RELATIVISTIC DESCRIPTION OF EXCLUSIVE REACTIONS IN NUCLEI

- **Introduction**
- **RDWIA approach to exclusive (e,e'p) reactions**
- **Some remarks about factorization**
- **RIA: Elastic p-A scattering and exclusive (p,2p) reactions**
- **Summary**

What do we mean by relativistic mean field (RMF)?

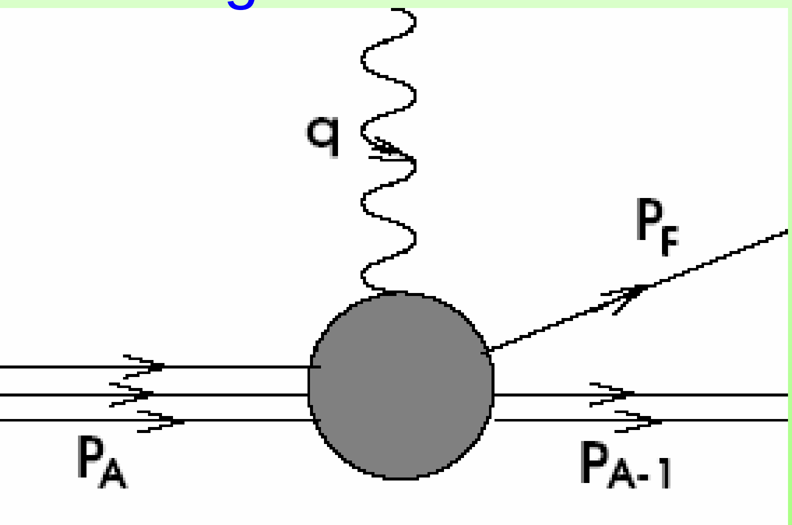
- We mean the use of the Dirac equation with its relativistic treatment of dynamics and kinematics as opposed to the nonrelativistic Schrödinger equation (which can also include relativistic kinematics) to describe single nucleon motion in nuclei

- Relativity is important at low energies, and even at zero incident energy!!!

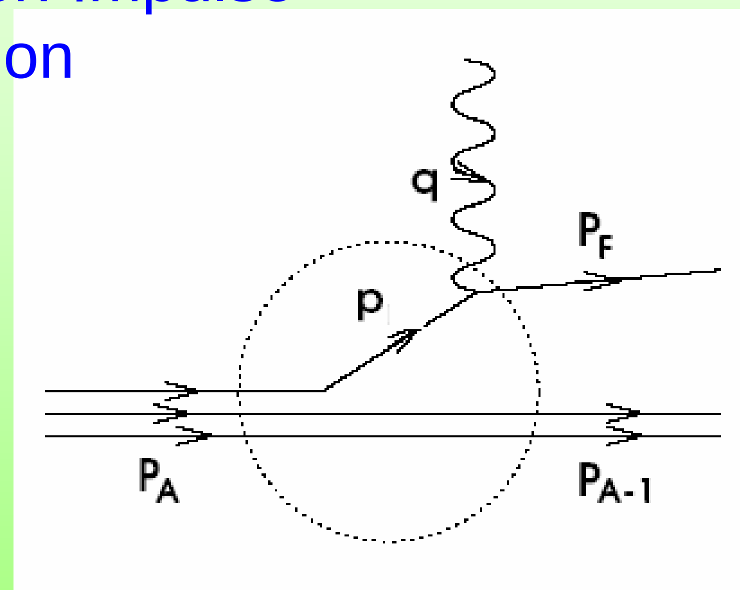
- The Dirac equation provides a natural description of spin-1/2 particles and, hence, provides a good framework for studying spin observables

OVERVIEW OF THE MODEL (ingredients)

Simple: One photon exchange:



Even simpler: Impulse Approximation



$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\,\hat{J}_N^\mu(\omega,\vec{q})\,\psi_B(\vec{p})$$

- **Look at exclusive (e,e'p) reactions at the top of the quasielastic peak (x=1)**
- **Best place to justify the use of Impulse Approximation and Mean Field models plus one body operators**
- **EM interaction is well known**

Physics Motivation

Deviations from independent particle motion for orbits near the Fermi surface are attributed to effects beyond mean field (correlations) which reveal their pressence in two ways:

(i) Changes in the occupation and spectroscopic factors with respect to mean-field predictions

(ii) Changes in the momentum distribution of particles, particularly at high momentum and binding energies

V.R. Pandharipande, I. Sick and P.K.A. deWitt Huberts, Independent particle motion and correlations in fermions systems, **Reviews of Modern Physics 69** (981) **1997**

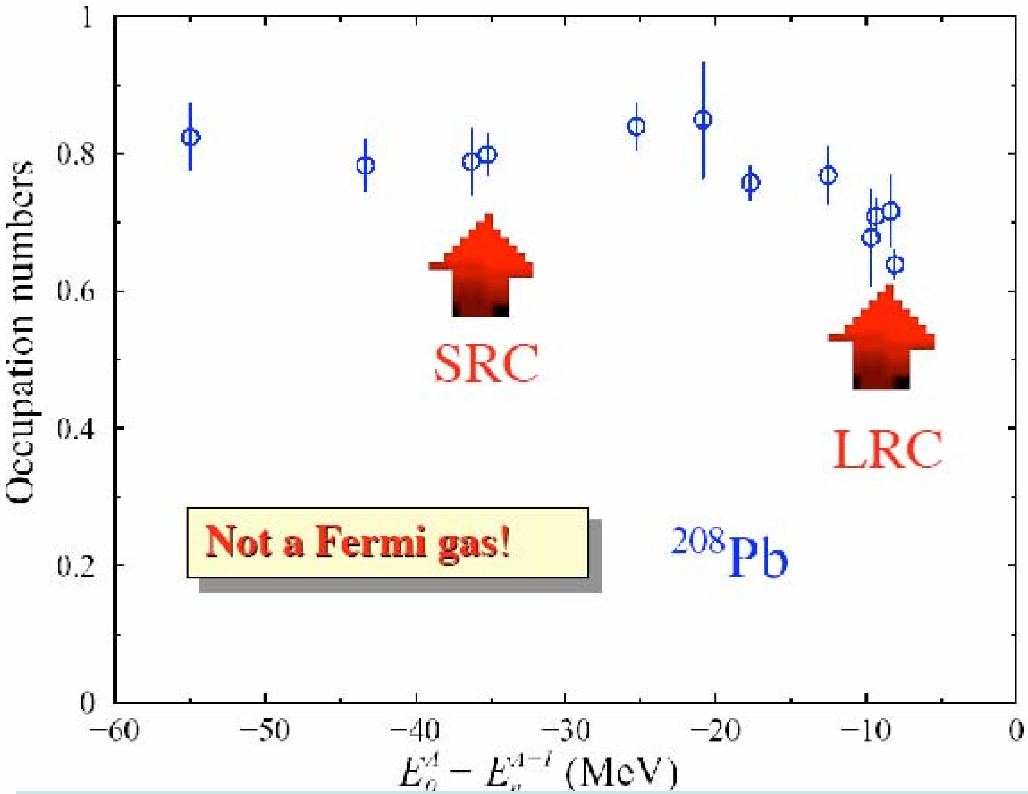
Physics Motivation

Complutense

- *The (e,e'p) reaction at quasielastic kinematics and under exclusive conditions, for the outermost shells, becomes one of the most powerful and cleanest test of the mean field and the correlations needed to supplement it*

- ^{208}P*b is the most suitable candidate to employ the mean field prediction, and thus it has been measured in the past in order to determine spectroscopic factors, mainly in parallel kinematics and for moderate values of* Q^2 ($Q^2 << 1$ (GeV/c)^2)

•Shell model (mean field) calculations: the shape of the experimental cross-section is well described, but the measured spectroscopic factors are below the mean field prediction. How large/small must be the spectroscopic factors?



About 30% depletion is observed for states near the Fermi level. This cannot be explained only with short-range correlations

Shape at moderate p_m and parallel kinematics is well understood

Long range correlations are predicted to be visible at large p_m

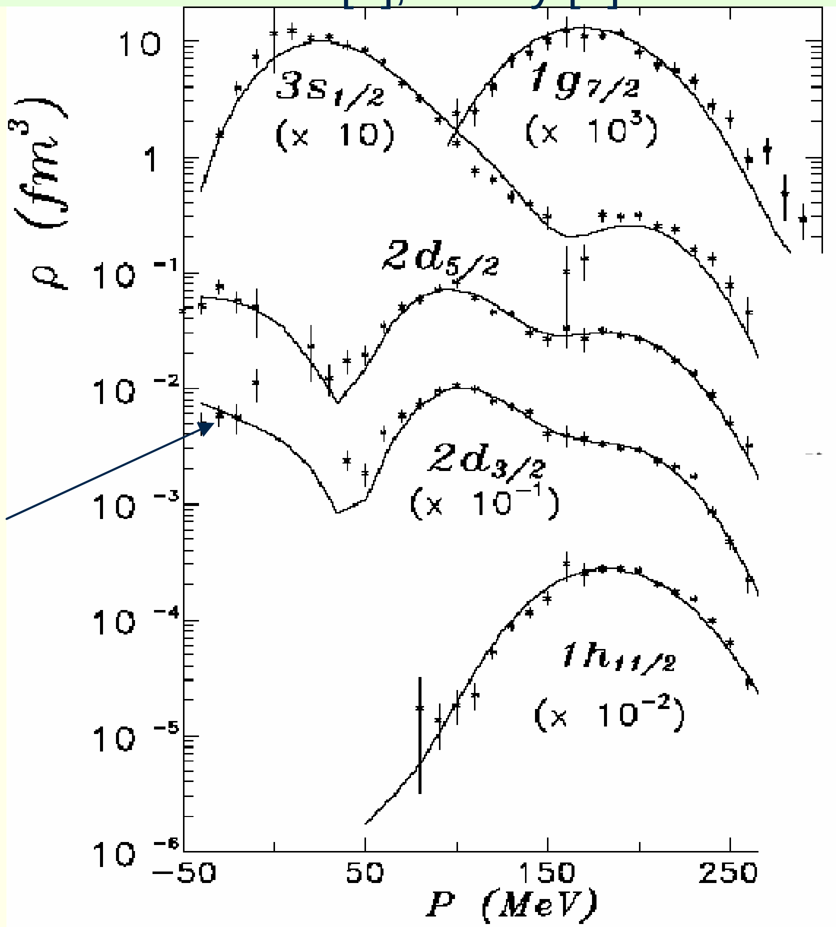
M. van Batenburg (thesis, 2001) & L. Lapikás from ^{208}Pb (e,e´p) ^{207}Tl

Still open issues: (i) possible dependence on Q^2 of the spectroscopic factors?

data [4], theory [5].

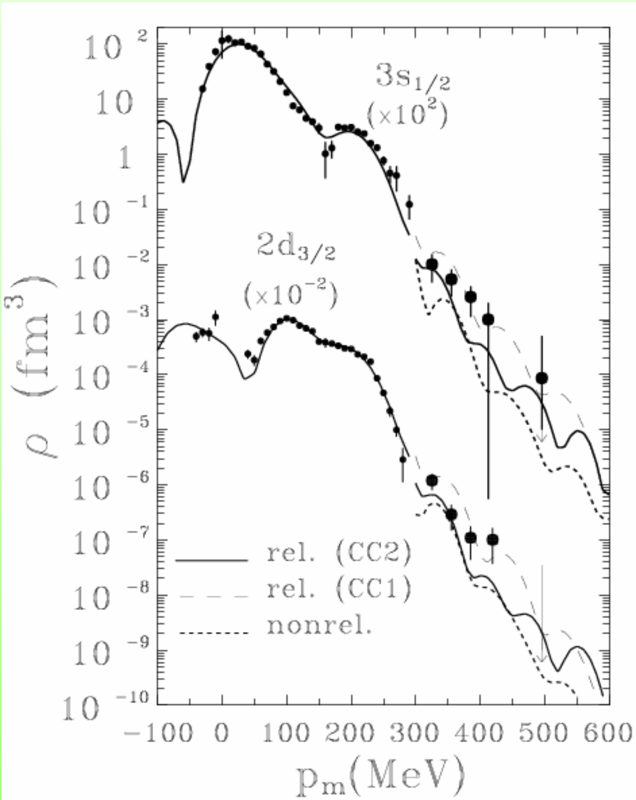
$^{12}C(e,e'p)$ data over wide range of Q^2. There appears to be a Q^2 dependence to the spectroscopic factors observed in this reaction[L. Lapikas et al. PRC 61, 064325 (2000)]. This interpretation has been disputed and the Q^2 dependence attributed to the way of introducing SRC[H. Müther and I. Sick, PRC70 041301R]

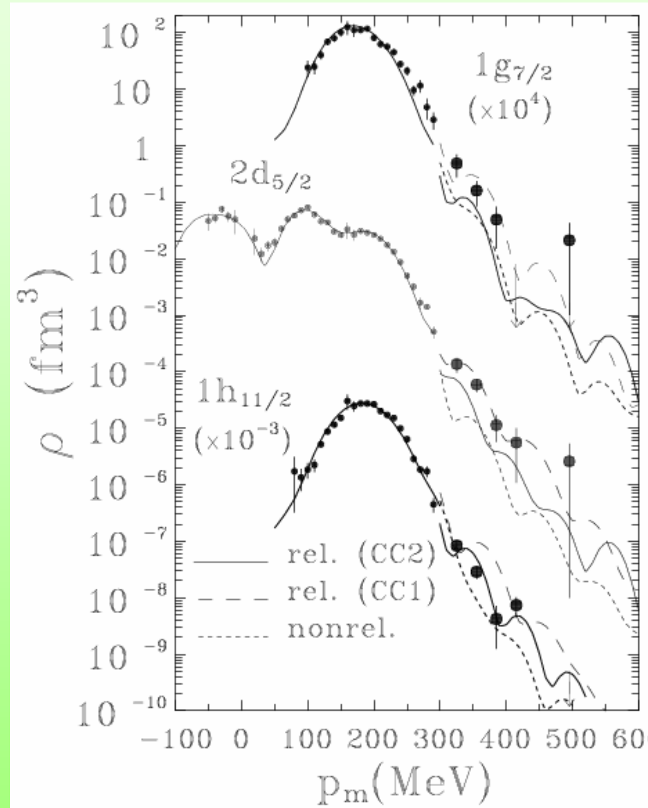
$^{208}Pb(e,e'p)$ has been studied in the past at low momentum transfers and spectroscopic factors for the valence shells in the range of 0.6 to 0.7 have been reliably extracted at parallel kinematics at low Q^2



A measurement at several high values of Q^2 will directly address the question of momentum transfer dependence of the spectroscopic factors

Open issues: (ii) Long range correlations and cross-sections at high p_m (> 300 MeV/c)





x_B = 0.18

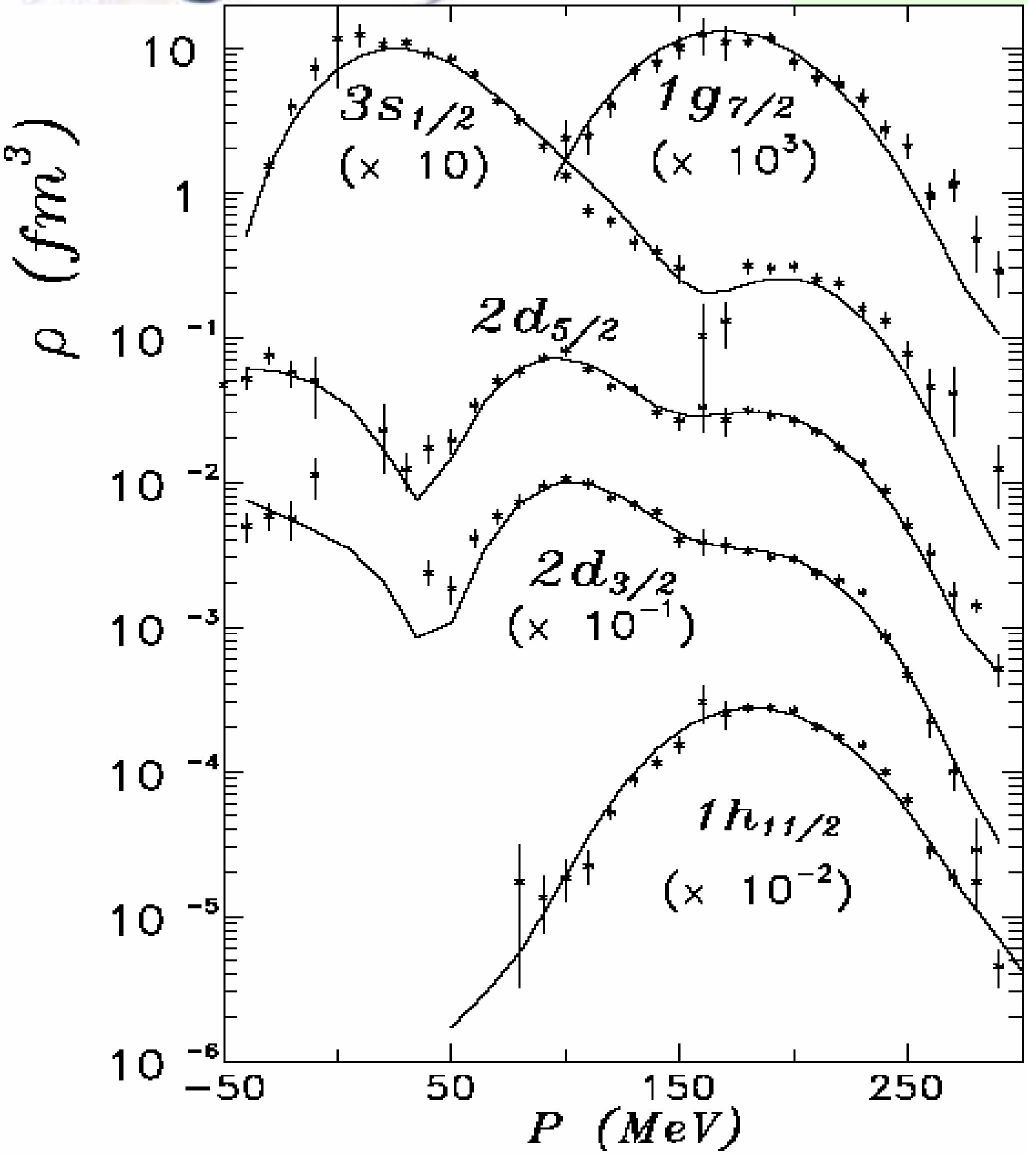
E. Quint, thesis, 1988, NIKHEF

I. Bobeldijk et al., PRL 73 (2684)1994

Rel. Theory: PRC 48 (2731) 1994, PRC 51 (3246) 1996
J.M. Udias et al.

If long range correlations are the reason for the small spectroscopic factors, then they may produce some visible effect at high missing momentum. An experiment was performed at NIKHEF-K to measure the large momentum region, but the kinematics was far from X_B=1. Additional strength was indeed found, but this can be explained either via long-range correlations [I. Bobeldijk] or by relativistic effects in the mean field model.

Reasonably good agreement with data in parallel kinematics



Only R_L and R_T contribute in this kinematics

	$3s_{1/2}$	$2d_{3/2}$	$1h_{11/2}$	$2d_{5/2}$	$1g_{7/2}$
Non rel. (Ref. [41])	50 %	53 %	42 %	44 %	19 %
Non rel. (Ref. [42])	55 %	57 %	58 %	54 %	26 %
Rel. (Refs. [40, 6])	70 %	72 %	64 %	60 %	30 %

Relativistic analyses provide larger scale factors, due to 'Darwin term' (PRC 51 (1995) 3246)

[41] E. Quint et al. (1988).

[42] I. Bobeldijk et al. PRL 73 (1994) 2684.

Complex nuclei!!!. Use the simplest ingredients: Relativistic Mean Field (RMF)

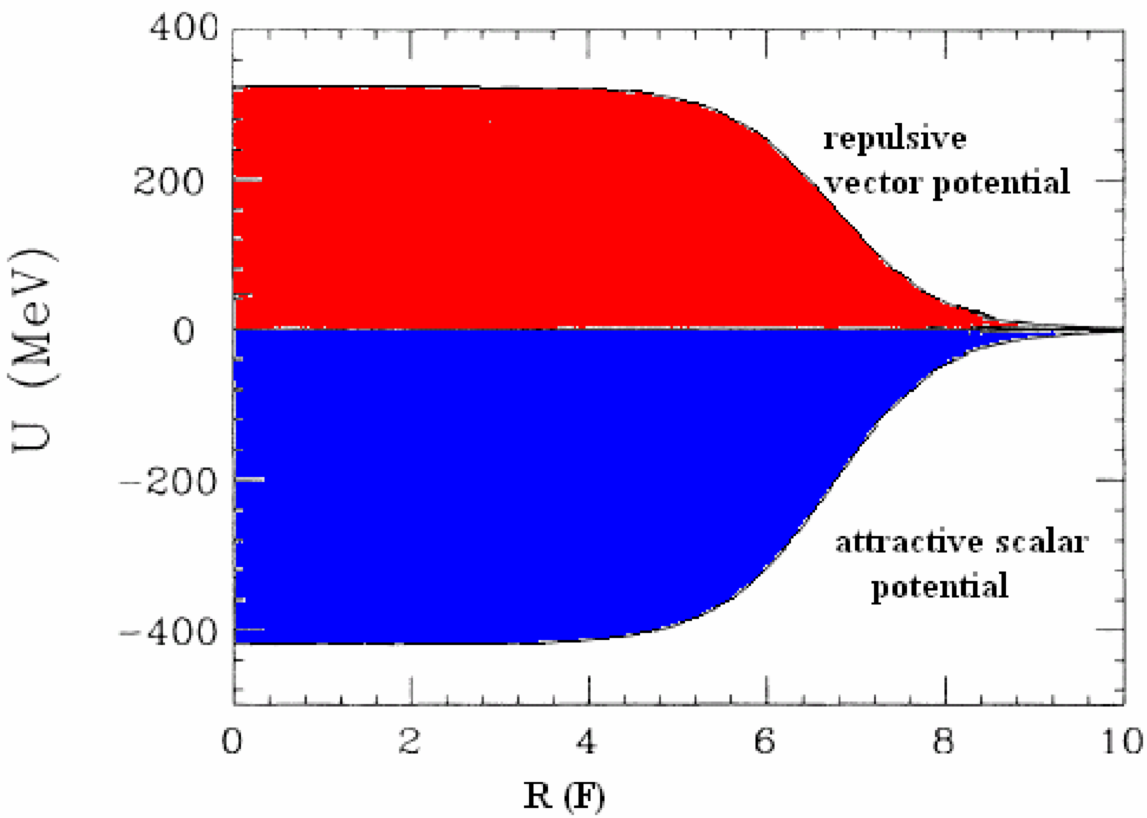
$$(\tilde{E}\gamma_0 - \vec{p}\cdot\vec{\gamma} - \tilde{M})\psi = 0$$

$$\tilde{E} = E - V(r)$$
$$\tilde{M} = M - S(r)$$

- Solve a Dirac-like equation
- Bound state: Phenomenological σ-ω lagrangeans (Serot and Walecka model or extensions) at mean field level
- Final State: Phenomenological S-V potentials (B. Clark, E.D. Cooper et al.) or RIA (IA1)
- Current operator: 'free' prescription, cc1, cc2 or whatever
- Relativistic, FSI by means of partial waves and Impulse App.:

RDWIA

Within RMF, parameters are phenomenologically chosen to reproduce the saturation properties of nuclear matter



- A strong (hundreds of MeV's) repulsive vector potential and attractive scalar one is obtained within the Dirac treatment

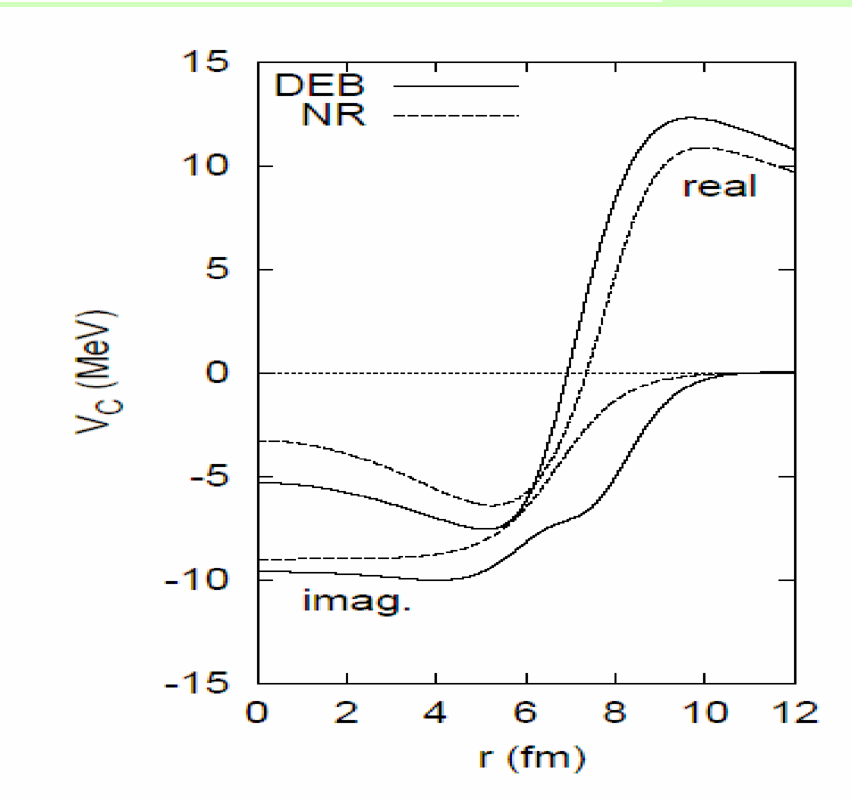
- The small (tens of MeV) binding energy arises as a result of cancellations and is just the 'tip' of the iceberg

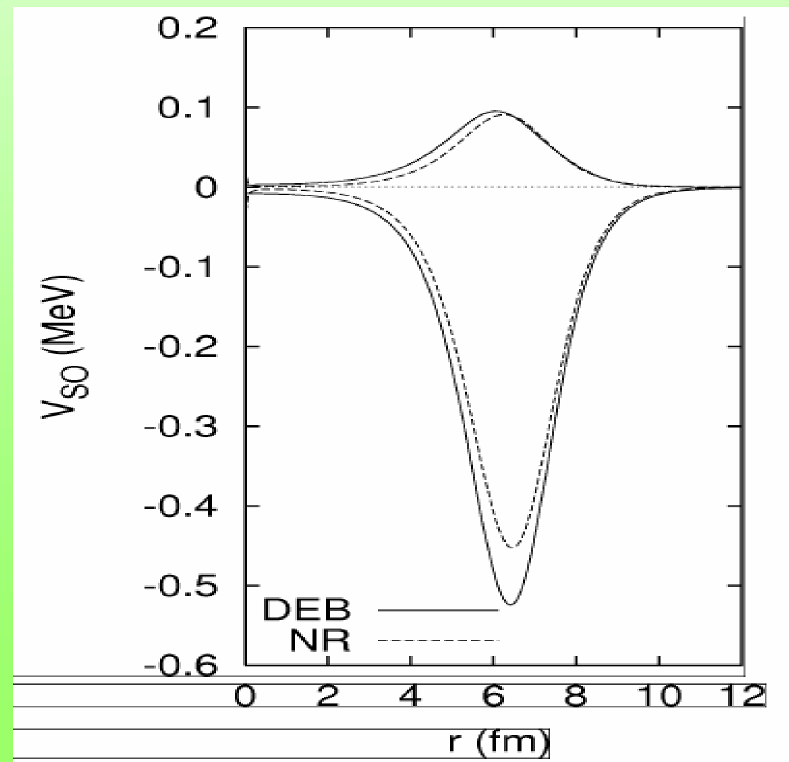
Comparison to standard NR phenomenology

$$V_c = S + \frac{E}{M}V + \frac{1}{2M}(S^2 - V^2)$$

$$V_{so} = -\frac{1}{2Mr}\frac{\frac{\partial}{\partial r}(S - V)}{E + M + S - V}$$

- Additional (strong) E-dependence
- Spin-orbit well predicted





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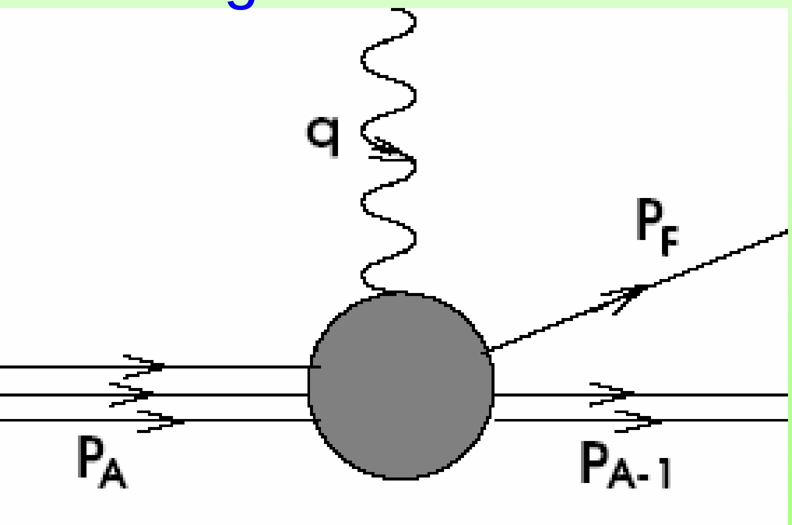
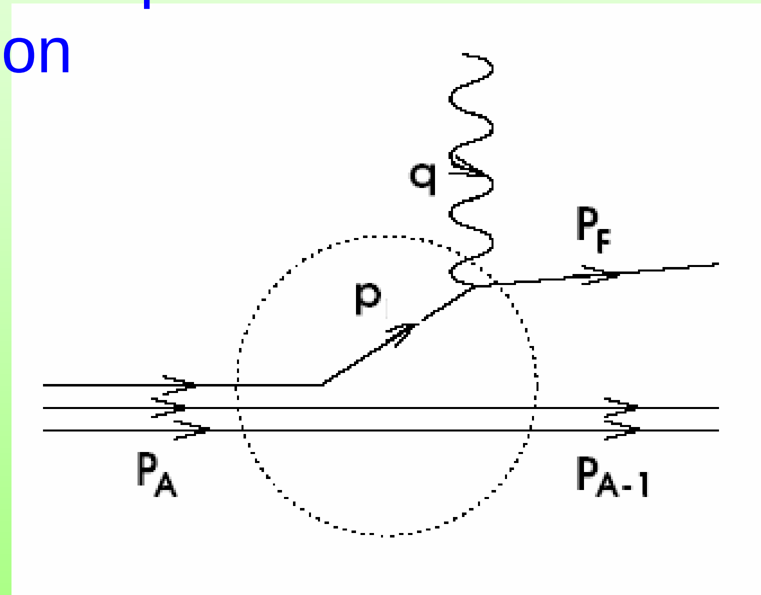


Even simpler: Impulse Approximation



$$J_N^{\mu}(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\,\hat{J}_N^{\mu}(\omega,\vec{q})\,\psi_B(\vec{p})$$

Unpolarized and in plane:

$$\frac{d\sigma}{d\Omega_e d\varepsilon' d\Omega_F} = K\sigma_{Mott} f_{rec} \left[v_L R^L + v_T R^T + v_{TL} R^{TL} \cos\phi_F + v_{TT} R^{TT} \cos 2\phi_F \right]$$

$$\rho^{exp}(\mathbf{p}_m) = \frac{\left(\frac{d\sigma}{d\varepsilon_f d\Omega_f d\Omega_F}\right)^{exp}}{E_F p_F f_{rec} \sigma_{ep}} .$$

$$A_{TL} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-},$$

One-photon exchange approximation yields, for the most general case:

$$\frac{d\sigma}{d\varepsilon_f d\Omega_f d\Omega_F} = \frac{E_F p_F}{(2\pi)^3}\sigma_M f_{rec}\frac{1}{2}\left\{v_L\left(R^L + R_n^L\widehat{S}_n\right) + v_T\left(R^T + R_n^T\widehat{S}_n\right)\right.$$
$$+ v_{TL}\left[\left(R^{TL} + R_n^{TL}\widehat{S}_n\right)\cos\phi_F + \left(R_l^{TL}\widehat{S}_l + R_s^{TL}\widehat{S}_s\right)\sin\phi_F\right]$$
$$+ v_{TT}\left[\left(R^{TT} + R_n^{TT}\widehat{S}_n\right)\cos 2\phi_F + \left(R_l^{TT}\widehat{S}_l + R_s^{TT}\widehat{S}_s\right)\sin 2\phi_F\right]$$
$$+ h\left\{v_{TL'}\left[\left(R_l^{TL'}\widehat{S}_l + R_s^{TL'}\widehat{S}_s\right)\cos\phi_F + \left(R^{TL'} + R_n^{TL'}\widehat{S}_n\right)\sin\phi_F\right]\right.$$
$$\left.\left.+ v_{T'}\left[R_l^{T'}\widehat{S}_l + R_s^{T'}\widehat{S}_s\right]\right\}\right\},$$

R's proportional to $W^{\mu\nu}$:

$$W^{\mu\nu} = \frac{1}{2j_b+1}\sum_{\mu_b} J^{\mu *}(\omega,\mathbf{q})J^{\nu}(\omega,\mathbf{q}).$$

Signatures of RMF: Enhancement of the lower components

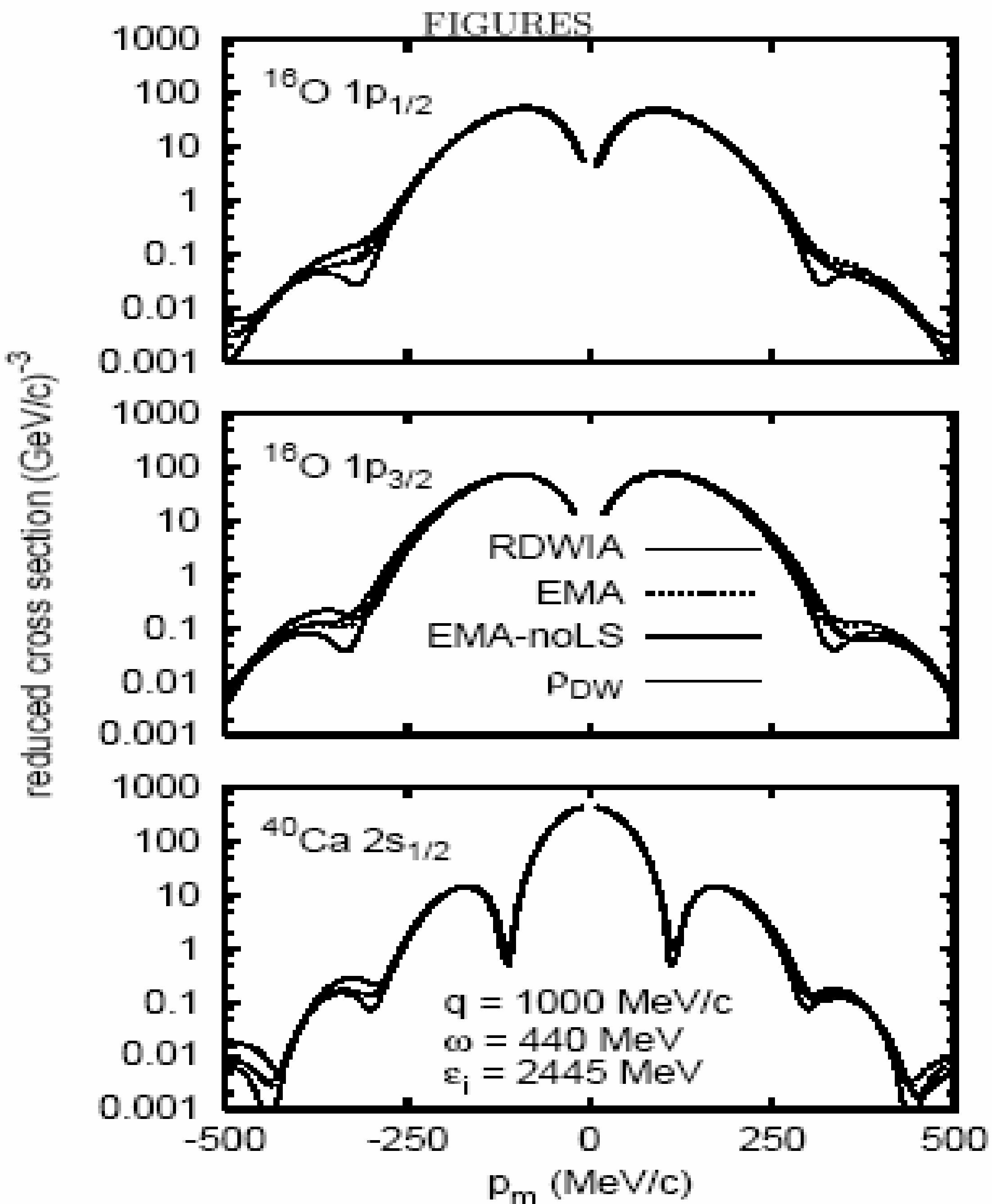
- Solutions of Dirac eq. with S and V potentials have enhanced lower component spinors, making them different from nonrelativistic solutions

- We can force 'on shell' the initial and final nucleon imposing their wave functions to fullfill the ***free*** Dirac equation: **EMA (or EMA-noSV).** Gordon transformation will be valid for these EMA spinors. Matrix element factorize into the one for free nucleons

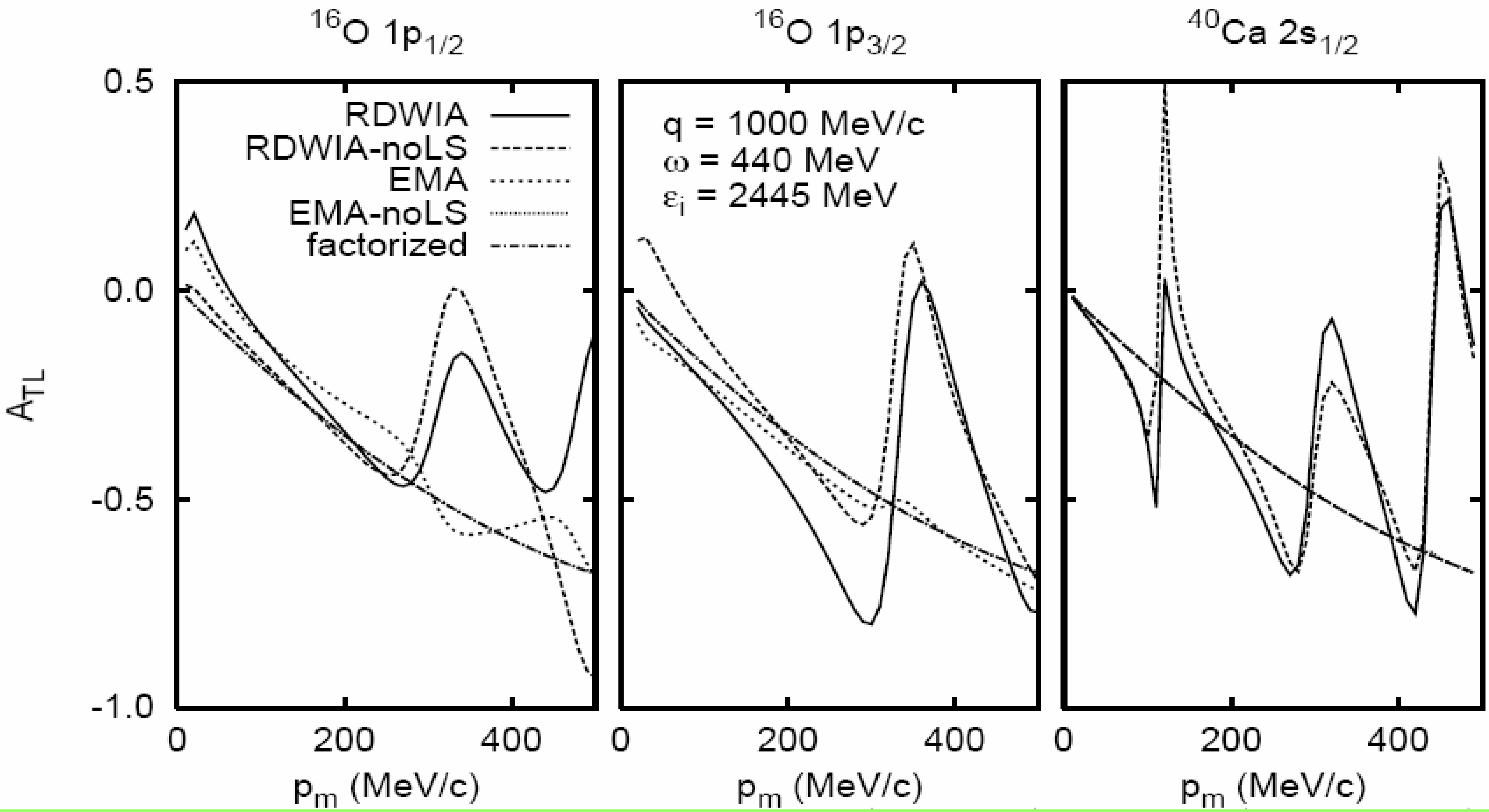
$$\bullet\ \psi_{RDWIA}(\vec{p}) = \begin{pmatrix} \psi_{up}(\vec{p}) \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+M+S-V}\psi_{up}(\vec{p}) \end{pmatrix} \rightarrow$$

$$\psi_{EMA}(\vec{p}) = \begin{pmatrix} \psi_{up}(\vec{p}) \\ \frac{\vec{\sigma}\cdot\vec{p}_{as}}{E_{as}+M}\psi_{up}(\vec{p}) \end{pmatrix}$$

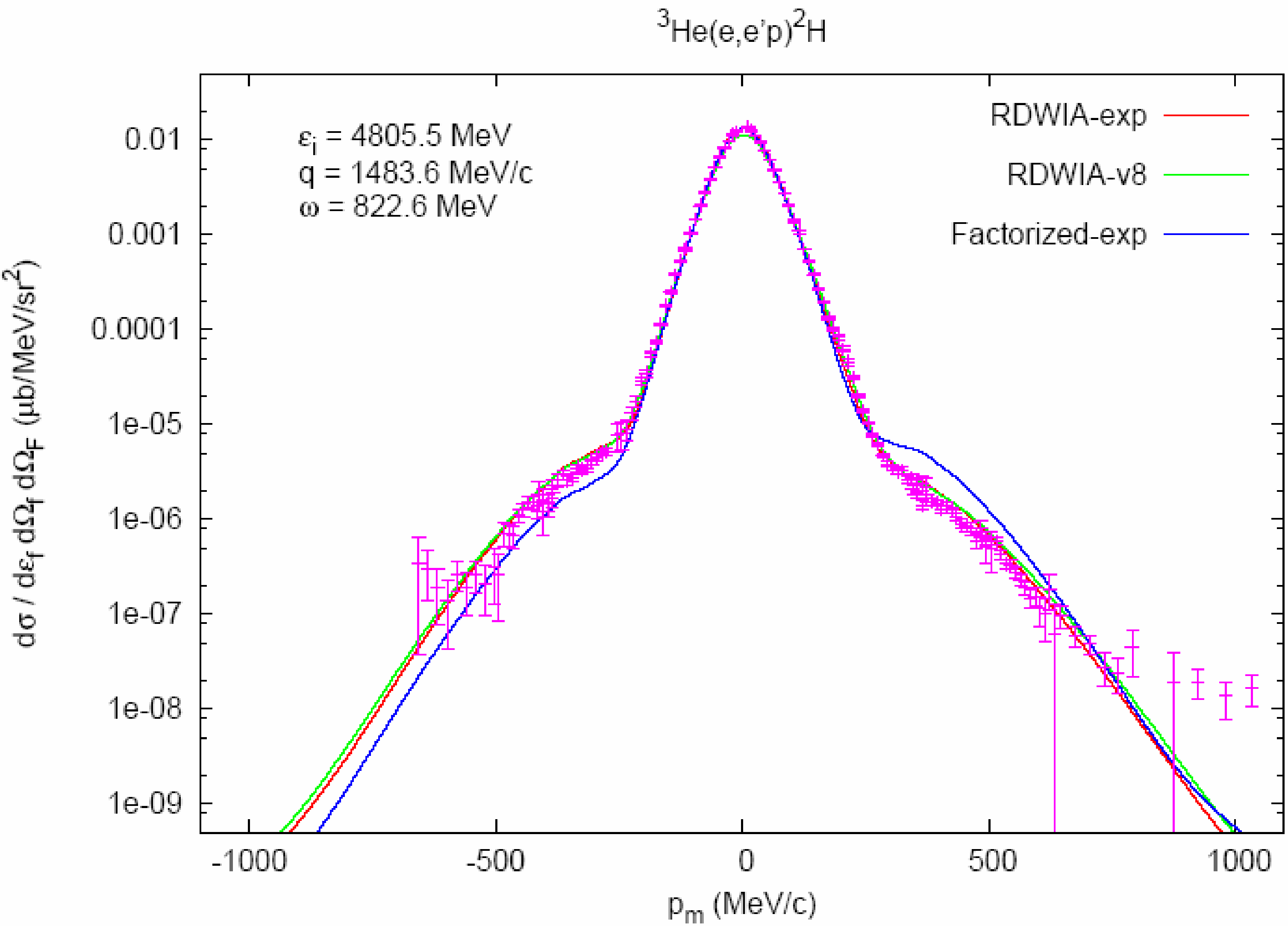
Small effect in cross-section at moderate p_m



But large effects on A_{TL}



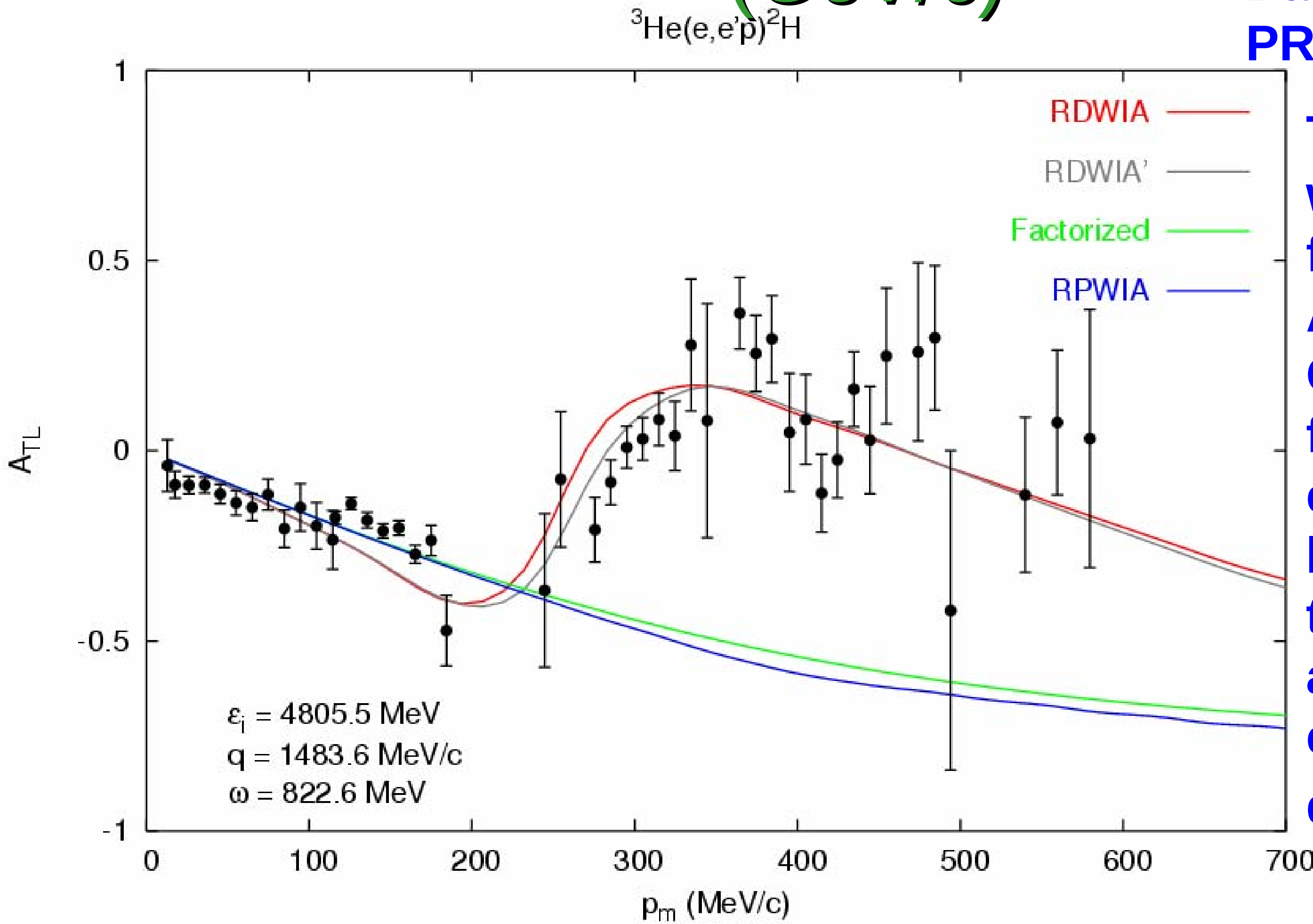
Breakdown of factorization will be seen at **demanding** kinematics (q-ω constant, high momentum)



Data: M.M. Ravchev, PRL 94 (2005) 192302

Breakdown of factorization will clearly be seen in A_{TL} at Q^2 larger than, say, 0.5 $(GeV/c)^2$

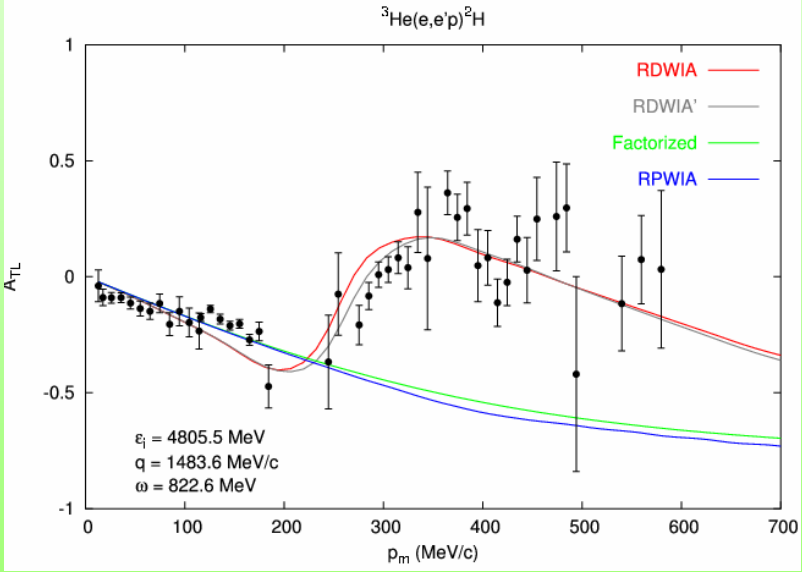
Data: M.M. Ravchev, PRL 94 (2005) 192302



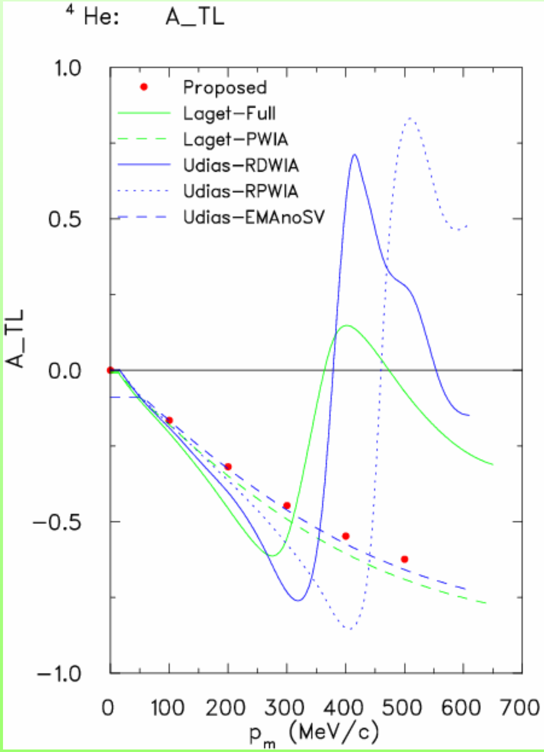
Theory: relativized wave function from Fadeev with AV8' interaction. Optical potential from RIA-IA1 with effective NN lagrangian fitted to $^4He(p,p)$ data and using experimental density

A_{TL} in ^{3}He, ^{4}He and ^{16}O

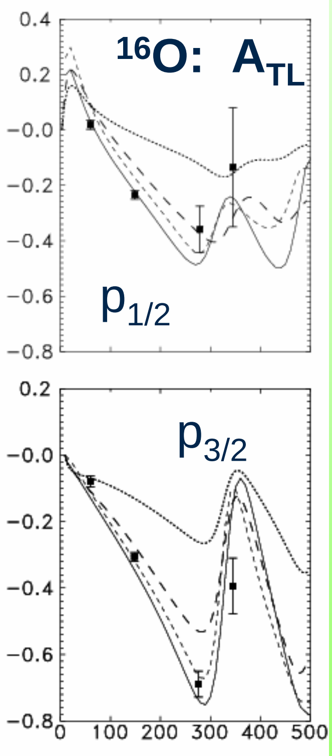
If there are relativistic dynamical effects, a strong impact on A_{TL} would be seen, particularly at moderate p_m.There is a noticeable difference in A_{TL} between ^{3}He and ^{4}He due to the density difference and in ^{16}O



M. Rvachev et al. PRL 94:12320,2005



E04-107,2004

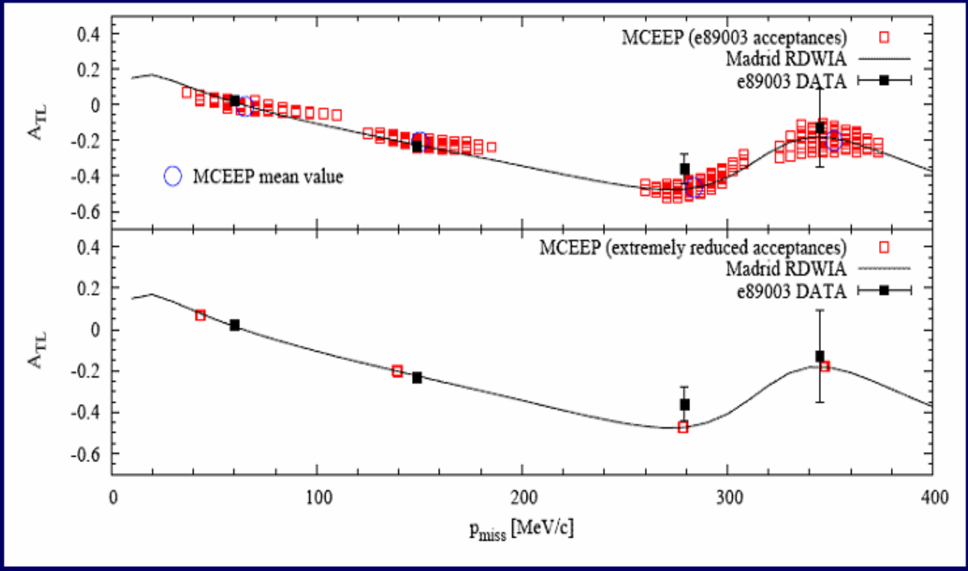


J. Gao et al. PRL84:3265, 2000

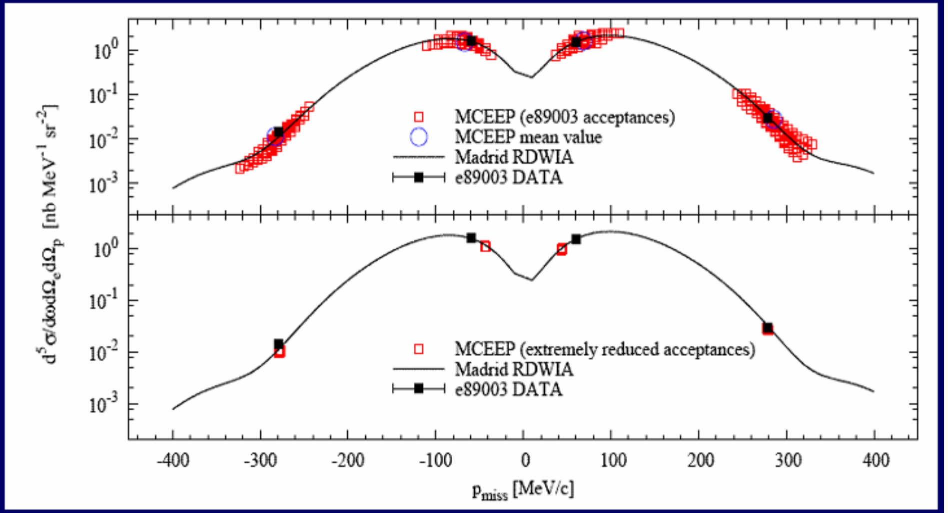
Almost here the newest results in $^{16}O(e,e'p)$

A_{TL}

$$A_{TL} = \frac{\sigma(\phi = 0^\circ) - \sigma(\phi = 180^\circ)}{\sigma(\phi = 0^\circ) + \sigma(\phi = 180^\circ)}.$$



CROSS SECTION



Cross section for spectrometer angles of θ_{pq} = ±2.5 and ±16.0 degrees.

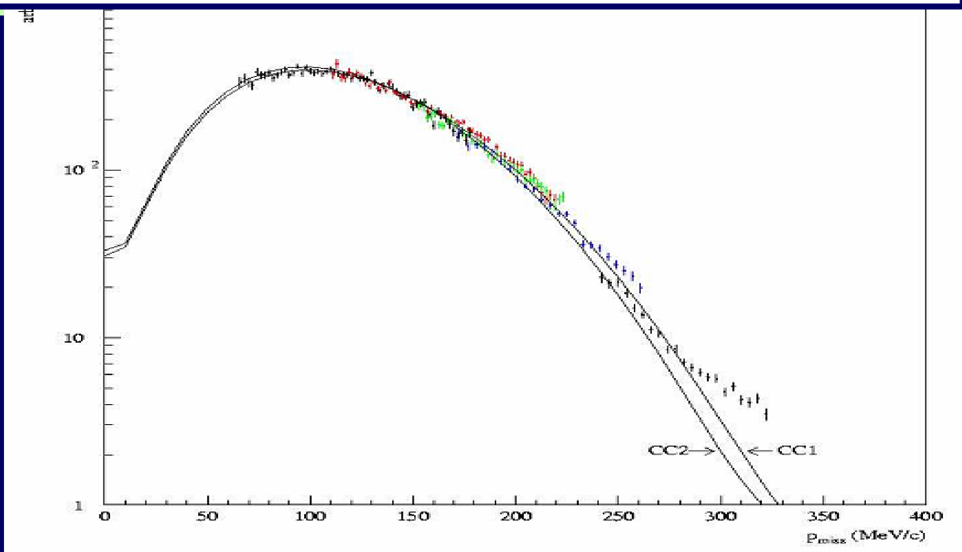
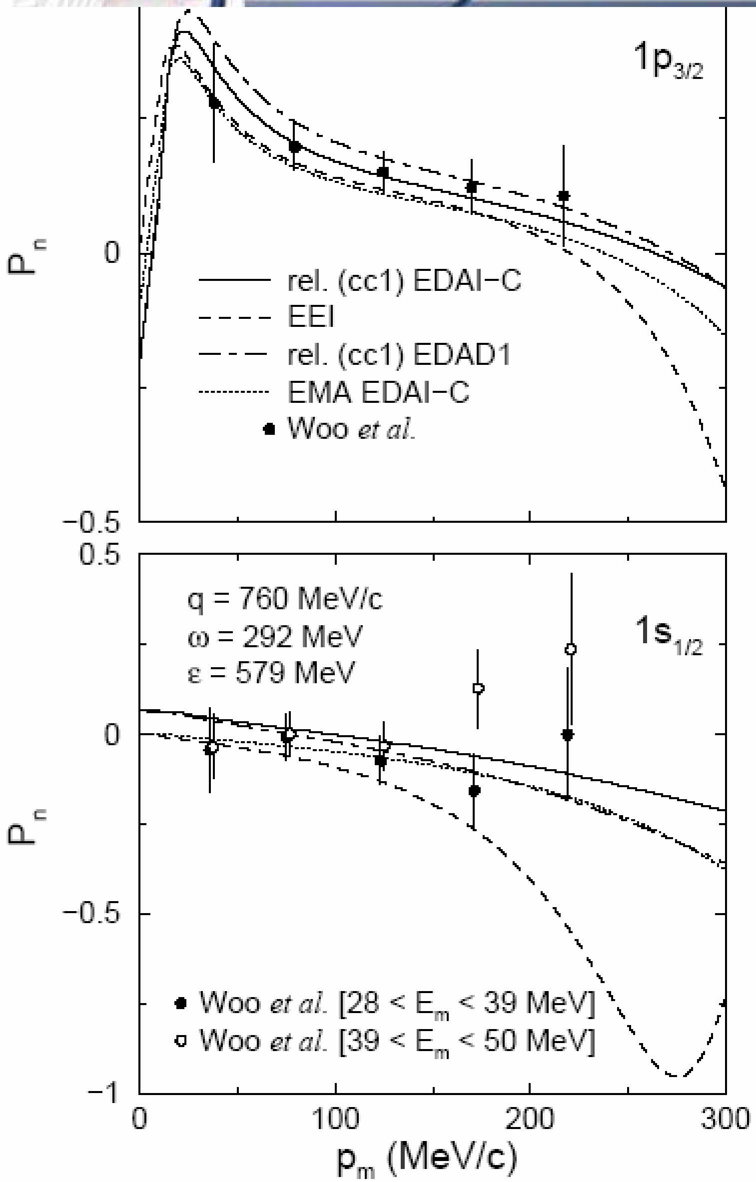


Figure 4.1: Relative cross-section data for $1p_{1/2}$-proton removal from ^{16}O using the $(e, e'p)$ reaction compared to the Relativistic Distorted-Wave Impulse Approximation (RDWIA) calculations of Udías *et al.* [31]. See text for details.

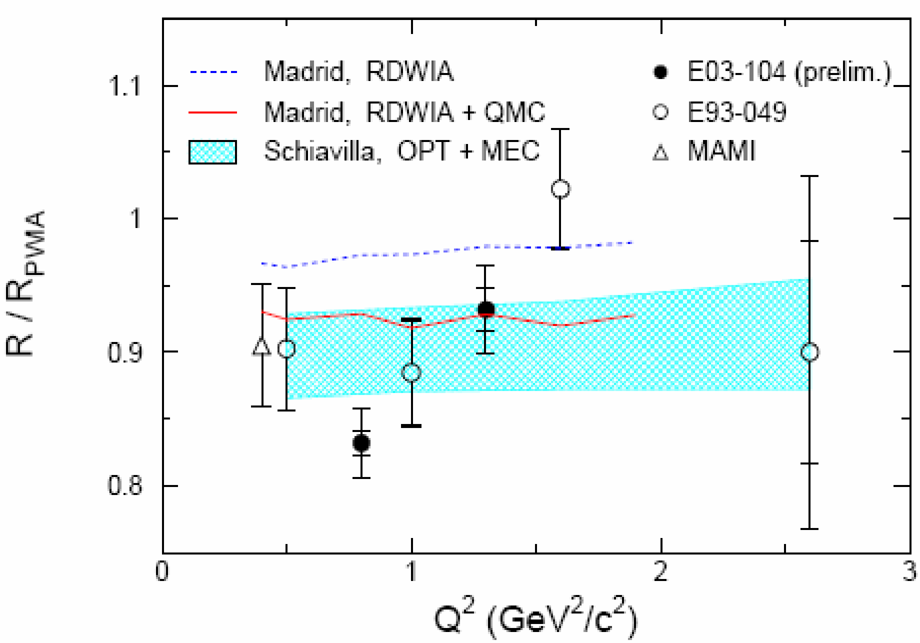
Induced polarizations: probe FSI and have little sensitivity to lower components

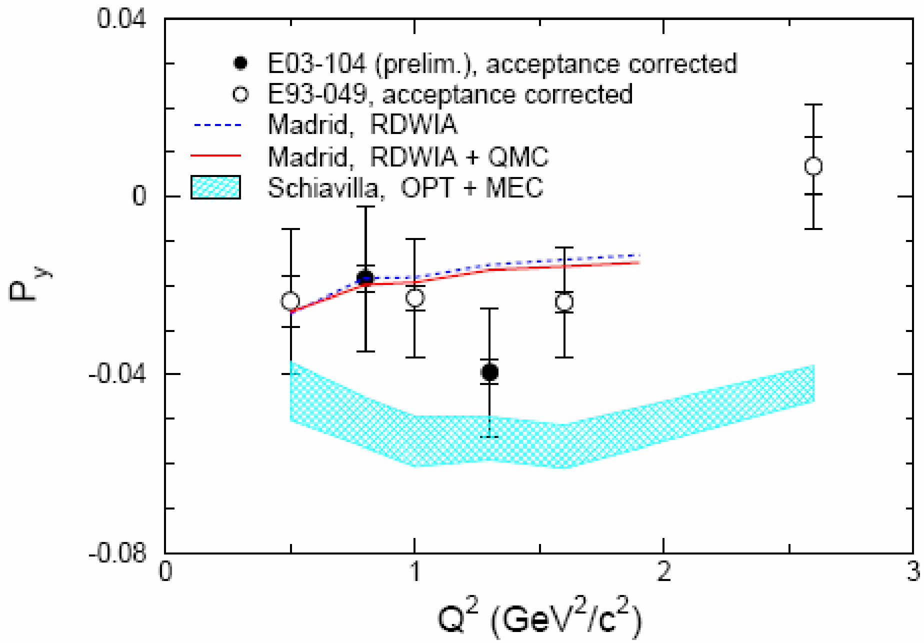


Left: P_y in ^{12}C at Q^2 of 0.5 $(GeV/c)^2$ measured at BATES, Woo et al, PRL 80 (1998) 456.

Polarization superratio in ^{4}He

S. Strauch et al. PRL 91 (2003) 052301 and E03-104 (preliminiminary)
Data have been unfolded for acceptance effects

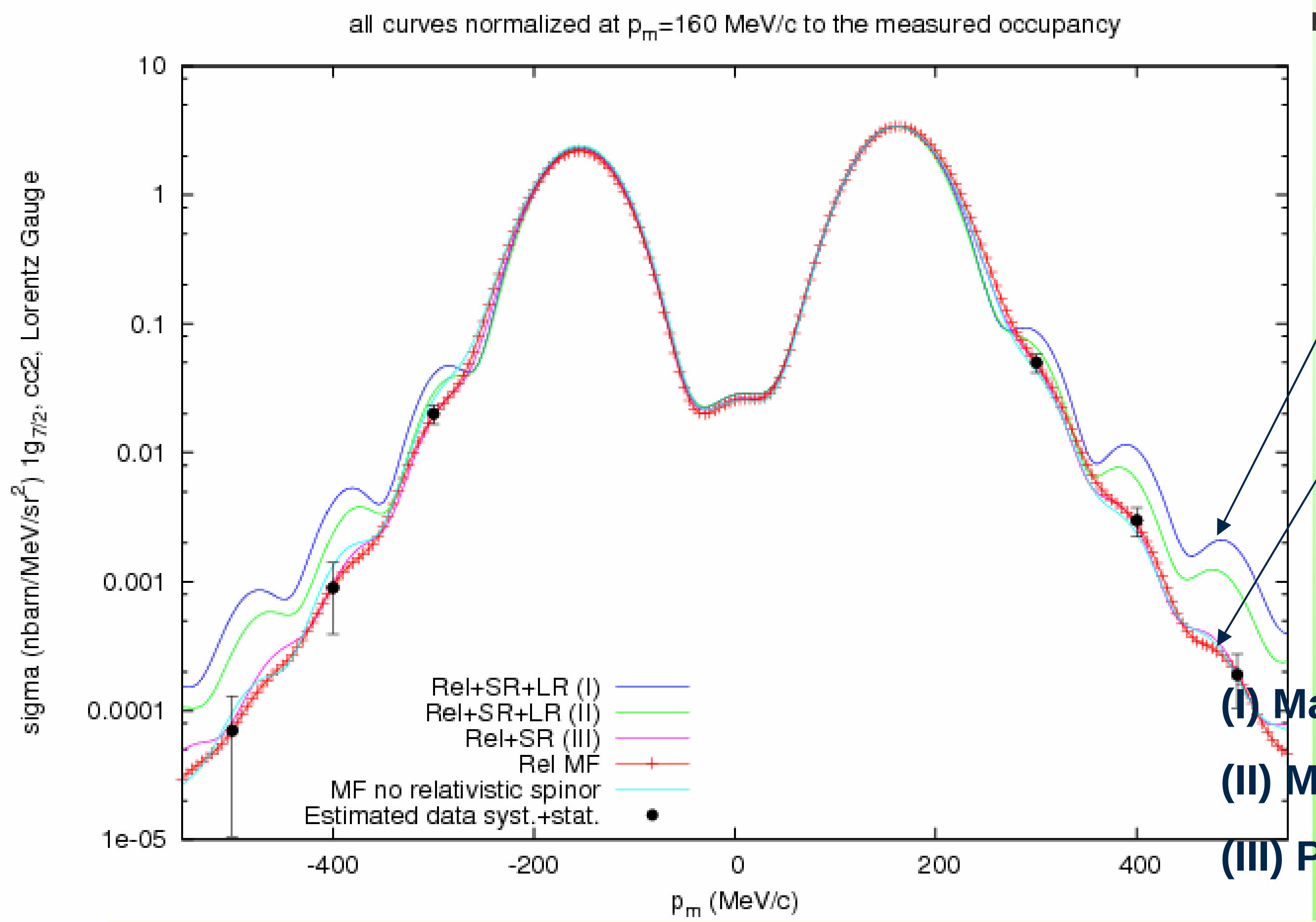




^{208}Pb(e,e'p)^{207}Tl(3.470 MeV)

Look at large p_{miss} for correlations.

$x_B = 1$



(I) Mahaux and Sartor (S_F=0,6)

(II) Ma and Wambach (S_F=0,7)

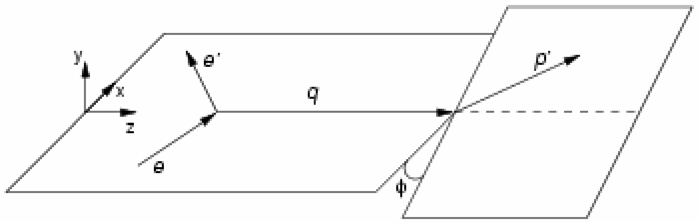
(III) Pandharipande et al (S_F=0,8)

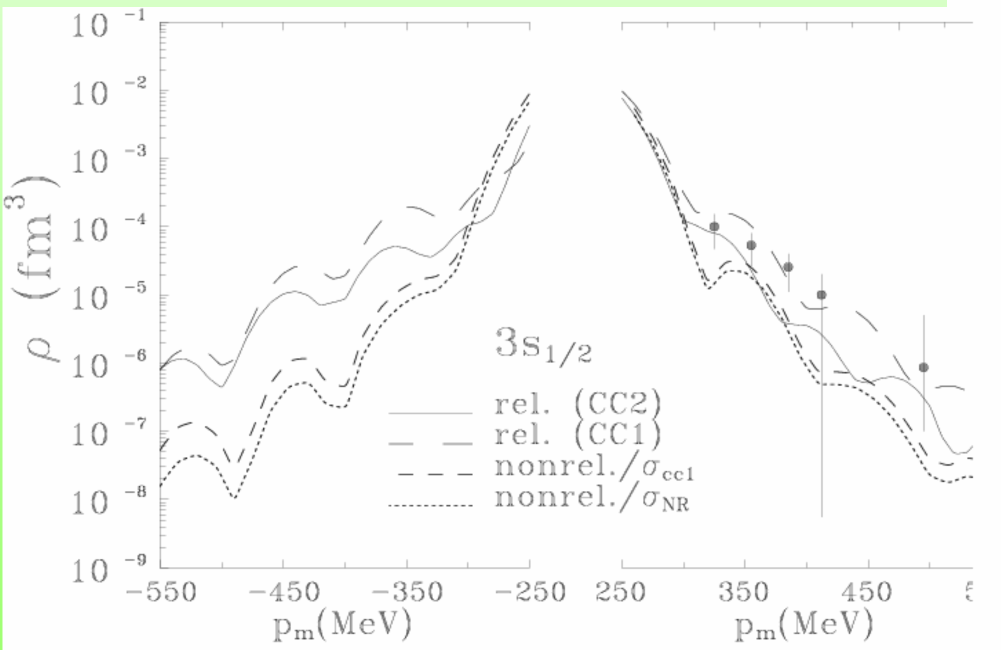
Long range correlations are needed to explain the 30% depletion. At $x_B = 1$ neither Nonrel. or Rel. theory produces large strength at high p_m if long range correlations are excluded. This is in contrast to the ambiguous signature at $x_B << 1$ of former experiment at NIKHEF-K

Cross Section Asymmetry A_{TL}

The cross section asymmetry is defined around q

$$A_{TL} = \frac{\sigma(\phi=0) - \sigma(\phi=180)}{\sigma(\phi=0) + \sigma(\phi=180)}.$$

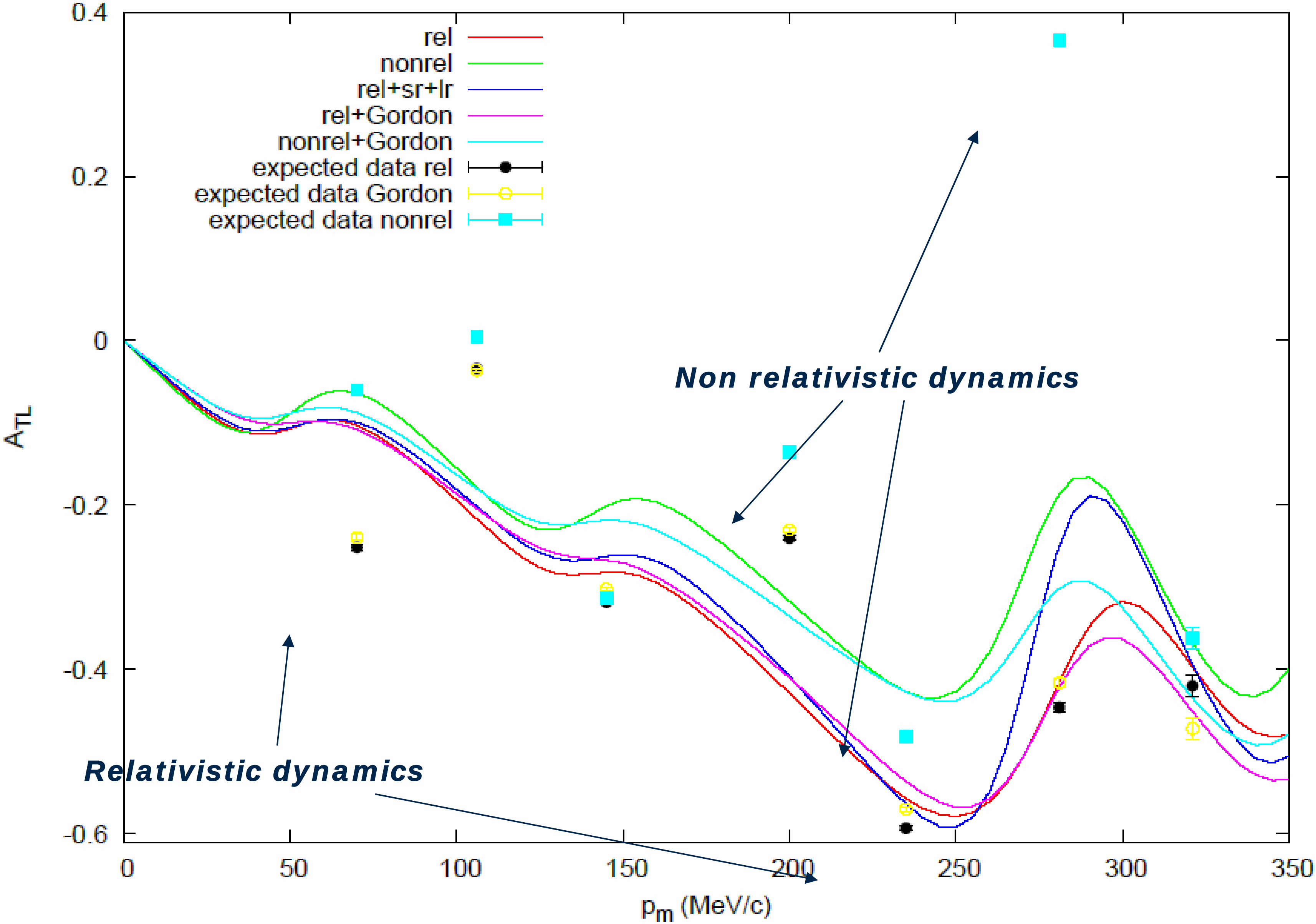




***Data from [6] I. Bobeldijk et al.*, PRL 73 (2684)1994**

The data taken at NIKHEF [6] were backward of ***q*** where both theoretical (relativistic and nonrelativistic) are relatively closer. But forward of ***q*** the theories can disagree by two orders of magnitude

Looking for unmistakable signatures of correlations at high p_{miss} from (e,e'p) cross sections alone is a hard task for x_B <<1



A_{TL} for all the shells added up, compared with the acceptance averaged simulations

Summary of recent measurements in lead

(1) The first measurements ever made in quasielastic kinematics on the paradigmatic shell model nucleus, ^{208}Pb at high Q^2 have been done. Accurate spectroscopic factors will be obtained at *Q^2 of 0.8, 1.4 and 2.0 $(GeV/c)^2$* (maybe also for ^{12}C)

(2) Strength for p_{miss} > 300 MeV/c will give insight into nuclear structure issues and will settle the long standing question about the amount of long range correlations

(3) A_{TL} for the five low lying states of ^{207}Tl will be measured. A_{TL} can help distinguishing between relativistic and nonrelativistic structure of the wave functions

Summary: what have we learnt from exclusive measurements??

- **Relativistic impulse approximation (RIA) + RMF is simple and capable of explaining many different experimental results, including polarization measurements**
- **Improved experimental information with:**
  - **improved statistics**
  - **larger A coverage (^{208}Pb, ^{16}O (e00102), ^{4}He, ^{12}C)**
  - **x=1**
  - **different Q^2 values**

is arriving in the next few months, what would allow to disentangle relativistic effects and/or long range correlations

Relativistic Impulse Approximation (RIA) to N-A scattering

•It assumes that the interaction between the projectile and target nucleons has the same form as the interaction between two nucleons in free space. The RIA allows us to combine the empirical free-space scattering amplitude with a relativistic (or not) calculation of the nuclear ground state density

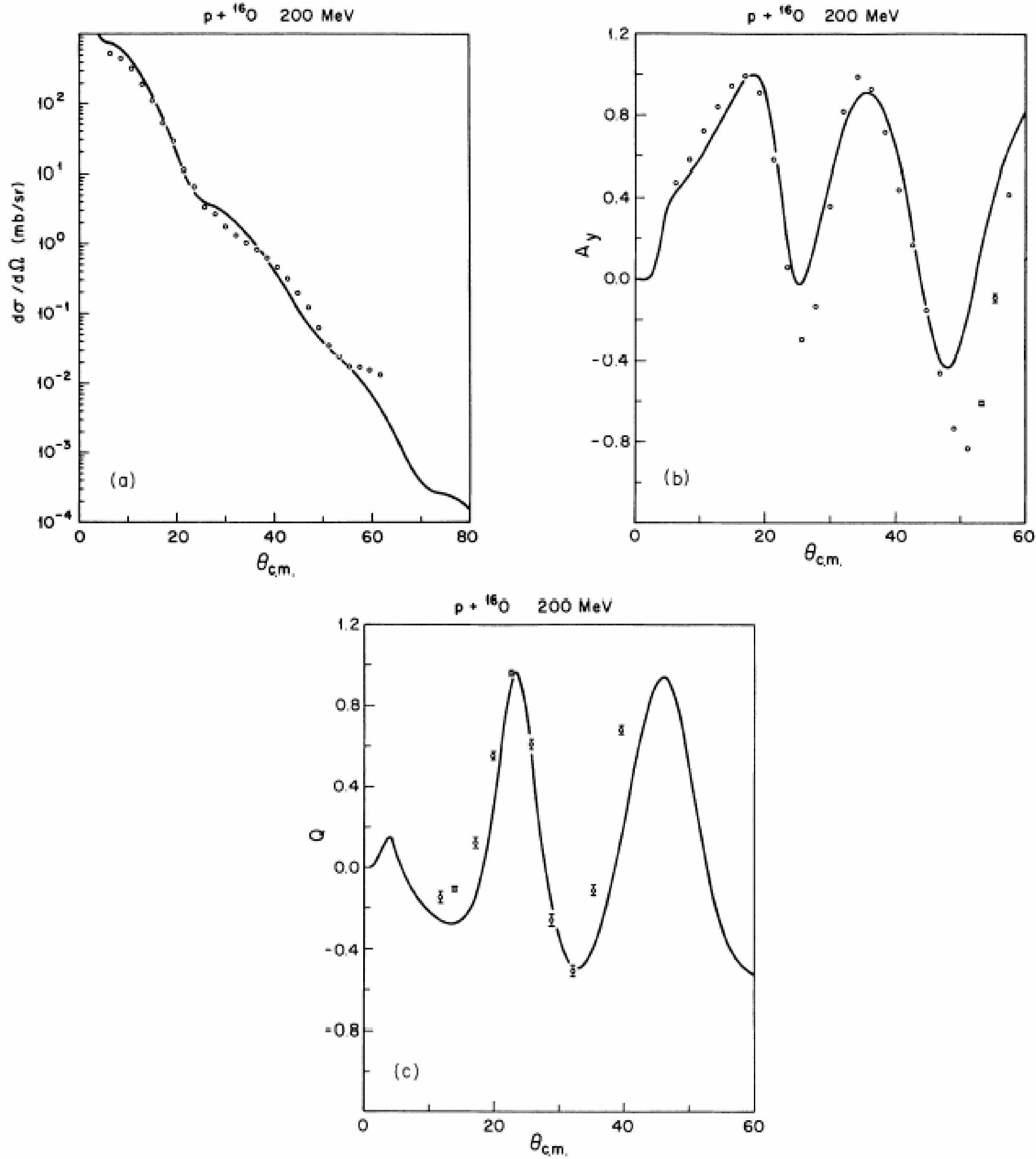
•The experimental NN scattering amplitude is represented by a set of Lorentz covariant functions that multiply the "Fermi invariant" Dirac matrices. An effective NN interaction is thus built. A few independent invariants are enough for the on-shell version of RIA (IA1)

•The Lorentz covariant functions are then folded with the (for instance) Dirac–Hartree target densities to produce a first-order optical potential for use in the Dirac equation for the projectile

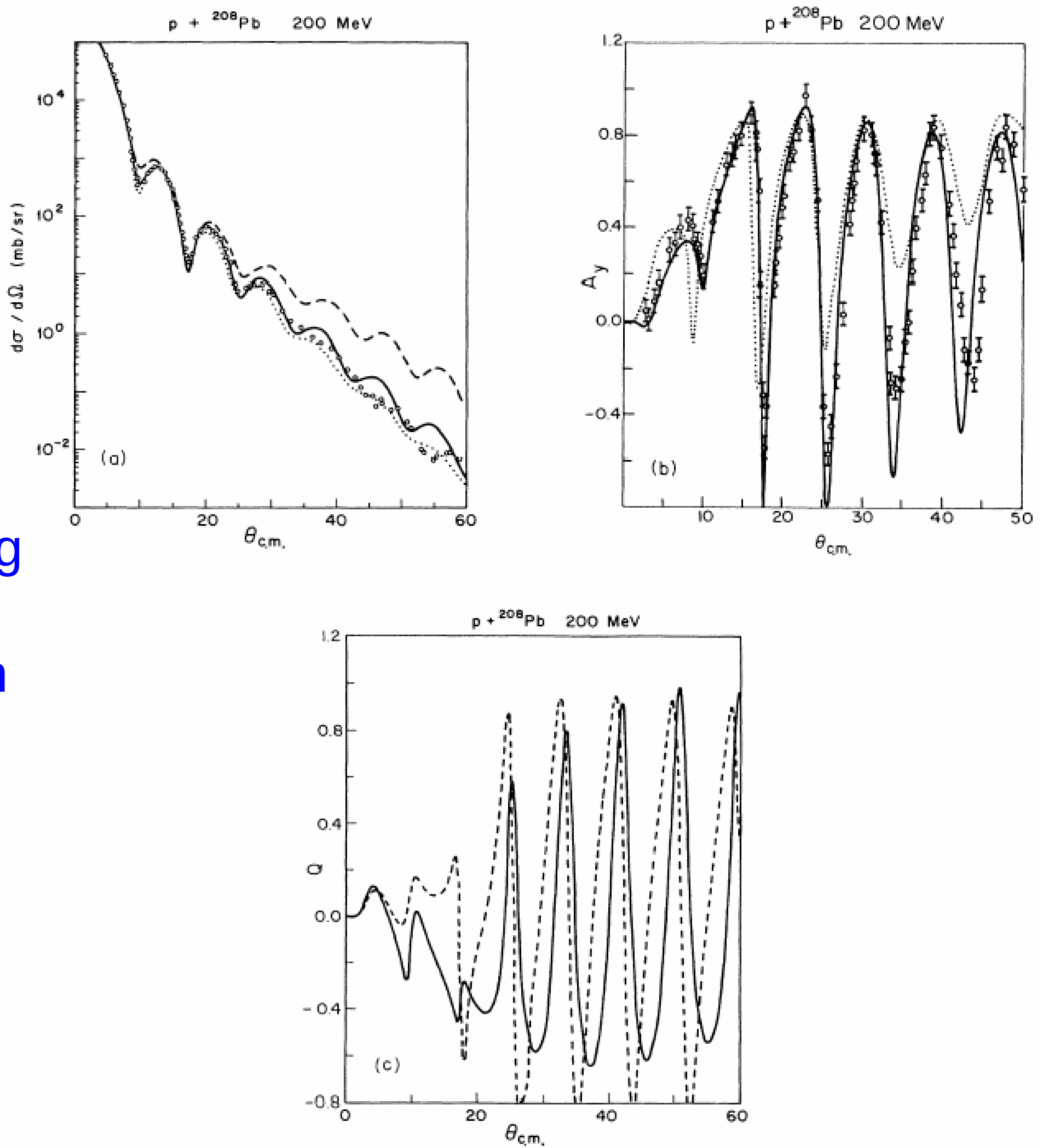
•Some medium modification of the NN amplitudes (Pauli blocking) can be incorporated

•Results are good, for nucleon kinetic energies above, say, 200 MeV, if the ground state density is reasonably realistic. Isospin dependence of the potential is also predicted

•Conversely, proton scattering data can be employed to fit or at least constrain the ground state density



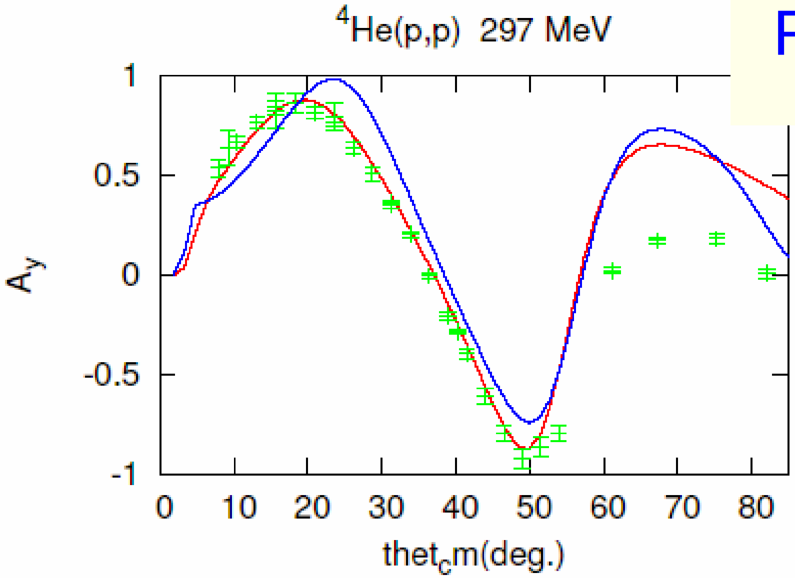
Results from the standard RIA+Pauli blocking (dotted), without Pauli blocking (dashed) from RMF densities and with an empirical density (solid)

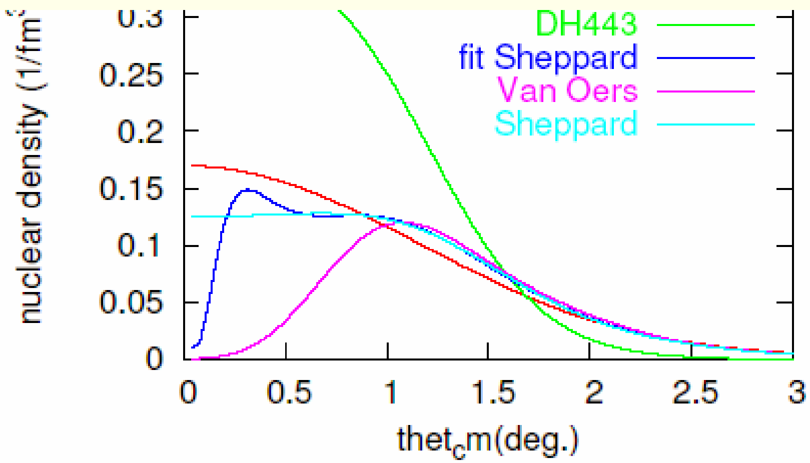


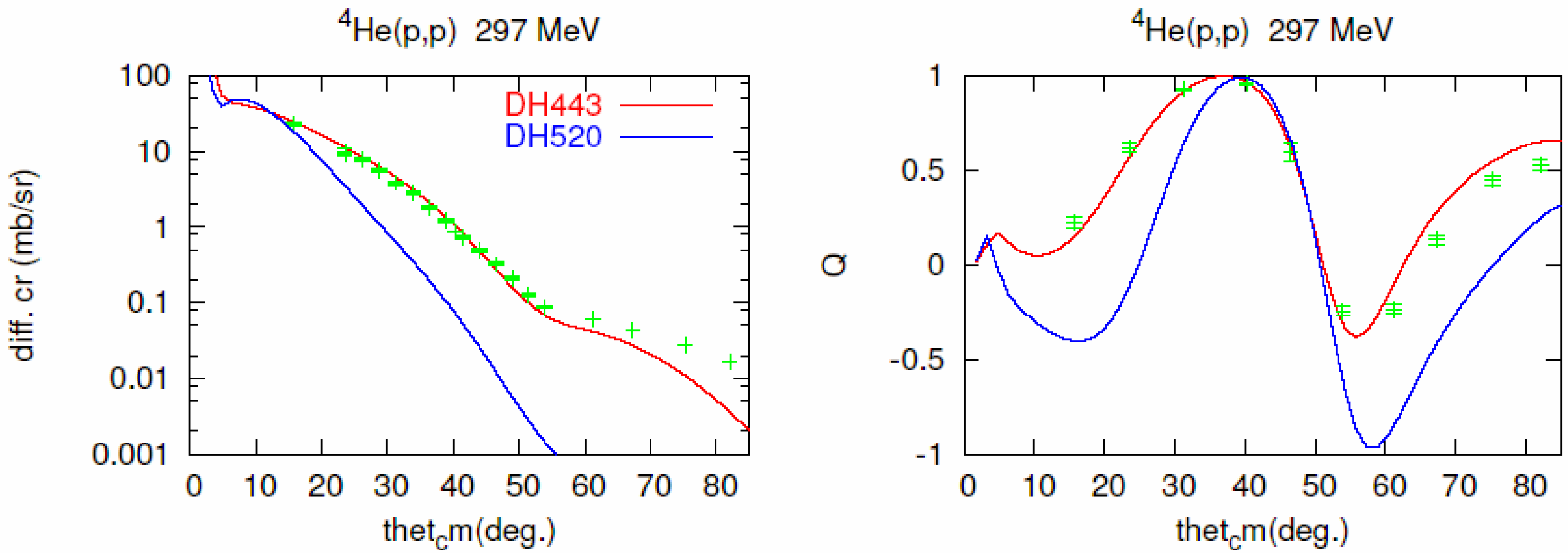
RIA do a decent job for light nuclei (^{4}He)

Blue: RIA+standard RMF ^{4}He density

Red: RIA+just one parameter of the RMF Lagrangian adjusted to the data







Compu

References

(just to mention a few):

PHYSICAL REVIEW C 72, 014608 (2005)

Comparison of optical model results from a microscopic Schrödinger approach to nucleon-nucleus elastic scattering with those from a global Dirac phenomenology

P. K. Deb,[1,*] B. C. Clark,[1,†] S. Hama,[2,‡] K. Amos,[3,§] S. Karataglidis,[3,||] and E. D. Cooper[4,¶]

PHYSICAL REVIEW C VOLUME 47, NUMBER 1 JANUARY 1993

Global Dirac phenomenology for proton-nucleus elastic scattering

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Department of Physics, The Ohio State University, Columbus, Ohio 43210

PHYSICAL REVIEW C VOLUME 37, NUMBER 3 MARCH 1988

Dirac optical potentials constrained by a Dirac-Hartree approach to nuclear structure

PHYSICAL REVIEW C VOLUME 33, NUMBER 6 JUNE 1986

Relativistic effects on spin observables in quasielastic proton scattering

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PHYSICAL REVIEW C VOLUME 31, NUMBER 4 APRIL 1985

Relativistic Love-Franey model: Covariant representation of the NN interaction for N-nucleus scattering

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Relativistic description of (p,n) reactions to the isobaric analog state

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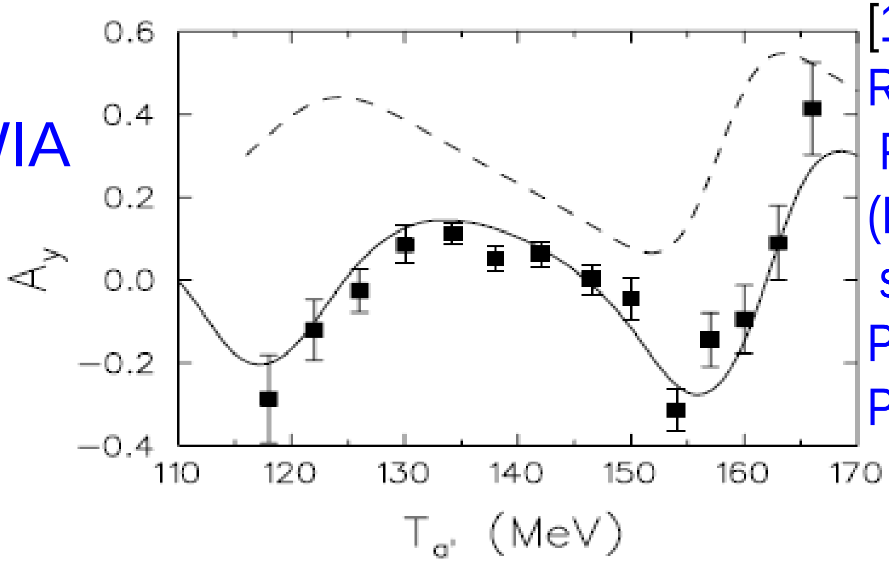
RIA approximation to A(**p**,2p)A-1 reactions

- Use initial ground state given by RMF or some other suitable model
- Use final state described by RIA optical potential or by any of the phenomenological relativistic S-V optical potentials
- Employ the RIA effective NN interaction plus one further use of the Impulse Approximation to describe the interaction of the hadron projectile with the knocked out proton
- No adjustable parameters in the model

Out of the box excellent predictions for $^{208}Pb(p,2p)^{207}Tl$

Solid: RDWIA

Dashed: NRDWIA



[1] Neveling et. al., Phys. Rev. C 66, 034602 (2002).
PhD thesis of T Ishida (Kyushu University).
see G.C. Hillhouse et al. PRC 67,064604(2003), PRC 68 034608 (2003)

FIG. 1: Energy-sharing analyzing power A_y for the knockout of protons from the $3s_{1/2}$ state in ^{208}Pb, at an incident energy of 202 MeV, for coincident coplanar scattering angles ($\theta_{a'} = 28.0°$, $\theta_b = -54.6°$), plotted as a function of the kinetic energy of the proton scattered at angle $\theta_{a'}$. The dashed and solid curves represent the nonrelativistic and relativistic distorted wave predictions respectively. The data are from Ref. [1].

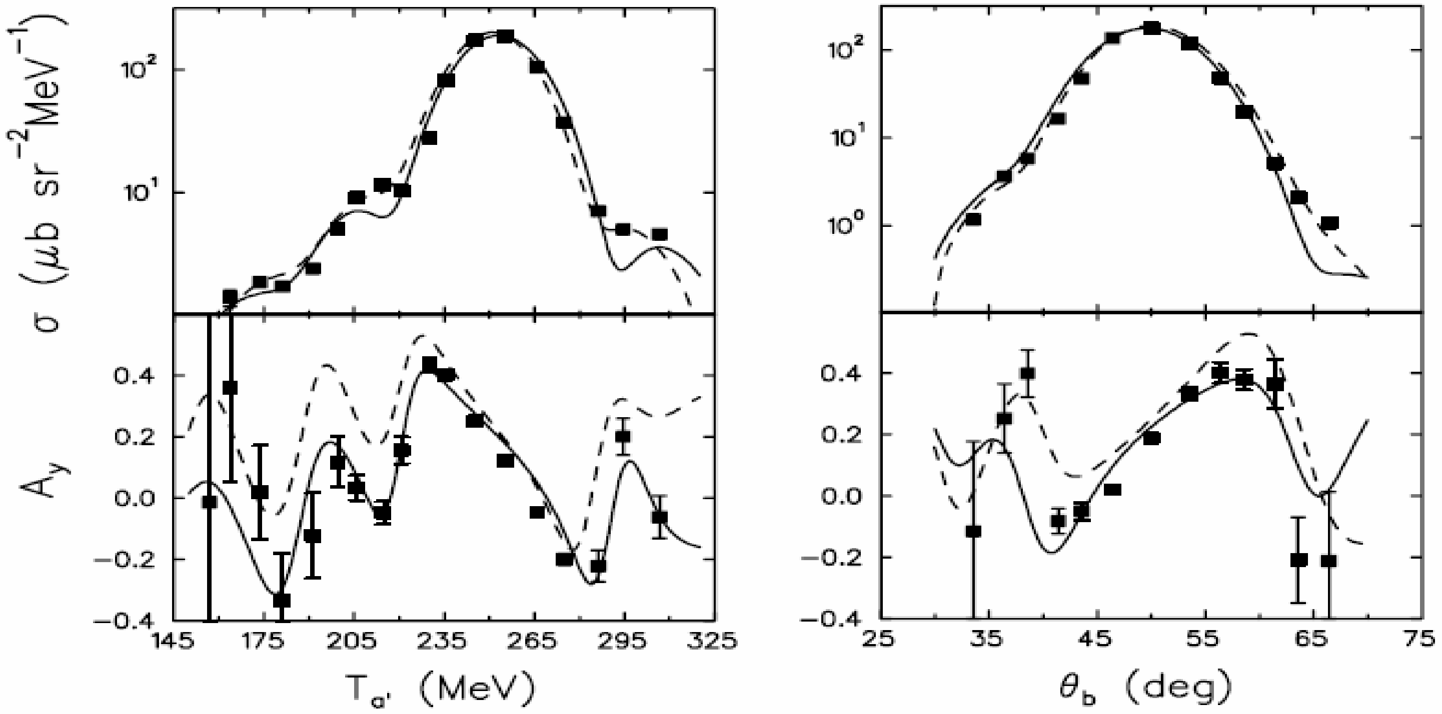


FIG. 4: Unpolarized triple differential cross section σ and analyzing power A_y for proton knockout from the $3s_{1/2}$ state in ^{208}Pb at an incident energy of 392 MeV plotted as a function of the kinetic energy $T_{a'}$ for coincident coplanar laboratory scattering angles (32.5°, −50.0°) (left panel), and as a function of the scattering angle θ_b, for $T_{a'}$ = 250 MeV and $\theta_{a'}$ = 32.5° (right panel). The dashed and solid curves represent the nonrelativistic and relativistic distorted wave predictions respectively. The data are from Ref. [3].

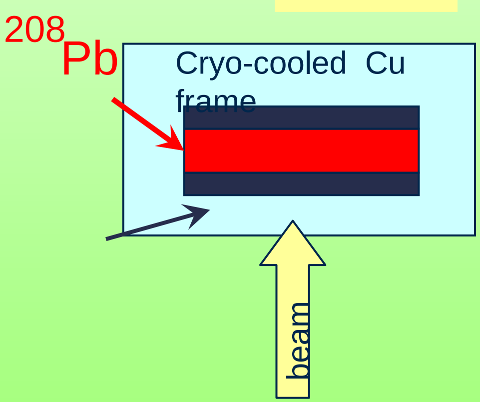
Out of the box excellent predictions for $^{208}Pb(p,2p)^{207}Tl$

- The relativistic distorted wave model provides a quantitative description of the (p,2p) analyzing power for $3s_{1/2}$ knockout from ^{208}Pb at both incident energies of 202 and 392 MeV
- The nonrelativistic model consistently over-predicts the analyzing power
- The above result *suggests* that the relativistic Dirac equation is adequate to effectively describe the (p,2p) analyzing power

PREX: 208Pb Radius Experiment

Neutron distribution will be measured by direct, clean, electroweak means

Tested lead / diamond target to $\sim 100 \mu A$



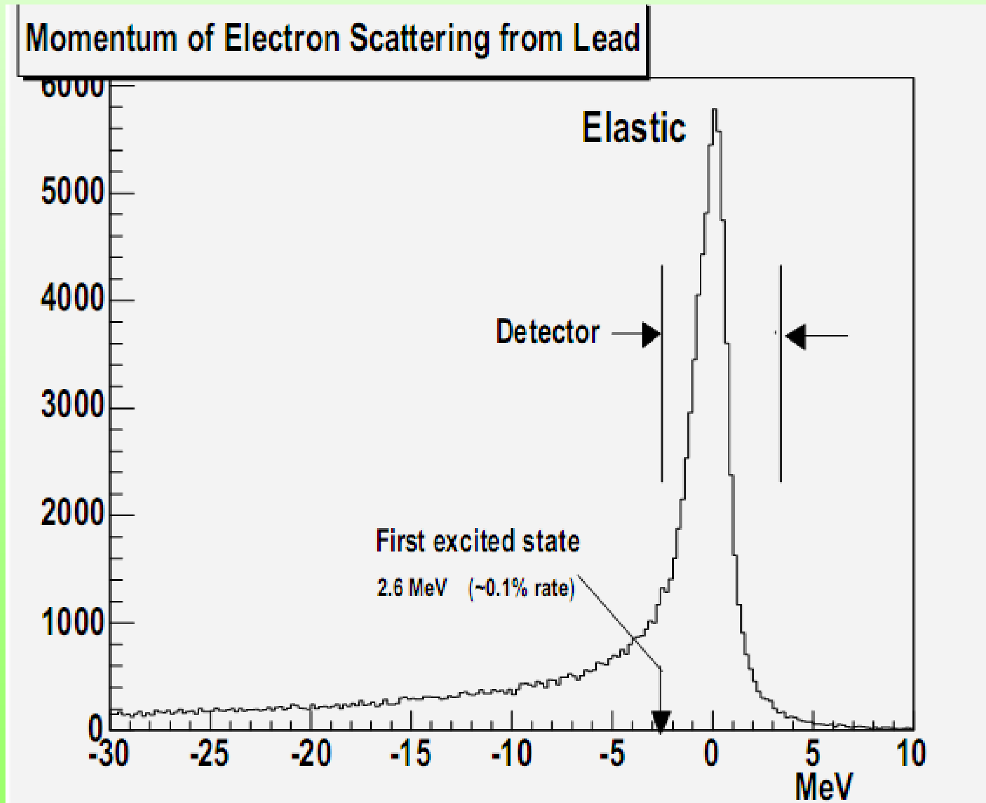


FIGURE 3. Data from our 2005 test run with lead target. The momentum spectrum of the elastic peak, showing the extent of the detector to discriminate possible inelastic levels. The 1st state is at 2.6 MeV and is ~0.1% of our rate.

Isospin mixing in ^{12}C will also be measured via PV asymmetry