Single proton knock-out at JLab, MAMI, and MIT-Bates

S. Širca, U. of Ljubljana, Slovenia Milos, Greece, 10 Sep 2007

Topics [the $(\mathrm{e},\mathrm{e}'\mathrm{p})$ 'hierarchy']

▷ Complex nuclei

- Limits of the impulse approximation
  - Dynamical relativistic effects
  - Nuclear transparency
  - Short-range correlations → J. Watson
  - Connection to neutrino probes
  - Medium modification of FFs → S. Strauch, O. Buss

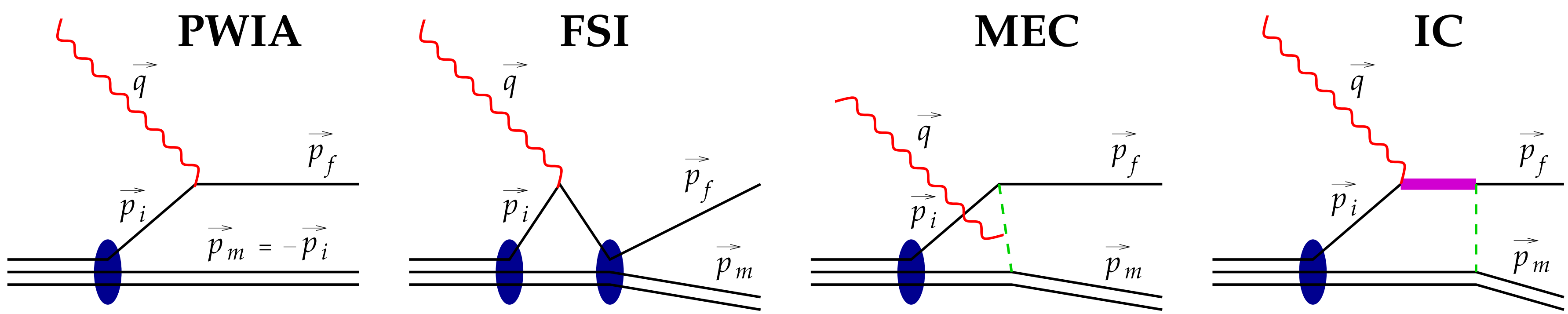
▷ ^{4}He, ^{3}He

- Testing ground of few-body theories
  - Benchmark experiments
  - Breakdown of factorization at high p_{m}
  - 3-body mechanisms
  - ^{3}He ground-state WF components
  - Triple polarization

▷ Deuteron

- The nucleus we don't know well enough
  - Severe discrepancies even at low E

The $A(e, e'N)A-1$ alphabet



missing energy $E_m = \omega - T_N - T_{A-1}$

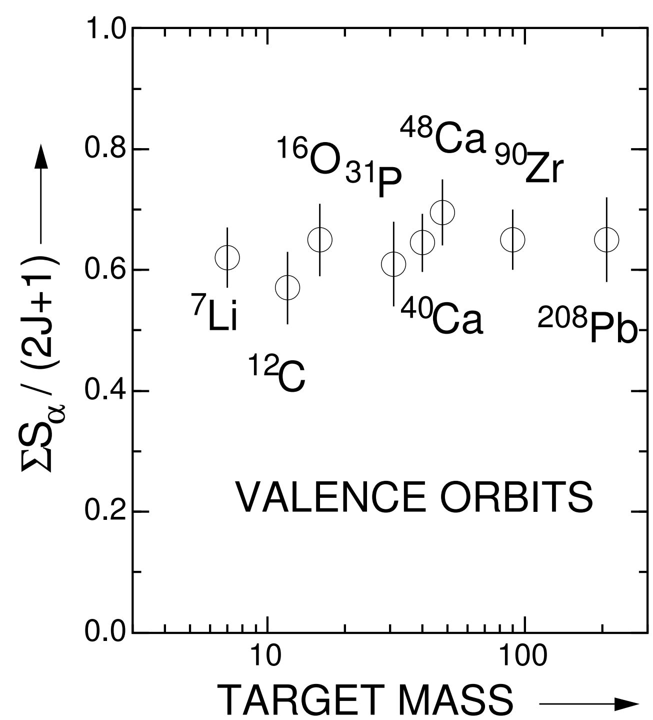
missing momentum $\vec{p}_m = \vec{q} - \vec{p}_f$

PWIA $$\frac{d^6\sigma}{d\omega\, d\Omega_e\, dp_f\, d\Omega_N} = K\sigma_{eN}\, S(E_m, \vec{p}_m)$$

$$S(E_m, \vec{p}_m) = \sum_\alpha S_\alpha |\Phi_\alpha(-\vec{p}_m)|^2 \delta(E_\alpha - E_m)$$

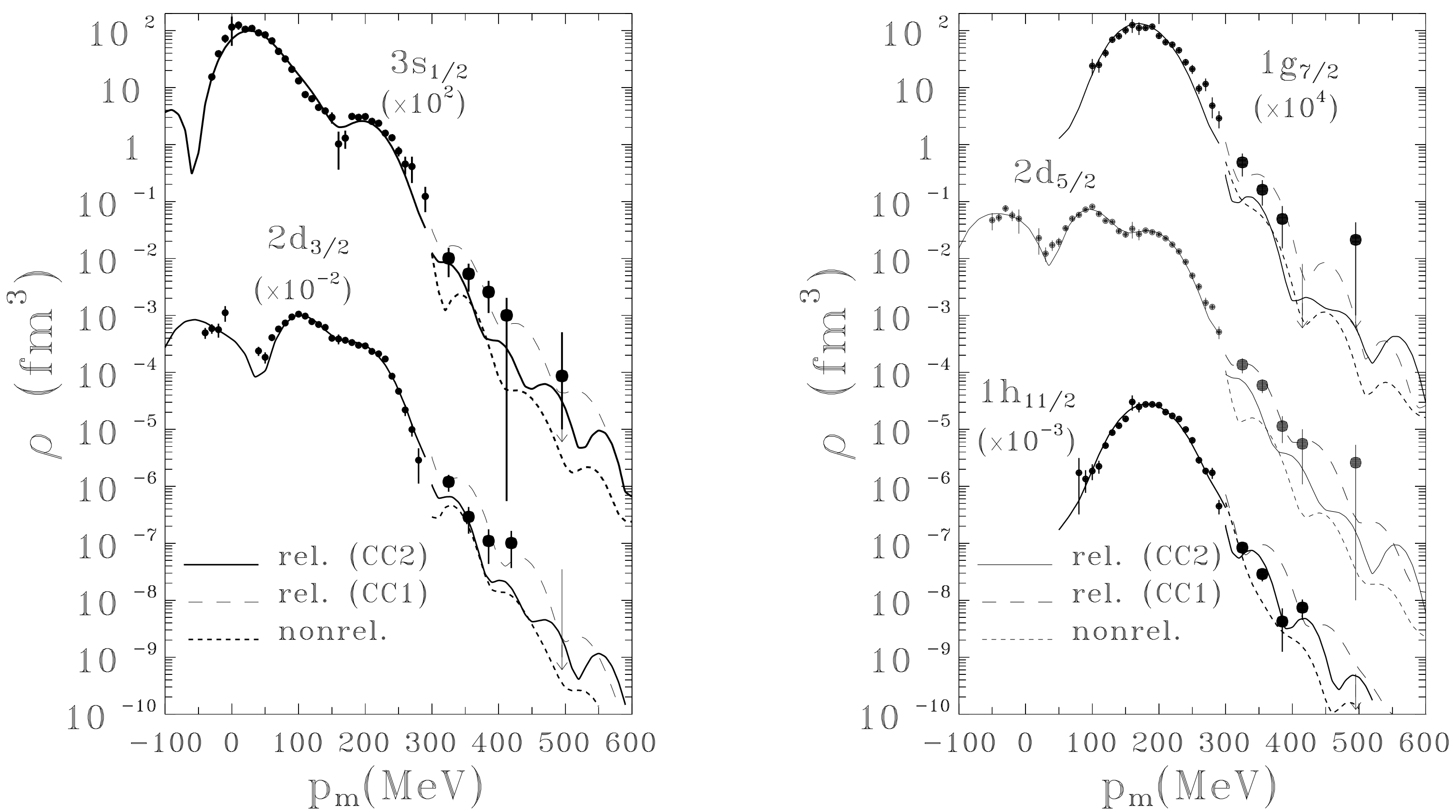
DWIA $$\frac{d^6\sigma}{d\omega\, d\Omega_e\, dp_f\, d\Omega_N} = K\sigma_{eN}\, D(E_m, \vec{p}_m, \vec{p}_f)$$

reduced XS $\rho \sim d^6\sigma / K\sigma_{eN}$

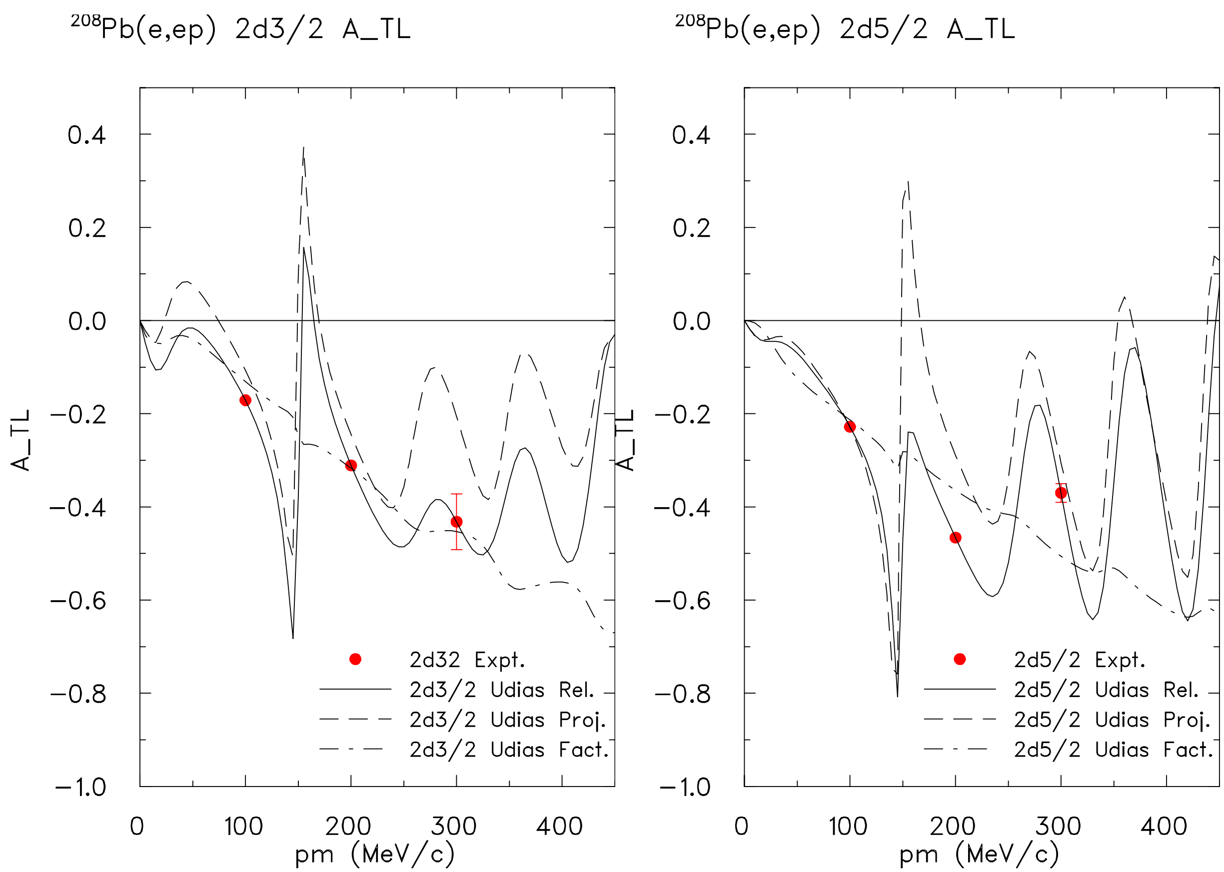


Complex nuclei $^{208}\mathrm{Pb}(\mathrm{e},\mathrm{e}'\mathrm{p})^{207}\mathrm{Tl}$

- Successes and limitations of experimental studies and theory
- ^{208}Pb: textbook nucleus for MF approaches
- Exclusive $(\mathrm{e},\mathrm{e}'\mathrm{p})$ process probes different regions of interior ($0 \leq l \leq 5$)
  $E_\mathrm{m} = 0$ ($3s_{1/2}$), 0.351 ($2d_{3/2}$), 1.348 ($1h_{11/2}$), 1.683 ($2d_{5/2}$), 3.470 MeV ($1g_{7/2}$)



- Cross-sections to $p_{\mathrm{m}} \approx 500\,\mathrm{MeV/c}$ and A_{LT} up to $p_{\mathrm{m}} \approx 300\,\mathrm{MeV/c}$
- First time in true QE kinematics at fixed $(\omega, \vec{q}) = (430, 1000)$
- Origin of excess strength at high p_{m} — LRC or relativity?
- Compare spectroscopic factors to those at lower Q^2



Nuclear transparency in $(\mathrm{e},\mathrm{e}'\mathrm{p})$

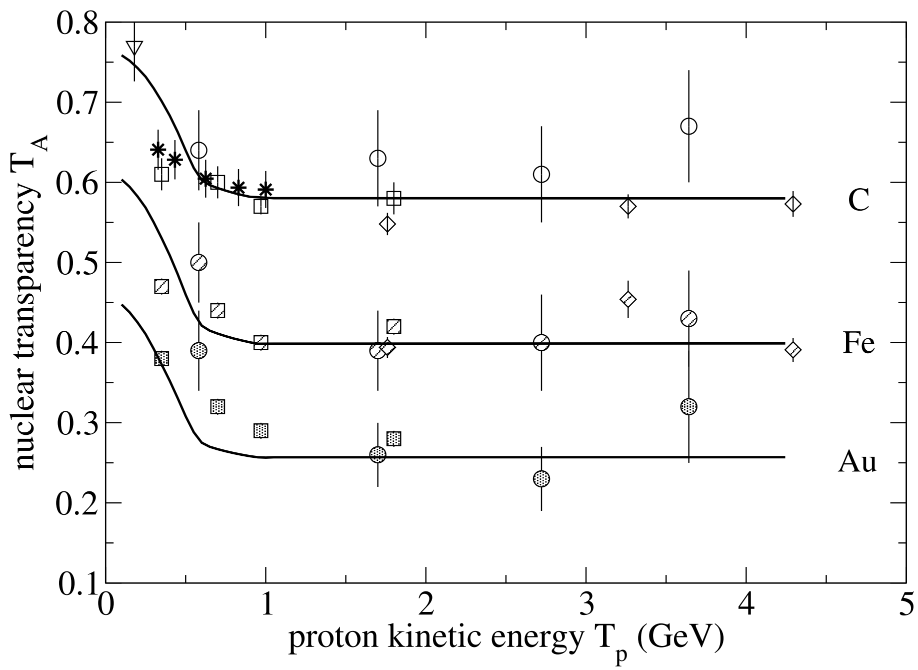
- (Final-state) reduction of proton flux in $(\mathrm{e},\mathrm{e}'\mathrm{p})$ at high T_p

$$T_A(Q^2) = \frac{1}{\varepsilon^{\mathrm{SRC}}(A)} \frac{\int_V d^3p_\mathrm{m}\, dE_\mathrm{m}\, N^{\mathrm{exp}}(E_\mathrm{m},\vec{p}_\mathrm{m})}{\int_V d^3p_\mathrm{m}\, dE_\mathrm{m}\, N^{\mathrm{calc}}(E_\mathrm{m},\vec{p}_\mathrm{m})}$$

$$N^{\mathrm{calc}} = N^{\mathrm{PWIA}}, \quad \varepsilon^{\mathrm{SRC}}(A) \neq 1$$

$$\text{better}: \; N^{\mathrm{calc}} = (1-x)N^{\mathrm{IPSM}} + xN^{\mathrm{SRC}}, \quad \varepsilon^{\mathrm{SRC}}(A) \equiv 1$$

- Validity of optical-potential vs. Glauber approaches for FSI

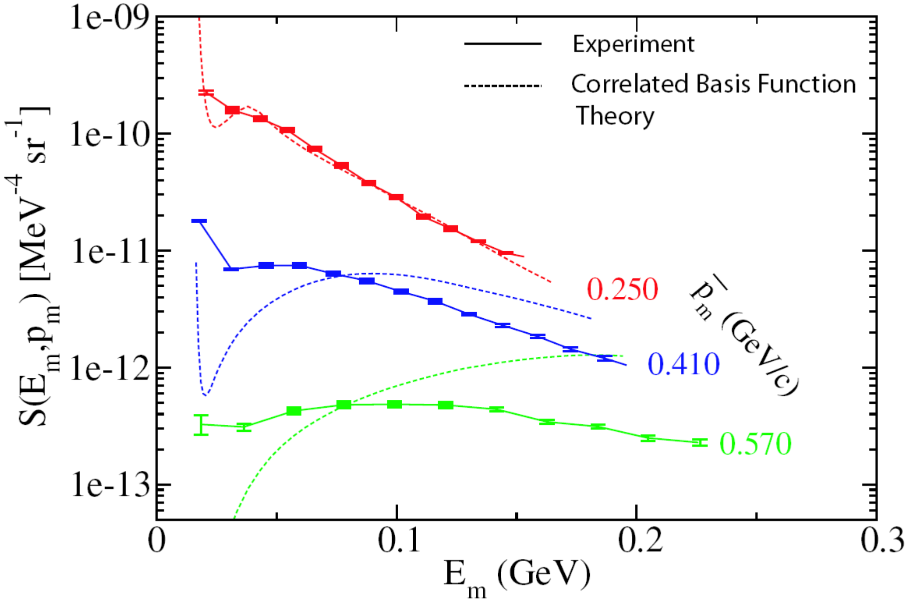


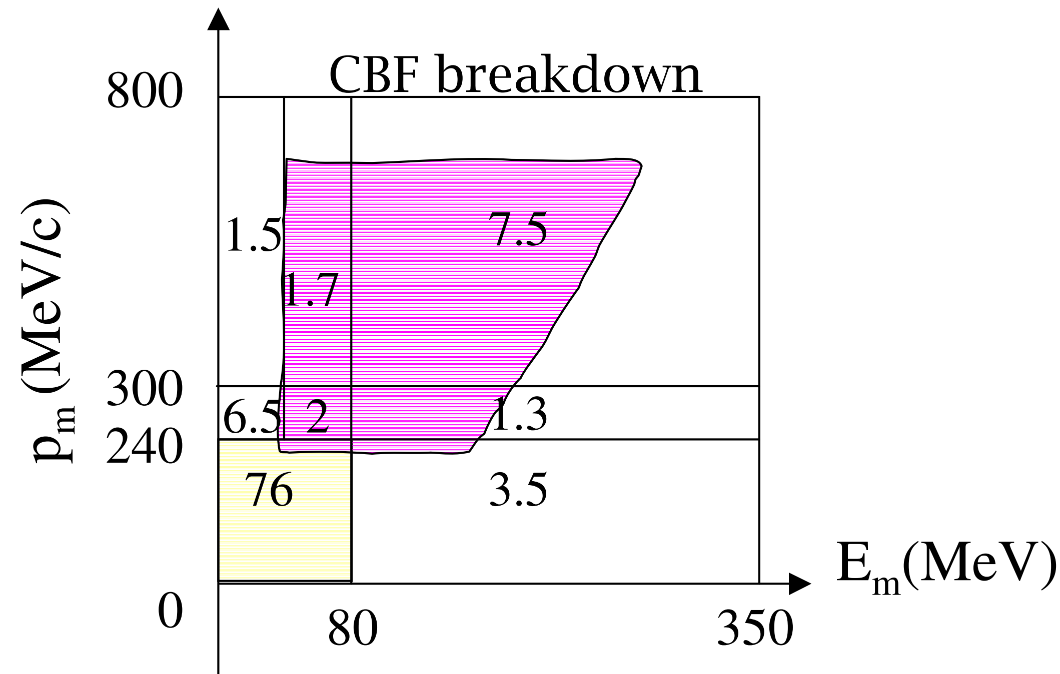
PRC **72** (2005) 054602

PRC **68** (2003) 064603

Correlated strength in $S(E_\mathrm{m}, p_\mathrm{m})$

- correlations depopulate IP strength at low E, k (= E_m, p_m in PWIA)
- but also directly identifiable at high E ***and*** k, quasi-$\parallel$ kinematics best bet
- $\sim$ 80 % of IP motion (CBF, NPA **505** (1989) 267)
- correlated strength 0.61 ± 0.06 (exp), 0.64 (CBF) in measured region
  (in terms of # protons) 1.32 (CBF) total

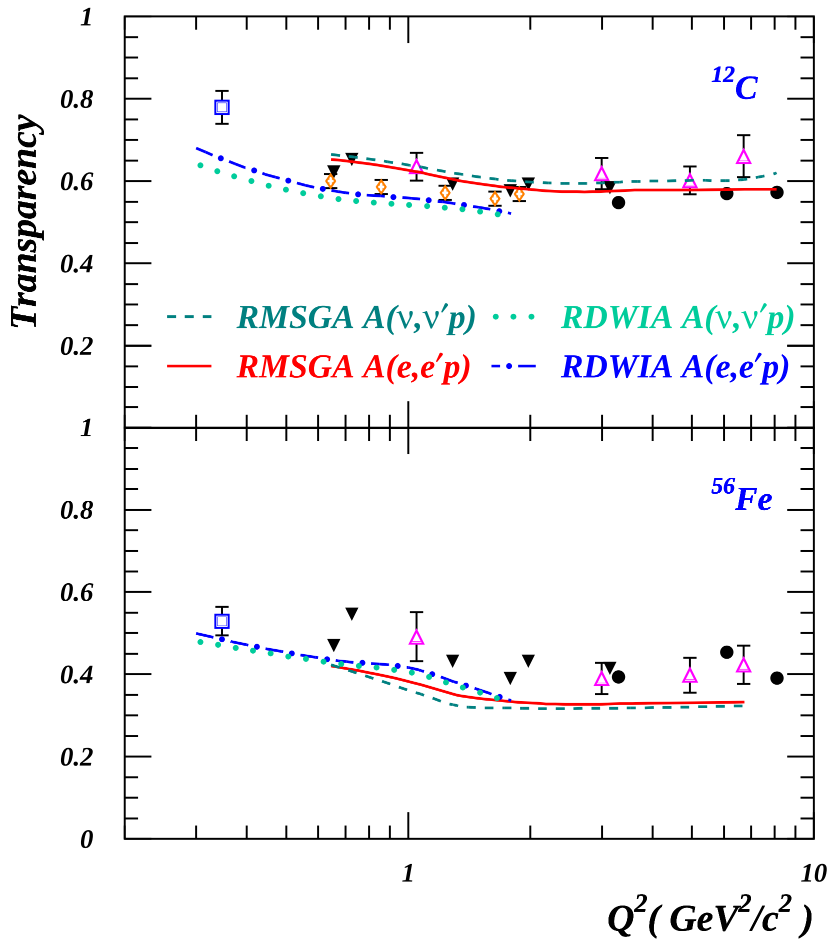


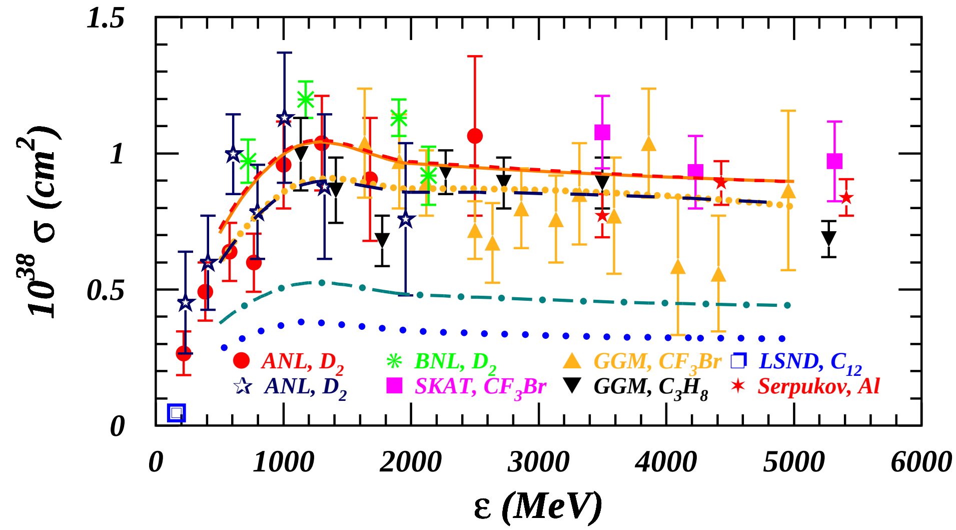


PRL **93** (2004) 182501

- minor issue: measured and calculated $S(E, k)$ differ

- RDWIA: complex optical potentials for p − A FSI
- RMSGA: Glauber multiple-scattering extension of eikonal + frozen approx
- goal: obtain FSI estimates for A(ν, ν′p) from transparency in A(e, e′p)



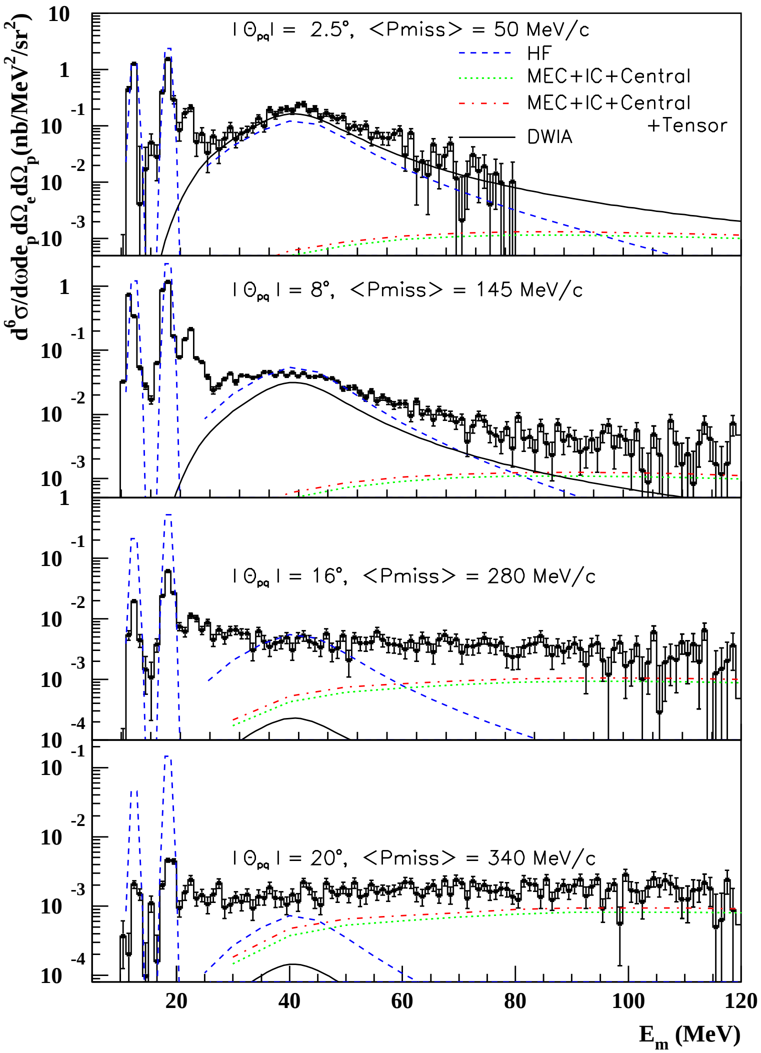


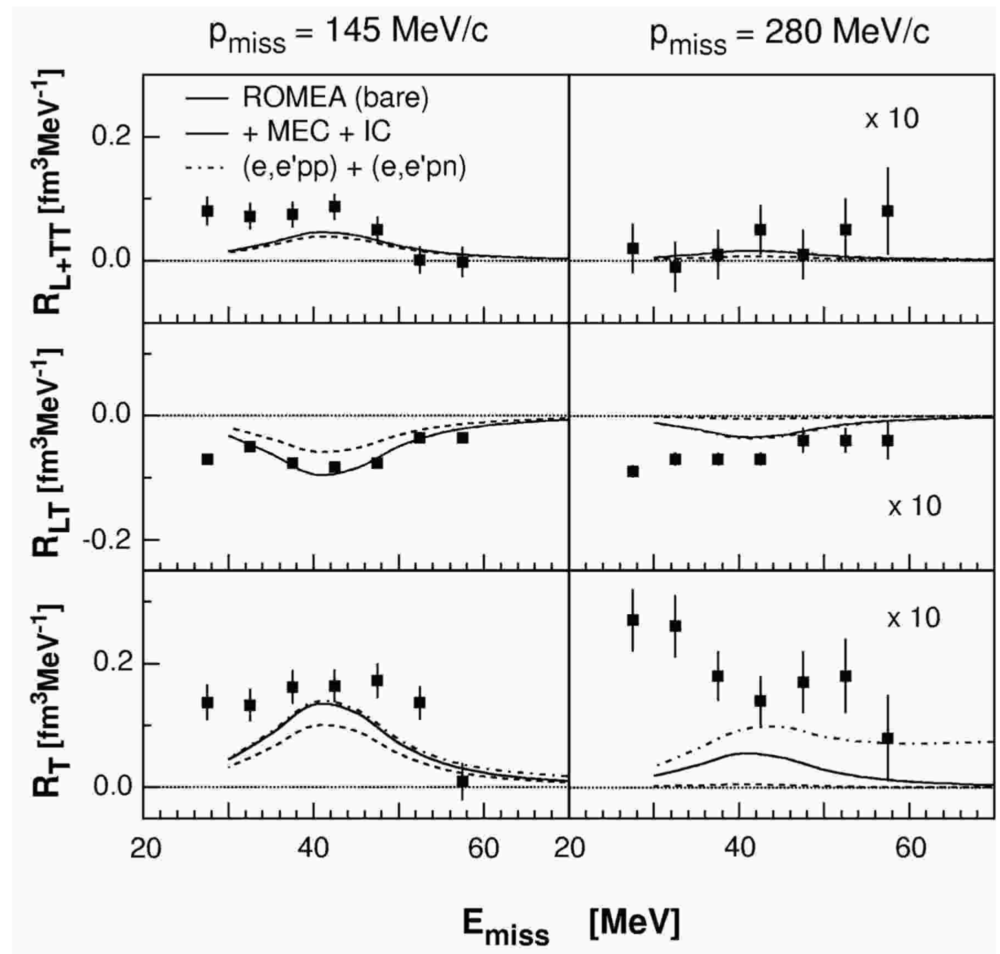
- T independent of leptonic probe
- RDWIA, RMSGA, RPWIA×T all agree
- ∼ 50 % of measured (ν_μ, μ^-) strength is single-nucleon knockout
- π production (Δ): work in progress

PRC **73** (2006) 024607

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

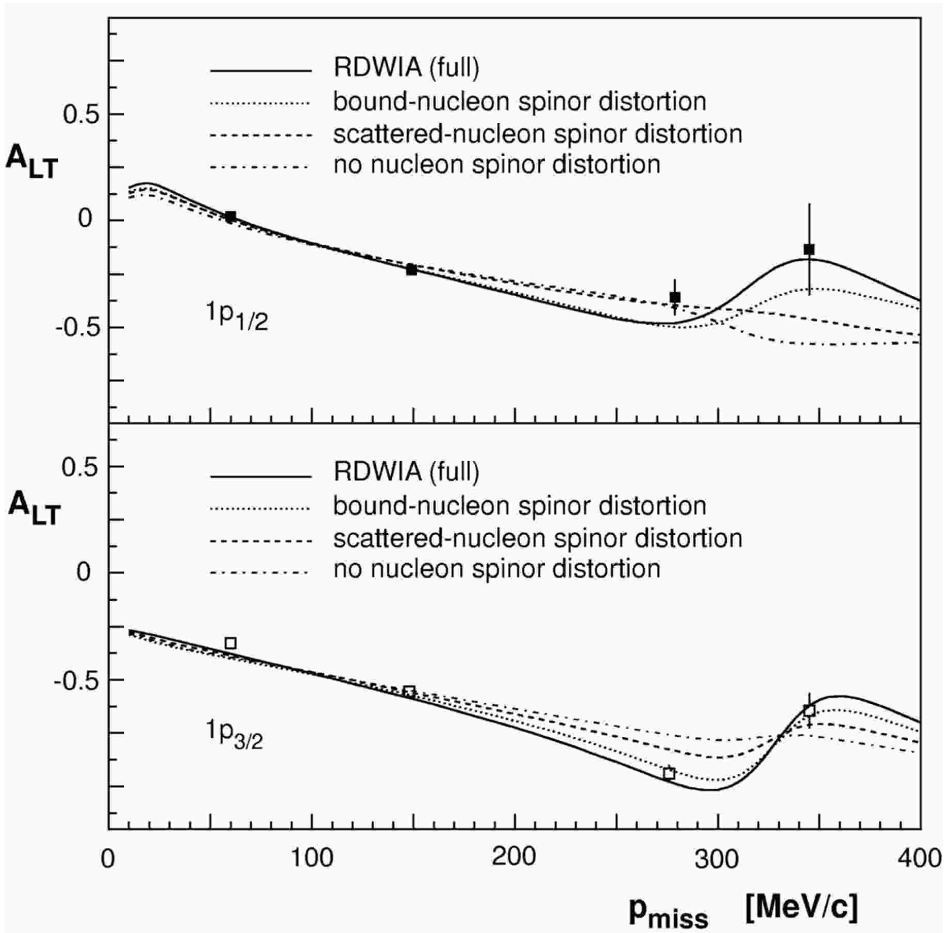
- $d^6\sigma$, R_T, R_{L+TT}, R_{LT} measured for $25 \le E_m \le 120$ MeV and $p_m \le 340$ MeV/c





PRC **70** (2004) 034606, PRL **86** (2001) 5670

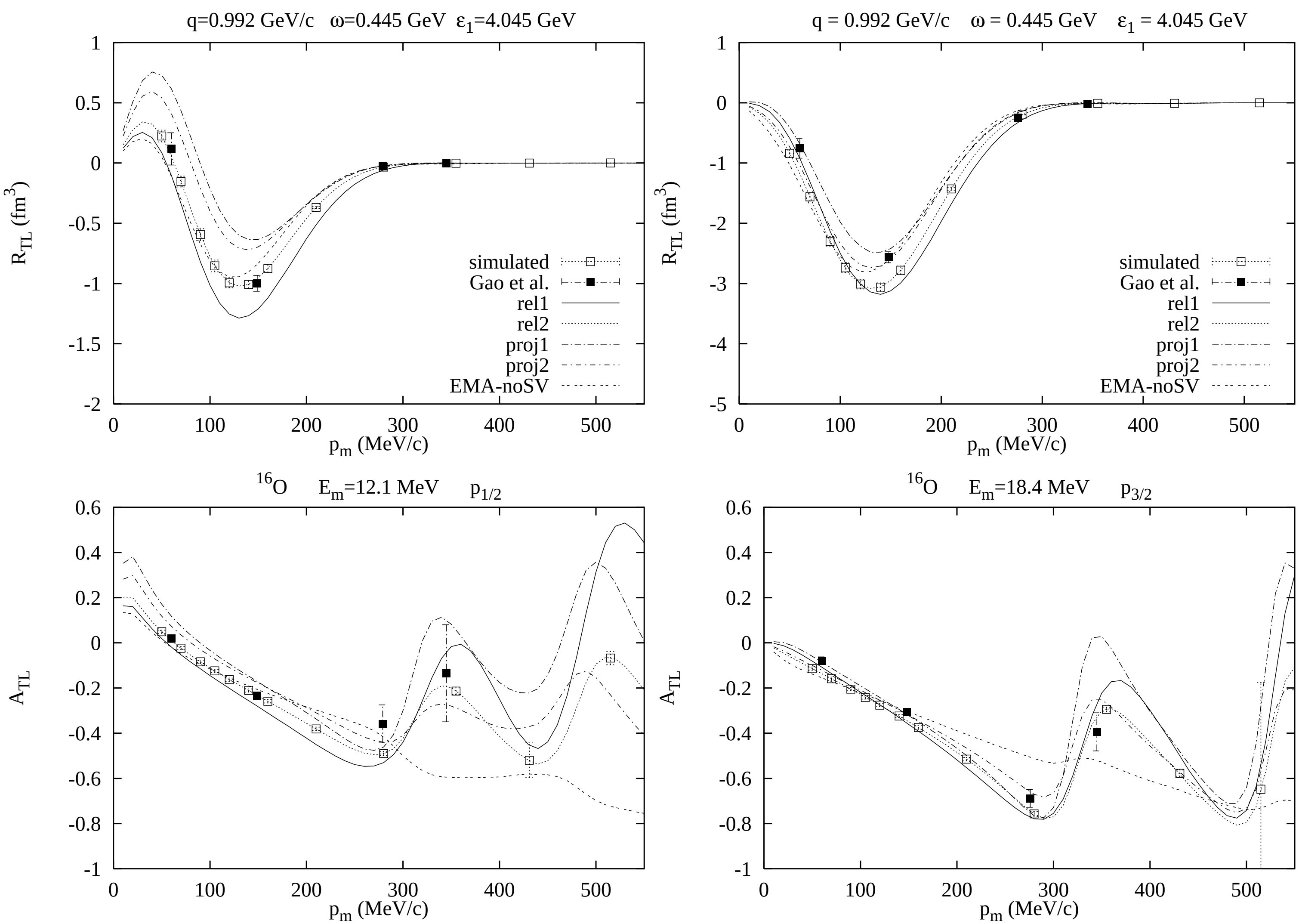
$^{16}O(e,e'p)n : (1p_{1/2}, 1p_{3/2})$ **states**



Enhancement of lower components of bound (and scattered) Dirac spinors crucial in description of A_{LT}, R_{LT}

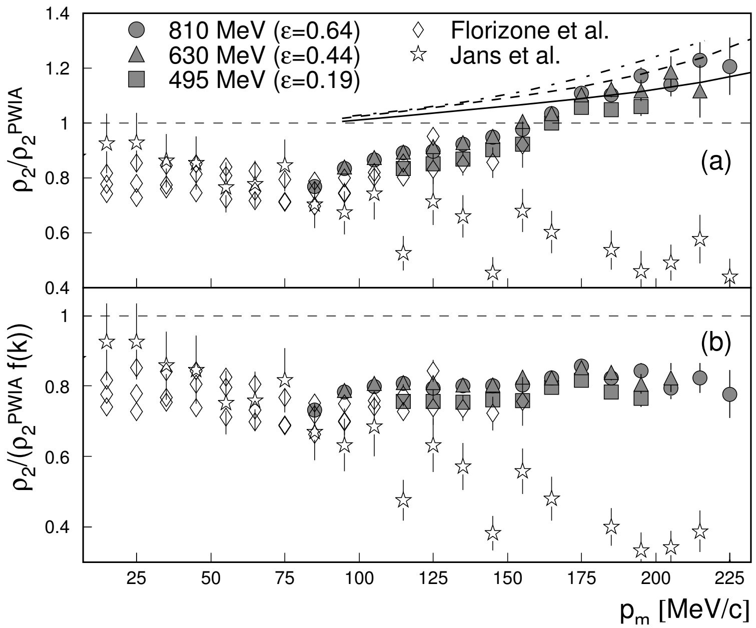
PRC **70** (2004) 034606, PRL **84** (2000) 3265

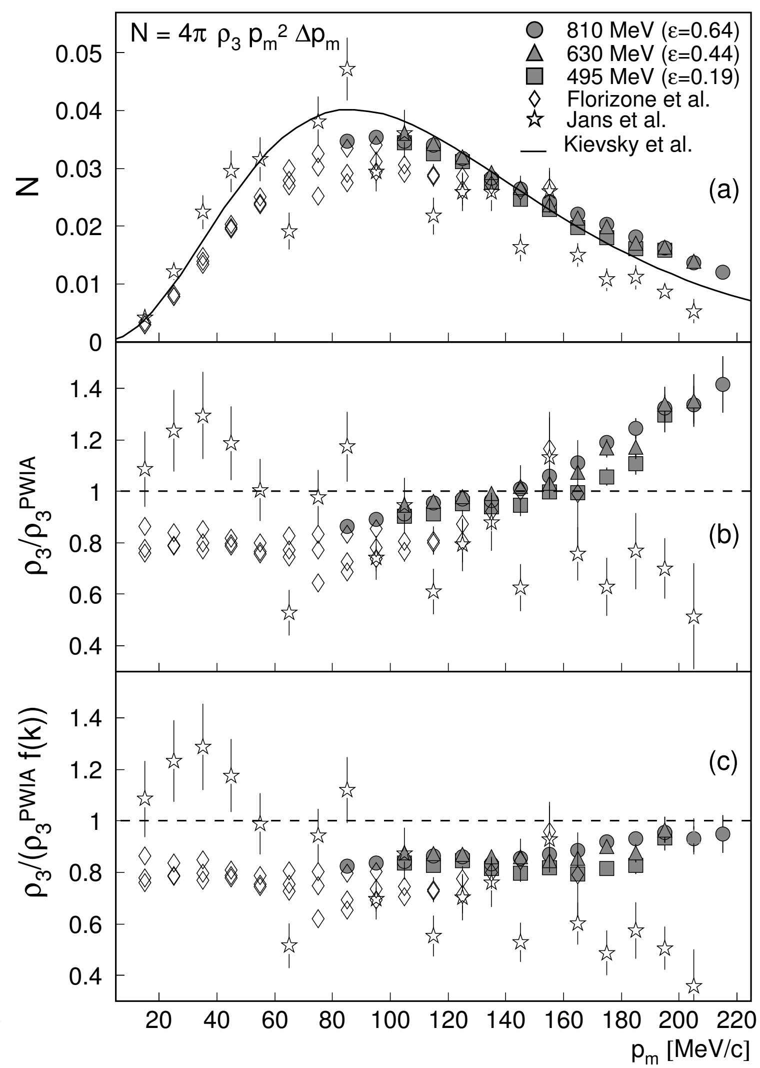
$^{16}O(e, e'p)n$ JLab E00-102



... work in progress

$^3\mathrm{He}(e,e'p)pn$ **and** $^3\mathrm{He}(e,e'p)d$ **below QE peak** **MAMI/A1**





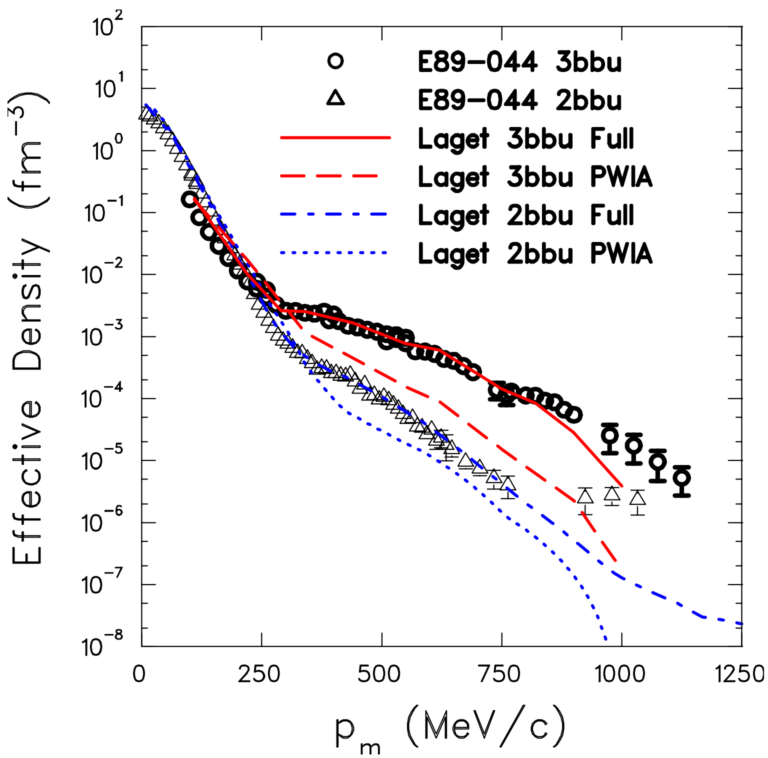
- low p_{m}: data ≈ 20% below full Faddeev ($f(k)$ roughly accounts for FSI + MEC)
  ... now improving
- high p_{m}: ≈ correct p_{m} dependence
- (?) relativistic dynamics ($q \approx 700\,\mathrm{MeV/c}$)

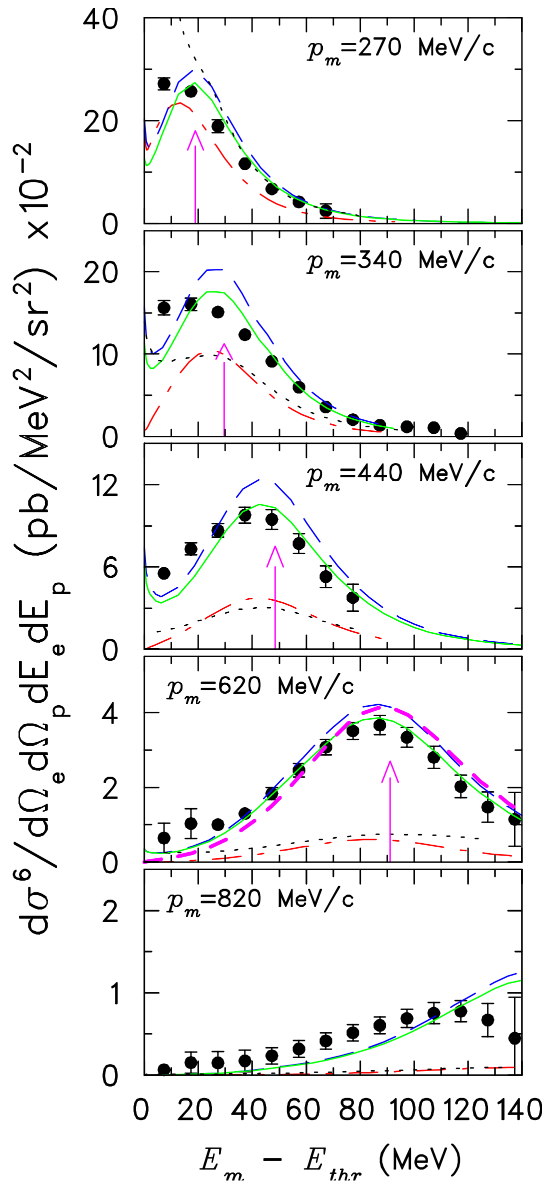
PRL **93** (2004) 132301

^{3}He(e, e′p)pn **on the QE peak** E89-044

- fixed $q = 1500\,\text{MeV/c}$, $\omega = 840\,\text{MeV}$
- p_m up to 1 GeV/c, E_m up to π threshold
- benchmark data (both channels)

$$\eta(p_\text{m}) = \int (\text{d}^6\sigma / K\sigma_\text{ep})\,\text{d}E_\text{m}$$



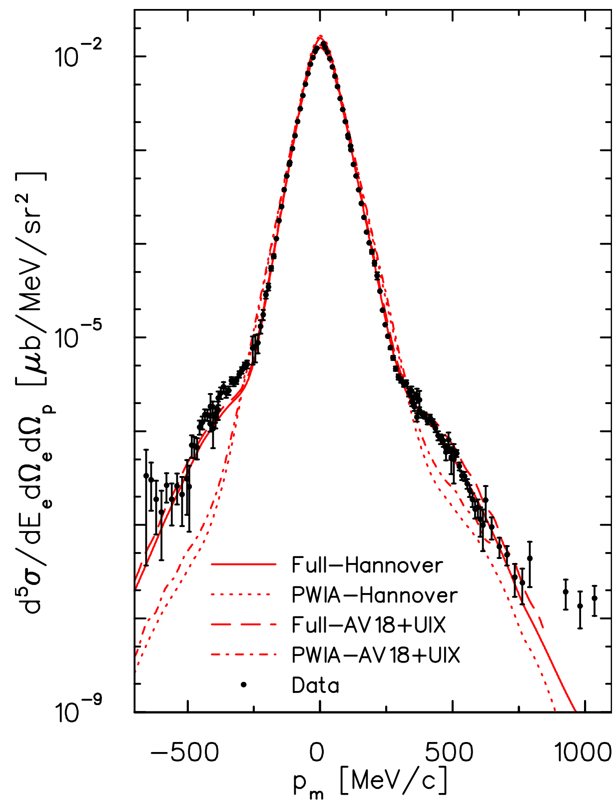


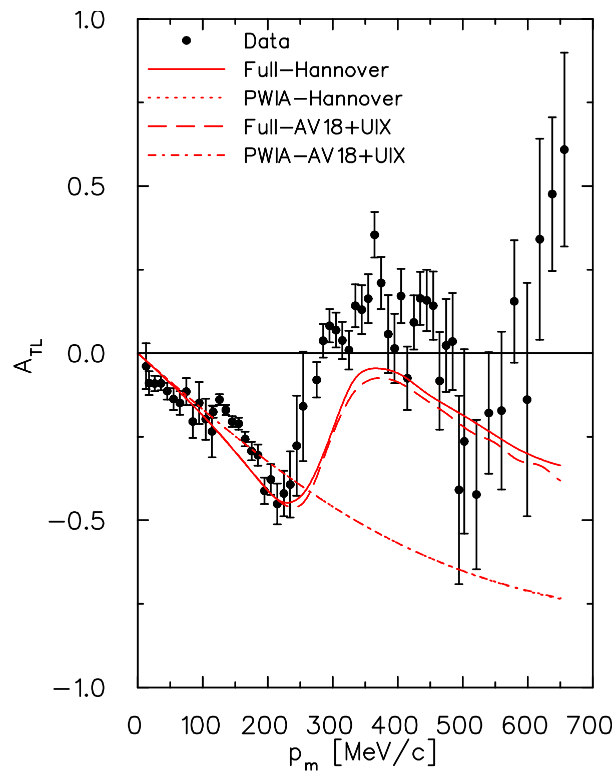
- role of correlations (3bbu)

PRL **94** (2005) 082305

$^3He(e, e'p)^2H$ on the QE peak

- [same e^- kinematics] strong FSI for $150 \leq p_m \leq 750$ MeV/c
- large discrepancies wrt theory near $p_m = 1000$ MeV/c
- A_{LT} shows breakdown of factorization (IF of PWIA & rescattering amps)



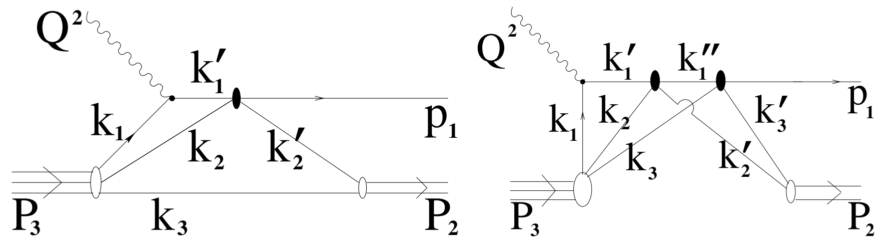


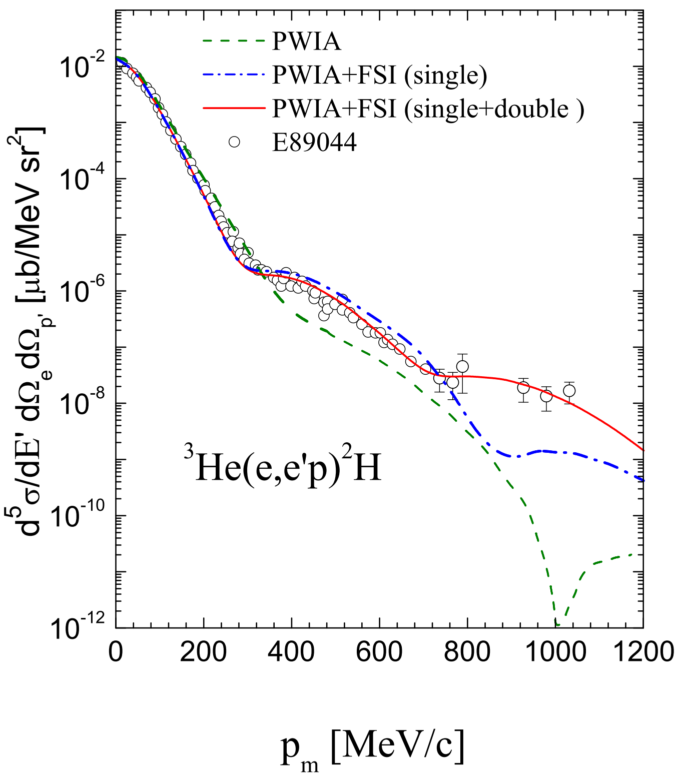
PRL **94** (2005) 192302

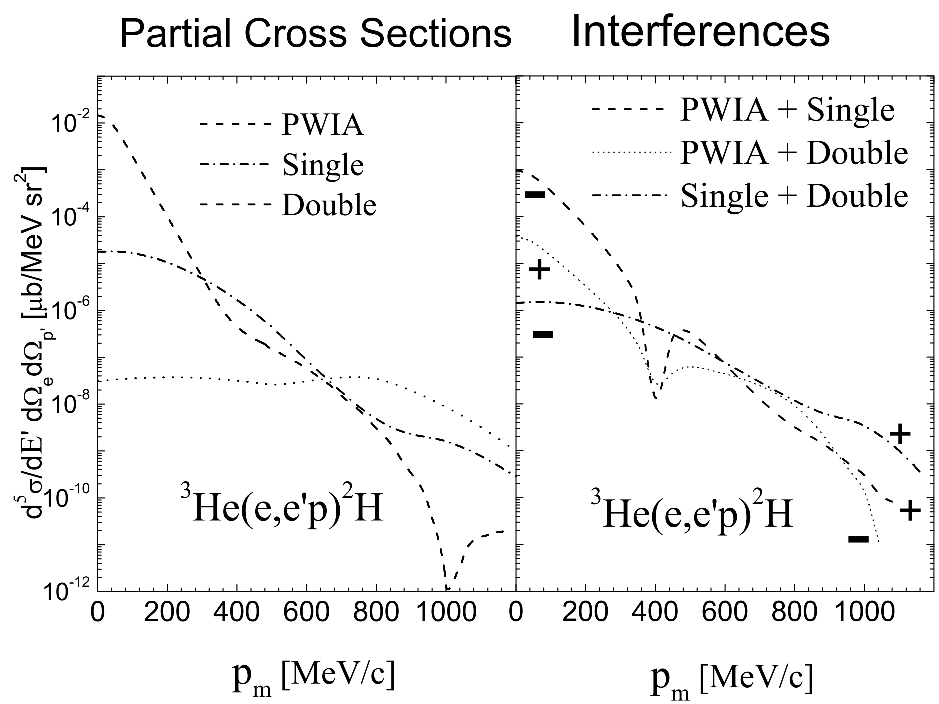
★ ★ ★ see also nucl-th/0705.3951 (**unfactorized calculations !**)

FSI in $^3\mathrm{He}(\mathrm{e},\mathrm{e}'\mathrm{p})^2\mathrm{H}$ at high p_m

- GEA: generalized eikonal approx (++rescatterings, $A-1$ excitation) ← FSI
- Pisa WFs (AV18) ← initial-state correlations
- no MEC (small), no IC (small)
- **2bbu**: excellent agreement w/ GEA

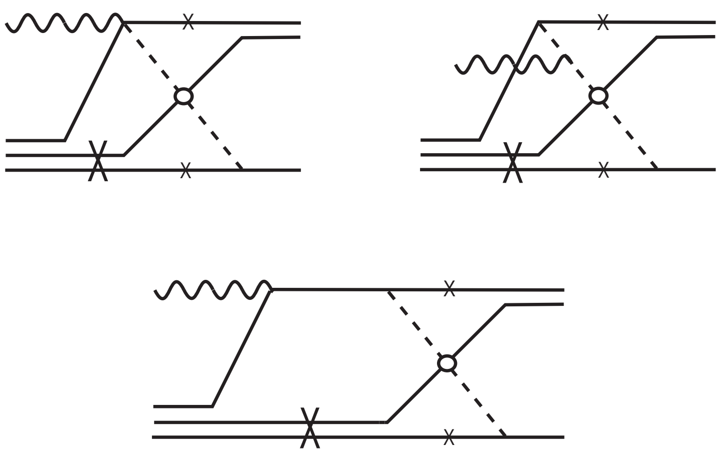


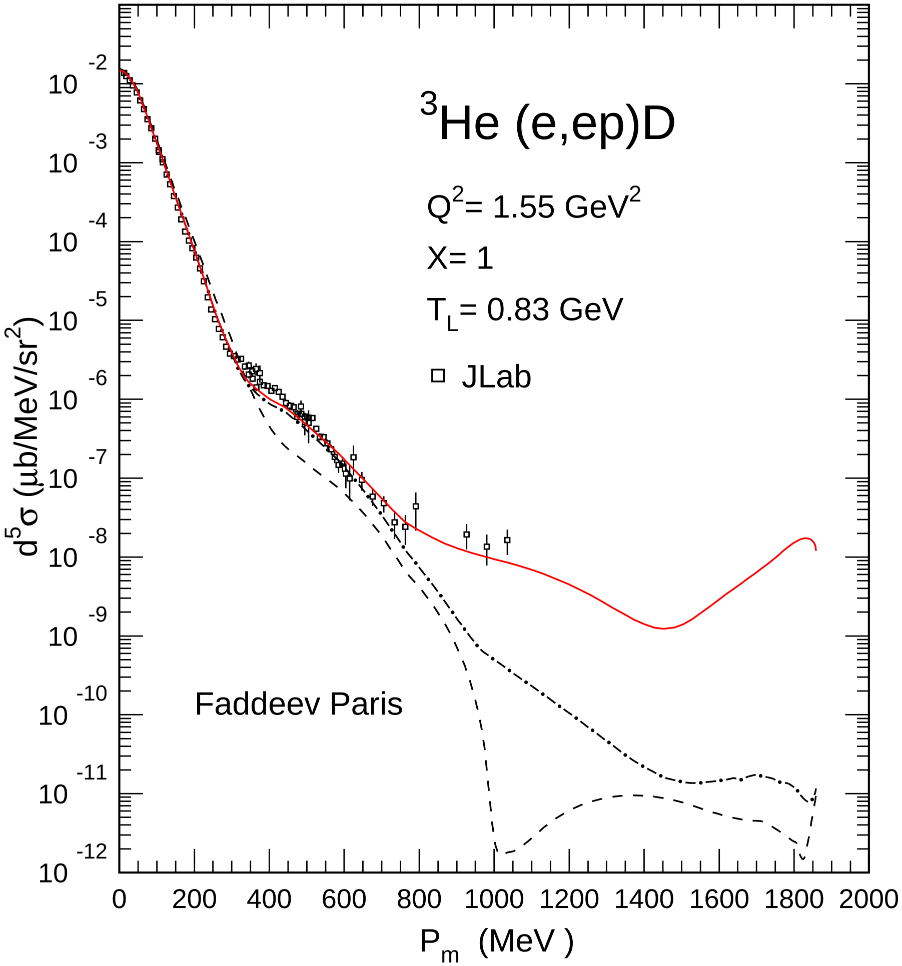




- **3bbu**: data underestimated by $\approx 20\,\%$ at $p_\mathrm{m} \gtrsim 800\,\mathrm{MeV/c}$ PRL **95** (2005) 052502

- particular 3-body mechanism at $p_\mathrm{m} \gtrsim 700\,\mathrm{MeV/c}$
- maximal in QE kinematics ($x = 1$)
- connects to pd-elastic at $\theta = \pi$

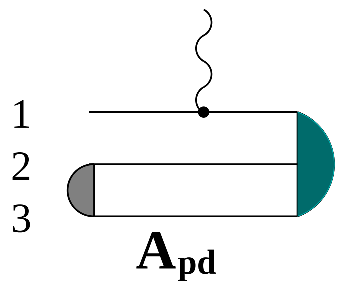


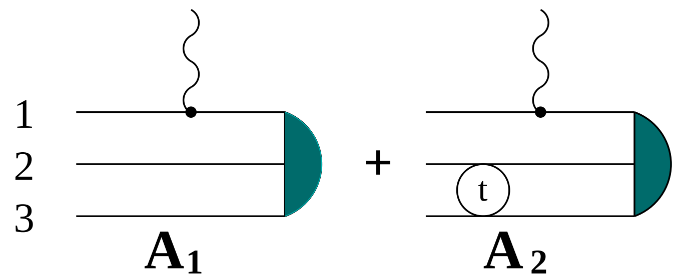


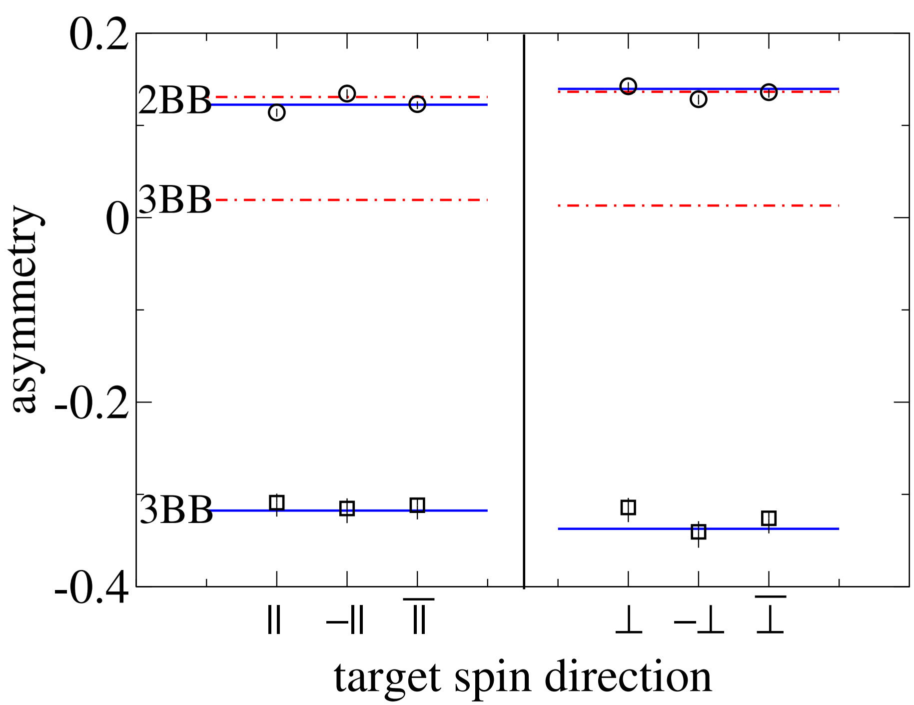
PRC **72** (2005) 024001, PRC **72** (2005) 064003

$^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})^2\mathrm{H}$ and $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})\mathrm{pn}$ MAMI/A1

- QE ($Q^2 = 0.31$, $\omega = 135$, $q = 570$ central)
- 3NF, MEC negligible, FSI small in 2bbu, large in 3bbu







▷ 2bbu

$A_{\mathrm{PWIA}} \approx A_{\mathrm{PWIA+FSI}}$

$\|$ kinematics + small p_{d}

$\Longrightarrow$ polarized p target, $P_{\mathrm{p}} \approx -\frac{1}{3}P_{\mathrm{He}}$

▷ 3bbu

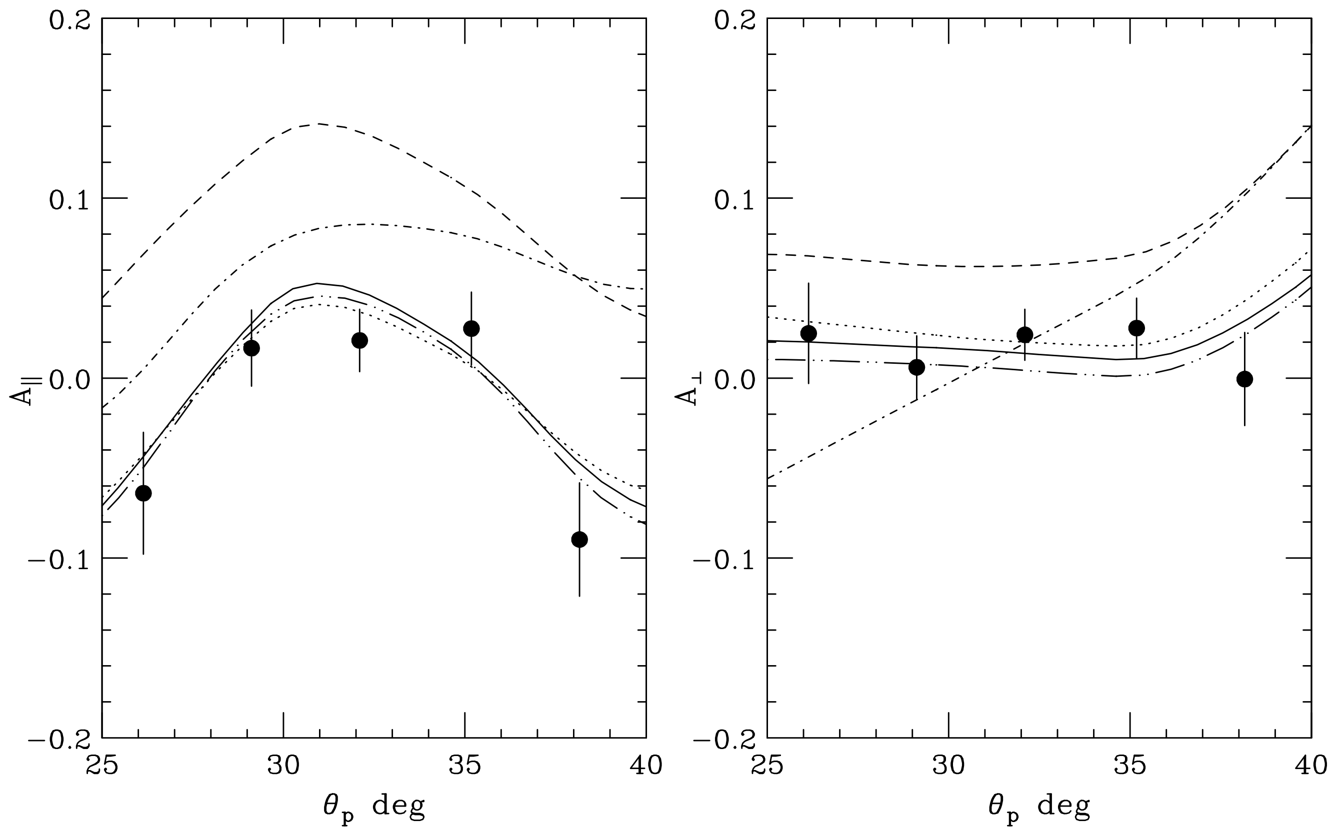
$A_{\mathrm{PWIA}} \approx 0$ (p $\uparrow$ p $\downarrow$)

$A_{\mathrm{PWIA+FSI}}$ large & negative

not a polarized p target

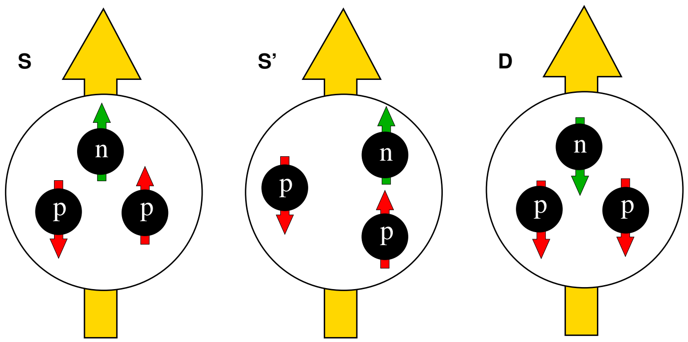
PRC **72** (2005) 054005, EPJA **25** (2005) 177

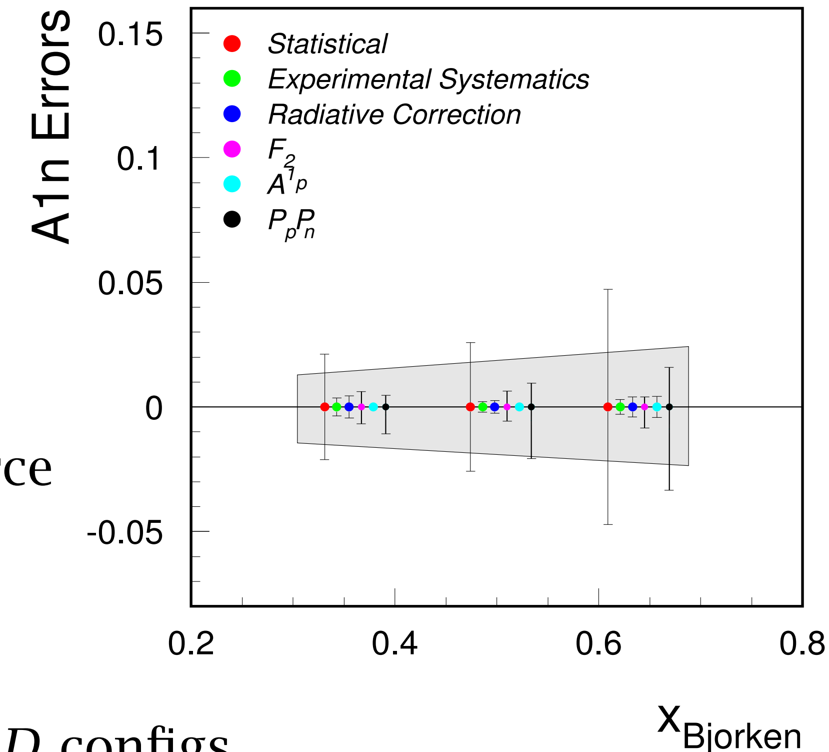
- $Q^2 = 0.67$ at QE peak and on low-ω side
- non-relativistic calc no longer applicable
- relativistic kinematics + approximate FSI (A_2-term) sufficient



PLB **559** (2003) 41

- better understand ^{3}He as opposed to using it as effective n target
- any polarized ^{3}He exp depends on this to some extent





S (90 % WF) space symmetric, p ↑ p ↓

D (8.5 % WF) tensor component of NN force

S′ (1.5 % WF) mixed symmetry config
(spin-isospin)-space correlations

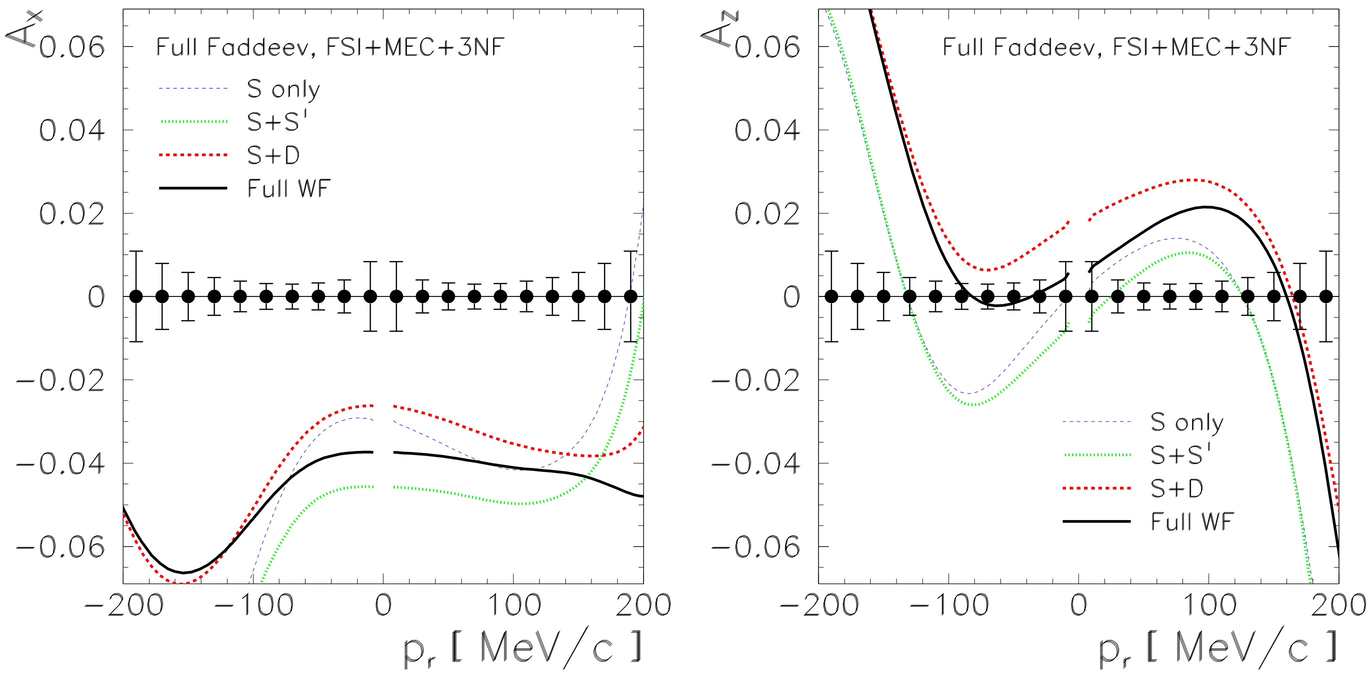
× protons partly polarized due to *S′* and *D* configs

- (iso)spin dependence of reaction mechanism (MEC, IC)

$^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{d})$ — Krakow/Bochum calculations E05-102

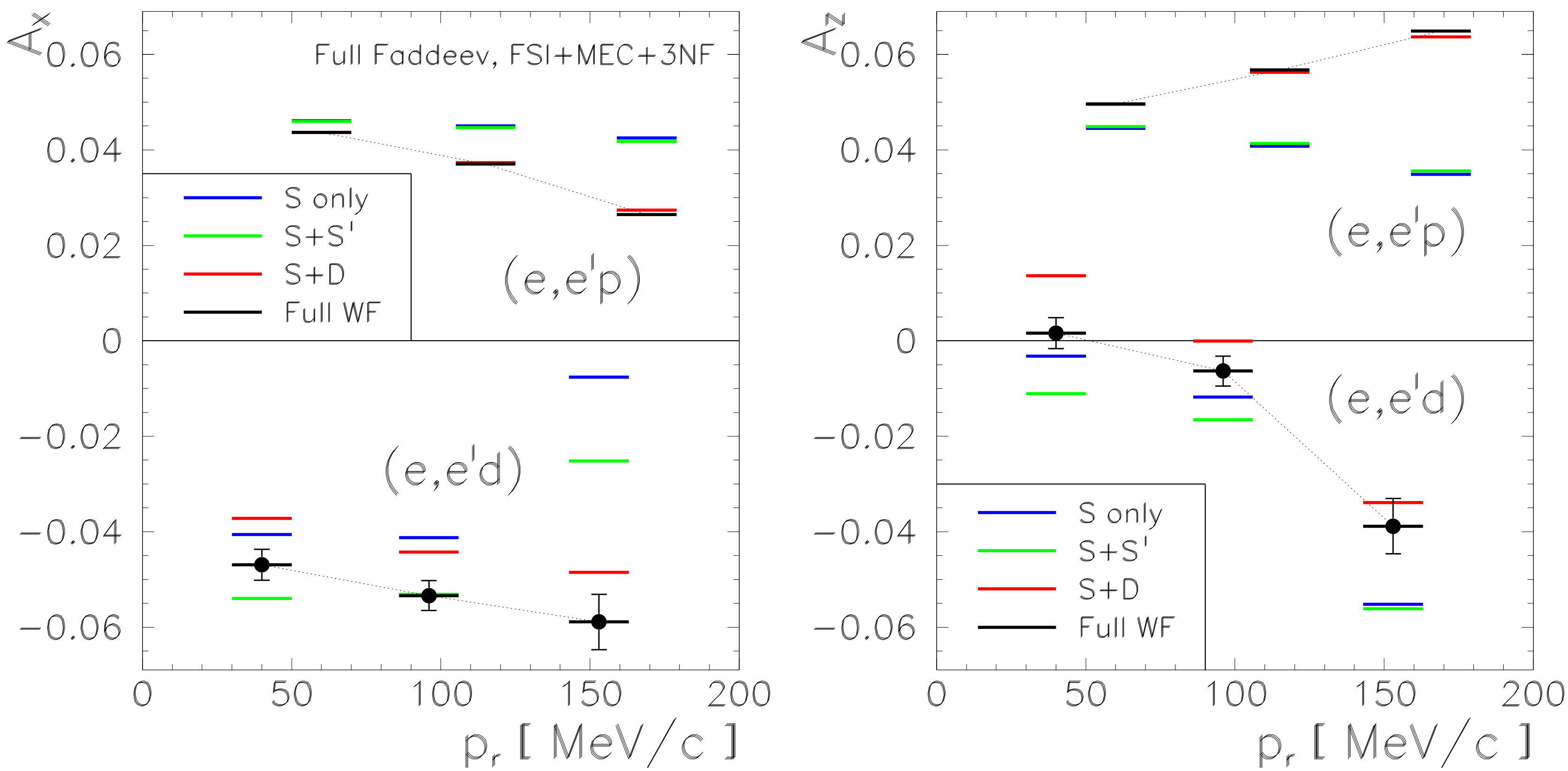
$$\frac{\mathrm{d}\sigma(h,\vec{S})}{\mathrm{d}\Omega_\mathrm{e}\,\mathrm{d}E_\mathrm{e}\,\mathrm{d}\Omega_\mathrm{d}\,\mathrm{d}p_\mathrm{d}} = \frac{\mathrm{d}\sigma_0}{\cdots}\left[\,1+\vec{S}\cdot\vec{A}^0 + h(A_\mathrm{e}+\vec{S}\cdot\vec{A})\,\right]$$

$$A_{x,z} = \frac{[\,\mathrm{d}\sigma_{++}+\mathrm{d}\sigma_{--}\,]-[\,\mathrm{d}\sigma_{+-}+\mathrm{d}\sigma_{-+}\,]}{[\,\mathrm{d}\sigma_{++}+\mathrm{d}\sigma_{--}\,]+[\,\mathrm{d}\sigma_{+-}+\mathrm{d}\sigma_{-+}\,]}$$



- sensitivity to small-WF components

$^3\vec{\mathrm{He}}(\vec{e}, e'd)p$ vs. $^3\vec{\mathrm{He}}(\vec{e}, e'p)d$ E05-102



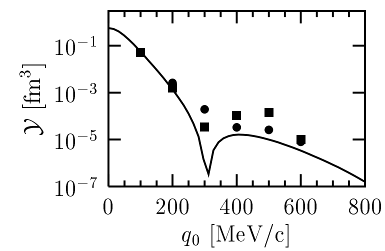
- no sensitivity to S' in proton channel

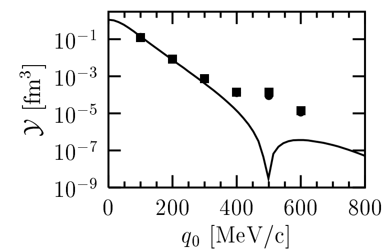
- spin-dependent momentum distributions of $\vec{p}\vec{d}$ clusters in polarized ^{3}He

$$N_\mu = \left\langle \Psi^{(-)}_{\mathrm{pd}} M_{\mathrm{d}} m \,|\, \hat{j}_\mu(\vec{q}) \,|\, \Psi M \right\rangle$$

$$\mathcal{Y}\left(M = \frac{1}{2}, M_{\mathrm{d}} = 0, m = +\frac{1}{2}\right) \propto \left| N^{\text{spin PWIA}}_{-1}\left(\frac{1}{2}, 0, -\frac{1}{2}\right)\right|^2$$

$$\mathcal{Y}\left(M = \frac{1}{2}, M_{\mathrm{d}} = 1, m = -\frac{1}{2}\right) \propto \left| N^{\text{spin PWIA}}_{+1}\left(\frac{1}{2}, 1, +\frac{1}{2}\right)\right|^2$$



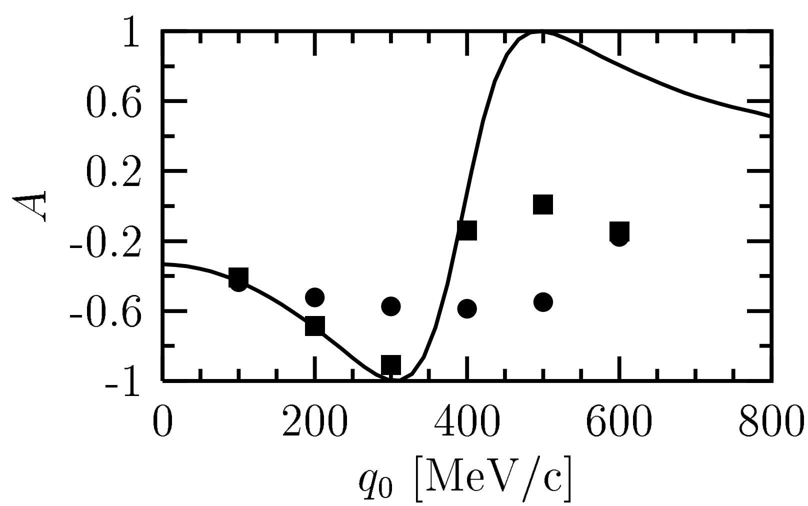


$$A = \frac{\mathcal{Y}(1/2, 0, 1/2) - \mathcal{Y}(1/2, 1, -1/2)}{\mathcal{Y}(1/2, 0, 1/2) + \mathcal{Y}(1/2, 1, -1/2)}$$

$$\sigma_{\mathrm{L}} \propto |N_0|^2$$

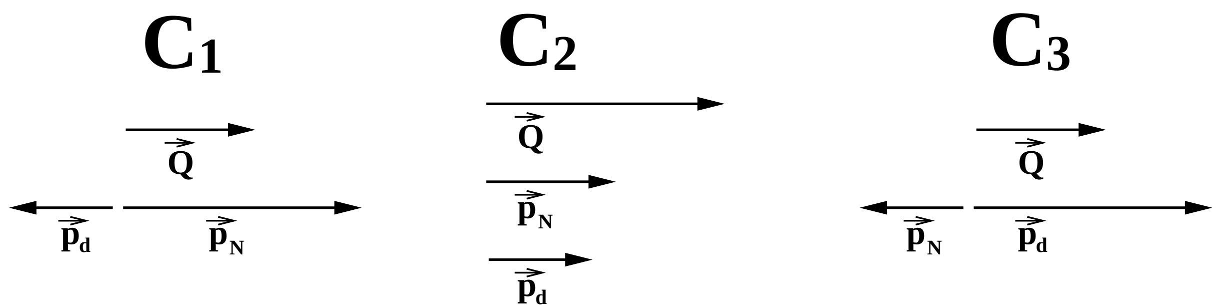
$$\sigma_{\mathrm{T}} \propto |N_{+1}|^2 + |N_{-1}|^2$$

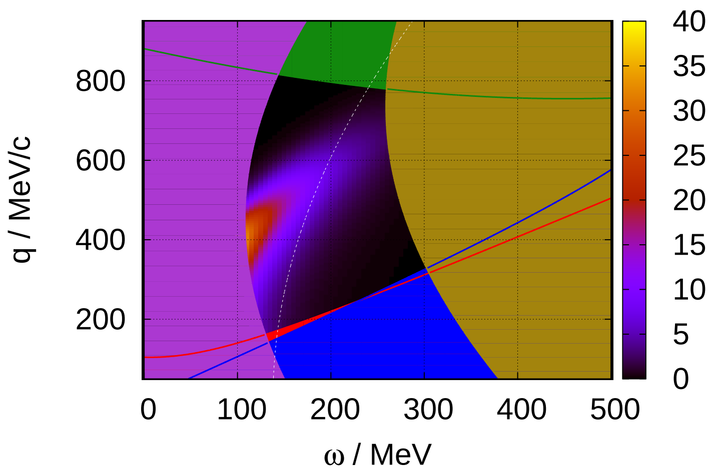
$$\sigma_{\mathrm{T}'} \propto |N_{+1}|^2 - |N_{-1}|^2$$



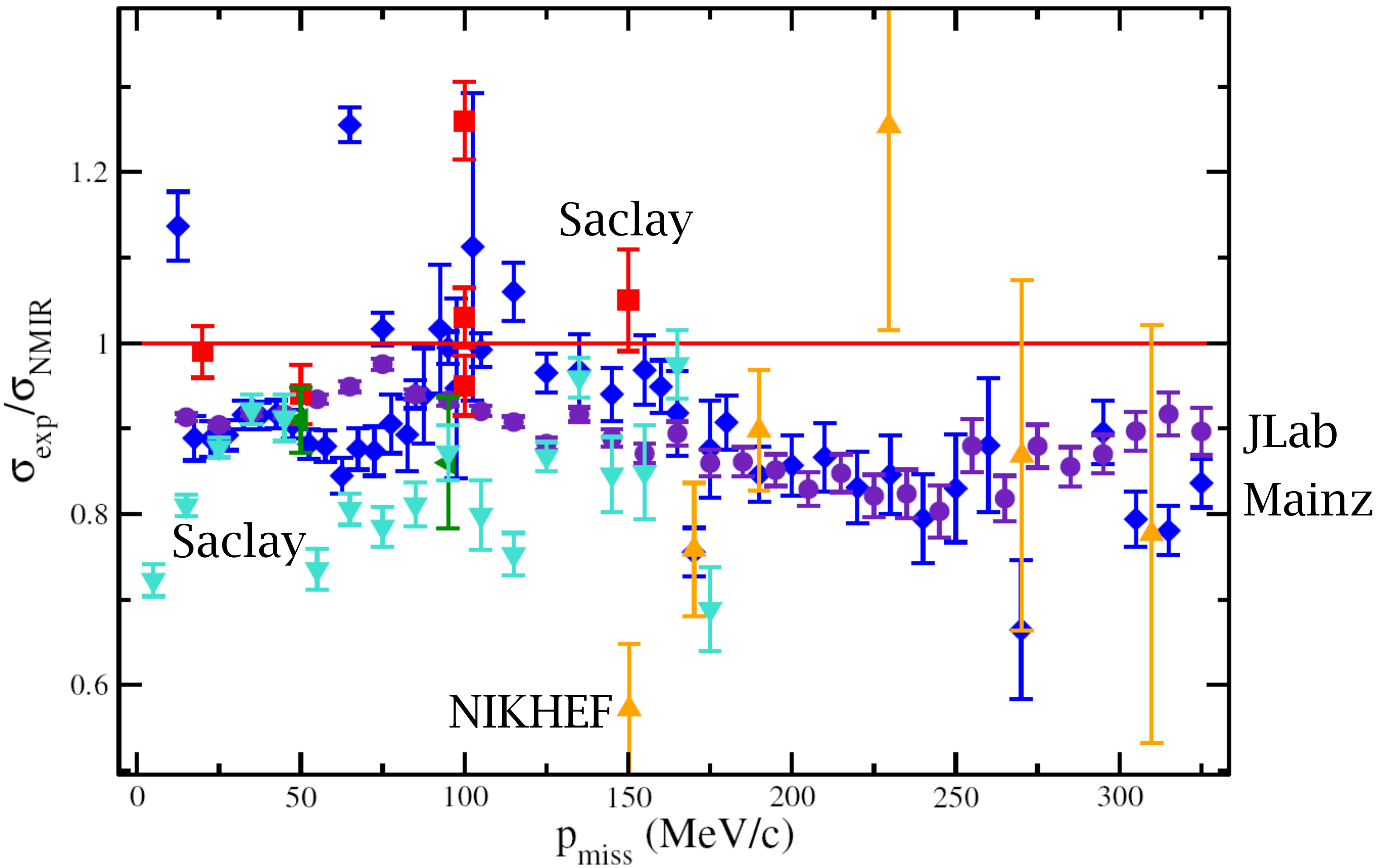
PRC **65** (2002) 064004

- PWIA: σ_L, σ_T, $\sigma_{\mathrm{T}'}$ yield spin-dependent momentum distribution
- FSI, MEC preclude direct access except at $p_\mathrm{d} \lesssim 2\,\mathrm{fm}^{-1}$
- rich interplay ▷ final-state symmetrization: large effect in C_3
  ▷ FSI: largest in C_2
  ▷ MEC: most prominent in C_1



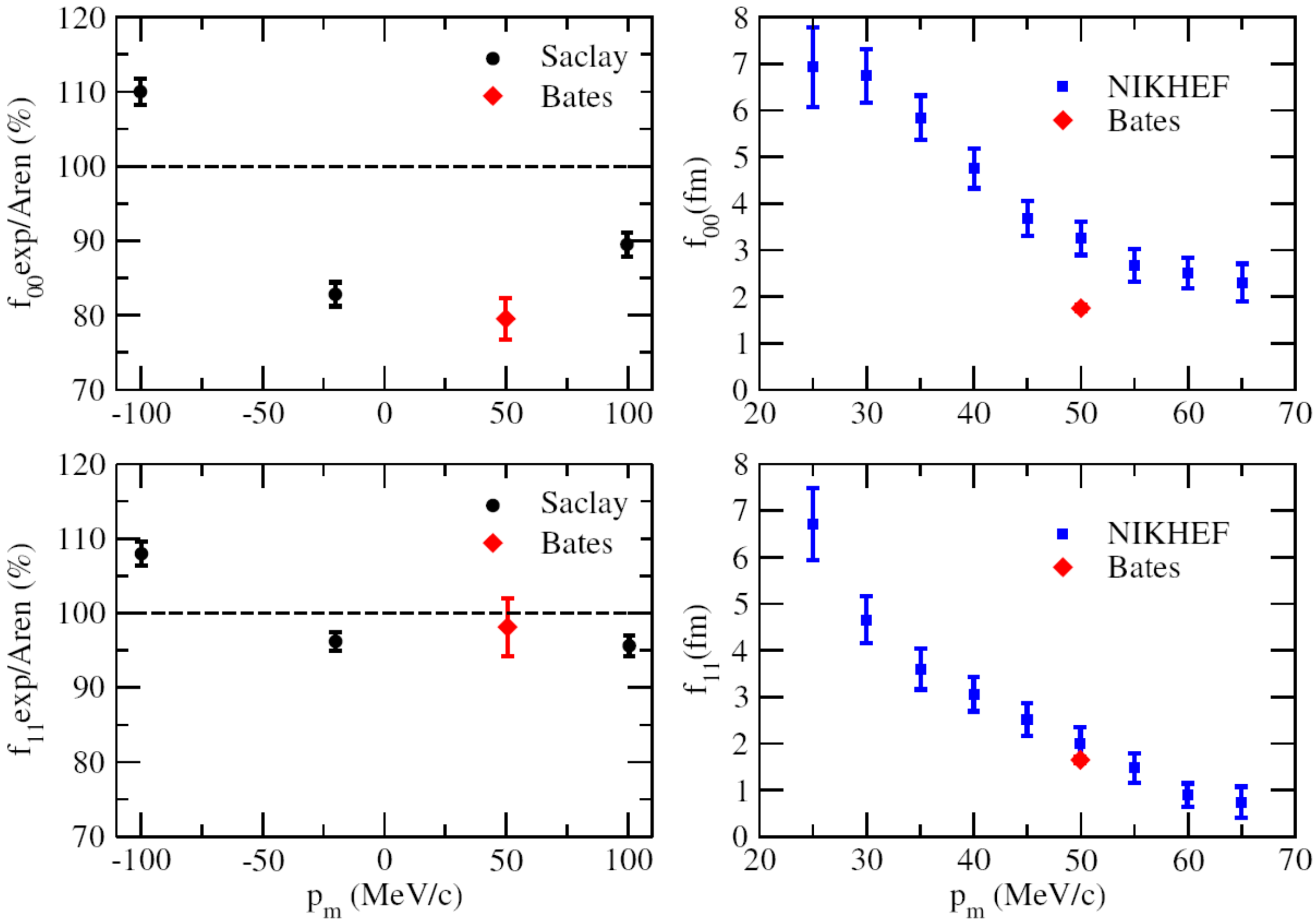


$d(e, e'p)$



- experiments ~ self-consistent
- all are ~ 10 % below theory

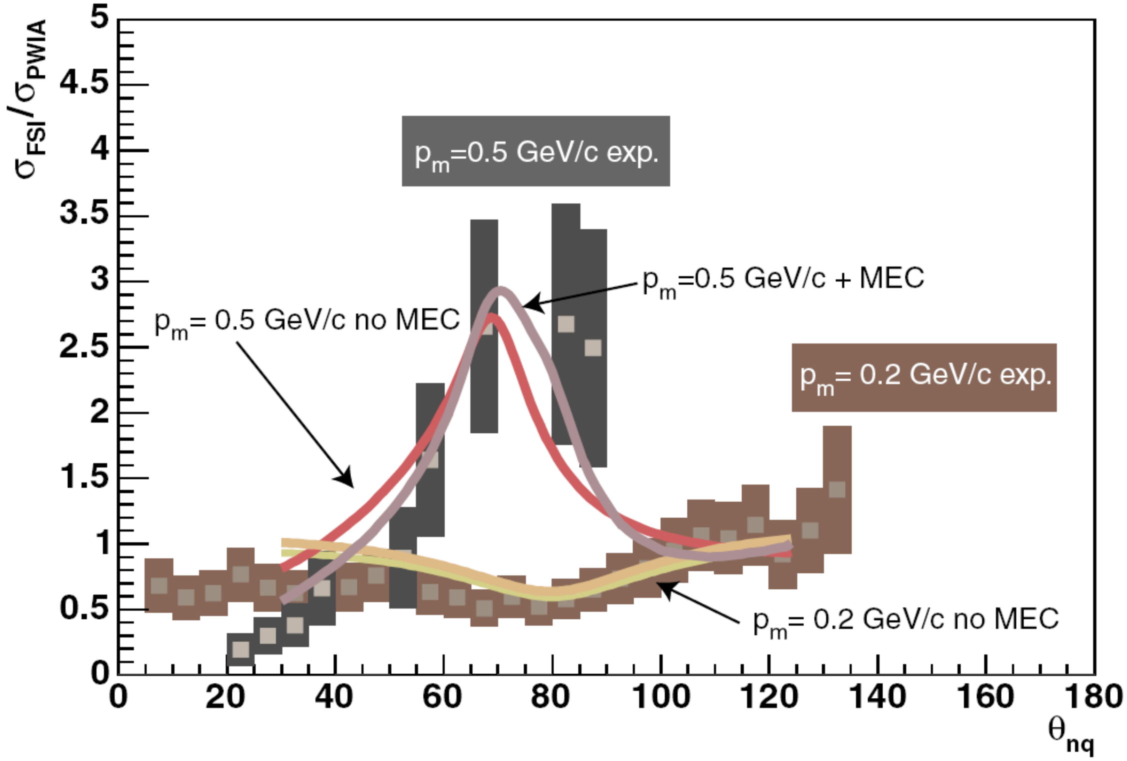
L/T separation in d(e, e′p)



- also L/T data from Mainz but experimental error at low p_m
- discrepancies in L and T and no experimental program to address them

d(e, e′p) at high Q^2 **E01-020**

- $Q^2 = 0.8,\ 2.1,\ 3.5\,\mathrm{GeV}^2$ for $0 \lesssim p_\mathrm{m} \lesssim 500\,\mathrm{MeV/c}$
- test Generalized Eikonal Approximation of FSI
- characteristic θ_nq-dependence with predicted max. at 80°

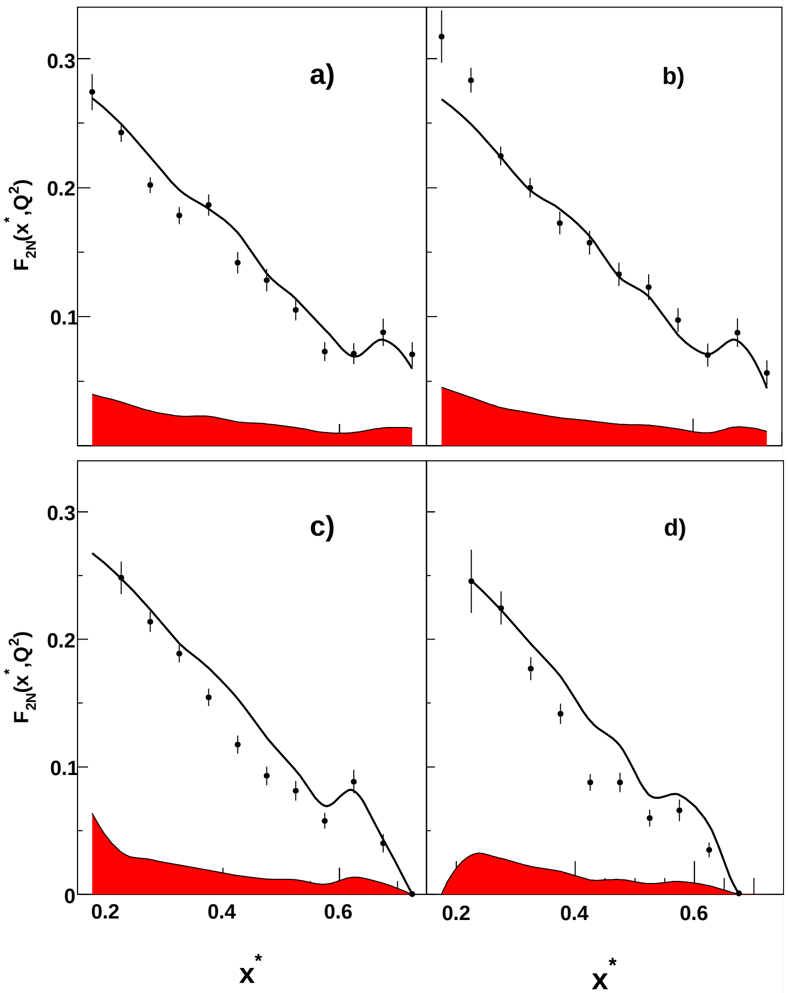


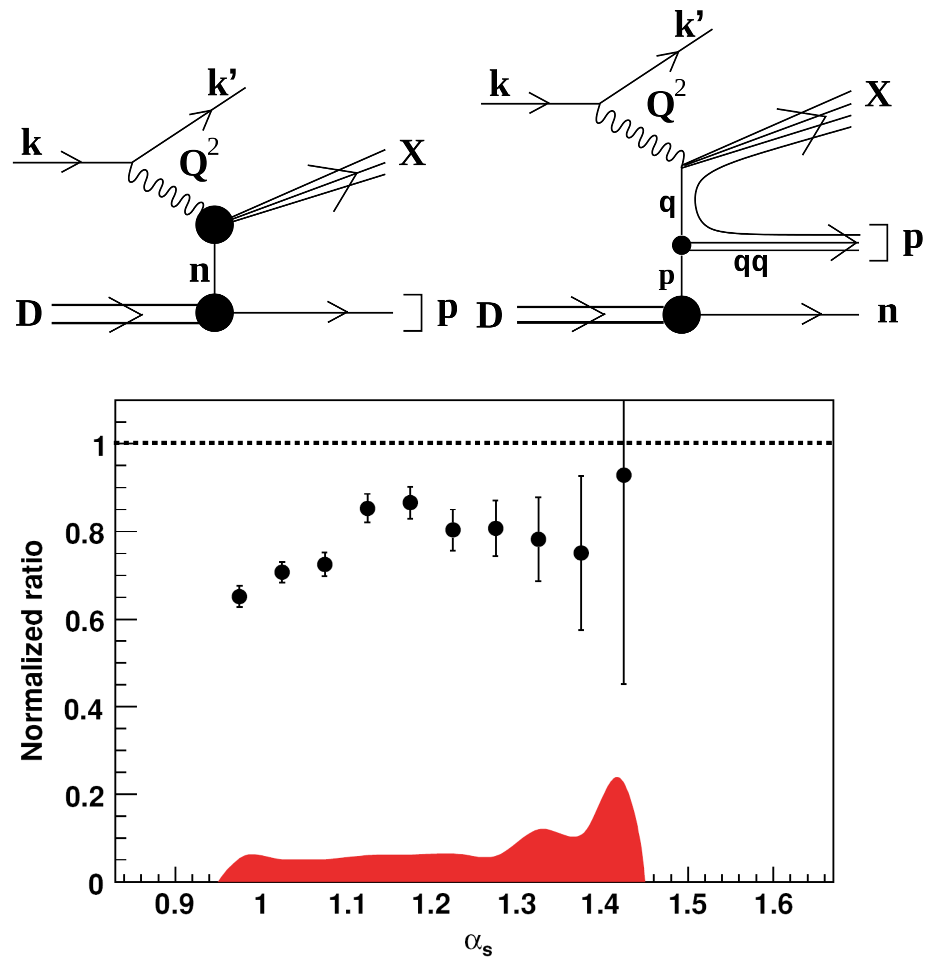
PRELIMINARY EPJA **28** s01 (2006) 19

see also CLAS E94-019

Semi-inclusive deep-inelastic $^2H(e, e' p_s)X$

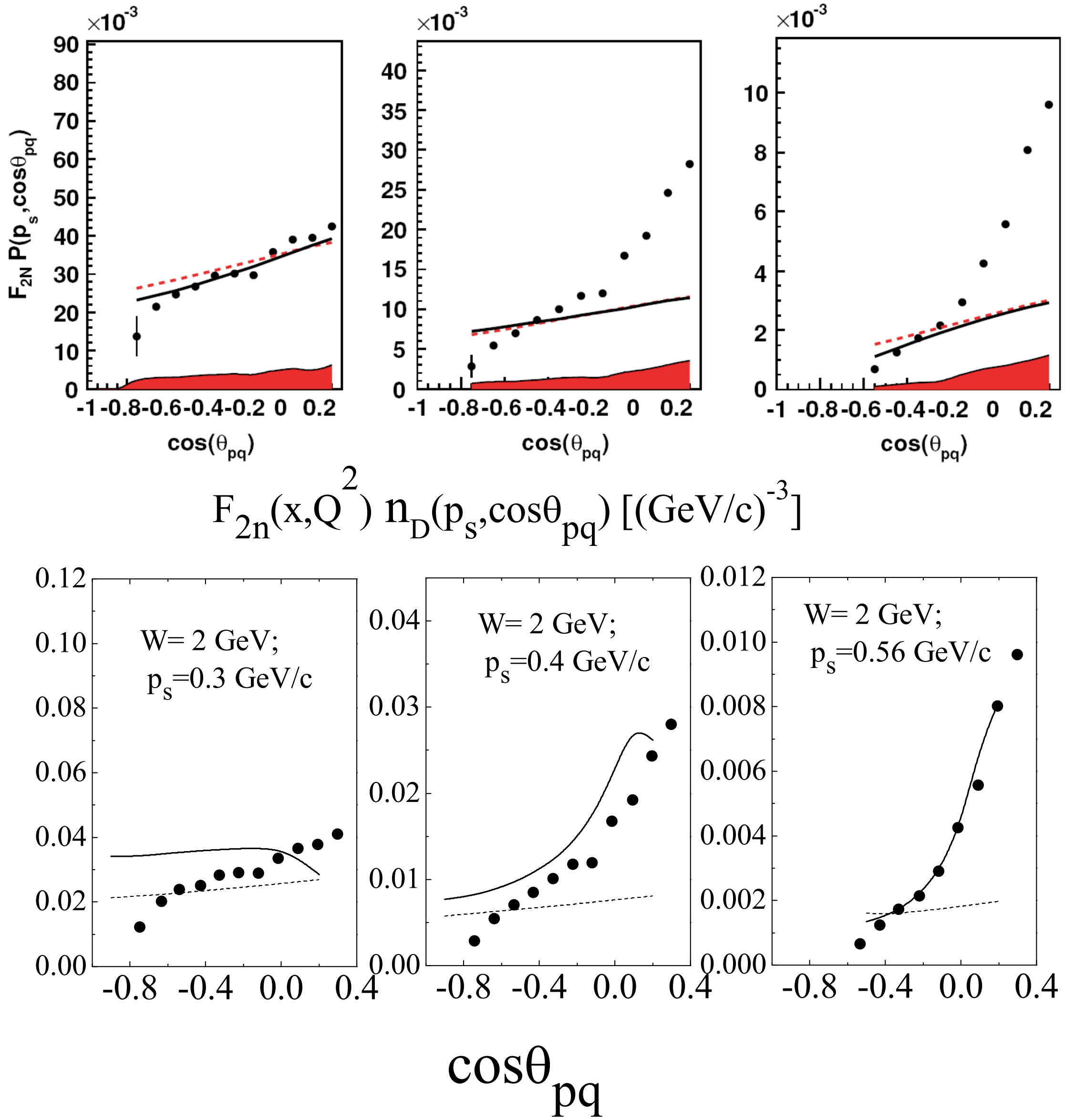
- regions where FSI minimized $\Longrightarrow$ investigation of DIS structure functions
- regions where FSI maximized $\Longrightarrow$ study hadronization mechanisms





PRC **73** (2006) 035212

FSI in $^2H(e, e'p_s)X$ $W = 2$ GeV



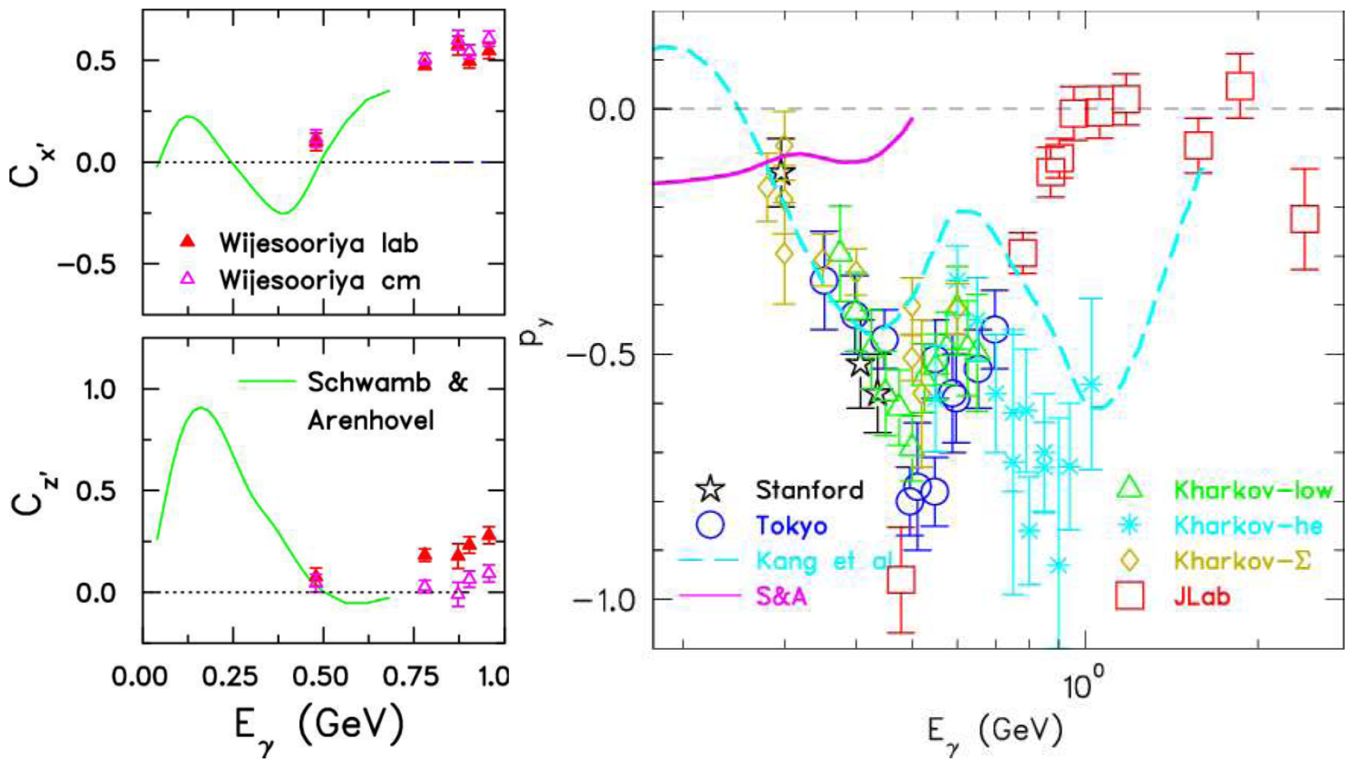
nucl-th/0705.3617

Polarization observables in $\vec{\gamma}d \to \vec{p}n$

PRL **98** (2007) 182302
PRL **86** (2001) 2975

- agreement w.r.t. theory for C'_x and C'_z but not for p_y
- but $\sigma(\theta)C'_x = 2\,\mathrm{Re}\sum_{i=1}^{3}\left[F^*_{i,+}F_{i+3,-} + F_{i,-}F^*_{i+3,+}\right]$

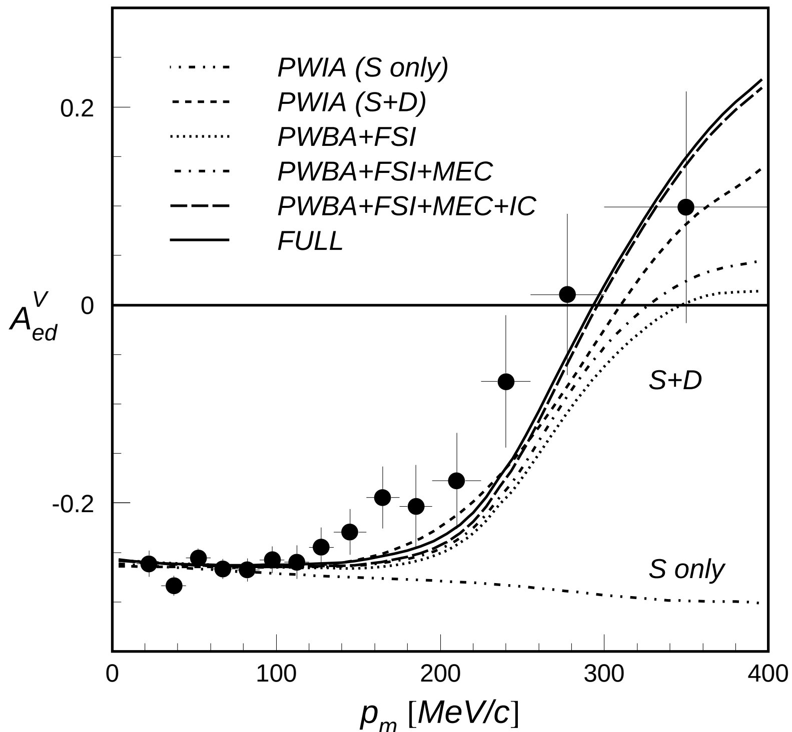
$$\sigma(\theta)p_y = 2\,\mathrm{Im}\sum_{i=1}^{3}\left[F^*_{i,+}F_{i+3,-} + F_{i,-}F^*_{i+3,+}\right]$$



- clean up the mess in existing data, in particular on p_y
- input to (state-of-the-art) theory beyond $E_\gamma \sim 300\,\mathrm{MeV}$

Spin-correlation parameter A^{V}_{ed} in $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$ BLAST

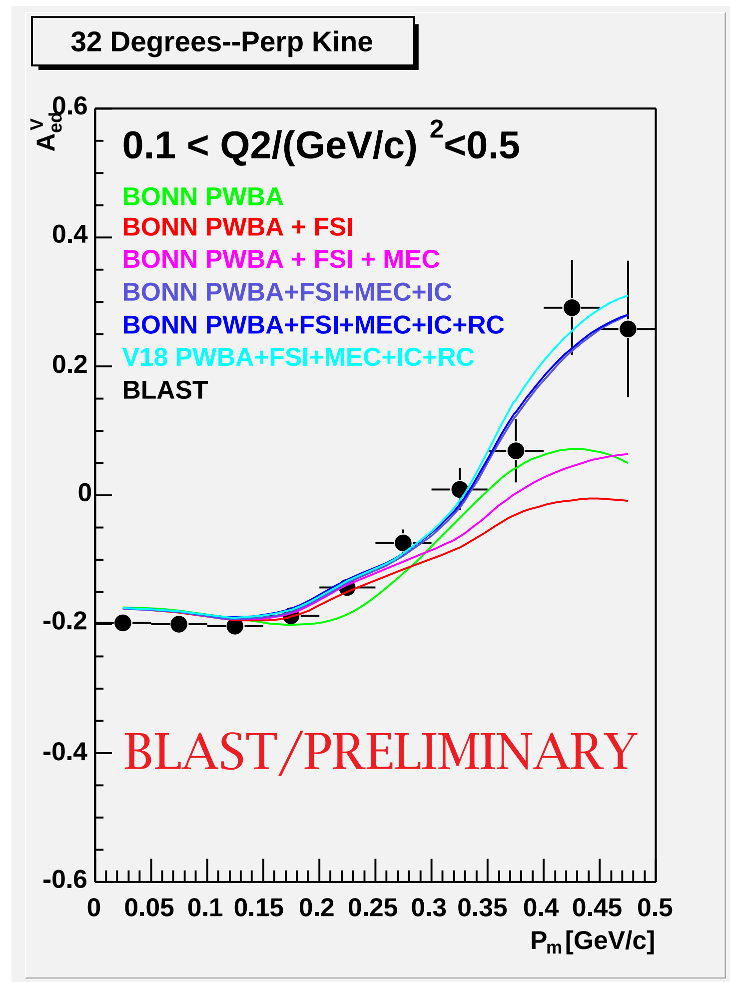
$$\sigma = \sigma_0 \left\{1 + P^{\mathrm{d}}_1 A^{\mathrm{V}}_{\mathrm{d}} + P^{\mathrm{d}}_2 A^{\mathrm{T}}_{\mathrm{d}} + h\left(A_{\mathrm{e}} + P^{\mathrm{d}}_1 A^{\mathrm{V}}_{\mathrm{ed}} + P^{\mathrm{d}}_2 A^{\mathrm{T}}_{\mathrm{ed}}\right)\right\}$$



NIKHEF

$\langle Q^2 \rangle = 0.21\,\mathrm{GeV}^2$

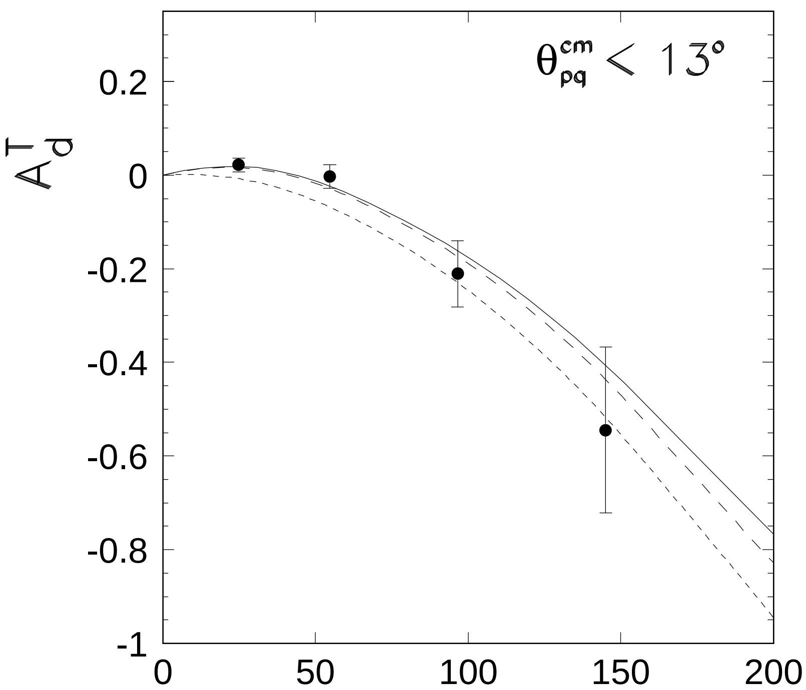
PRL **88** (2002) 102302



Tensor analyzing power A_d^T in $^2\vec{H}(e, e'p)$ **BLAST**

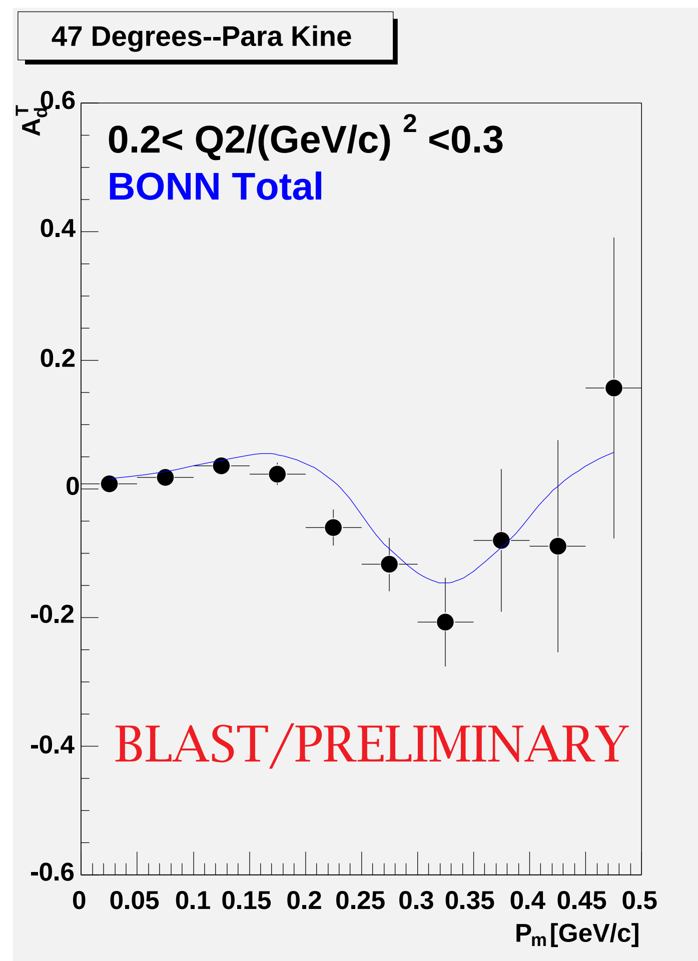
$$\sigma = \sigma_0 \left\{ 1 + P_1^d A_d^V + P_2^d A_d^T + h\left(A_e + P_1^d A_{ed}^V + P_2^d A_{ed}^T \right) \right\}$$

$$\text{PWIA}: \quad A_d^T \propto \left(2R_0(p)R_2(p) + \sqrt{\tfrac{1}{2}} R_2(p)^2 \right) / \left(R_0(p)^2 + R_2(p)^2 \right)$$



NIKHEF

PRL **82** (1999) 687



Conclusions and outlook

▷ Complex nuclei
- Breakdown of factorization
- Dynamical relativity
- Q^2-dependence of spectroscopic factors
- Optical-potential vs. Glauber approaches to FSI

▷ ^{3}He
- Unpolarized ≈ OK except very high p_{m}
- (e,e′d) vs. (e,e′p) correspondence (g.s. WF components)
- Intricate interplay of FSI, MEC, IC
- Triple polarization

▷ Deuteron
- Unresolved discrepancies in XS, L/T responses
- Simultaneous description of C_x' and p_y
- Upcoming BLAST data on $A_{\mathrm{ed}}^{\mathrm{V}}$ and $A_{\mathrm{d}}^{\mathrm{T}}$
- Pion and resonance physics with polarization

Dynamical relativity ("spinor distortion") in $\mathrm{A(e,e'p)}$

$$
\begin{aligned}
\left[\vec{\alpha}\cdot\vec{p} + \beta(M+S_{\mathrm{b}}) + (V_{\mathrm{b}} - E_{\mathrm{b}})\right]\Phi &= 0 \qquad \text{bound} \\
\left[\vec{\alpha}\cdot\vec{p} + \beta(M+S_{\mathrm{c}}) + (V_{\mathrm{c}} - E_{\mathrm{c}})\right]\Psi &= 0 \qquad \text{continuum}
\end{aligned}
$$

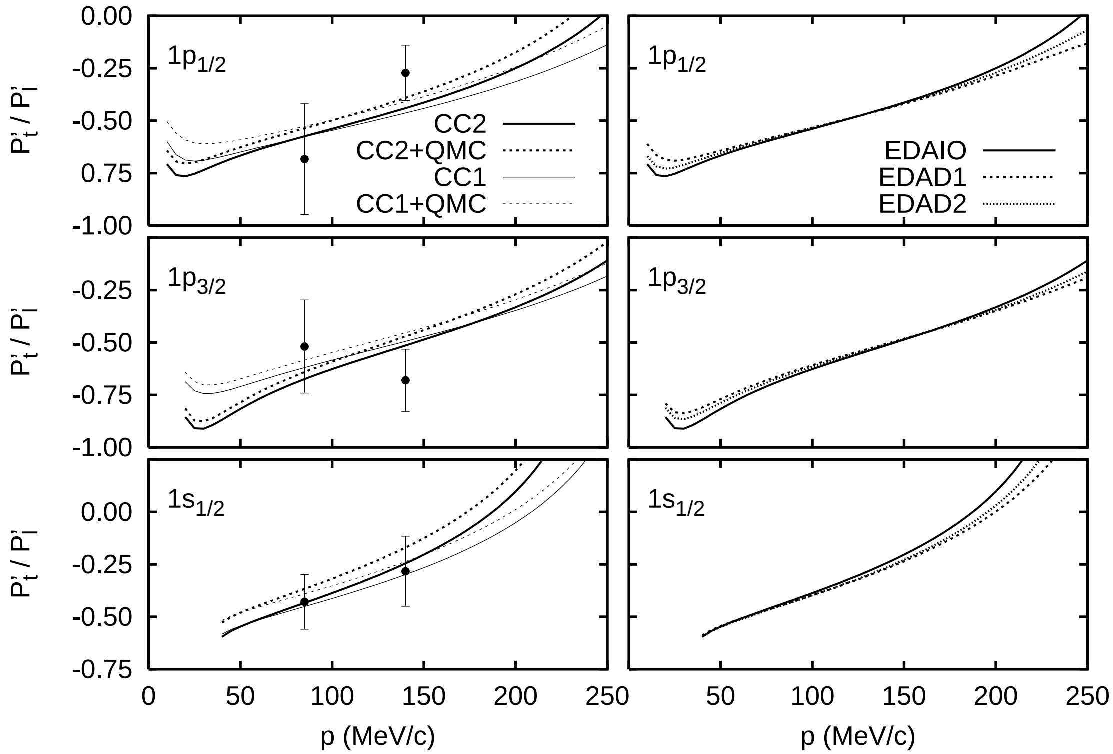
$$
\begin{aligned}
\Longrightarrow \quad \left[\nabla^2 + E^2 - M^2 - 2E\left(U^{\mathrm{C}} + U^{\mathrm{LS}}\vec{L}\cdot\vec{\sigma}\right)\right]\xi &= 0 \\
U^{\mathrm{C}} &= V + \frac{M}{E}S + \frac{S^2 - V^2}{2E} + \frac{1}{2E}\left[-\frac{1}{2Dr^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2 D'\right) + \frac{3}{4}\left(\frac{D'}{D}\right)^2\right] \\
U^{\mathrm{LS}} &= -\frac{1}{2Er}\frac{D'}{D} \\
D(r) &= 1 + \frac{S(r) - V(r)}{E+M}
\end{aligned}
$$

$$
\Phi = \Omega_{\mathrm{b}}\xi_{\mathrm{b}}\,, \quad \Psi = \Omega_{\mathrm{c}}\xi_{\mathrm{c}}\,, \qquad \Omega\left(\vec{p}, r\right) = \begin{pmatrix} 1 \\ \frac{\vec{\sigma}\cdot\vec{p}}{(E+M)D(r)} \end{pmatrix} D^{1/2}(r)
$$

PRC **72** (2005) 014602, PRC **71** (2005) 064610

$^{16}O(\vec{e}, e'\vec{p})$: polarization transfer

- quest for modification of proton FF inside the nuclear medium
- pol. observables least sensitive to most nuclear structure uncertainties



▷ dynamical relativity
distortion of bound **and** scattered Dirac spinors

▷ kinematical rel. effects
relativistic kinematics
relativistic N current operator

▷ realistic description of FSI
relativistic optical potentials

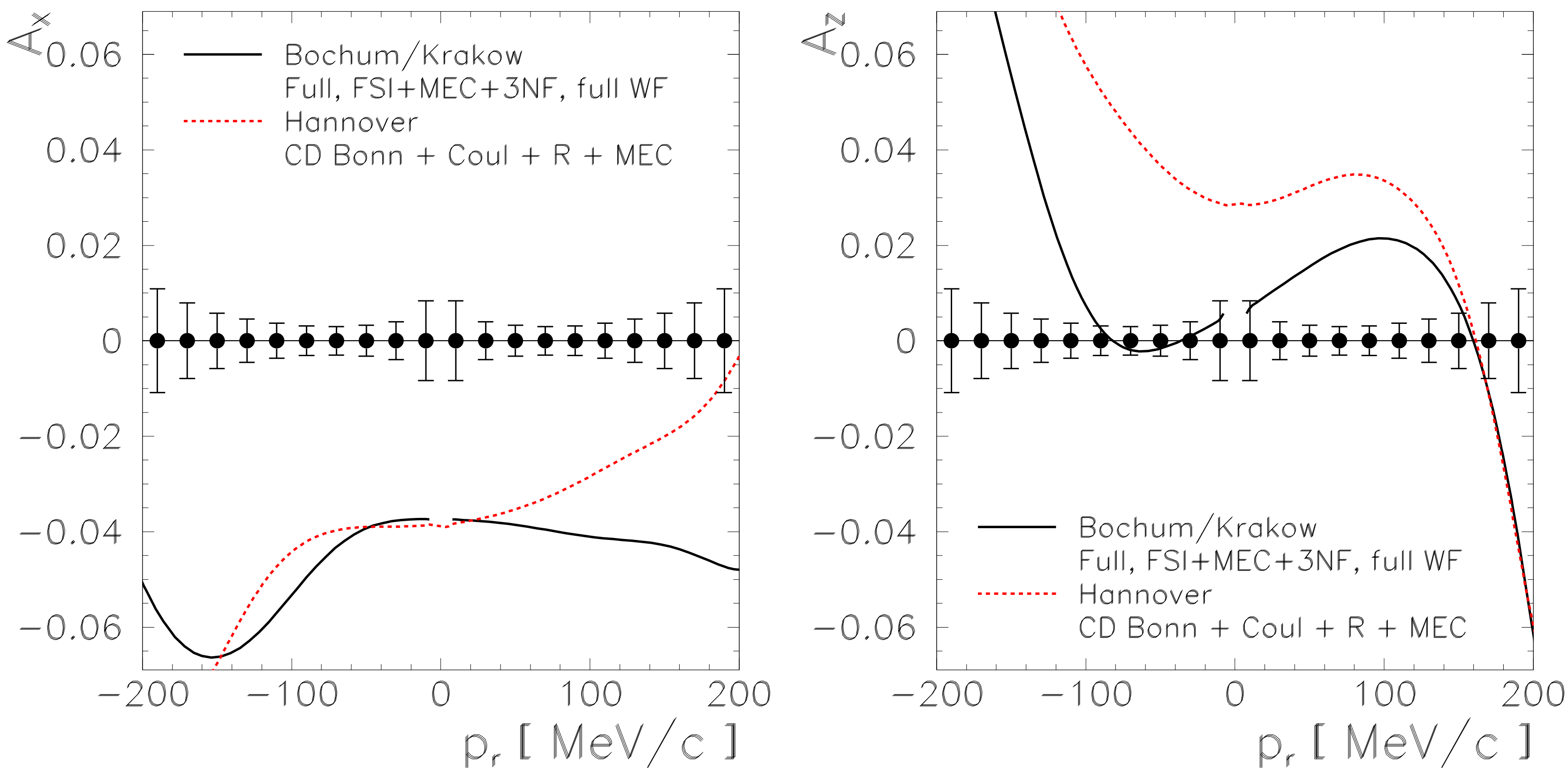
▷ medium-modified FFs
density dependence

$$G_{E,M}(Q^2, \rho) = G_{E,M}^{GK}(Q^2) \frac{G_{E,M}^{QMC}(Q^2, \rho)}{G_{E,M}^{QMC}(0, \rho)}$$

PRC **69** (2004) 034604

$^3\vec{He}(\vec{e}, e'd)$ — Krakow vs. Hannover

E05-102



- discrepancies in theories everyone believes in
- expected to run in 2008/09