SO WHERE ARE THE QUARKS?

Seven Years of Nuclear Physics at CEBAF

Larry Weinstein
Old Dominion University
(and a cast of thousands)*

- What we knew then
- What we wanted to learn
- Our wonderful new equipment
- What we learned

* EXPERIMENTALISTS, THEORISTS, ACCELERATOR PHYSICISTS, CEBAF STAFF, FUNDING AGENCIES, ...

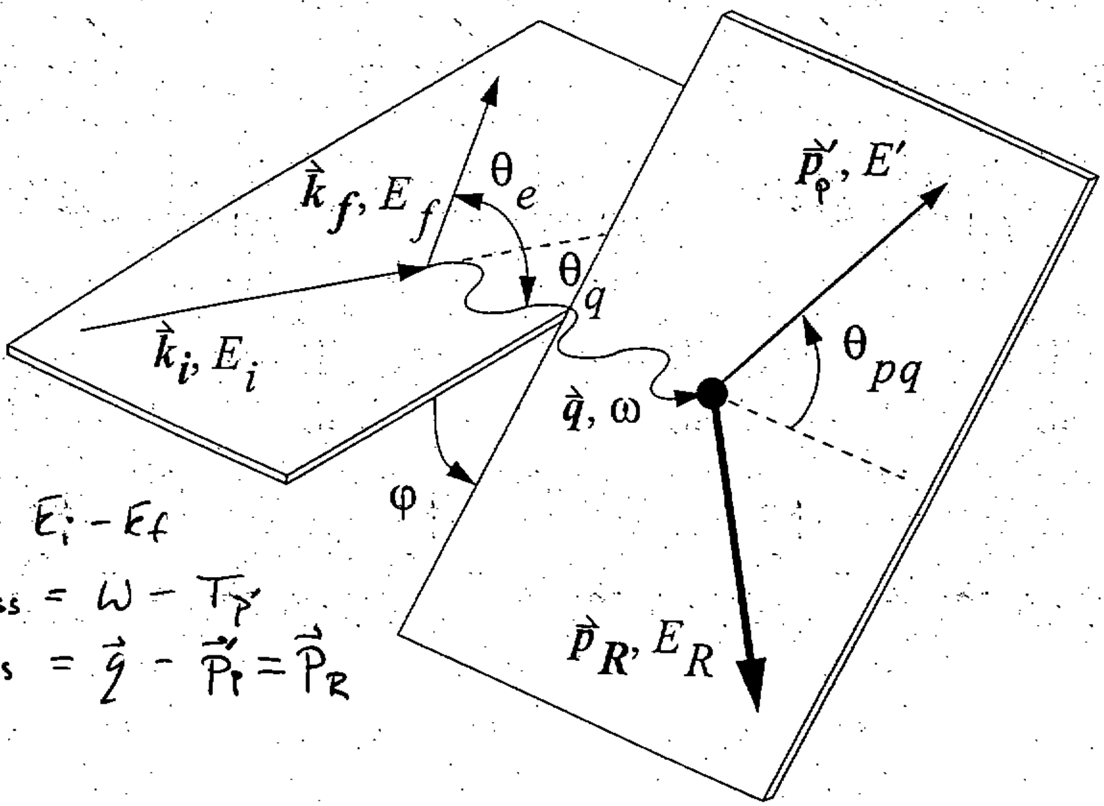
1996 – What We Knew Then
Nuclear Theory

Useful Degrees of Freedom: Nucleons and Mesons
Useless (but fundamental) DoF: Quarks and Gluons

The Nucleon-Meson Picture

- The Nucleus – individual nucleons interacting via 2- and 3- body potentials fit to NN elastic scattering phase shifts ($p_{rel} < 350$ MeV/c)
  - Short range interactions poorly constrained
  - 'Exact' solutions only possible for
    * $A = 3$ below pion threshold
    * $A \leq 6$ bound states
  - $A > 6$ treated as mean field plus correlations
  - Continuum interactions treated via an optical potential
- Electromagnetic Probe – interacts via 1-, 2- and many-body currents
  - 2- and many-body currents hard to calculate and not well constrained

(e,e′p) in the Born approximation:



$\omega = E_i - E_f$

$E_{miss} = \omega - T_{p'}$

$\vec{P}_{miss} = \vec{q} - \vec{P}'_p = \vec{P}_R$

$$\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_{miss} d\omega} = \frac{|\vec{p}|E}{(2\pi)^3}\sigma_{Mott}\,[\, v_L \mathbf{R_L} + v_T(\theta_e)\mathbf{R_T} + v_{LT}(\theta_e)\mathbf{R_{LT}}\cos(\phi) + v_{TT}\mathbf{R_{TT}}\cos(2\phi)\,]$$

$$\mathbf{R_L} = \langle \rho\rho^\dagger \rangle$$

$$\mathbf{R_T} = \langle J_\parallel J_\parallel^\dagger + J_\perp J_\perp^\dagger \rangle$$

$$\mathbf{R_{LT}}\cos(\phi) = -\langle \rho J_\parallel^\dagger + J_\parallel \rho^\dagger \rangle$$

$$\mathbf{R_{TT}}\cos(2\phi) = \langle J_\parallel J_\parallel^\dagger - J_\perp J_\perp^\dagger \rangle$$

$$\frac{d^6\sigma}{d\Omega_e d\Omega_p dE_{miss} d\omega} = K\sigma_{ep} S^D(E_{miss}, P_{miss})$$

The Response Functions

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

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

$$R_L = \left|\rho_{fi}(\vec{q})\right|^2 = \left(\frac{\vec{q}}{\omega}\right)^2 \left|J^0_{fi}(\vec{q})\right|^2$$

$$R_T = \left|J^{+1}_{fi}(\vec{q})\right|^2 + \left|J^{-1}_{fi}(\vec{q})\right|^2$$

$$R_{TT} = 2\,\mathrm{Re}\left\{J^{+1}_{fi}(\vec{q})\, J^{-1}_{fi}(\vec{q})\right\}$$

$$R_{LT} = -2\,\mathrm{Re}\left\{\rho_{fi}(\vec{q})\left(J^{+1}_{fi}(\vec{q}) - J^{-1}_{fi}(\vec{q})\right)\right\}$$

Including electron and recoil proton polarizations

$$\left(\frac{d^6\sigma}{d\Omega_e d\Omega_p dp\, d\omega}\right)_{LAB} = \frac{pE}{(2\pi)^3}\sigma_M \{v_L(R_L + R_L^n S_n) + v_T(R_T + R_T^n S_n)$$
$$+ v_{LT}[(R_{LT} + R_{LT}^n S_n)\cos\varphi_x + (R_{LT}^l S_l + R_{LT}^t S_t)\sin\varphi_x]$$
$$+ v_{TT}[(R_{TT} + R_{TT}^n S_n)\cos 2\varphi_x + (R_{TT}^l S_l + R_{TT}^t S_t)\sin 2\varphi_x]$$
$$+ h v_{LT'}[(R_{LT'} + R_{LT'}^n S_n)\sin\varphi_x + (R_{LT'}^l S_l + R_{LT'}^t S_t)\cos\varphi_x]$$
$$+ h v_{TT'}(R_{TT'}^l S_l + R_{TT'}^t S_t)\}$$

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

and other v's defined as before

1996 – What We Knew Then
Experiment

The nucleus is made of nucleons and mesons.
At $x \geq 1$ ($y \leq 0$) there are not many mesons.

- $A(e, e')$ scales in y (at $y = -0.2$ GeV and $Q^2 > 1$ GeV/c^2) showing that quasielastic scattering measures the nucleon momentum distribution
  - but the details are complicated
- $A(e, e')$ longitudinal/transverse (L/T) ratio < 1. Not quantitatively understood.
- The Coulomb Sum Rule – the integral of the quasielastic $A(e, e')$ longitudinal response should give the number of protons ($\int (R_L/G_E) d\omega \propto Z$)
  - satisfied for small A
  - depleted for larger A???
- valence proton momentum distributions measured by $(e, e'p)$ (at $Q^2 < 1$ GeV^2 and $p < 300$ MeV/c) are well described by standard models but we don't see all the protons
- No $(e, e'p)$ color transparency seen ($Q^2 < 7$ GeV^2)
- NN knockout predominantly transverse

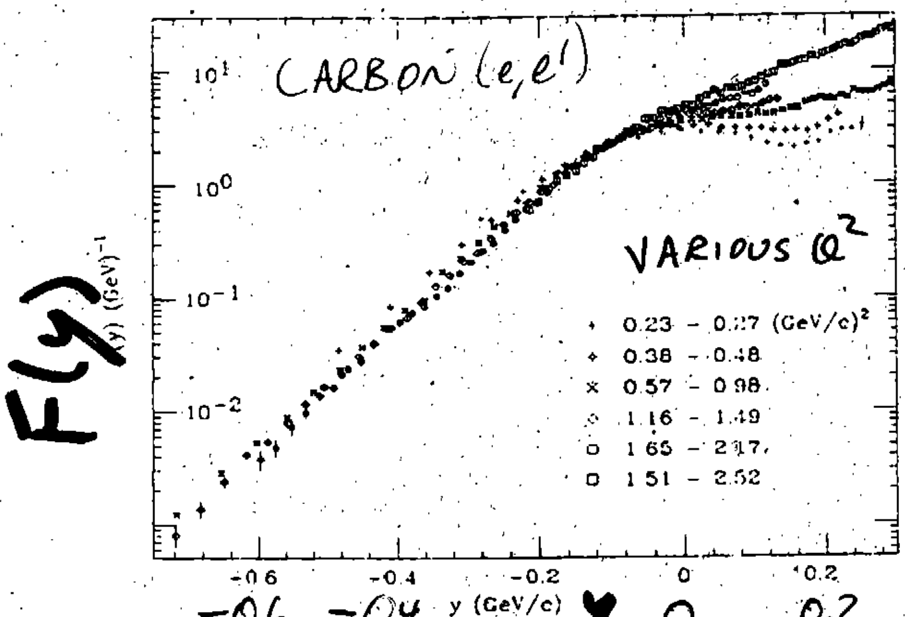


FIG. 2. $F(y)$ for data of Fig. 1 through Eq. (2). Only data that are more than 50 MeV above the threshold for breakup and have fractional errors less than 0.3 are shown.

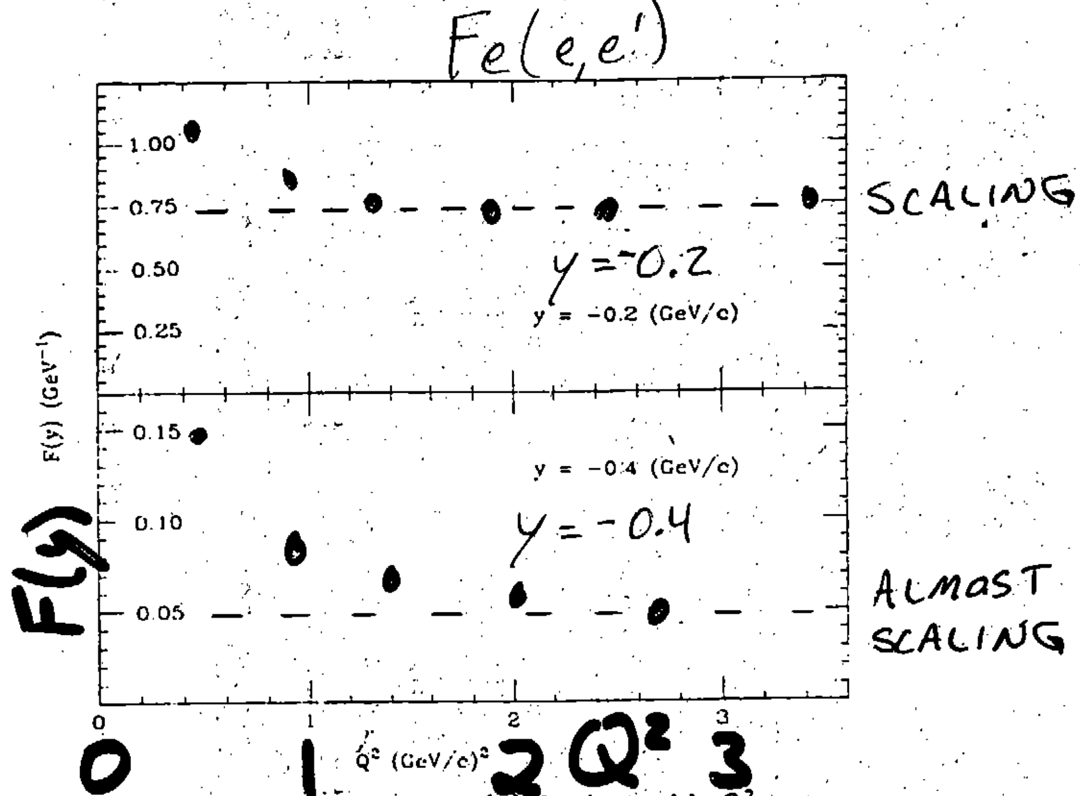


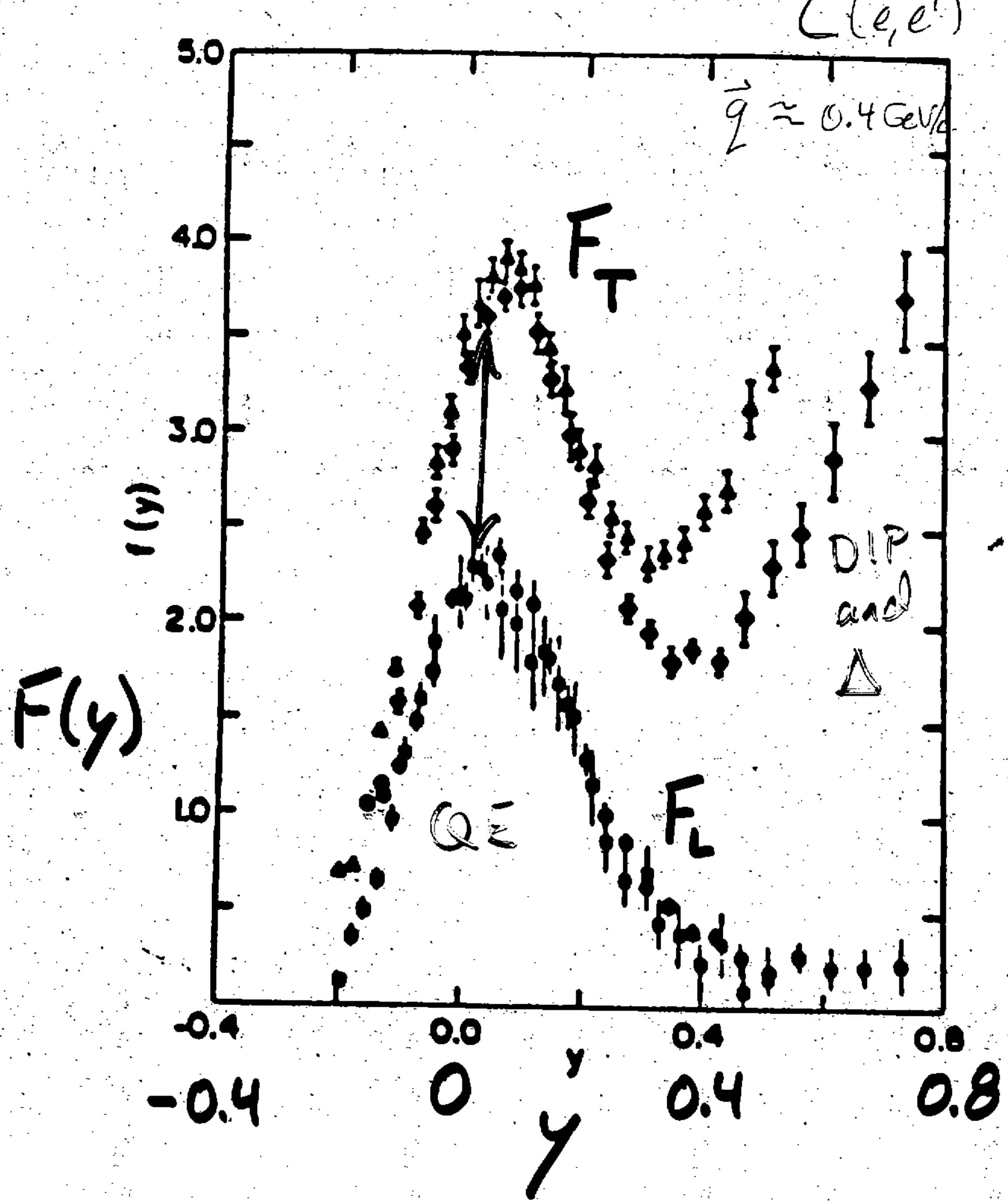
FIG. 3. The convergence of $F(y)$ for iron with Q^2 at two values of y.

$$F(y) = \frac{d^2\sigma}{d\omega\, d\Omega} \frac{1}{Z\sigma_{ep}(q) + N\sigma_{en}(q)} \frac{d\omega}{dy}$$

$y(q,\omega) = k_{\parallel}$ = MINIMUM NUCLEAR RECOIL MOMENTUM

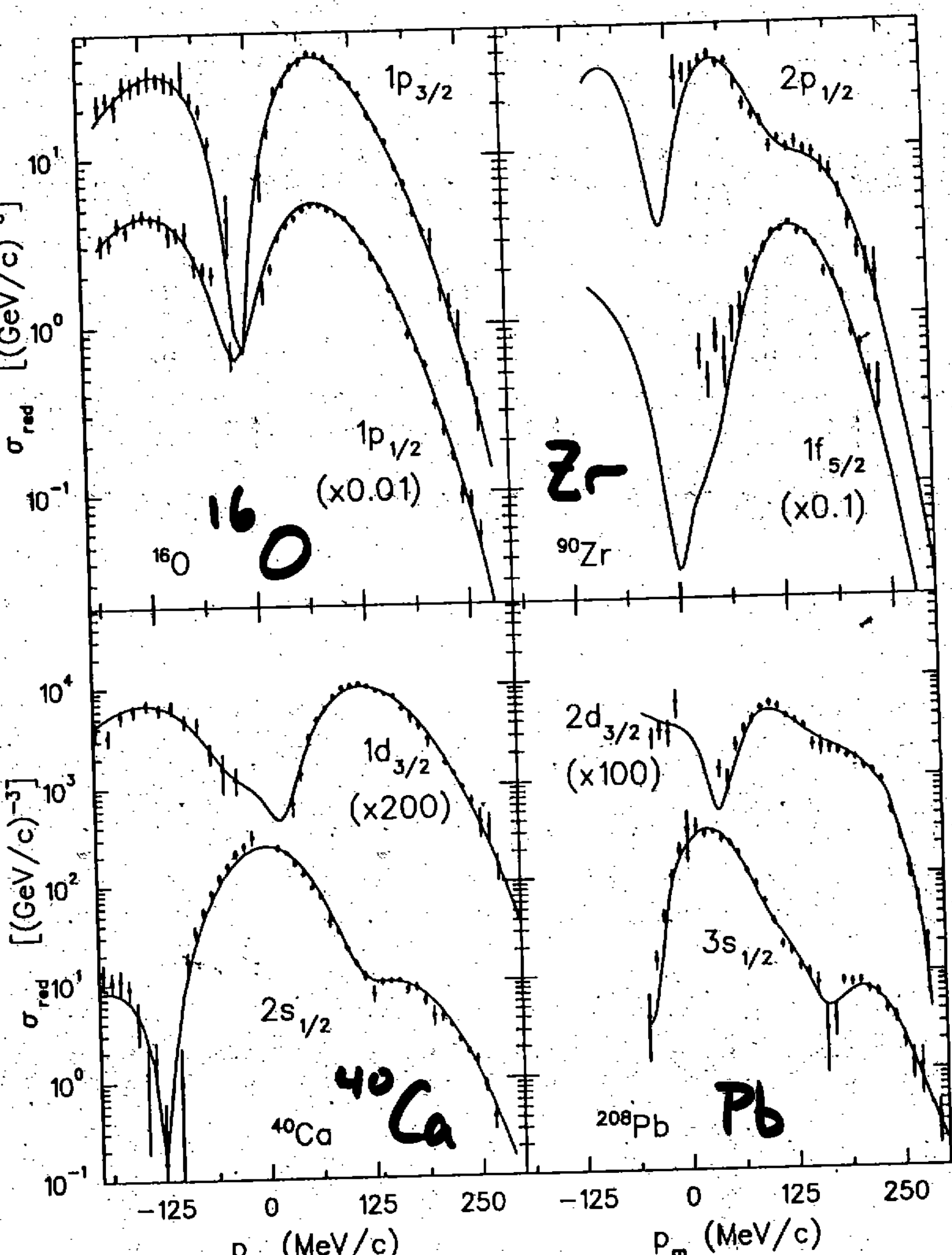
$$\omega + M_A = \left[(\vec{k}+\vec{q})^2 + m_p^2\right]^{1/2} + \left[k^2 + M_{A-1}^2\right]^{1/2}$$

DAY et al, PRL 59, 427 (1987)



Finn et al, PRC 29, 2230 (1984)

A(e,e'p)

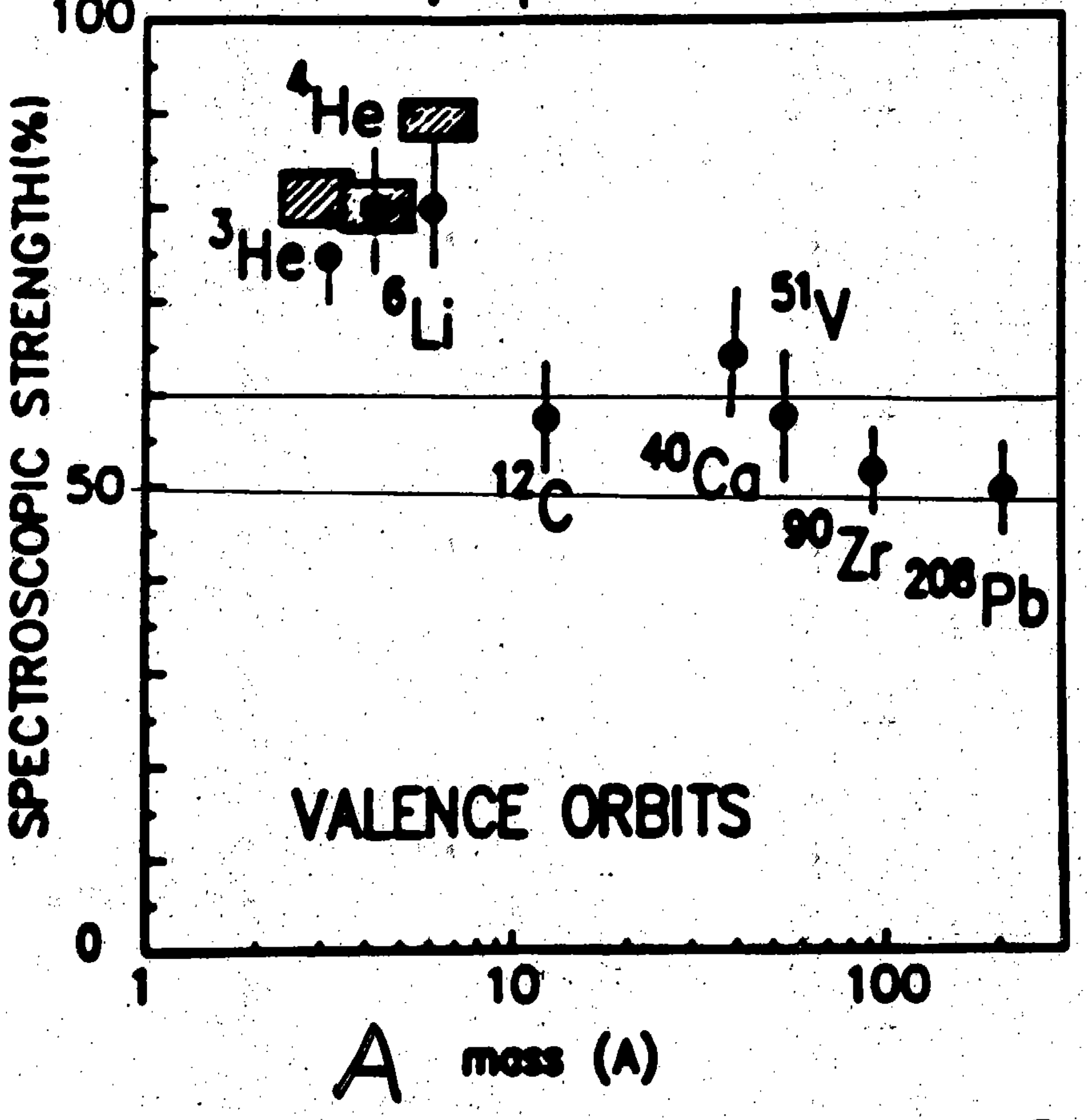


J.J. Kelly, Adv Nucl Phys 23, 75 (1996)

P_{miss}

$P_{miss} = \vec{q} - \vec{p}'$

A(e,e'p)



LAPIKAS, NP A553, 297c (1993)

WHERE DID THE OTHER PROTONS GO?

COLOR TRANSPARENCY (OR LACK THEREOF)

$$T = \frac{\int \sigma(e,ep)}{\int \sigma_{PWIA}}$$

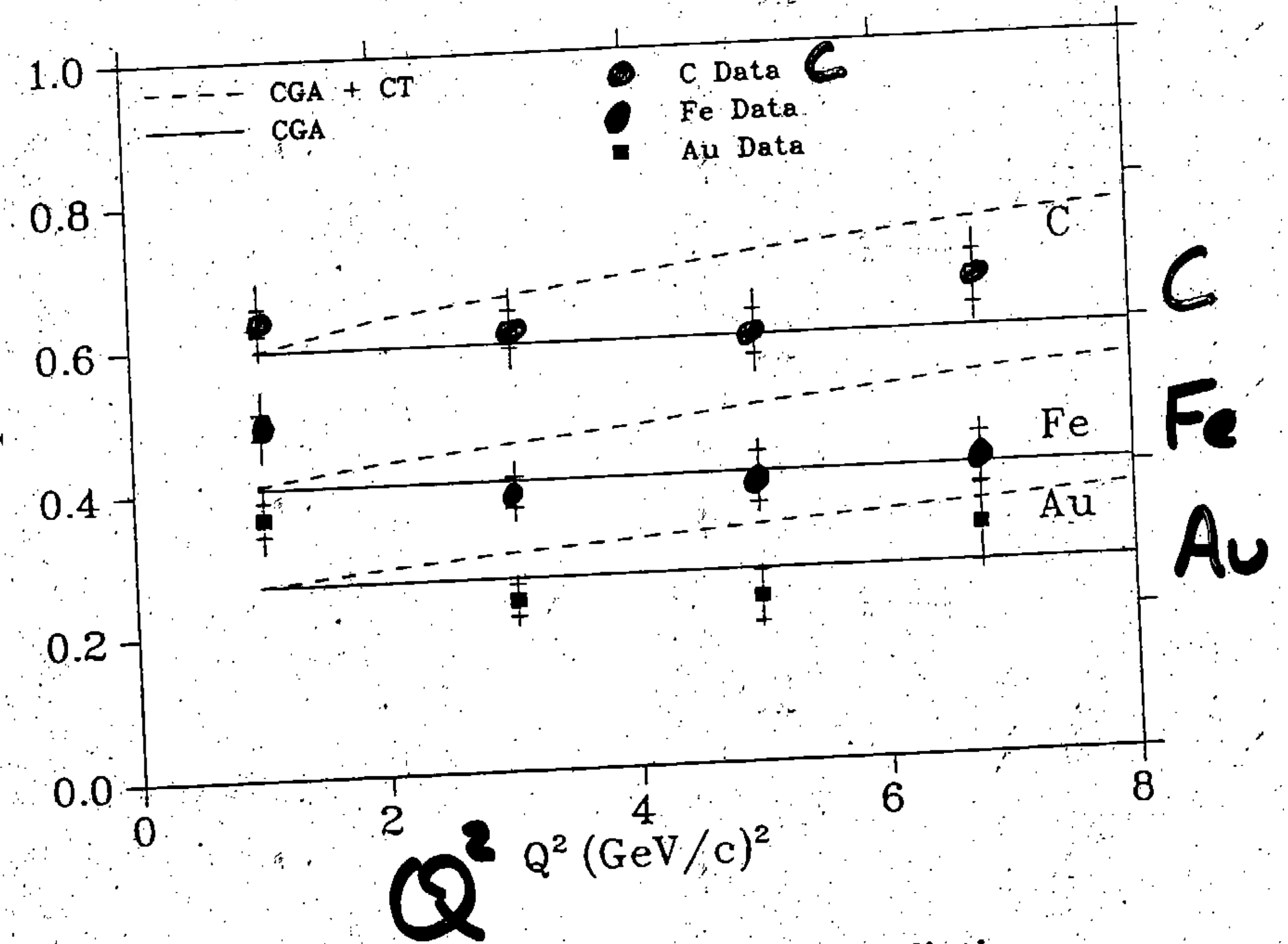
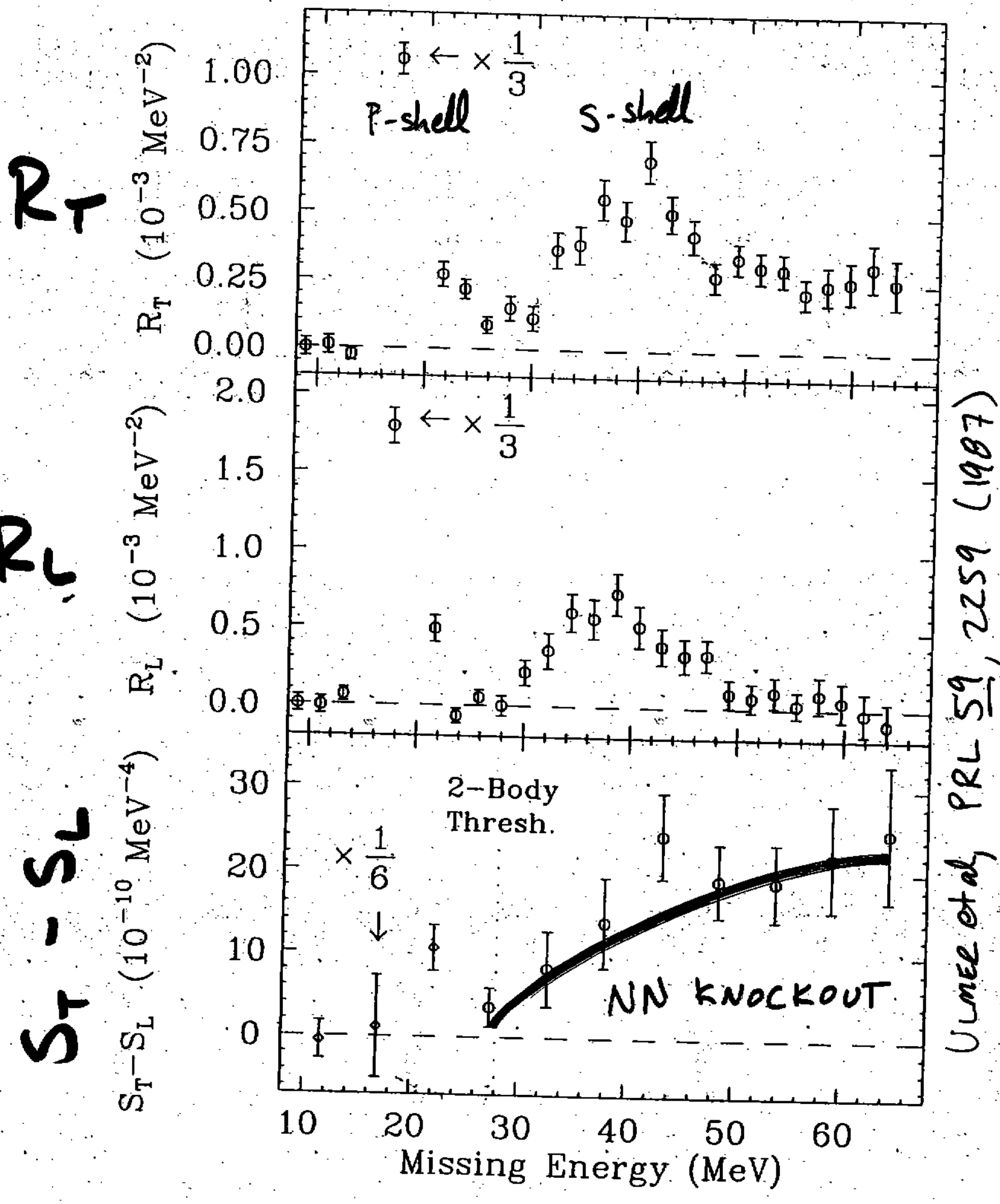


Figure 5.24: Benhar *et al.* [5] C, Au T predictions

T. O'NEILL, PHD THESIS, CALTECH, 1994

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

$q = 0.4$ GeV

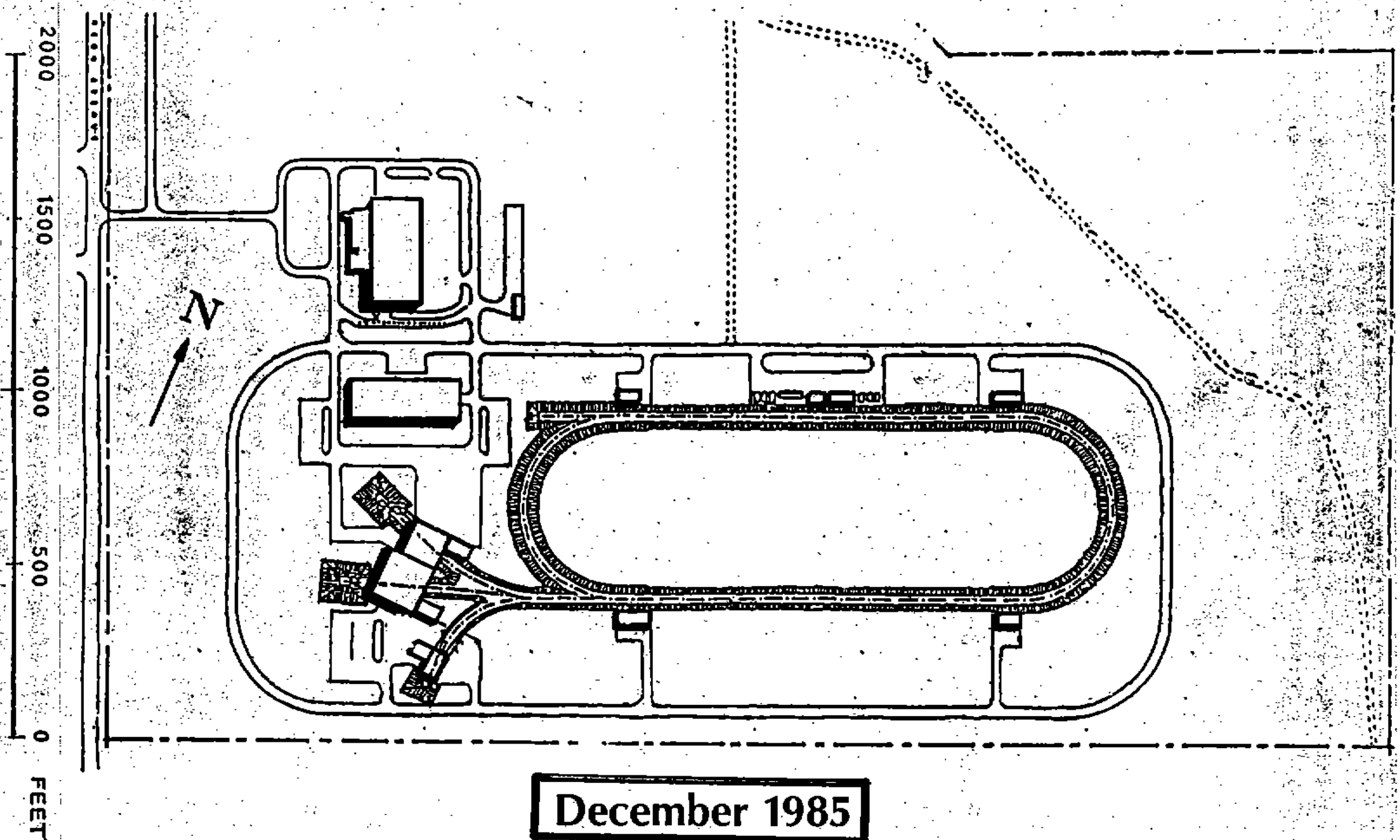


$E_{miss} = \omega - T_p$

WHAT WE WANTED TO LEARN

CEBAF

PRECONCEPTUAL DESIGN REPORT



December 1985

Continuous Electron Beam Accelerator Facility
Newport News, Virginia
Project Number 87-R-203

2.4 Highlights of the Proposed Experimental Program

Over twenty experiments planned for CEBAF are described in the 1982 SURA proposal, and in the report of the Workshop on Future Directions in Electromagnetic Nuclear Physics(6) published in 1981. This section will describe five key experimental programs, which illustrate both the science and the experimental requirements for the end stations. The first one or two paragraphs describing each program are intended for the general reader; the subsequent discussion is more technical. The key programs are:

- coincidence measurements of single-particle densities,
- two-body correlations in nuclei
- production of excited nucleons,
- production of hypernuclei, and
- charge structure of the neutron and deuteron.

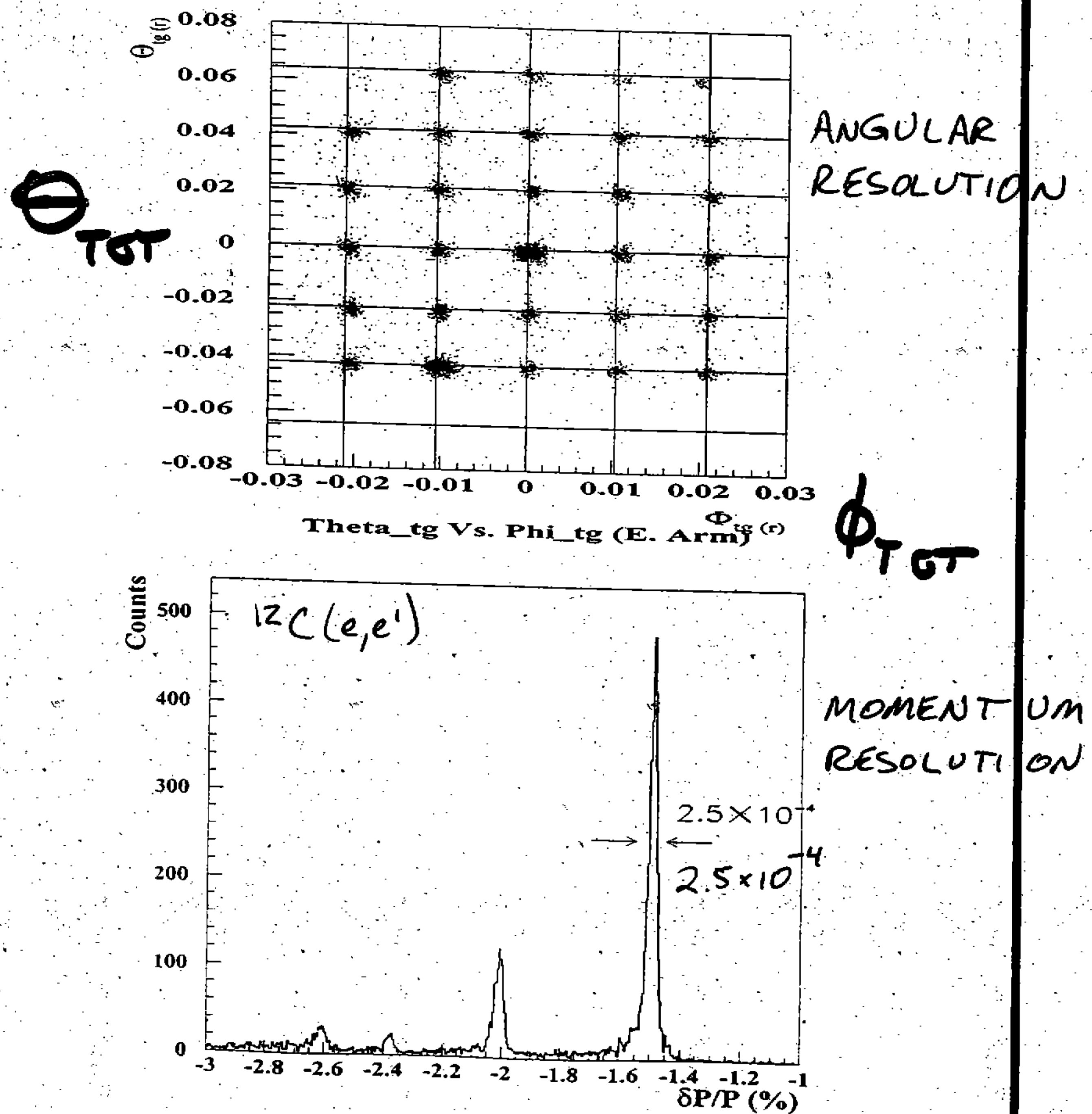
PCDP 1985

Our wonderful new equipment

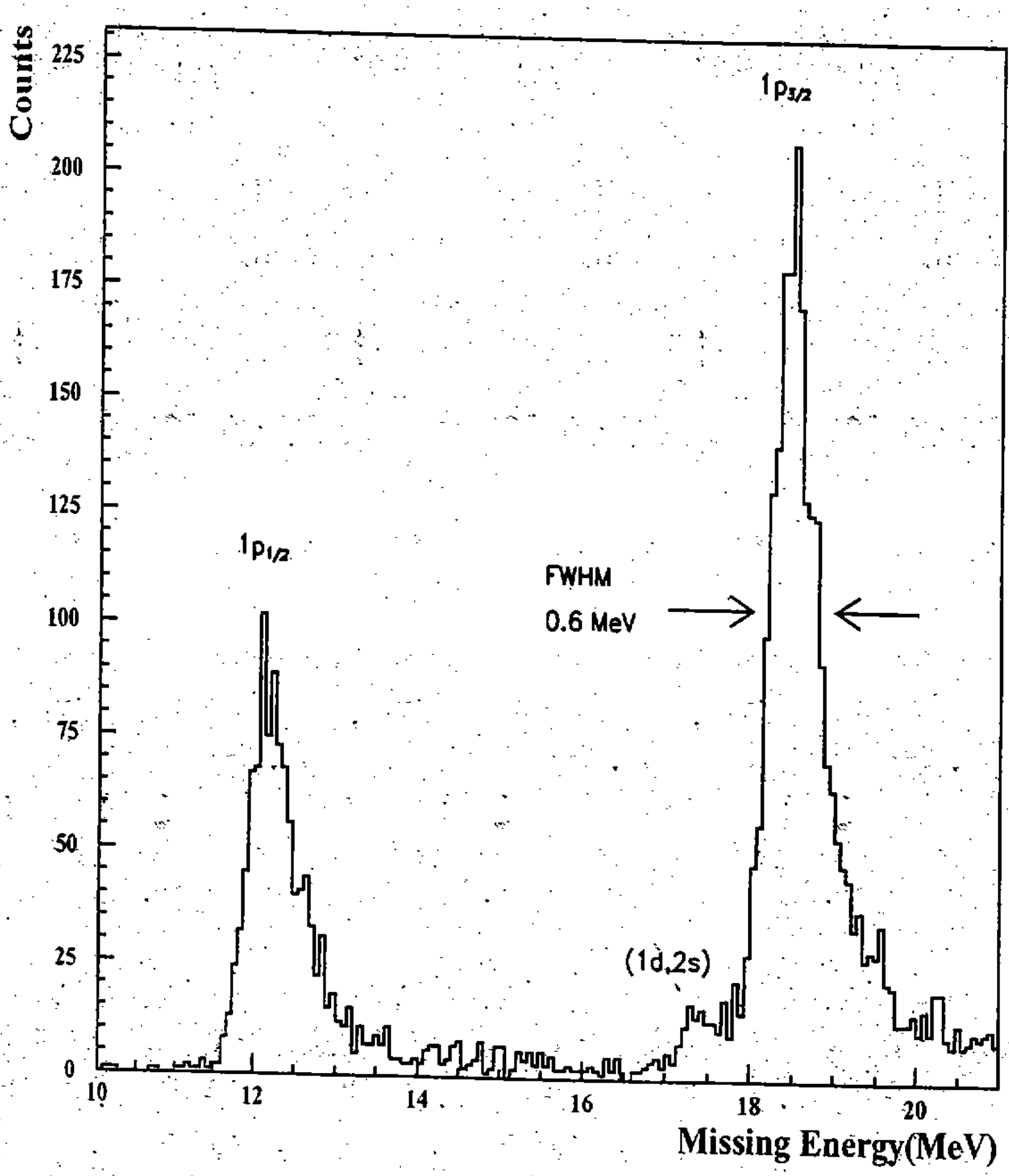
- angular resolution
- momentum resolution
- timing resolution
- target position resolution
- systematic errors

HALL A

- trajectories localized using 5 mm W sieve slit
- χ^2 optimization of each q_{tg} performed *orthogonally*



^{16}O(e,e′p) E_{miss} for $\theta_{pq} = +8°$ at
$E_{beam} = 0.845$ GeV



TIME RESOLUTION

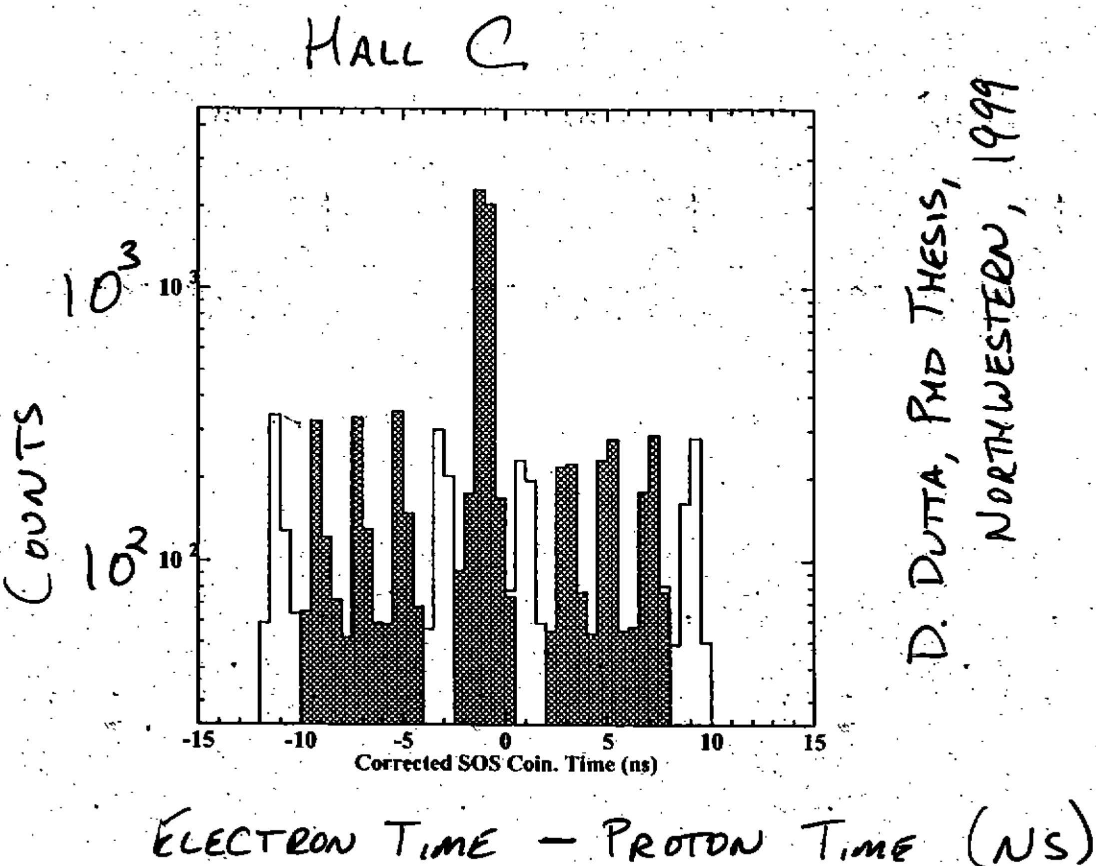
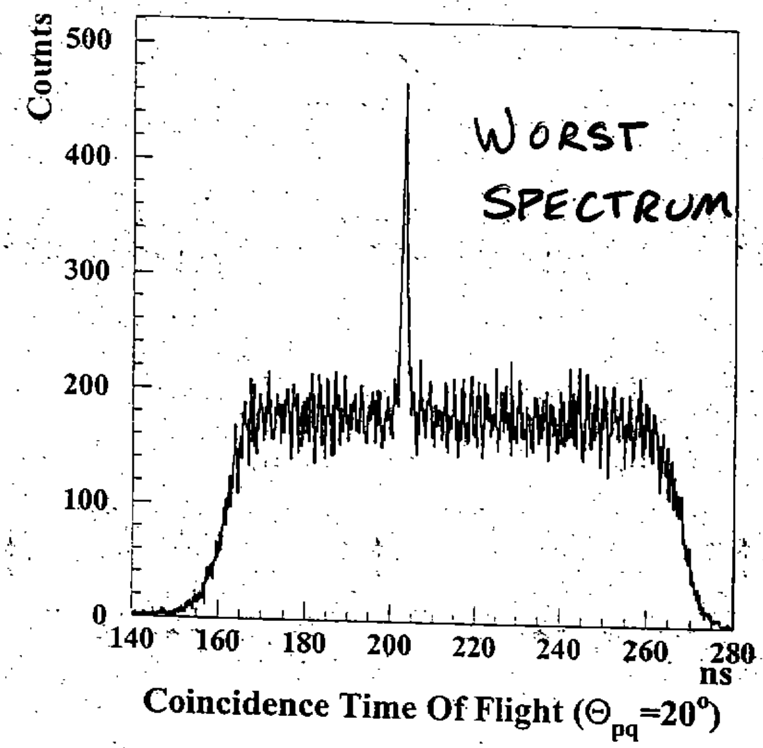


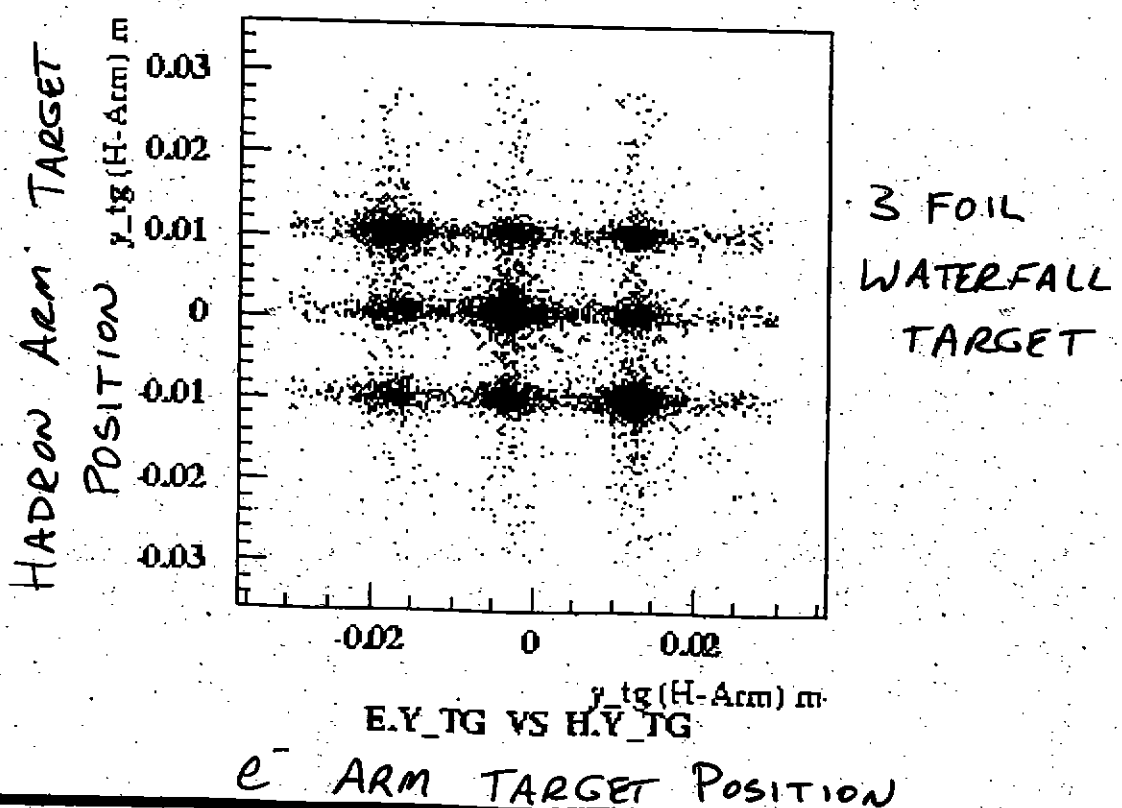
Figure 52: A typical corrected coincidence time spectrum is shown in log scale. The shaded peak in the center is taken as the good cointime peak while the shaded region on either side of the peak is used to calculated the random coincidences.

Analysis:

1. Yield

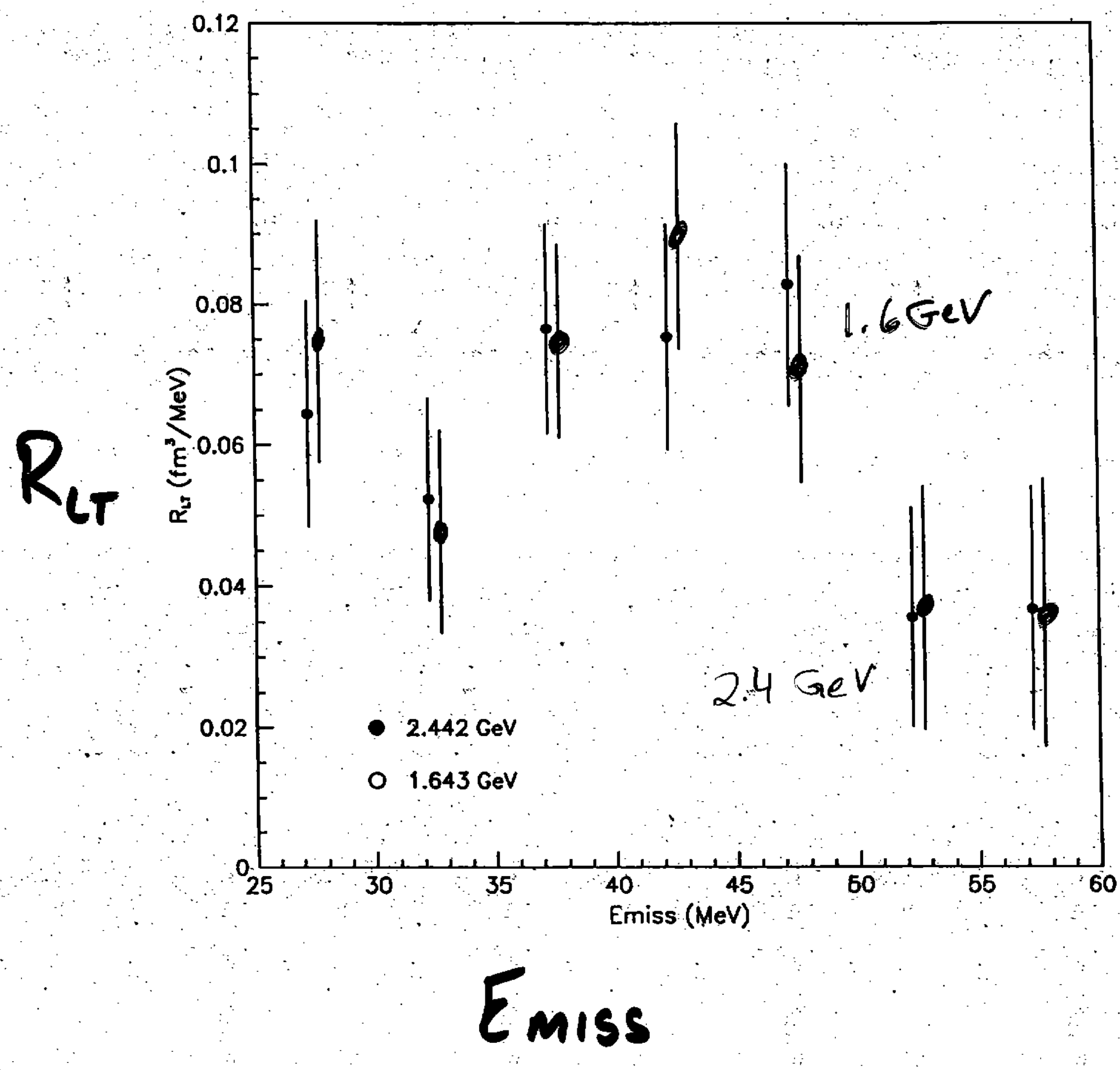
O(e,e'p)





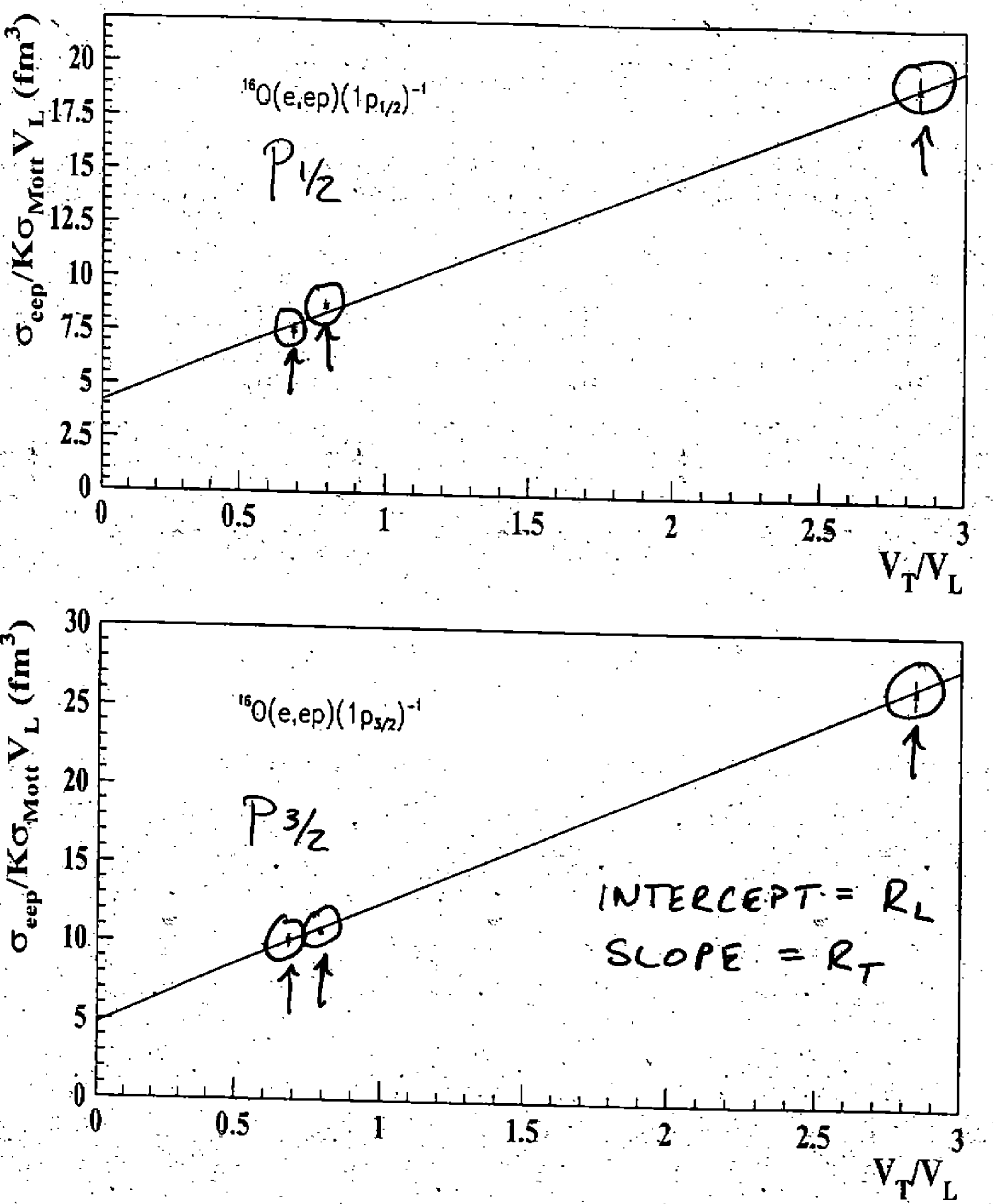
O(e,e'p)

SYSTEMATIC ERROR CHECK
R_{LT} MEASURED AT TWO DIFFERENT
BEAM ENERGIES (FIXED Q^2, ω)



O(e,e'p) SYSTEMATIC ERROR CHECK

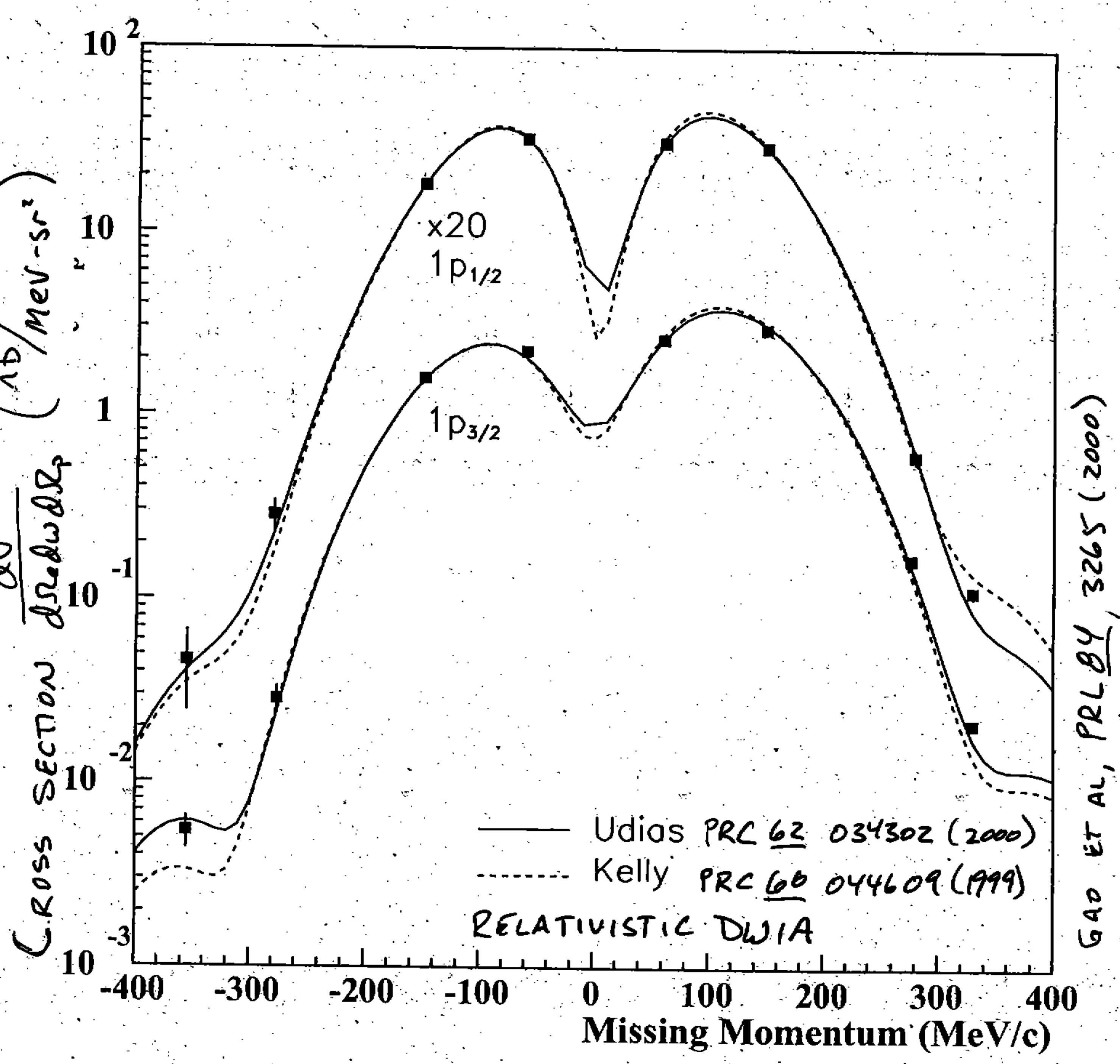
Data quality (systematics):



What We Learned

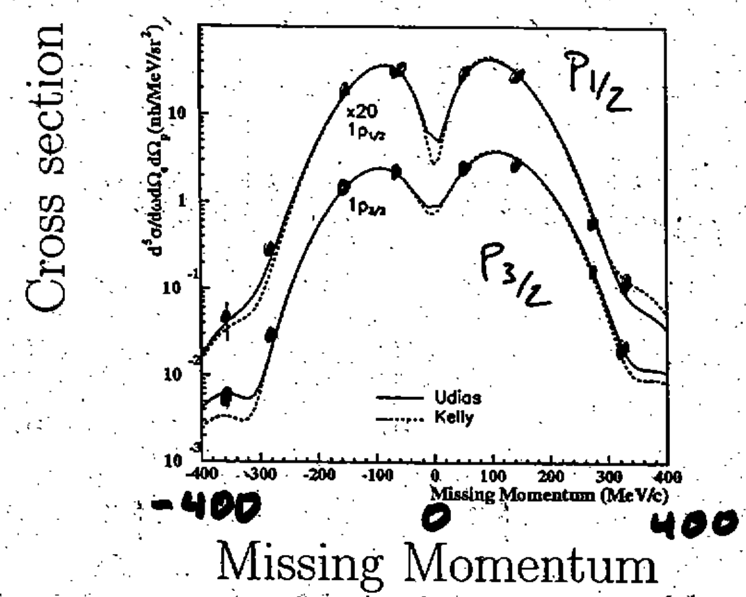
- Nucleons are nucleons
  - $O(e, e'p)$ and $O(\vec{e}, e'\vec{p})$ at $Q^2 = 0.8$ GeV^2
  - $A(e, e'p)$ at $Q^2 \leq 8$ GeV^2
- ... but might be distorted
  - ^{4}He$(\vec{e}, e'\vec{p})$
- Two-body currents are important
  - ^{16}O,^{12}C$(e, e'p)$ R_L and R_T
- ... but we don't fully understand them yet
  - $A(e, e'p)$ at large missing energy
- Short Range Correlations exist.
  - y-scaling and $A(e, e')/d(e, e')$ ratios at $x > 1$
- ... but they are hard to measure (obscured by MEC)
  - ^{3}He$(e, e'pp)n$
- The quarks are hiding from us!
  - ξ scaling in $A(e, e')$

O(e,e'p)



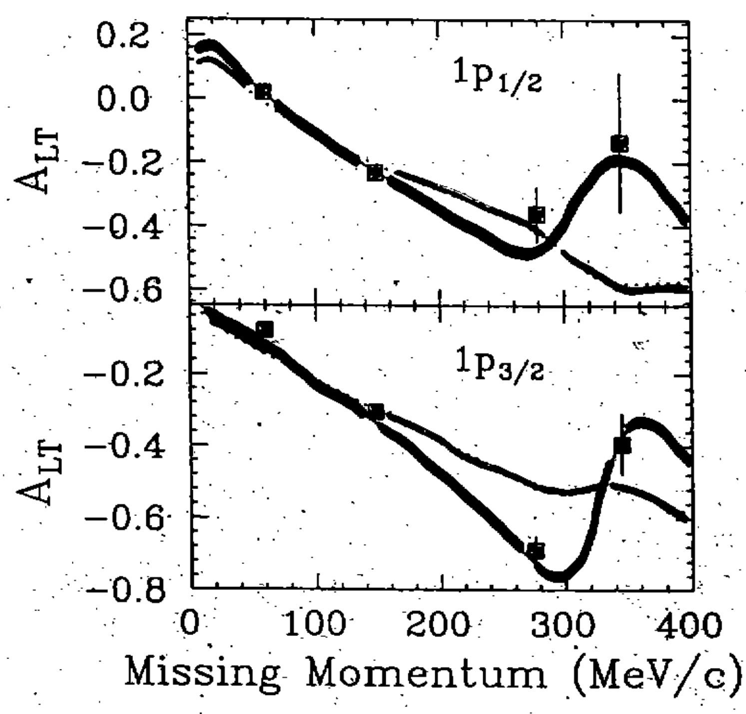
RELATIVISTIC DWIA WORKS!
NUCLEONS ARE NUCLEONS

O(e,e'p) p shell knockout



dash – Kelly

solid – Udias



RELATIVISTIC

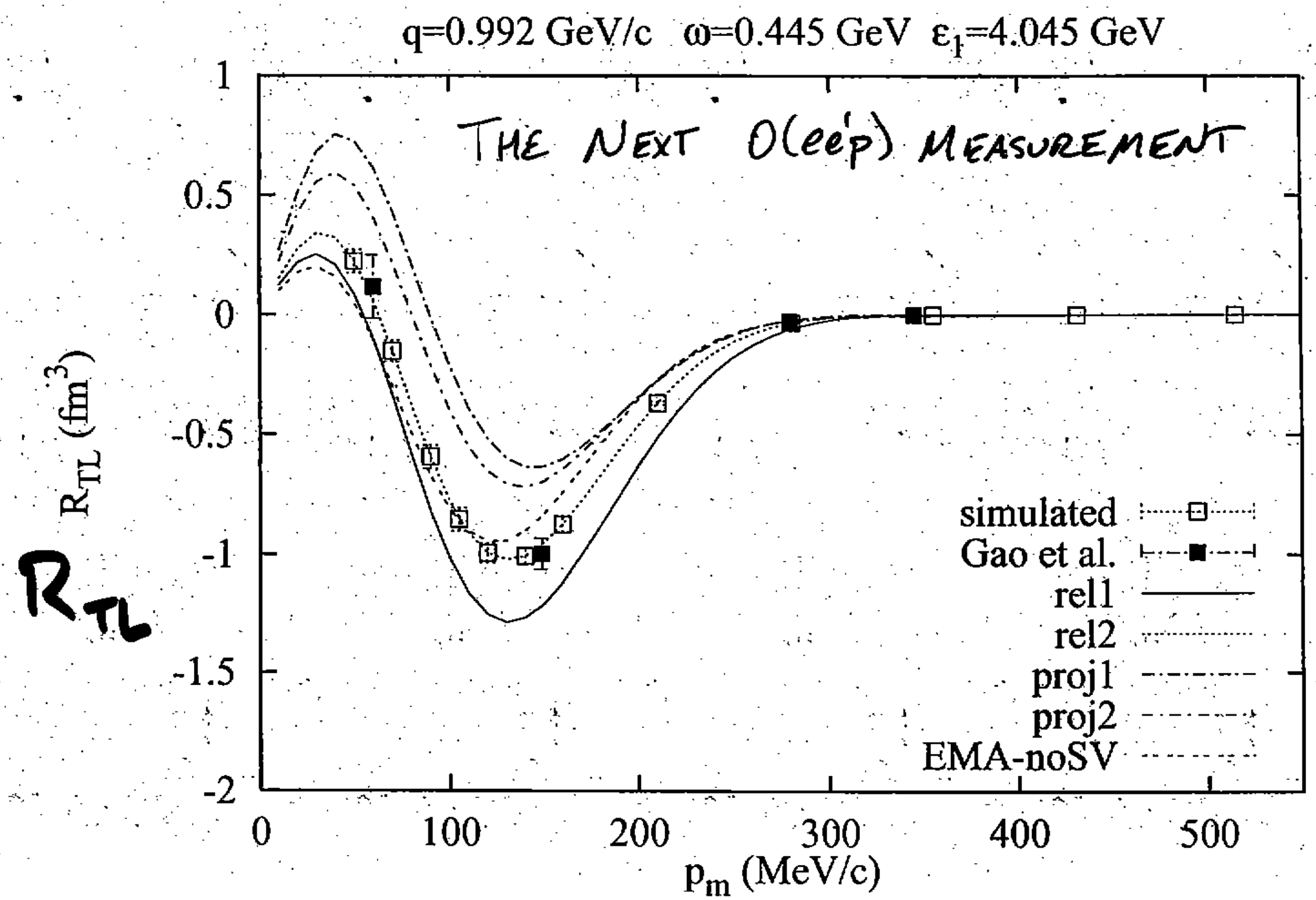
solid – Udias, full calc

dot – Udias, free

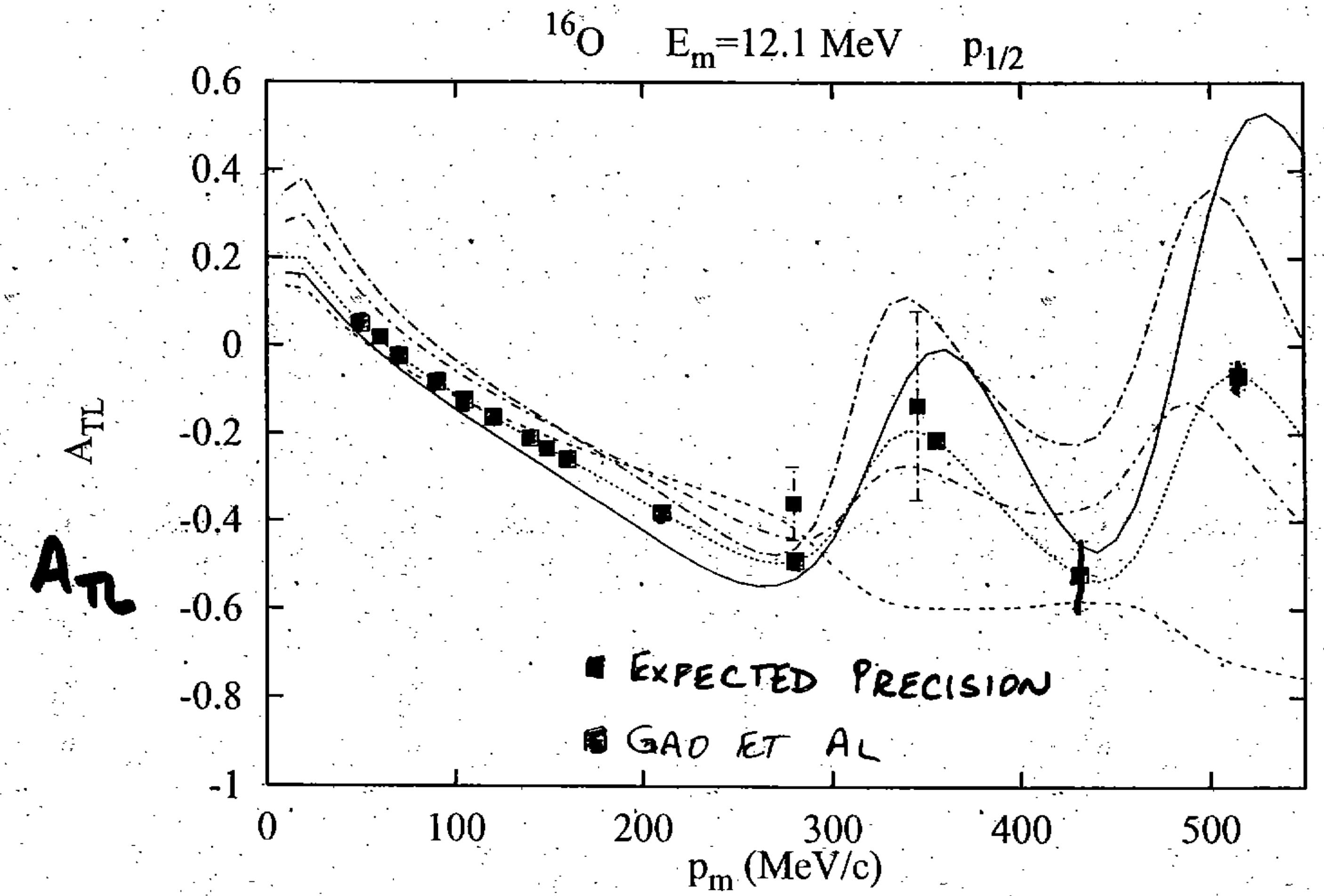
Dirac spinors

EQUIVALENT TO NON-RELATIVISTIC

- DWIA using modern wavefunctions agree with data
- Dynamic relativistic effects needed for DWIA to decribe A_{LT}



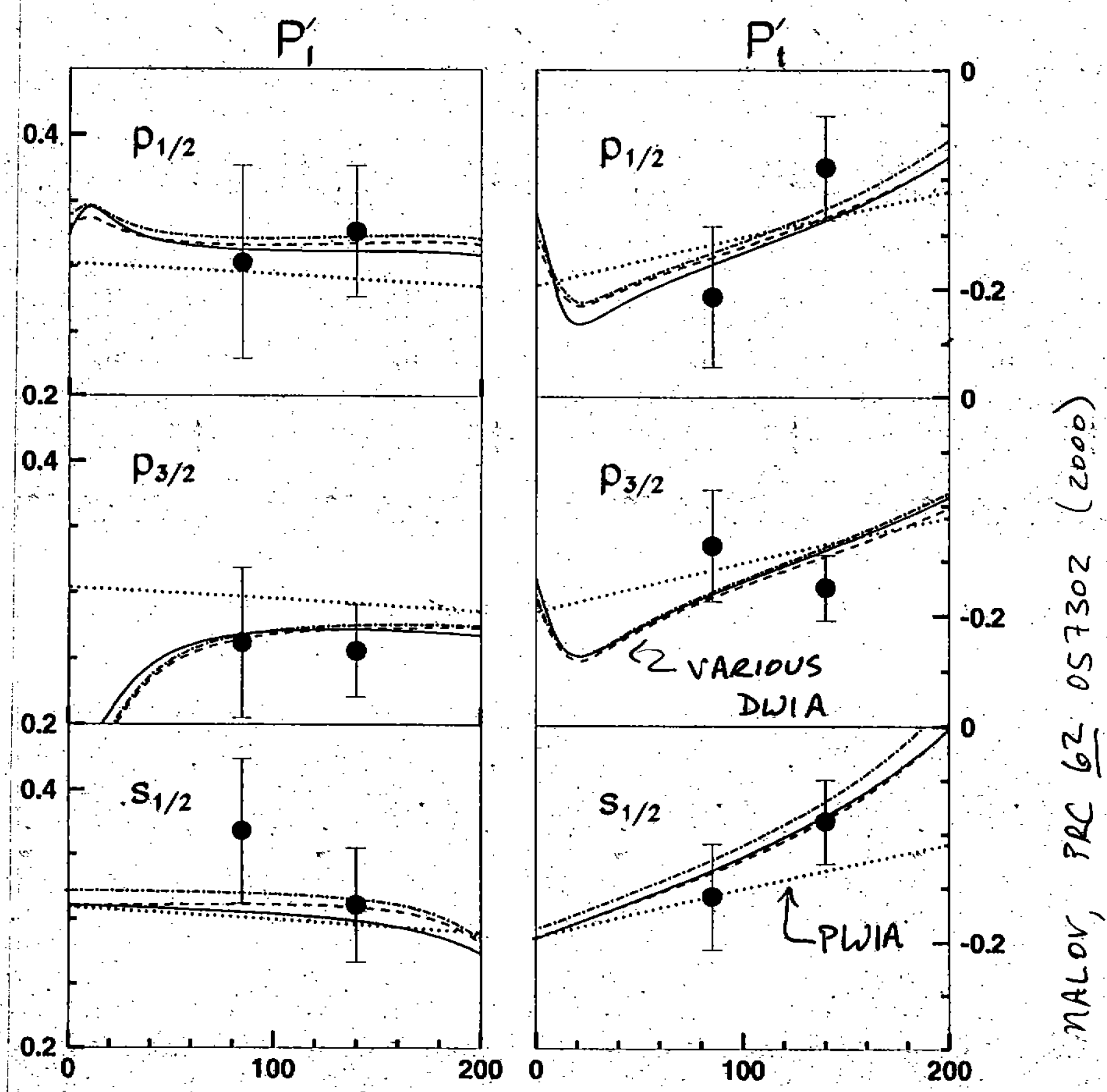
q=0.992 GeV/c ω=0.445 GeV ε1=4.045 GeV
THE NEXT O(ee'p) MEASUREMENT
RTL (fm3)
RTL
simulated
Gao et al.
rel1
rel2
proj1
proj2
EMA-noSV
pm (MeV/c)



16O Em=12.1 MeV p1/2
ATL
ATL
EXPECTED PRECISION
GAO ET AL
pm (MeV/c)

O(e⃗, e′p⃗)

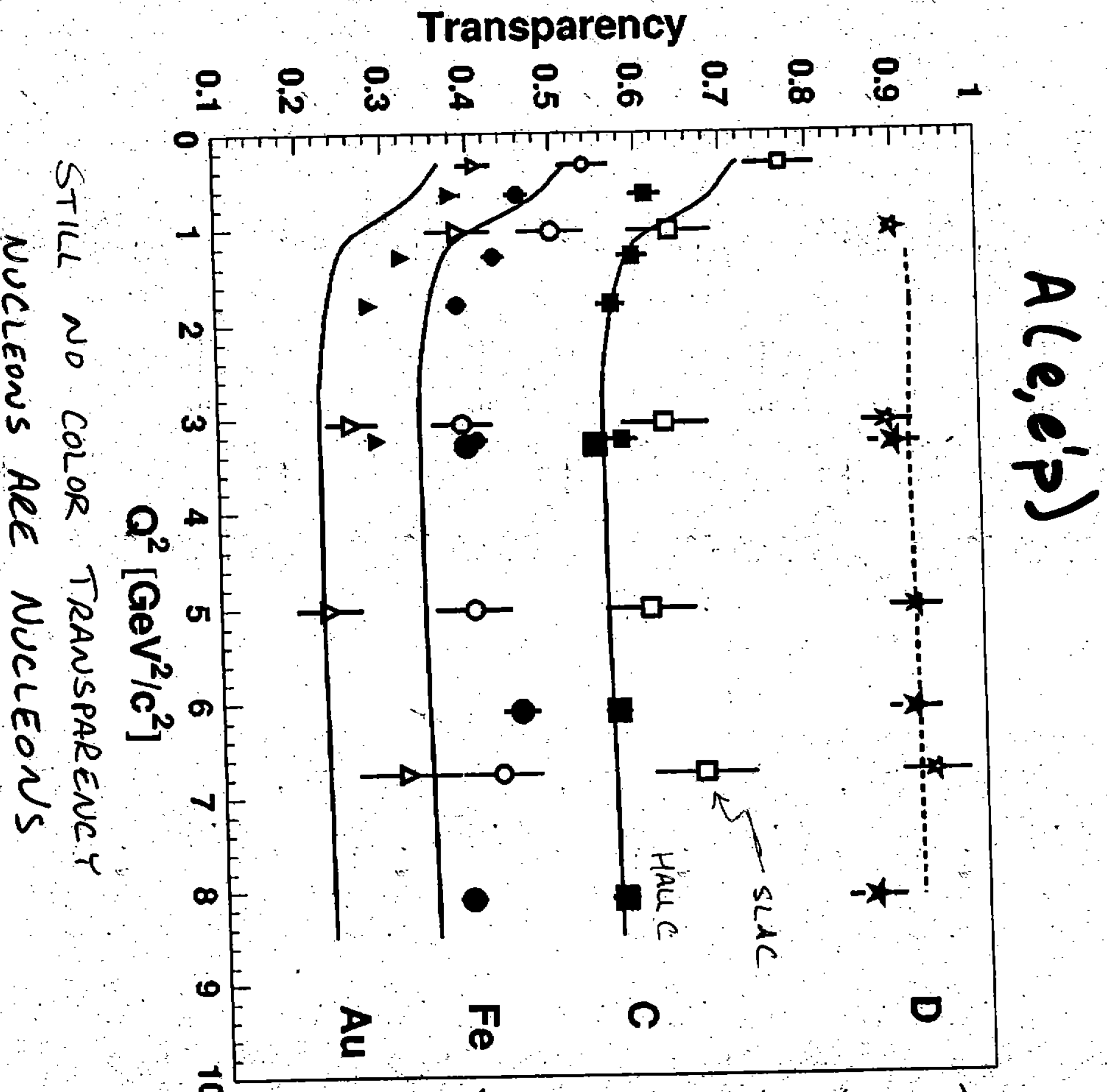
WE CAN MEASURE PROTON POLARIZATION



MISSING MOMENTUM

THEORY: UDIAS
KELLY

$T = \int \sigma_{DATA} \Big/ \int \sigma_{PWIA}$



GARROW et al, PRC 66 044613 (2002)

ABBOT et al, PRL 80 5072 (1998)

Proton Polarization and Form Factors

Free $\vec{e}p$ scattering

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

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

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

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

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

... but might be distorted

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

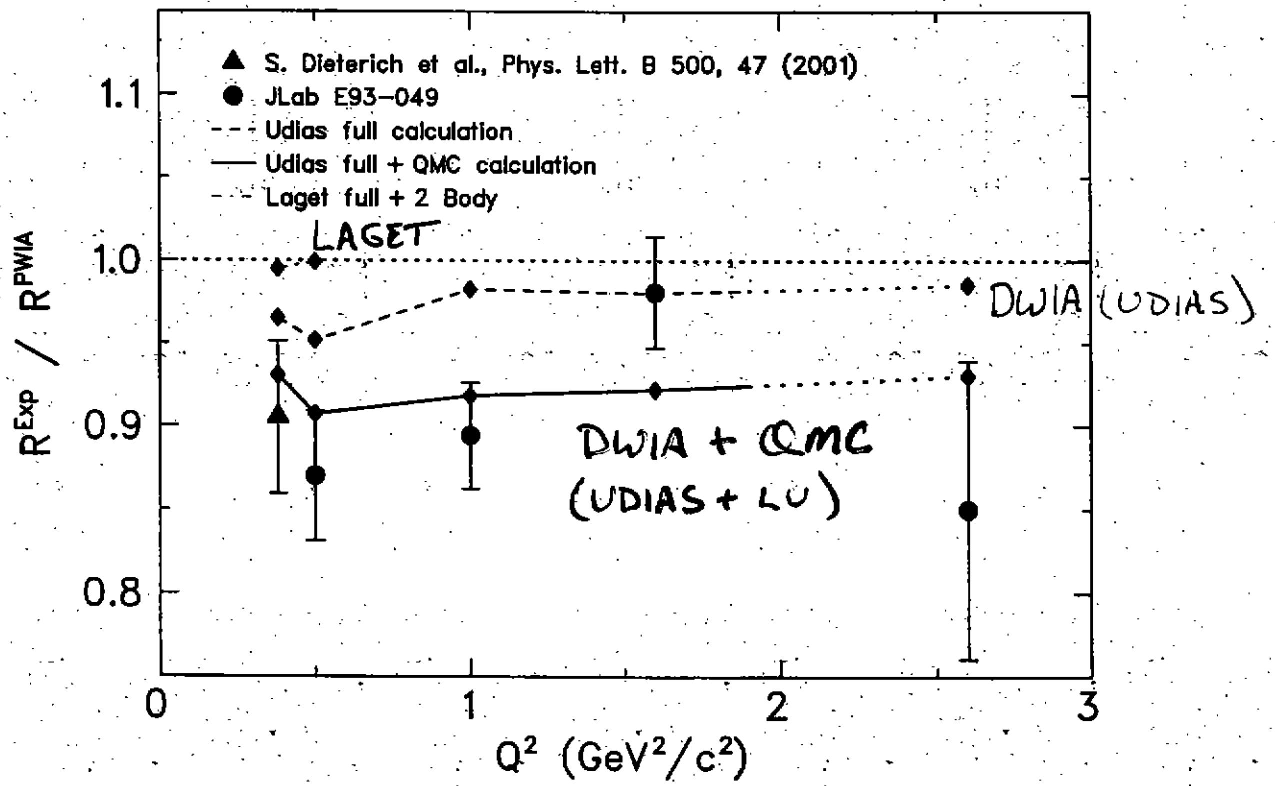


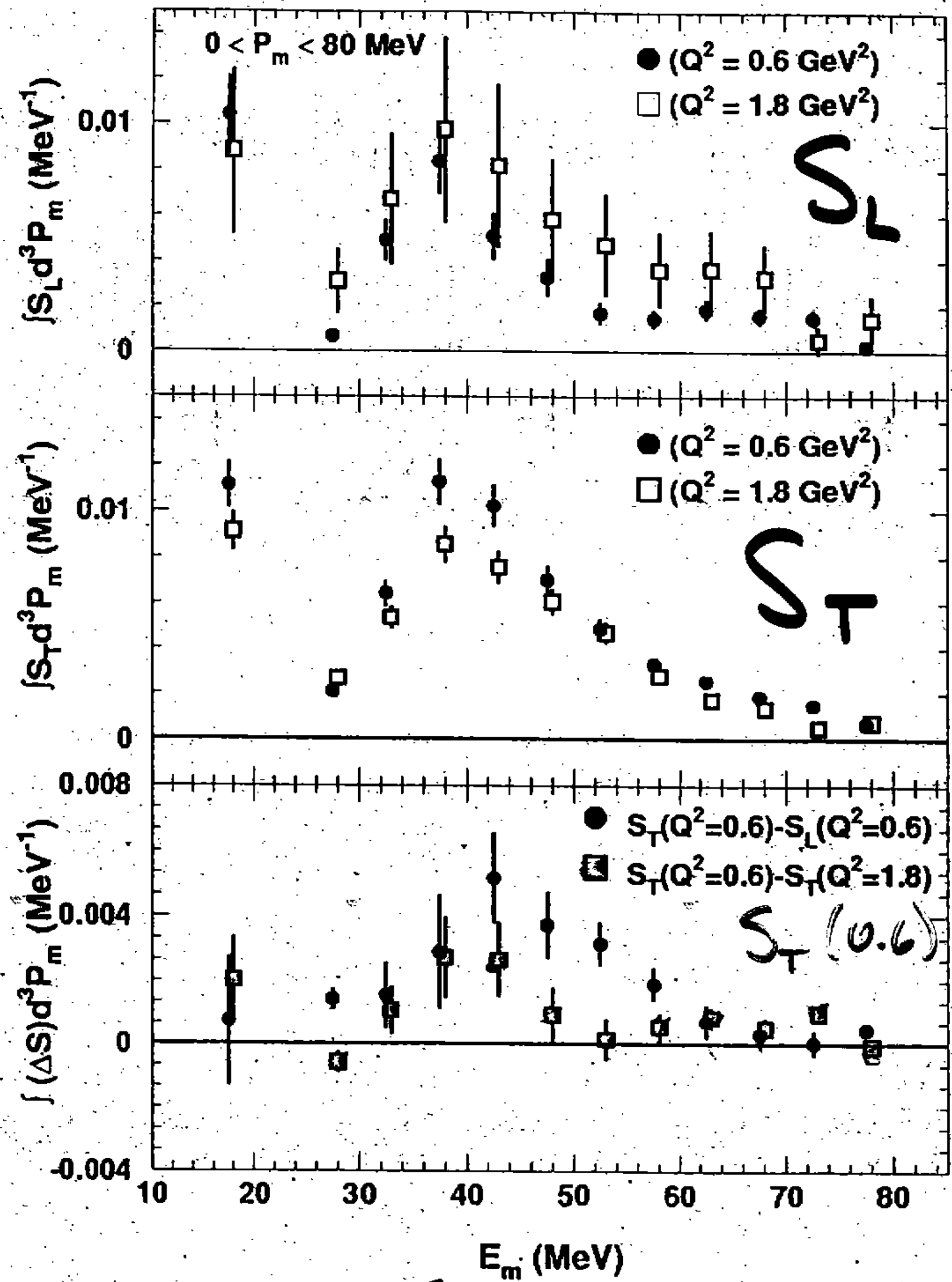
Figure 6.6: Super–Ratio R^{exp}/R^{PWIA} for all Q^2 compared to phase space averaged theoretical predictions (diamond symbols). Diamonds connected by the dash–dotted line represent Laget's calculation with two body currents. Diamonds connected by the dashed line represent the result from the full calculation by Udias; diamonds connected by the solid line represent the same calculation including medium modified form factors as calculated in the QMC model.

$$R = \frac{P'_x / P'_z \big|_{HELIUM}}{P'_x / P'_z \big|_{PROTON}}$$

TWO BODY CURRENTS ARE IMPORTANT

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

$P_{miss} < 80$ MeV/c



$S_T - S_L$

$S_T(0.6) - S_T(1.8)$

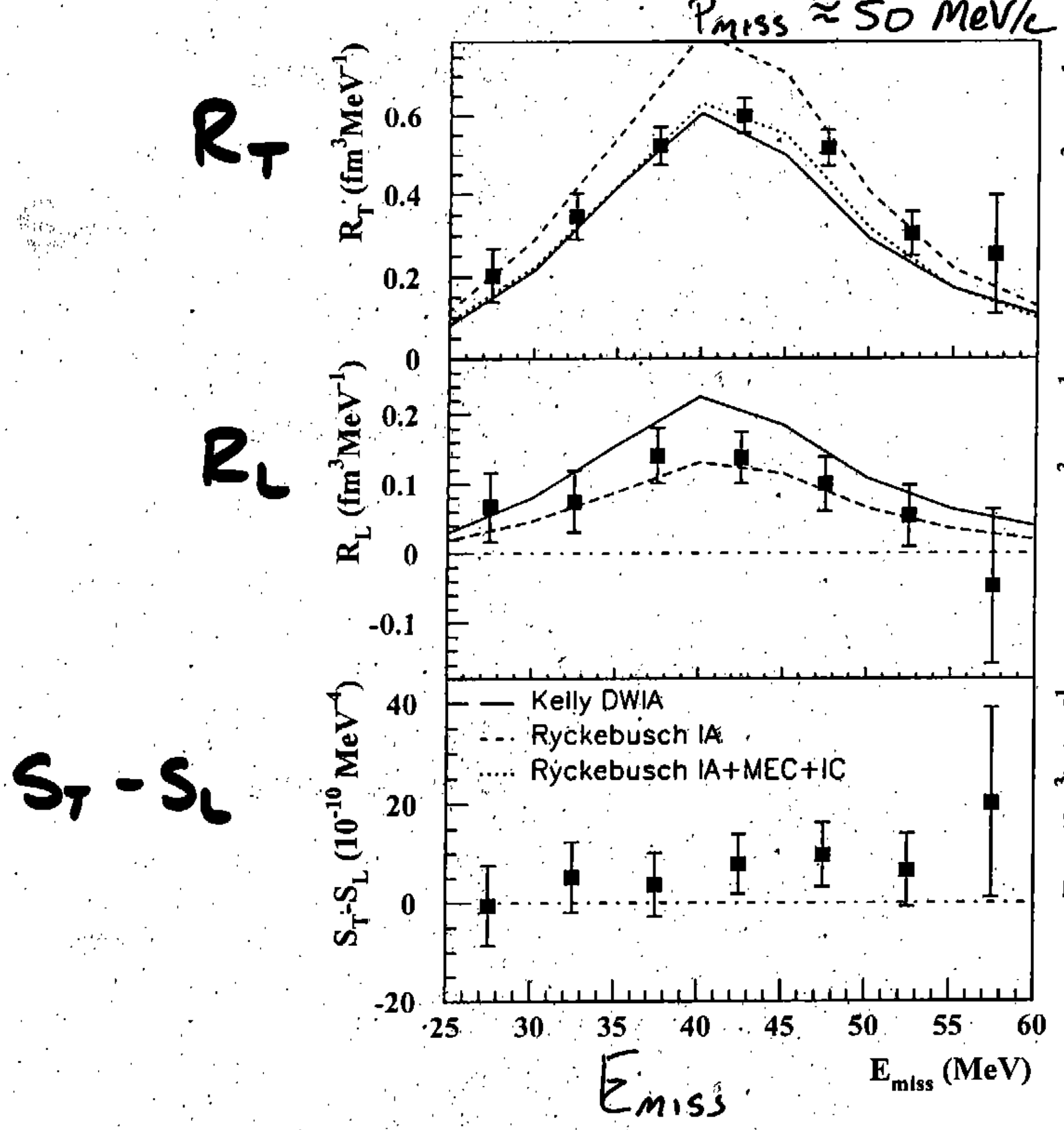
DECREASE WITH Q^2 ??

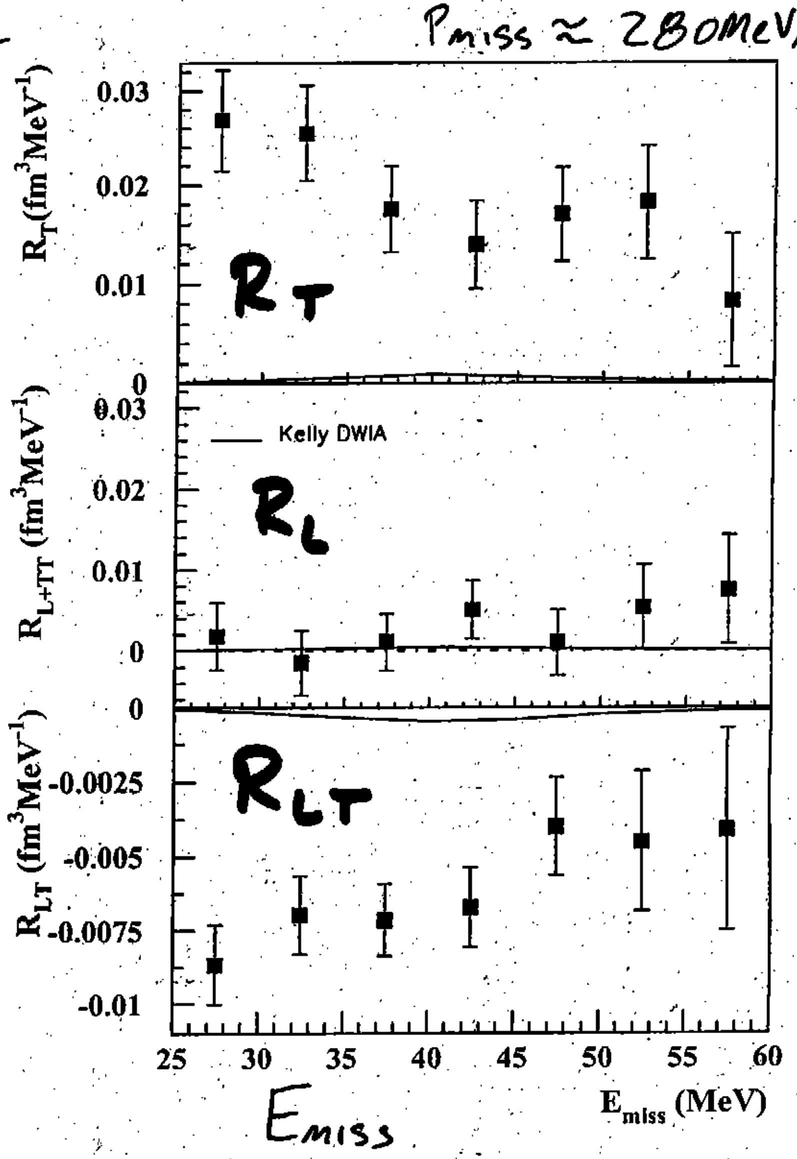
Emiss

D. Dutta et al, PRC 61 061602 (2000)

Two Body Currents Are Important

O(e,e'p) $Q^2 = 0.8$ GeV^2

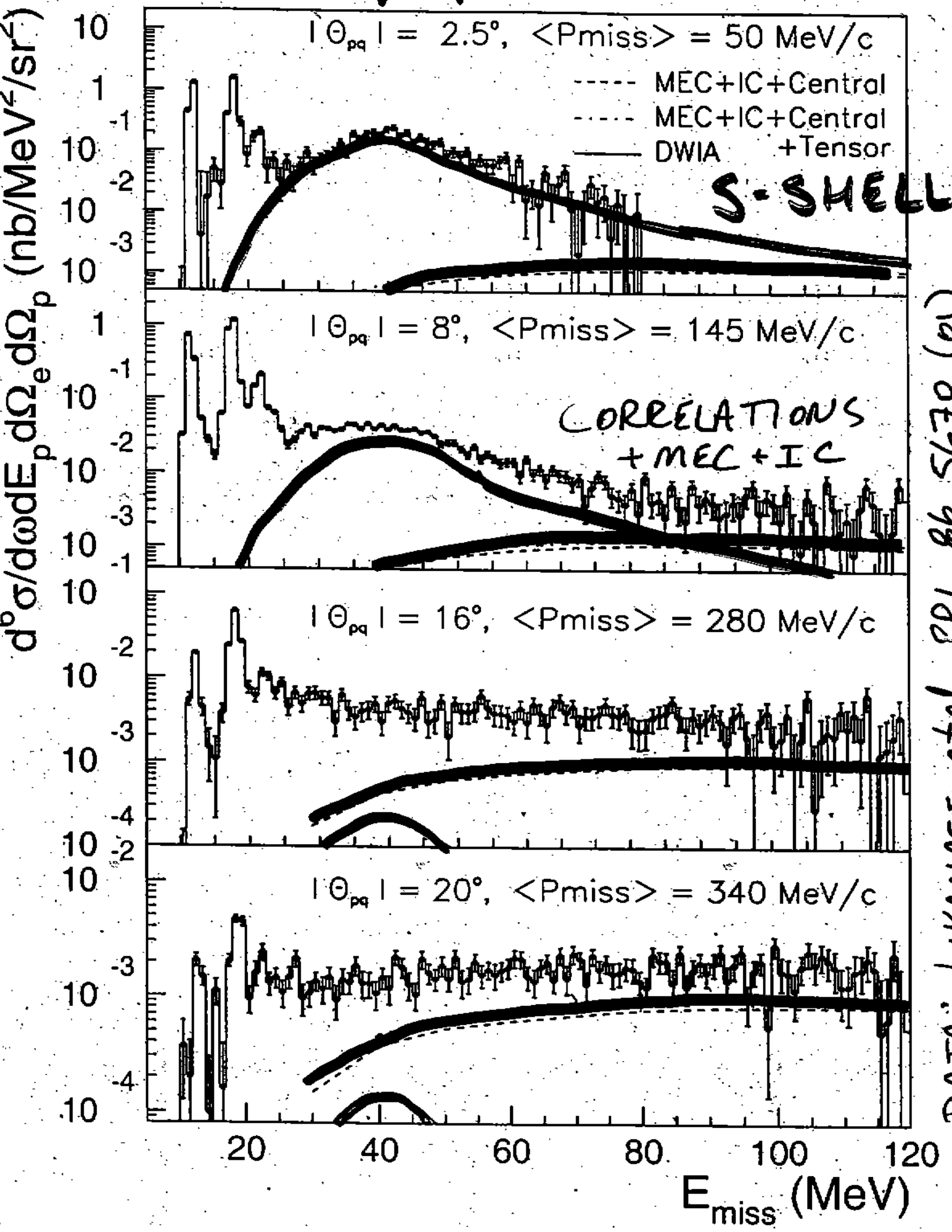




Liyanage et al, PRL 86, 5670 (01)
Kelly, PRC 60, 044609 (99)
Janssen et al, NP A672 285 (00)

BUT WE DON'T FULLY UNDERSTAND THEM YET

O(e,e'p)

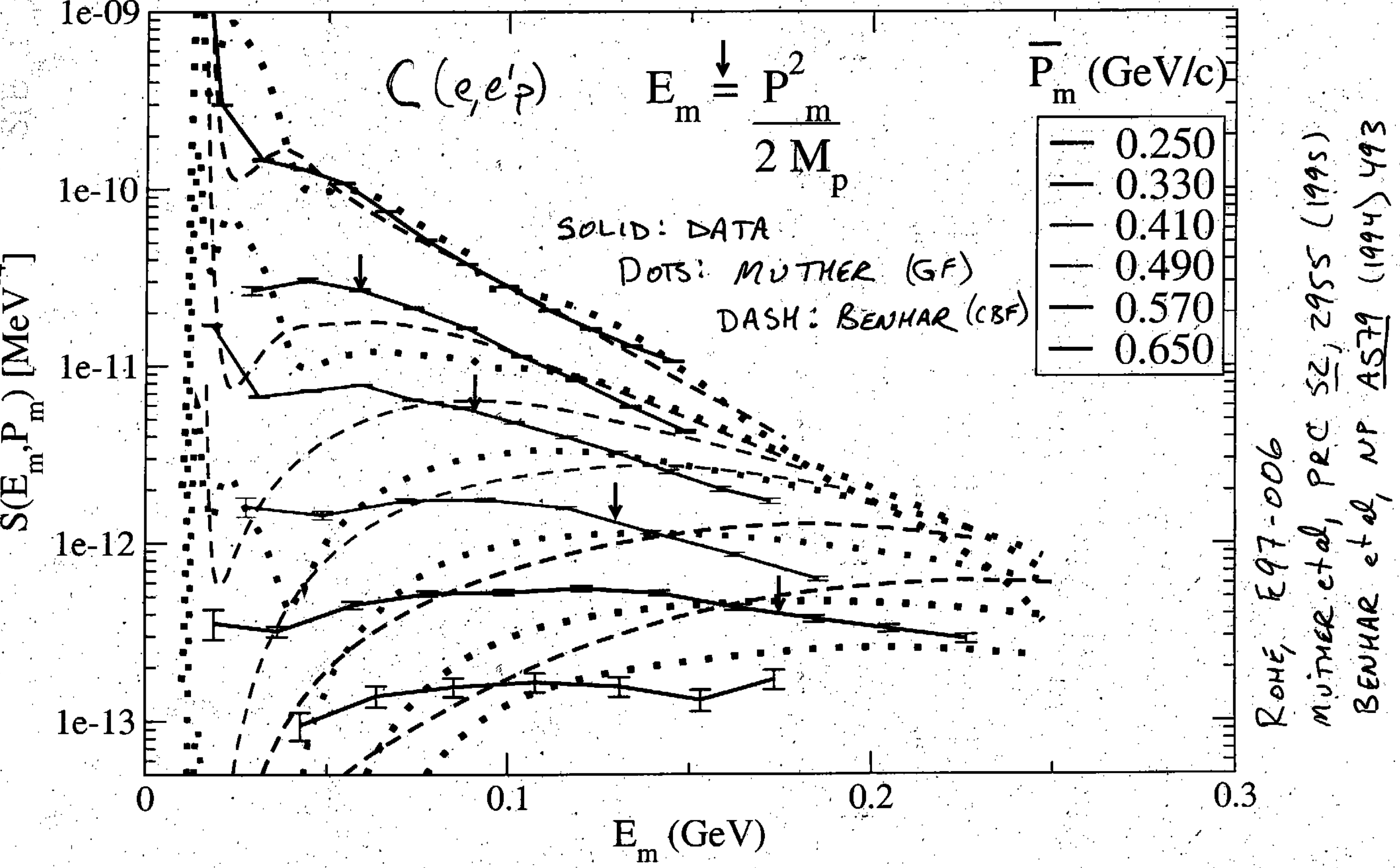


DATA: LIYANAGE et al, PRL 86, 5670 (01)

S-SHELL DWIA: KELLY, PRC 60, 044609 (99)

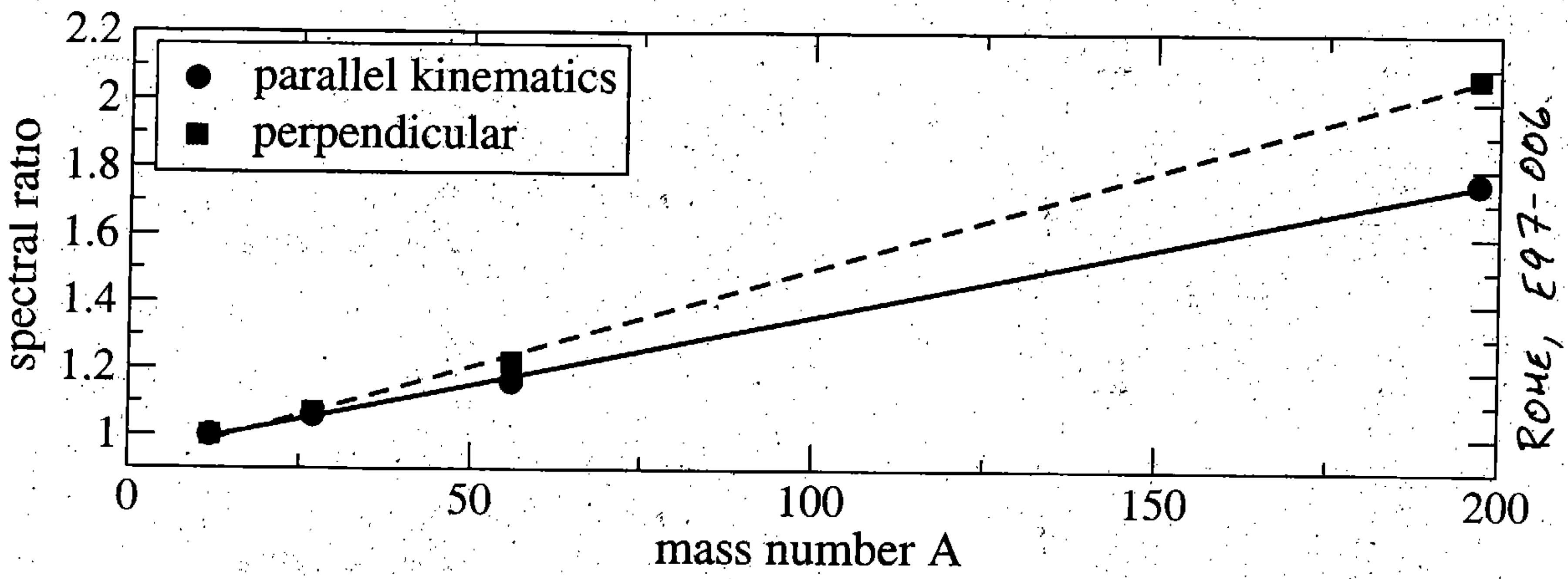
CORRELATIONS: JANSSEN et al, NP A672 285 (00)

BUT WE DON'T UNDERSTAND THEM YET



BUT WE DON'T UNDERSTAND THEM YET

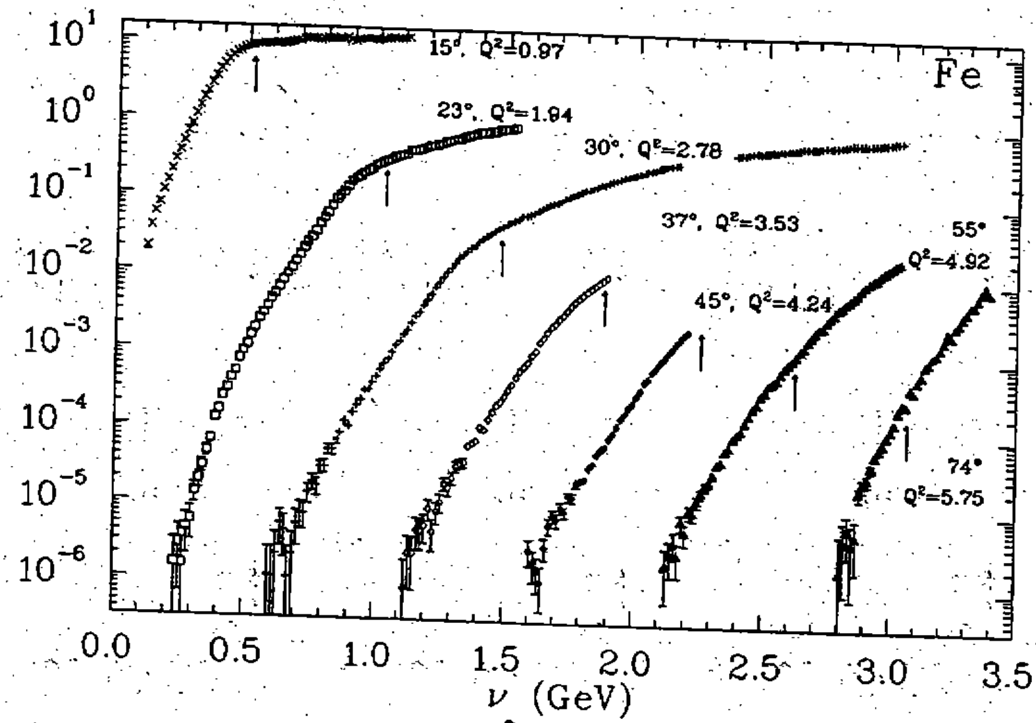
Ratio Al, Fe, Au to C spectral function



SHORT RANGE CORRELATIONS EXIST:
Y-SCALING: THE NUCLEUS CONTAINS NUCLEONS

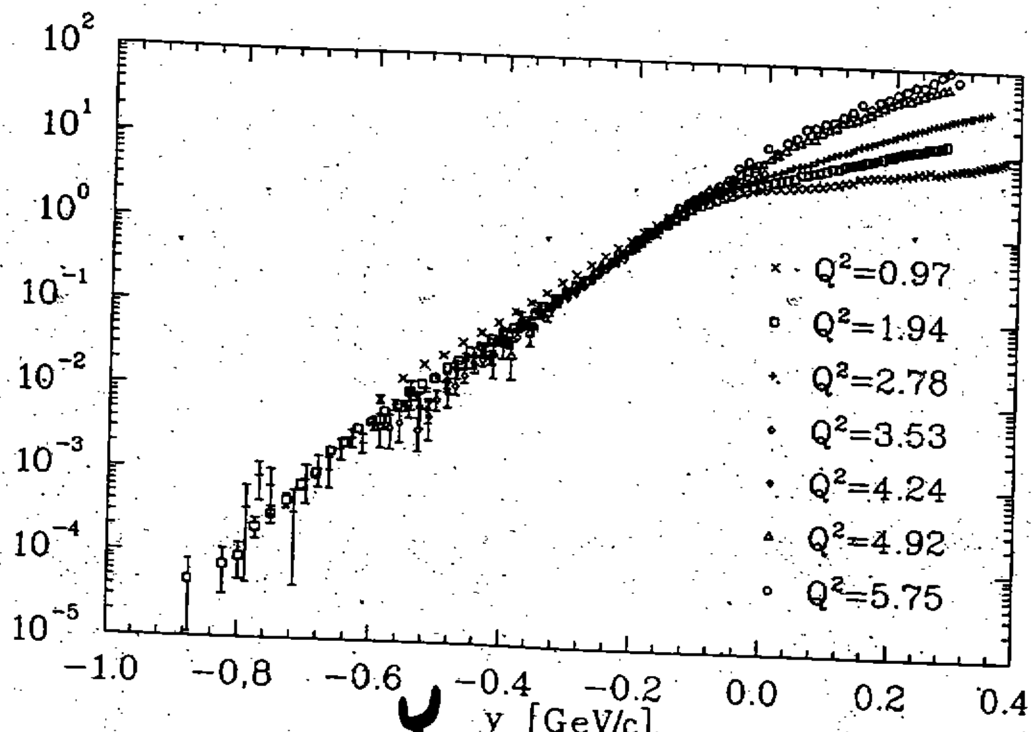
Fe(e,e')

CROSS SECTION



ν

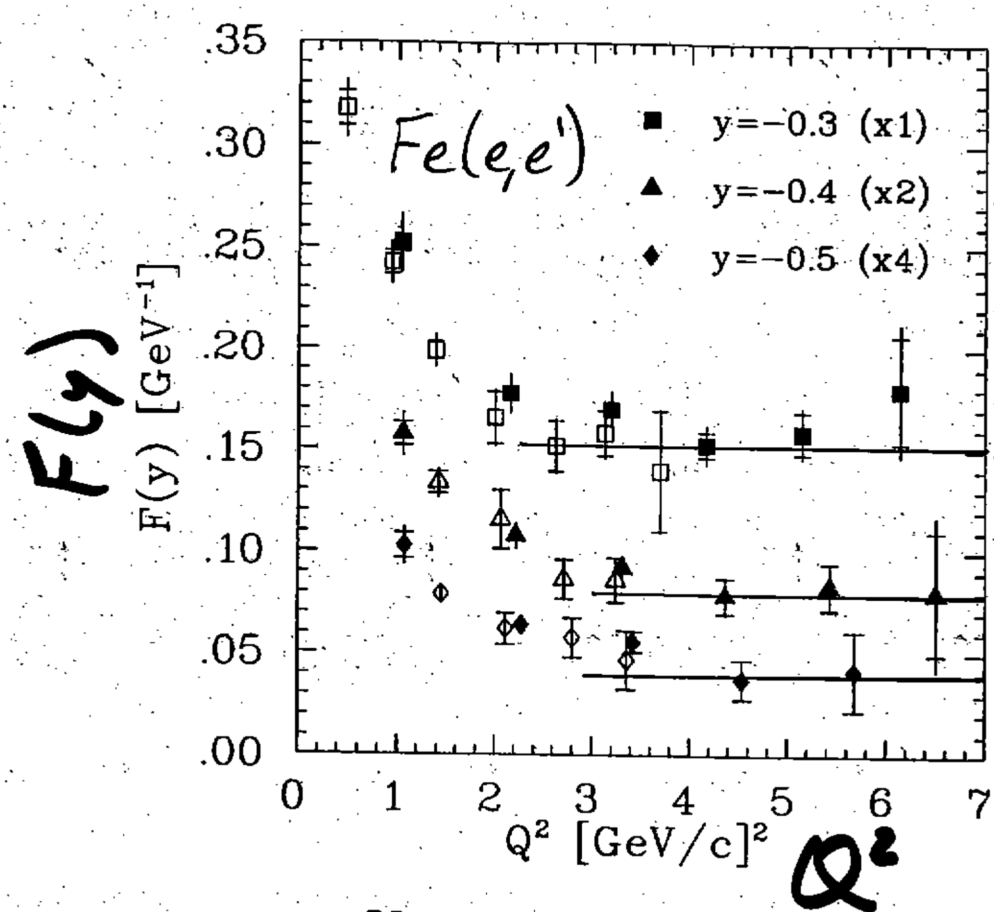
F(y)



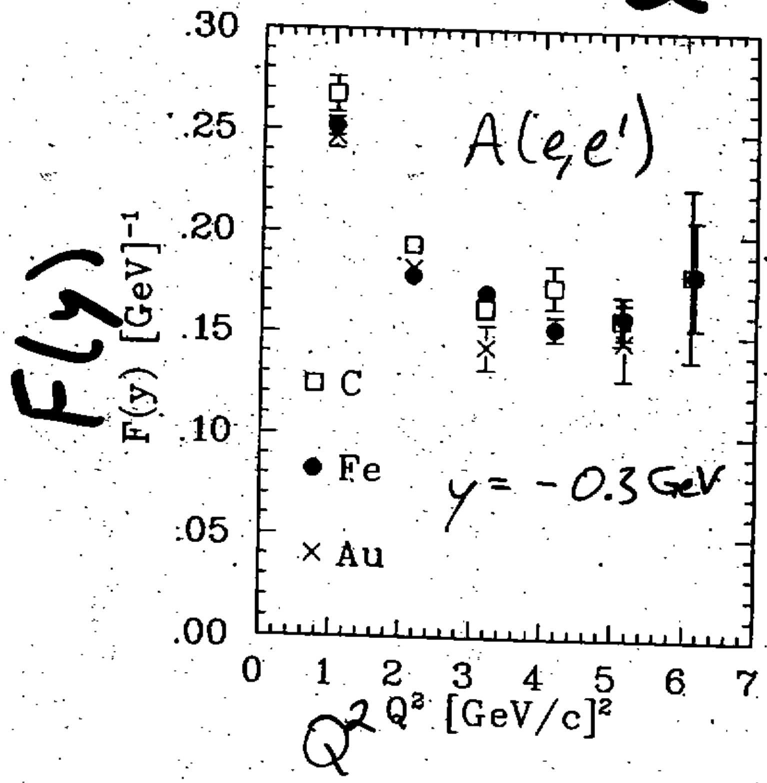
Y

ARRINGTON, PRL 82 2056 (99)

$y(Q^2, \nu)$ = MINIMUM NUCLEAR [A-1] RECOIL MOMENTUM



SCALING!



A INDEPENDENT
⇒
CORRELATIONS!

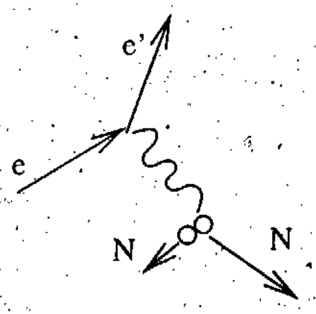
Correlations in Nuclei

(e,e'NN) -- Measure Correlated NN Momentum Distribution
(e,e') -- Measure Probability of Correlations

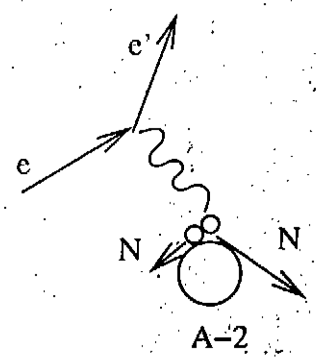
(e,e')

NN Short Range Correlations

⟶ High Momentum Components



d(e,e')



A(e,e')

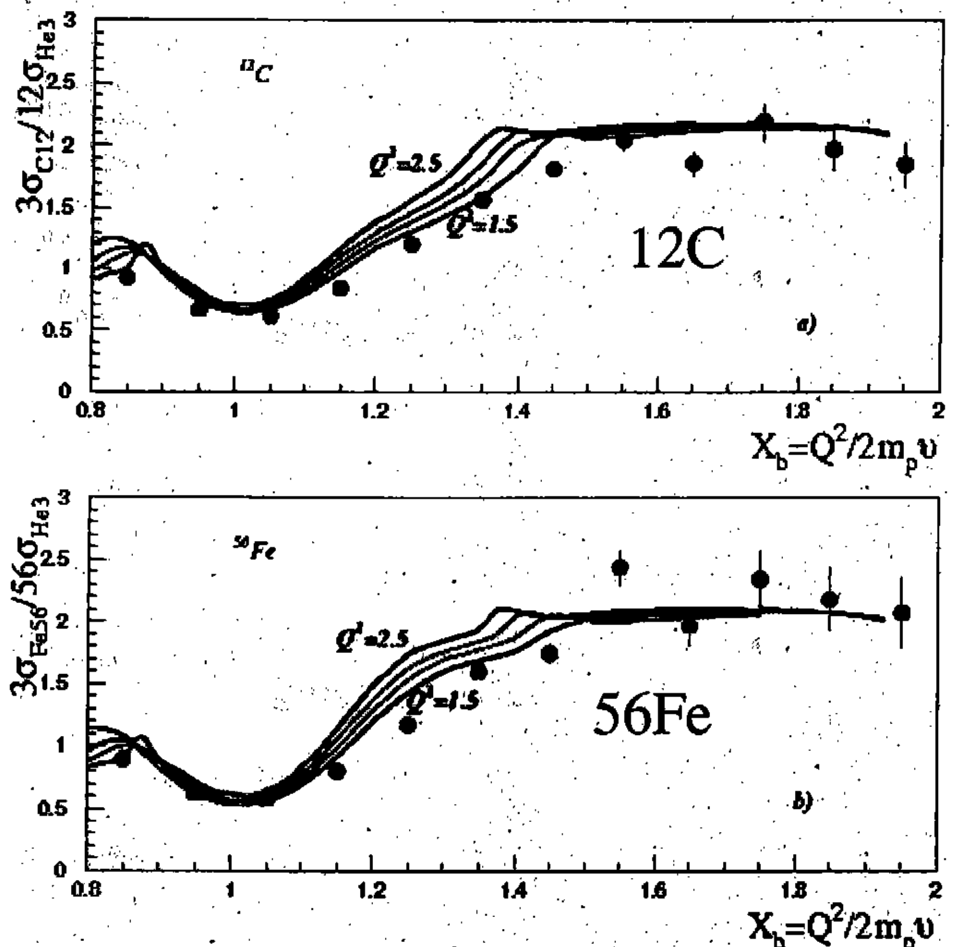
Ratio of (e,e') cross sections should be independent of x and Q^2 (for Q^2 > 1 and x >> 1)

Ratio is related to the relative per–nucleon probability of SRC in nucleus A relative to d

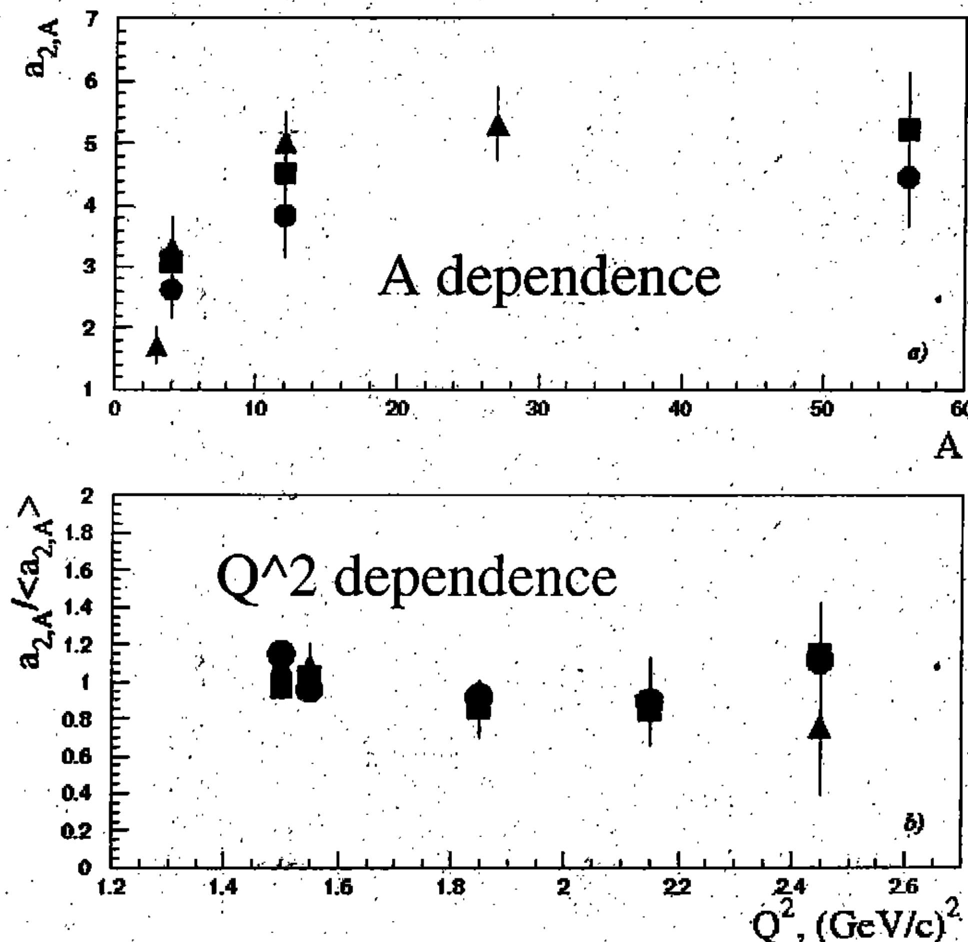
(e,e′)

Ratio of Cross sections to 3Helium

A(e,e′), 1.4<Q²<2.6



A and Q^2 dependence of ratios



EGIYAN et al, PRC IN PRESS

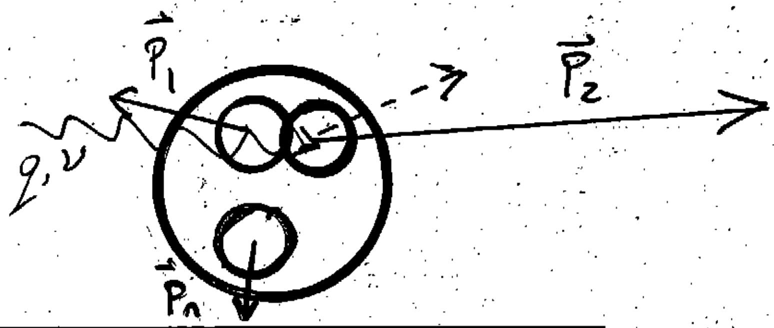
No x or Q^2 dependence for x > 1.5 ⟶ SRC model valid

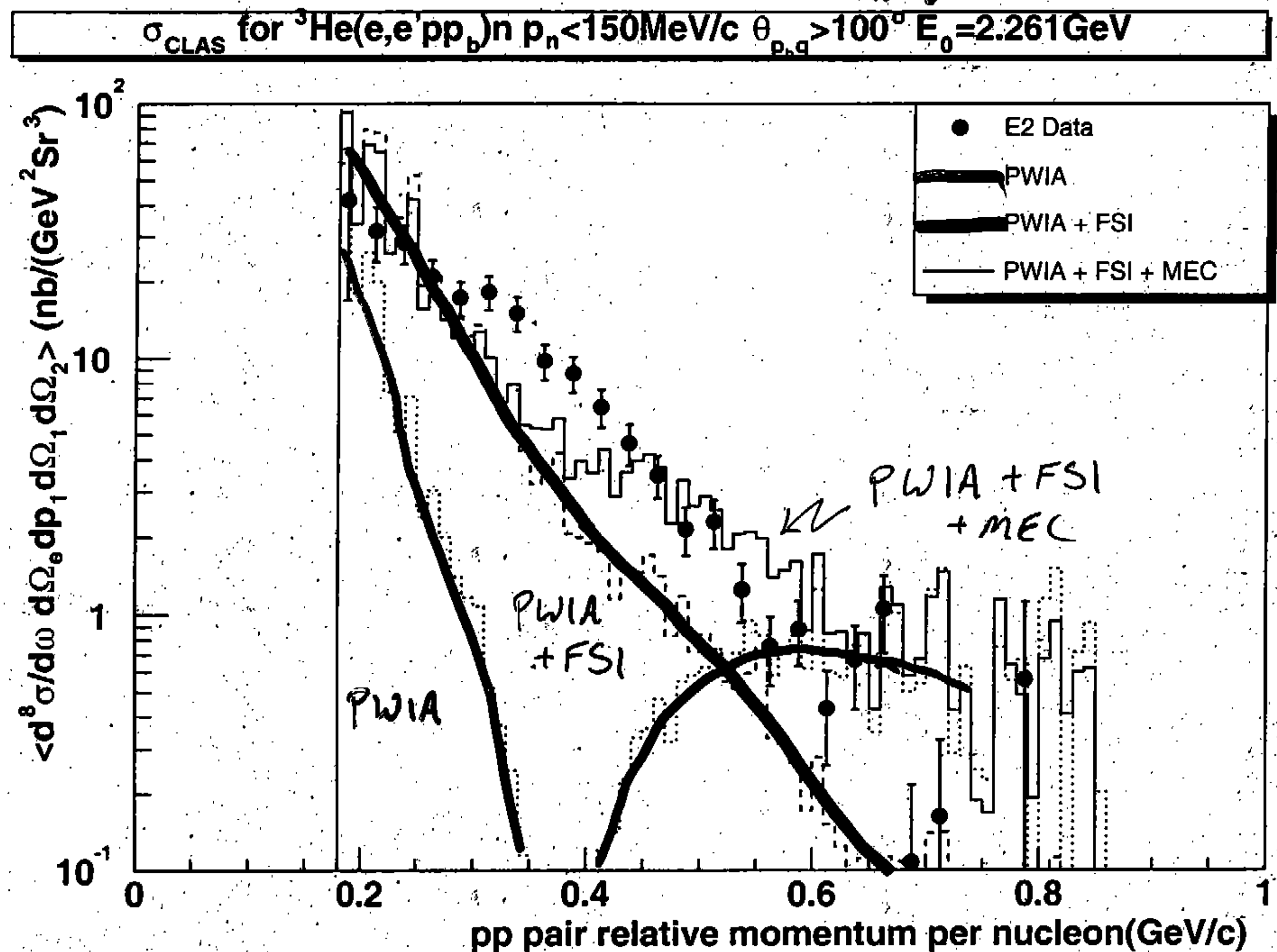
5 times more SRC for A > 10 than in deuterium

K. Egiyan. H. Baghdasaryan

BUT THEY ARE HARD TO MEASURE

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





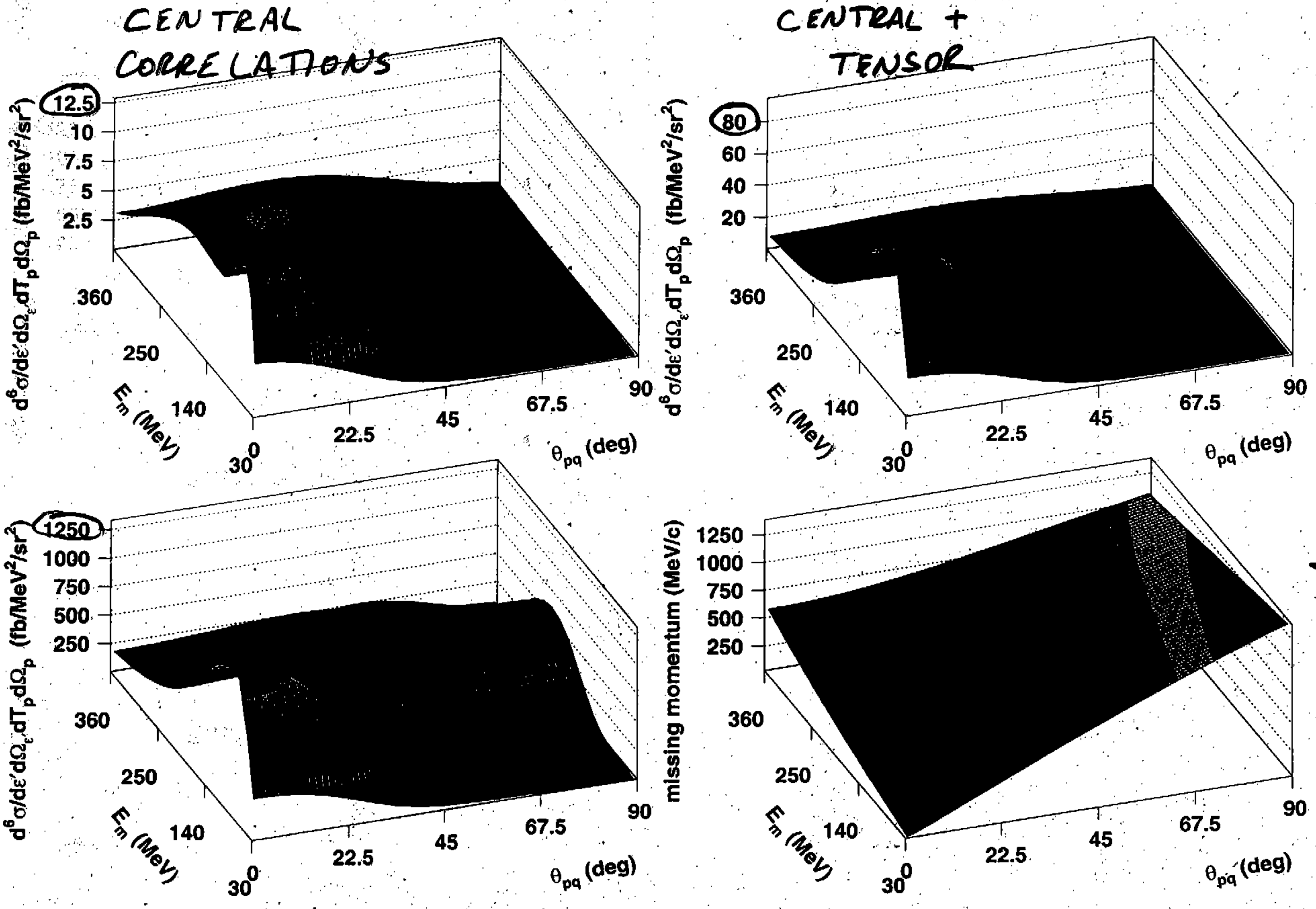
$\frac{1}{2}\left[(\vec{p}_2 - \vec{q}) - \vec{p}_1\right]$

B. ZHANG, et al IN PREPARATION

THEORY: LAGET

BUT THEY ARE HARD TO MEASURE (OBSCURED BY 2-BODY CURRENTS)

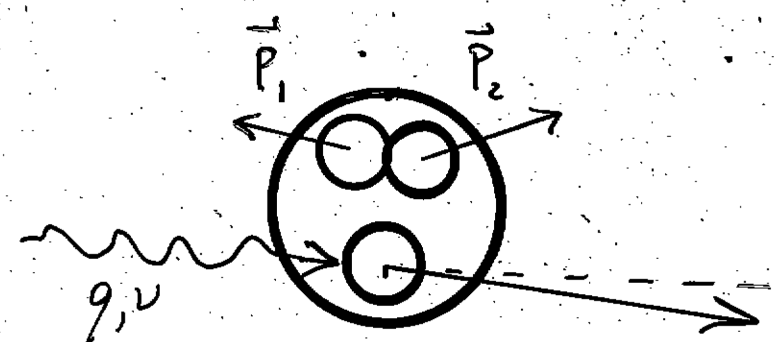
$O(e,e'p)$ $Q^2 = 0.8$ GeV^2

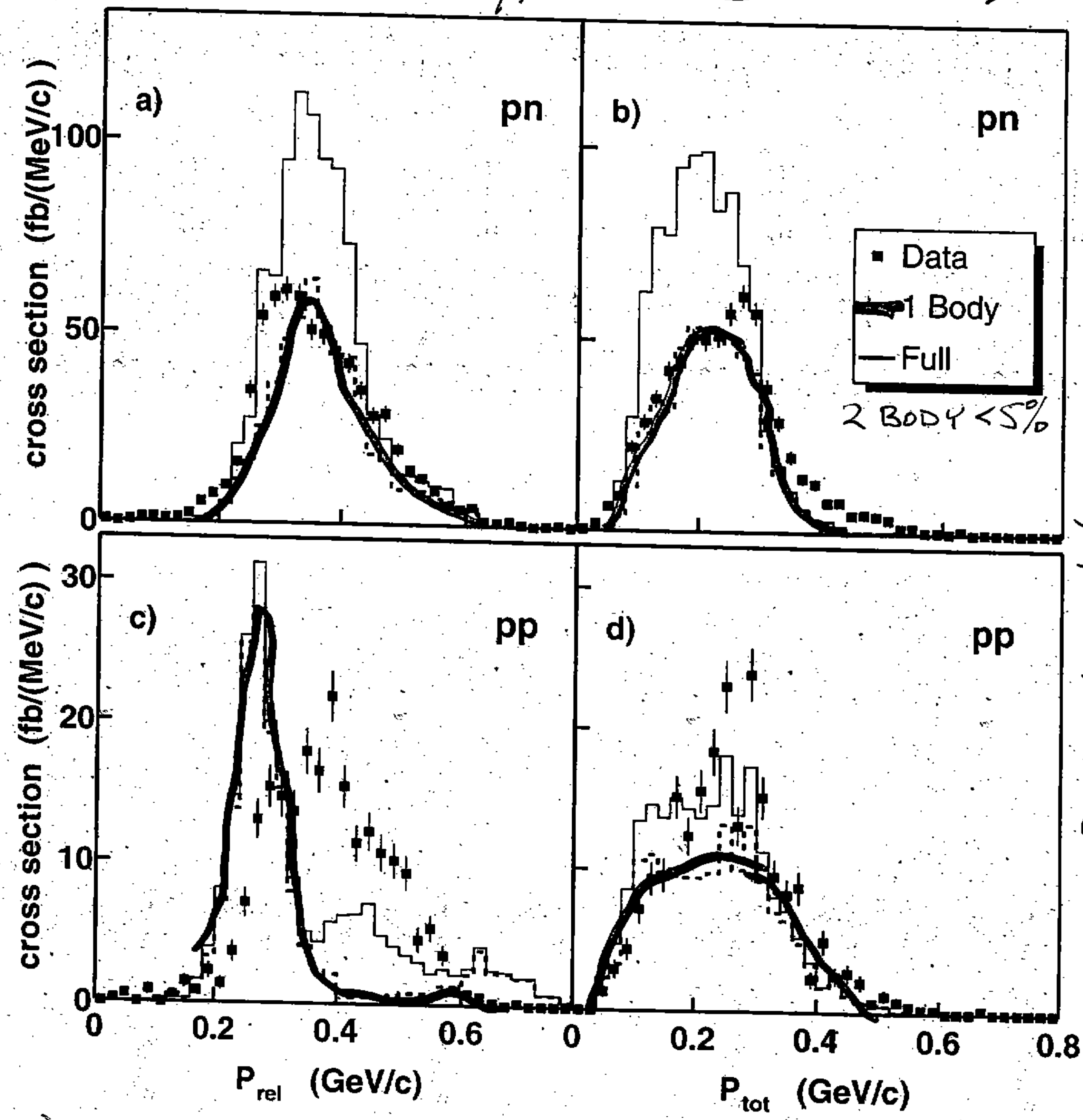


JANSSEN et al, NP A672, 285 (2000)

MEASURING SPECTATOR PAIRS:

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





DATA: R. NIYAZOV, et al. IN PREPARATION

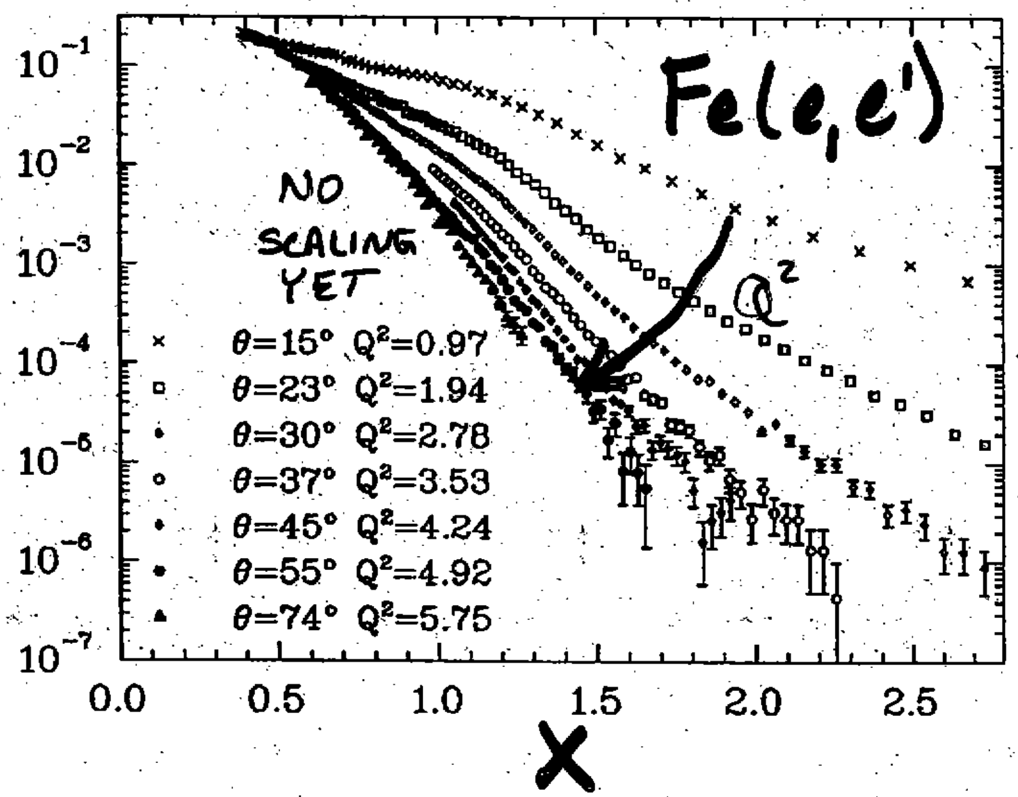
THEORY: LAGET

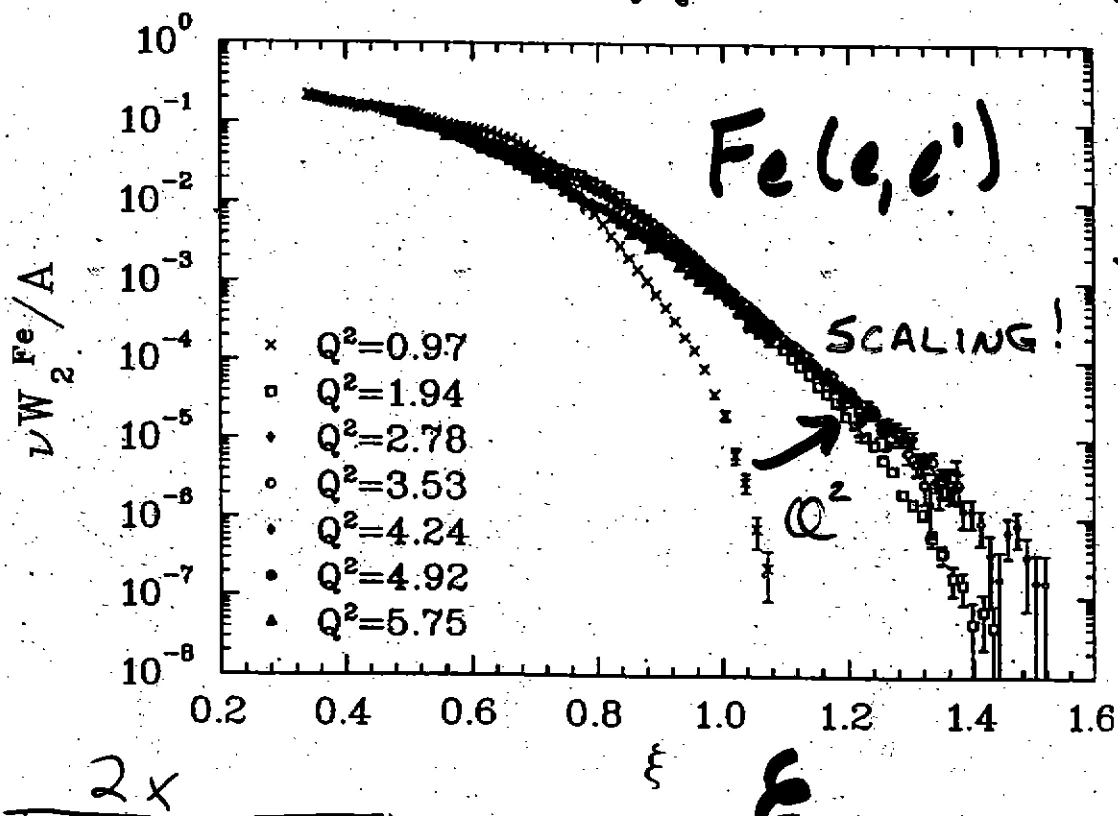
$\vec{P}_{REL} = \frac{1}{2}(\vec{P}_1 - \vec{P}_2)$

$\vec{P}_{TOT} = \vec{P}_1 + \vec{P}_2$

THE QUARKS ARE HIDING FROM US!

ξ SCALING: THE NUCLEUS CONTAINS QUARKS.



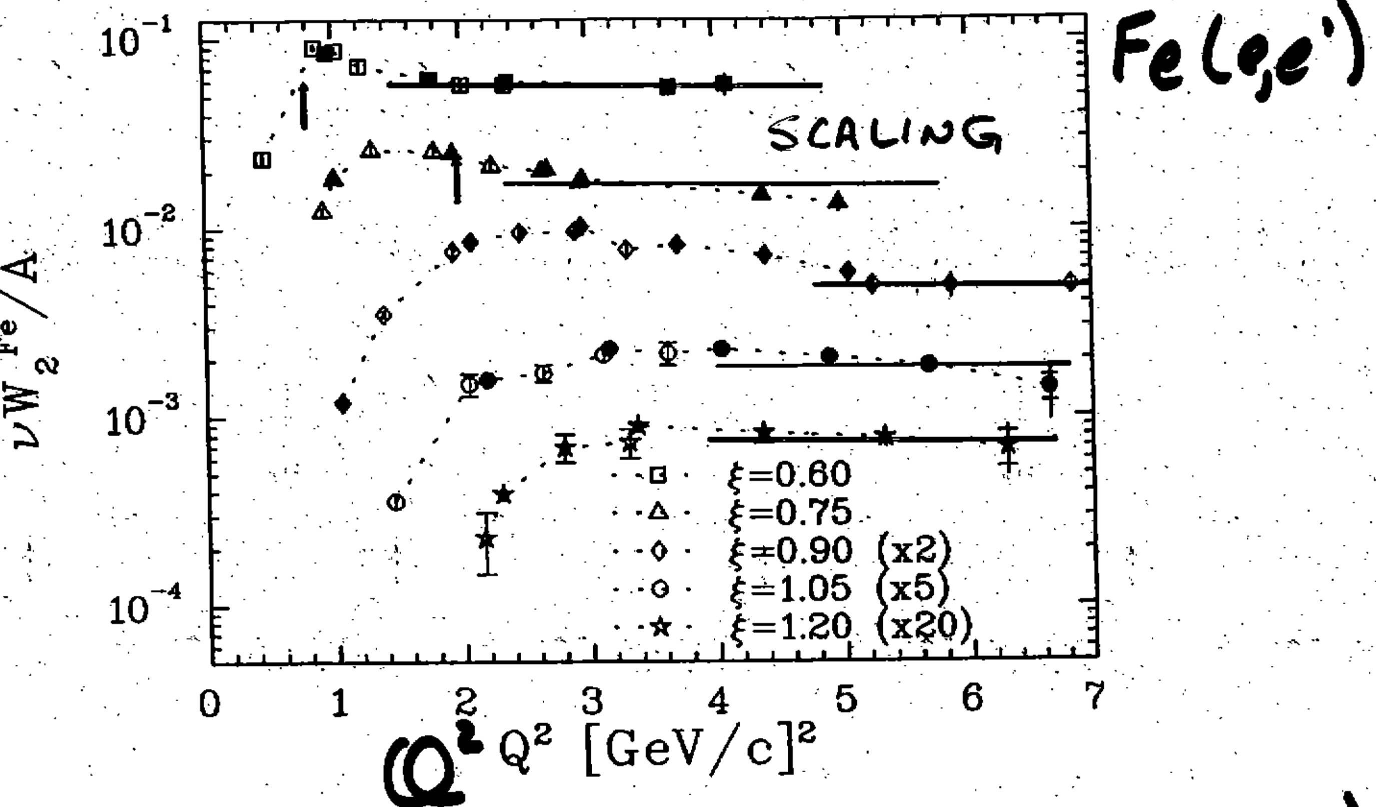


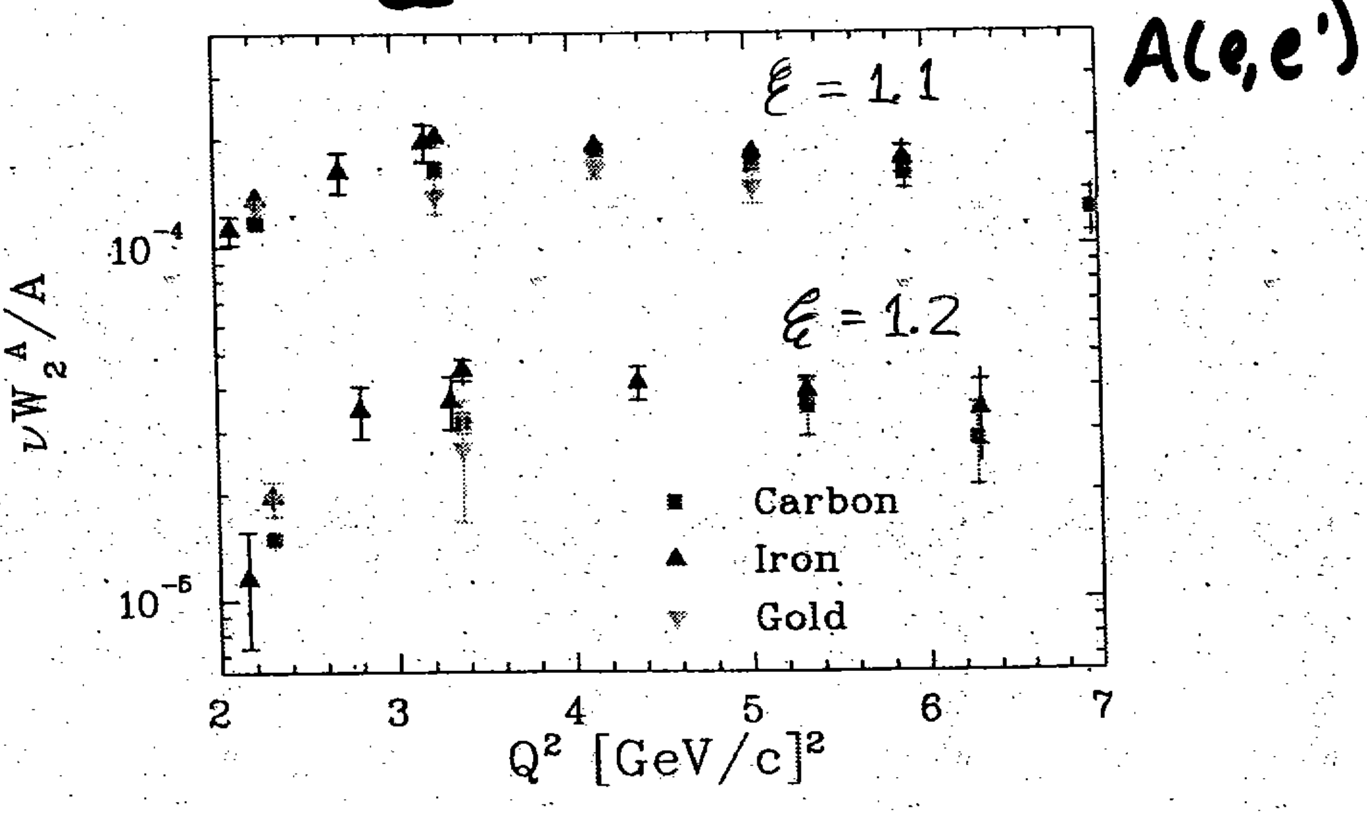
$$\nu W_2 = \frac{\nu}{1+\beta} \frac{d\sigma/d\Omega dE'}{\sigma_{Mott}}$$

ARRINGTON et al, PRC 64 014602 (2001)

$$\xi = \frac{2x}{1 + \sqrt{1 + 4M^2x^2/Q^2}}$$

THE QUARKS ARE HIDING FROM US!





Summary

- Nucleons are nucleons
  - single-particle distributions 'measured'
  - distortions/many-body effects
  - relativity
- Two body currents are important
  - probably decrease with Q^2
  - not yet fully understood
- Short Range Correlations exist
  - frequently obscured by 2-body currents
  - can be measured
- The quarks are hiding from us!
  - THEY ARE HIDING INSIDE NUCLEONS

SUMMARY OF THE SUMMARY

WE DID WHAT WE PLANNED TO DO