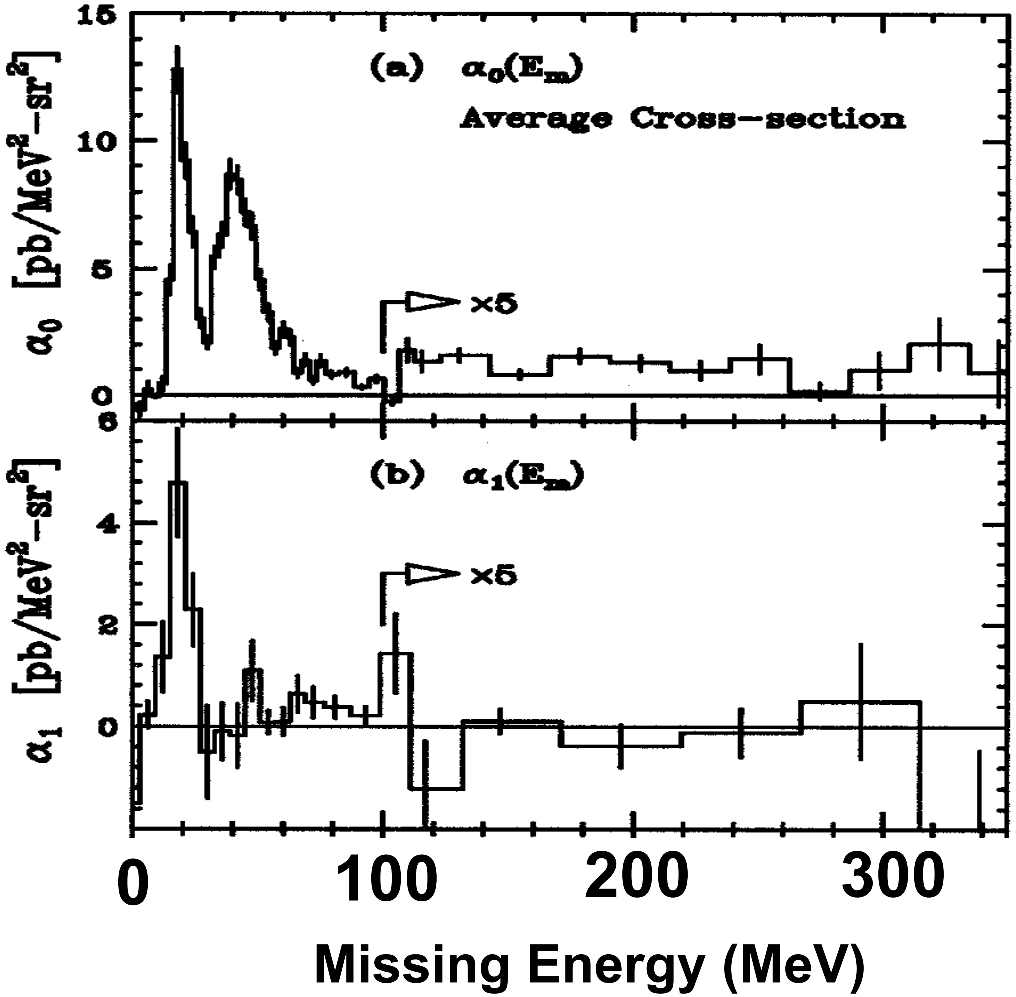
Quasielastic



L.B. Weinstein *et al.*,
Phys. Rev. Lett. **64**, 1646 (1990).

Bates Linear Accelerator

$^{12}C(e,e'p)$ q=990 MeV/c, ω=475 MeV



$$\frac{d^6\sigma}{d\Omega_e d\Omega_p d\omega\, d\varepsilon_m} = \sum_{l=0}^{l_{max}} \alpha_l(\varepsilon_m) P_l\left(\frac{\omega - \omega_0}{\Delta\omega/2}\right)$$

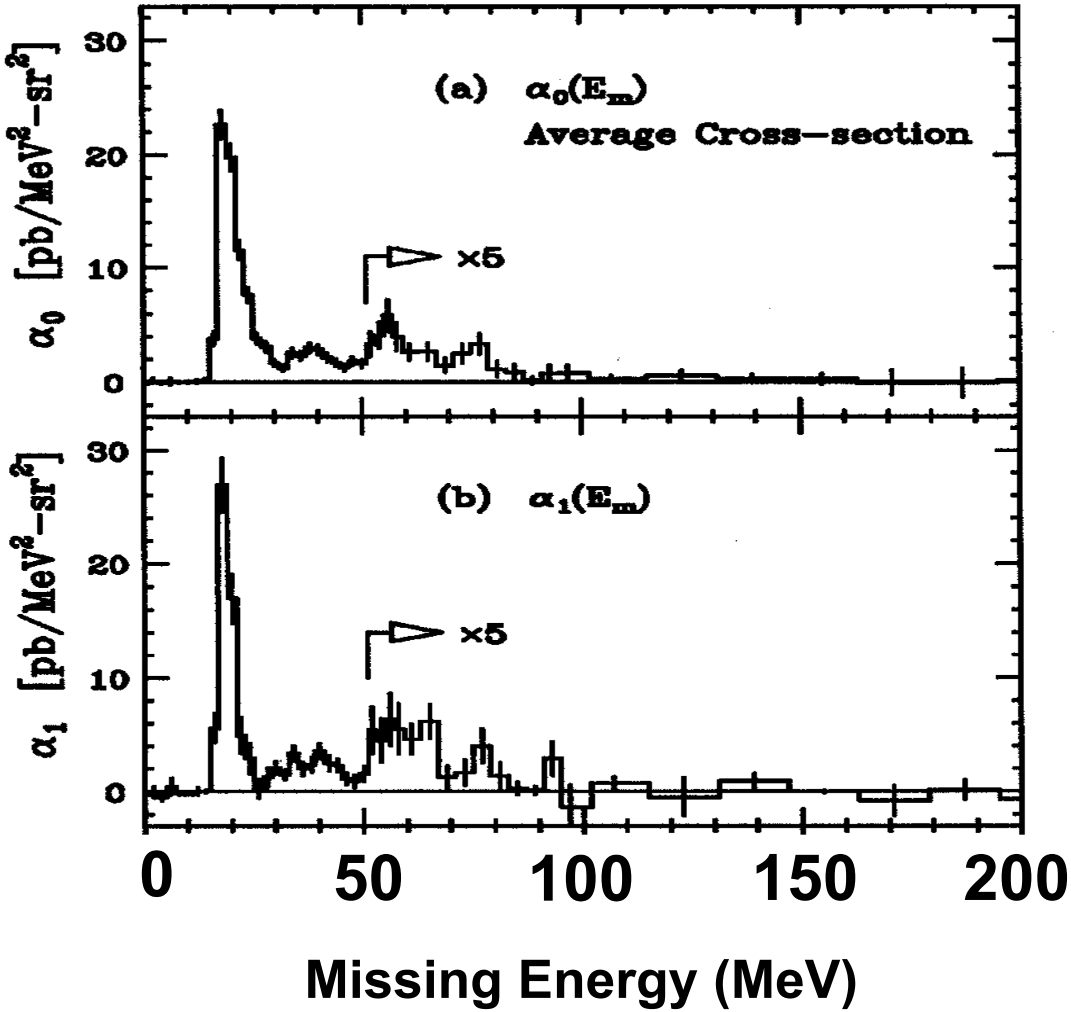
For 60<ε_m<100 MeV, continuum cross section increases strongly with ω.

Large continuum strength continues up to 300 MeV.

Bates Linear Accelerator

Figure adapted from J.H. Morrison *et al.*, Phys. Rev. C **59**, 221 (1999).

$^{12}C(e,e'p)$ q=970 MeV/c, ω=330 MeV



$$\frac{d^6\sigma}{d\Omega_e d\Omega_p d\omega\, d\varepsilon_m} = \sum_{l=0}^{l_{max}} \alpha_l(\varepsilon_m) P_l\left(\frac{\omega - \omega_0}{\Delta\omega/2}\right)$$

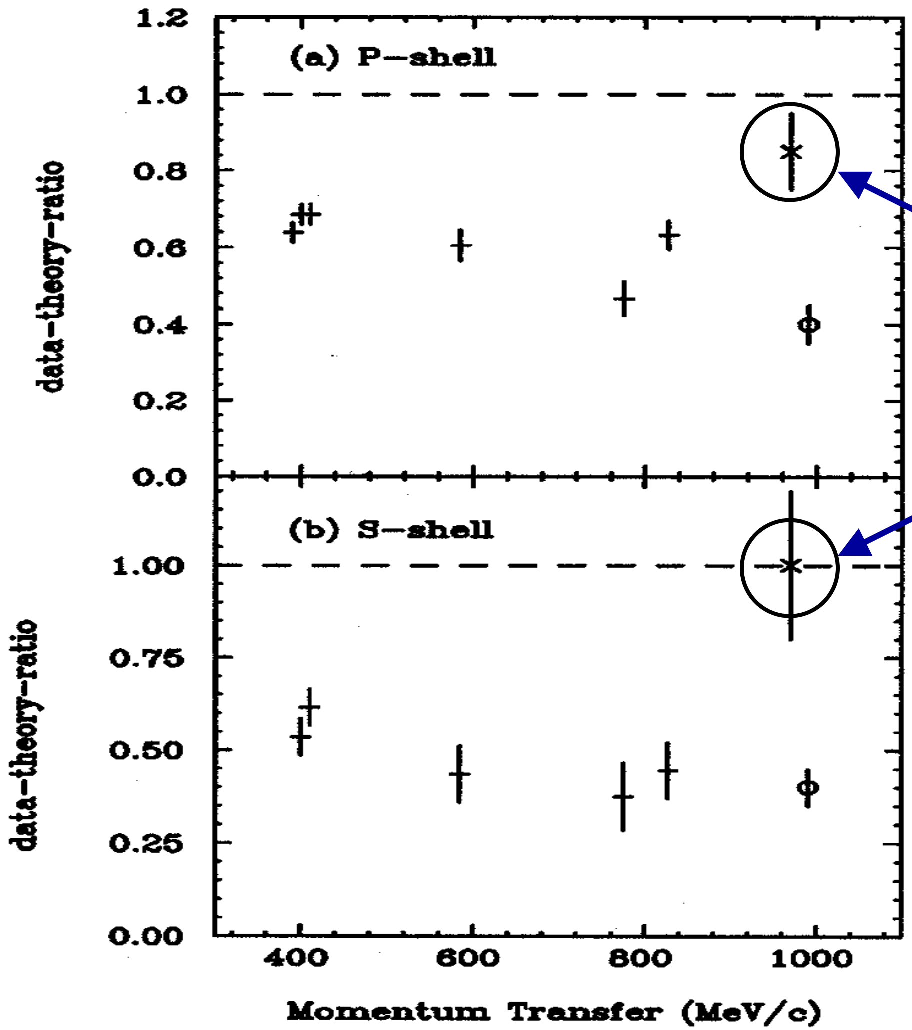
Continuum strength increases strongly with ω.

Continuum cross section is smaller at high ε_m.

Figure adapted from J.H. Morrison *et al*., Phys. Rev. C **59**, 221 (1999).

Bates Linear Accelerator

$^{12}C(e,e'p)$

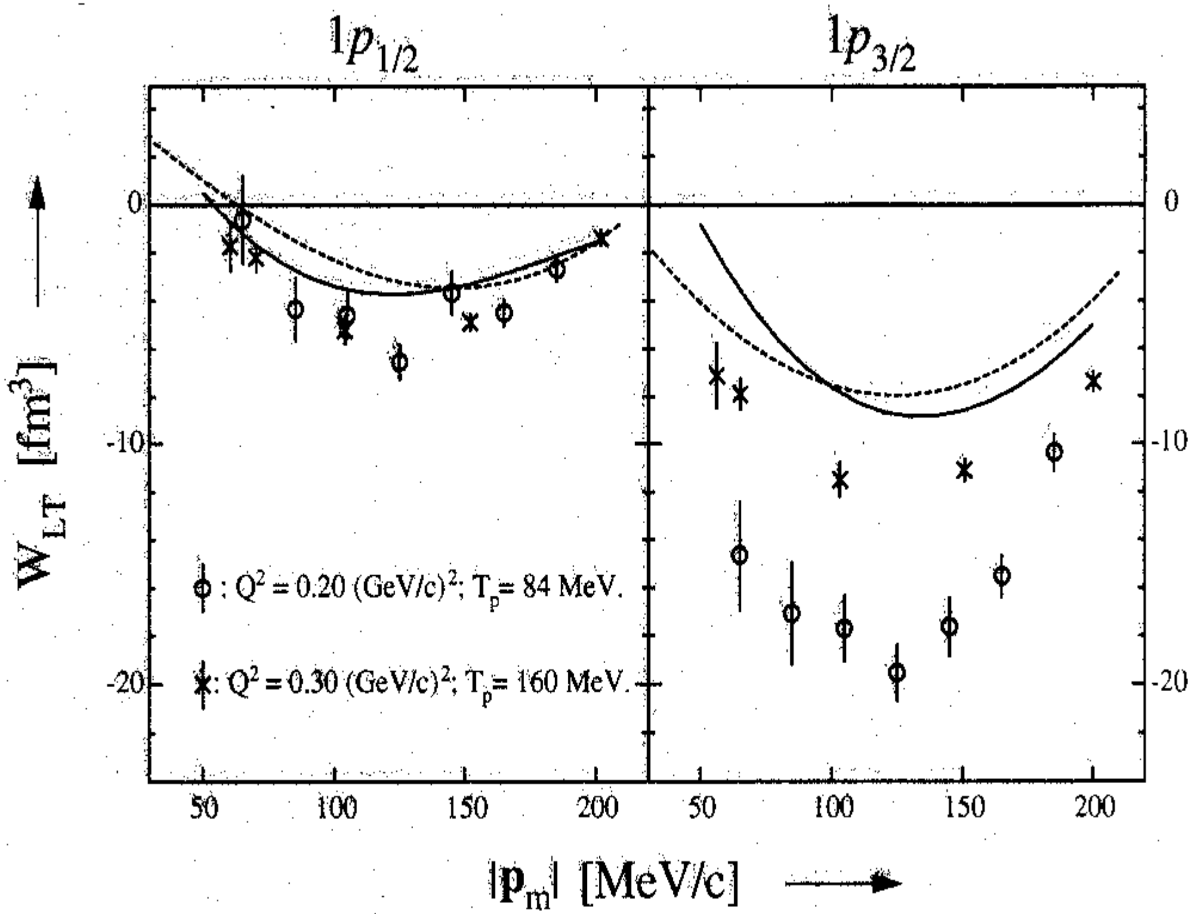


For $\omega<\omega_{QE}$, spectroscopic factors consistent with naïve expectations.

Bates Linear Accelerator

J.H. Morrison *et al*., Phys. Rev. C **59**, 221 (1999).

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



Large discrepancy for $1p_{3/2}$.

Relativistic effects predicted to be small here.

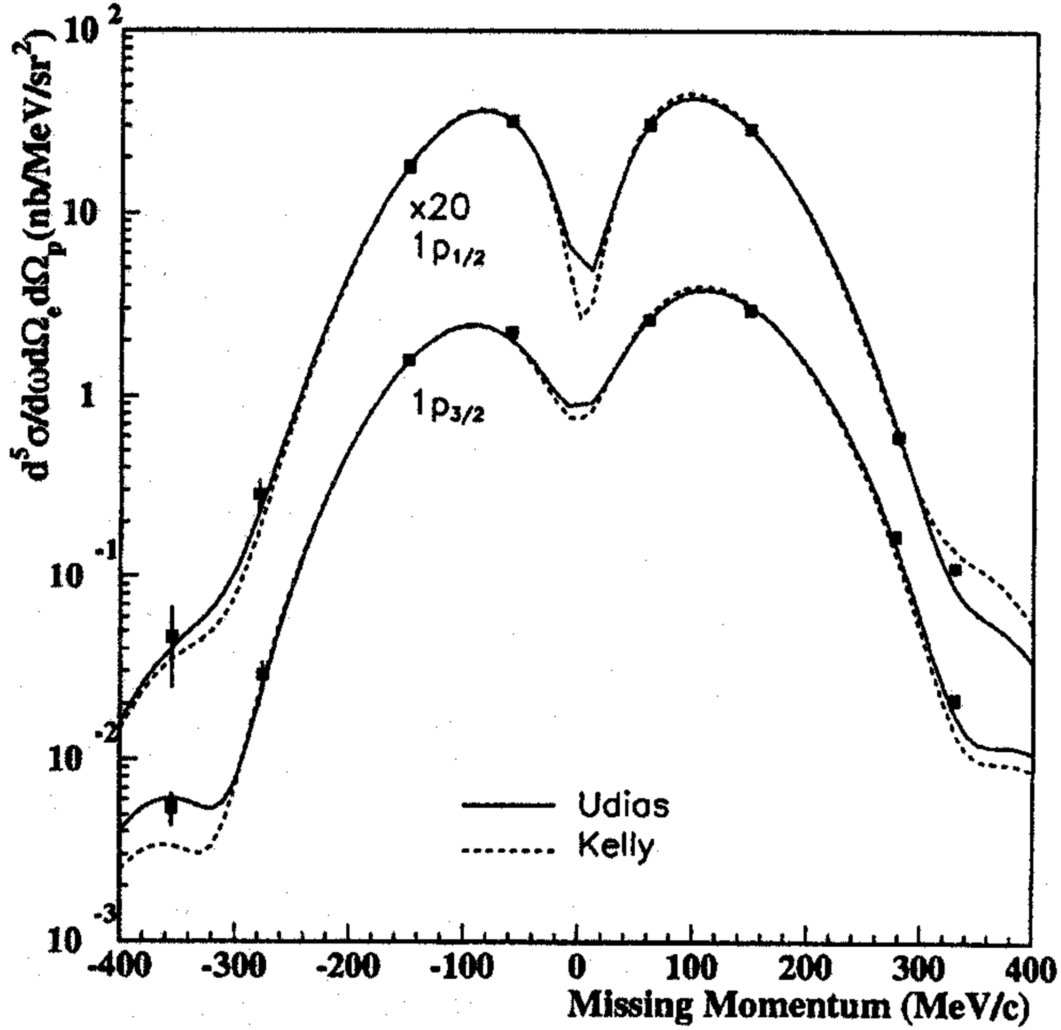
Two-body currents responsible??

C.M. Spaltro *et al.*, Phys. Rev. C **48**, 2385 (1993).

Circles (solid) – NIKHEF-K

Crosses (dashed) - Saclay

$^{16}O(e,e'p)$ Q^2=0.8 GeV^2 Quasielastic

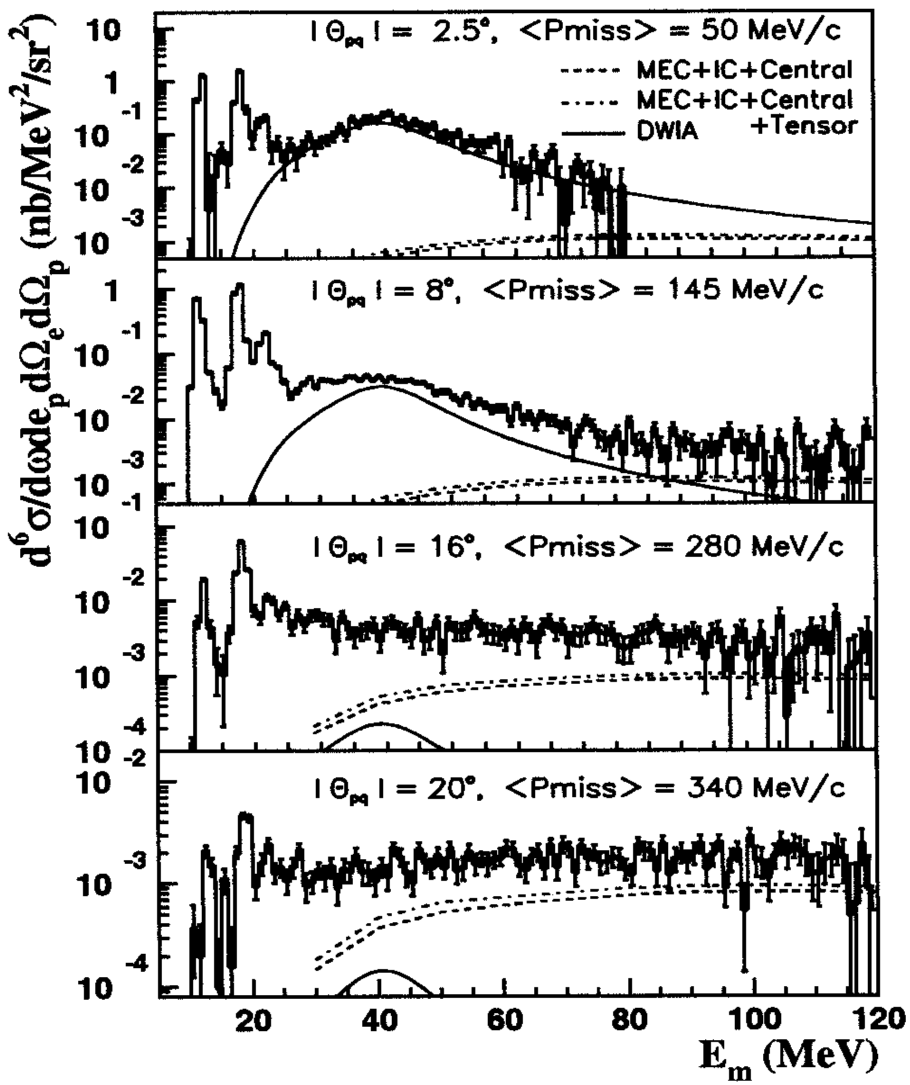


Relativistic DWIA gives good agreement with data.

JLab Hall A

J. Gao *et al*., Phys. Rev. Lett. **84**, 3265 (2000).

$^{16}O(e,e'p)$ Q^2=0.8 GeV^2 Quasielastic



Two-body calculations of Ryckebusch *et al.*, give flat distribution, as seen in the data, but underpredict by a factor of two.

JLab Hall A

N. Liyanage *et al.*, Phys. Rev. Lett. **86**, 5670 (2001).

At high energies, R_{LT} interference response function sensitive to relativistic effects.

For example, spinor distortion …

Spinor Distortions

$$\Psi = \begin{pmatrix} \Psi_+ \\ \Psi_- \end{pmatrix}$$

$$\Psi_- = \frac{\sigma \cdot p}{E + m + S - V} \Psi_+$$

N.R. reduction

S+*V* → Mean field

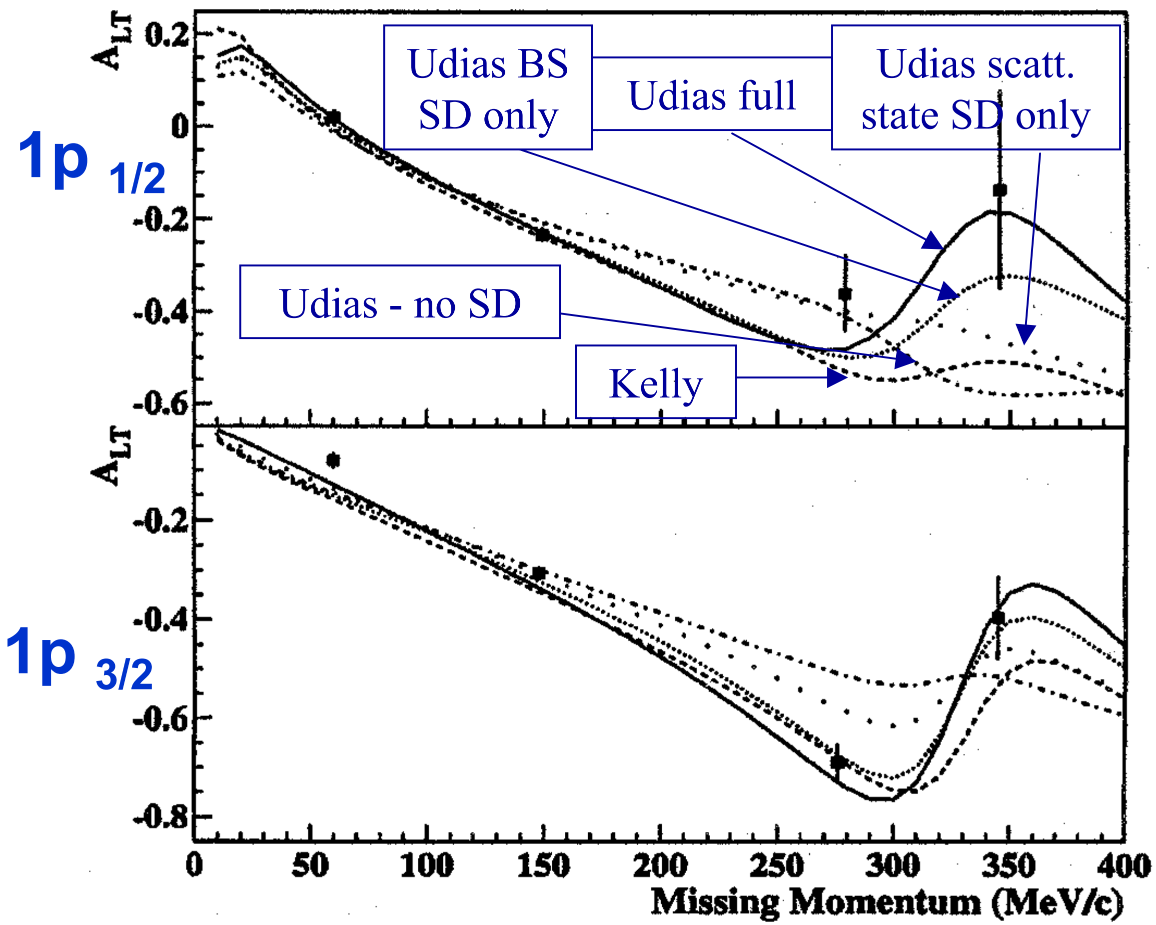
S+*V* relatively small

Dirac spinor

S–*V* affects lower components

S–*V* large

^{16}O(e,e'p) Q^2=0.8 GeV^2 Quasielastic



Sensitive to "spinor distortions"

JLab Hall A

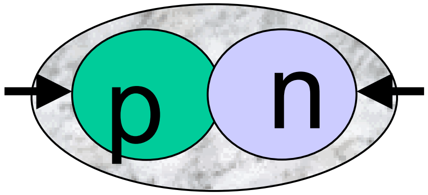
J. Gao *et al*., Phys. Rev. Lett. **84**, 3265 (2000).

Few-body Nuclei …

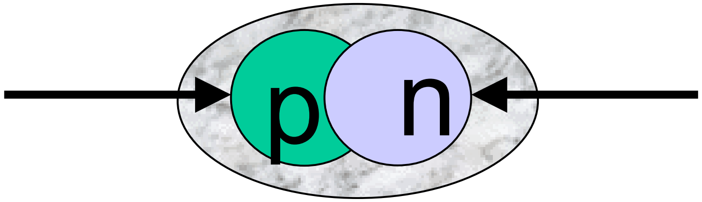
The Deuteron

Short-distance Structure

Low p_m

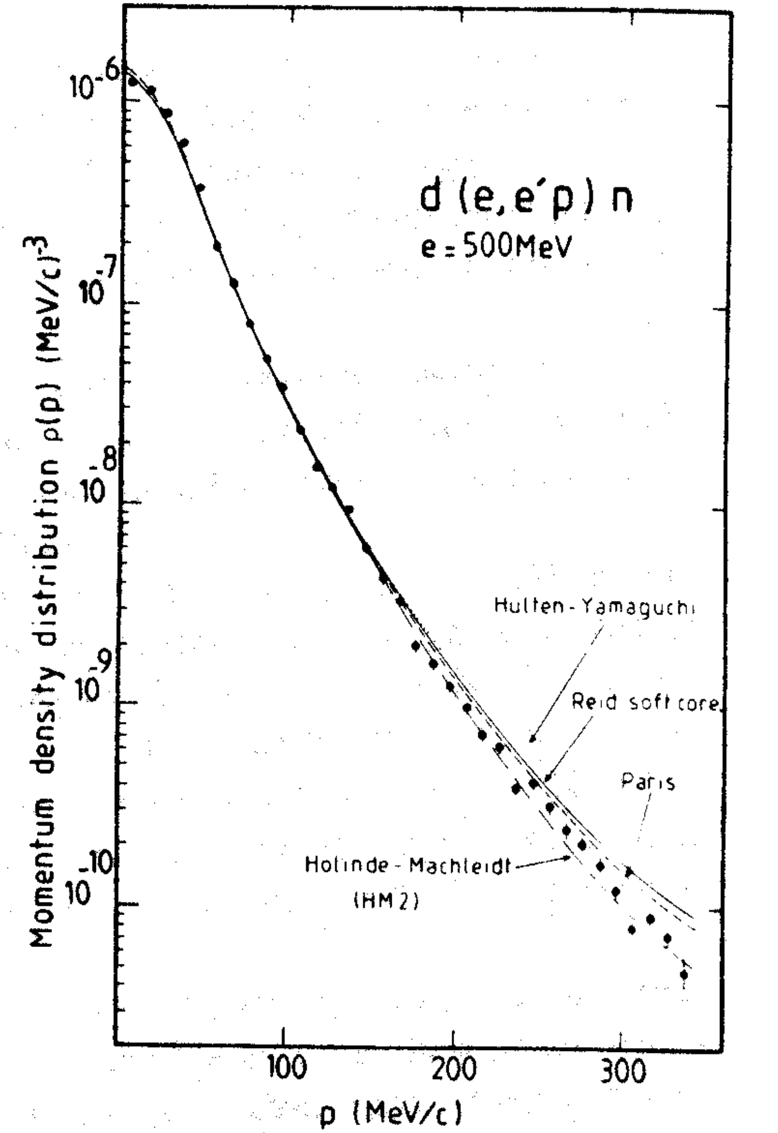


High p_m



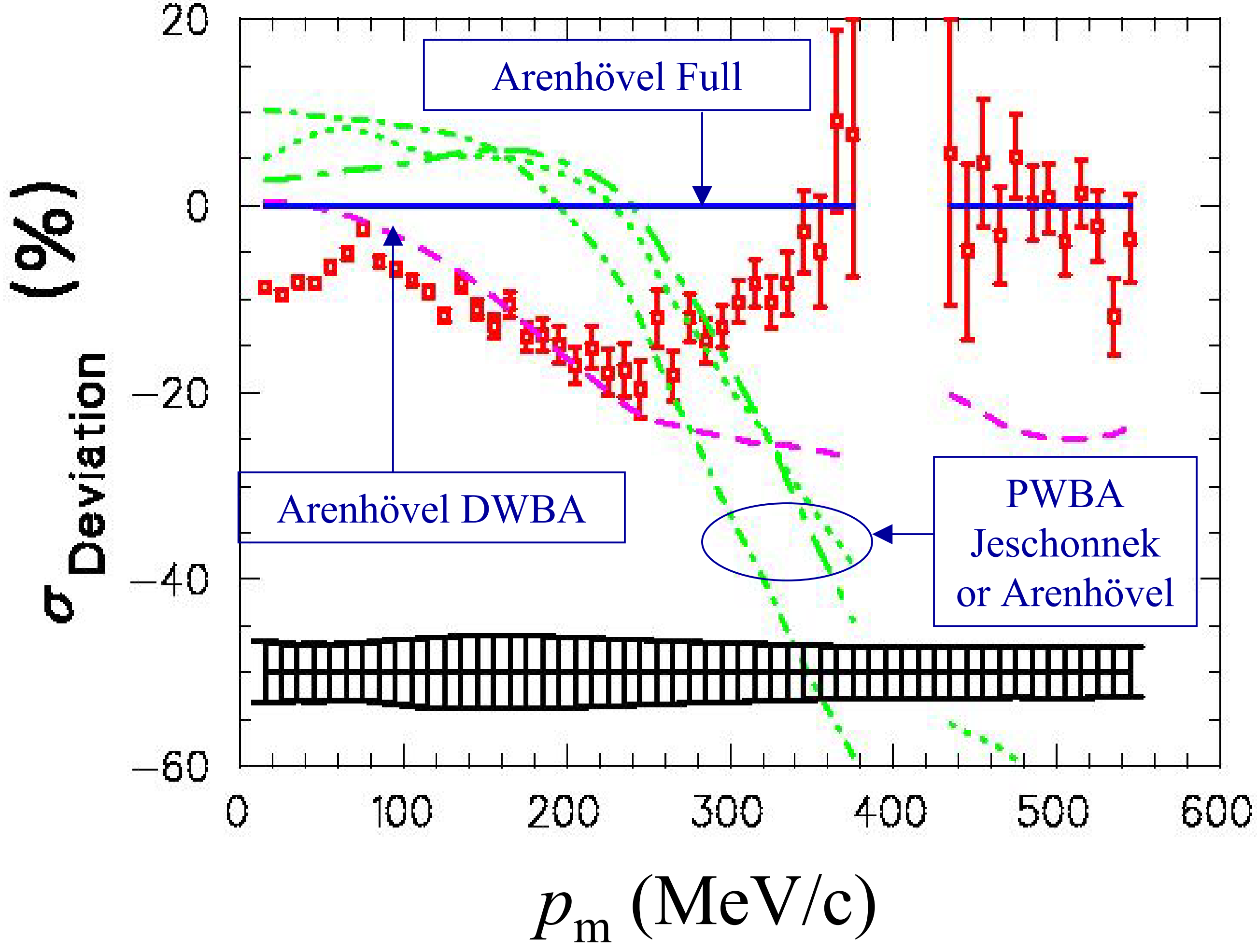
For large overlap, nucleons may lose individual identities:

Quark/gluon d.o.f.?



Saclay
Linac,
France

M. Bernheim *et al*., Nucl. Phys. **A365**, 349 (1981).



Large FSI/non-nucleonic effects.

Problem at p_m=0.

JLab
Hall A

P.E. Ulmer *et al*., Phys. Rev. Lett. **89**, 062301 (2002).

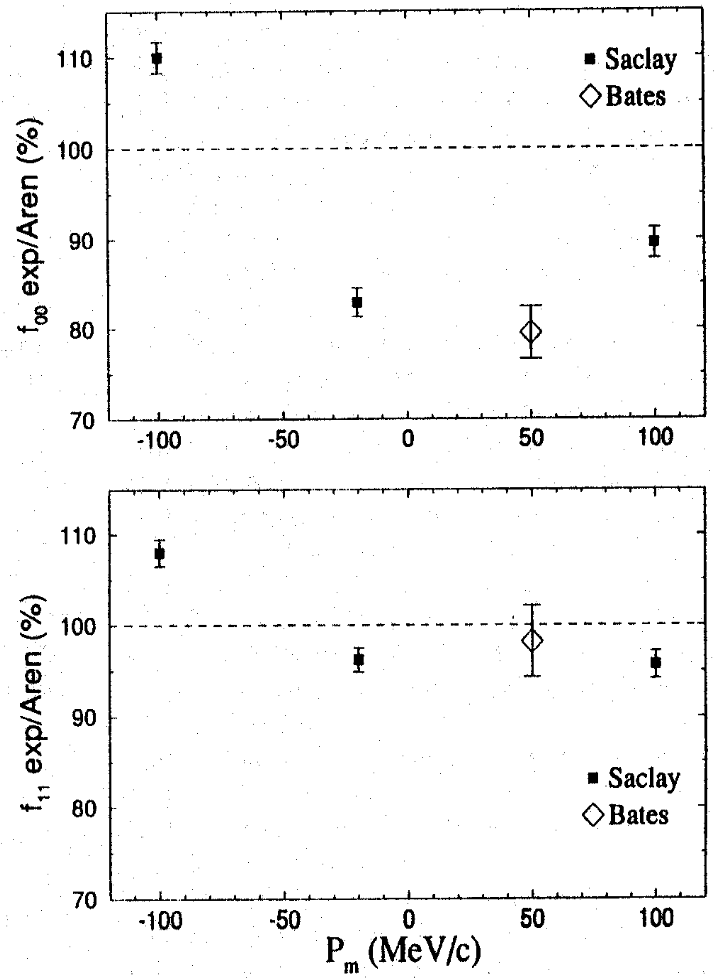


FIG. 1. Ratio of measured f_{00} and f_{11} structure functions to Arenhövel's calculation for this experiment and the Saclay experiment of Ducret *et al.* [6]. Only statistical errors are shown.

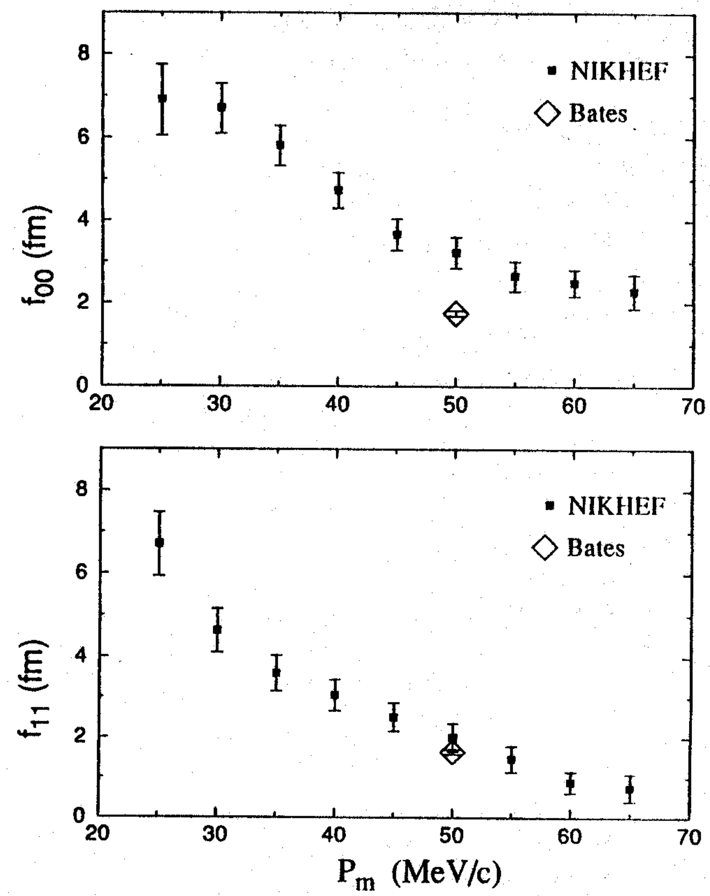
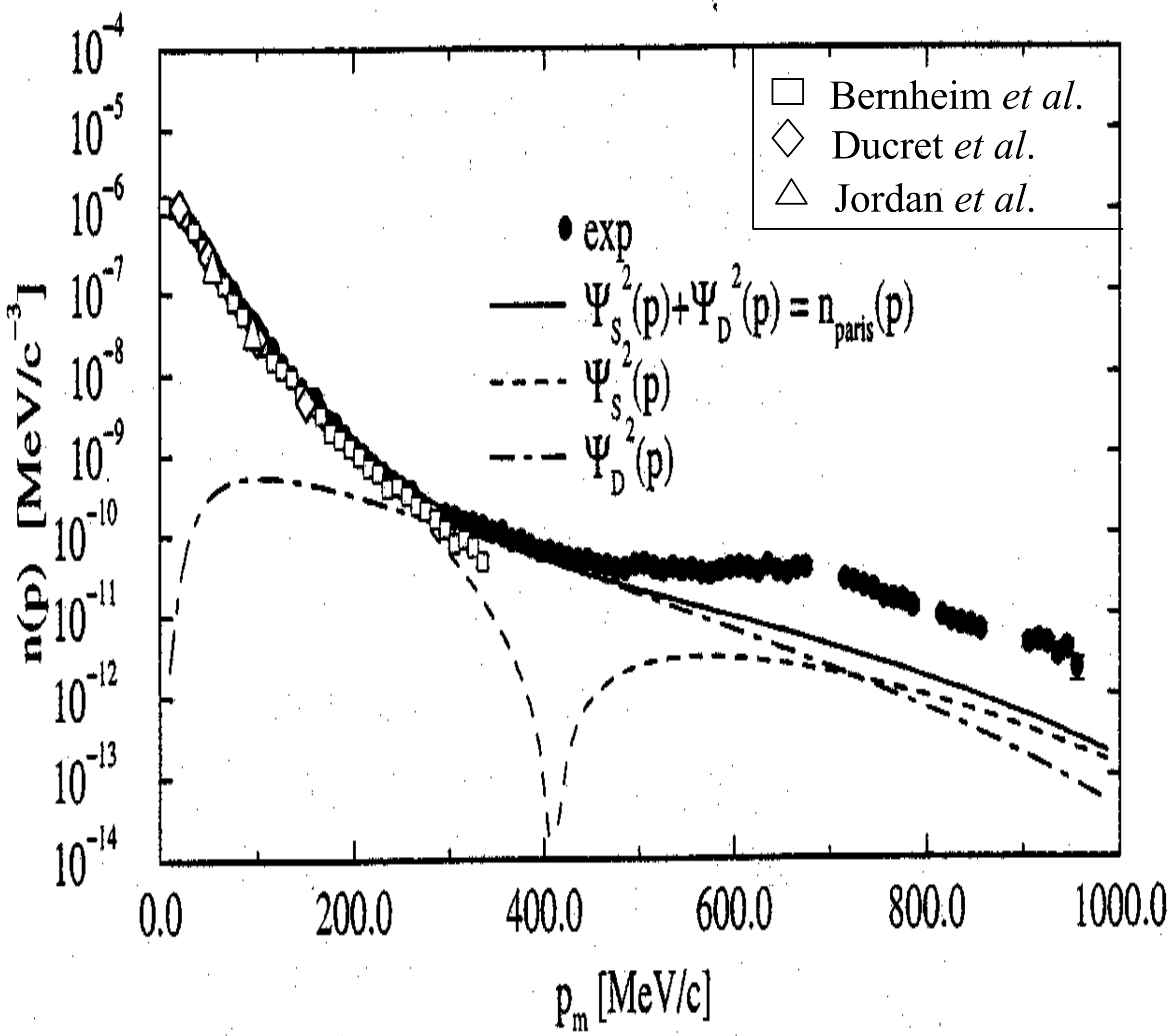


FIG. 2. Separated f_{00} and f_{11} structure functions for this experiment and the NIKHEF experiment of van der Schaar *et al.* [5]. The NIKHEF data ($q = 380$ MeV/c) are averaged over 5 MeV/c bins in p_m. The Bates data ($q = 400$ MeV/c) are averaged over the range of 30 to 70 MeV/c in p_m. Only statistical errors are shown.

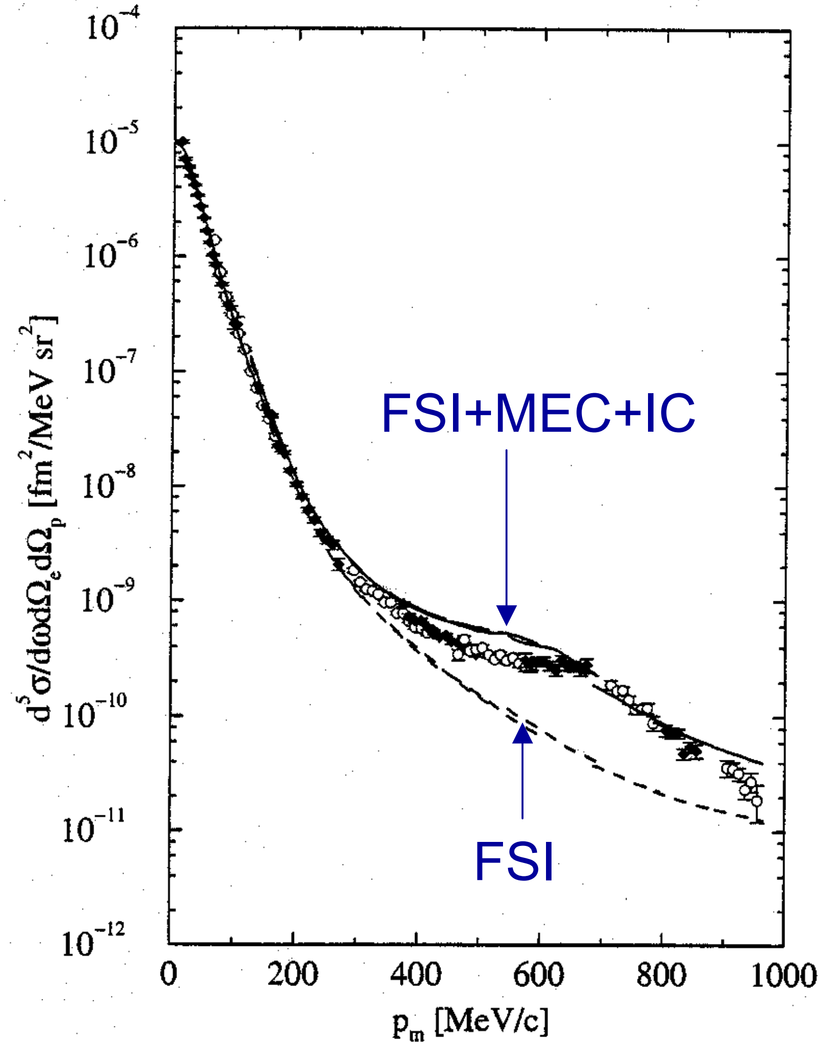
D. Jordan *et al.*, Phys. Rev. Lett. **76**, 1579 (1996).



Blomqvist *et al.* data cover kinematics beyond Δ. Also neutron exchange diagram important.

MAMI
Mainz,
Germany

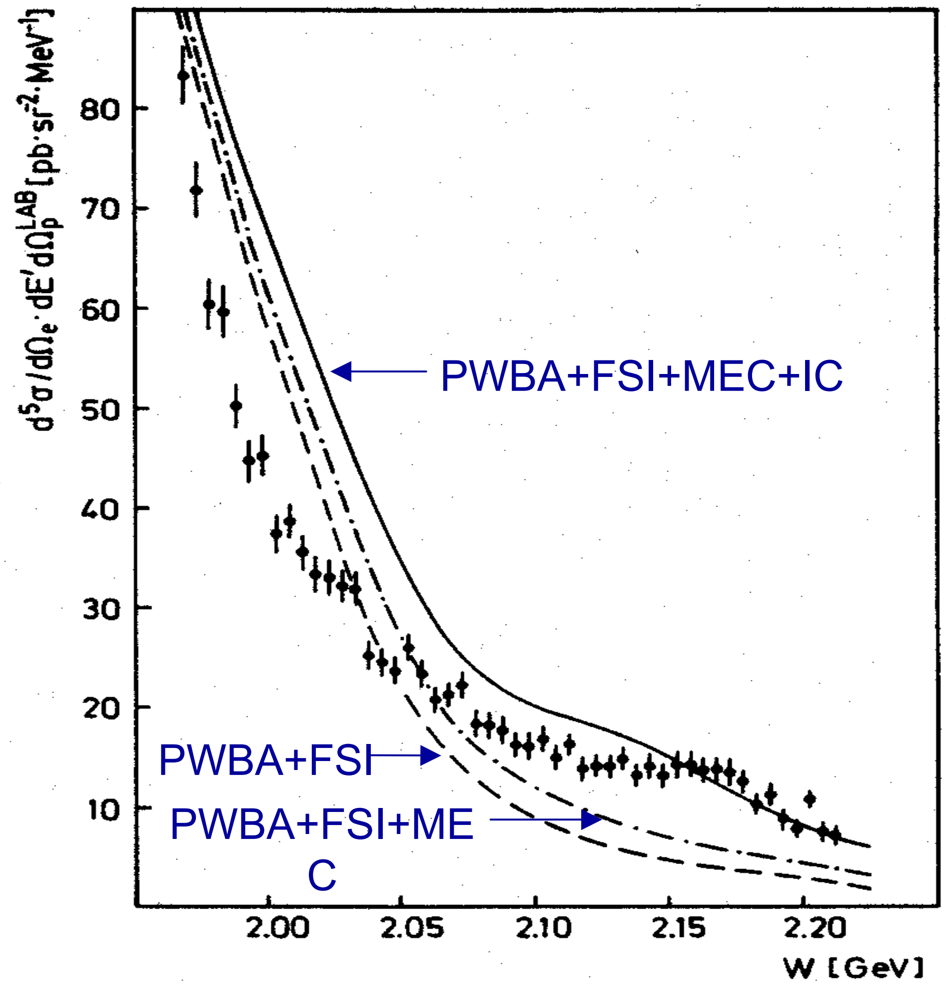
K.I. Blomqvist *et al*., Phys. Lett. B **424**, 33 (1998).



K.I. Blomqvist *et al*., Phys. Lett. B **424**, 33 (1998).

Calculations: H. Arenhövel

^{2}H(e,e'p) Q^2=0.23 GeV^2 near Δ

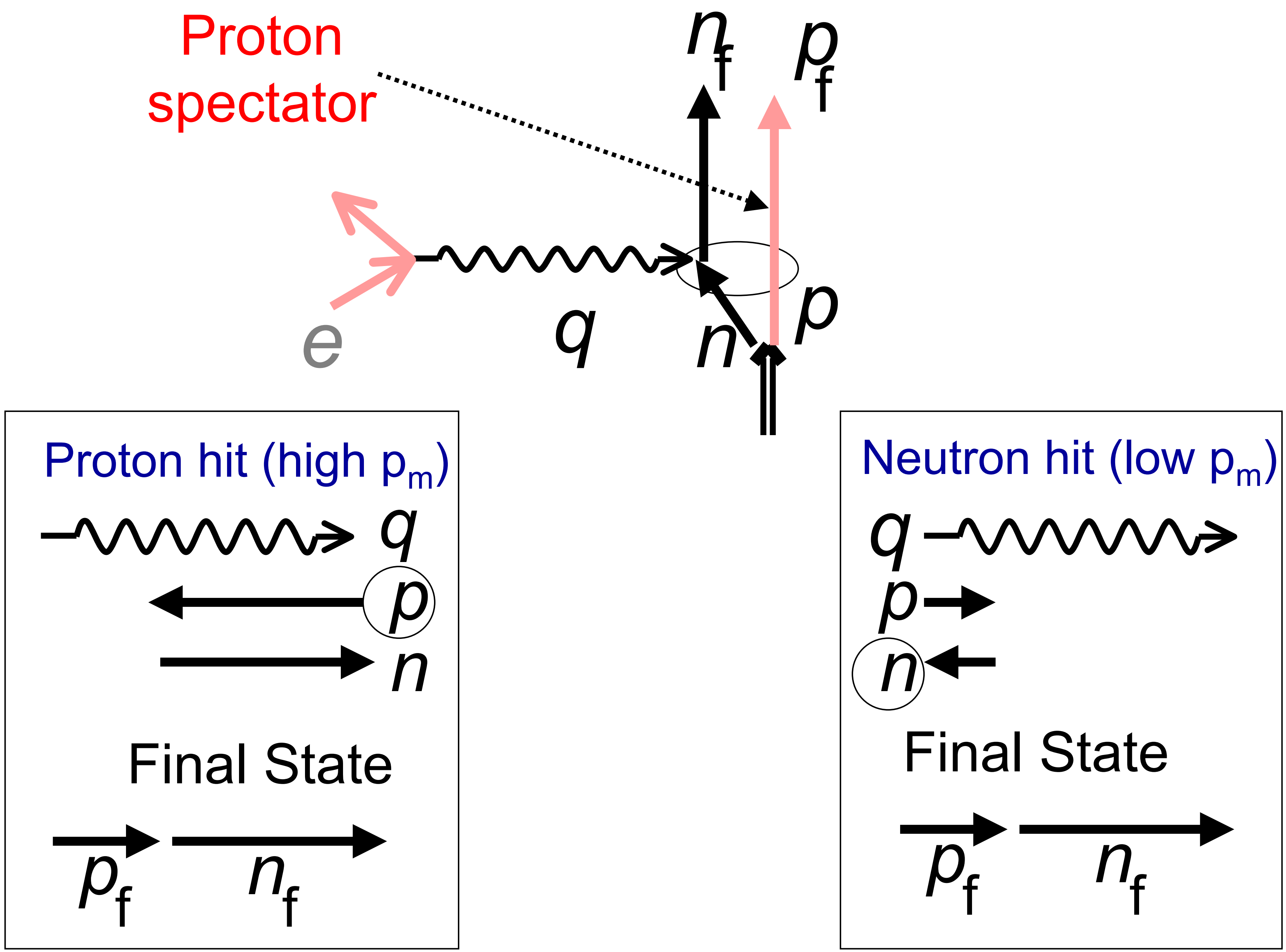


Δ clearly important

Bonn Electron Synchrotron, Germany

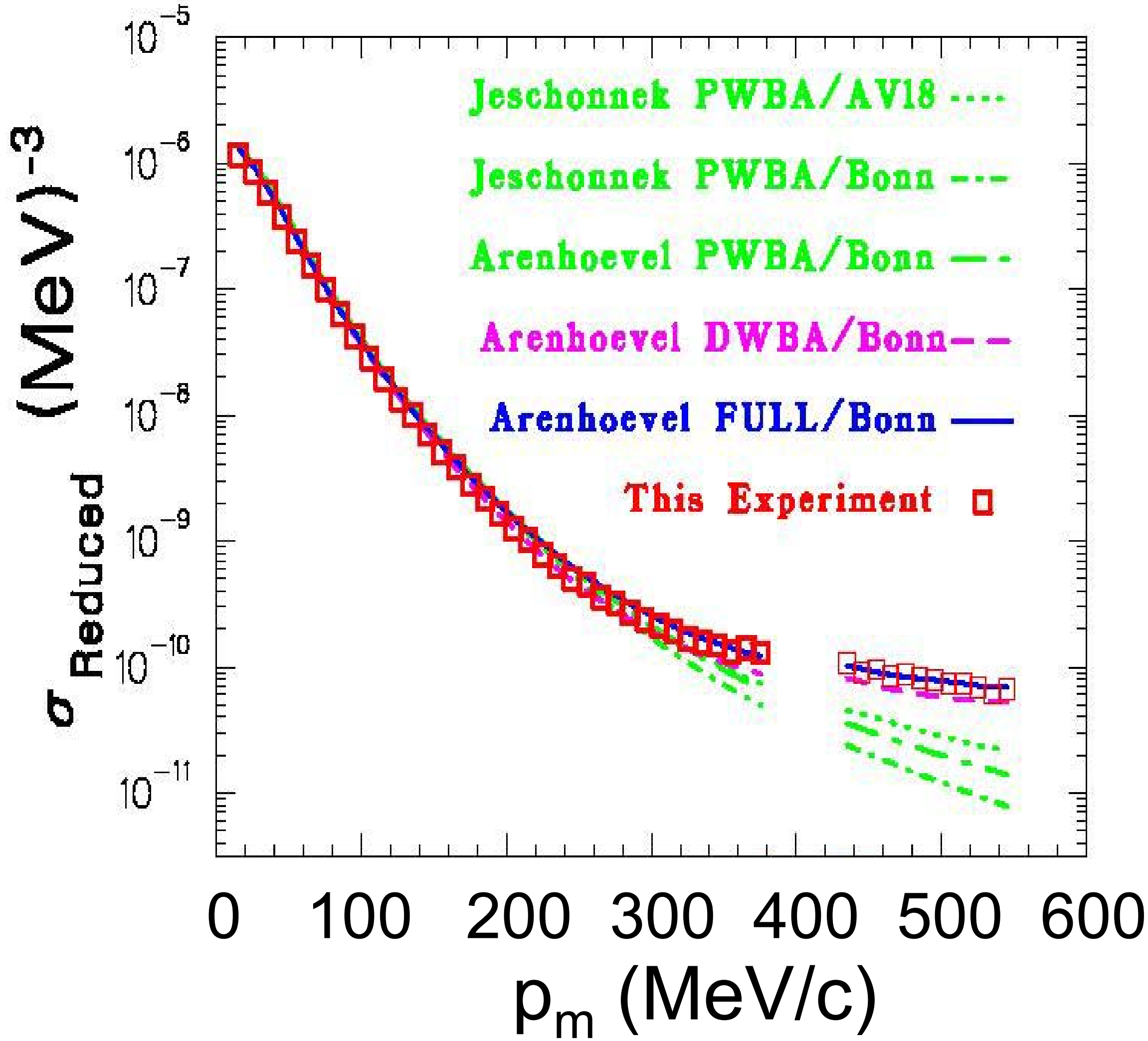
H. Breuker *et al*., Nucl. Phys. **A455**, 641 (1986).

Calculations: Leidemann and Arenhövel



Proton
spectator
n
f
p
f
e
q
n
p
Proton hit (high p
m
)
q
p
n
Final State
p
f
n
f
Neutron hit (low p
m
)
q
p
n
Final State
p
f
n
f

Q^2=0.67 GeV^2 Quasielastic



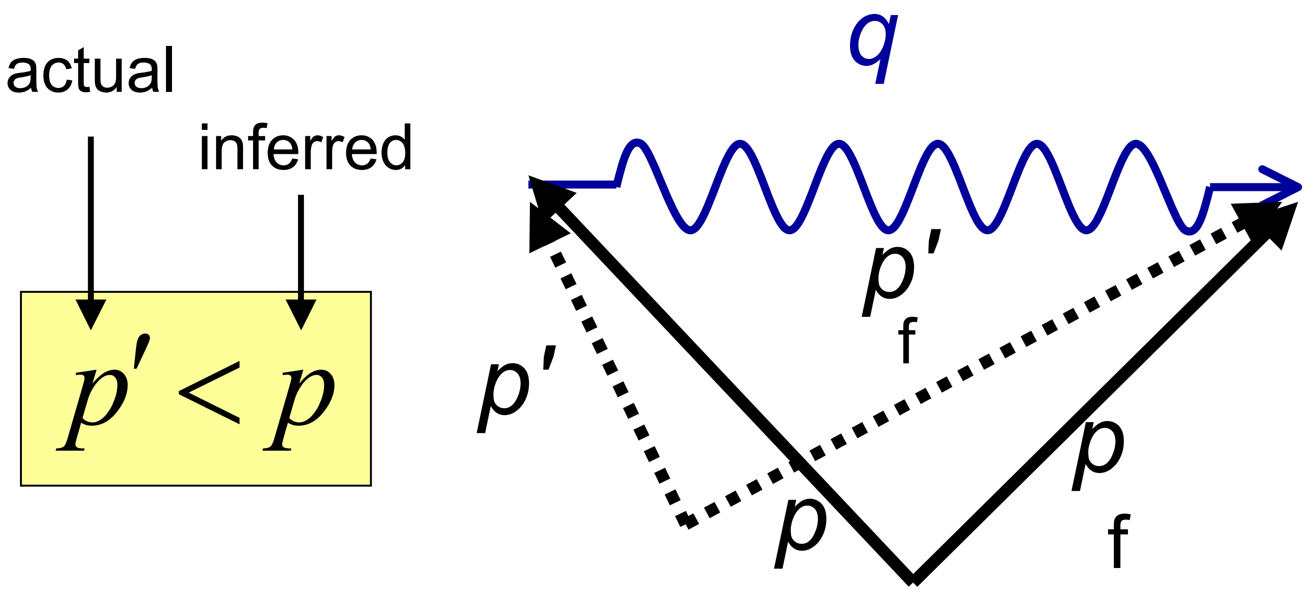
Large FSI effects.

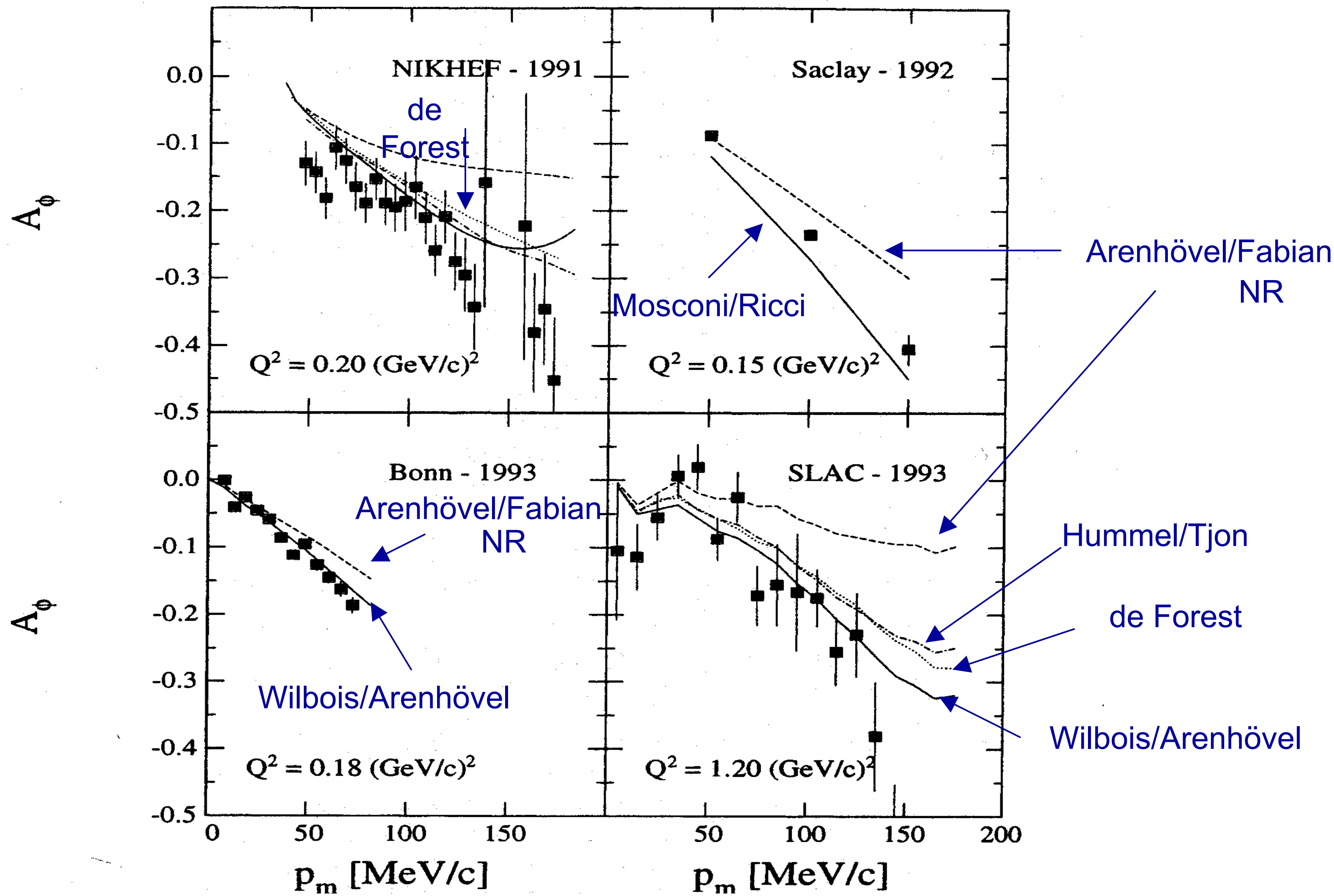
Also, substantial non-nucleonic effects.

JLab
Hall A

P.E. Ulmer *et al.*, Phys. Rev. Lett. **89**, 062301 (2002).

Final State Interactions Can be LARGE





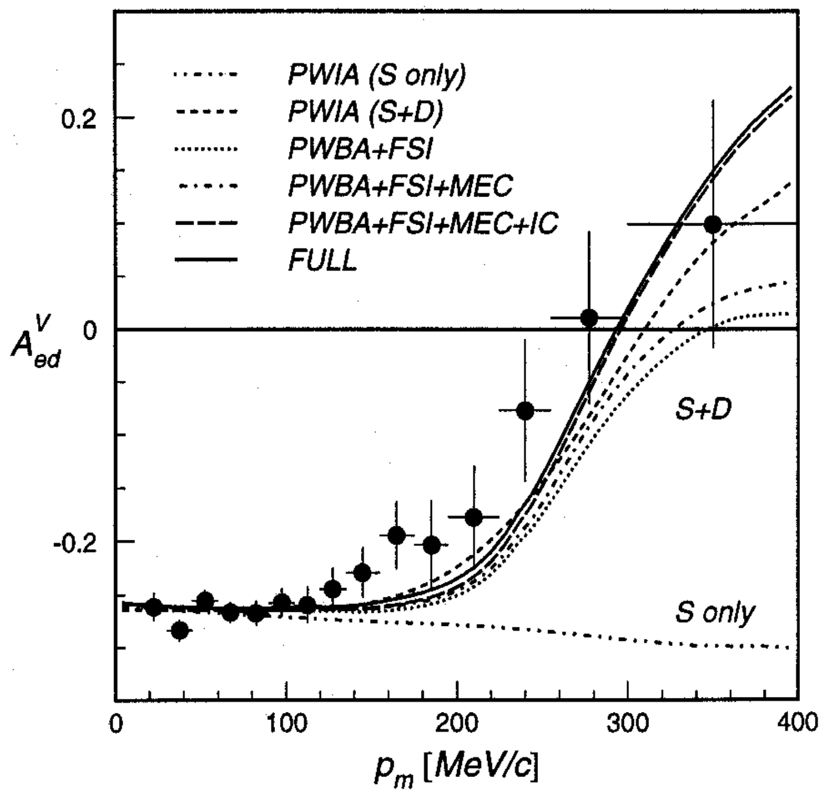
G. van der Steenhoven, Few-Body Syst. **17**, 79 (1994).

What do all these data and curves suggest?

- Relativistic effects substantial in A_ϕ (and R_{LT}).

- de Forest "CC1" nucleon cross section gives same qualitative features as more complete calculations → here, relativity more related to nucleonic current, as opposed to deuteron structure.

$^2\vec{\mathrm{H}}(\vec{e},e'p)$



***D*-state important**

AmPS
NIKHEF-K
Amsterdam

I. Passchier *et al*., Phys. Rev. Lett. **88**, 102302 (2002).

$$\sigma = \sigma_0\left[1 + P_1^d A_d^V + P_2^d A_d^T + h\left(A_e + P_1^d \boxed{A_{ed}^V} + P_2^d A_{ed}^T\right)\right]$$

Lots more d(e,e'p) data on the way!

^{2}H(e,e'p)n   E01-020 Hall A

Perpendicular: R_{LT}

Q^2 : 0.80, 2.10, 3.50 $(\mathrm{GeV/c})^2$

x=1: p_m from 0 to $\pm$ 0.5 GeV/c

Parallel/Anti-parallel

Q^2 : 2.10 $(\mathrm{GeV/c})^2$

vary x: p_m from 0 to 0.5 GeV/c

Neutron angular distribution

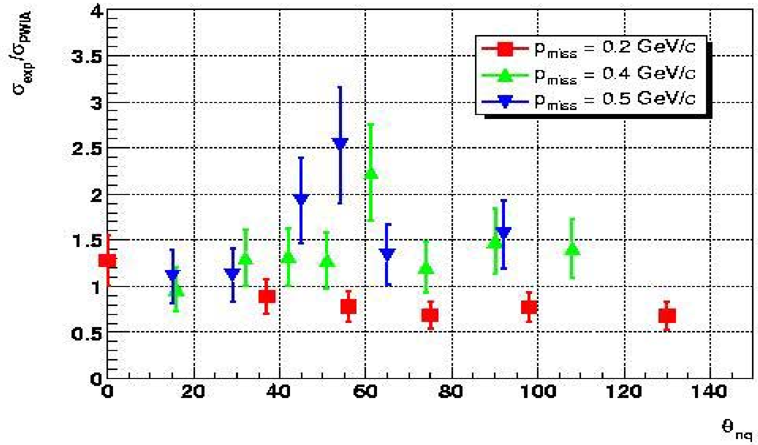
Q^2 : 0.80, 2.10, 3.50 $(\mathrm{GeV/c})^2$

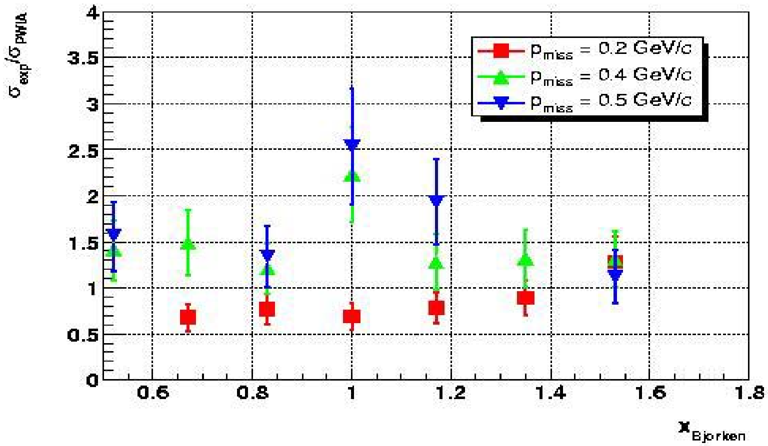
$Q^2 = 0.8\ (GeV/c)^2$

PRELIMINARY

20% error added to statistical error

$^2H(e,e'p)n$
E01-020 Hall A



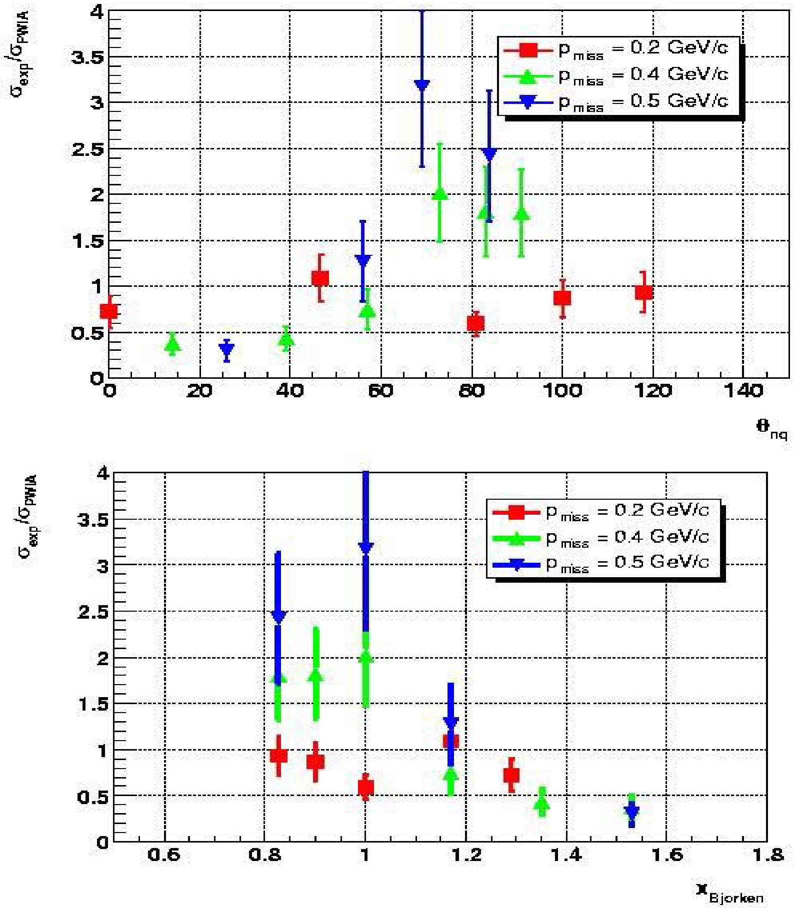


$Q^2 = 3.5\ (GeV/c)^2$

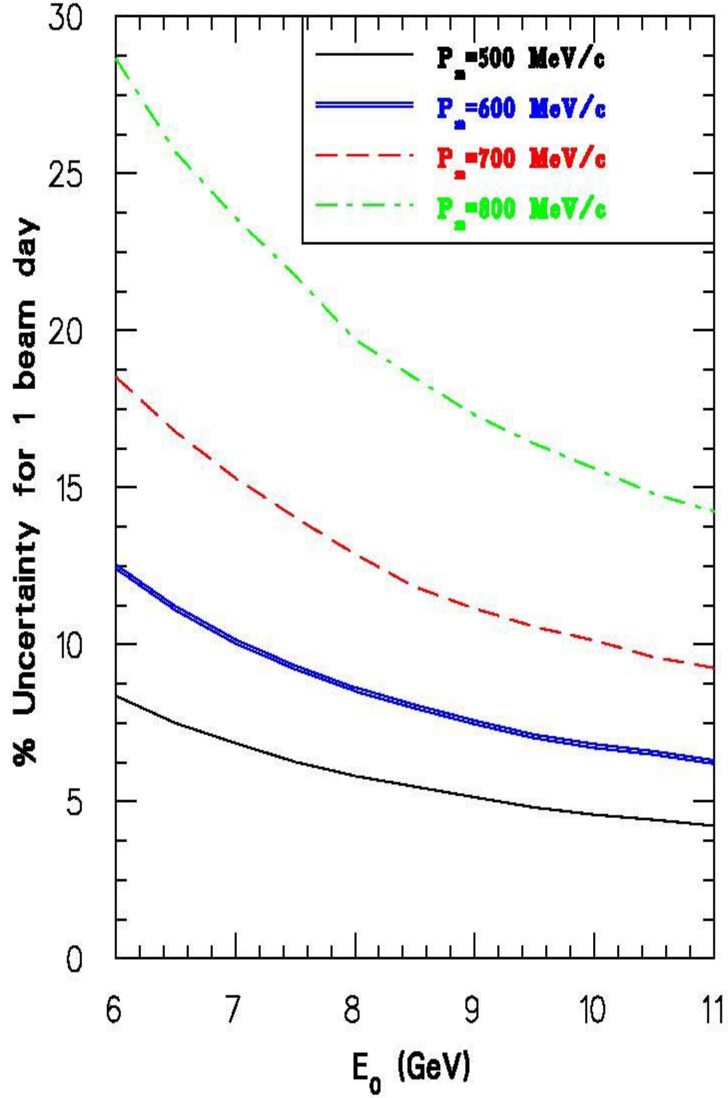
$^2H(e,e'p)n$ E01-020 Hall A

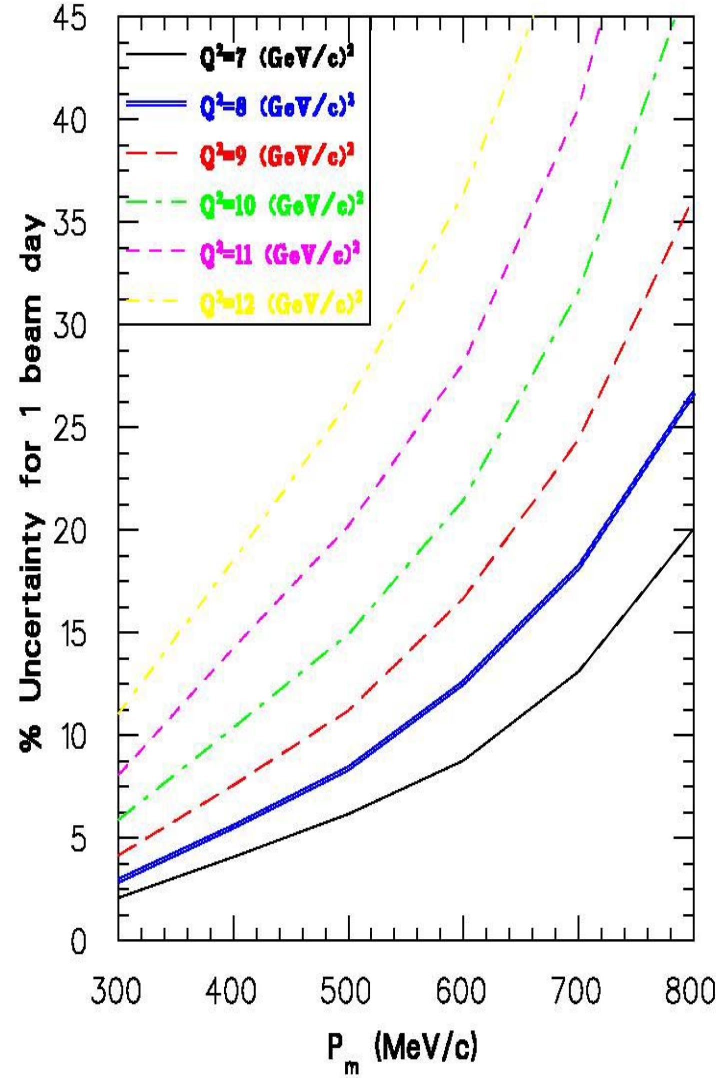
PRELIMINARY

20% error added to statistical error

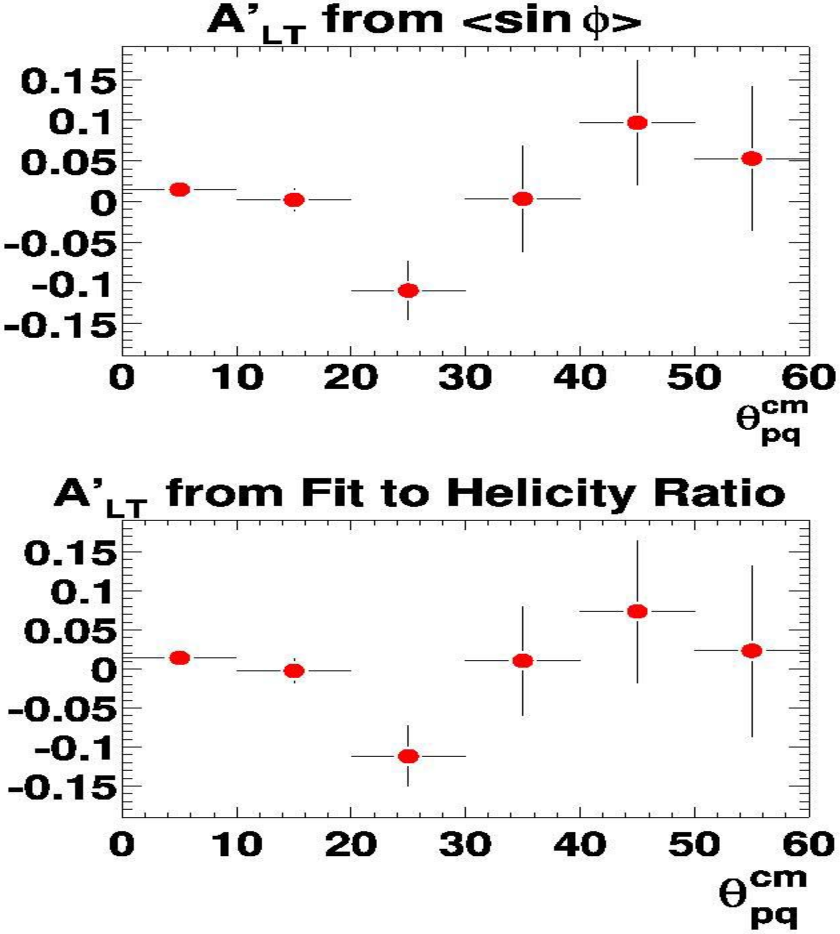


$^2H(e,e'p)n$ with JLab 12 GeV upgrade





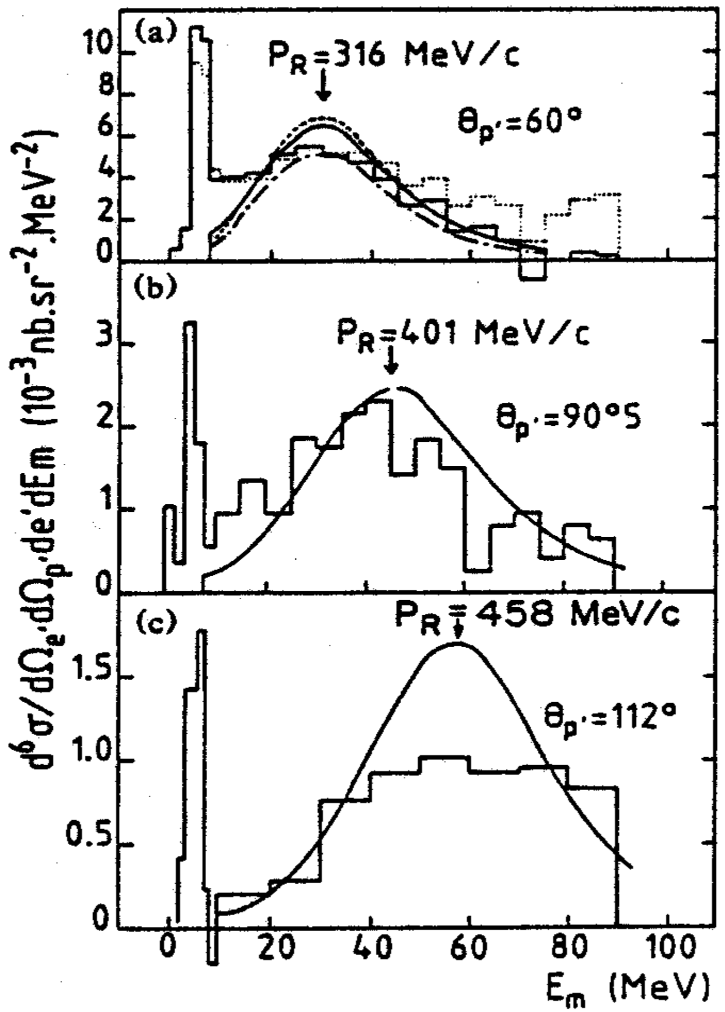
Preliminary Hall B E5 Data – $^2H(e,e'p)$



Hall B data covers large range of Q^2 and excitation as well as ϕ coverage to separate R_{LT}, R_{LT}' and R_{TT}.

$^{3,4}He$

$^3He(e,e'p)$



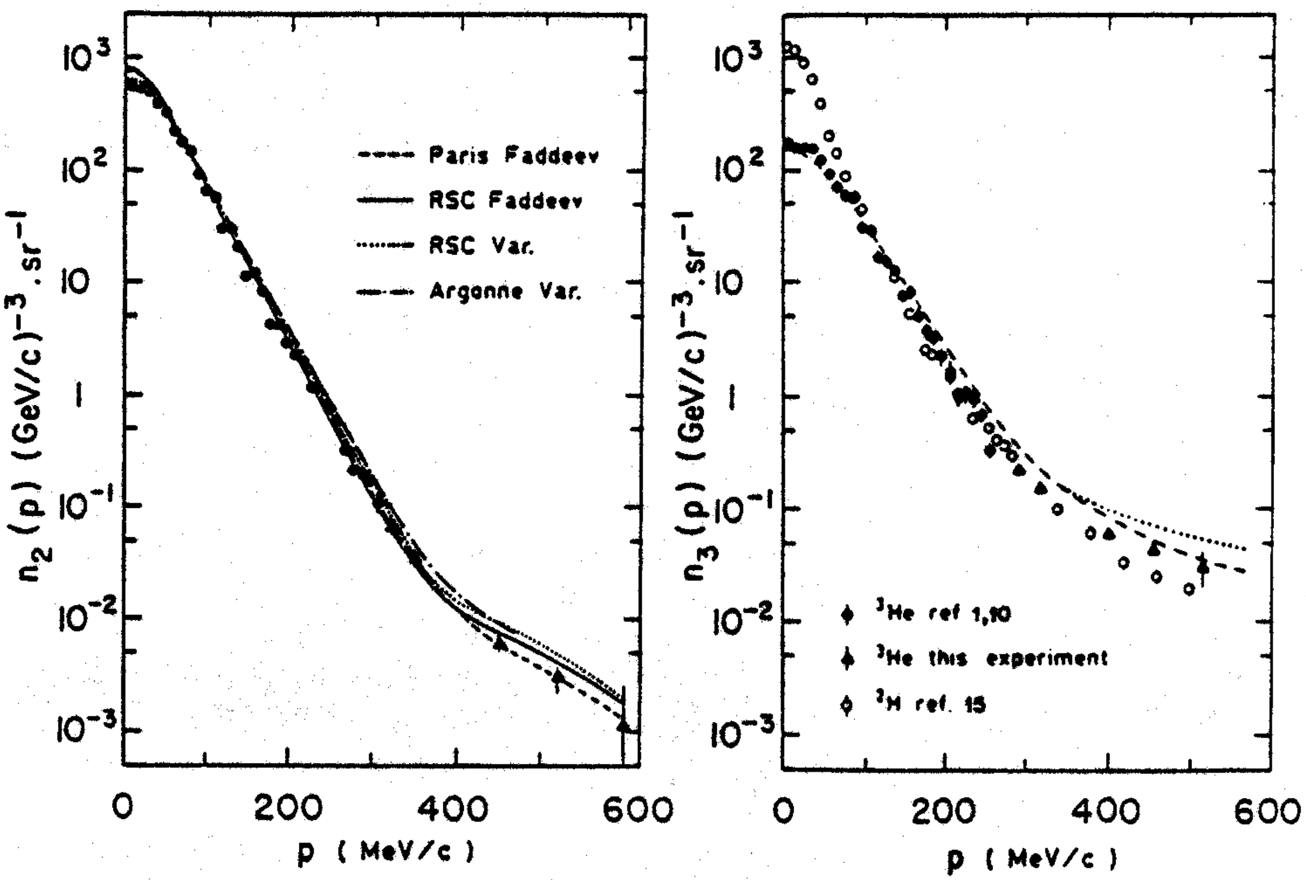
Calculations by Laget:
dashed=PWIA
dot-dashed=DWIA
solid=DWIA+MEC

Arrows indicate expected position for correlated pair.

C. Marchand *et al.*,
Phys. Rev. Lett. **60**, 1703 (1988).

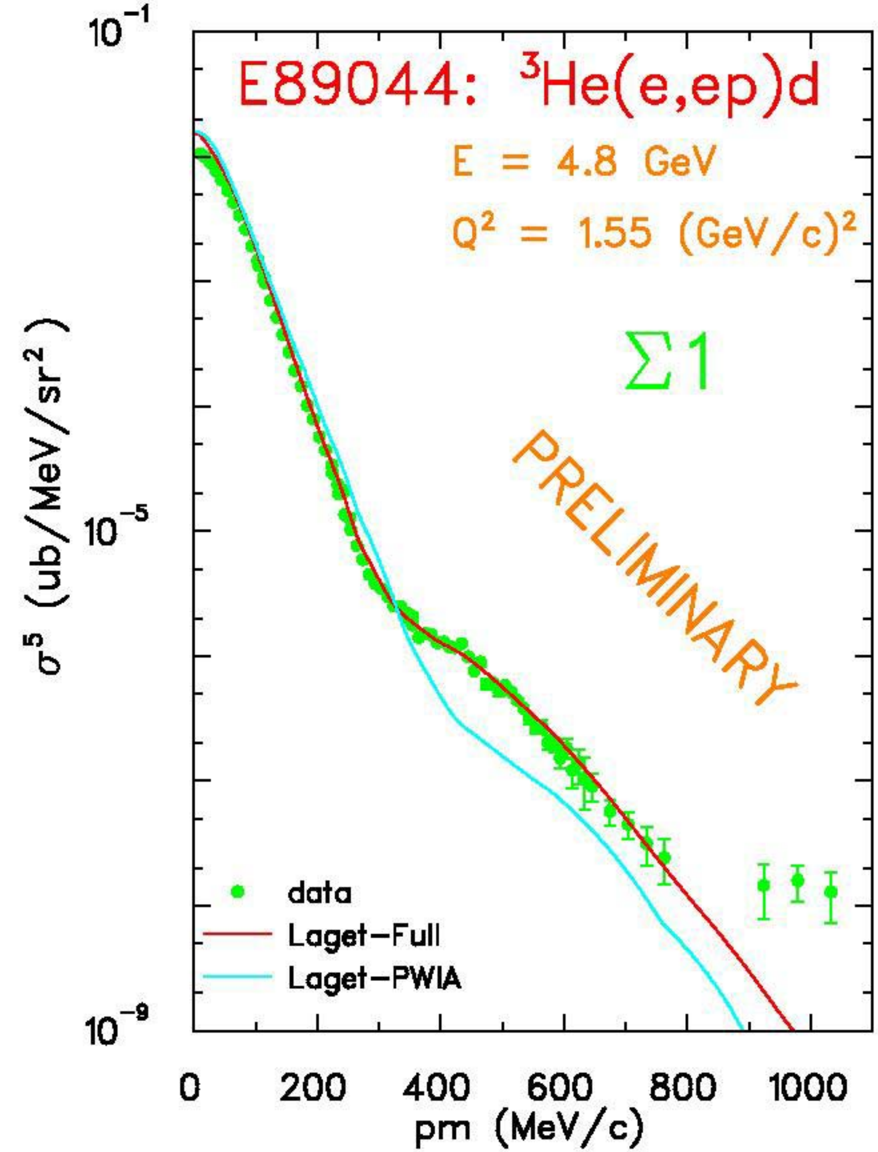
Saclay Linear Accelerator

$^3He(e,e'p)d$ $^3He(e,e'p)np$



3BBU
similar
to
d→np

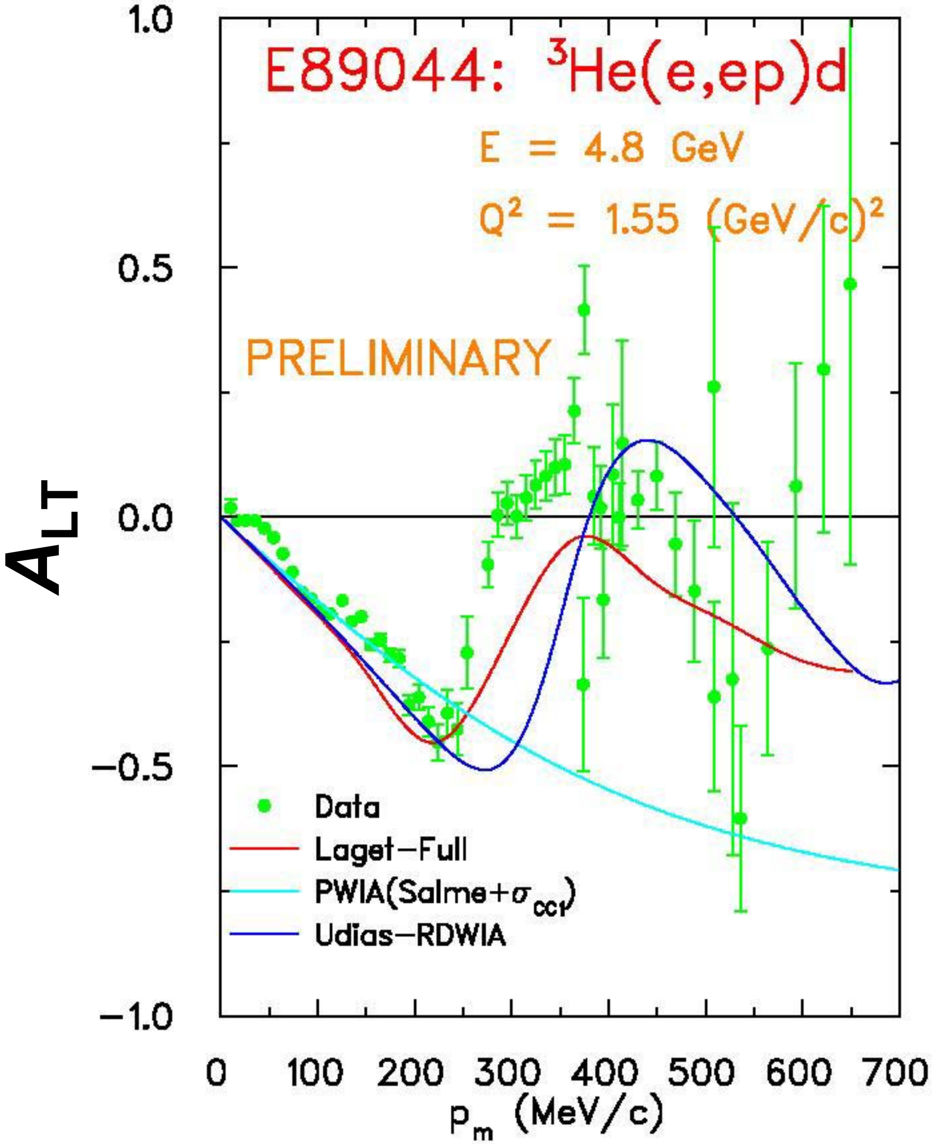
C. Marchand *et al.,* Phys. Rev. Lett. **60**, 1703 (1988).



Large effects from FSI and non-nucleonic currents.

Highest p_m shows excess strength.

JLab
Hall A



General features reproduced but not at correct values of p_m.

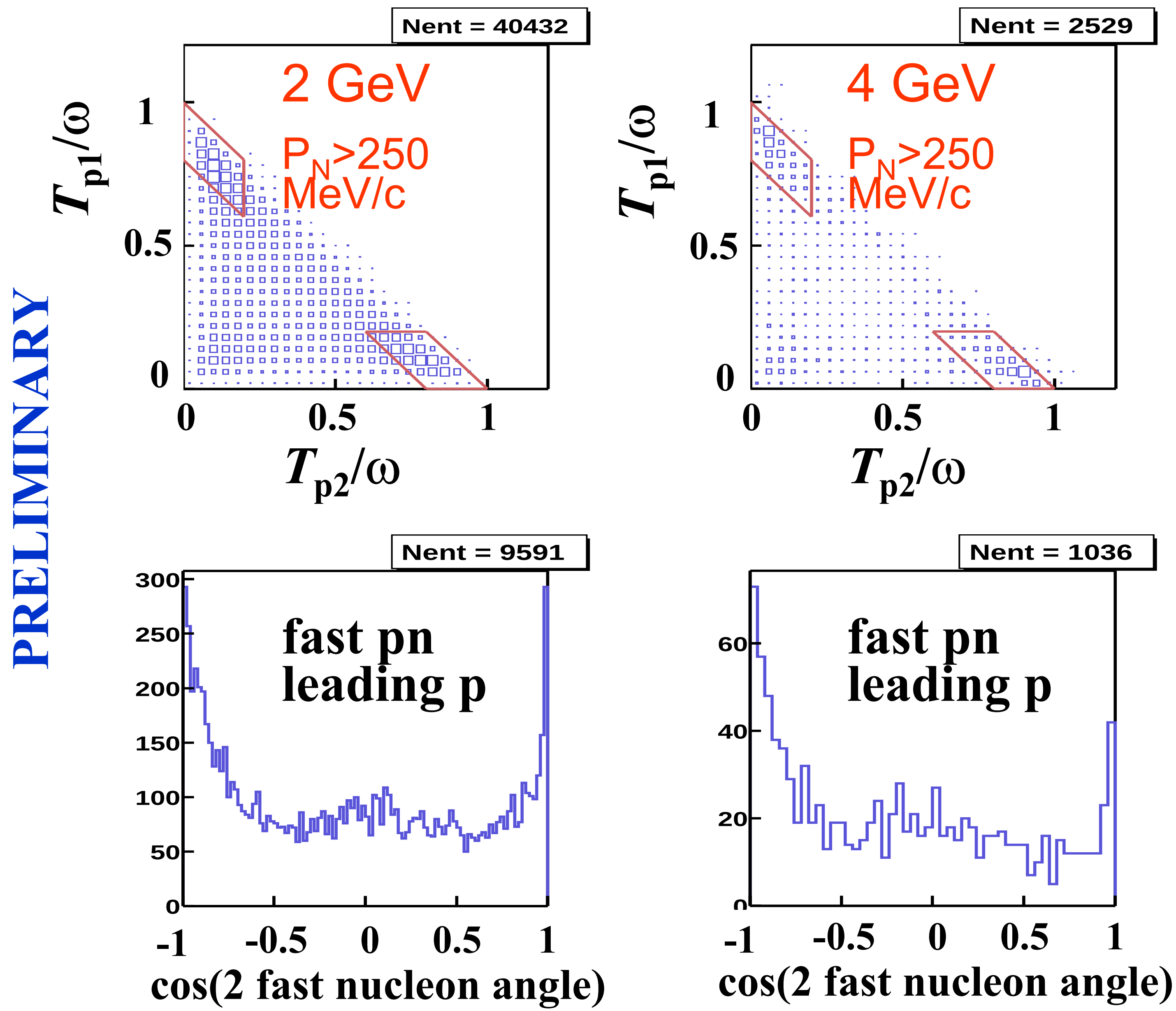
JLab
Hall A

The most direct way to look for correlated nucleons?

Detect both of them

→ JLab Hall B

$^3He(e,e'pp)n$ Hall B

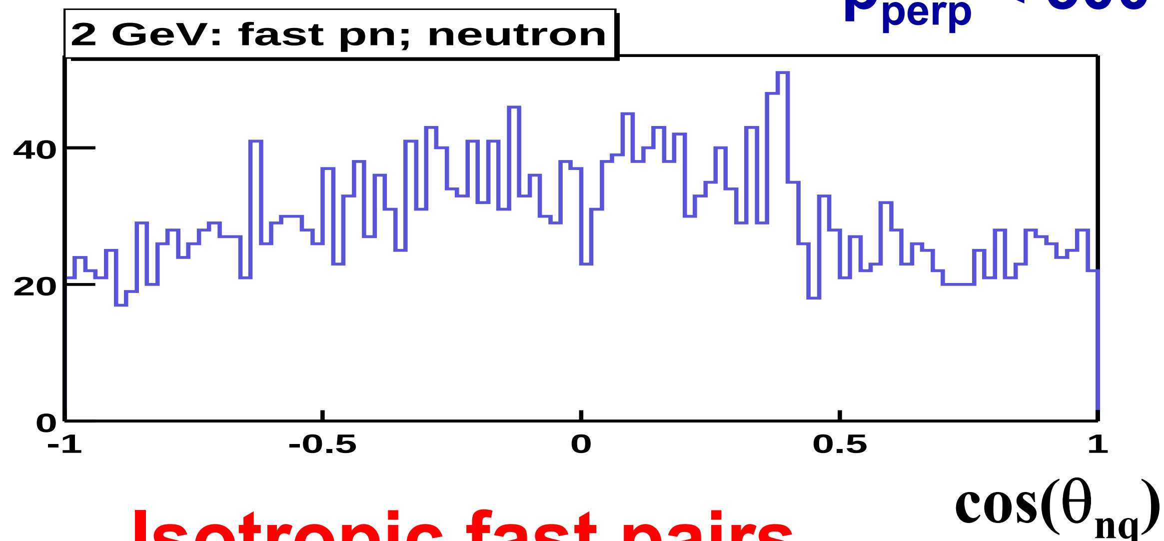


Hall B

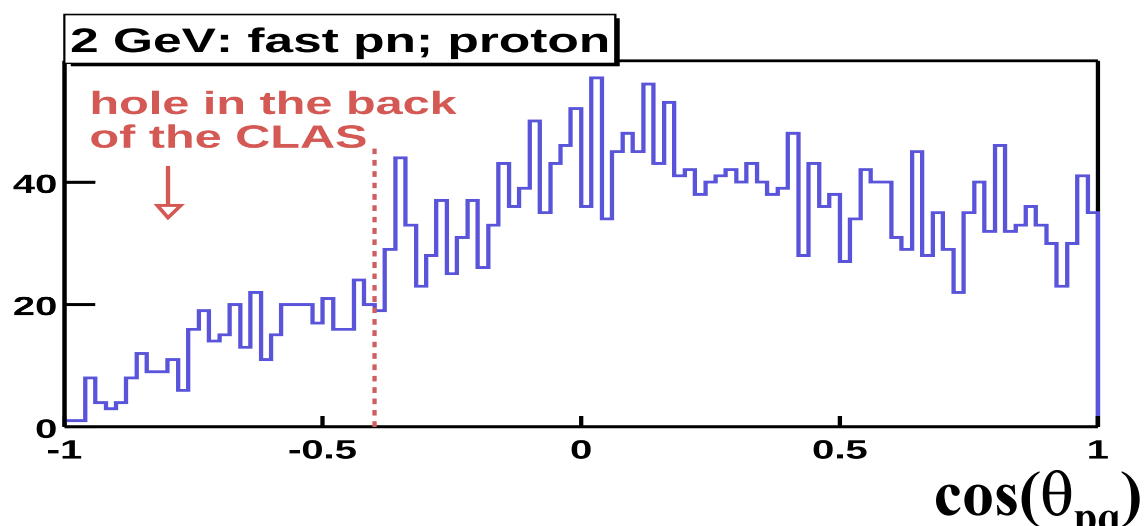
$^3He(e,e'pp)n$ 2 GeV

p_{perp} < 300 MeV/c

PRELIMINARY

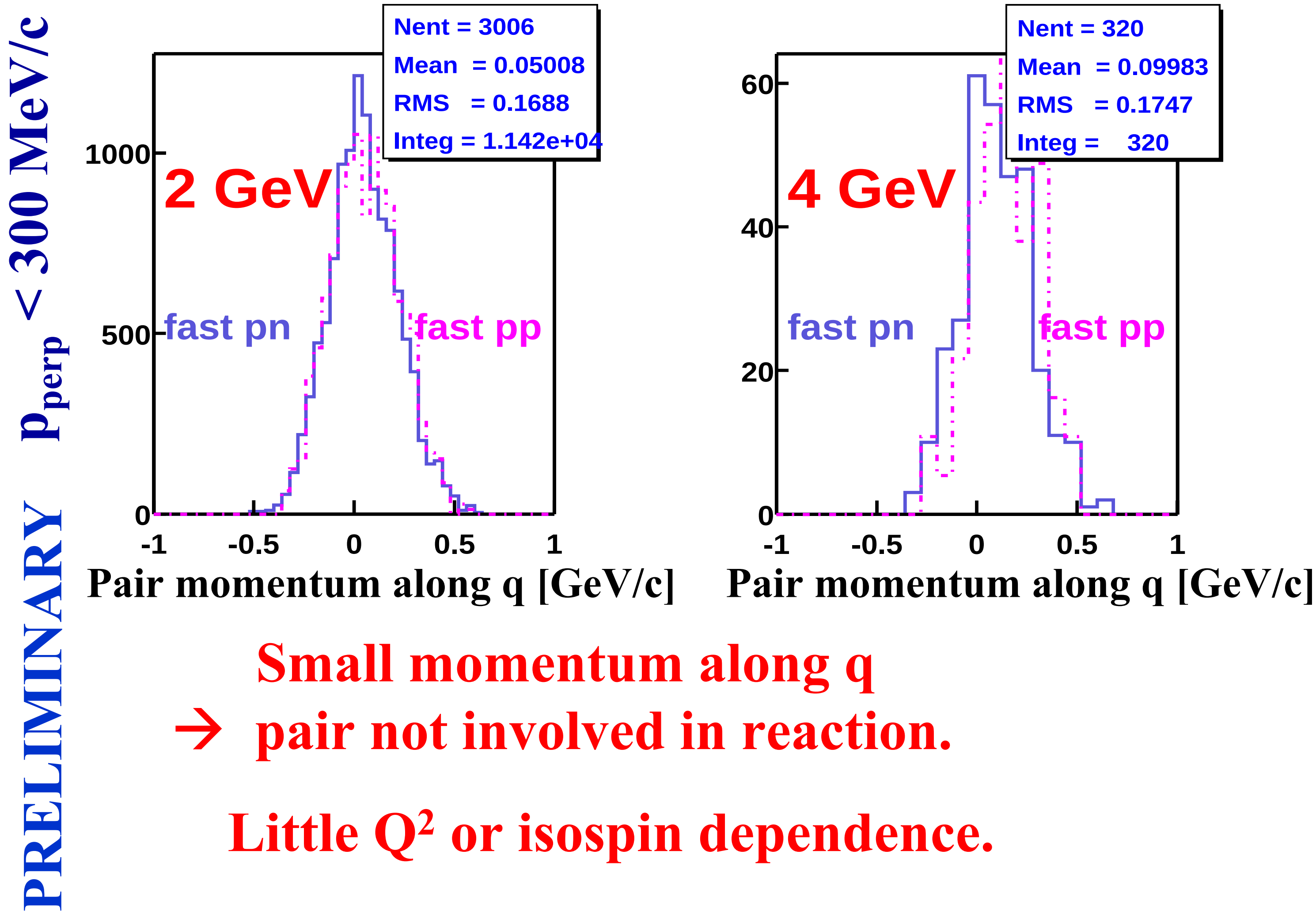


Isotropic fast pairs
→ pair not involved in reaction.



Hall B

$^3He(e,e'pp)n$

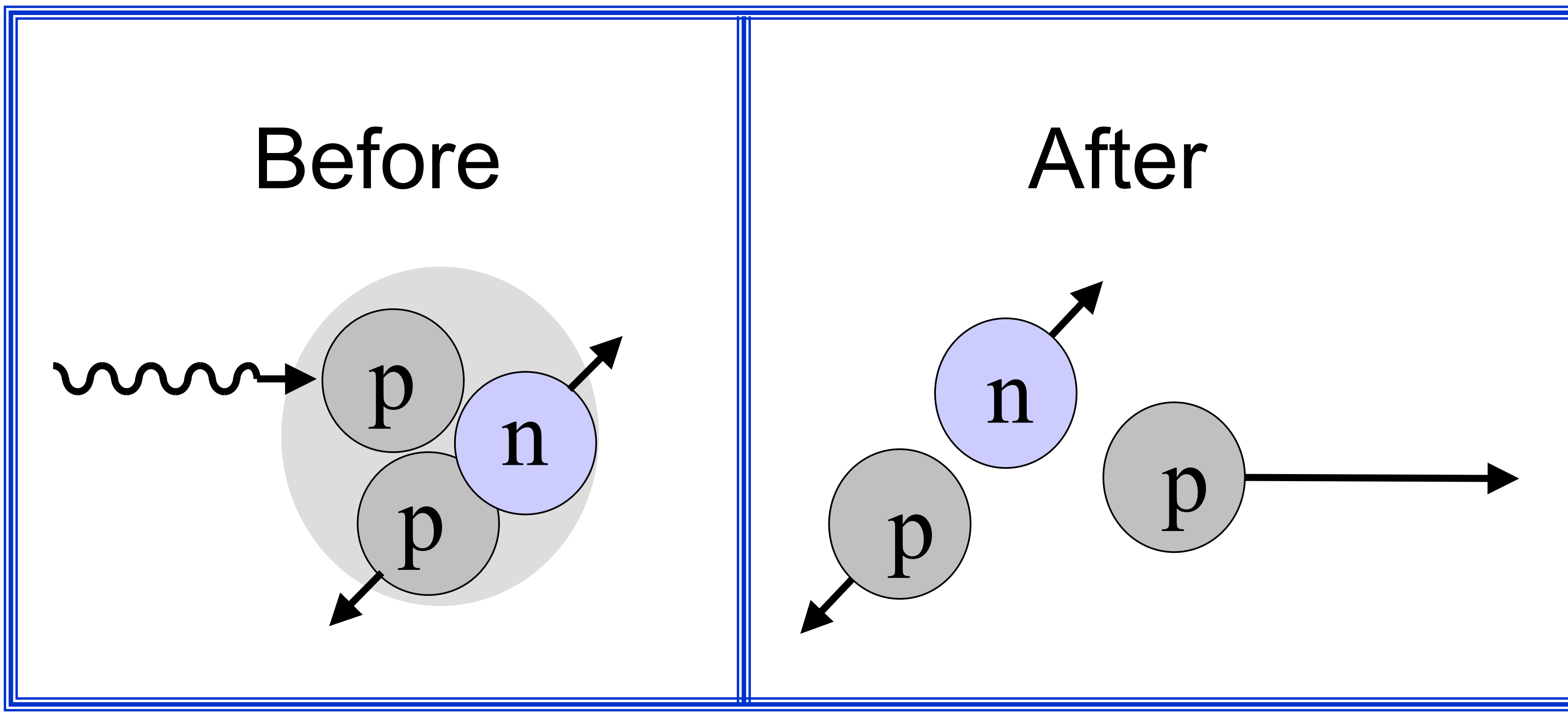


Small momentum along q
→ pair not involved in reaction.

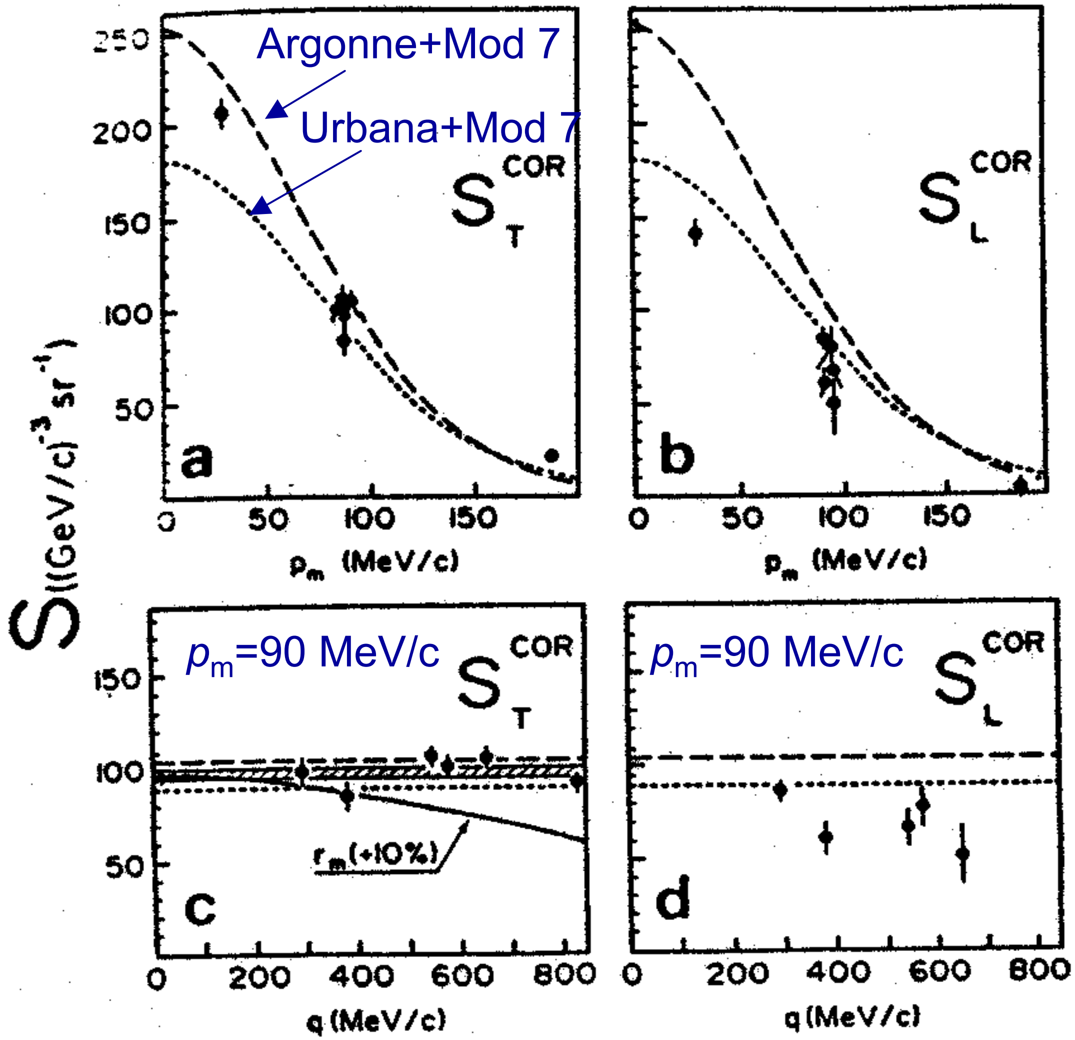
Little Q^2 or isospin dependence.

2 GeV has acceptance corrections

Direct evidence of NN correlations



$^4He(e,e'p)^3H$



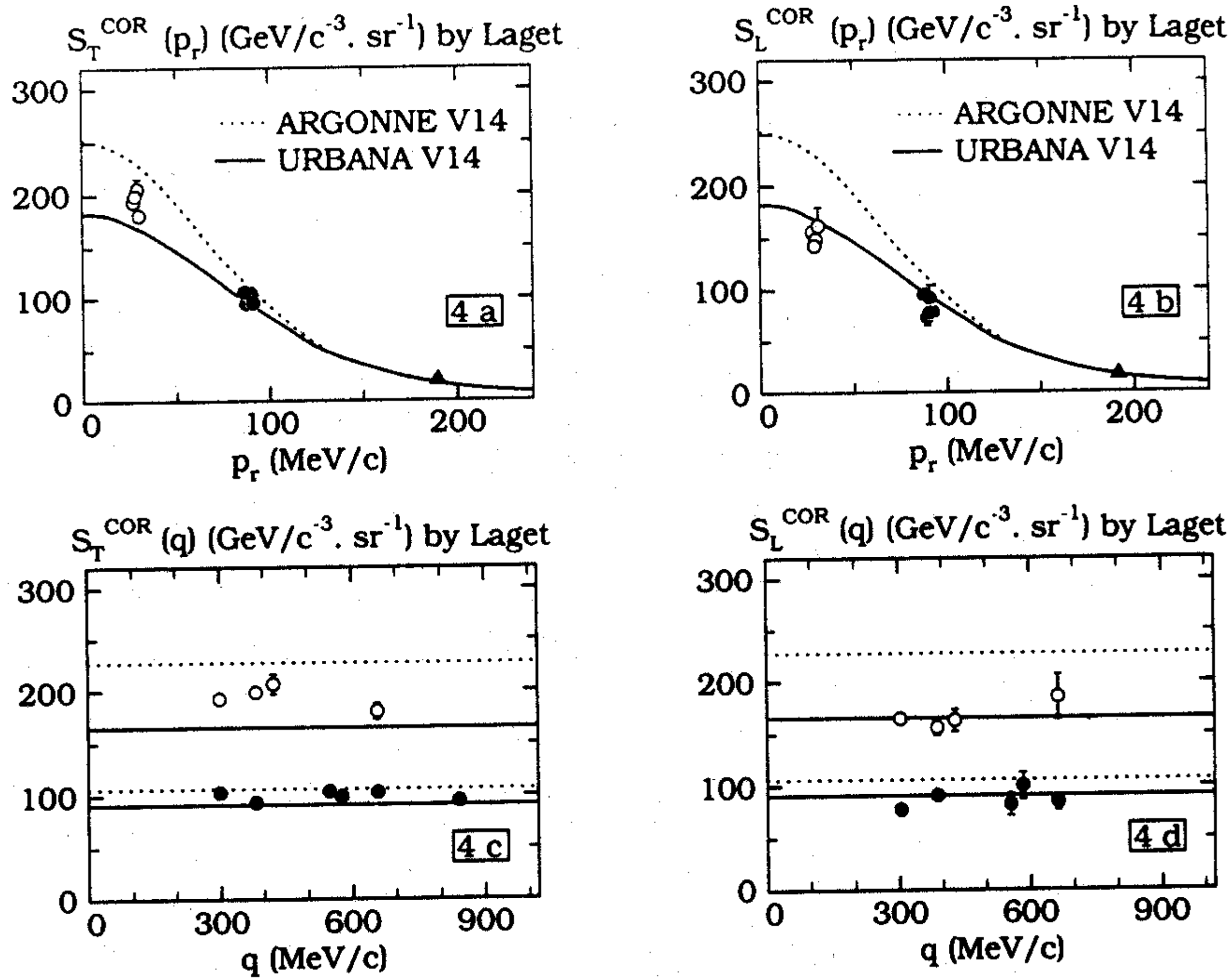
Data and calculations "corrected" for MEC+IC (Laget).

Longitudinal overpredicted.

Saclay

A. Magnon *et al.*, Phys. Lett. B **222**, 352 (1989).

$^4He(e,e'p)^3H$

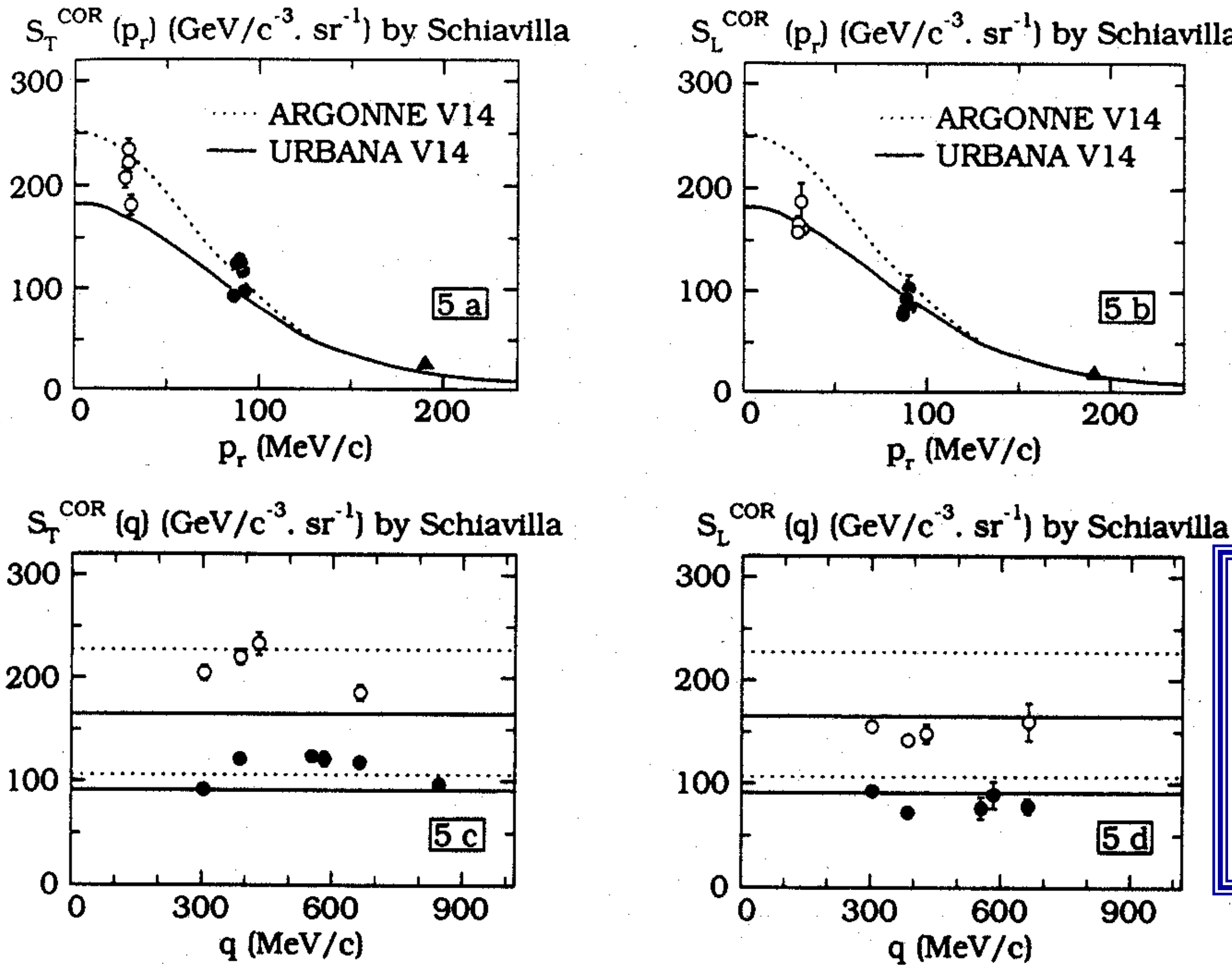


Calculations predict *q* dependence.

Saclay

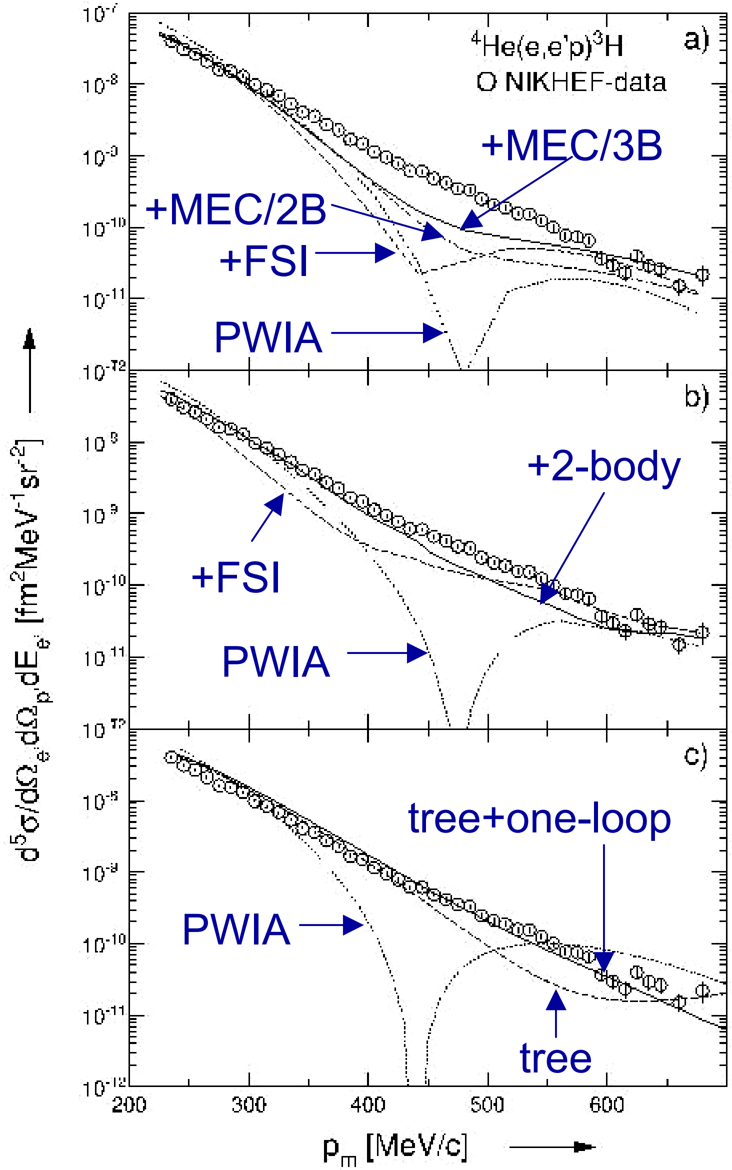
J.E. Ducret *et al.*, Nucl. Phys. **A556**, 373 (1993).

$^4He(e,e'p)^3H$



Again, calculations predict *q* dependence.

J.E. Ducret *et al.*, Nucl. Phys. **A556**, 373 (1993).



^{4}He(e,e'p)^{3}H

Laget

Schiavilla

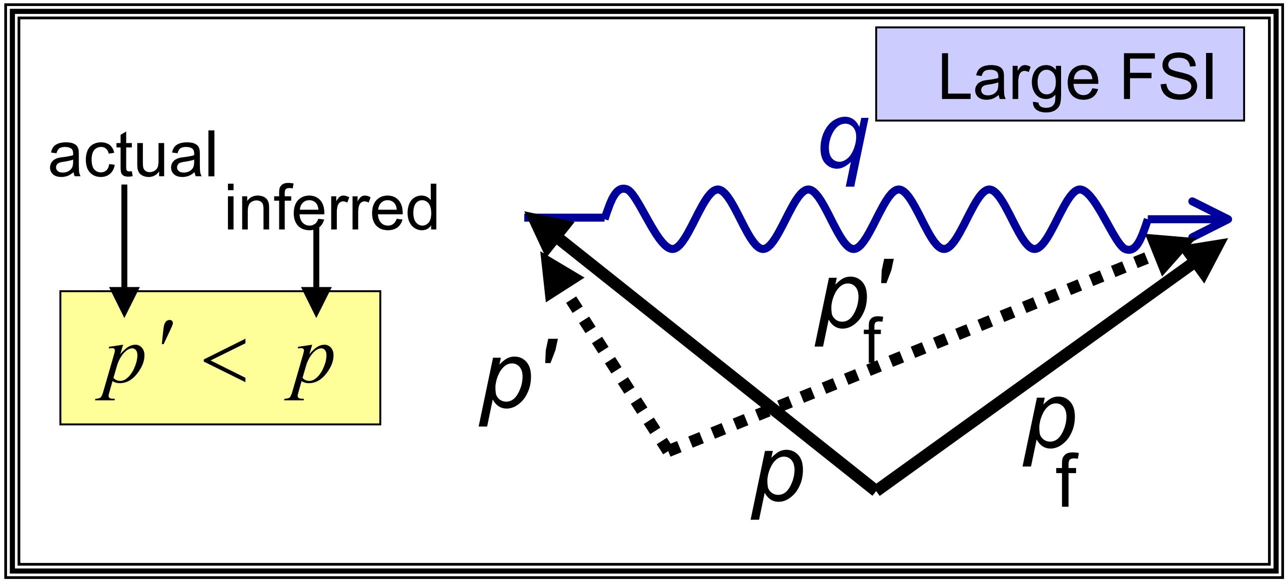
Nagorny

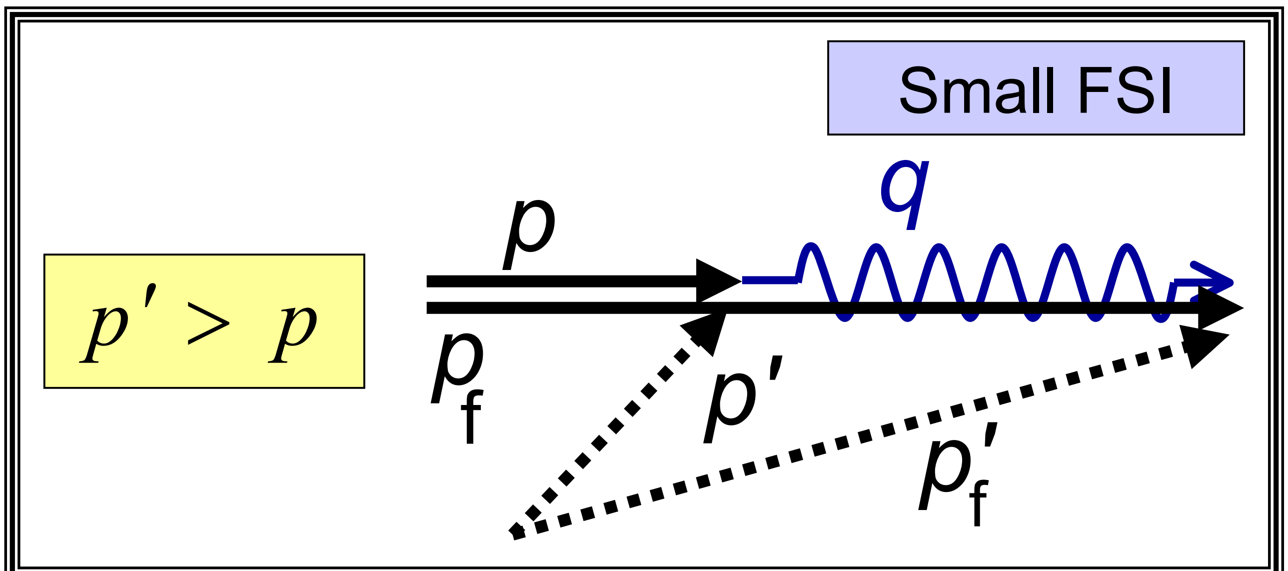
Minimum filled in by FSI and 2&3-body currents.

AmPS
NIKHEF-K
Amsterdam

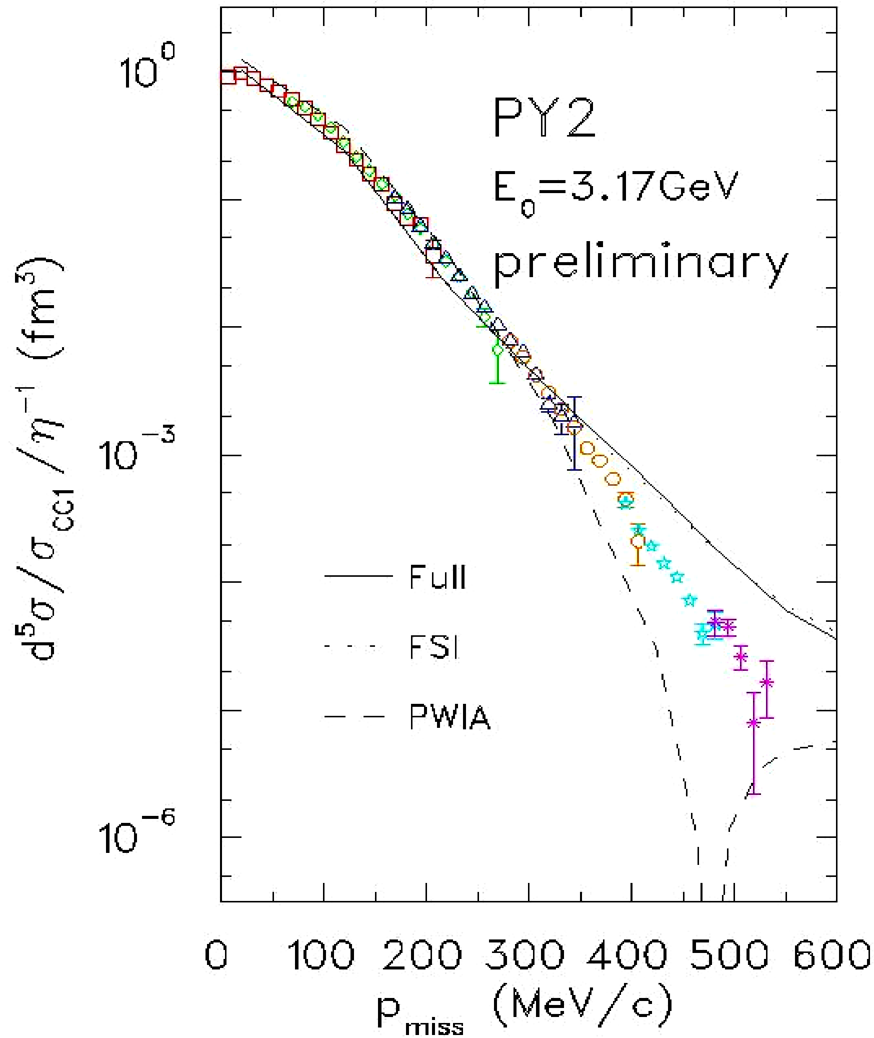
J.J. van Leeuwe *et al.*, Phys. Rev. Lett. **80**, 2543 (1998).

FSI: dependence on kinematics





$^4He(e,e'p)^3H$



It looks like the minimum is filled in here as well.

JLab Hall A Experiment E97-111, J. Mitchell, B. Reitz, J. Templon, cospokesmen

Summary

- (e,e'p) sensitive to single-particle aspects of nucleus, but …
- More complicated physics is clearly important.
- Spectroscopic factors reduced compared to naïve shell model (including FSI corrections).
- Missing strength at least partly due to interaction currents: direct interaction with with exchanged mesons or interaction with correlated pairs (spreads strength over ε_m).

Summary cont'd.

- After several decades of experimental and theoretical effort, there are still unanswered questions.
- What is the nature of the interaction of the virtual photon with the "nucleon": medium and offshell effects?
- Handling FSI and other reaction currents still problematic, though realistic calculations are now available for the lighter systems.
- High energy program is underway, pushing to shorter distance scales, emphasizing relativistic effects, …