Overview of the (e,e'p) Reaction

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EEP03: International Workshop on

Probing Nucleons and Nuclei via the (e,e'p) Reaction

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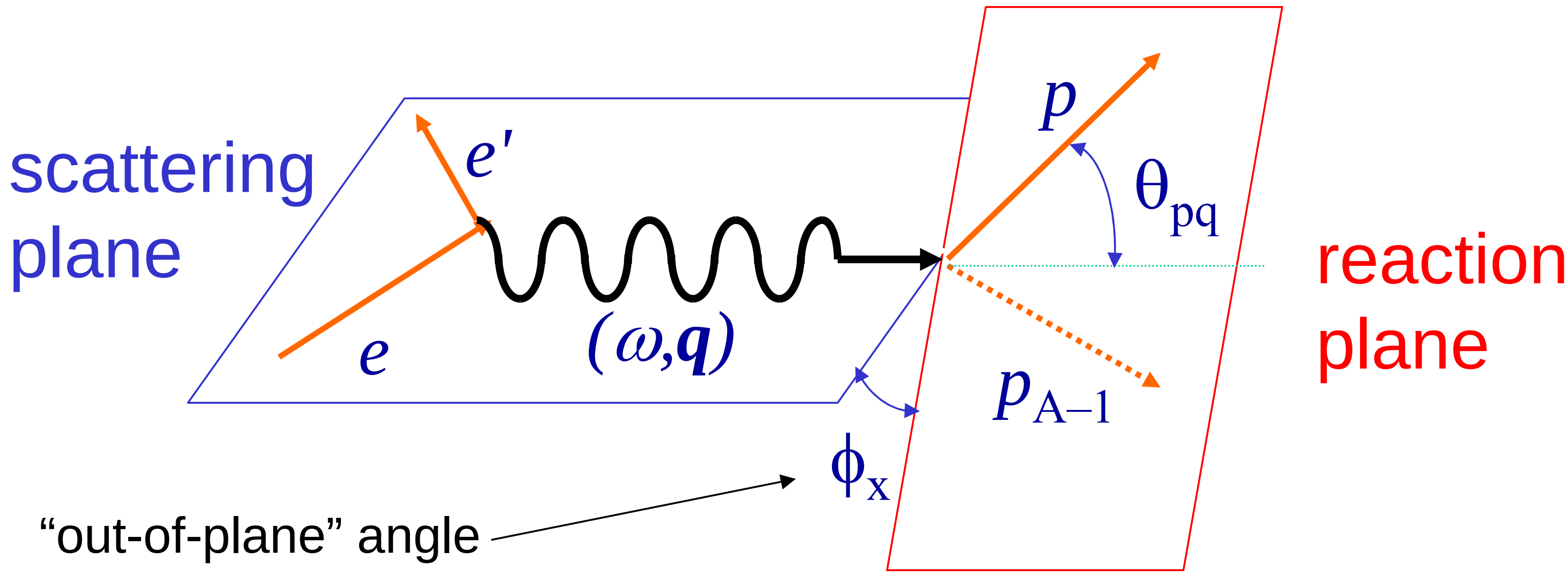
Grenoble, France

Outline

- Nuclei
  - Spectroscopic factors
  - *NN* correlations
  - Reaction mechanism
- Deuteron and the *NN* interaction
- Nucleons
  - Elastic form factors
  - Medium modifications
  - Color transparency
  - Pion electroproduction
  - Virtual Compton Scattering

Kinematics



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

Missing momentum: $\boldsymbol{p}_\mathrm{m} = \boldsymbol{q} - \boldsymbol{p} = \boldsymbol{p}_{\mathrm{A}-1} \equiv -\boldsymbol{p}_0$

PWIA

Missing mass: $\varepsilon_\mathrm{m} = \omega - T_p - T_{\mathrm{A}-1}$

Response Functions (OPEA)

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

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

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

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

$$+ h v_{TT'}(R_{TT'}^l S_l + R_{TT'}^t S_t) \Big\}$$

where the $v's$ depend only on the (known) electron kinematics.

The Spectral Function

In nonrelativistic PWIA:

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

e-p cross section

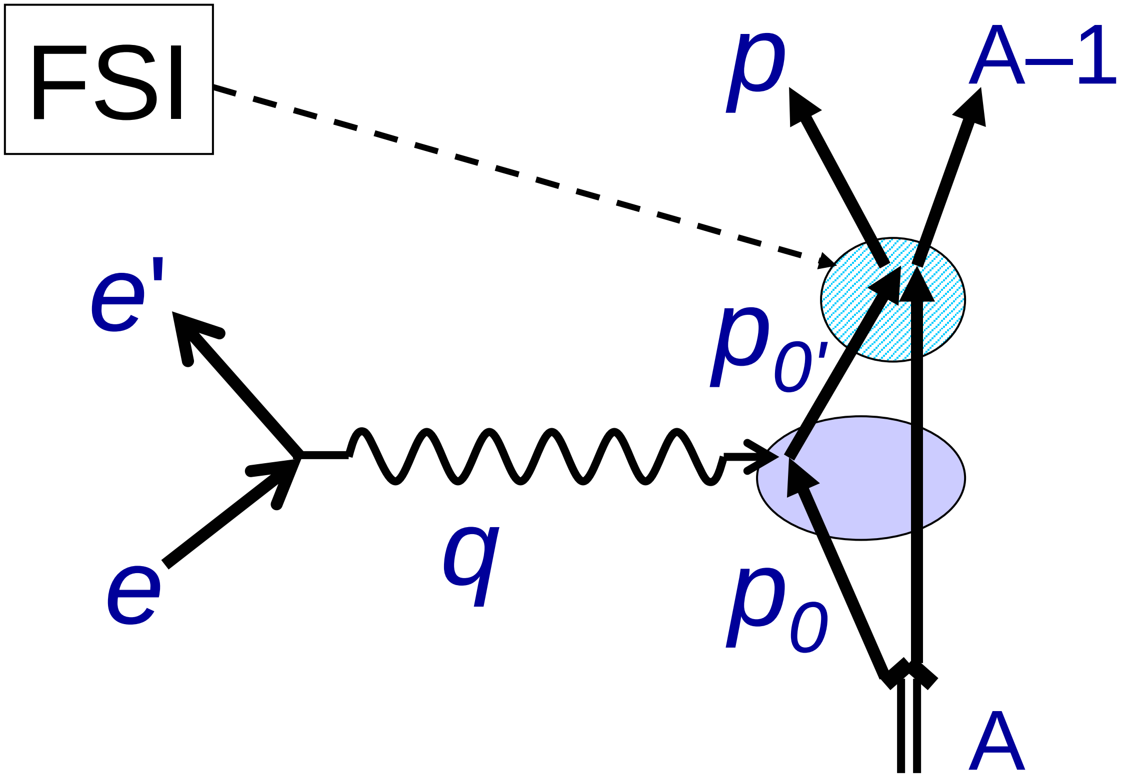
nuclear spectral function

For bound state of recoil system:

proton momentum distribution

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

Final State Interactions (FSI)



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

Distorted Wave Impulse Approximation (DWIA)

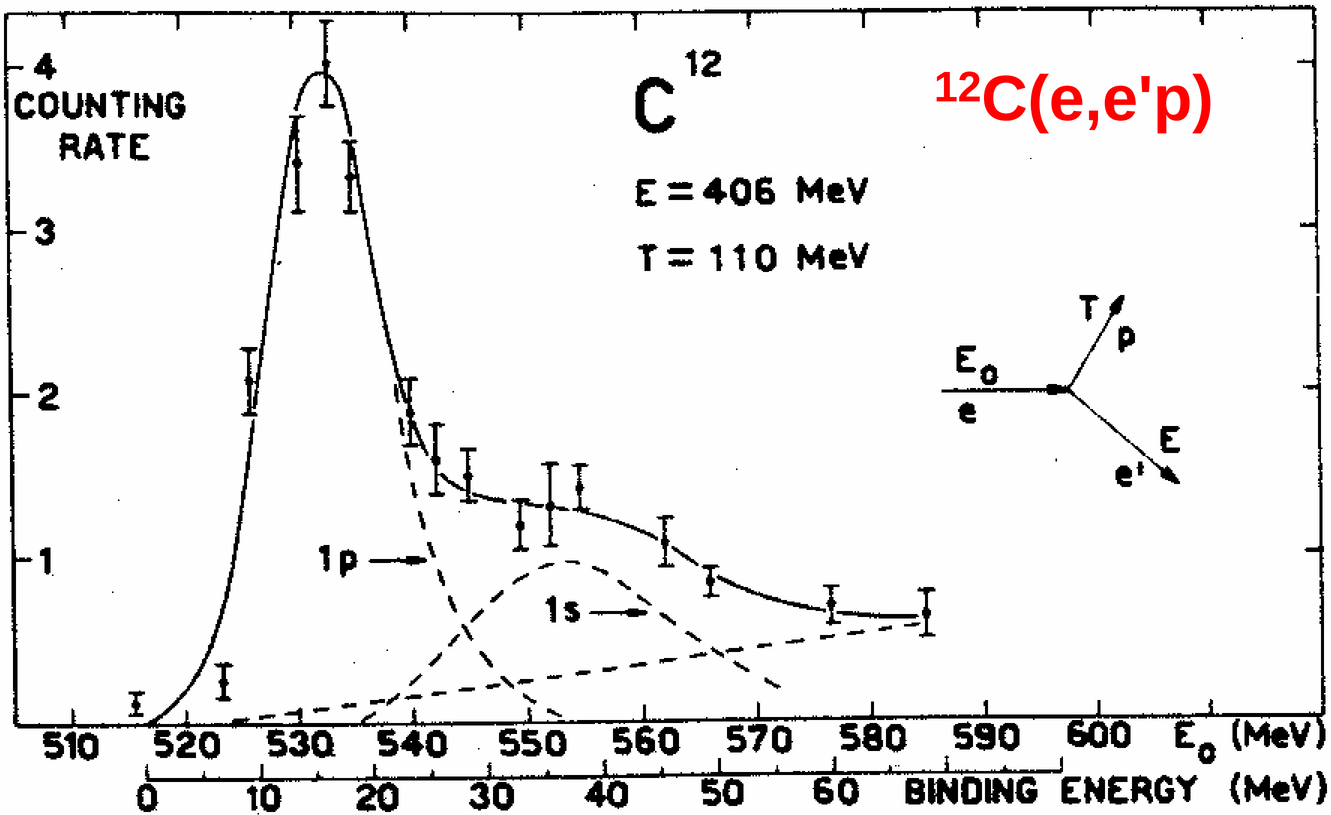
Treat outgoing proton distorted waves in presence of potential produced by residual nucleus (*optical potential*).

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

“Distorted” spectral function

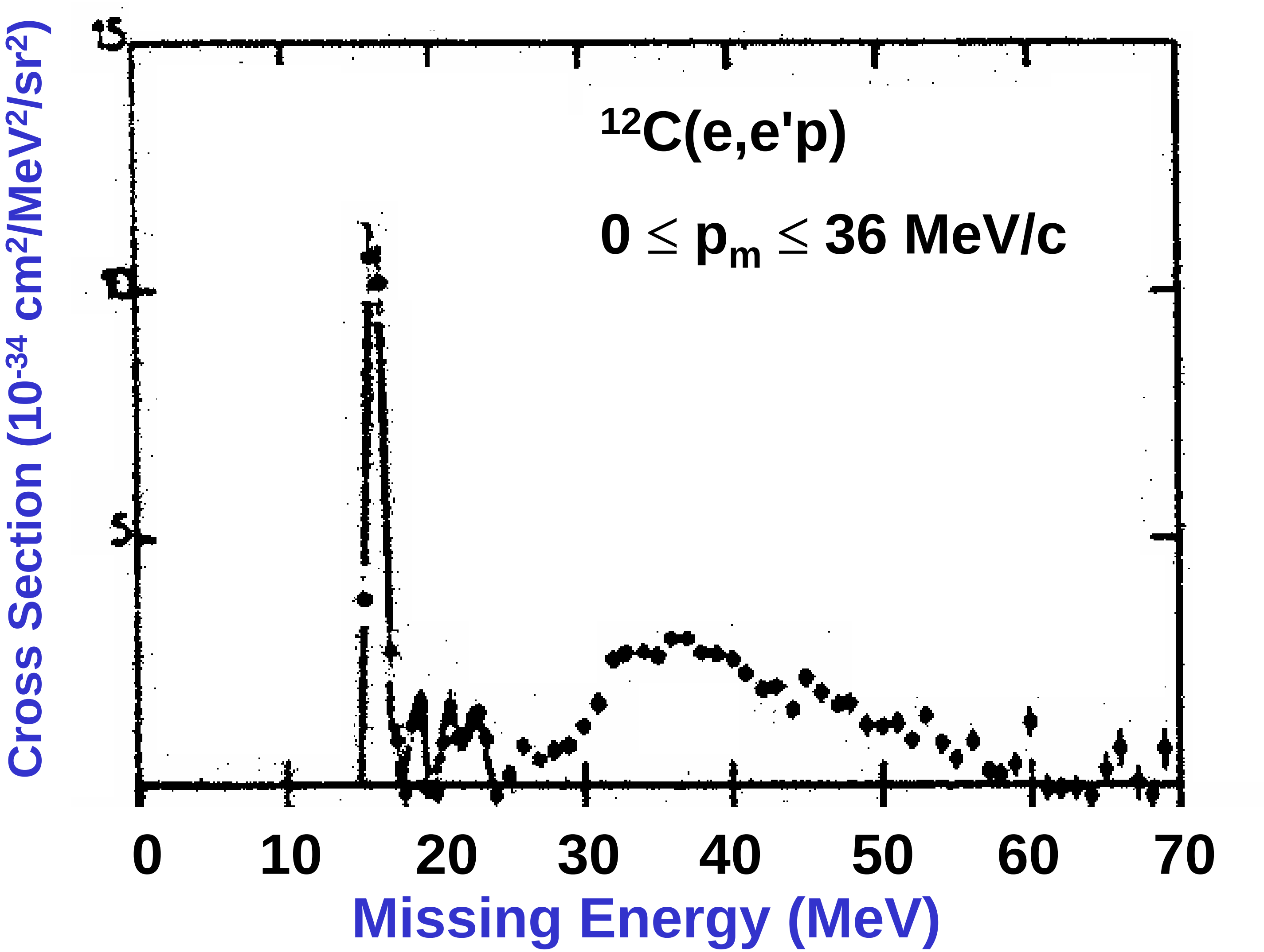
Nuclei

1964: Frascati Synchrotron



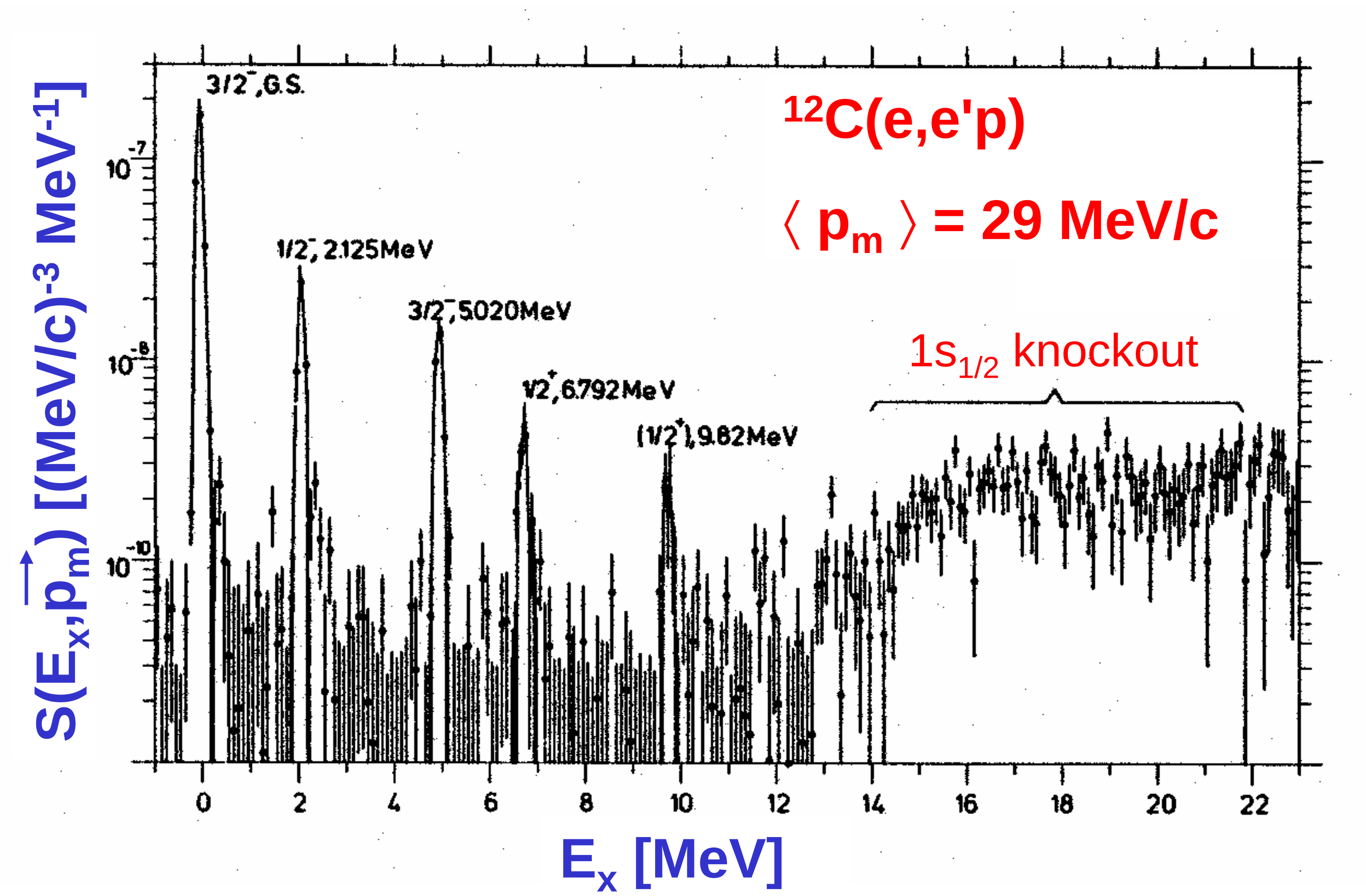
U. Amaldi, Jr. *et al.*, Phys. Rev. Lett. **13**, 341 (1964).

1976: Saclay

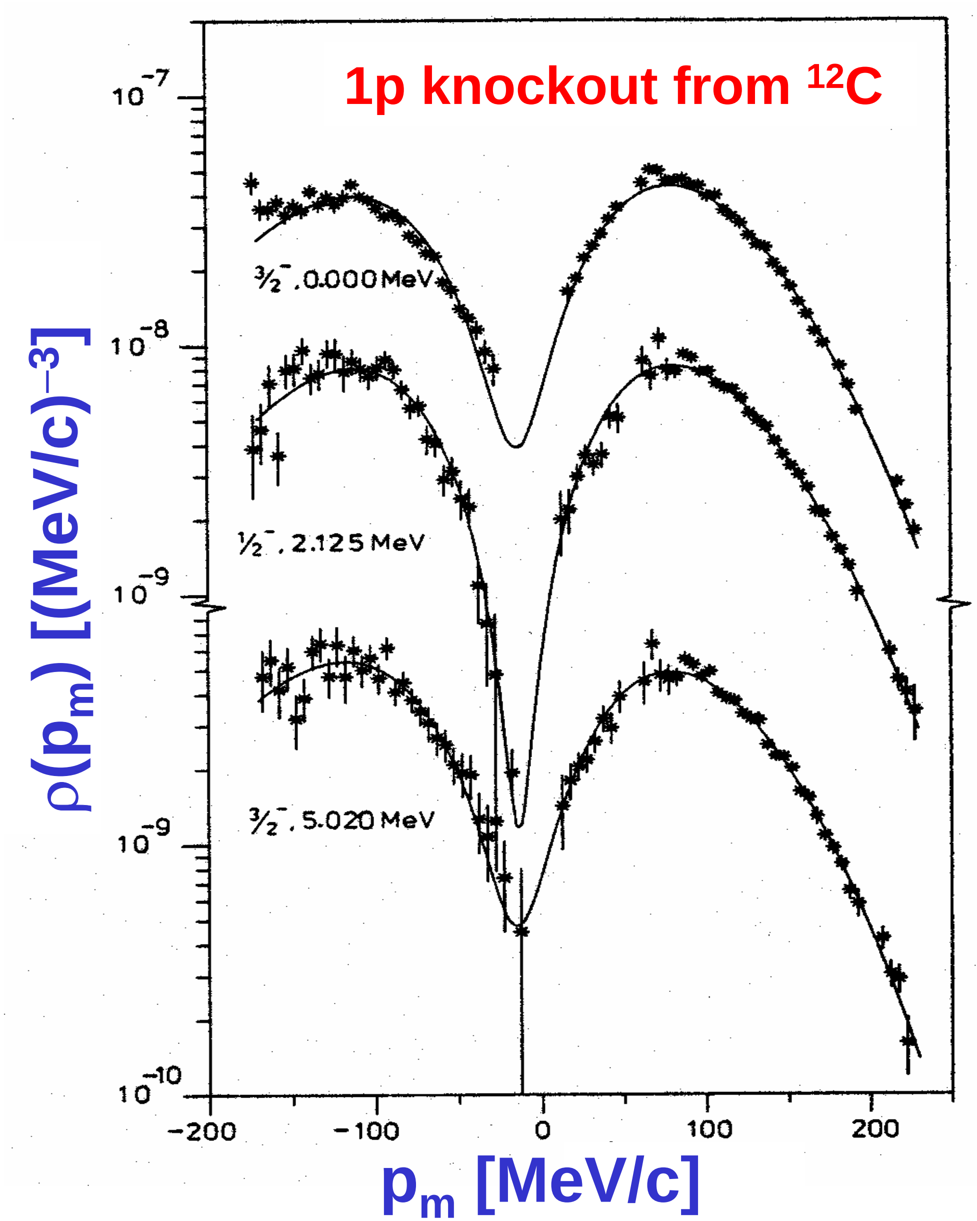


J. Mougey *et al.*, Nucl. Phys. **A262**, 461 (1976).

1988: NIKHEF



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



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

DWIA calculations give correct shapes, but:

Missing strength observed.

NIKHEF

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

“Spectroscopic” Factors …

Normalization factors

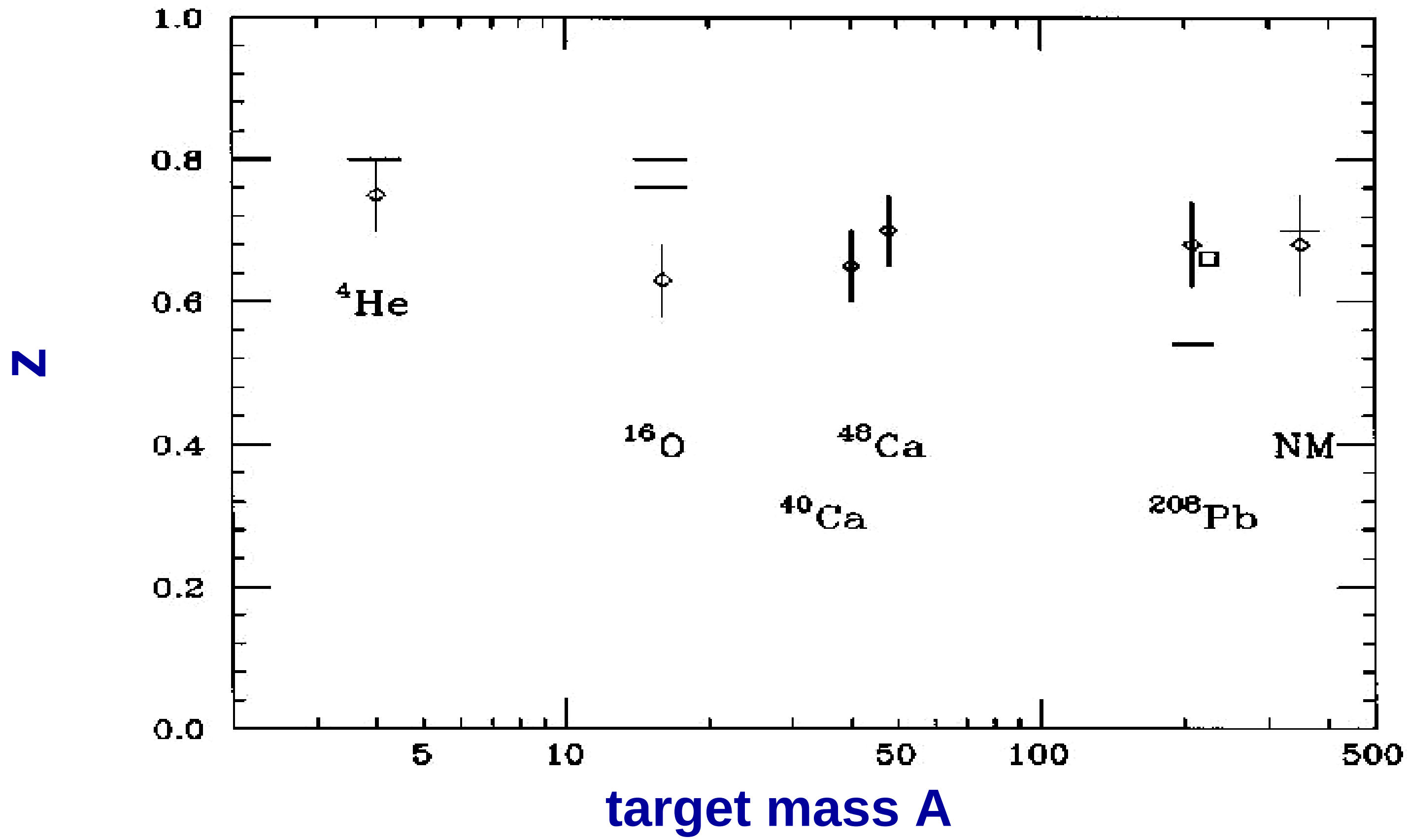


FIG. 12. z factors ($\diamond$) from $(e,e'p)$ and (e,e') reactions; ($\square$), from optical potential analysis; and from (—) theory.

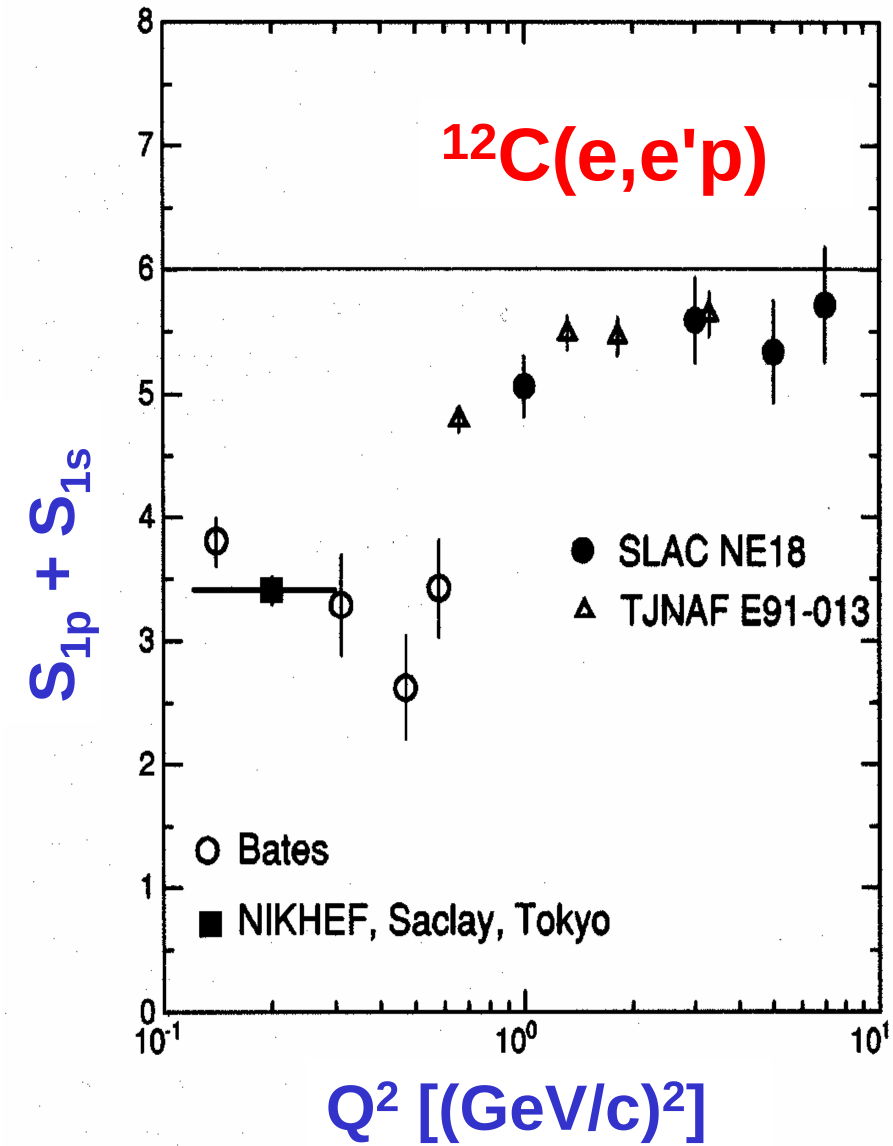
V. Pandharipande, I. Sick and Peter K.A. deWitt Huberts, Rev. Mod. Phys. **69**, 981 (1997).

Transfer Reactions and Normalization Factors

TABLE I. Cross sections for the reactions $^{12}C(^{12}C,^{11}B)X$, $^{12}C(^{12}C,^{11}C)X$, $^{12}C(^{16}O,^{15}N)X$ and $^{12}C(^{16}O,^{15}O)X$.

^{A-1}Z	E_B MeV/ nucleon	E^*	σ_{sp}(mb) [a] Strip.	Diffr.	σ_{th} (mb)	σ_{expt} (mb)	R_s
^{11}B	250	a	21.9	1.8	100.5	65.6(26) [b]	0.65(3)
	1050	a	20.8	1.9	96.1	48.6(24) [c]	0.51(3)
	2100	a	20.6	2.0	96.1	53.8(27) [c]	0.56(3)
^{11}C	250	a	21.4	1.7	98.2	56.0(41) [b]	0.57(4)
	1050	a	20.2	1.8	93.4	44.7(28) [c]	0.48(3)
	2100	a	20.1	1.9	93.3	46.5(23) [c]	0.50(3)
^{15}N	2100	0	15.40	1.77			
		6.324	12.95	1.30			
		Sum			80.2	54.2(29) [b]	0.68(4)
^{15}O	2100	0	14.63	1.61			
		6.176	12.54	1.23			
		Sum			76.9	42.9(23) [c]	0.56(3)

B.A. Brown *et al.*, Phys. Rev. C **65**, 061601 (2002).



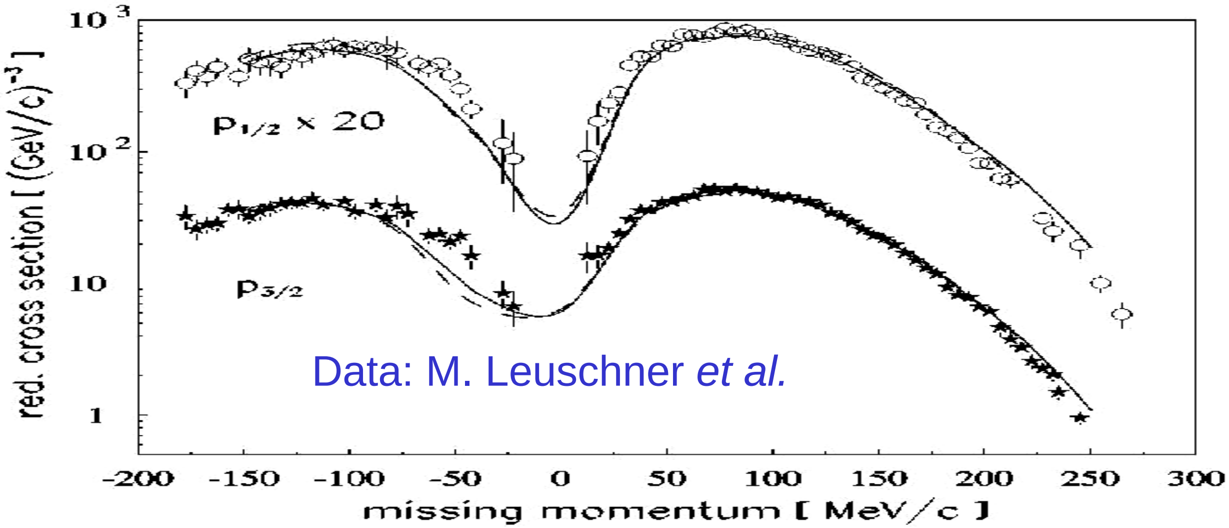
Low Q^2: optical potential

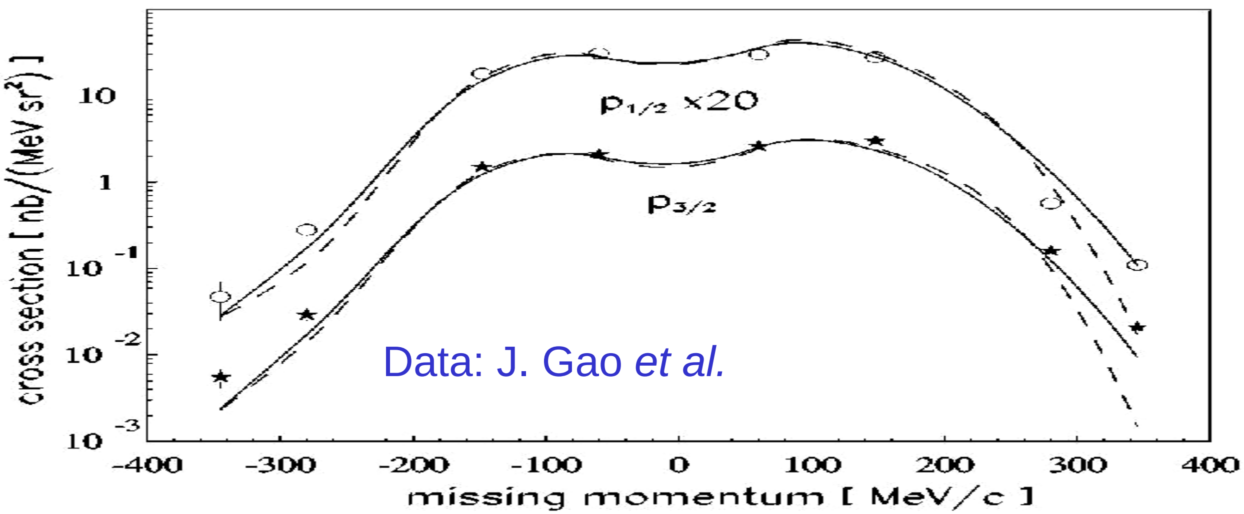
High Q^2: Glauber

Discontinuity seen with strength nearly saturated at high Q^2.

L. Lapikás, *et al*., Phys. Rev. C **61**, 064325 (2000).

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

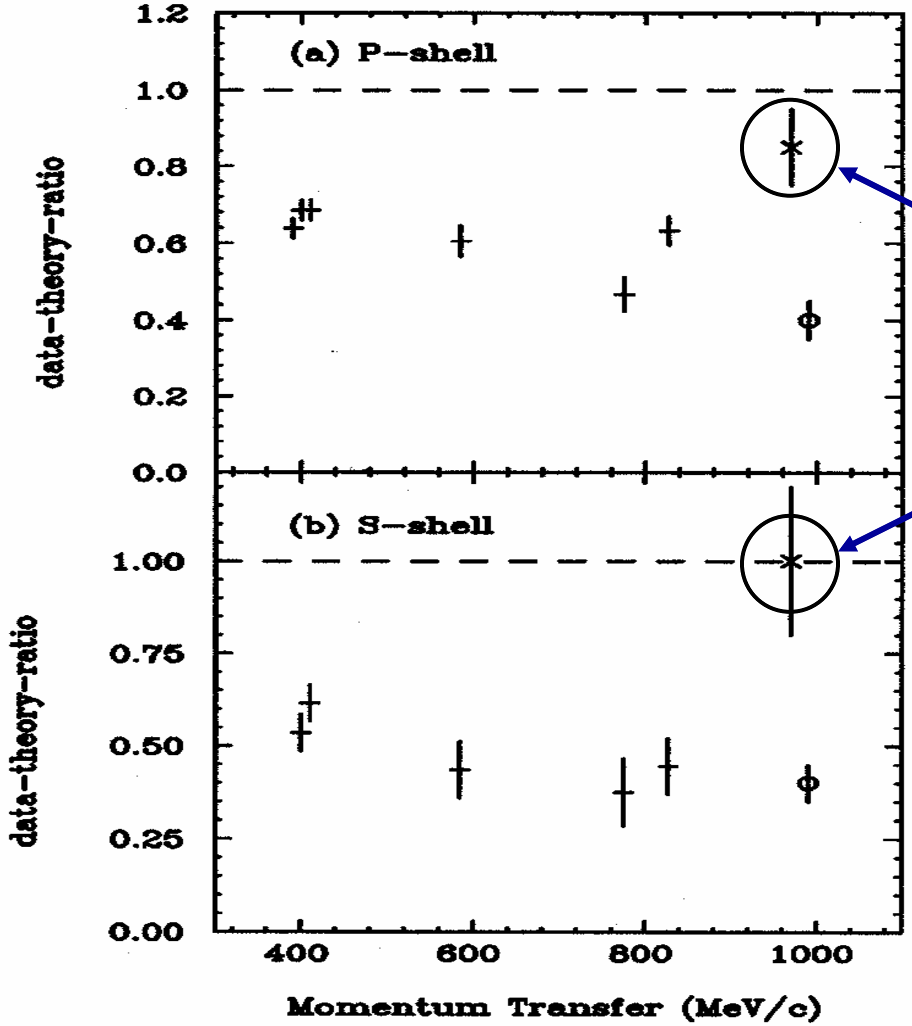




The same spectroscopic factors used throughout: 0.644 ($p_{1/2}$) and 0.537 ($p_{3/2}$).

Marco Radici, W.H. Dickhoff and E. Roth Stoddard, Phys. Rev. C **66**, 014613 (2002).

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



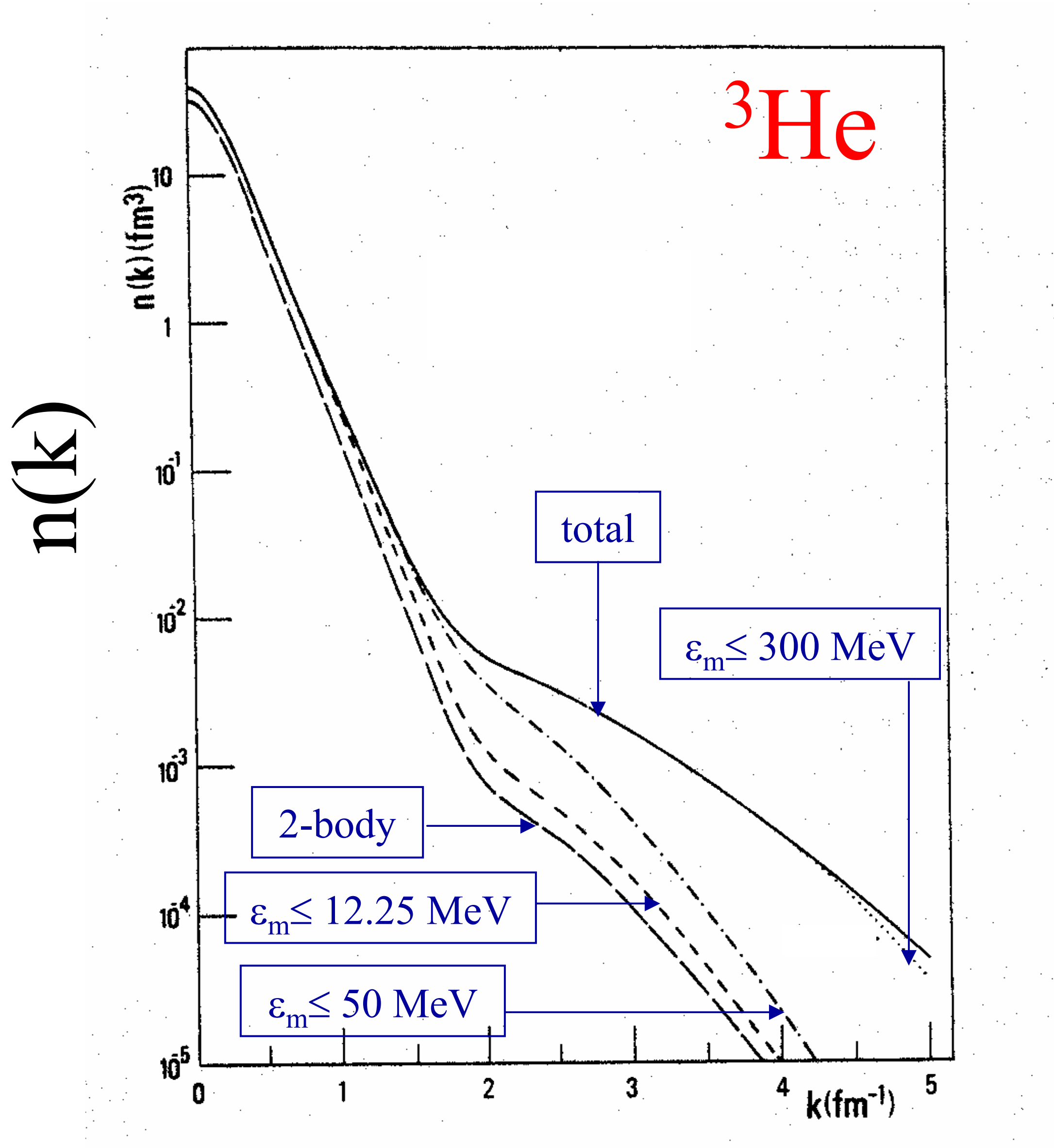
For $\omega < \omega_{QE}$, essentially no quenching is observed.

Bates Linear Accelerator

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

Where does the missing strength go?

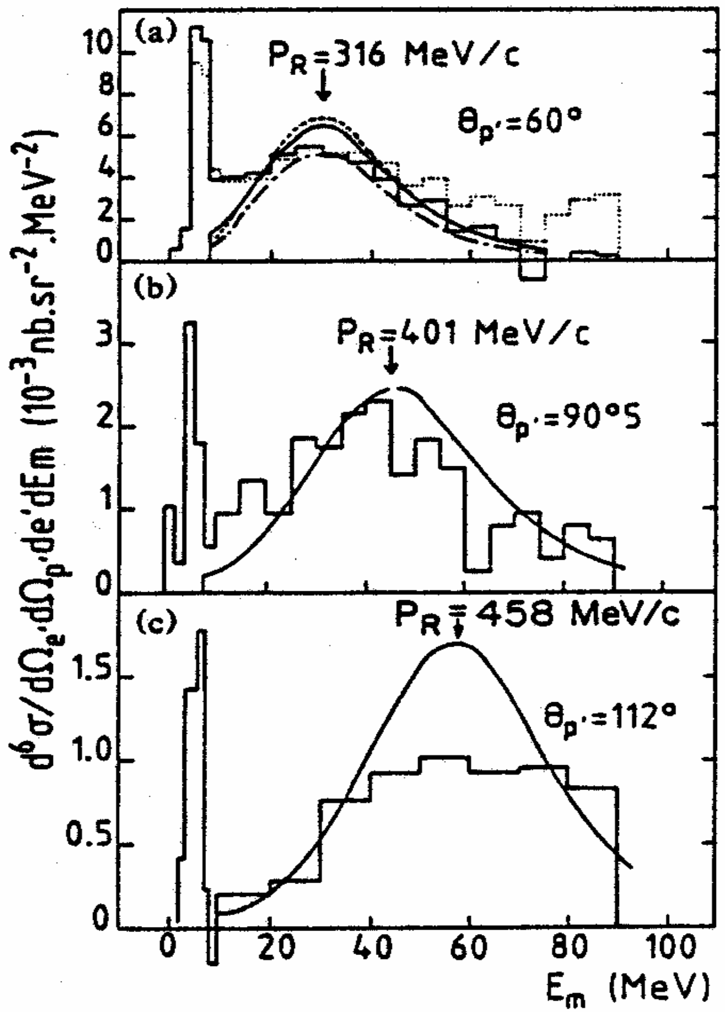
Short-range correlations? …



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).

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



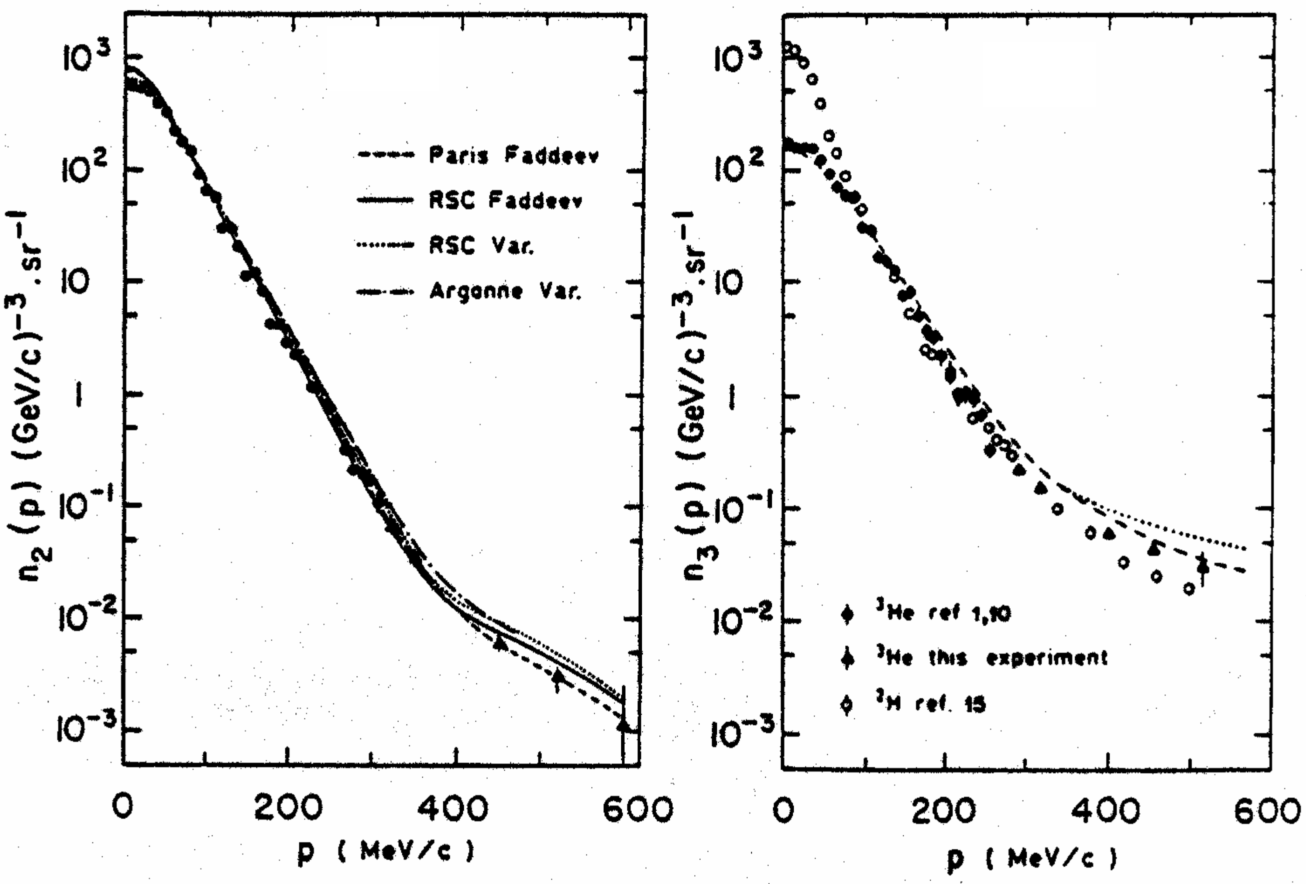
C. Marchand *et al.*,
Phys. Rev. Lett. **60**, 1703 (1988).

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

Arrows indicate expected position for correlated pair.

Saclay

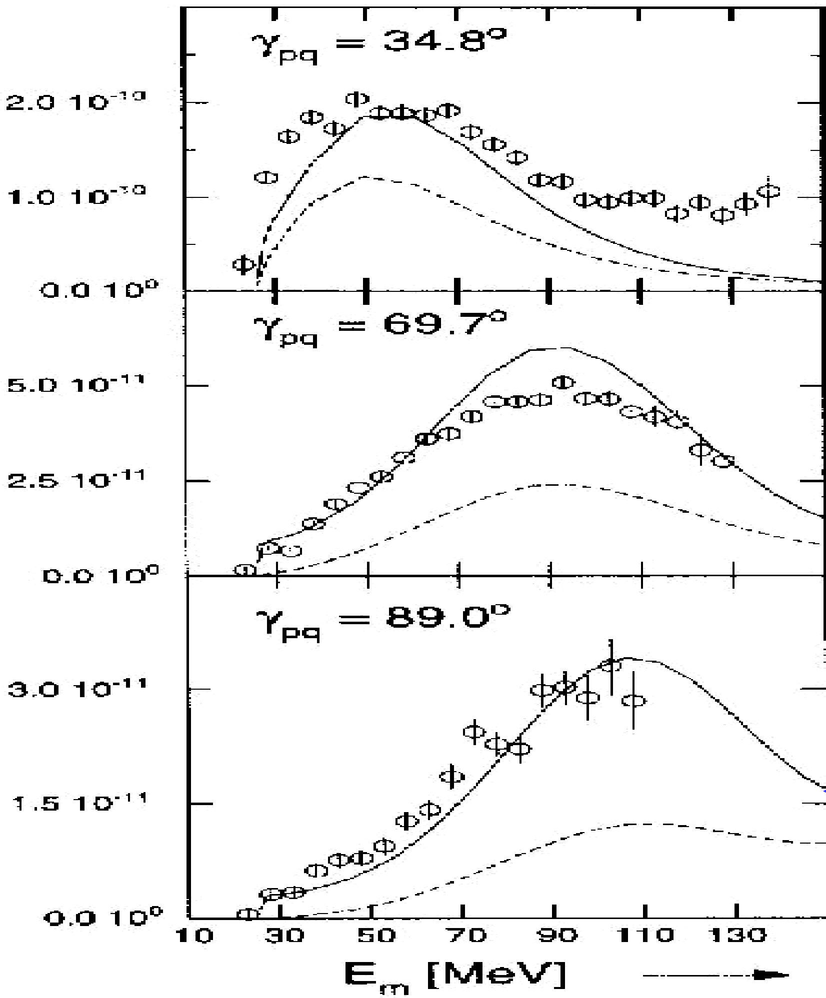
^{3}He(e,e'p)d ^{3}He(e,e'p)np



3BBU similar to d→np

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

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



Peak roughly tracks kinematics of knockout of correlated 2N pair

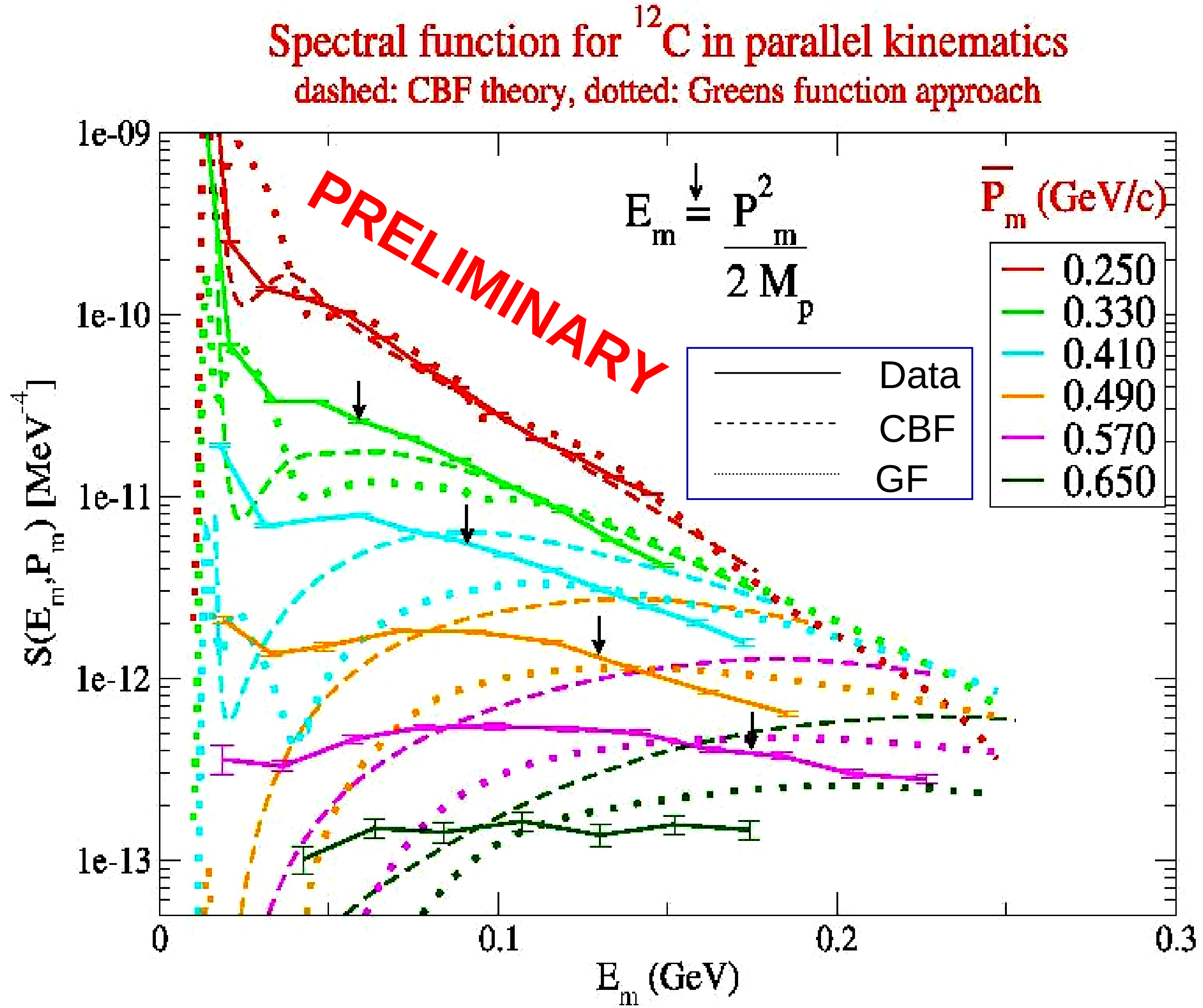
$$E_m \approx \frac{A-2}{A-1}\frac{p_m^2}{2m} + E_{thr}$$

Laget: full

Laget: no MEC/IC

AmPS NIKHEF-K

J.J. van Leeuwe *et al*., Nucl. Phys. **A631**, 593c (1998).



Data do not seem to follow naïve expectation for *NN* correlation peak.

Data: D. Rohe, E97-006 (Preliminary)

GF: H. Müther *et al*., Phys. Rev. C **52**, 2955 (1995).

CBF: O. Benhar *et al*., Nucl. Phys. **A579**, 493 (1994).

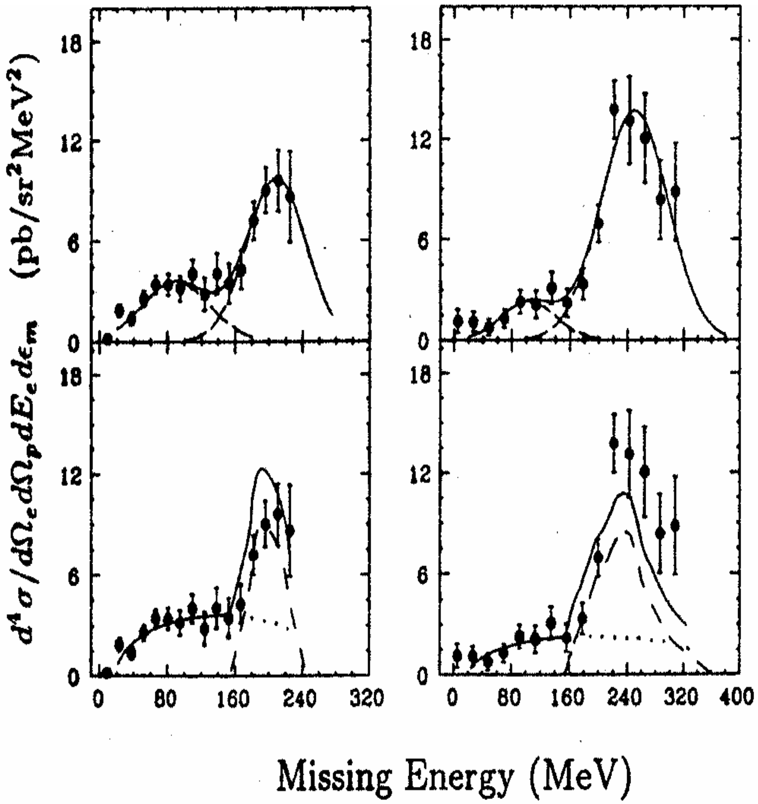
JLab
Hall C

Reaction Mechanism

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

“Delta”

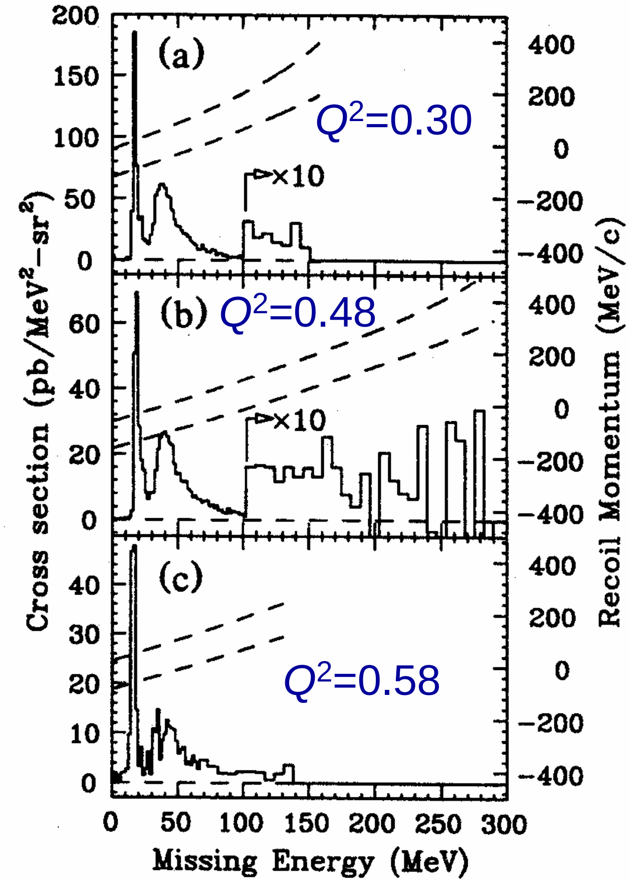
Between dip and Δ　　Peak of Δ



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

Bates Linear Accelerator

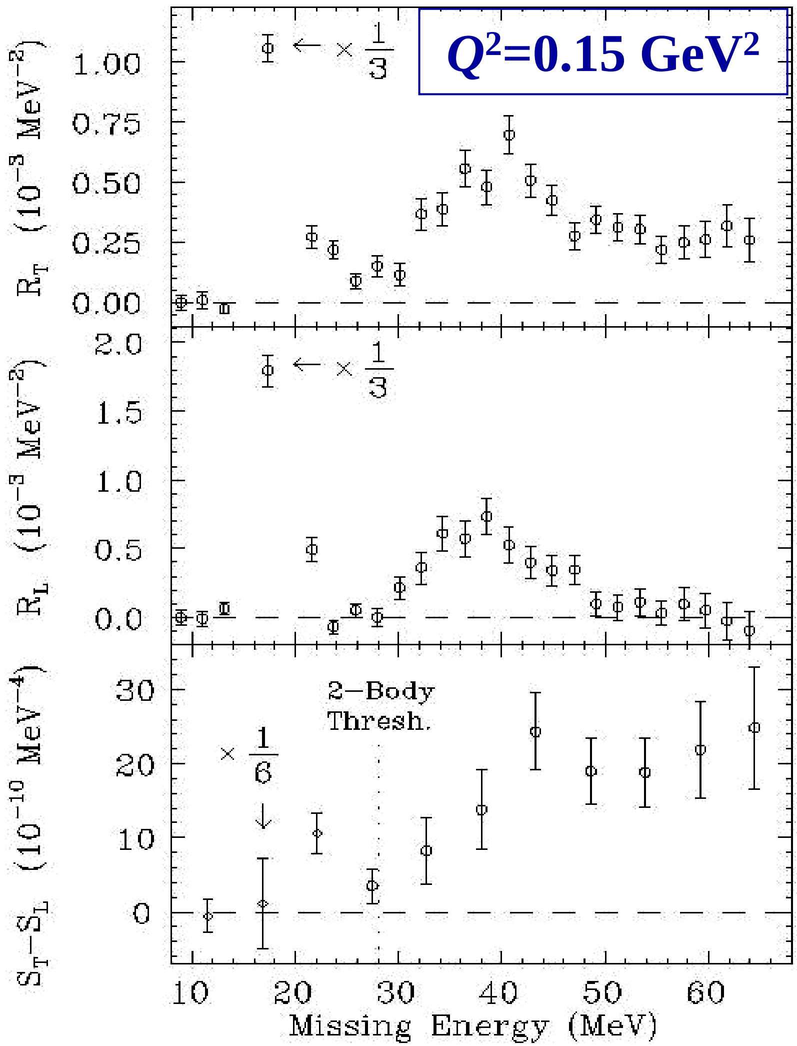
Quasielastic



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

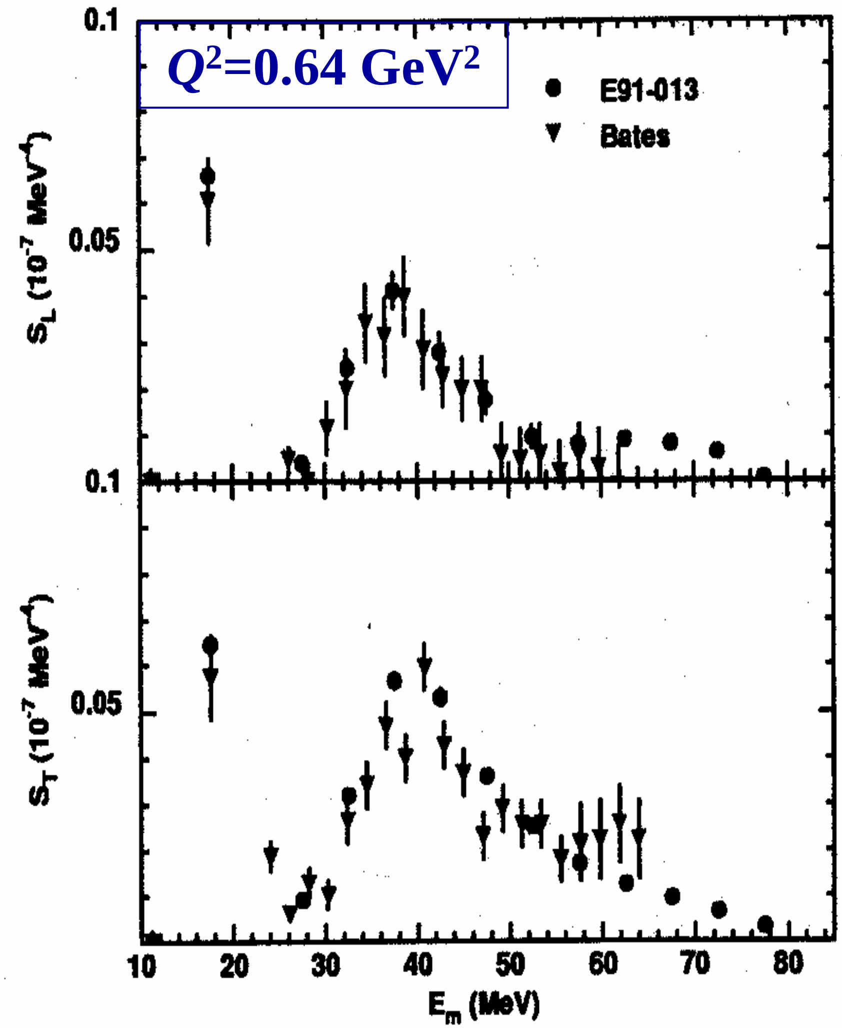
Bates Linear Accelerator

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



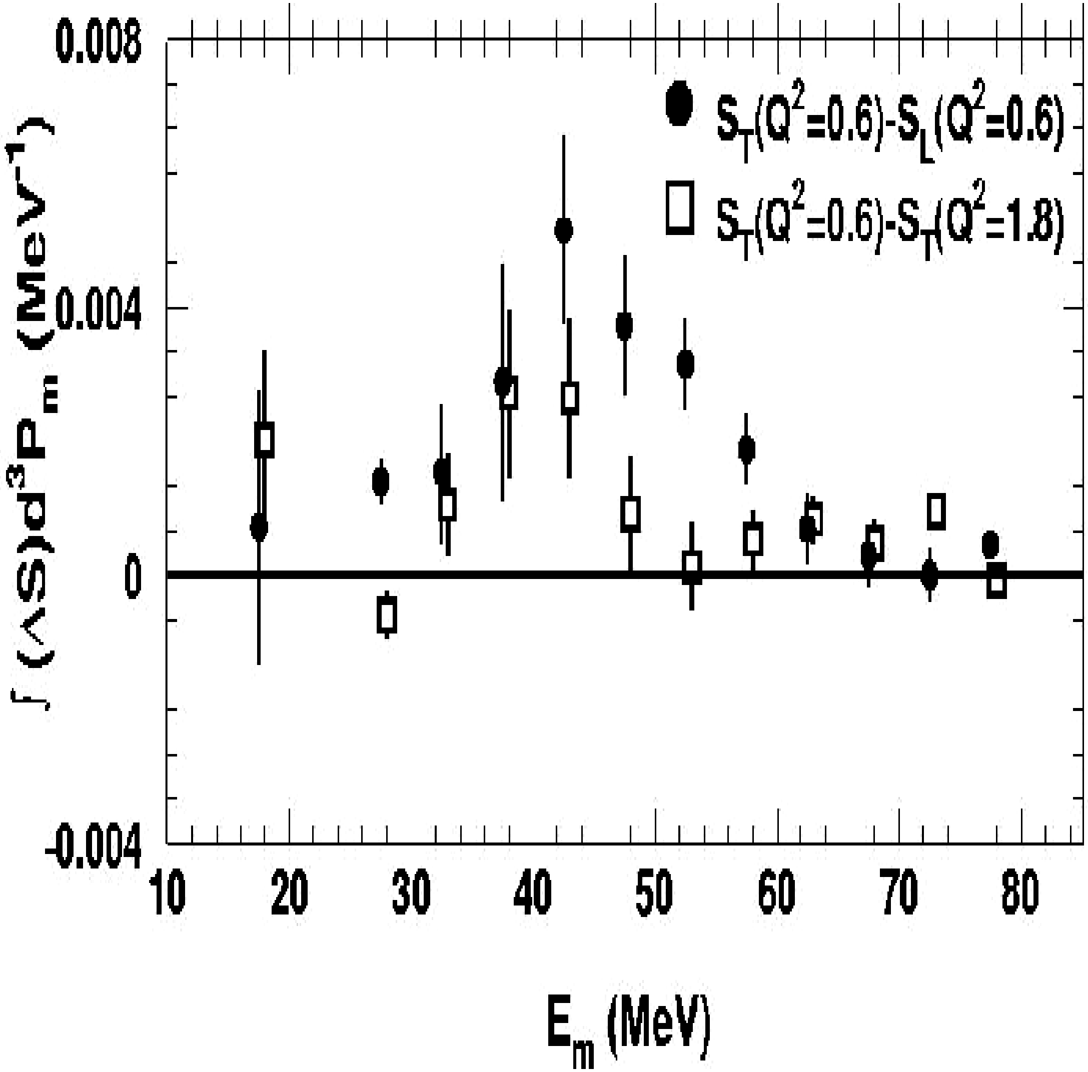
P.E. Ulmer *et al*., Phys. Rev. Lett. **59**, 2259 (1987).

Bates Linear Accelerator



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

JLab Hall C



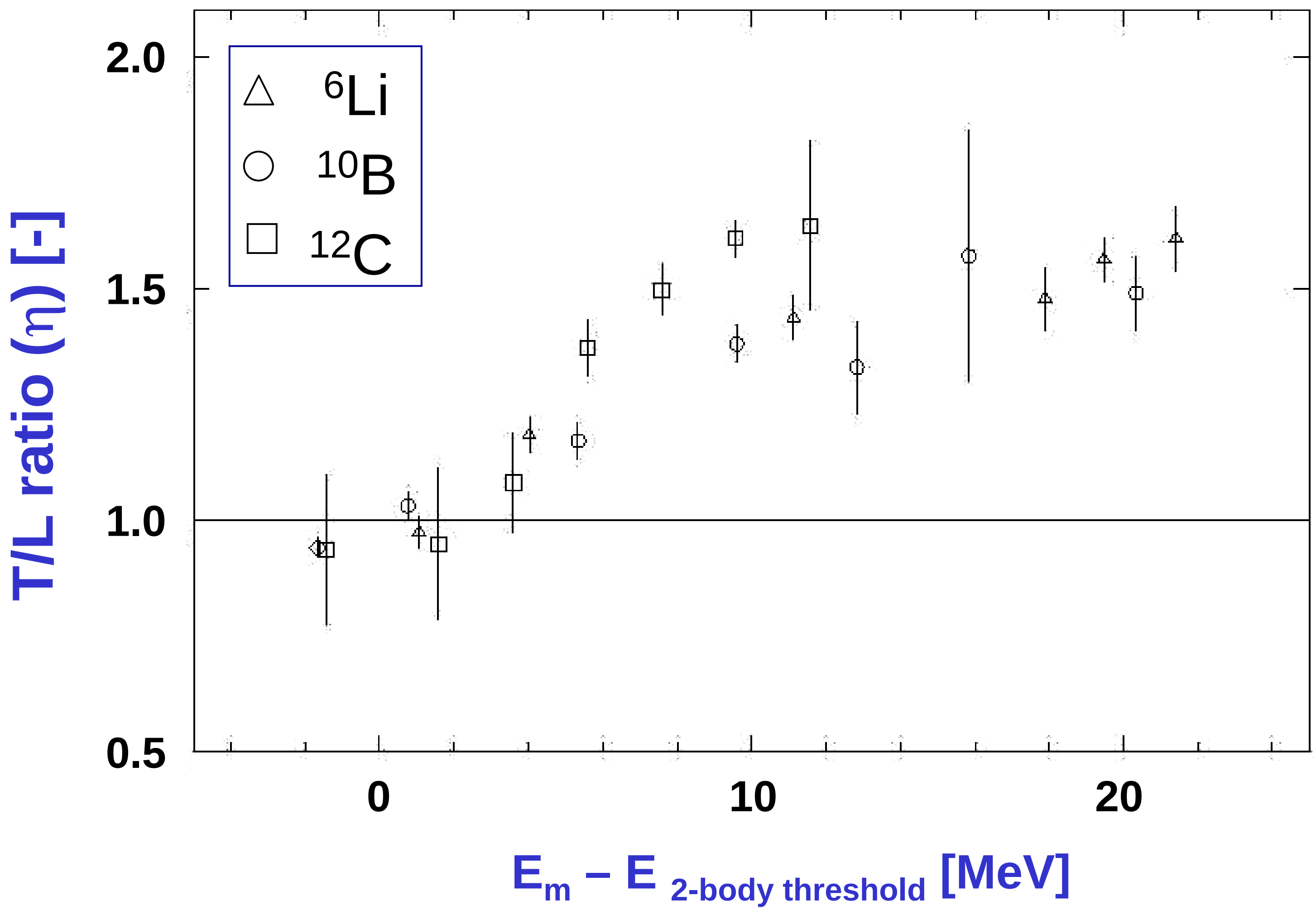
Excess transverse strength at high ε_m.

Persists, though declines, at higher Q^2.

JLab Hall C

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

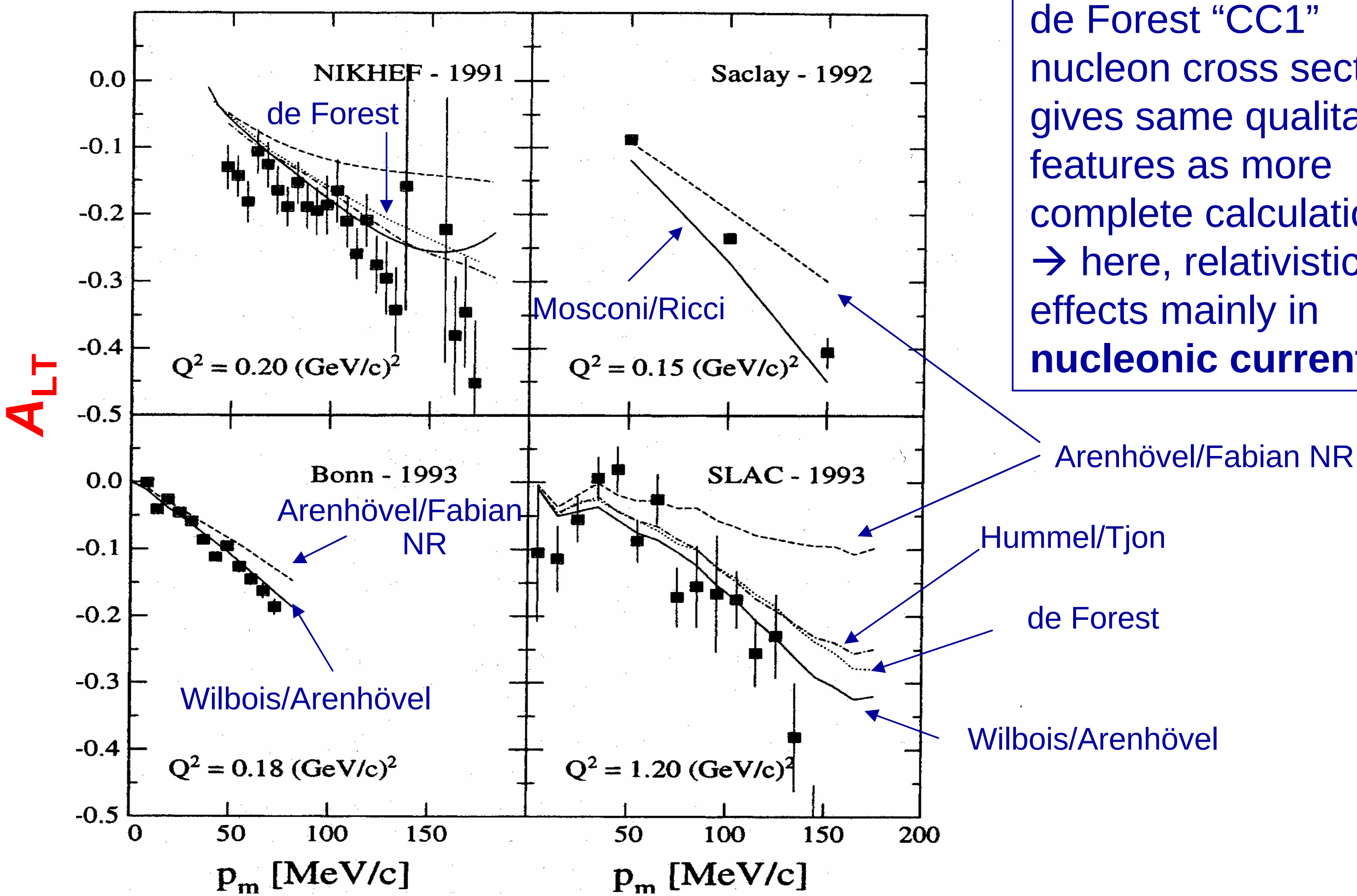
Transverse Enhancement



J.J. Kelly, Adv. Nucl. Phys. **23**, 75 (1996).

Relativity …

$^2H(e,e'p)n$ A_{LT}

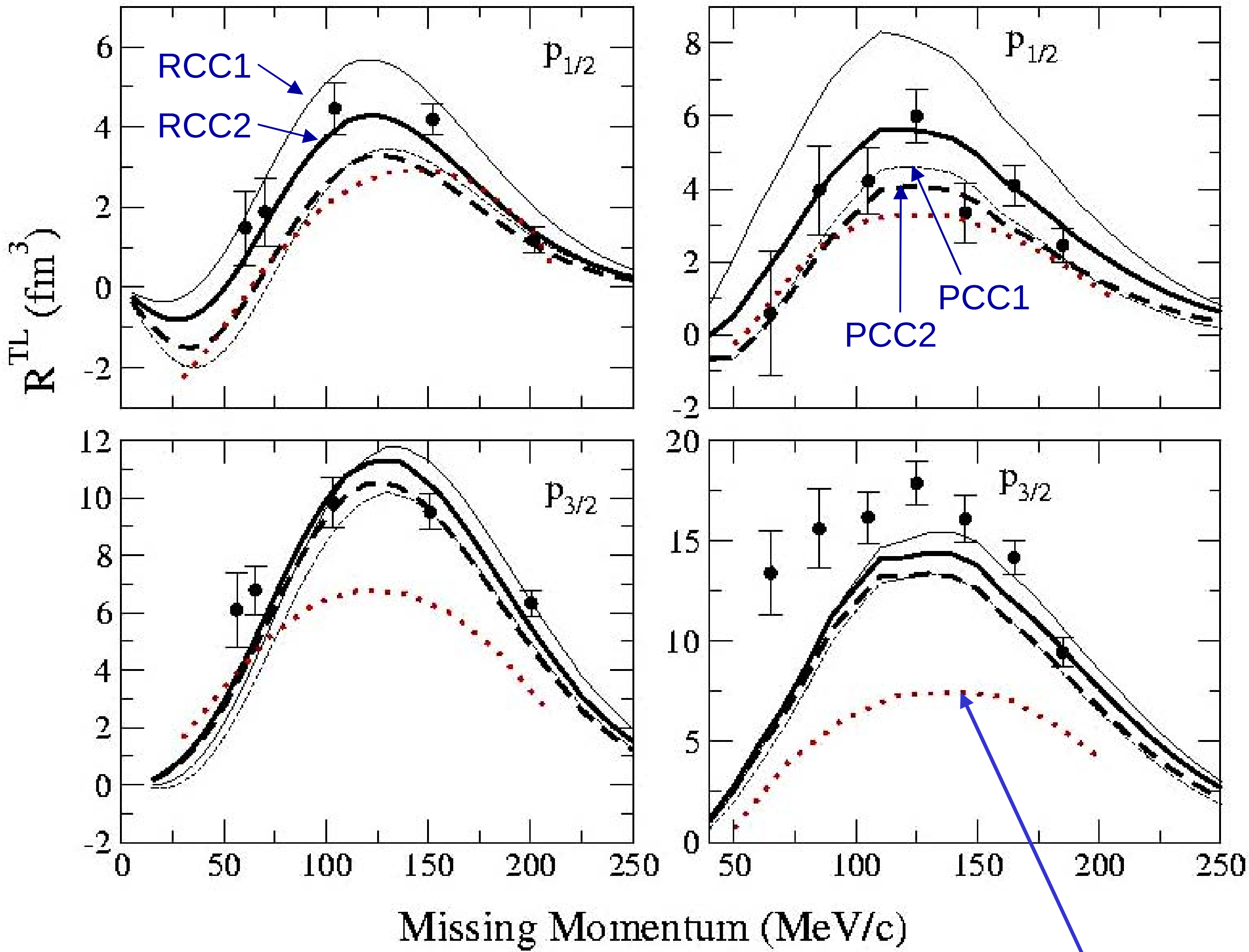


de Forest "CC1" nucleon cross section gives same qualitative features as more complete calculations → here, relativistic effects mainly in **nucleonic current**.

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

Saclay data: L. Chinitz *et al.* NIKHEF data: C.M. Spaltro *et al.*

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



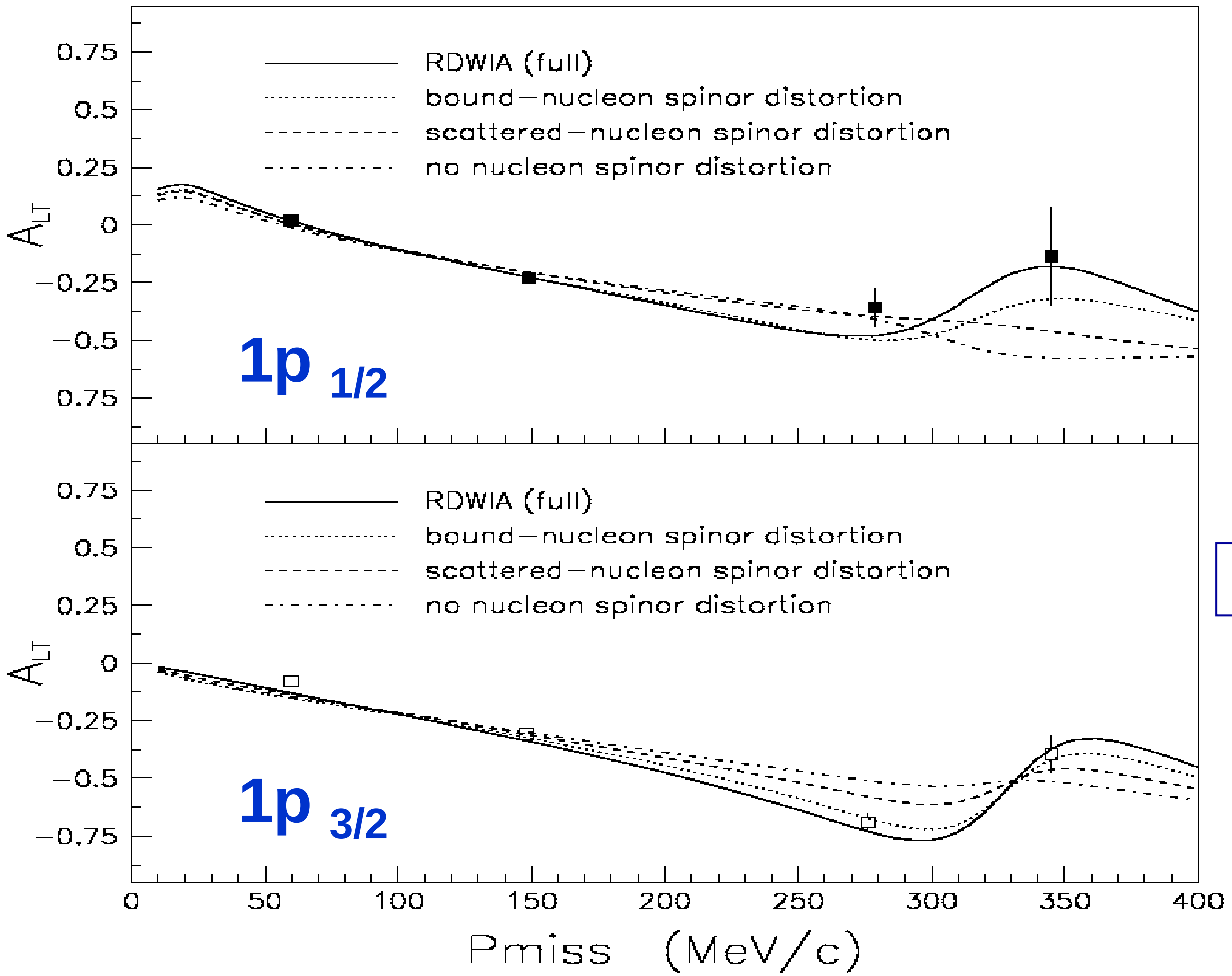
Discrepancy reported earlier was based on non-relativistic calculations.

Relativistic treatment is required even at these modest momenta.

Previous non-relativistic analysis

J.M. Udías *et al.,* Phys. Rev. C **64**, 024614 (2001).

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



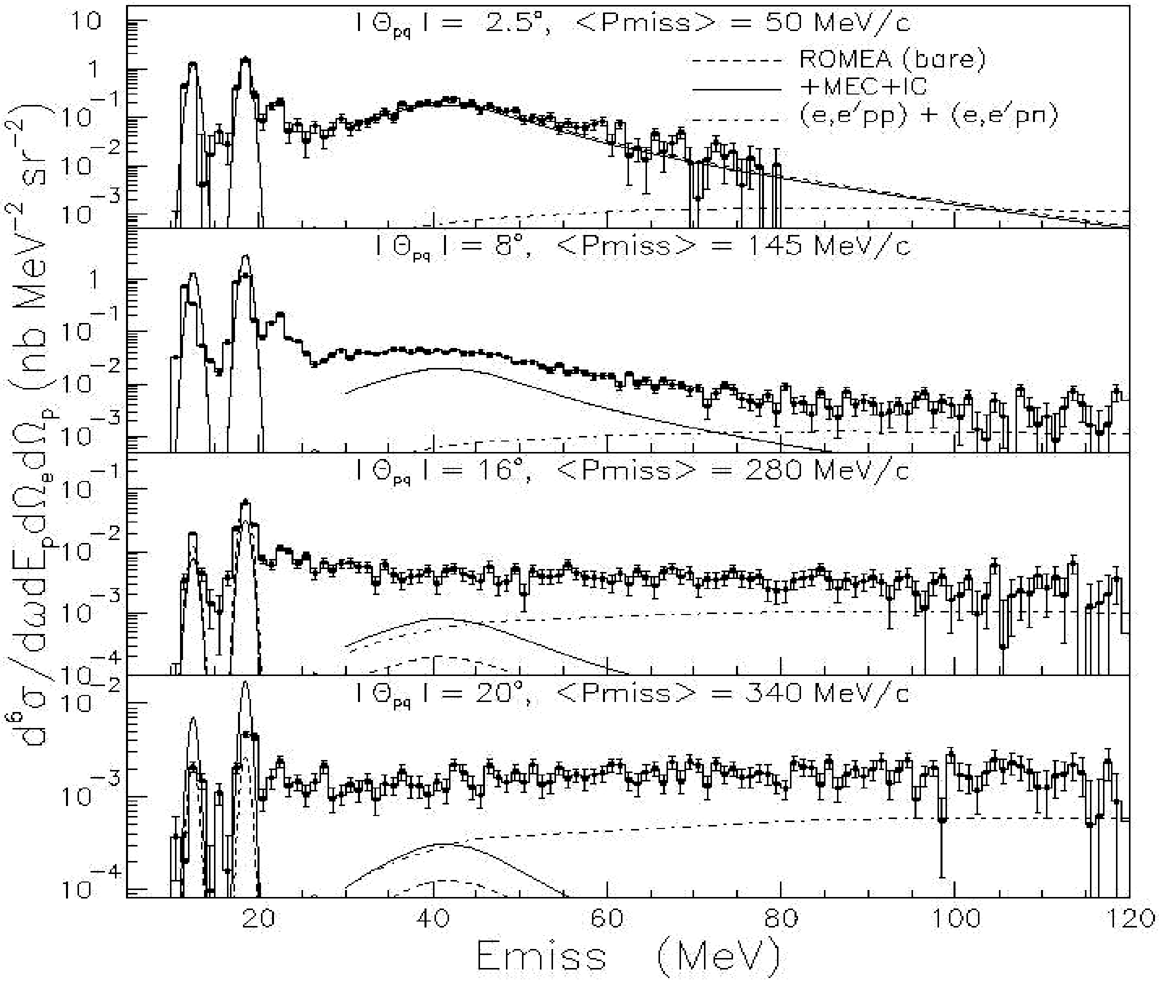
Effect of spinor distortion significant.

Calculations: Udías, *et al*.

JLab Hall A

J. Gao *et al*., Phys. Rev. Lett. **84**, 3265 (2000) and K.G. Fissum *et al*., in preparation, to be submitted to Phys. Rev. C.

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

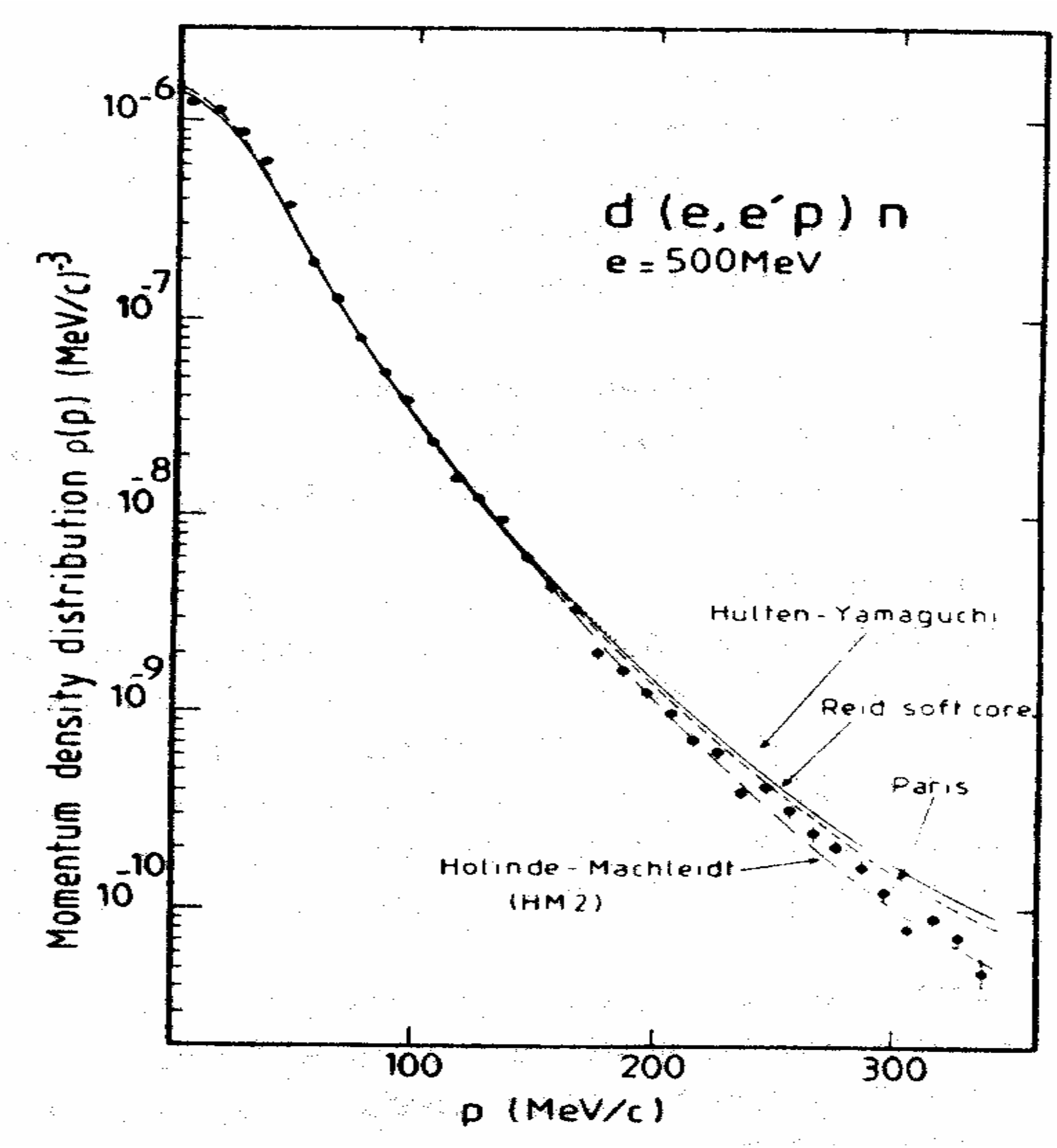


Two-body calculations (Janssen *et al*.) reproduce flat distribution, but **underpredict** by roughly a factor of two.

JLab Hall A

J. Gao *et al*., Phys. Rev. Lett. **84**, 3265 (2000) and K.G. Fissum *et al*., in preparation, to be submitted to Phys. Rev. C.

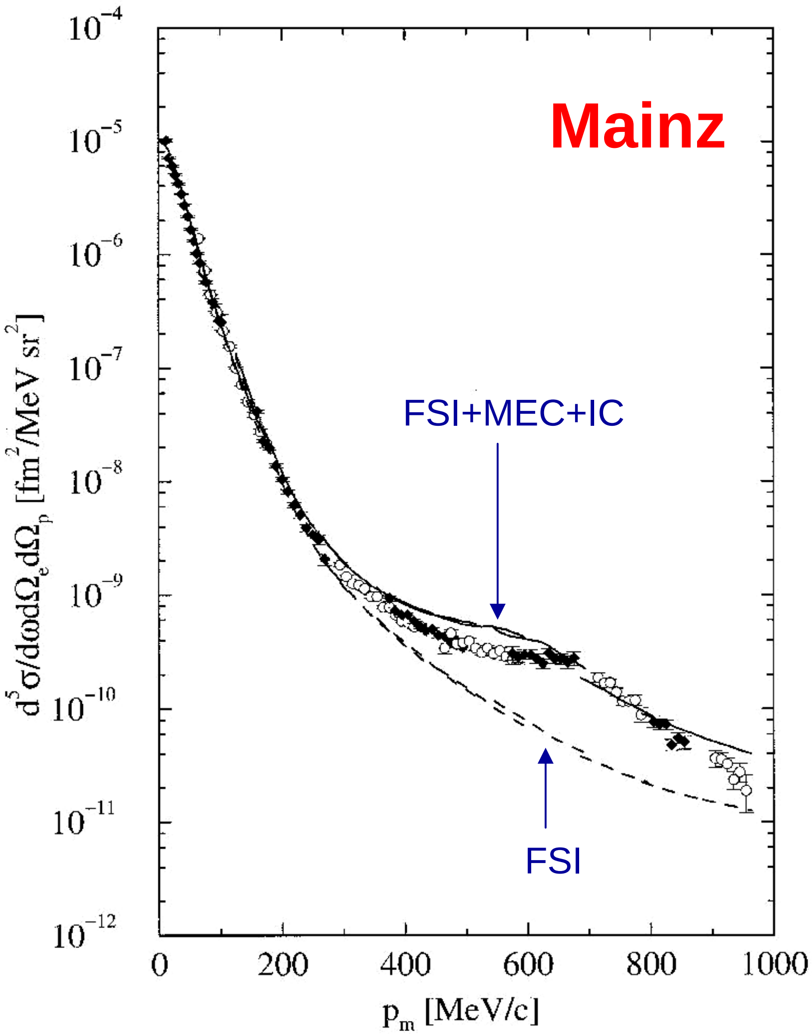
The deuteron and the ***NN*** interaction



Saclay

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

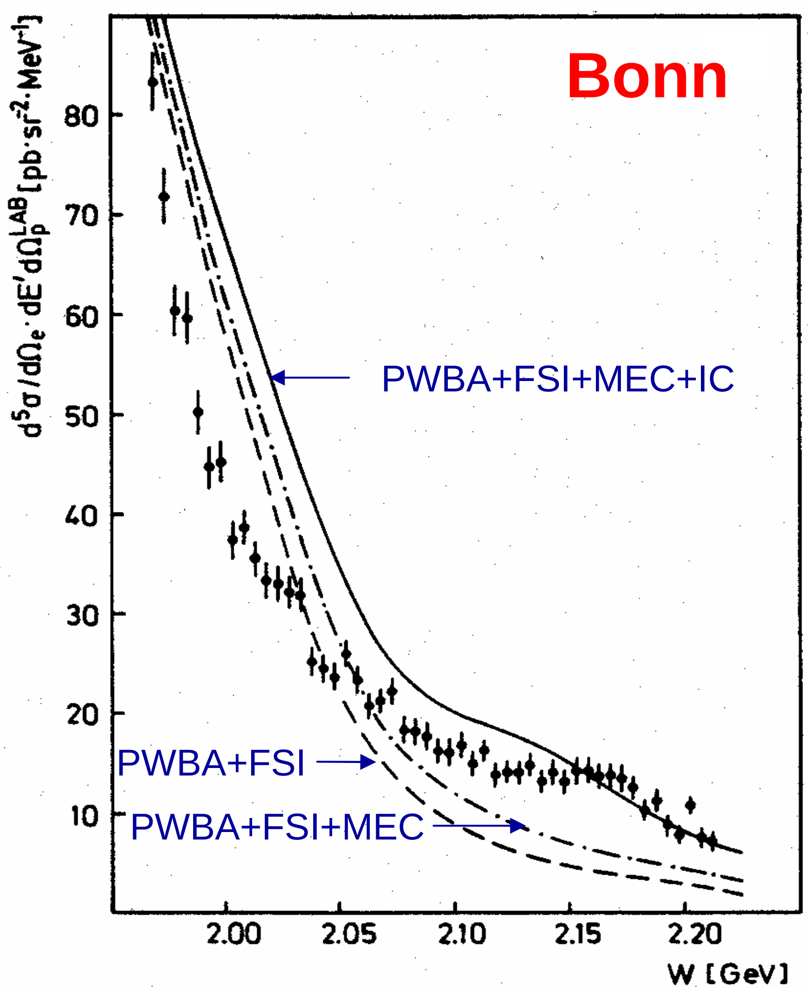
^{2}H(e,e'p) varying Q^2, x



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

Calculations: H. Arenhövel

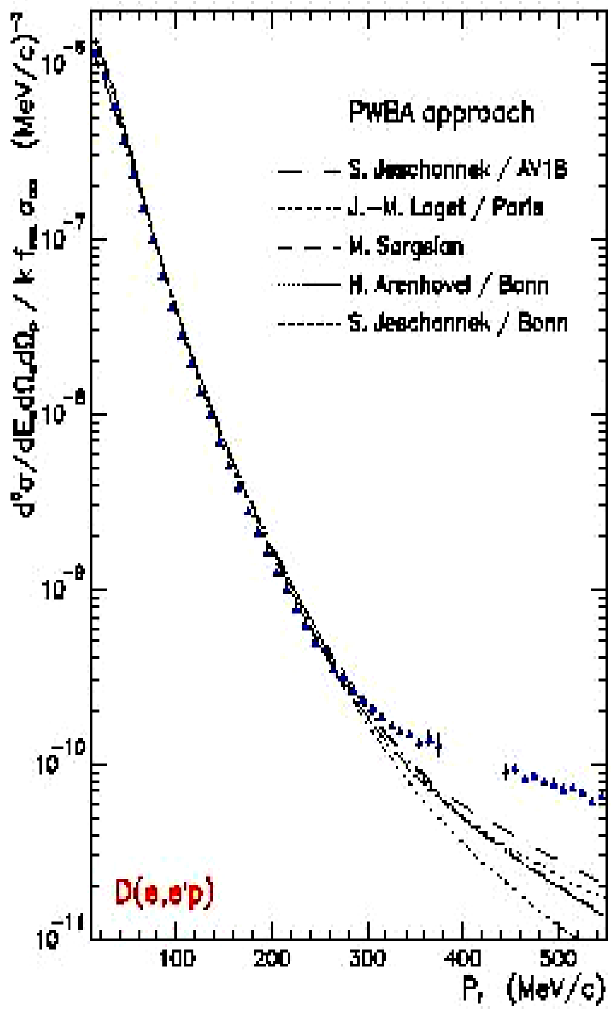
^{2}H(e,e'p) Q^2=0.23 GeV^2 near Δ



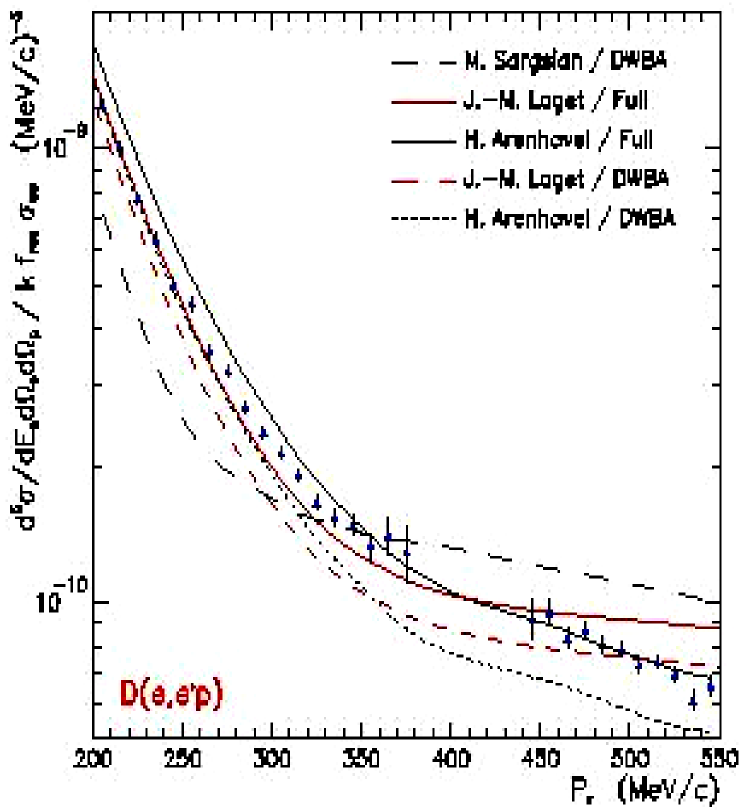
H. Breuker *et al*., Nucl. Phys. **A455**, 641 (1986).

Calculations: Leidemann and Arenhövel

$^2H(e,e'p)n$ $Q^2 = 0.67$ GeV^2 $x = 0.96$



High momentum structure of ^{2}H?



JLab Hall A

→ Evidence for large FSI

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

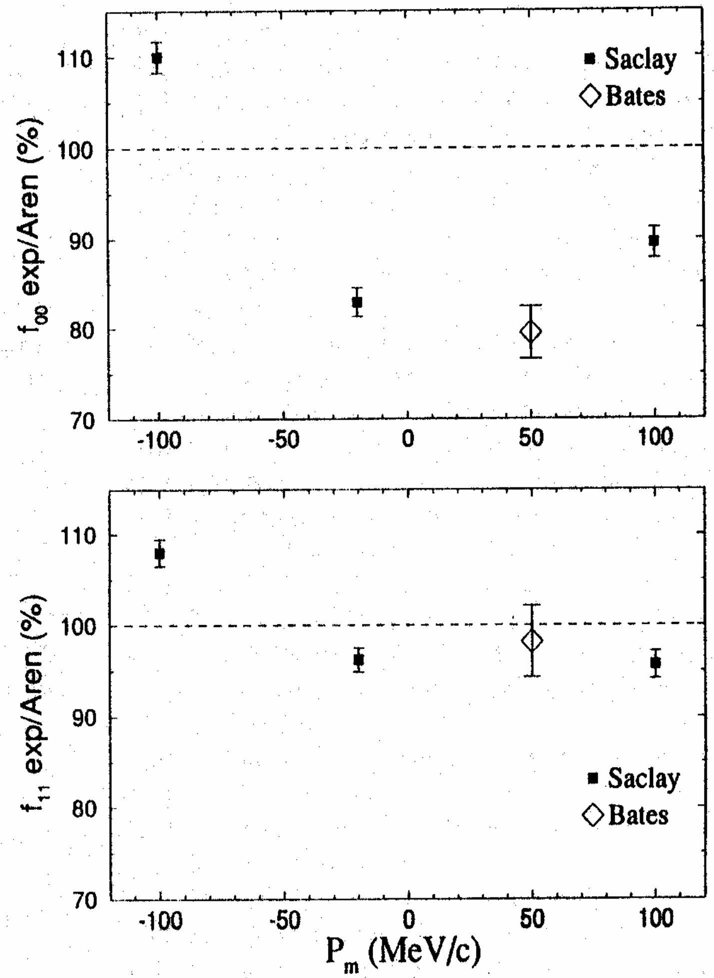


FIG. 1. Ratio of measured f_{00} and f_{11} structure functions to Arenhövel's calculation for this experiment and the Saclay experiment of Ducret *et al.* [6]. Only statistical errors are shown.

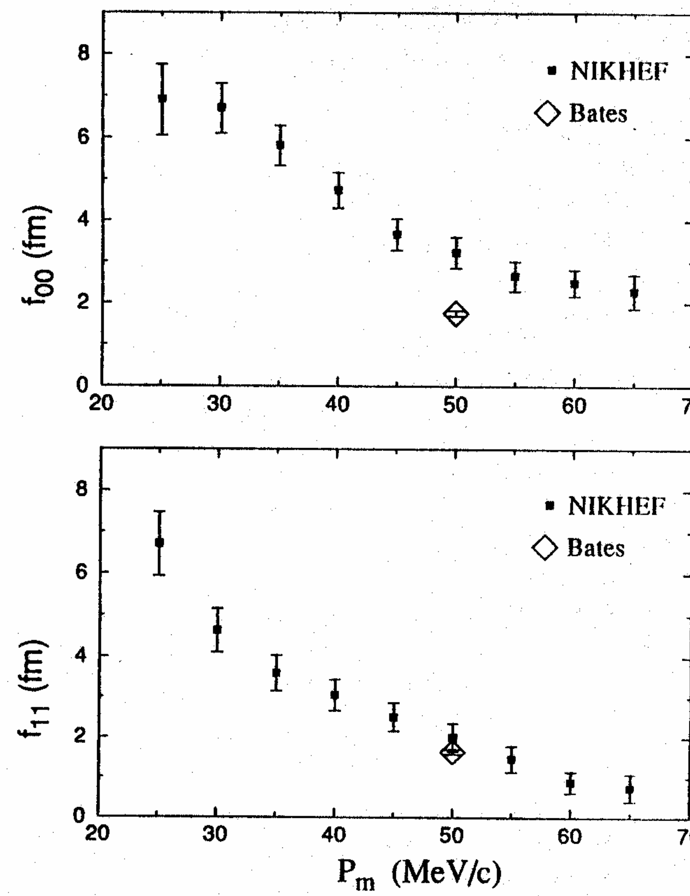
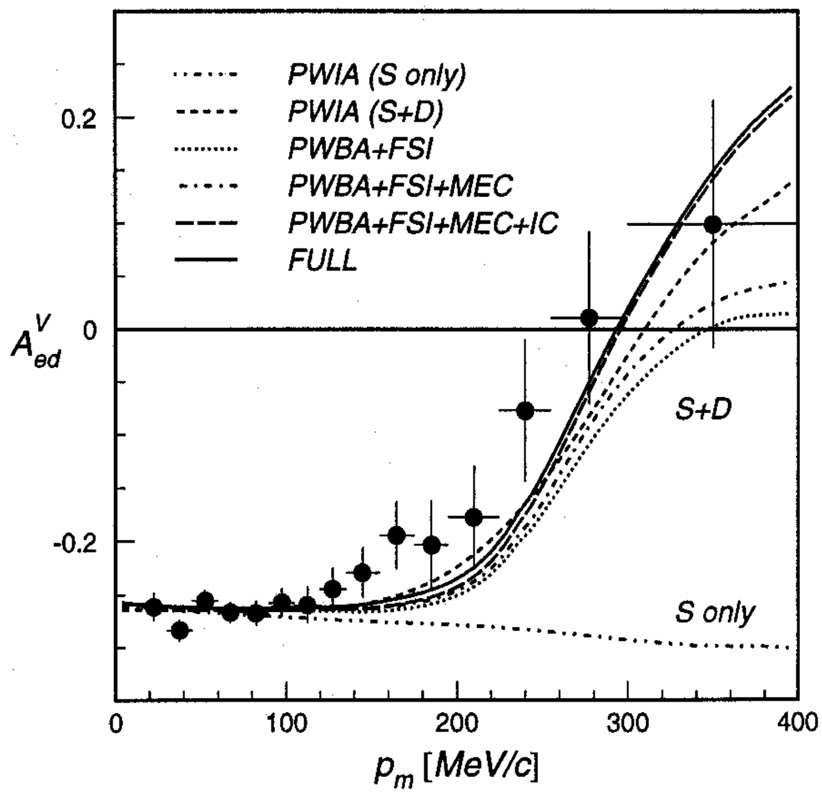


FIG. 2. Separated f_{00} and f_{11} structure functions for this experiment and the NIKHEF experiment of van der Schaar *et al.* [5]. The NIKHEF data ($q = 380$ MeV/c) are averaged over 5 MeV/c bins in p_m. The Bates data ($q = 400$ MeV/c) are averaged over the range of 30 to 70 MeV/c in p_m. Only statistical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

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

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



Sensitive to *D*-state

AmPS NIKHEF-K

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

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

The Nucleon

Proton Polarization and Form Factors

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

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

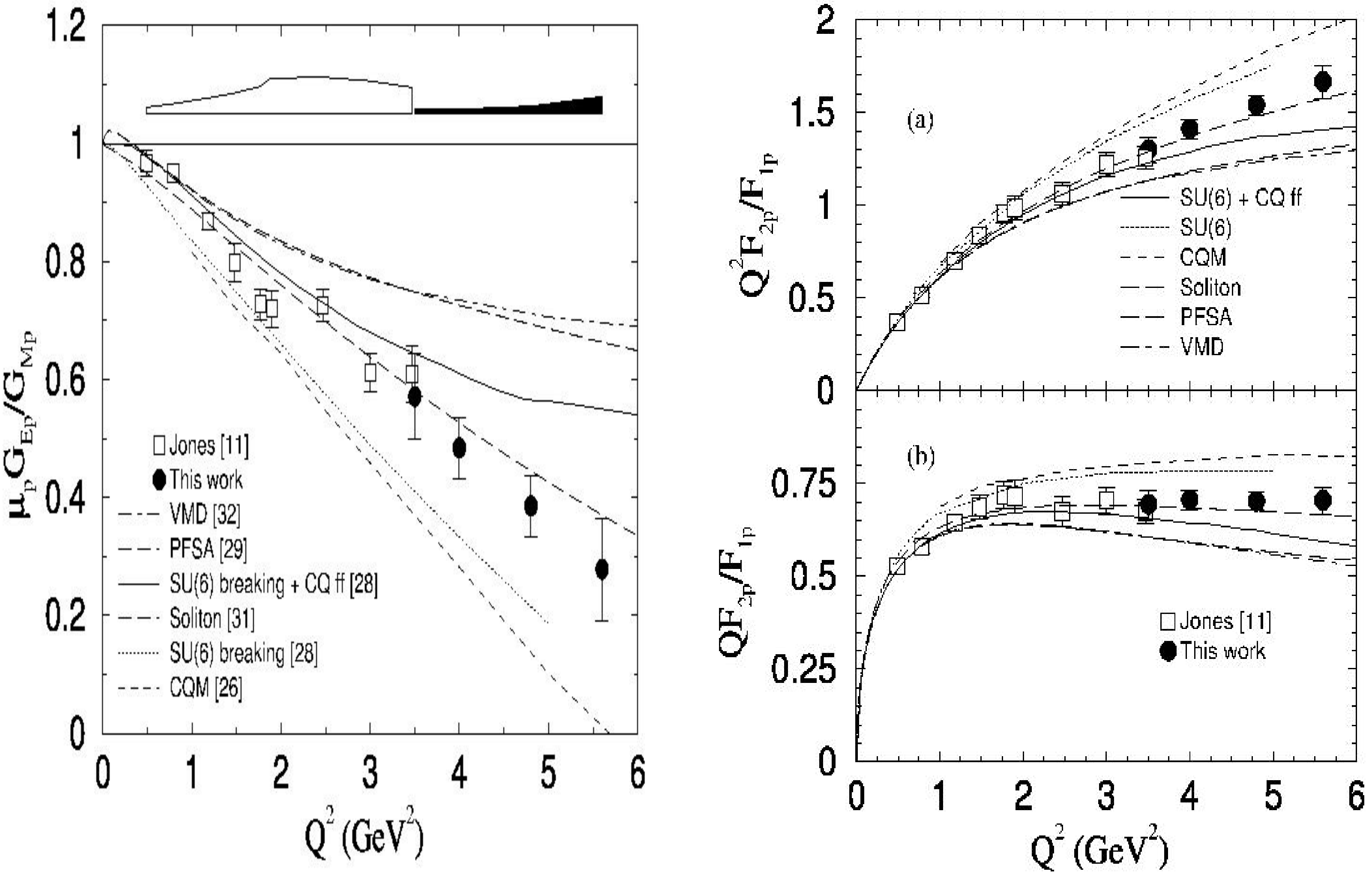
$$I_0 P'_z = \frac{e+e'}{m}\sqrt{\tau(1+\tau)}\,G_M^2 \tan^2\left(\frac{\theta_e}{2}\right)$$

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

$$\boxed{\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\cdot\frac{e+e'}{2m}\tan\left(\frac{\theta_e}{2}\right)} \xrightarrow[\textbf{model assumptions}]{\textbf{in nucleus}} \boxed{\frac{\widetilde{G}_E}{\widetilde{G}_M}}$$

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

Proton Elastic Form Factors via $^1H(\vec{e},e'\vec{p})$



O. Gayou, *et al*., Phys. Rev. Lett. **88**, 092301 (2002).

Searching for Medium Effects on the Nucleon …

In parallel kinematics:

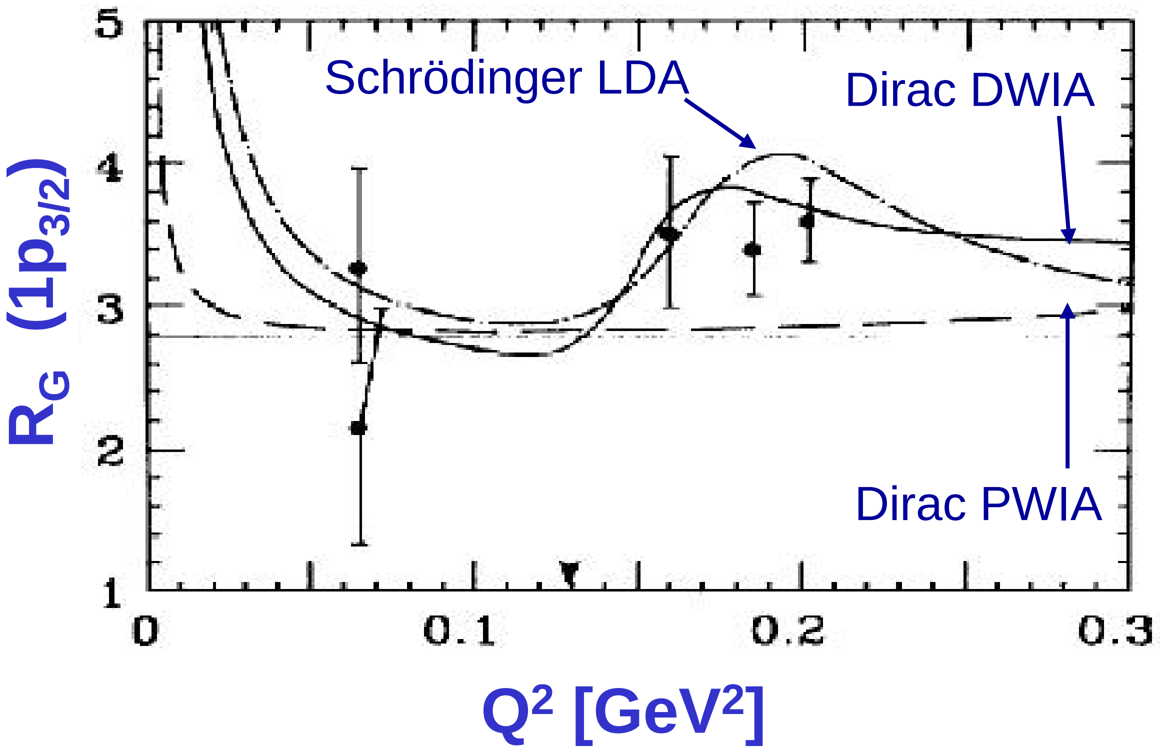
$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_\mathrm{p}\mathrm{d}p\,\mathrm{d}\omega} = \frac{pE}{(2\pi)^3}\sigma_\mathrm{M}[v_L R_L + v_T R_T]$$

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

PWIA

This relies on (unrealistic) model assumption.

Medium Modifications or FSI?



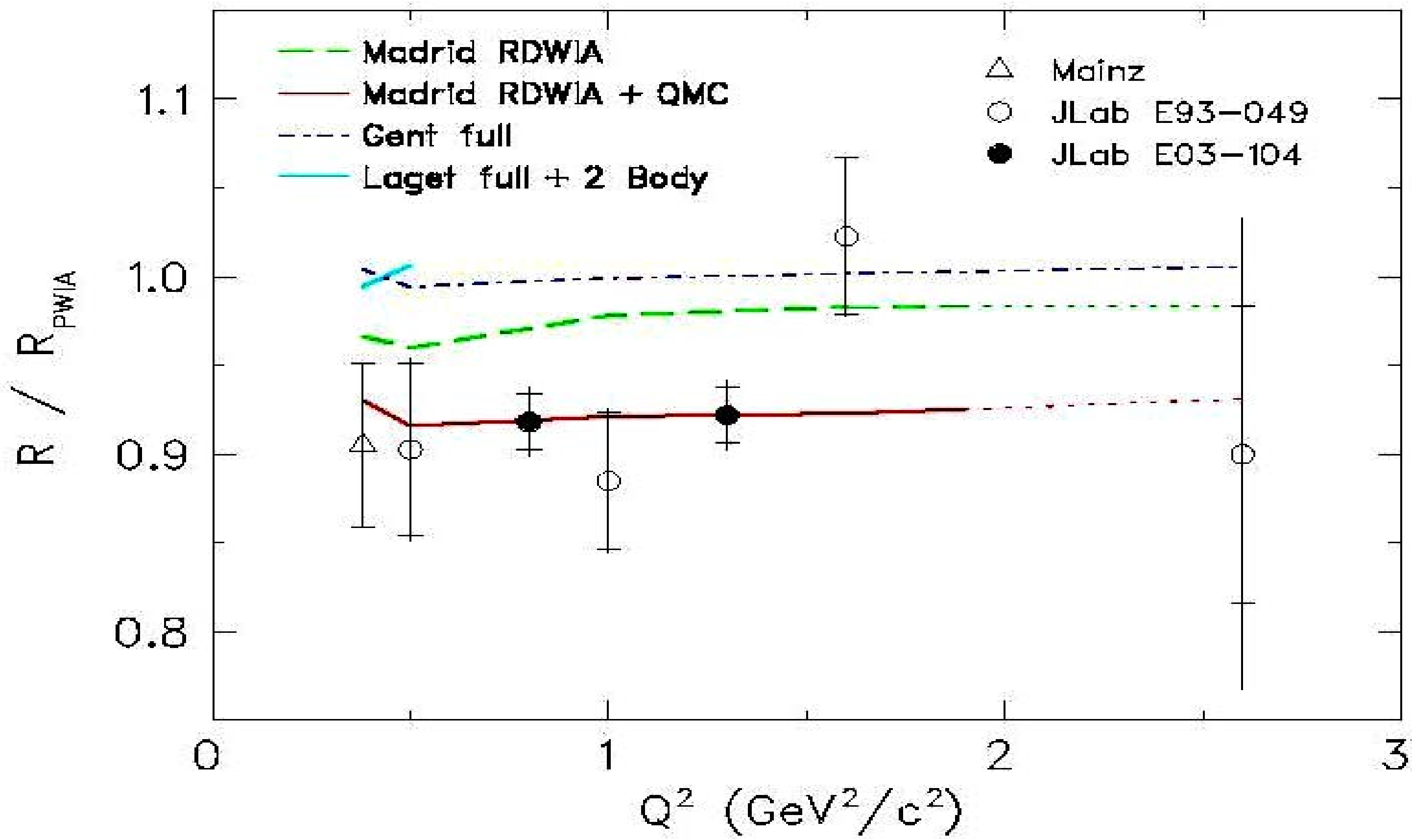
Calculations (^{16}O): T.D. Cohen, J.W. Van Orden, A. Picklesimer, Phys. Rev. Lett. 59, 1267 (1987).

Data (^{12}C): G. Van der Steenhoven et al., Phys. Rev. Lett. 57, 182 (1986).

Another, less model-dependent, method …

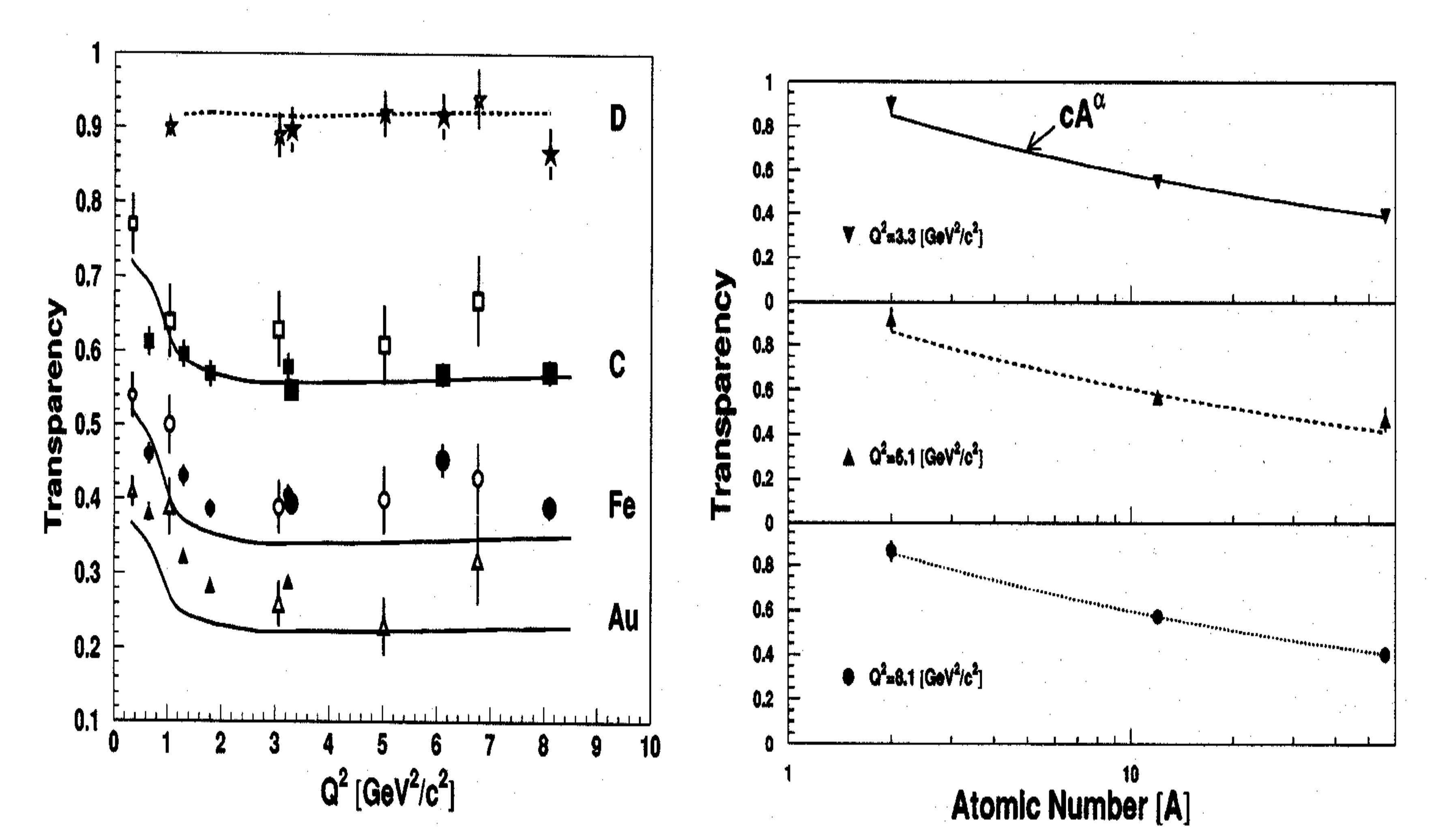
$\boxed{\text{Polarization Transfer}}$

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



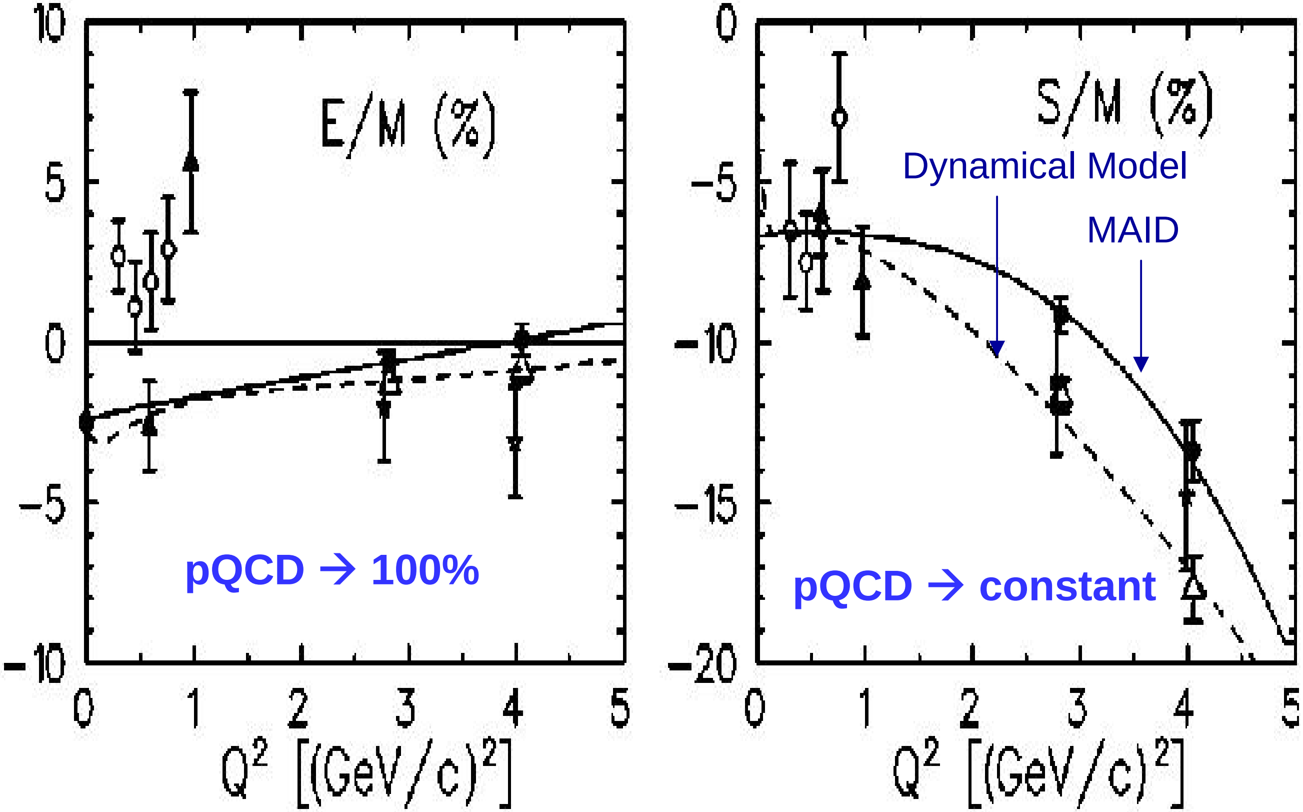
Mainz:	S. Dieterich *et al.*, Phys. Lett. **B500**, 47 (2001).
E93-049:	S. Strauch *et al*., Phys. Rev. Lett. **91**, 052301 (2003).
E03-104:	Projected Data, Strauch, Ent, Ransome, Ulmer, cospokespersons

Color Transparency?



K. Garrow, *et al*., Phys. Rev. C **66**, 044613 (2002).

p(e,e'p)π^0 and $\gamma^* N \rightarrow \Delta$



Sabit S. Kamalov *et al*., Phys Rev. C **64**, 032201 (2001).

JLab Hall C data (Q^2=2.8, 4.0 GeV^2): V.V. Frolov *et al*., Phys. Rev. Lett. **82**, 45 (1999); their analysis shown by stars.

Summary

- Single-particle picture describes some gross features of experiments at least in quasielastic kinematics.
- Quenching of strength gives indirect evidence of *NN* correlations. Also, some direct evidence, but …
- Reaction dynamics still not well understood.
- Relativistic treatment essential at moderate/high Q^2, but also essential at low Q^2 for certain observables.
- *NN* interaction studies via d(e,e'p)n now being fully exploited: reaction dynamics/short-range structure of *NN* force.
- A wealth of new information now coming out on the nucleon: elastic and inelastic structure, medium modifications, color transparency, polarizabilities, …