RELATIVISTIC EIKONAL MODELS FOR eA and νA REACTIONS

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Outline

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- Physics motivation!

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- Relativistic Multiple-Scattering Glauber Approximation (RMSGA) for computing exclusive $A(l, l'N)$ observables.
  (Bound and scattering states; lepton-nucleon coupling)

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*eA: PRC **62** (2000) 024611 ; PLB **527** (2002) 62 ;*
*NPA **699** (2002) 65 ; NPA **720** (2003) 226 ;*
*PLB **595** (2004) 177 ; PRC **71** (2005) 014605 ;*

*ν A: PRL **93** (2004) 0855011 ; PRC **71** (2005) 034604 ; nucl-th/0505008*

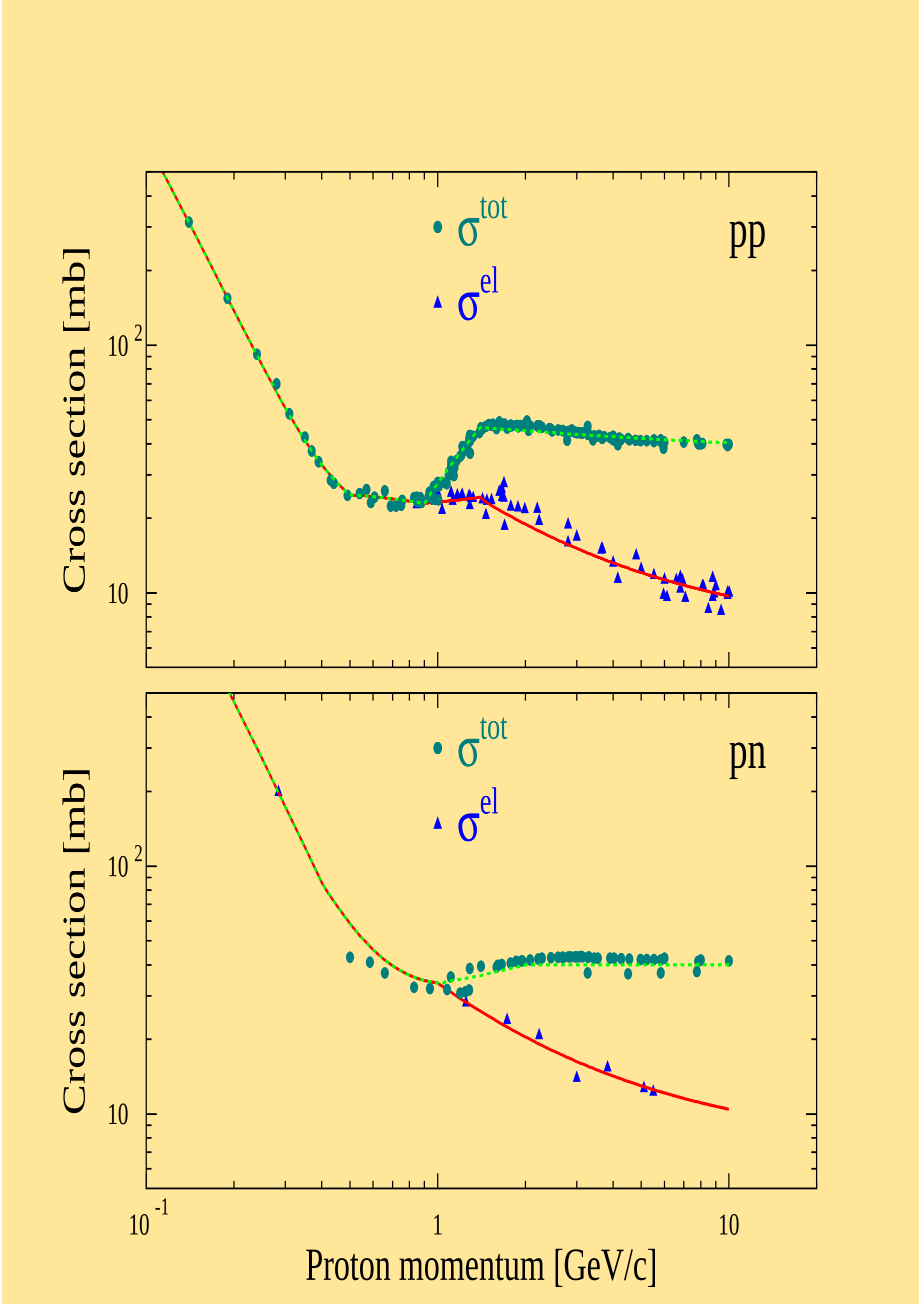
Electroweak interactions with nuclei in the new millenium

- Towards a QCD-inspired description of nuclei
  (Dynamics of strongly overlapping baryons)
- To what extent are nucleons modified in the medium?
  (Stringent tests of constituent-quark models, Electron-nucleon coupling in the medium "σ_{ep}".)
- Nuclear transparency
  (Any signatures for the onset of QCD dynamics?)
- Hadron production and formation in DIS lepton-nucleus scattering.
  (Hadronization, finite-formation times.)
- Constrain nuclear effects in νA
  (neutrino oscillations, axial form factors)

PROVIDED ... a GLOBAL FRAMEWORK for reliably modeling the effect of Final-State Interactions is available.

Frameworks to treat FSI's in $A(l, l'N)$

- At "Low" energies
  ($p_p \leq 1$ GeV) :
  OPTICAL POTENTIALS
  (from global fits
  to $p + A \longrightarrow p + A$ data)
- At "High" energies
  ($p_p \geq 1$ GeV) :
  EIKONAL APPROACHES
  (from $p + N \longrightarrow p + N$ data)



Modeling FSI mechanisms in A$(l, l'N)$

- Optical-potential (or, distorted-wave) models exist in many different flavours !
(relativistic and non-relativistic)
- Frequently, in combination with the *impulse approximation* (single-nucleon photoabsorption) **(RDWIA and DWIA)**
- Modern (R)DWIA $A(l, l'N)$ models are unfactorized!
- Eikonal $A(l, l'N)$ models exist in many different flavors!
- Back in 2002: Most of the eikonal $A(e, e'N)$ models were *factorized* and adopted *non-relativistic wave functions and electron-proton couplings*.

Model for $\mathbf{A + e \longrightarrow (A-1) + e' + p}$ @ high $(\mathbf{q}, \omega)$

- **RELATIVISTIC**
  (Electron-nucleon coupling AND nuclear dynamics) !
- Accommodate both the **"optical potential"** and **"Glauber approach"**
  (Bridge the "low" and "high" energy regime !)
- Applicable to the "highest" Q^2 values and any target nucleus ($A \geq 4$).
- **UNFACTORIZED**
  (No formal separation between the *off-shell photon-nucleon coupling* and the *nuclear dynamics*).

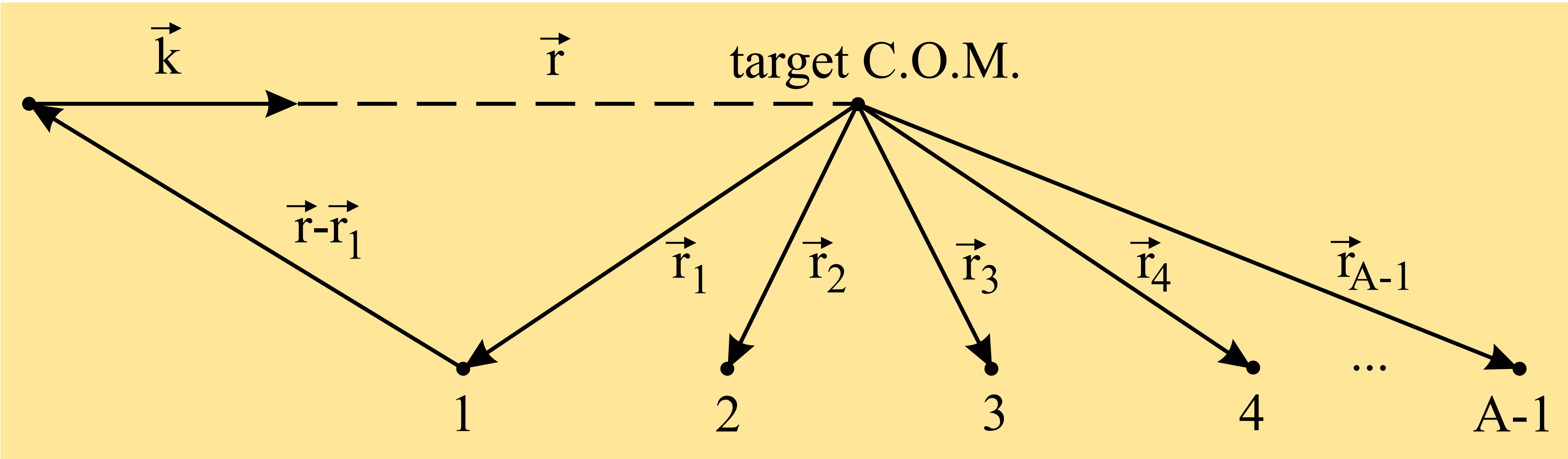
NOT BASED ON

$$\frac{d^4\sigma}{dT_p d\Omega_p d\epsilon' d\Omega_{\epsilon'}}(e, e'p) = \frac{p_p E_p}{(2\pi)^3} \sigma_{ep} P_D(\vec{p}_m, E_m) \ ,$$

Relativistic Multiple-Scattering Glauber Approximation (RMSGA)

(Diffractive pN scattering : s $\gg$ and -t $\ll$)

The spectator nucleons are considered as "frozen" and only elastic or "mildly inelastic" collisions are allowed !
($A - 1$ at low excitation energies !)



$$\psi_{\vec{k},s}^{(+)} \sim \mathcal{A}\left[\widehat{\mathcal{S}}\left(\vec{r},\vec{r}_2,\ldots\vec{r}_A\right)\left[\begin{array}{c}1\\ \frac{\vec{\sigma}\cdot\vec{k}}{E+M}\end{array}\right]e^{\imath\vec{k}\cdot\vec{r}}\chi_{\frac{1}{2}m_s}\Psi_{A-1}^{J_R\,M_R}\left(\vec{r}_2,\vec{r}_3,\ldots\vec{r}_A\right)\right]$$

$$\widehat{\mathcal{S}}\left(\vec{r},\vec{r}_2,\vec{r}_3,\ldots\vec{r}_A\right) \equiv \prod_{j=2}^{A}\left[1-\Gamma\left(\vec{b}-\vec{b_j}\right)\theta\left(z-z_j\right)\right]$$

A-body operator which accounts for final-state interactions ; product extends over all spectator nucleons ("scattering centers").

Often the following approximation is adopted

$$\widehat{\mathcal{S}}\left(\vec{r},\vec{r}_2,\vec{r}_3,\ldots\vec{r}_A\right) \approx 1-\sum_{j=2}^{A}\theta(z_j-z_1)\Gamma(\vec{b}_1-\vec{b}_j) + \sum_{j\neq k}\theta(z_j-z_1)\Gamma(\vec{b}_1-\vec{b}_j)\theta(z_k-z_1)\Gamma(\vec{b}_1-\vec{b}_k)-\ldots\ ,$$

Free passage
Single scatterings
Double scatterings

Profile Function for elastic pN scattering :

$$\Gamma(k_f, \vec{b}) = \frac{\sigma^{tot}_{pN}(1 - i\epsilon_{pN})}{4\pi(\beta_{pN})^2} \exp\left(-\frac{b^2}{2{\beta_{pN}}^2}\right) \ .$$

Input : σ^{tot}_{pN} cross sections, slope parameters (β_{pN}) and ratio of the real to imaginary scattering amplitude (ϵ_{pN})

From the data : (diffractive scattering)

$$\frac{d\sigma^{el}_{pN}}{dt} \approx \left.\frac{d\sigma^{el}_{pN}}{dt}\right|_{t=0} \exp - \left(\beta^2_{pN} \mid t \mid\right)$$

Cross-check :

$$\beta^2_{pN} = \frac{\left(\sigma^{tot}_{pN}\right)^2 \left(\epsilon^2_{pn} + 1\right)}{16\pi\sigma^{el}_{pN}}$$

The Dirac Glauber Phase

Basic quantity to be computed in a relativistic and unfactorized $A(e,e'p)$ model in the mean-field approximation

$$\langle J^\mu \rangle = \int d\vec{r} \phi^{\dagger}_{k_p m_s}(\vec{r})\, \mathcal{G}^{\dagger}(\vec{b},z) \gamma^0 J^\mu(\vec{r}) e^{\imath \vec{q}\cdot\vec{r}} \phi_{\alpha_1}(\vec{r}) \ ,$$

1. DIRAC-GLAUBER PHASE $\mathcal{G}(\vec{b},z)$
2. $\phi_{\alpha_1}(\vec{r})$: Dirac bswf from $\sigma - \omega$ model (Serot-Walecka).
3. $\phi^{\dagger}_{k_p m_s}(\vec{r})$: relativistic plane wave
4. $J^\mu(\vec{r})$: relativistic current operator

$$J^\mu_{cc2} = F_1(Q^2)\gamma^\mu + \imath \frac{\kappa}{2M} F_2(Q^2) \sigma^{\mu\nu} q_\nu \ ,$$

$$\mathcal{G}(\vec{b},z) = \prod_{\alpha_{occ}\neq\alpha} \left[1 - \int d\vec{r}' \left|\phi_{\alpha_{occ}}\left(\vec{r}'\right)\right|^2 \left[\theta\left(z'-z\right)\Gamma\left(\vec{b}'-\vec{b}\right)\right]\right] .$$

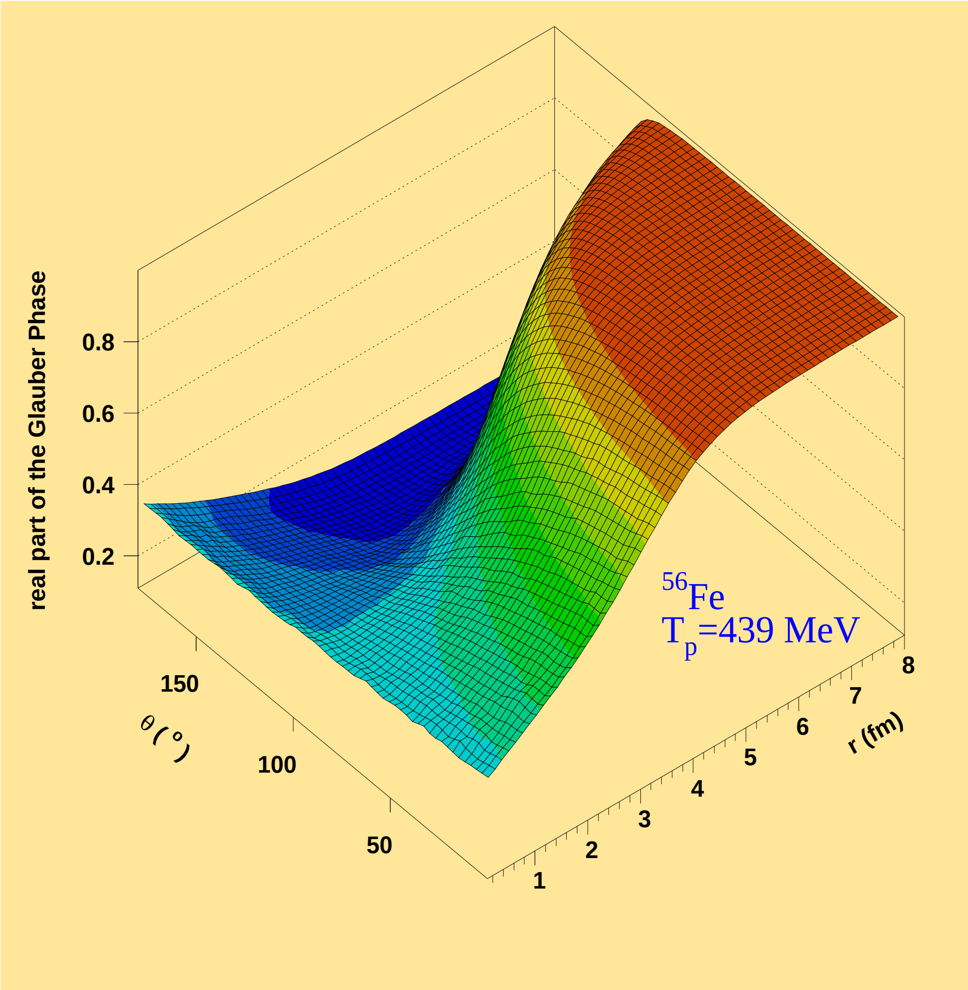
$$\mathcal{G}(\vec{b},z) = 1 - \prod_{\alpha_{occ}\neq\alpha} \Bigg\{ \frac{\sigma_{pN}^{tot}(1-i\epsilon_{pN})}{4\pi\beta_{pN}^2} \int_0^\infty b'db' \int_{-\infty}^{+\infty} dz'\theta(z'-z)$$
$$\left(\left[\frac{G_{n\kappa}\left(r'(b',z')\right)}{r'(b',z')} \mathcal{Y}_{\kappa m}(\Omega',\sigma) \right]^2 + \left[\frac{F_{n\kappa}\left(r'(b',z')\right)}{r'(b',z')} \mathcal{Y}_{\kappa m}(\Omega',\sigma) \right]^2 \right)$$
$$\times \exp\left[-\frac{(b-b')^2}{2\beta_{pN}^2} \right] \int_0^{2\pi} d\phi_{b'} \exp\left[\frac{-bb'}{\beta_{pN}^2} 2\sin^2\left(\frac{\phi_b-\phi_{b'}}{2} \right) \right] \Bigg\} .$$

z' : along the asymptotic direction of the ejectile

Each target nucleon (scattering center) represented by its own relativistic wave function (upper and lower component)!

Glauber phase: an example

Real part (=1 in PWA)

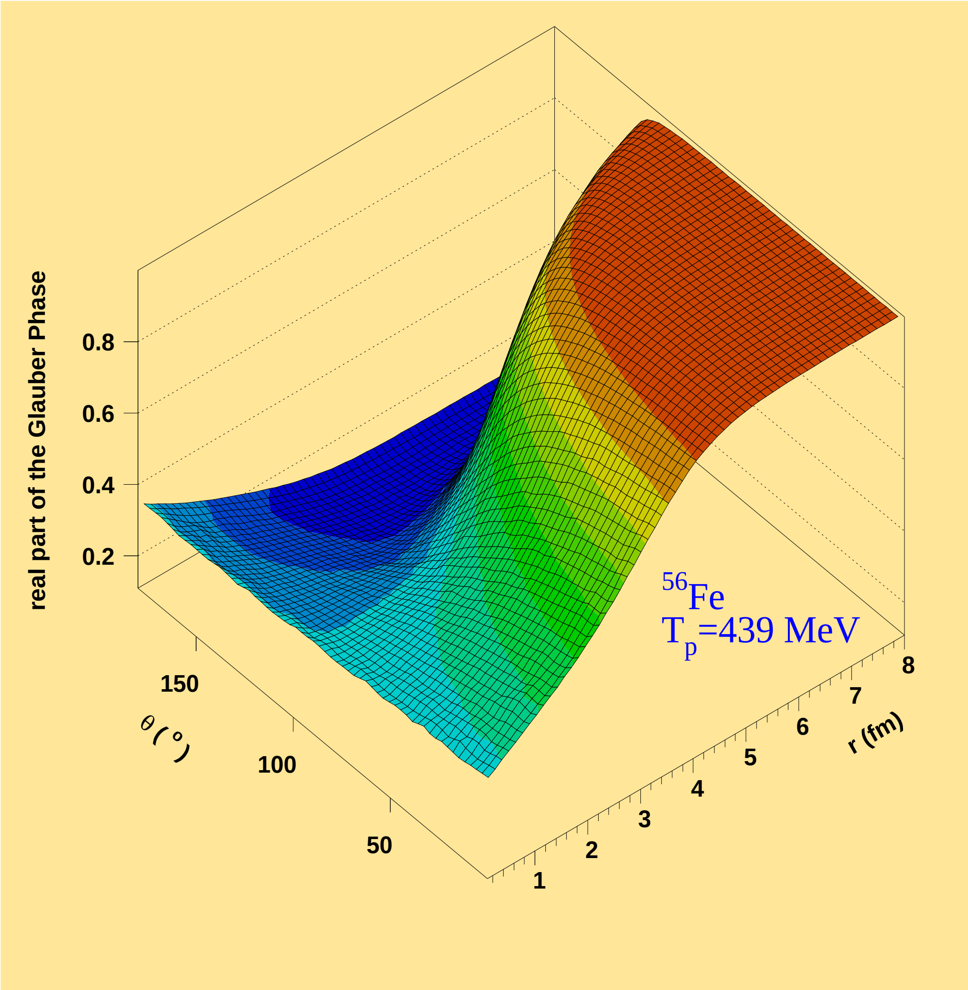


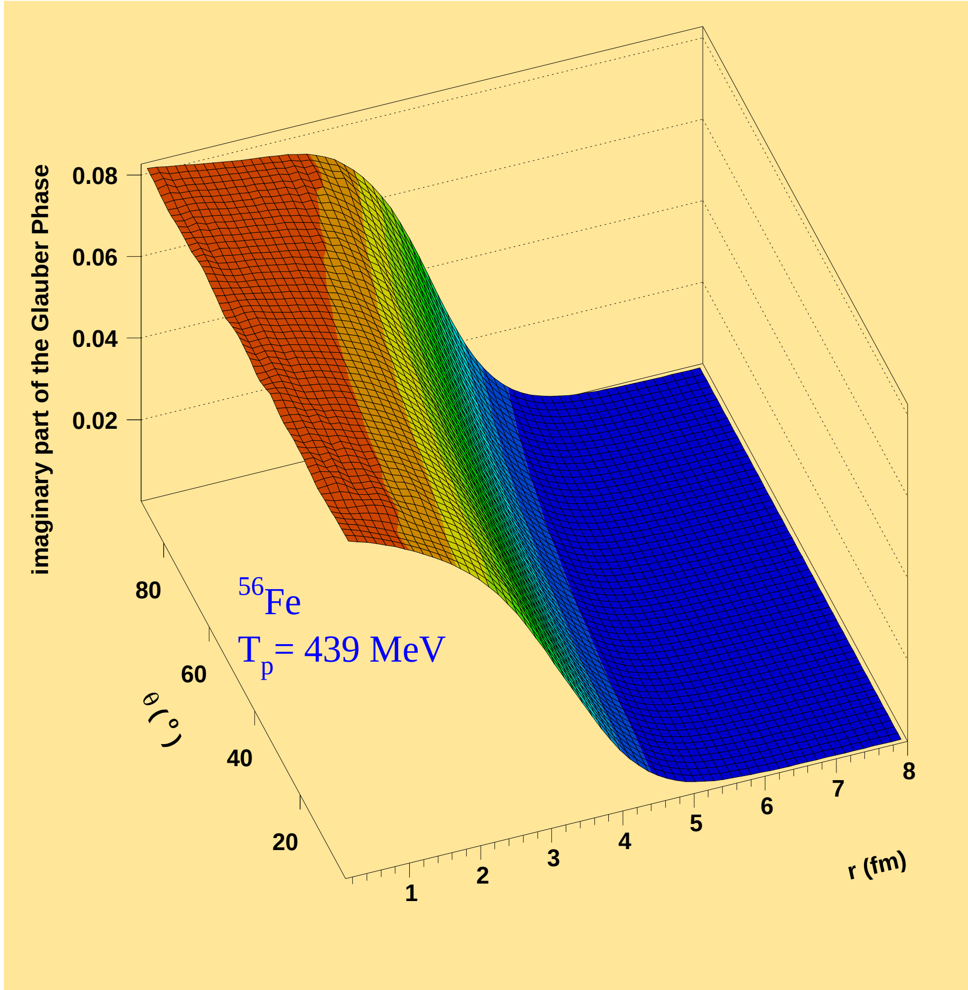
r: distance relative to the center of the nucleus

θ: polar angle relative to $\vec{k}_p$

Glauber phase: an example

Real part (=1 in PWA) **Imaginary part (=0 in PWA)**





r: distance relative to the center of the nucleus

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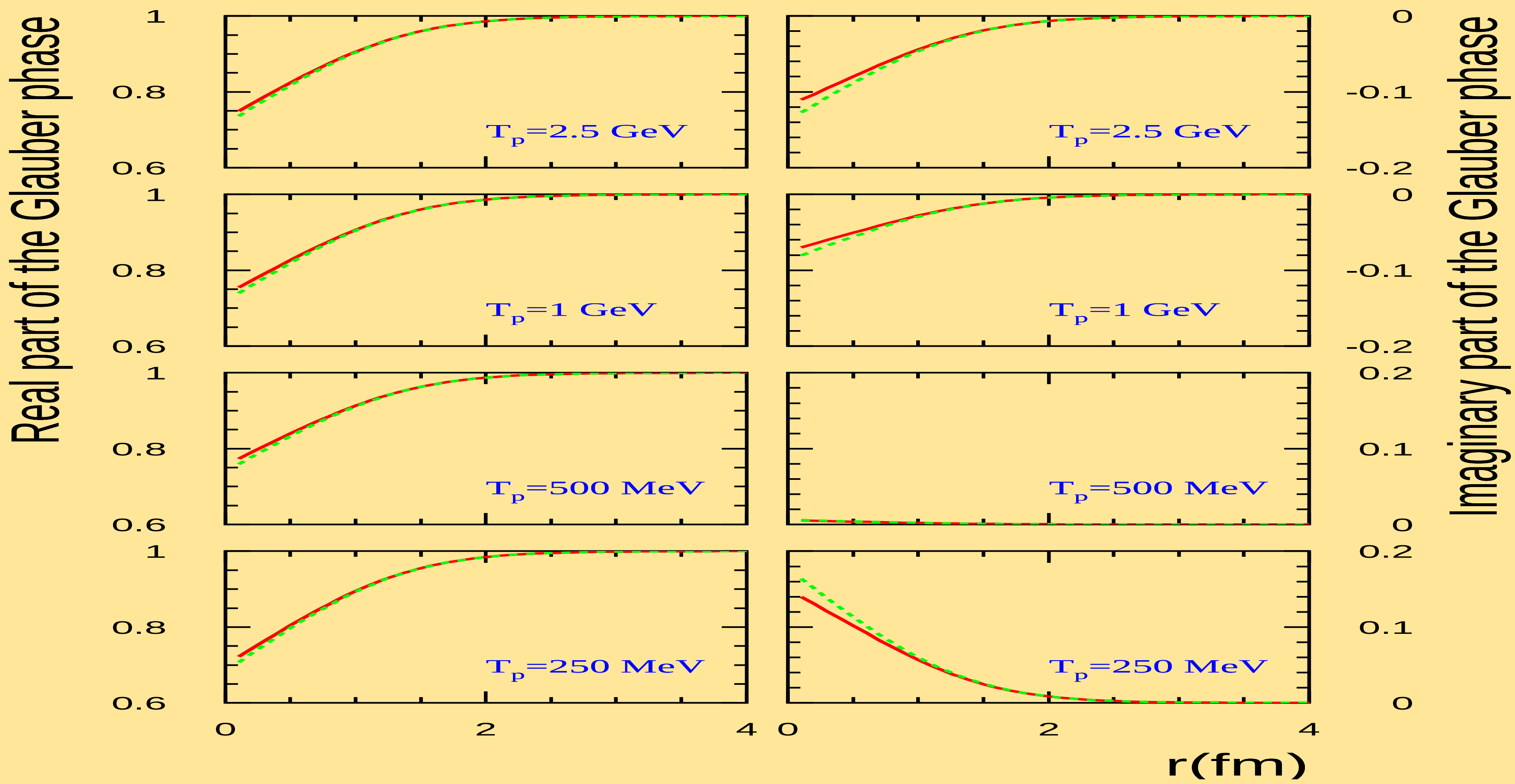
Glauber phases for ^{4}He at $\theta = 0^o$

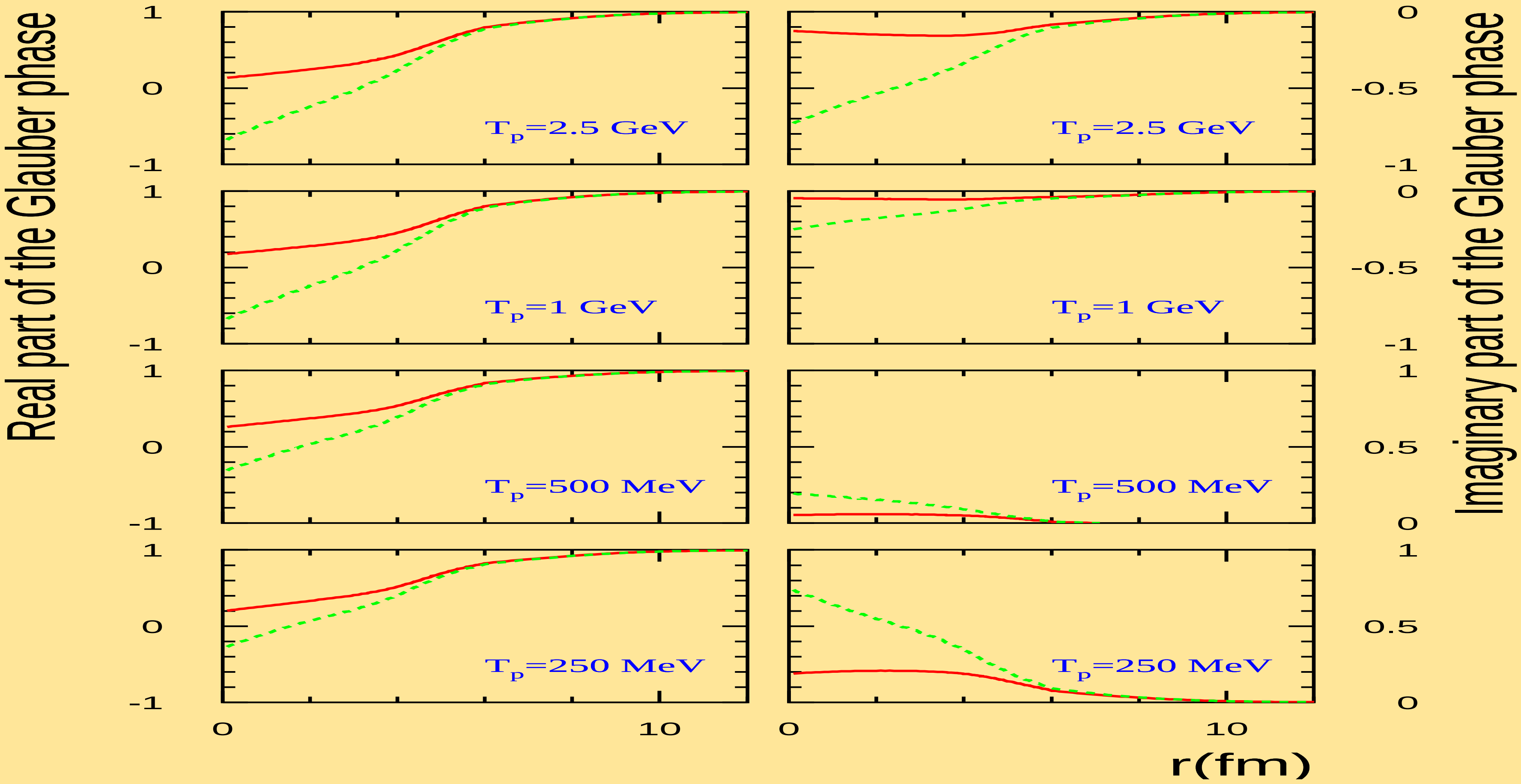
Real part (=1 in PWA) **Imaginary part (=0 in PWA)**



FULL SINGLE SCATTERING

Glauber phases for ^{208}Pb at $\theta = 0^o$

Real part (=1 in PWA) **Imaginary part (=0 in PWA)**

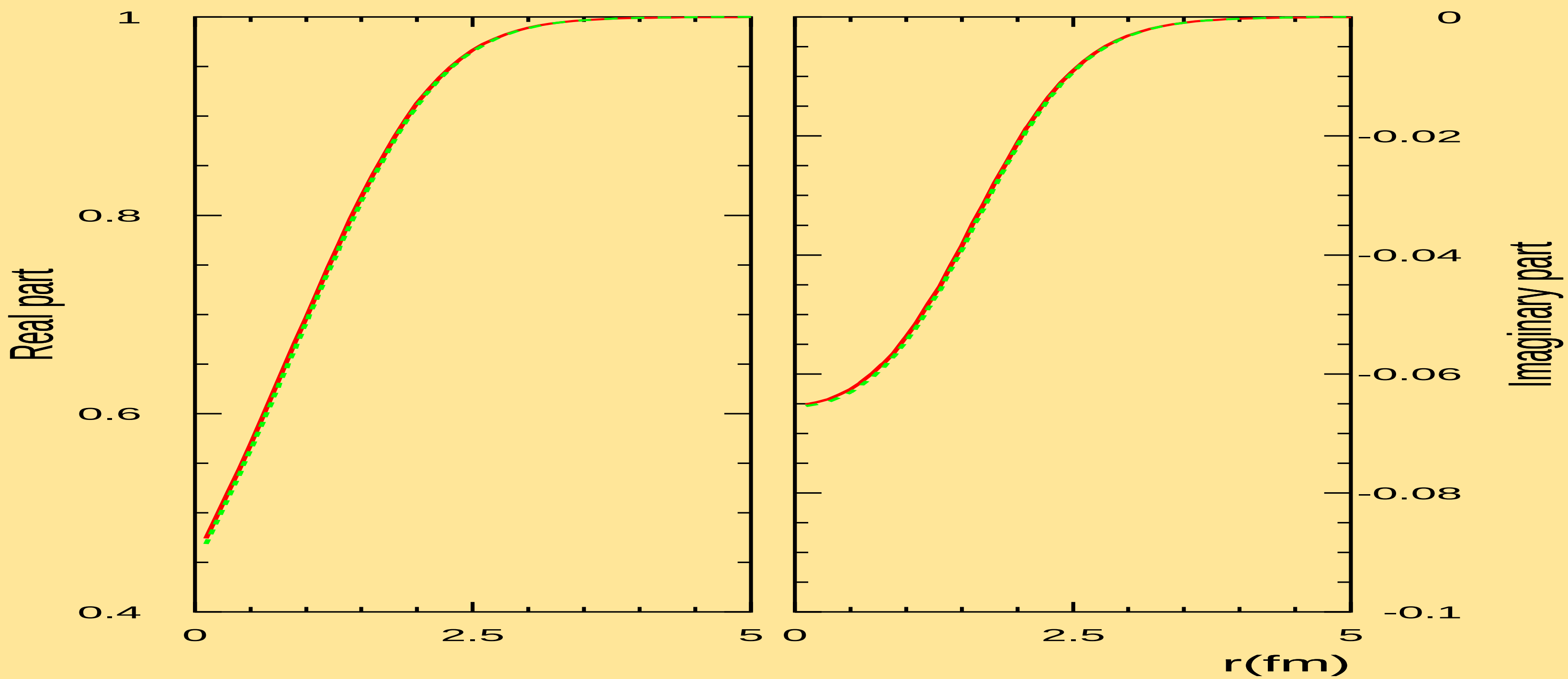


FULL SINGLE SCATTERING

CONVERGENCE : QUADRUPLE SCATTERING

Role of relativity in modeling FSI??

Glauberphase $\mathcal{G}$ for ^{12}C at T_p=1 GeV and $\theta = 0^o$



Fully relativistic RMSGA calculation

RMSGA calculation neglecting the lower components in the wavefunctions of the scattering centers

The effect of the lower components in the description of FSI in RMSGA is at the few percent level !

Nuclear Transparency from $\mathbf{A(e,e'p)}$

Likelihood that a struck "proton" escapes from the nucleus A

$$EXPERIMENT: \; T_{exp} = \frac{\int_{\Delta^3 k} d\vec{k} \int_{\Delta E} dE \frac{\frac{d^5\sigma}{d\Omega_p d\epsilon' d\Omega_{\epsilon'}}(e,e'p)}{K\sigma_{ep}^{CC1}}}{c_A \int_{\Delta^3 k} d\vec{k} \sum_\alpha S^\alpha_{NRPWIA}(\vec{k}, E)} ,$$

Integration over $\Delta^3 k$ and ΔE : kinematical domains in which the IA is plausible ($\mid \vec{p}_m \mid \leq k_F$ and $E_m \leq 80$ MeV).

$$THEORY: \; T_{th} = \frac{\int_{\Delta^3 k} d\vec{k} \sum_\alpha \frac{\frac{d^5\sigma}{d\Omega_p d\epsilon' d\Omega_{\epsilon'}}(e,e'p_\alpha)}{K\sigma_{ep}^{CC1}}}{c_A \int_{\Delta^3 k} d\vec{k} \sum_\alpha S^\alpha_{NRPWIA}(\vec{k})} ,$$

c_A=0.9 (^{12}C), 0.88 (^{28}Si), 0.82 (^{56}Fe) and 0.77 (^{208}Pb) (Accounts for the effect of short-range correlations)

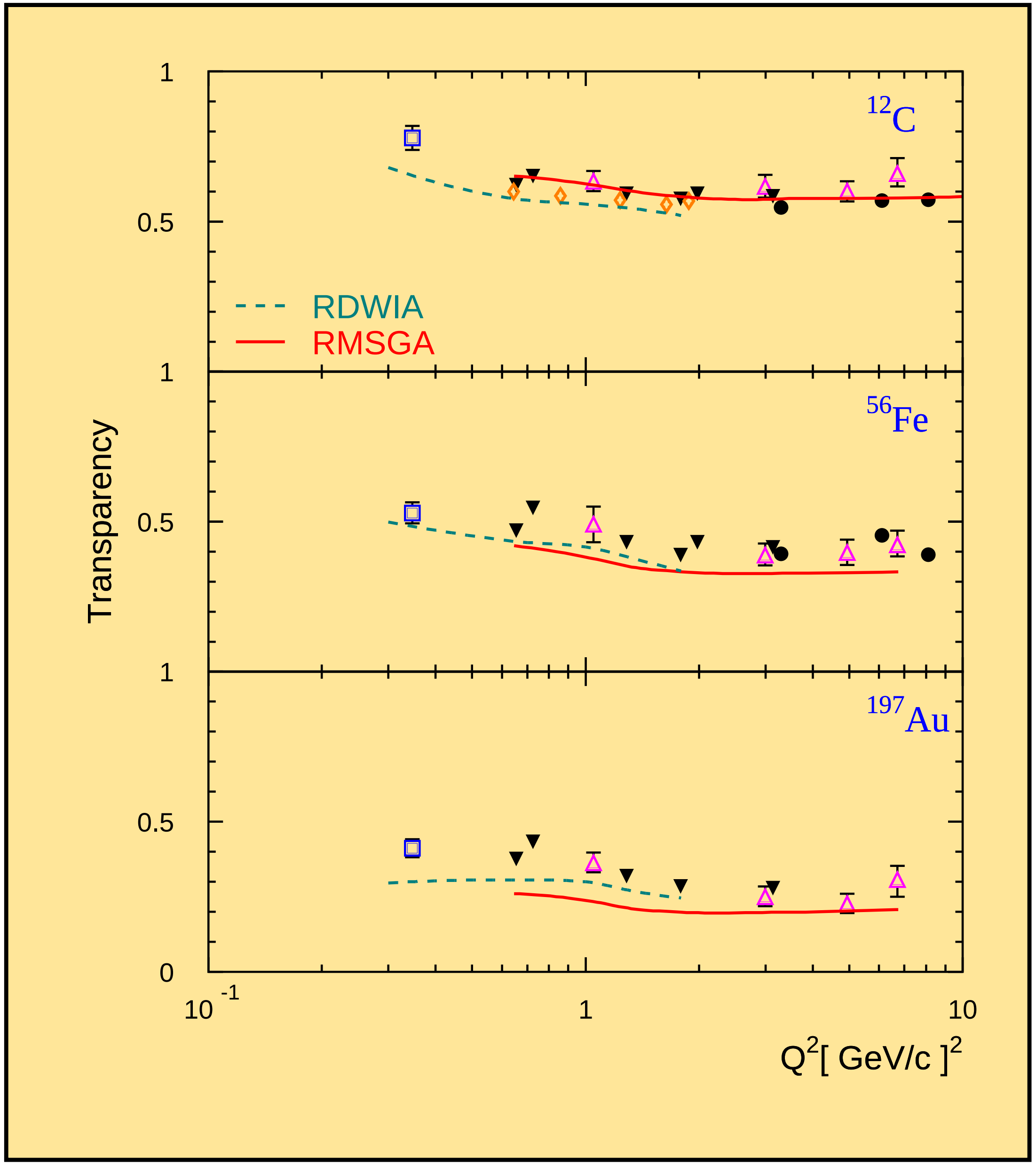
$\sum_\alpha$: sum extends over all occupied single-particle states

Transparency in relativistic $\mathbf{A}(\mathrm{e}, \mathrm{e}'\mathrm{p})$ models

- $A(e, e'p)$ transparency results cover a large range in T_p $(0.15 \leq T_p \leq 4$ GeV) !
- From global fits to elastic pA : relativistic optical potentials available for $T_p \leq 1$ GeV.
- Eikonal approximation becomes questionable at lower T_p (lower limit has not been established yet).
- Relativistic calculation with identical ingredients *(bound-state wave functions, electron distortion, recoil and binding effects, electron-proton coupling)* apart from treatment of the FSI effects !
  "low" T_p ($T_p \leq 1$ GeV) : optical potential (RDWIA)
  "high" T_p ($T_p \geq 0.25$ GeV): Glauber approach (RMSGA)
- Region of overlap in T_p : check the (in)consistency between the two "approaches".

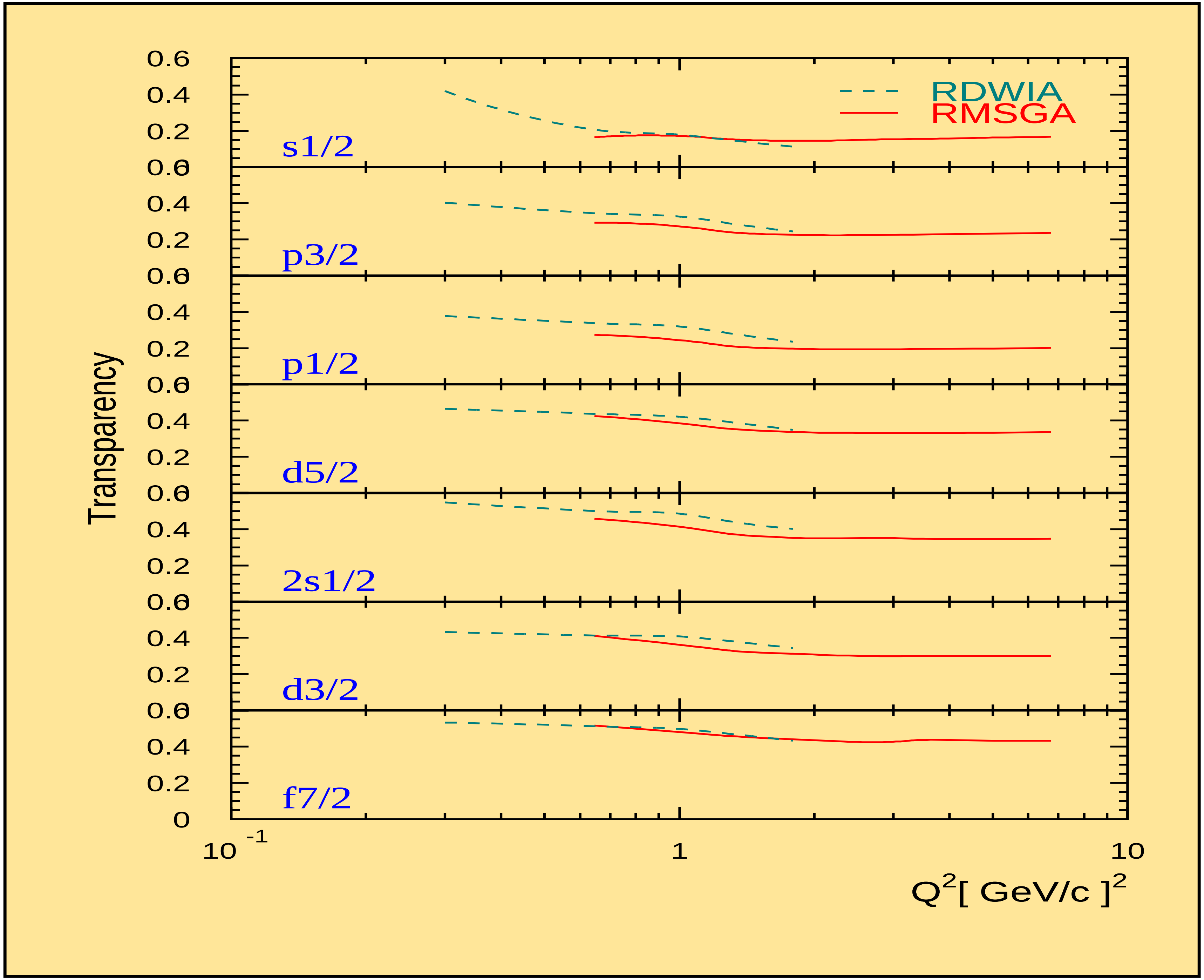
nucl-th/0401041 and Physics Letters B 595 (2004) 177

Nuclear Transparency : RMSGA and RDWIA results



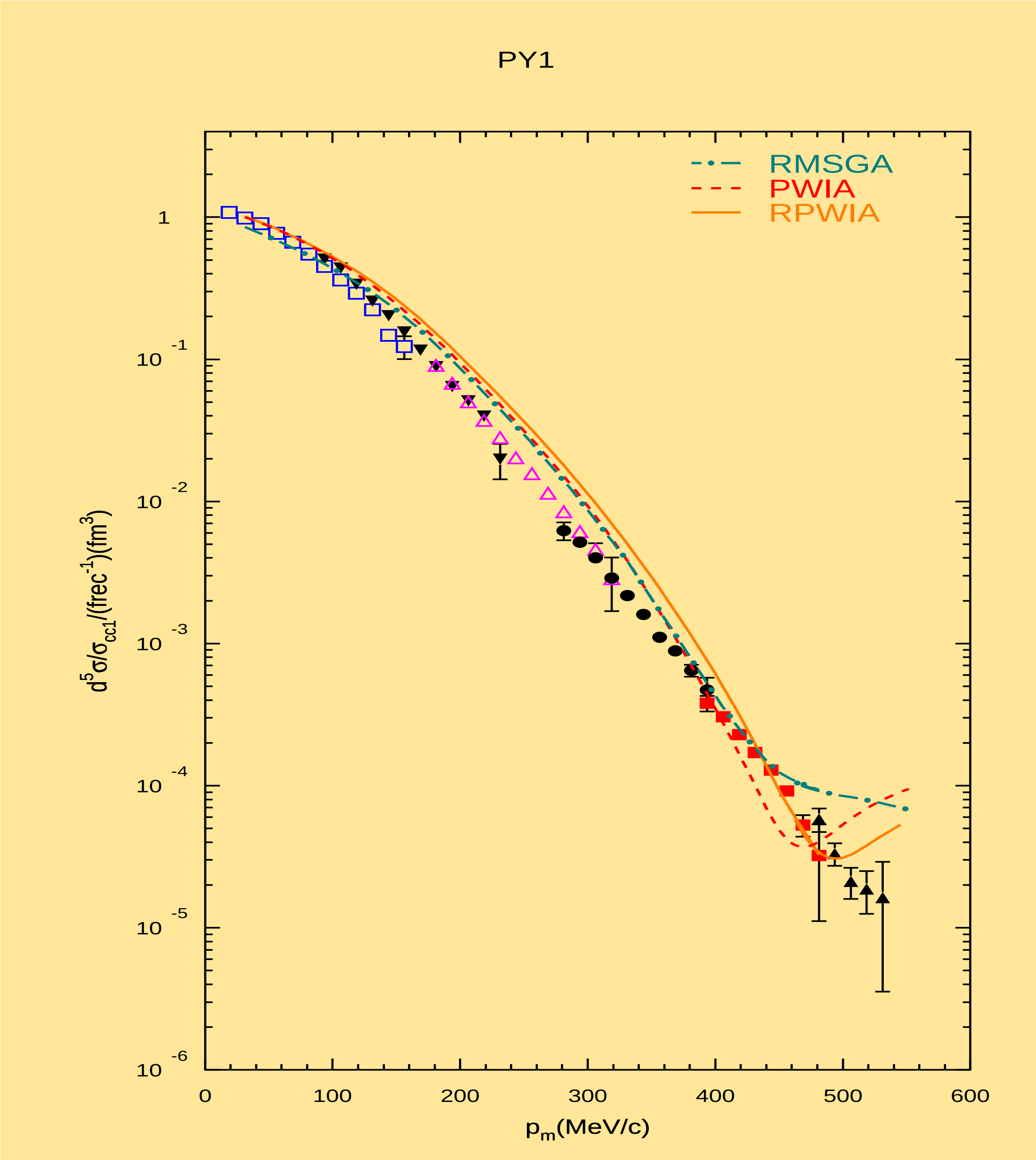
- Calculations tend to underestimate the measured transparencies ***(introduction of reduction factors would make matters worse)***.
- In the region of overlap: RMSGA and RDWIA predictions are not dramatically different !! ***(smooth transition between high- and low-energy description)***
- Data from MIT, JLAB and SLAC

Nuclear Transparency for individual levels in ^{56}Fe



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

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



Data from JLAB
(E97-111)
ϵ=2.4 GeV
$0.28 \leq Q^2 \leq 0.44$ (GeV)^2
$0.284 \leq \omega \leq 1.035$ GeV
Spectroscopic factor=1

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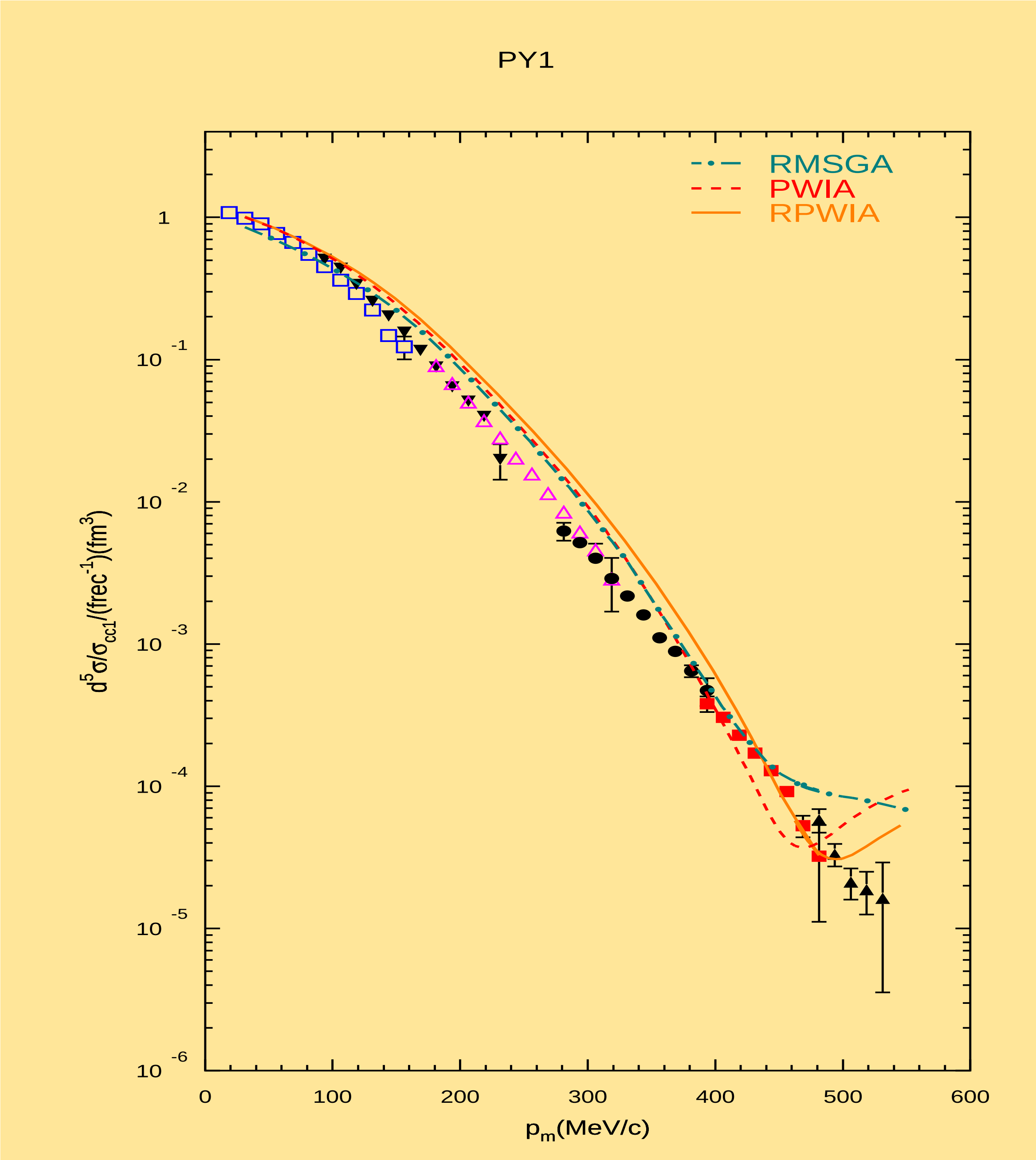

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1. (σ, ω)-model reasonable for ^{4}He
2. RMSGA predicts response functions

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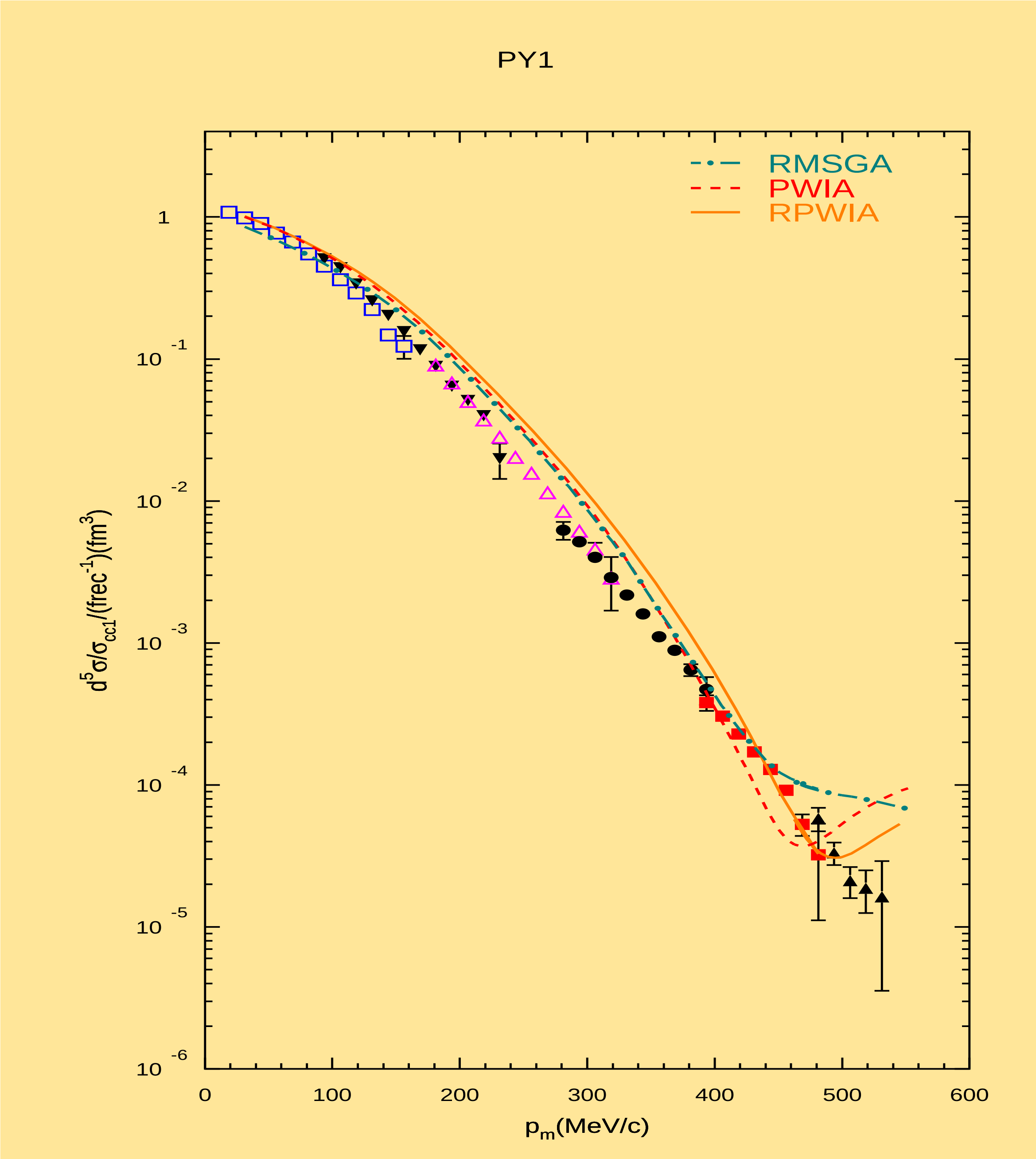

Data from JLAB
(E97-111)
ϵ=3.2 GeV
$0.57 \leq Q^2 \leq 0.89$ (GeV)^2
$0.537 \leq \omega \leq 1.481$ GeV
Spectroscopic factor=1

Medium modifications and $^{4}\mathrm{He}(\vec{e}, e'\vec{p})$

Many nucleon models predict measurable effects of the medium on the ratio of the electromagnetic form factors!

$\mathbf{G_{E,M}(Q^2)}$

Quark-meson coupling model : *D.H. Lu, K. Tsushima, A.W. Thomas, A.G. Williams and K. Saito, PRC* ***60****, 068201*

Chiral-quark soliton model : *J.R. Smith and G.A. Miller, PRC* ***70*** *(2004), 065205*

Skyrme model : *U.T. Yakhshiev, U.-G. Meissner and A. Wirzba, EPJA* ***16*** *(2003), 569.*

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$$\mathbf{G_{E,M}(Q^2) \Rightarrow G_{E,M}(Q^2, \rho(r))}$$

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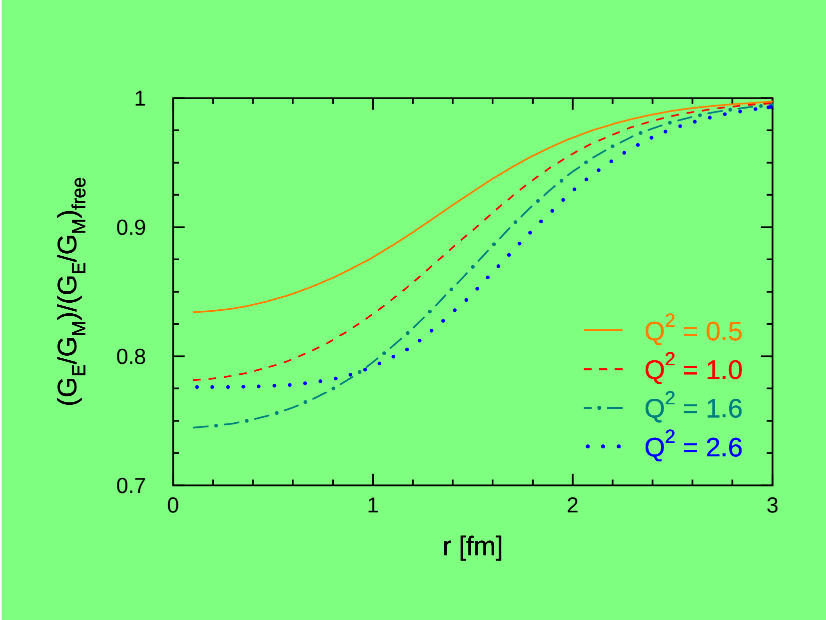

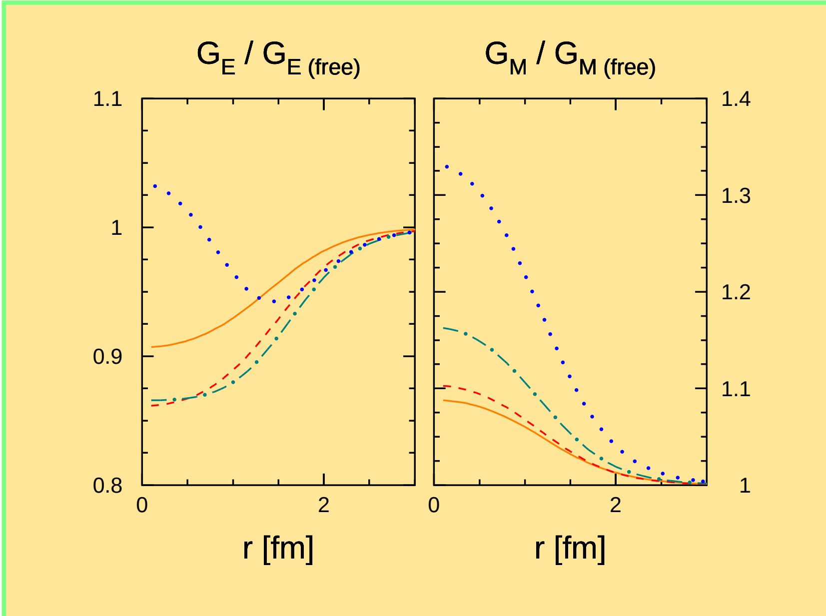

Quark-meson coupling model : *D.H. Lu, K. Tsushima, A.W. Thomas, A.G. Williams and K. Saito, PRC **60**, 068201* Predictions for ^{4}He on the r.h.s

Chiral-quark soliton model : *J.R. Smith and G.A. Miller, PRC **70** (2004), 065205*

Skyrme model : *U.T. Yakhshiev, U.-G. Meissner and A. Wirzba, EPJA **16** (2003), 569.*

Electron-nucleon scattering :

$p(\vec{e}, e')\vec{p}$ (Polarization Transfer in the hadronic plane) :

$$\frac{P'_l}{P'_t} = -\frac{G_M^p(Q^2)}{G_E^p(Q^2)} \frac{(e+e')tan\frac{\theta_e}{2}}{2M_p}$$

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$$\frac{P_l'}{P_t'} = -\frac{G_M^p(Q^2)}{G_E^p(Q^2)} \frac{(e+e')tan\frac{\theta_e}{2}}{2M_p}$$

Electron-nucleus scattering :

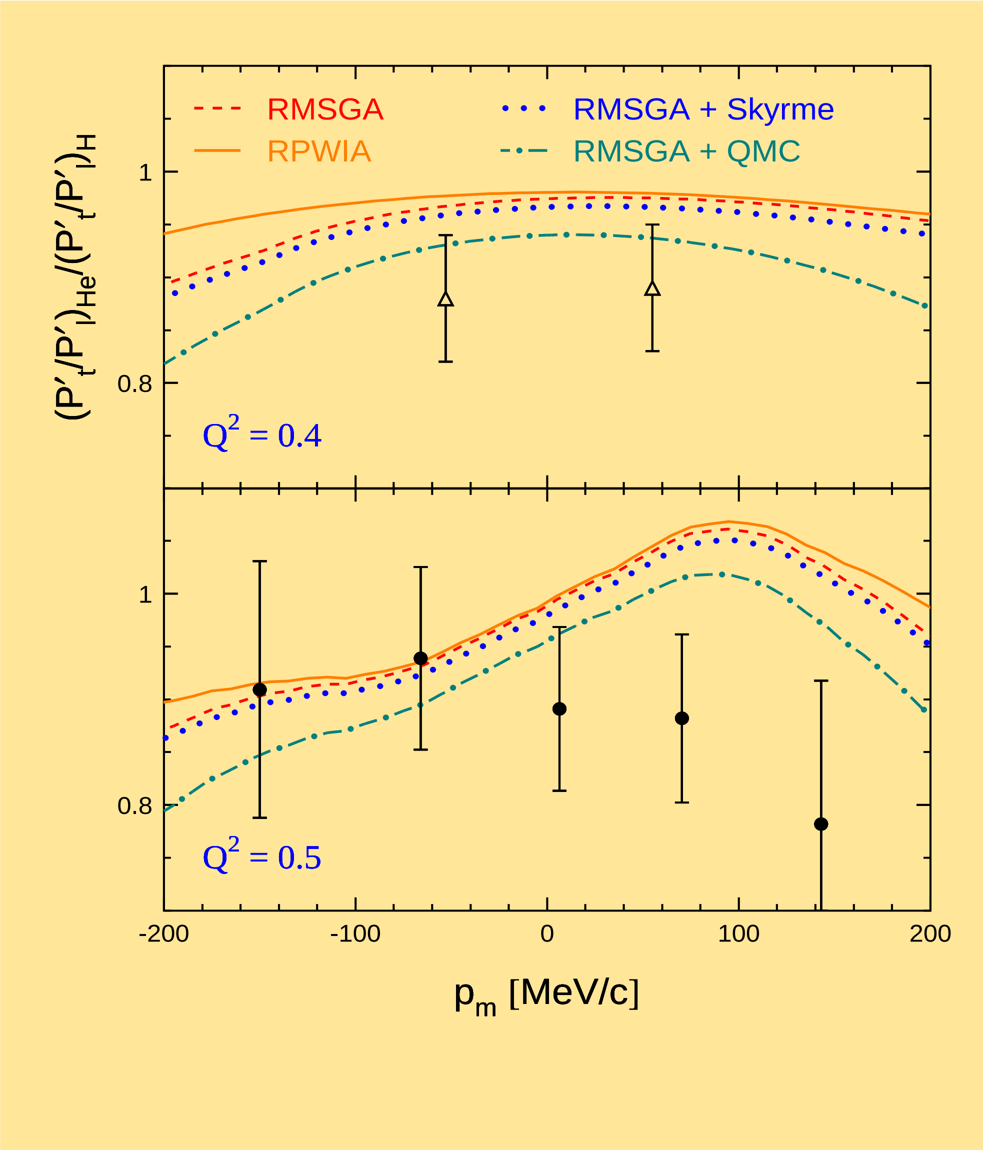
$^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ program @ MAMI and JLAB

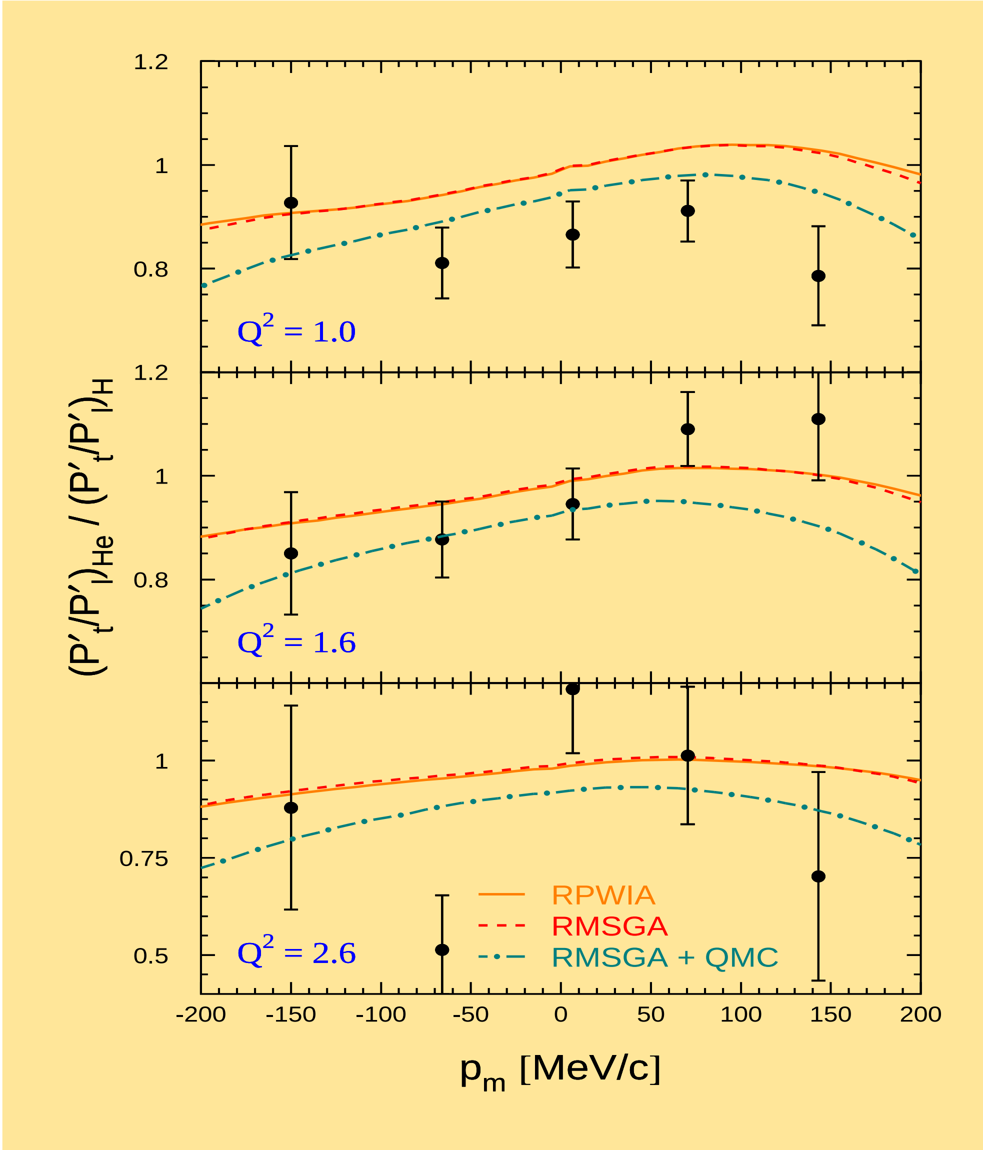
Results are usually given in terms of the "superratio"

$$\frac{R}{R_{RPWIA}} = \frac{\left(\frac{P_l'}{P_t'}\right)_{^4He}}{\left(\frac{P_l'}{P_t'}\right)_{^1H}}$$

After corrections for FSI effects, MEC and Δ-currents : deviation from 1 is a measure for the medium-dependence

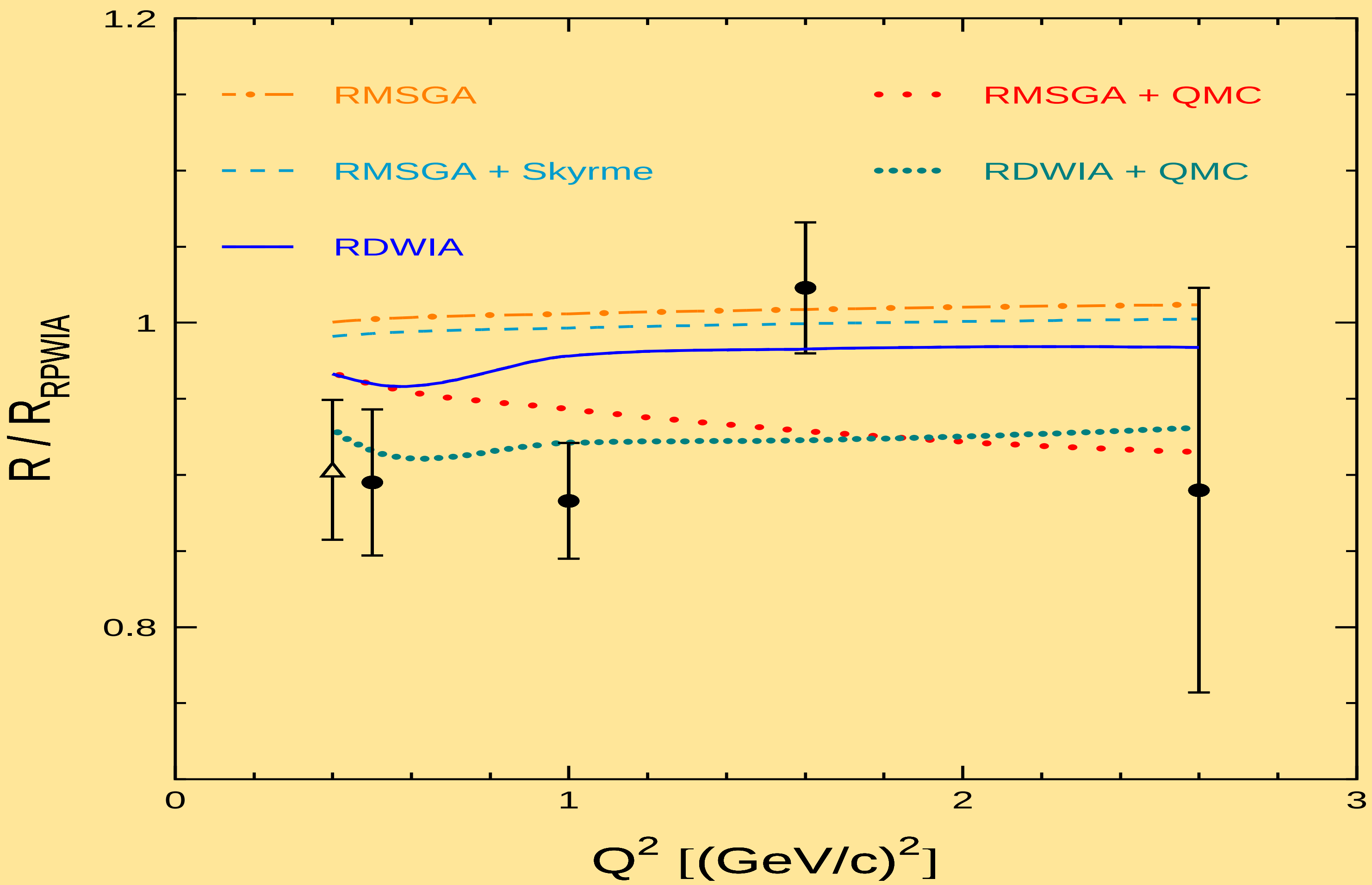
Polarization Transfer in $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$: p_m dependence





Data : S. Dieterich et al.*, PLB* ***500*** *(2001) 47 and S. Strauch* et al.*, PRL* ***91*** *(2003) 0523011.*

Polarization Transfer in $^4\text{He}(\vec{e}, e'\vec{p})^3\text{H}$: Q^2 dependence



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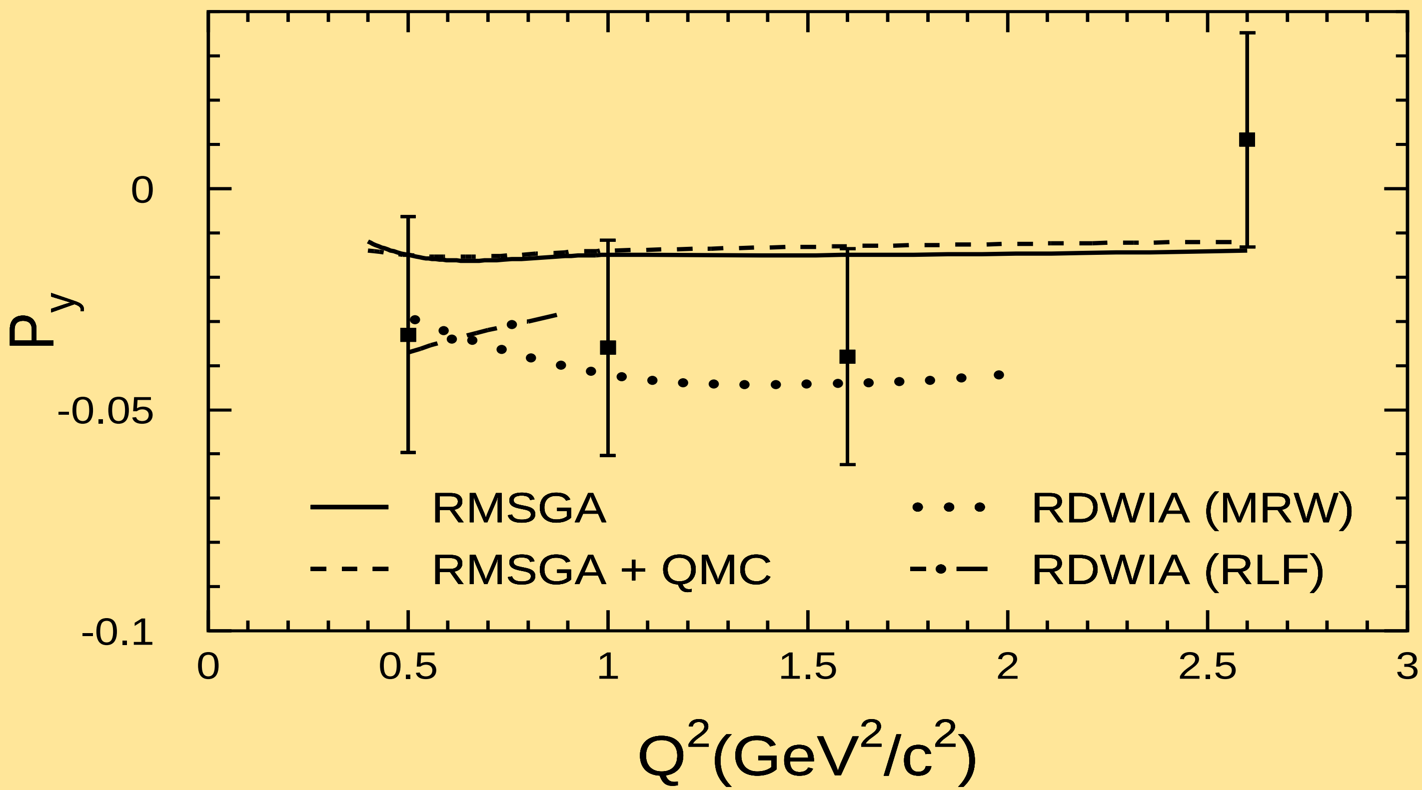
Controling the FSI in $^4\mathrm{He}(e, e'\tilde{p})^3\mathrm{H}$: the induced normal polarization $\mathrm{P_y}$



P_y vanishes in the absence of FSI!

The electron beam helicity asymmetry A'_{LT}

$$A'_{LT} = \frac{d\sigma^{h=+} - d\sigma^{h=-}}{d\sigma^{h=+} + d\sigma^{h=-}}$$

This quantity is extremely sensitive to FSI mechanisms !

$$A'_{LT} \sim \frac{\mathrm{Im}\left(\left\langle J^0 \right\rangle^{\dagger} \left\langle J^y \right\rangle\right)}{\text{unpolarized cross section}}$$

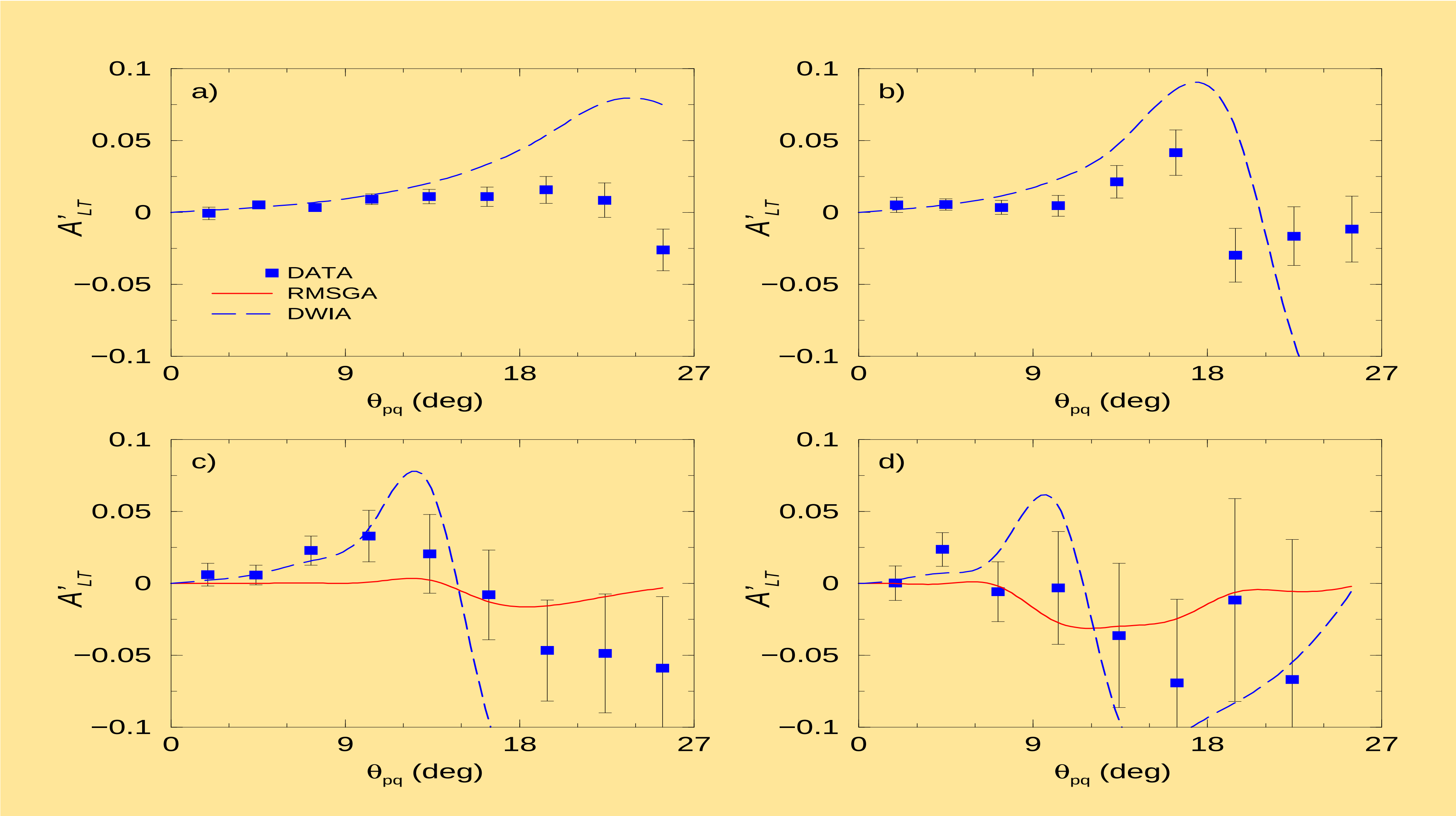
Subject of investigation by the CLAS collaboration (e2a run period)
*(Ph.D. thesis of D. Protopopescu (UNH, 2003), NPA **748** (2005) 357.)*

Data set covers

^{4}He$(\vec{e}, e'p)$ and ^{12}C$(\vec{e}, e'p)$
ϵ=2.2 GeV, $0.35 \leq Q^2 \leq 1.80$ GeV^2
ϵ=4.4 GeV, $0.80 \leq Q^2 \leq 2.40$ GeV^2

^{4}He$(\vec{e}, e'p)$: ϵ=2.2 GeV and QE kinematics

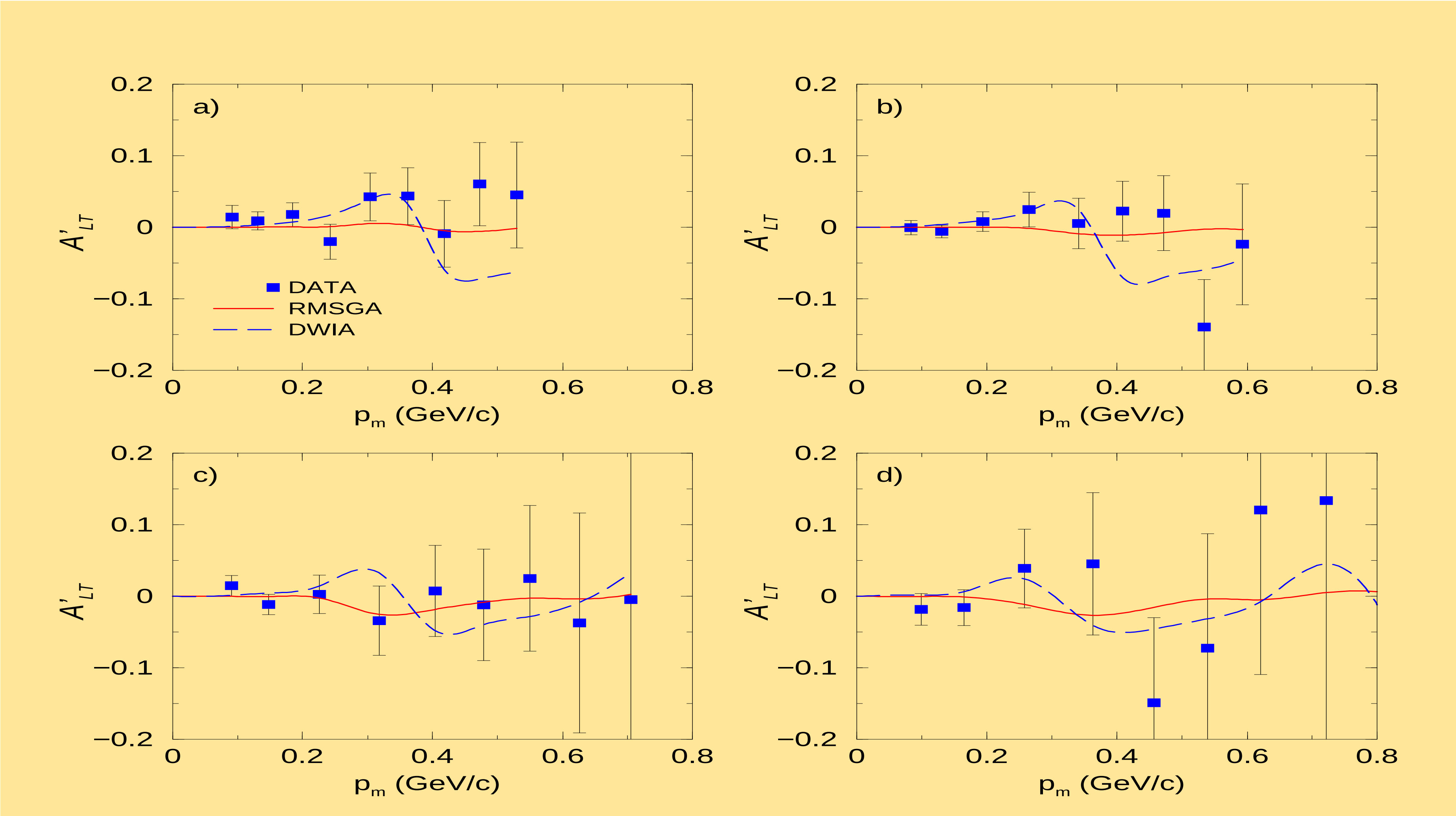
$0.35 \leq Q^2 \leq 0.71$ $\qquad$ $0.71 \leq Q^2 \leq 1.08$



$1.08 \leq Q^2 \leq 1.44$ $\qquad$ $1.44 \leq Q^2 \leq 1.80$

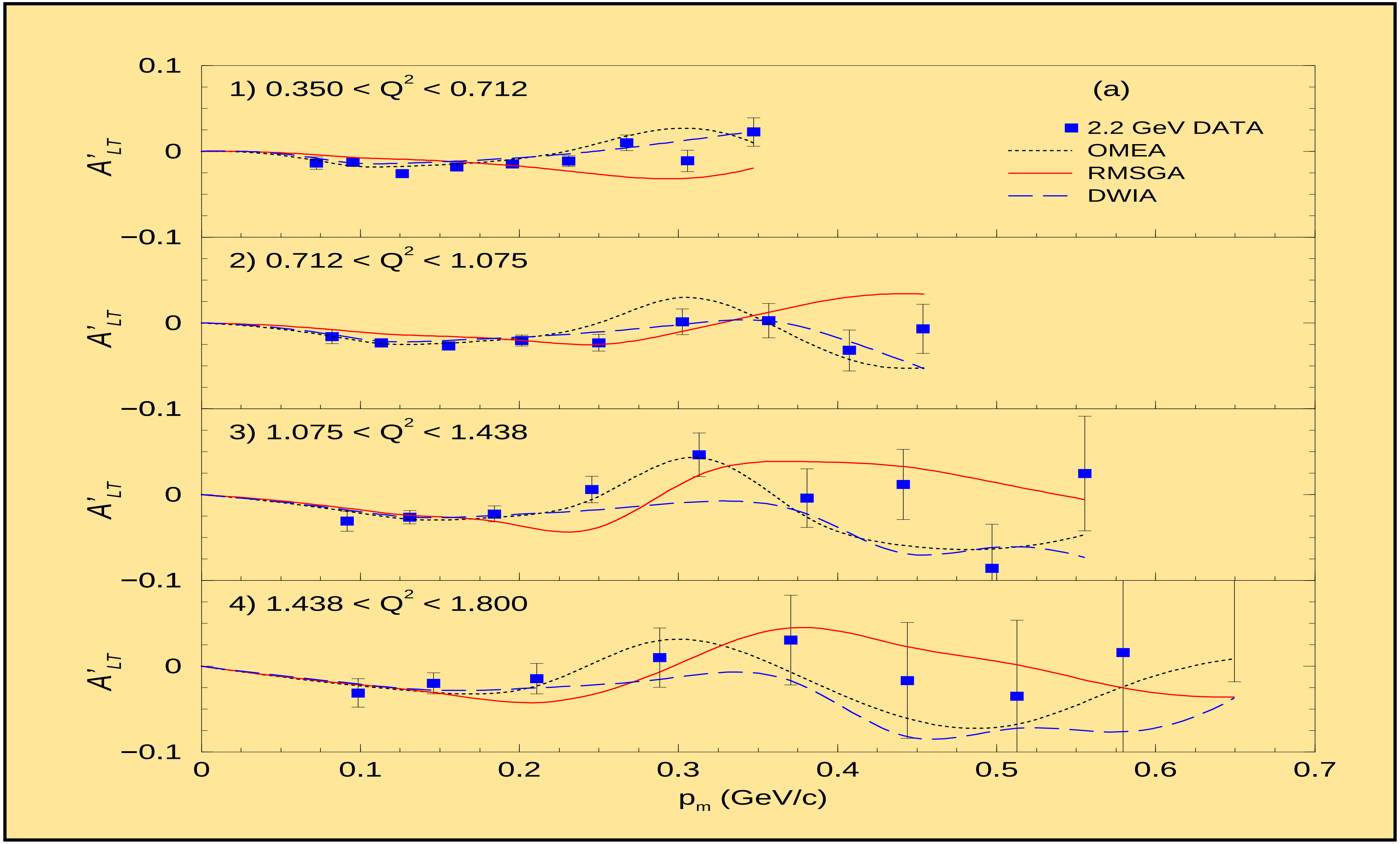
^{4}He$(\vec{e}, e'p)$: ϵ=4.4 GeV and QE kinematics

$0.80 \leq Q^2 \leq 1.20$ $1.20 \leq Q^2 \leq 1.60$



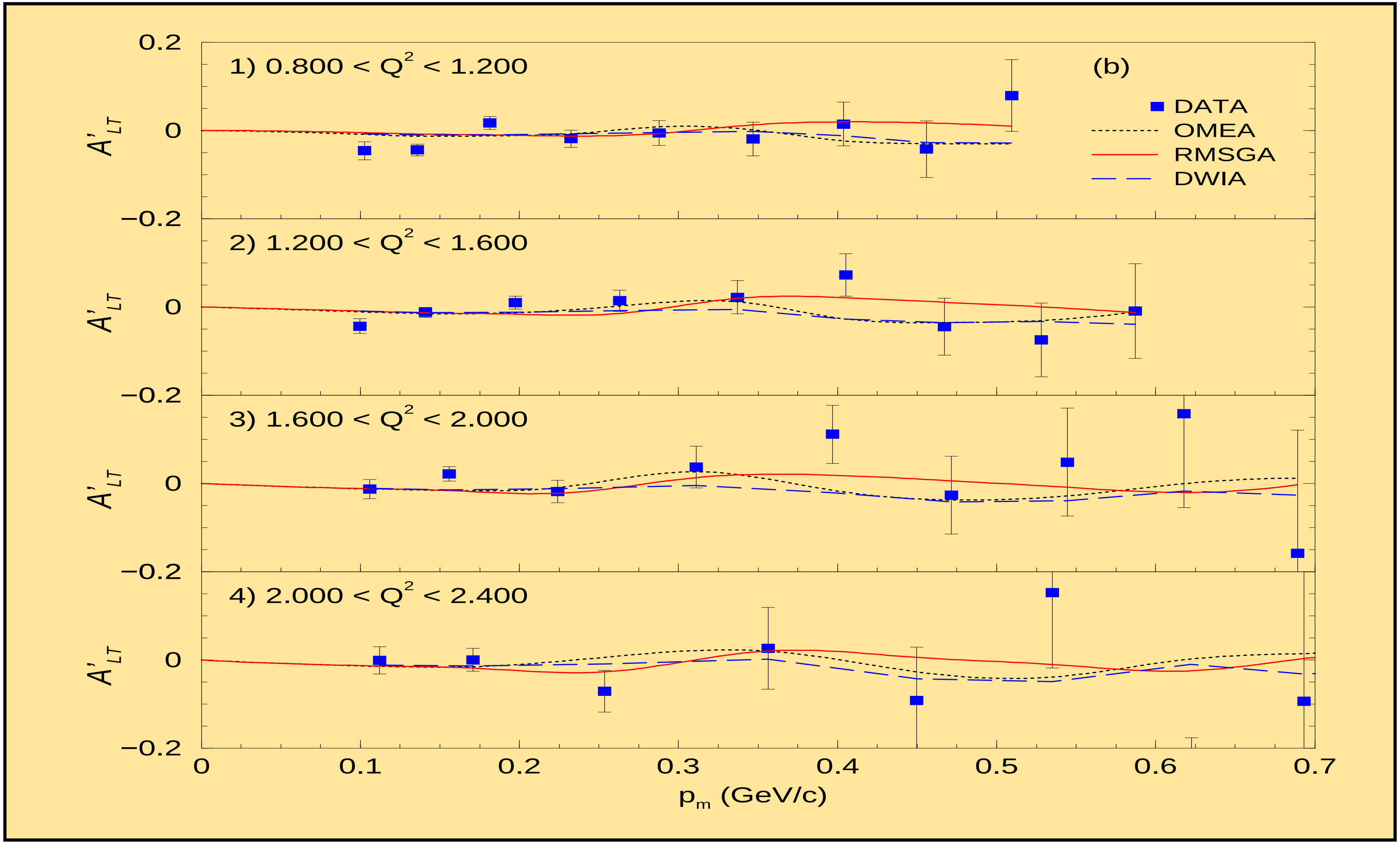
$1.60 \leq Q^2 \leq 2.00$ $2.00 \leq Q^2 \leq 2.40$

^{12}C$(\vec{e}, e'p)$: ϵ=2.2 GeV and QE kinematics



DWIA calculations : J. Kelly

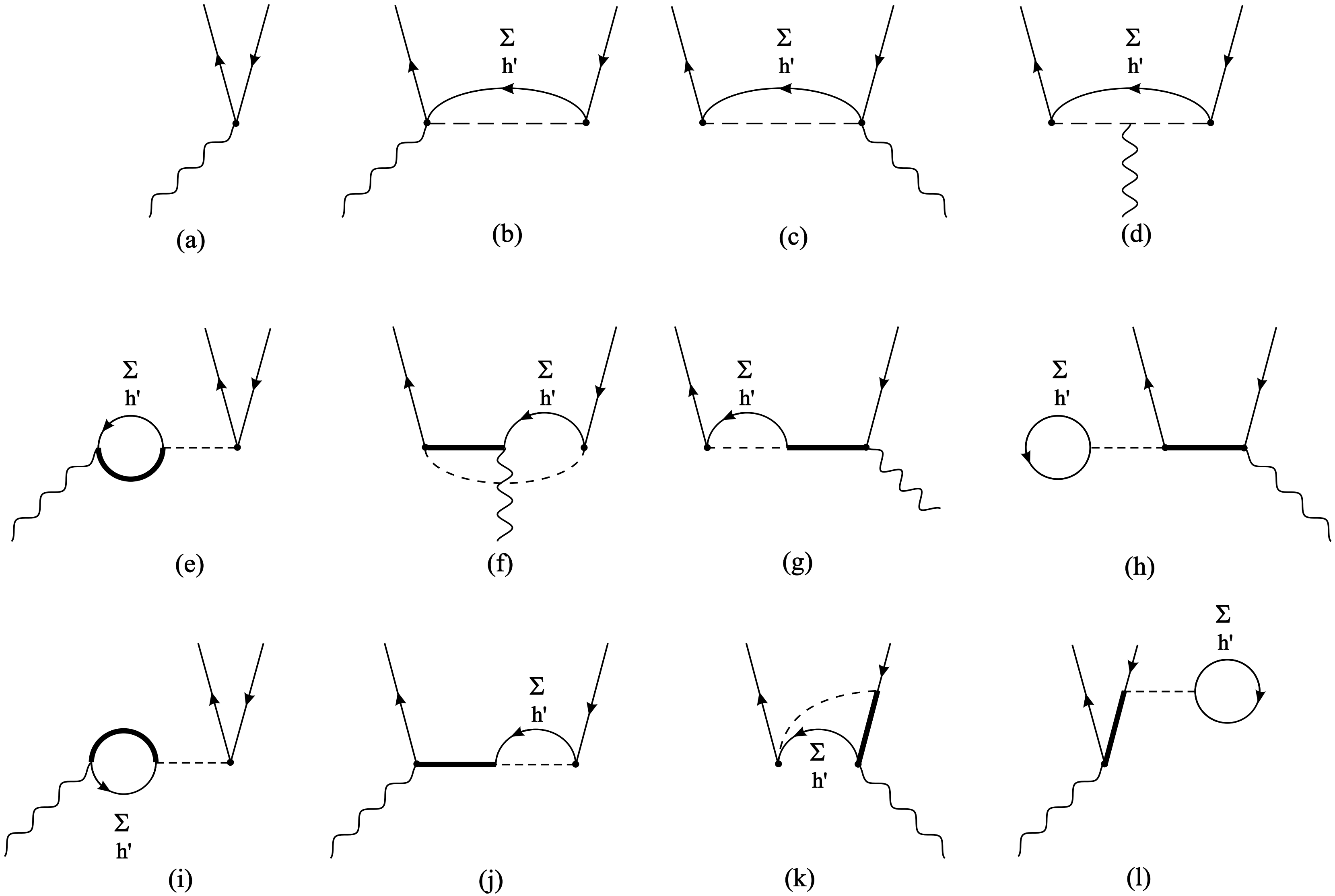
$^{12}C(\vec{e}, e'p)$: ϵ=4.4 GeV and QE kinematics



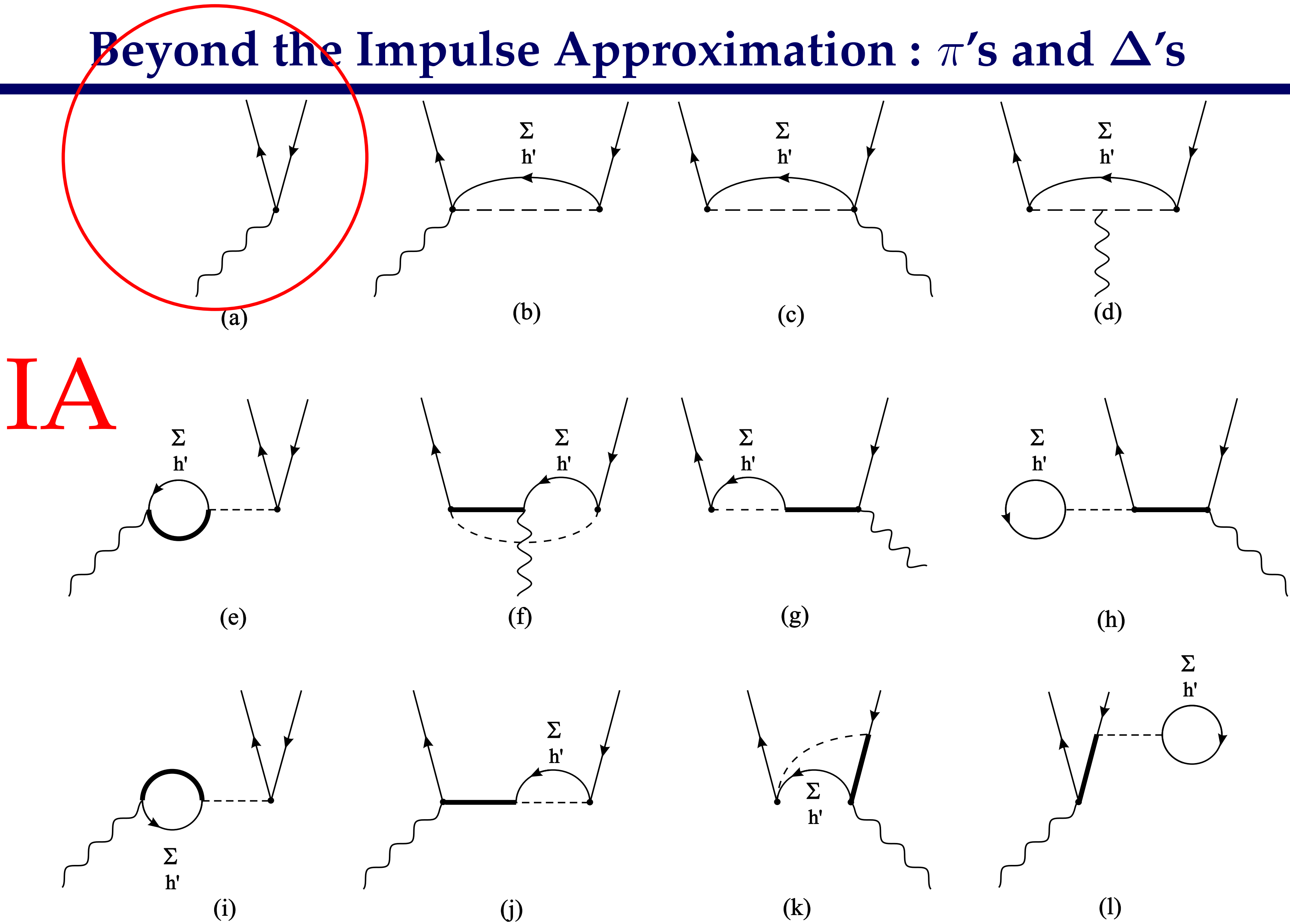
DWIA calculations : J. Kelly

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

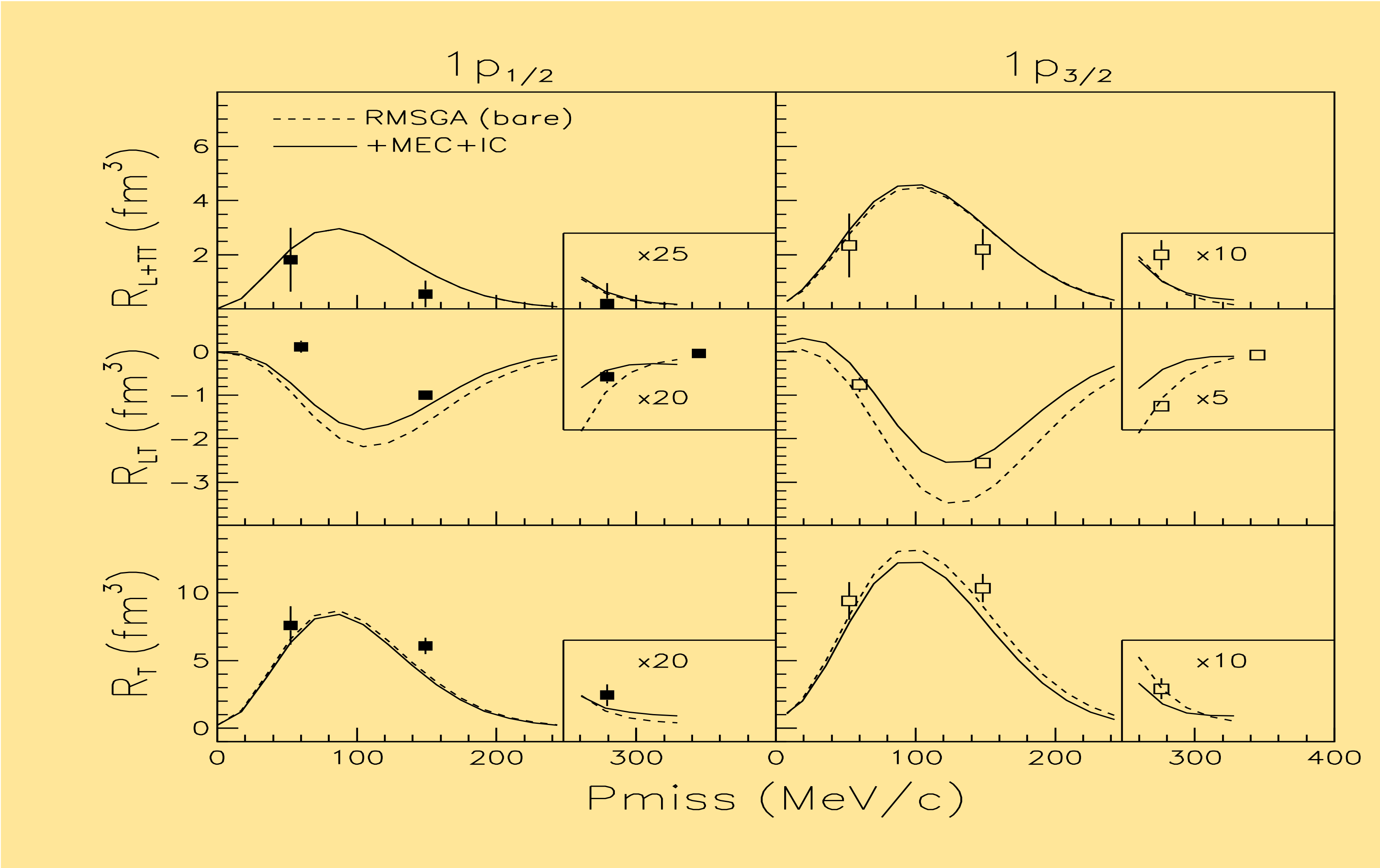
Beyond the Impulse Approximation : π's and Δ's



Beyond the Impulse Approximation : π's and Δ's

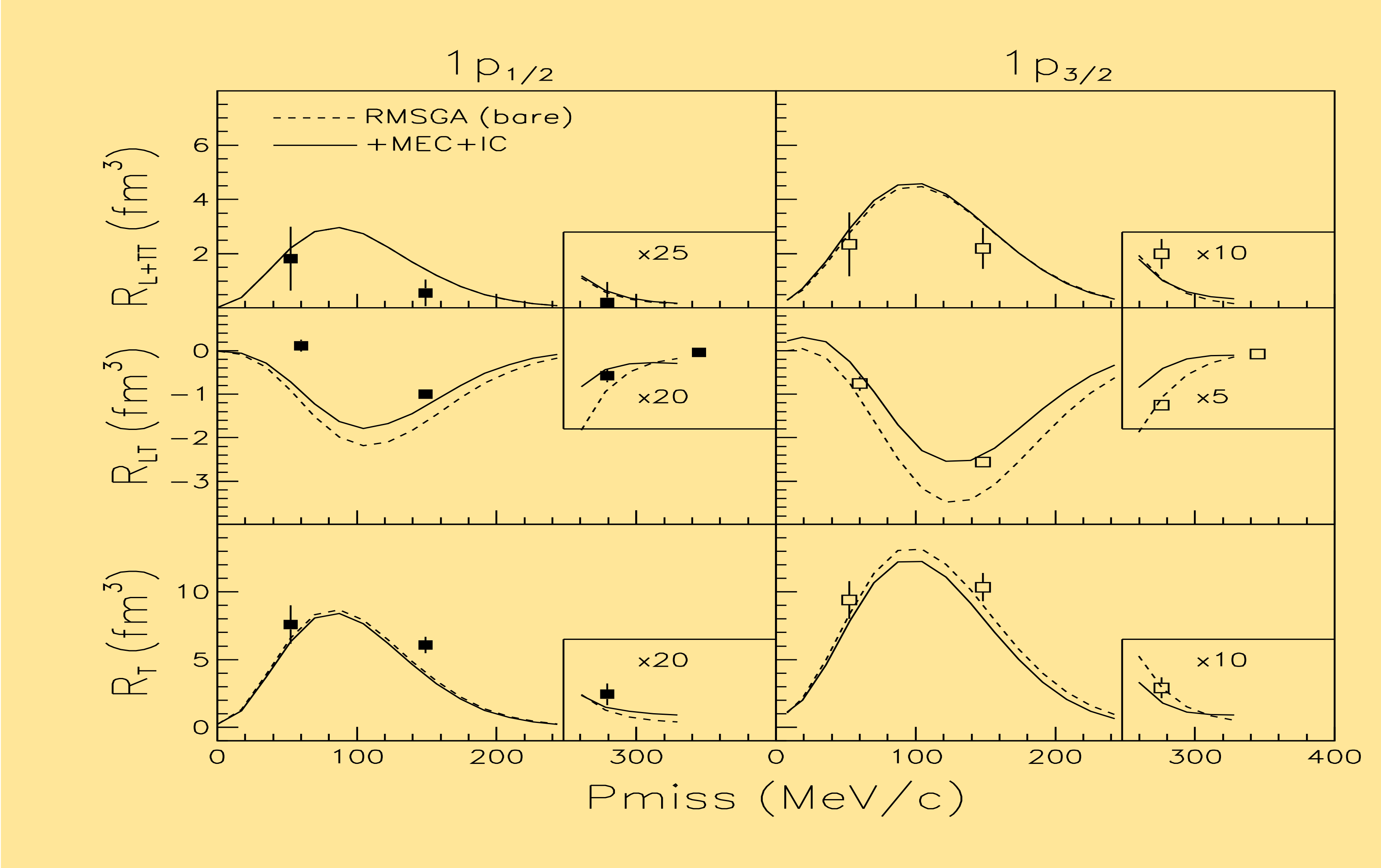


^{16}O$(e,e'p)$ at ω=0.439 GeV and Q^2=0.8 (GeV/c)^2



*K. Fissum (Hall-A collaboration), PRC **70** (2004) 034606*
*J. Gao et al., PRL **84** (2000) 3265*

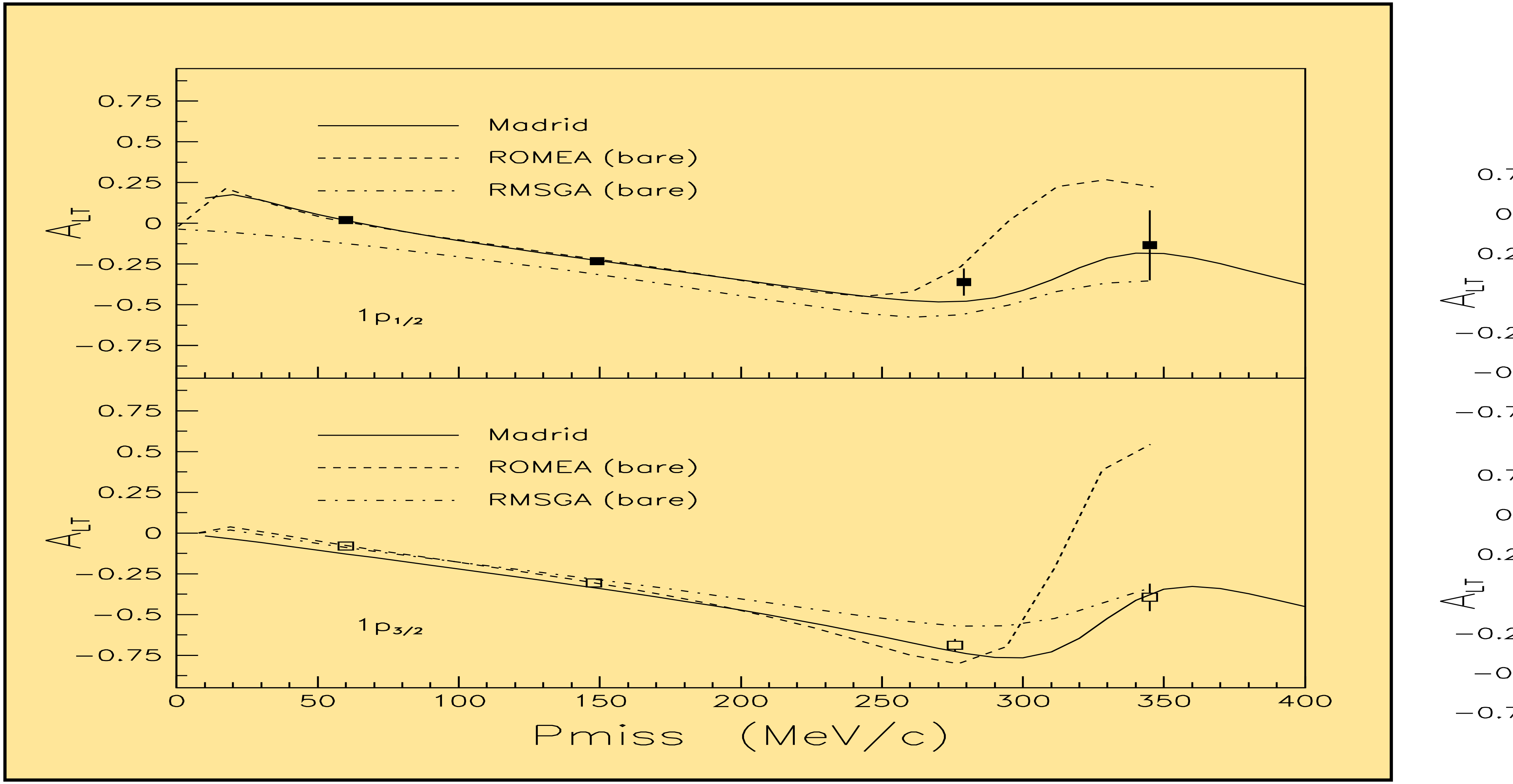
^{16}O$(e,e'p)$ at ω=0.439 GeV and Q^2=0.8 (GeV/c)^2



*K. Fissum (Hall-A collaboration), PRC **70** (2004) 034606*
*J. Gao et al., PRL **84** (2000) 3265*

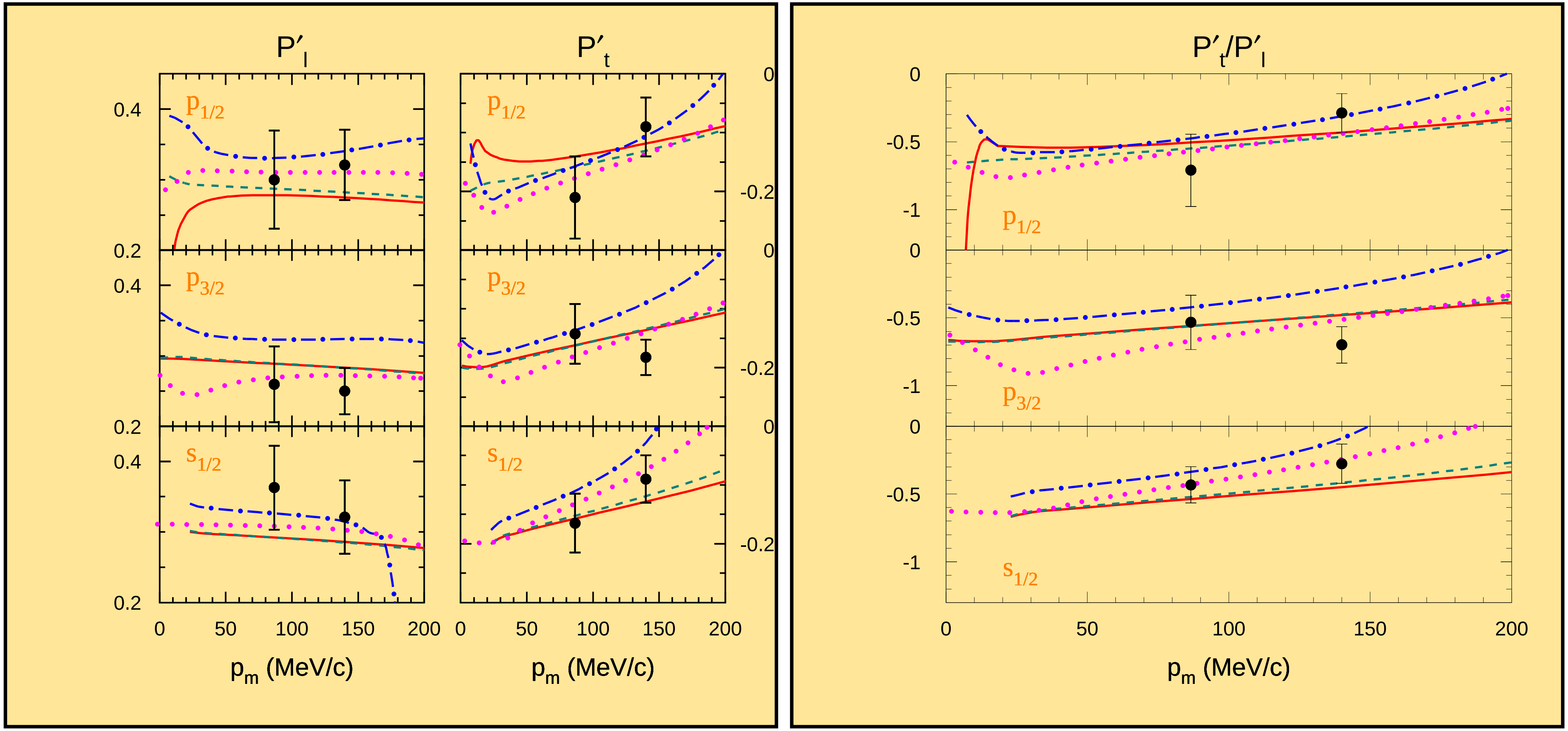
SPECTROSCOPIC FACTOR ≈ 0.7

$^{16}O(e, e'p)$ at ω=0.439 GeV and Q^2=0.8 $(GeV/c)^2$



Very sensitive to relativistic effects !!!

Polarization Transfer in $^{16}\mathrm{O}(\vec{e}, e'\vec{p})^{15}\mathrm{N}$



——— : RMSGA

– – – – –: RPWIA

–. – . – .: RMSGA+QMC

......: RDWIA (Madrid-Sevilla group)

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

CONCLUSIONS and OUTLOOK

- A "flexible" eikonal framework to model $A(l, l'N)$ processes at high Q^2 and $A \geq 4$
  1. *Unfactorized !*
  2. *Can accommodate "relativity" (dynamics and kinematics).*
  3. *Can be used in combination with both "optical potentials" (pA) and "Glauber Approach" (pN).*
  4. *Does not rely on thickness-function approximation*
  5. *Full $(A-1)$ multiple-scattering series!*
- The relativistic and unfactorized Glauber framework works reasonably well !
  (transparency predictions but ... even for structure functions and polarization observables).
- FSI's : smooth transition between "optical potential" (low-energy) and "Glauber" (high-energy) regime ($pA \Longleftrightarrow pN$)

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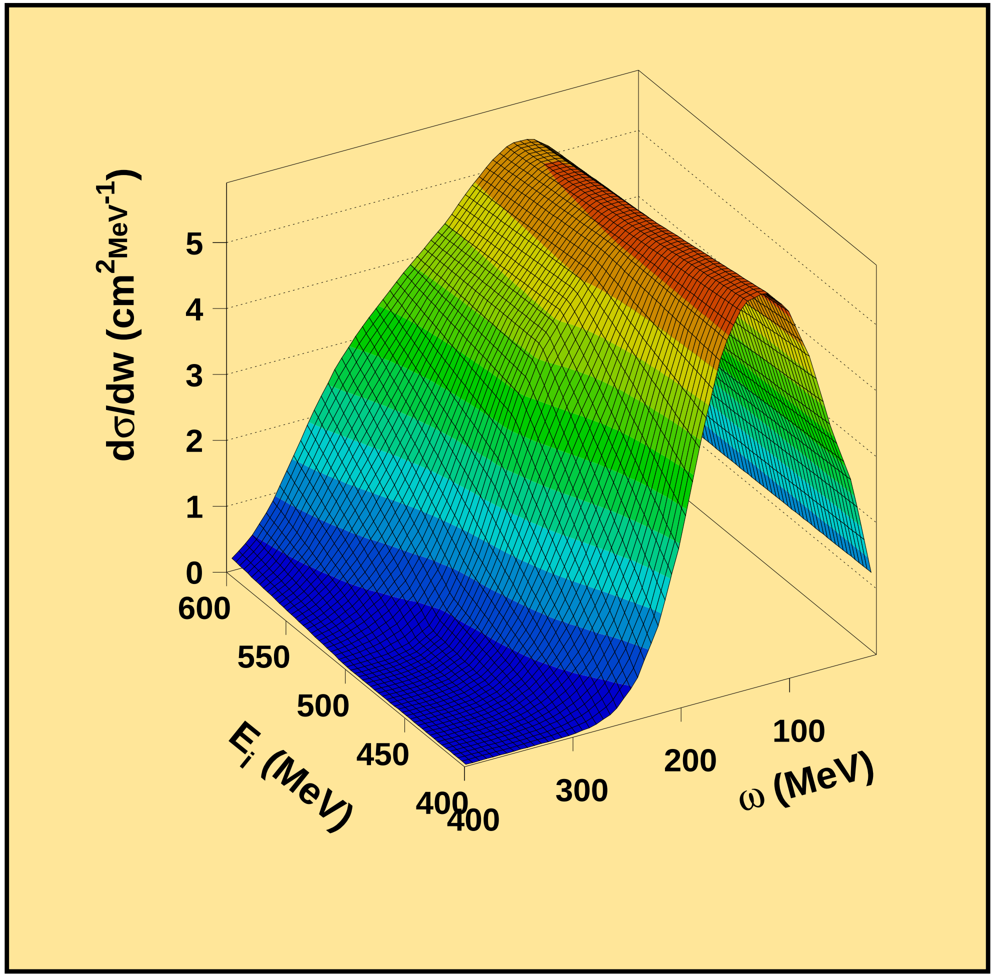
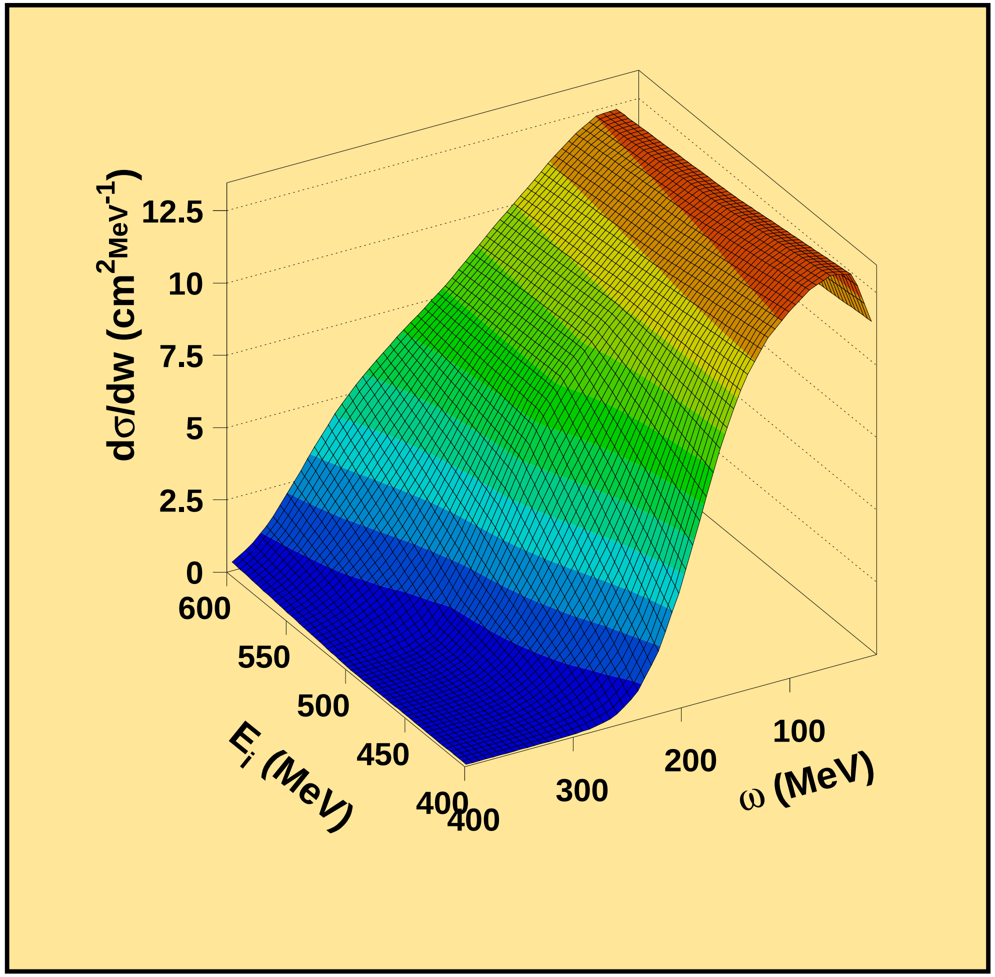
- FSI's : smooth transition between "optical potential" (low-energy) and "Glauber" (high-energy) regime ($pA \Longleftrightarrow pN$)
- Model can also be used to compute $A(\nu, \nu')$ and $A(p, 2p)$ observables

Effect of FSI and relativity on $^{16}O(\nu, \nu')$





RELATIVITY and FSI

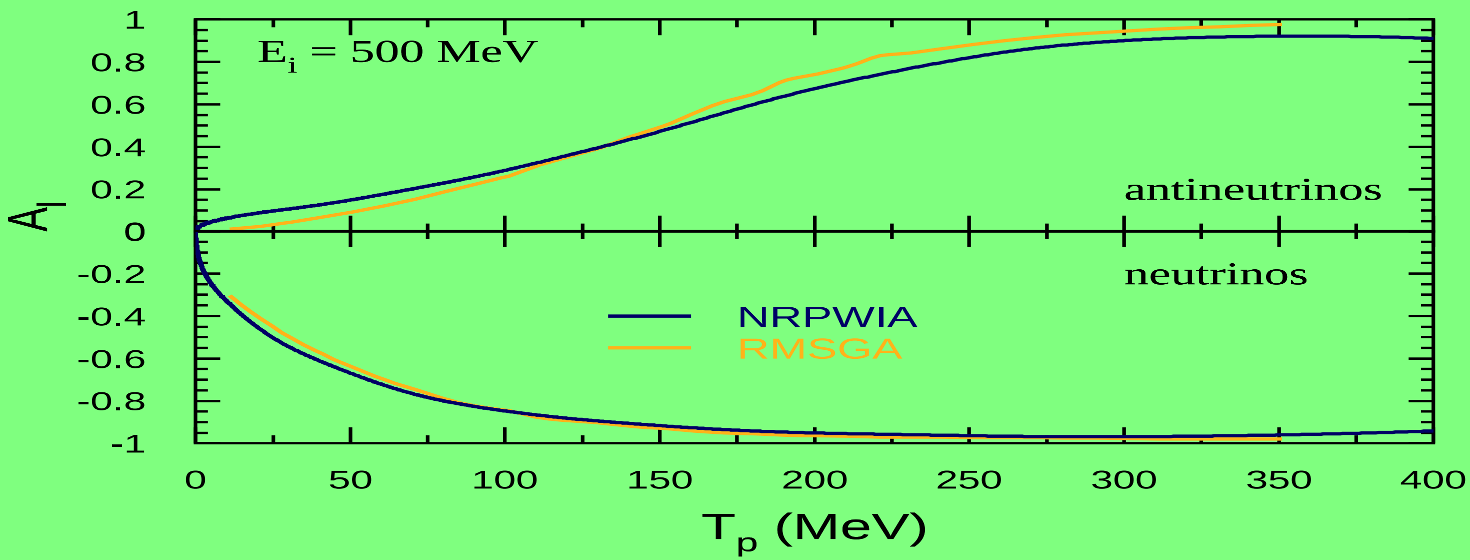
RELATIVITY

Discriminating between ν's and $\overline{\nu}$'s in Neutral-Current scattering

Measure the helicity asymmetry of the ejected nucleon !

*(PRL **93** (2004) 0825011, N. Jachowicz, K. Vantournhout, K. Heyde and J. Ryckebusch)*

$$A_l = \frac{d\sigma\left(\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} = +1\right) - d\sigma\left(\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} = -1\right)}{d\sigma\left(\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} = +1\right) + d\sigma\left(\frac{\vec{\sigma}\cdot\vec{p}}{|\vec{p}|} = -1\right)}$$



Relativistic eikonal model

Based on an Independent-Nucleon framework and the Impulse Approximation :

$A(\vec{e},e'\vec{p})$ observables from

$$\langle J^\mu \rangle = \int d\vec{r} \int d\vec{r}_2 \ldots \int d\vec{r}_A$$
$$\times \left(\Psi_A^{\vec{k}_p,m_s} \left(\vec{r},\vec{r}_2,\vec{r}_3,\ldots\vec{r}_A\right)\right)^\dagger \gamma^0 J^\mu(r) e^{i\vec{q}\cdot\vec{r}} \Psi_A^{gs} \left(\vec{r},\vec{r}_2,\vec{r}_3,\ldots\vec{r}_A\right) ,$$

$\Psi_A^{\vec{k}_p,m_s}$ and Ψ_A^{gs} : Slater determinants.
$J^\mu(r)$: one-body current

- FINAL STATE : Scattering Wave Function $u_f(K_f,s_f)$
- INITIAL STATE : Bound-state Wave Function $u_i(K_i,s_i)$
- OFF-SHELL ELECTRON-PROTON COUPLING : $\Gamma^\mu(K_f\ s_f,K_i\ s_i)$

Bound-state wave functions

Starting point : "$\sigma - \omega$ model" a relativistic quantum-field theory for nucleons (ψ) interacting through pions (π's), vector mesons (ρ's and ω's) and scalar mesons (σ's)

$$
\begin{aligned}
\mathcal{L} = {} & \bar{\psi}(\imath \not{\partial} - M)\psi + \frac{1}{2}(\partial_\mu \phi \partial^\mu \phi - m_s^2 \phi^2) - \frac{1}{4} G_{\mu\nu} G^{\mu\nu} \\
& + \frac{1}{2} m_v^2 V_\mu V^\mu - g_v \bar{\psi} \gamma_\mu \psi V^\mu + g_s \bar{\psi} \psi \phi \\
& + \frac{1}{2}(\partial_\mu \vec{\pi} \cdot \partial^\mu \vec{\pi} - m_\pi^2 \vec{\pi} \cdot \vec{\pi}) - \imath g_\pi \bar{\psi} \gamma_5 \vec{\tau} \cdot \vec{\pi} \psi \\
& - \frac{1}{4} \vec{B}_{\mu\nu} \cdot \vec{B}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{b}_\mu \cdot \vec{b}^\mu - \frac{1}{2} g_\rho \bar{\psi} \gamma_\mu \vec{\tau} \cdot \vec{b}^\mu \psi \\
& - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - e A_\mu [\bar{\psi} \gamma^\mu \frac{1}{2}(1 + \tau_3)\psi \\
& + (\vec{b}_\nu \times \vec{B}^{\nu\mu})_3 + (\vec{\pi} \times (\partial^\mu \vec{\pi} + g_\rho (\vec{\pi} \times \vec{b}^\mu)))_3] \, .
\end{aligned}
$$

solved in the Hartree approximation

$<\phi(r)>\equiv \phi_0(r)$ and $<V^\mu(r)>\equiv \delta^{\mu 0}V_0(r)$

Single-particle wave functions

$$\phi_\alpha(\vec{x}) \equiv \phi_{n\kappa m}(\vec{x}) = \left[\begin{array}{c} \imath \frac{G_{n\kappa}(r)}{r} \ \mathcal{Y}_{\kappa m}(\Omega, \vec{\sigma}) \\ -\frac{F_{n\kappa}(r)}{r} \ \mathcal{Y}_{-\kappa m}(\Omega, \vec{\sigma}) \end{array} \right] ,$$

$$\mathcal{Y}_{\kappa m}(\Omega, \vec{\sigma}) = \sum_{m_l m_s} \left\langle l m_l \frac{1}{2} m_s \mid jm \right\rangle Y_{l m_l}(\Omega) \chi_{\frac{1}{2} m_s}(\vec{\sigma}) \ ,$$

$$j = |\kappa| - \frac{1}{2} \ , \qquad l = \left\{ \begin{array}{ll} \kappa, & \kappa > 0 \\ -(\kappa+1), & \kappa < 0 \ . \end{array} \right.$$

Electron-Proton Coupling

Some arbitrariness translating itself in a variety of recipes.

$$< K_f S_f | J^\mu | K_i S_i >= \bar{u}_f(K_f, S_f)\Gamma^\mu(q^\mu, K_f, K_i) u_i(K_i, S_i) \ ,$$

$$\begin{aligned}
\Gamma^\mu_{cc1} &= G_M(Q^2)\gamma^\mu - \frac{\kappa}{2M} F_2(Q^2)(K_i^\mu + K_f^\mu) \ , \\
\Gamma^\mu_{cc2} &= F_1(Q^2)\gamma^\mu + \imath \frac{\kappa}{2M} F_2(Q^2)\sigma^{\mu\nu} q_\nu \ , \\
\Gamma^\mu_{cc3} &= \frac{1}{2M} F_1(Q^2)(K_i^\mu + K_f^\mu) + \imath \frac{1}{2M} G_M(Q^2)\sigma^{\mu\nu} q_\nu \ ,
\end{aligned}$$

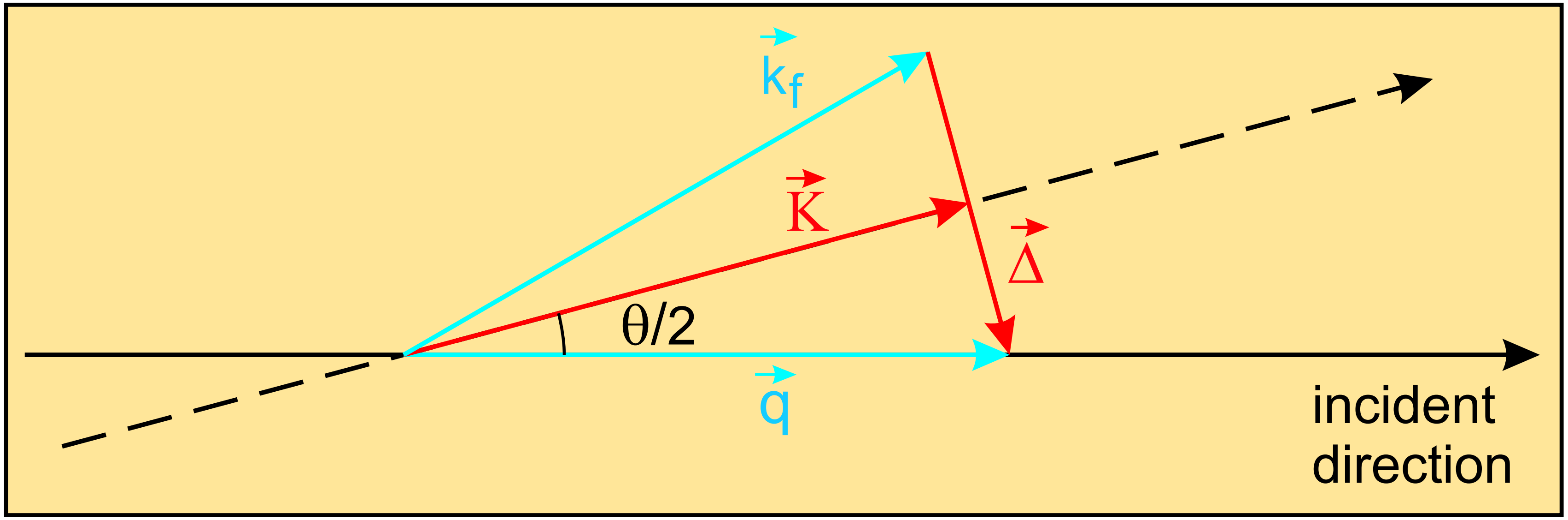
To restore gauge invariance :

$$J_\mu = \left(J_0, J_1, J_2, \frac{\omega J_0}{q}\right) \qquad \text{OR} \qquad J_\mu = \left(\frac{q J_3}{\omega}, J_1, J_2, J_3\right)$$

Relativistic Eikonal Approach to potential scattering

Semi-classical approximation

1. $\lambda_{deBroglie} \ll a$, a : typical range of the potential !
2. Missing momentum $\ll$ momentum transfer $\vec{q}$!



$$\psi^{(+)}_{\vec{k}_f,s} \sim \left[\frac{1}{\frac{1}{E+M+V_s-V_v}\vec{\sigma}\cdot\vec{p}} \right] e^{\imath \vec{k}_f\cdot\vec{r}} e^{\imath S(\vec{r})} \chi_{\frac{1}{2}m_s} \; ,$$

Differs from a relativistic plane wave !!!

- Dynamical relativistic effect on the lower components !

$$\imath S(\vec{b}, z) = -\imath \frac{M}{K} \int_{-\infty}^{z} dz' \, [V_c(\vec{b}, z') + V_{so}(\vec{b}, z')[\vec{\sigma} \cdot (\vec{b} \times \vec{K}) - \imath K z']],$$

- Eikonal Phase !

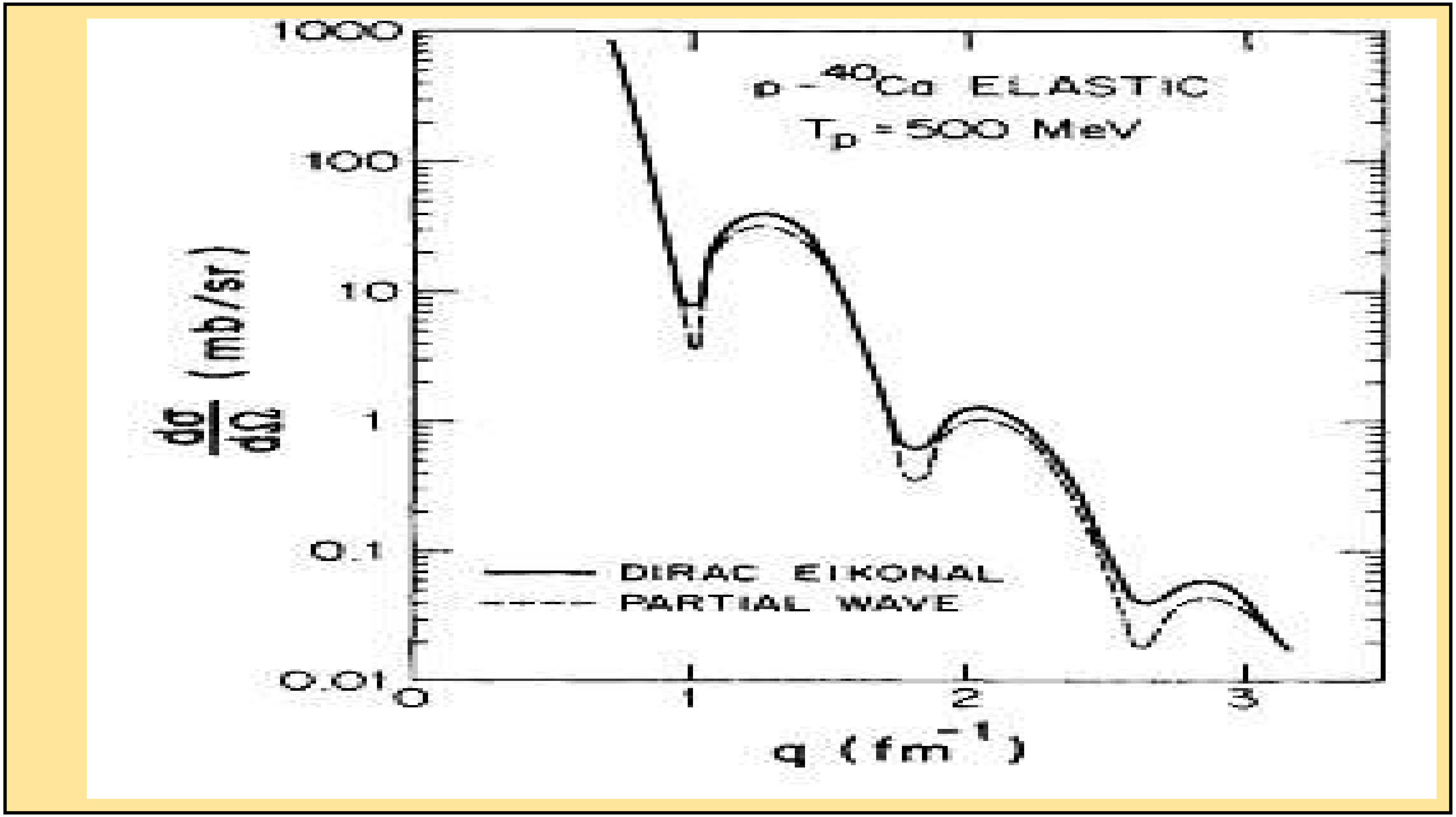
ROMEA : V_c and V_{so} from global optical-potential fits (e.g. (EDAI-X) : E. Cooper *et al.*, PRC **47** (1993) 297.).

RDWIA (*J. Vignote*) ⇔ ROMEA : identical ... apart from the use of the eikonal approximation to obtain the "scattering states".

The eikonal approximation

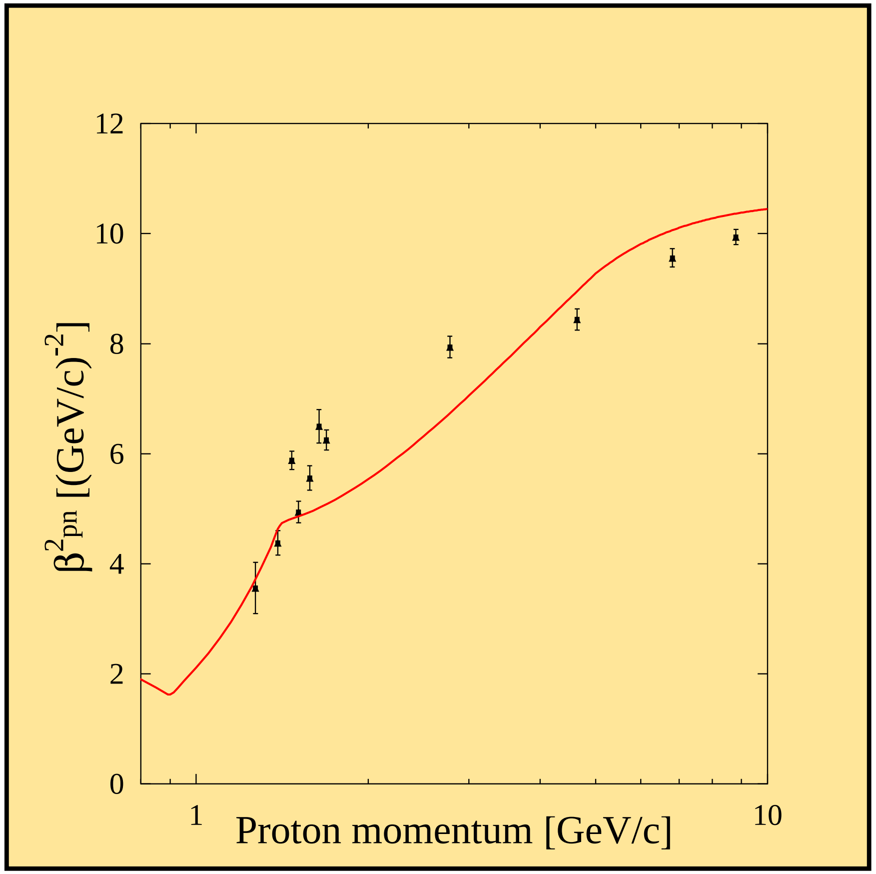
In proton-nucleus scattering the "Dirac" Eikonal approximation was shown to be fine!

(R. Amado et al., *PRC 28 (1983) 1663)*

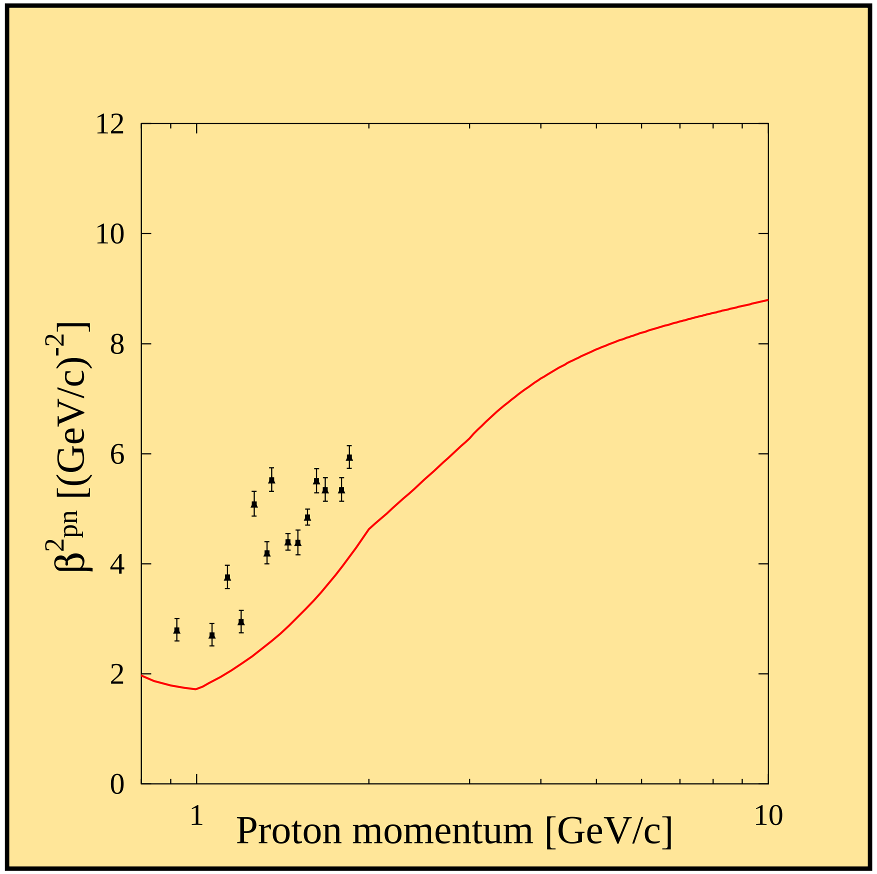


Slope parameters

Data : from fit to the angular distributions
Curves : from the ratio of the total to the elastic cross section pN data (PDG tables)



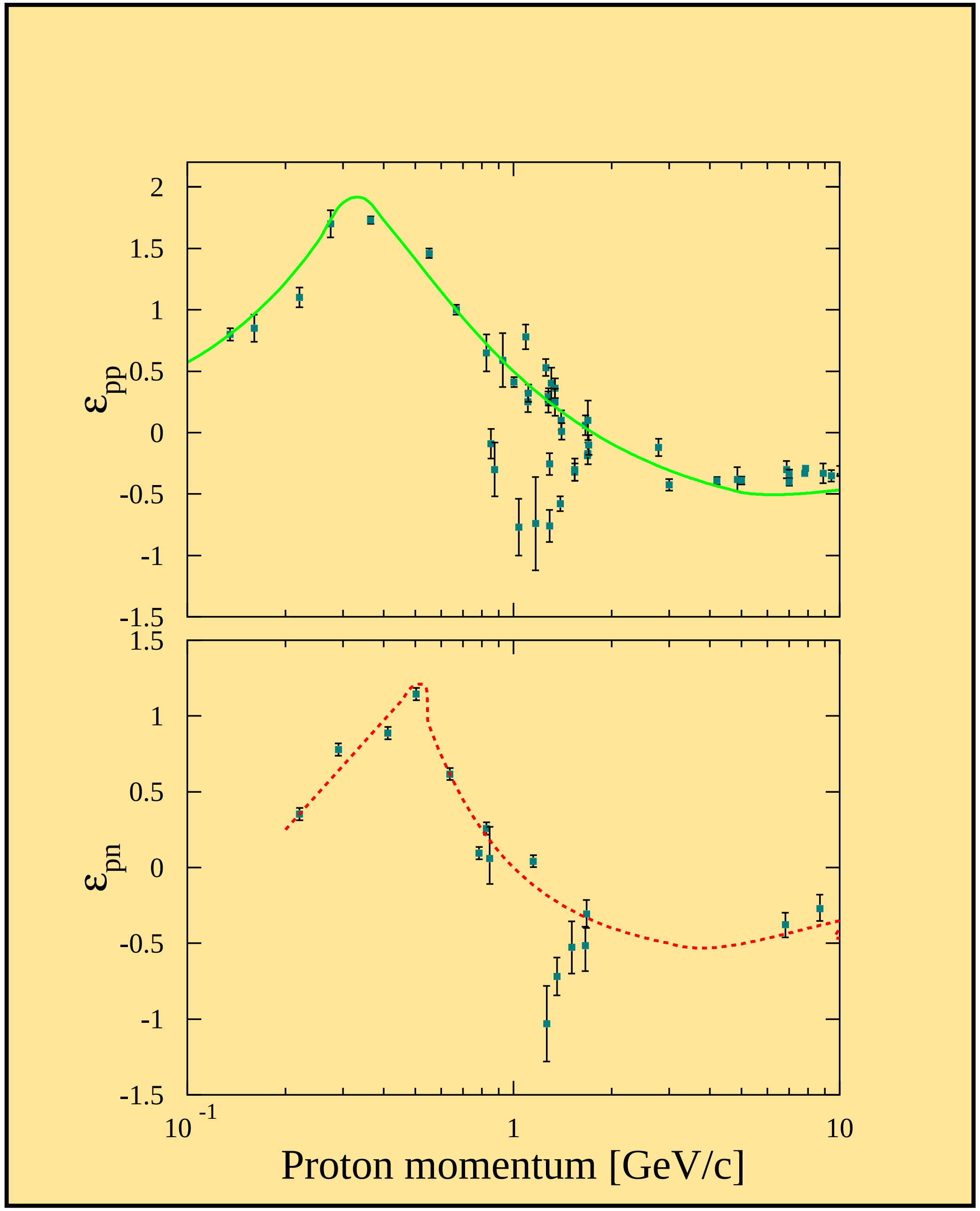
proton-proton



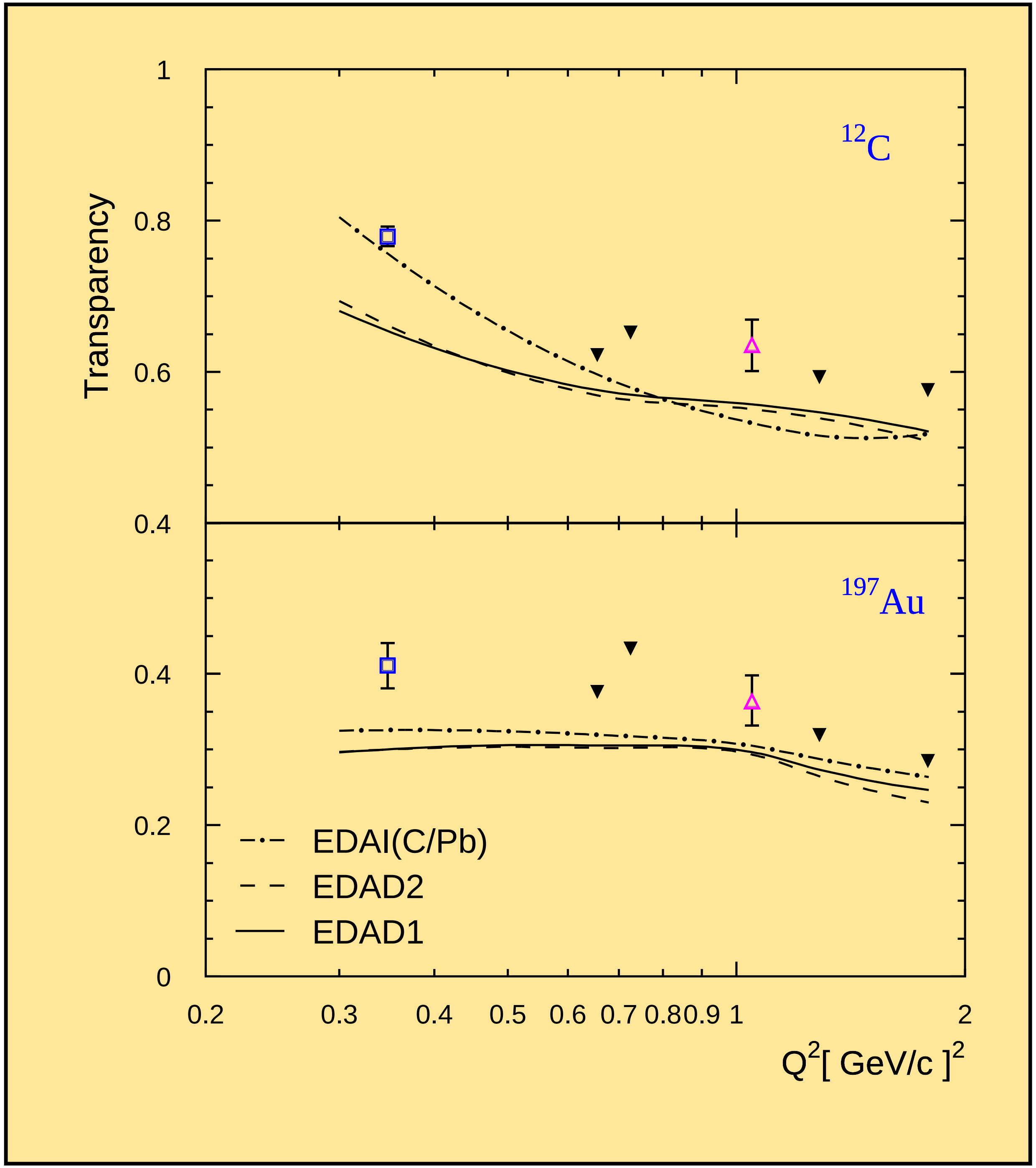
proton-neutron

The pN data are usually analyzed excluding the spin-dependent terms.

The ratio of the real to imaginary part of the central amplitude in pp and pn scattering !

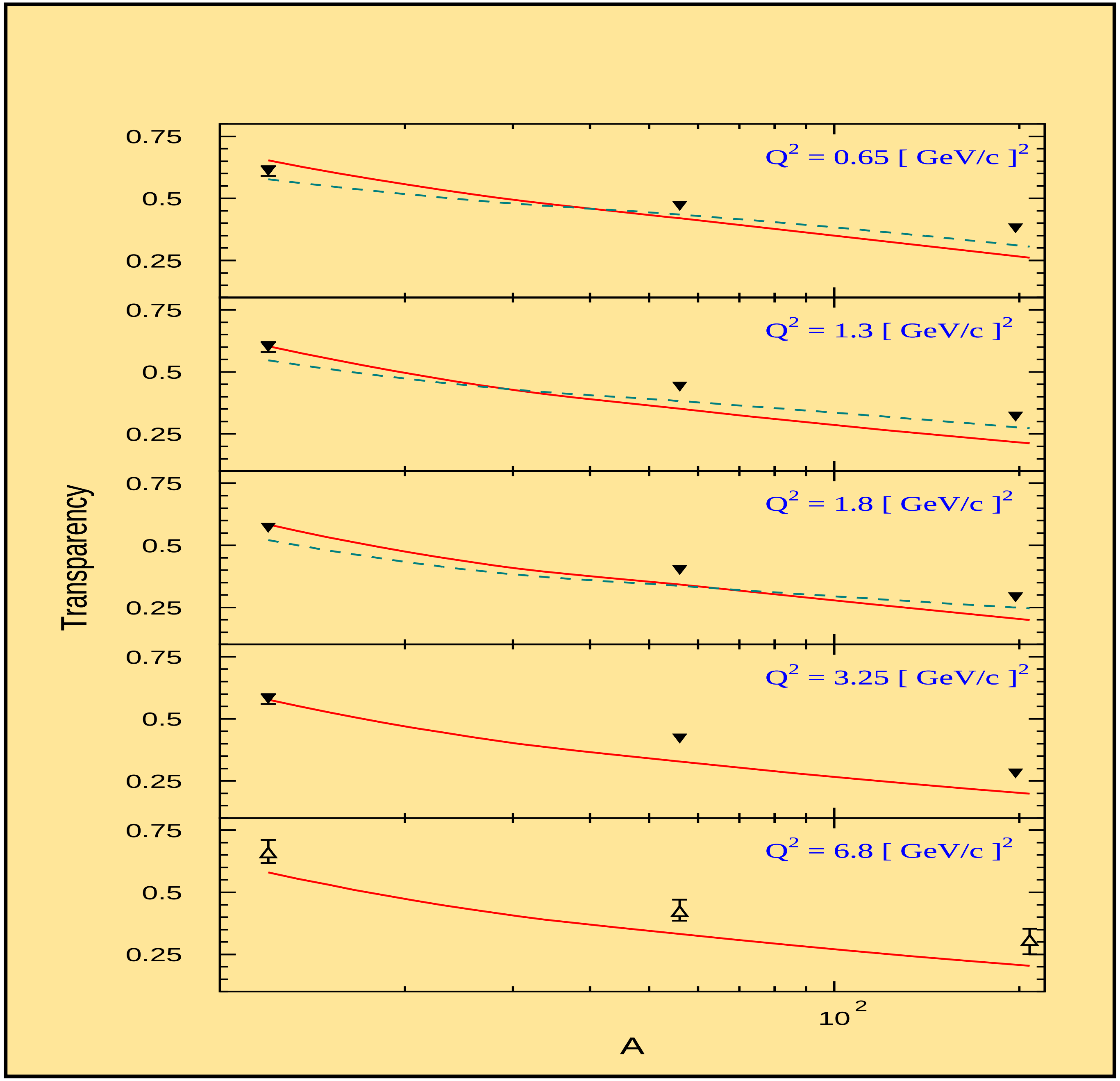


Nuclear Transparency : RDWIA results



- Transparency depends moderately on the choice for "optical potential"
- EDAD : global fit with various T_p AND A
- EDAI : global fit with various T_p

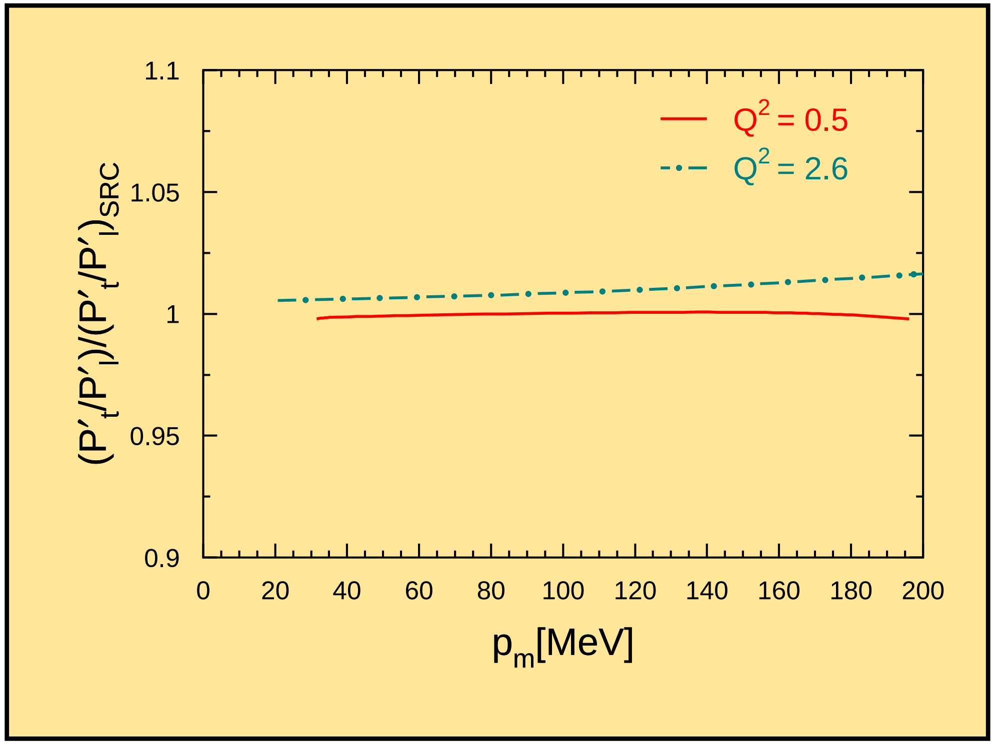
Nuclear Transparency : A dependence

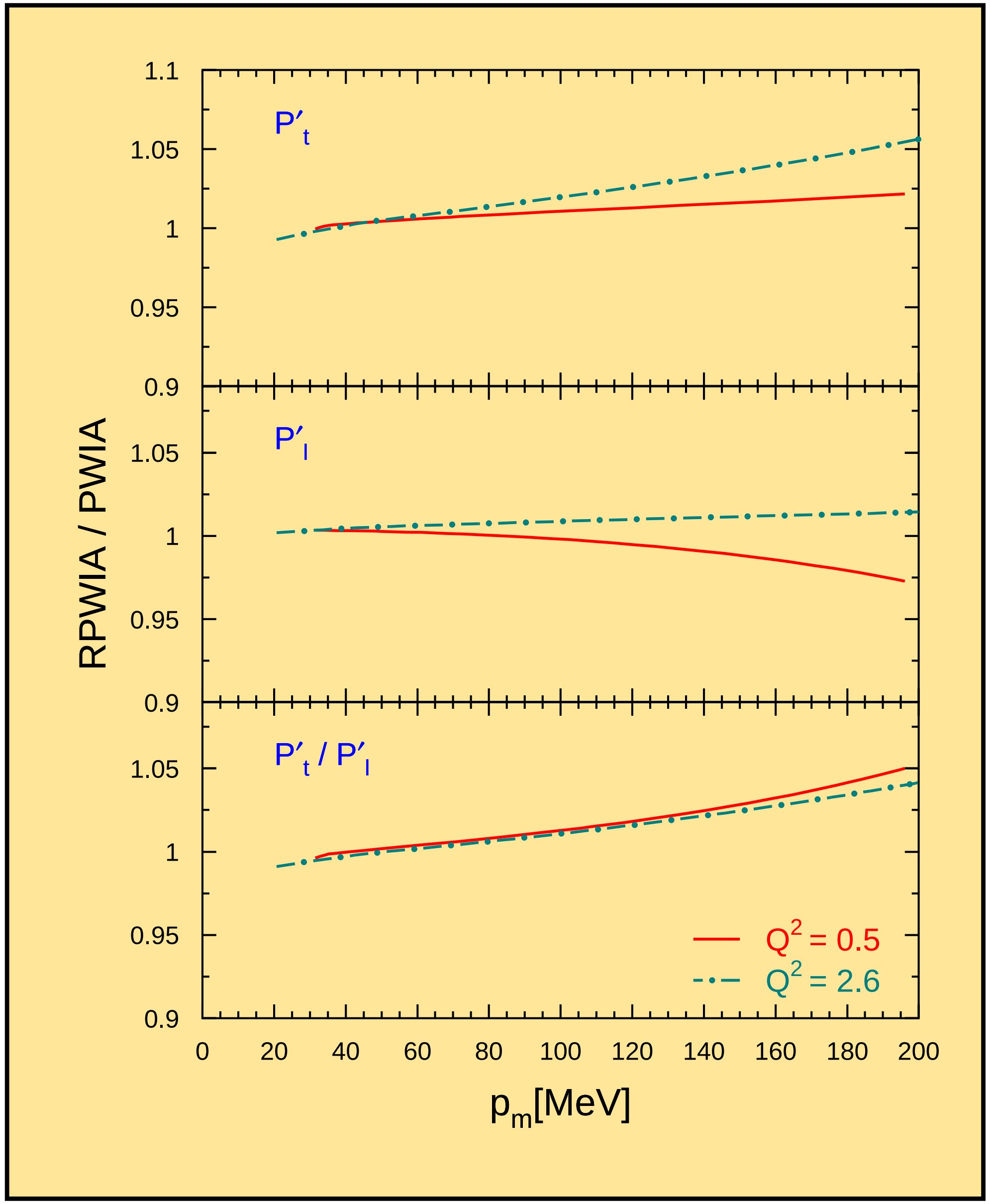


RDWIA
RMSGA

Very little room for medium-modification of pN interactions ; would introduce an additional A dependence !

^{4}He$(\vec{e}, e'\vec{p})^3$H : correlations and relativity

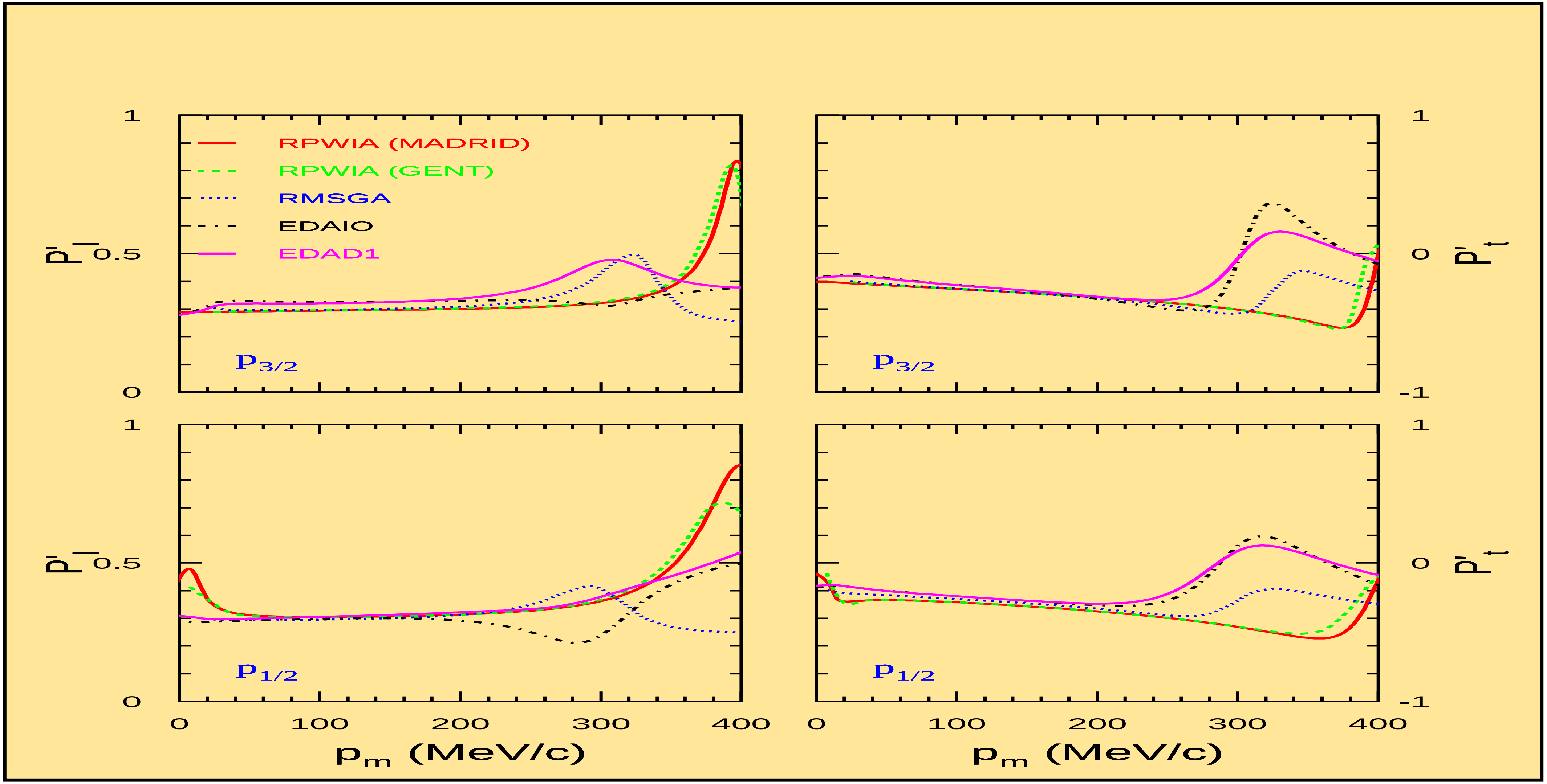




SHORT-RANGE CORRELATIONS **RELATIVITY**

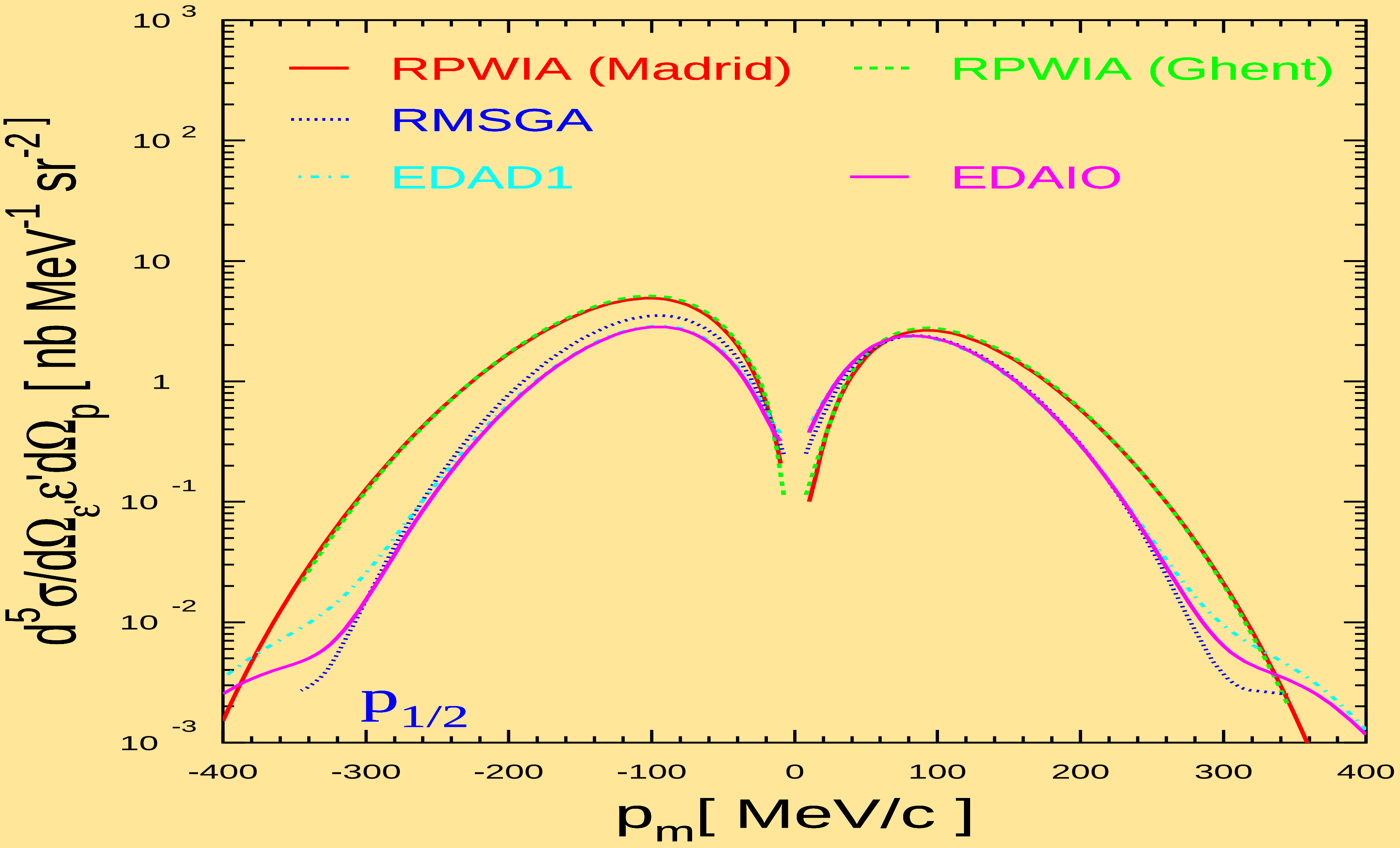
How does RMSGA compare to RDWIA ? (I)

$^{16}O(\vec{e}, e'\vec{p})$: ω=0.44 and q=1.0 GeV

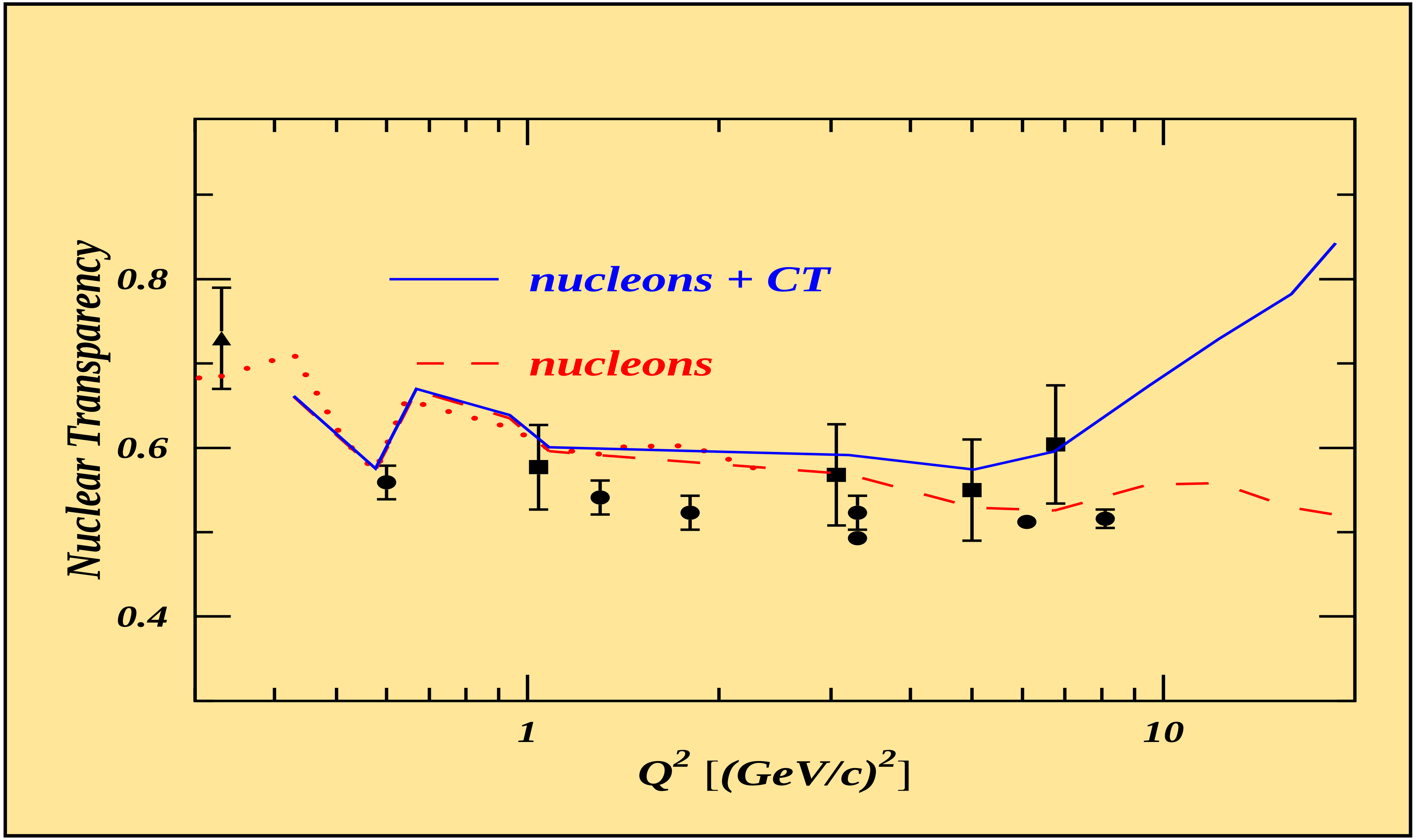


RPWIA(Madrid) : C. Martinez and J.M. Udías

How does RMSGA compare to RDWIA ? (II)



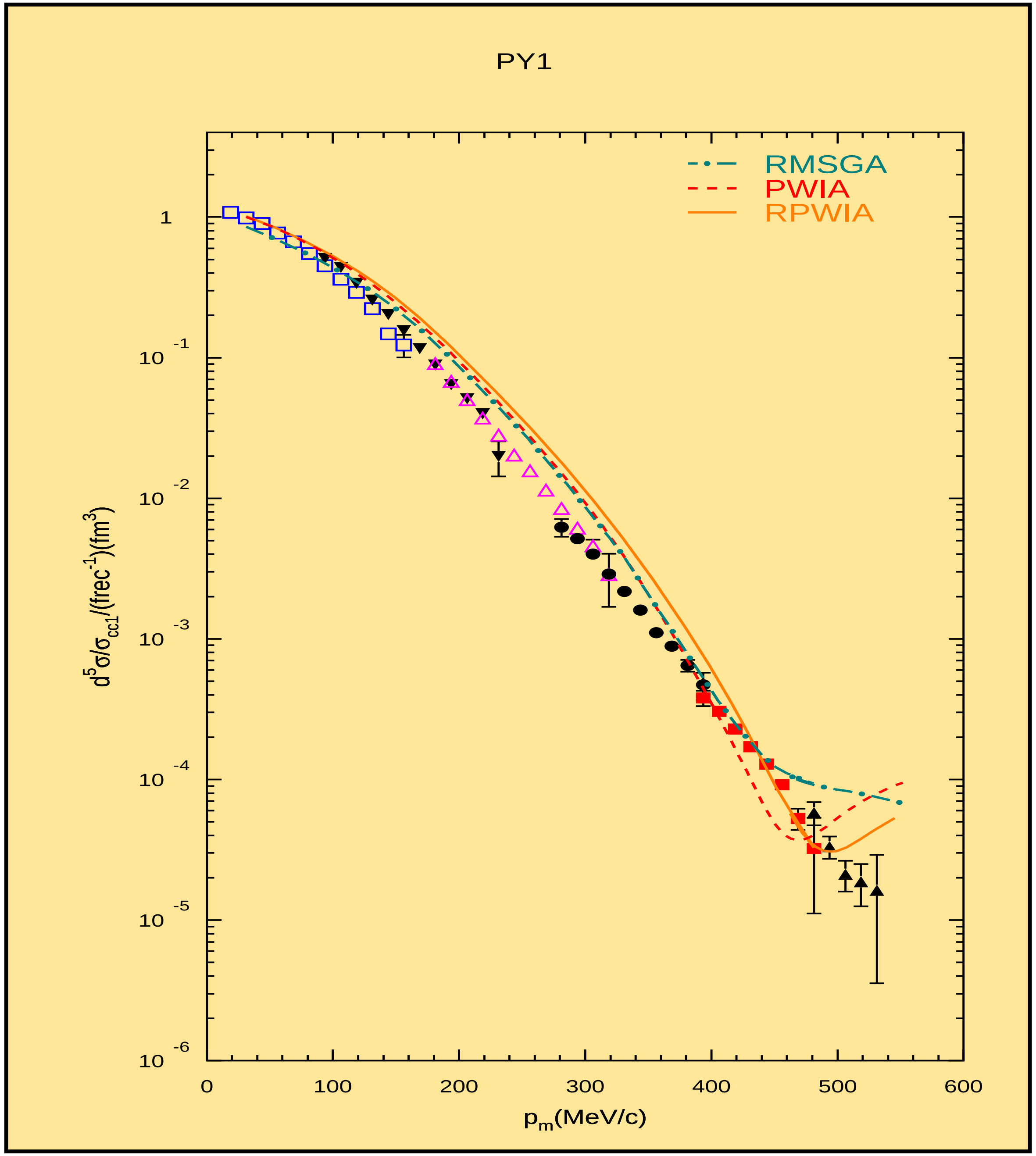
$^{12}C(e, e'p)$ Transparency : ROMEA ⇔ RMSGA



. . . . : ROMEA (pA picture)

- - - - : RMSGA (pN picture)

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



Data from JLAB
(E97-111)
ϵ=2.4 GeV
$0.28 \leq Q^2 \leq 0.44$ (GeV)^2
$0.284 \leq \omega \leq 1.035$ GeV
Spectroscopic factor=1