

The Deuteron Benchmarking Project

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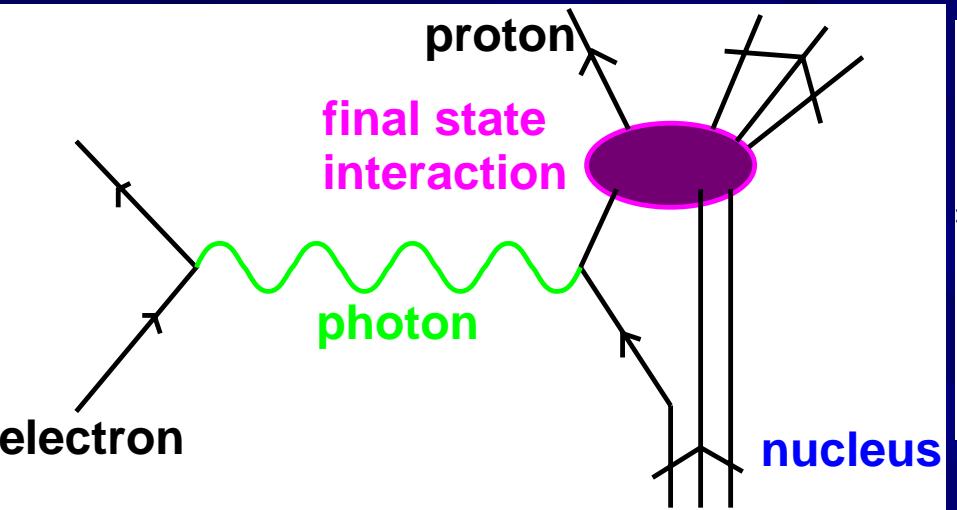
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Jefferson Lab User Group Meeting
June 2007

Outline

- Why D(e,e'p)?
- What is the deuteron benchmarking project ?
- Some promising testing grounds
 - unpolarized cross section
 - out-of-plane asymmetry $A_{LT'}$
- Challenges

The Reaction



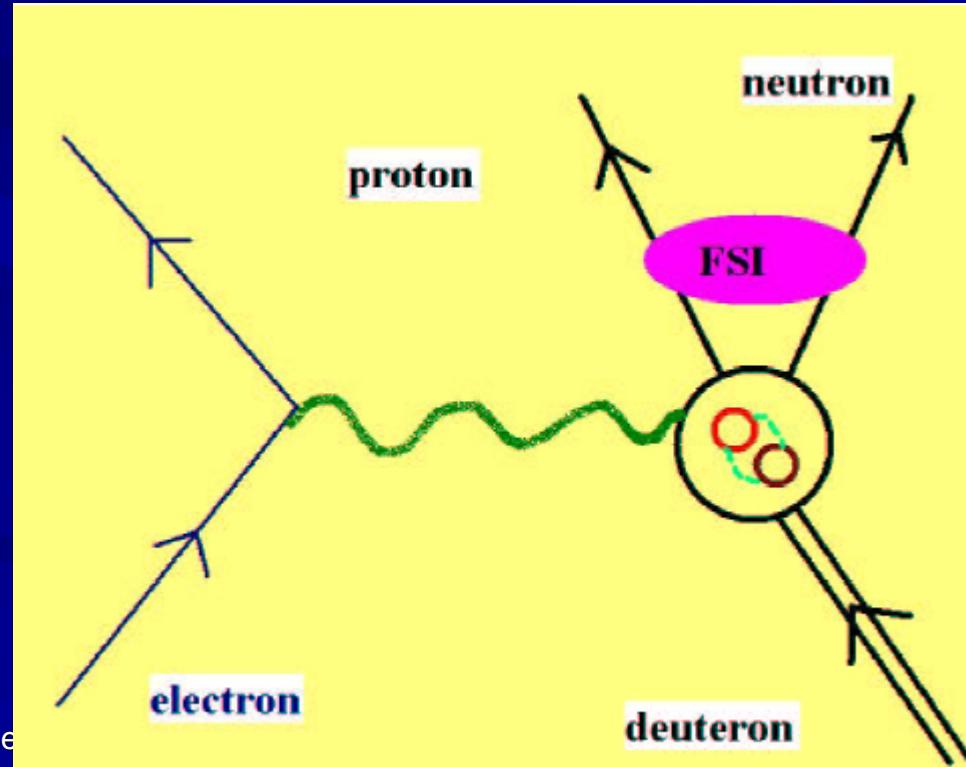
$$\begin{aligned}
 & \left(\frac{d\sigma^5}{d\epsilon' d\Omega_e d\Omega_N} \right)^h_{fi} \\
 &= \frac{m_N m_f p_N}{8\pi^3 m_i} \sigma_{Mott} f_{rec}^{-1} \\
 & [(v_L \mathcal{R}_{fi}^L + v_T \mathcal{R}_{fi}^T + v_{TT} \mathcal{R}_{fi}^{TT} + v_{TL} \mathcal{R}_{fi}^{TL}) \\
 & + h (v_{T'} \mathcal{R}_{fi}^{T'} + v_{TL'} \mathcal{R}_{fi}^{TL'})]
 \end{aligned}$$

$$\begin{aligned}
 \mathcal{R}_{fi}^L &\equiv |\rho(\vec{q})_{fi}|^2 \\
 \mathcal{R}_{fi}^T &\equiv |J_+(\vec{q})_{fi}|^2 + |J_-(\vec{q})_{fi}|^2 \\
 \mathcal{R}_{fi}^{TT} &\equiv 2 \Re [J_+^*(\vec{q})_{fi} J_-(\vec{q})_{fi}] \\
 \mathcal{R}_{fi}^{TL} &\equiv -2 \Re [\rho^*(\vec{q})_{fi} (J_+(\vec{q})_{fi} - J_-(\vec{q})_{fi})] \\
 \mathcal{R}_{fi}^{T'} &\equiv |J_+(\vec{q})_{fi}|^2 - |J_-(\vec{q})_{fi}|^2 \\
 \mathcal{R}_{fi}^{TL'} &\equiv -2 \Re [\rho^*(\vec{q})_{fi} (J_+(\vec{q})_{fi} + J_-(\vec{q})_{fi})]
 \end{aligned}$$

Response functions

Why D(e,e'p) reactions are interesting

- Learn about the initial nuclear state
 - D-wave content, six-quark admixtures?
 - High momentum components
- Understand the reaction mechanism
 - Final state interaction
 - Two-body currents
 - Role of isobars
- Use the nucleus as a lab
 - Neutron form factor
 - Color transparency



Recent ($e,e'p$) data (incomplete list)

- Deuteron target
 - $D(e,e'p)$ from Hall B, Hall A
 - TL' asymmetry from Hall B
 - Neutron form factor measurements
- Helium data
- Ratios of polarization transfer measurements
- ...

Deuteron Benchmarking Project

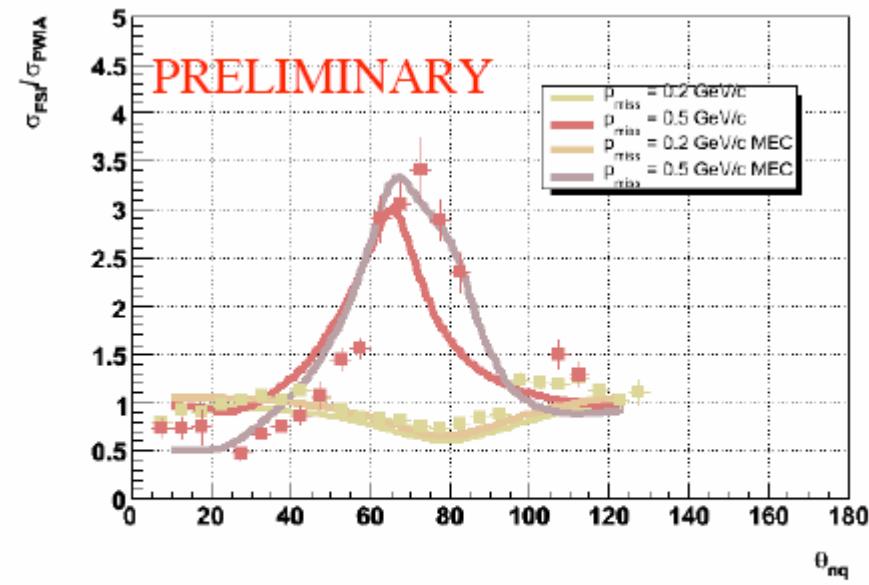
- Started recently, coordinated by Misak Sargsian & SJ
- Perform calculations for fixed kinematics, iterate: PWIA, FSI, FSI + MEC + Isobars
- Identify and understand sources of disagreement

Repository of results: <http://hule.fiu.edu/highnp.html>

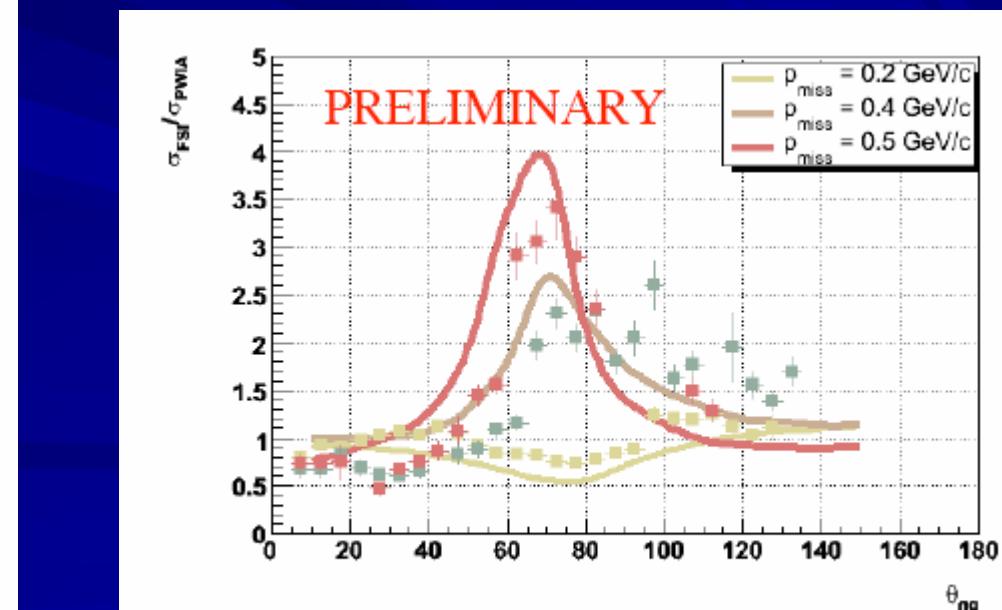
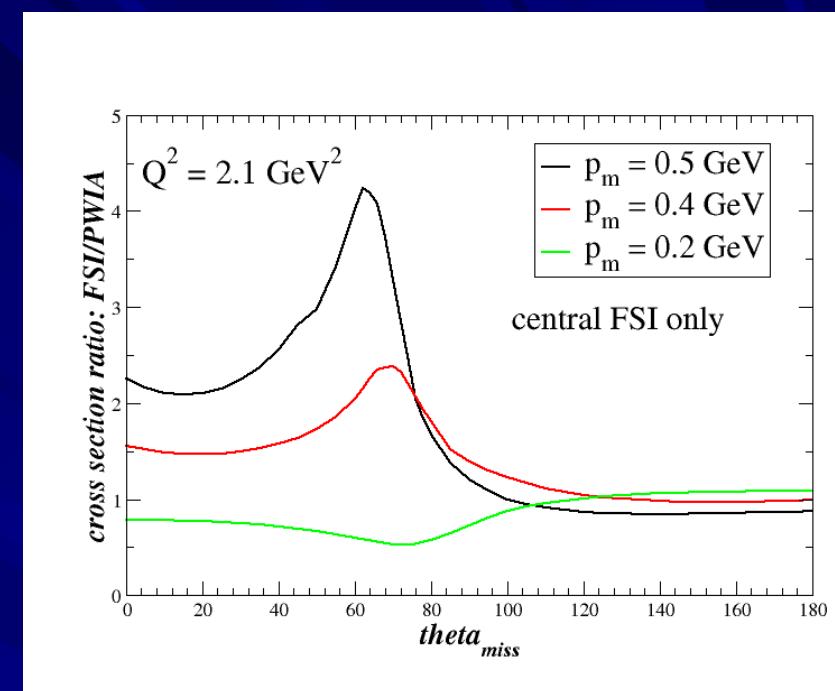
Please participate!!

Why benchmark?

Plots courtesy of Werner Boeglin,
E01-020 (Hall A data)



Calculation: J.M. Laget

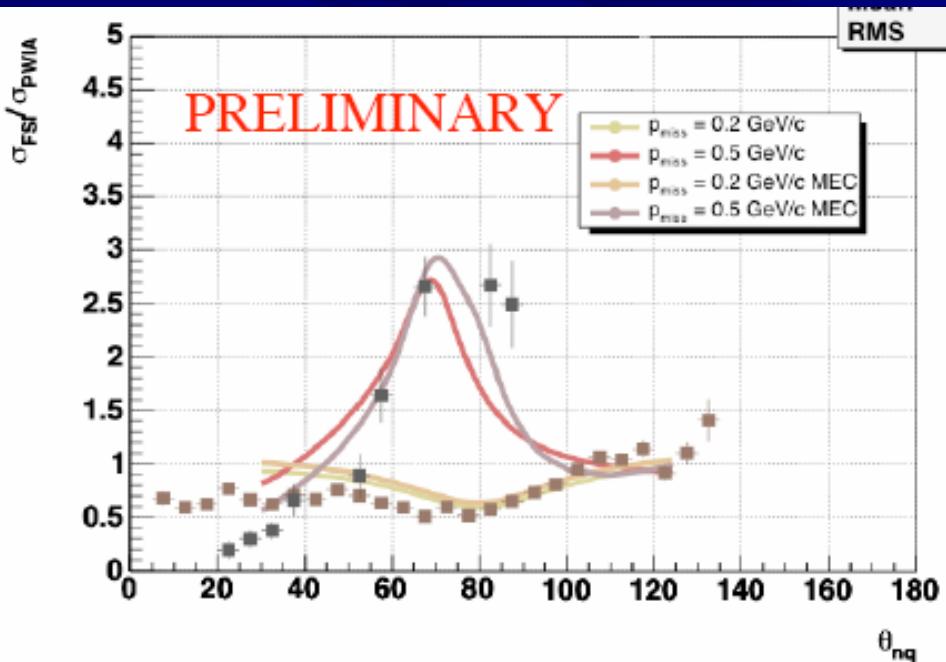


Benchmark

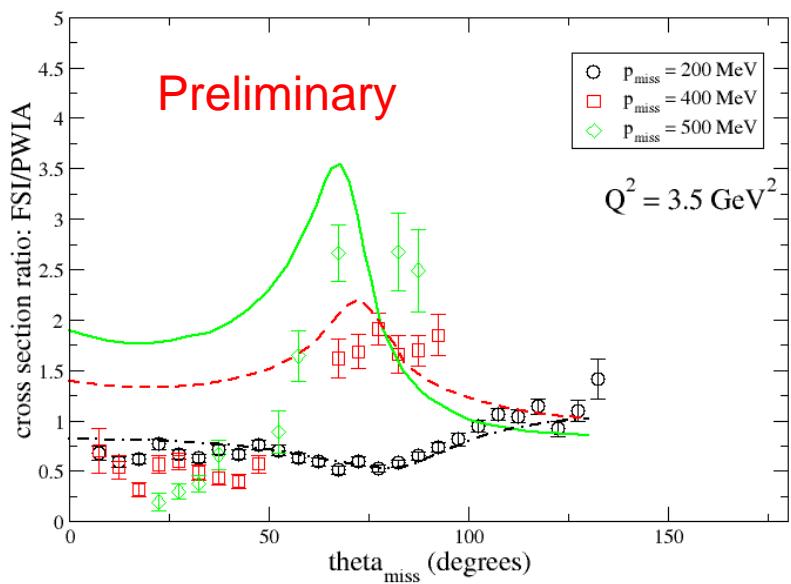
Calculation: M. Sargsian

Why benchmark?

Plots & data courtesy of Werner Boeglin,
E01-020 (Hall A data)



Calculation: J.M. Laget

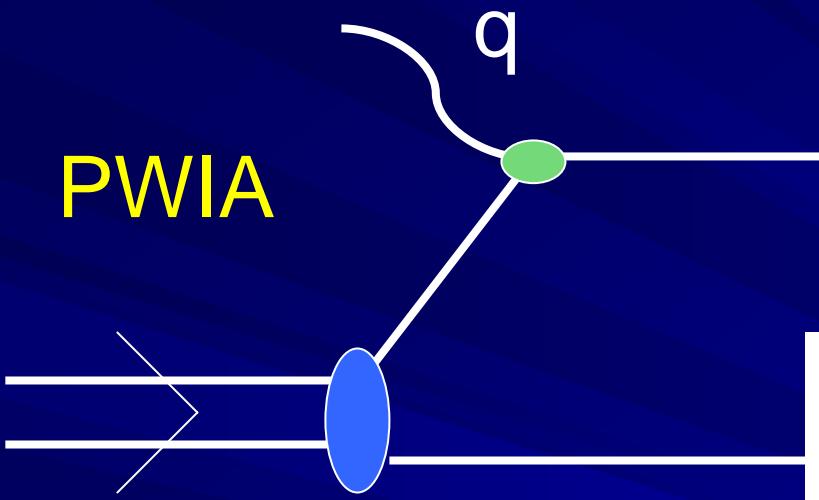


Calculation: M. Sargsian

Benchmarking Kinematics

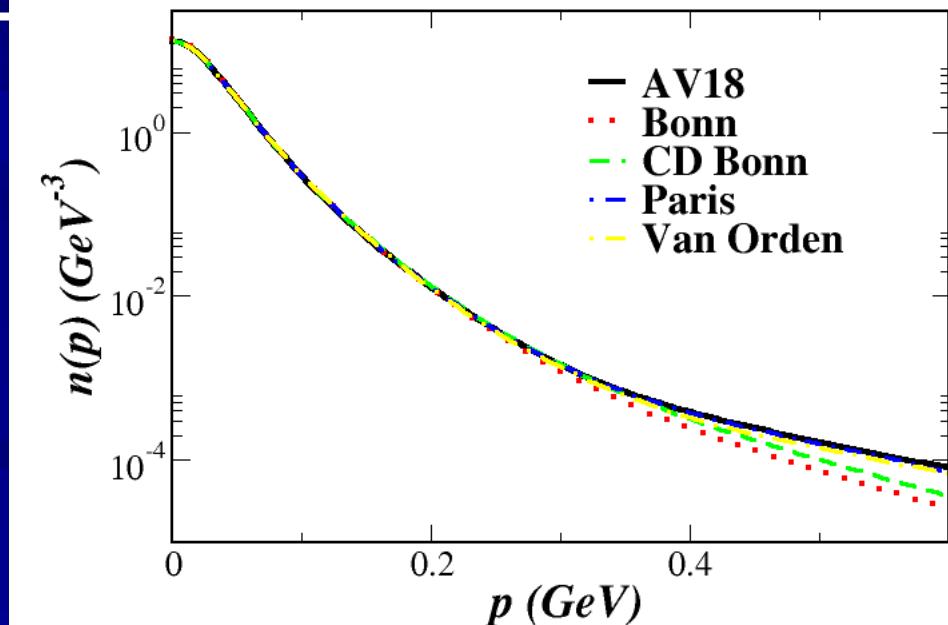
- Compare angular distributions of the missing momentum angle
- Cover missing momenta of 100, 200, 300, 400, 500 MeV/c
- Vary Q^2 starting at 2 GeV 2

Plane Wave Impulse Approximation (PWIA)



Need:

- wave function
- current operator



1st iteration: PWIA (in progress)

- Wave function, form factor parametrizations
- Current operator
 - relativistic corrections & expansion
- Off-shell choices

Current Operators

$$J^\mu(P\Lambda; P'\Lambda') = \bar{u}(P'\Lambda') \left[F_1 \gamma^\mu + \frac{i}{2m_N} F_2 \sigma^{\mu\nu} Q_\nu \right] u(P\Lambda)$$

Momentum space: no expansion necessary – all calculations shown here

Coordinate space: expansions are typically performed

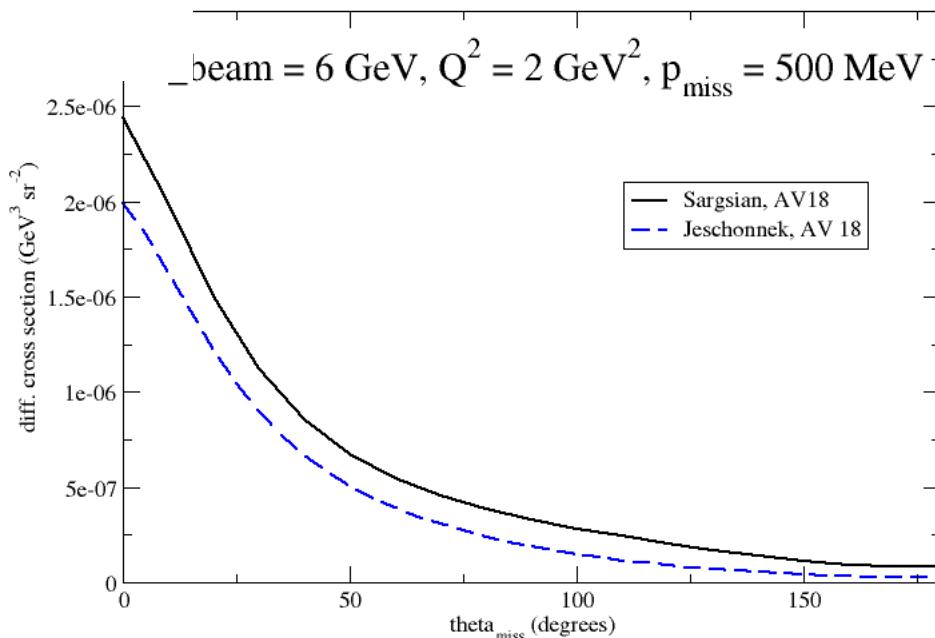
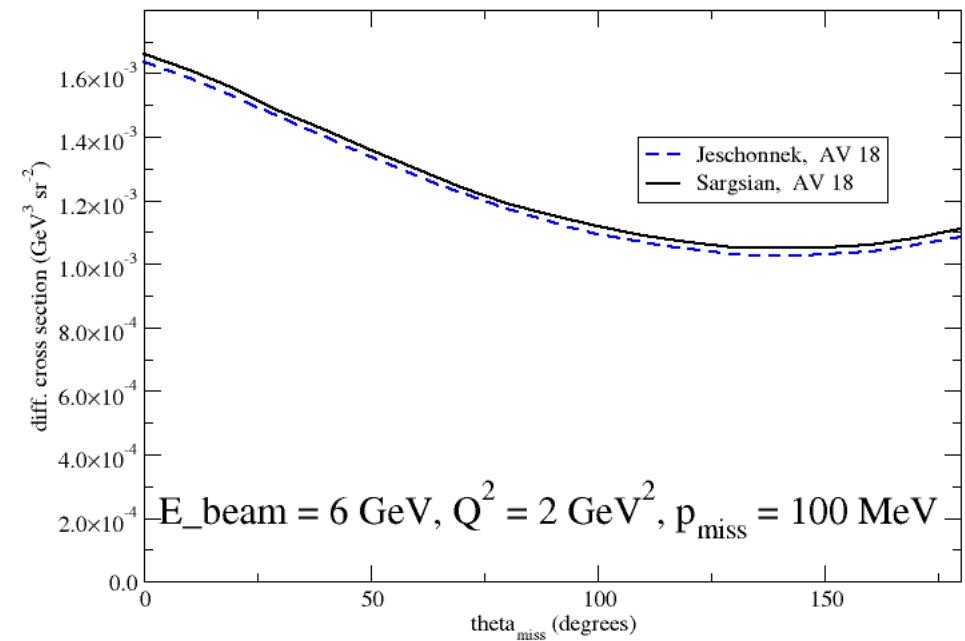
$$\eta = \frac{p}{m} \quad \text{Retain all orders in} \quad \kappa = \frac{q}{2m} \text{ and} \quad \lambda = \frac{\omega}{2m}$$

$$\begin{aligned}\bar{J}^0 &= \frac{\kappa}{\sqrt{\tau}} G_E + \frac{i}{\sqrt{1+\tau}} \left[G_M - \frac{1}{2} G_E \right] (\vec{\kappa} \times \vec{\eta}) \cdot \vec{\sigma} + \mathcal{O}(\eta^2) \\ \bar{J}^3 &= (\lambda/\kappa) \bar{J}^0 \\ \vec{\bar{J}}^\perp &= -\frac{\sqrt{\tau}}{\kappa} \left\{ i G_M \left([\vec{\kappa} \times \vec{\sigma}] + \frac{1}{2} \left(\frac{\lambda}{\kappa} \right) \frac{1}{\kappa} (\vec{\kappa} \cdot \vec{\sigma}) (\vec{\kappa} \times \vec{\eta}) \right) \right. \\ &\quad \left. - \left(G_E + \frac{1}{2} \tau G_M \right) \left[\vec{\eta} - \left(\frac{\vec{\kappa} \cdot \vec{\eta}}{\kappa^2} \right) \vec{\kappa} \right] \right\} + \mathcal{O}(\eta^2),\end{aligned}$$

SJ & Donnelly, PRC 57, 2438 (1998)

The Deuteron Benchmarking Project

First Benchmarking Plots (PWIA)



Current operators for bound nucleons

Free nucleon:

$$E = \sqrt{m^2 + \vec{p}^2}$$

$$J^\mu = \bar{u}(p') \left[\gamma^\mu F_1 + \frac{i}{2m_N} F_2 \sigma^{\mu\nu} Q_\nu \right] u(p)$$

$$J^\mu = \bar{u}(p') \left[\gamma^\mu (F_1 + F_2) + \frac{i}{2m_N} (p + p')^\mu F_2 \right] u(p)$$

Free nucleon: same results

Bound nucleon: results differ

Non-relativistic wave function: rewrite current operator to a two-dimensional form

2nd Iteration: FSI

- Diagrams, generalized eikonal approximation, Glauber
- (non)-factorization
- NN amplitude
 - Central and spin-dependent parts
 - Different parametrizations

Final State Interaction (FSI)

$$S(\vec{r}) = 1 - \theta(z) \exp(i\Delta z) \Gamma(\vec{b})$$

Current matrix elements: $\mathcal{M}_{fi} = \langle f | S J_{em} | i \rangle$

Profile function and N N scattering amplitude:

$$\Gamma(\vec{b}) = \frac{1}{2\pi ik} \int d^2 \vec{l} \exp(-il \cdot \vec{b}) f(\vec{l})$$

NN scattering amplitude in the c.m. frame:

$$f(\vec{l}) = A(\vec{l}) + B(\vec{l}) (\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \hat{n} + C(\vec{l}) (\vec{\sigma}_1 \cdot \hat{n}) (\vec{\sigma}_2 \cdot \hat{n}) + D(\vec{l}) (\vec{\sigma}_1 \cdot \hat{m}) (\vec{\sigma}_2 \cdot \hat{m}) + E(\vec{l}) (\vec{\sigma}_1 \cdot \hat{h}) (\vec{\sigma}_2 \cdot \hat{h})$$

Central FSI

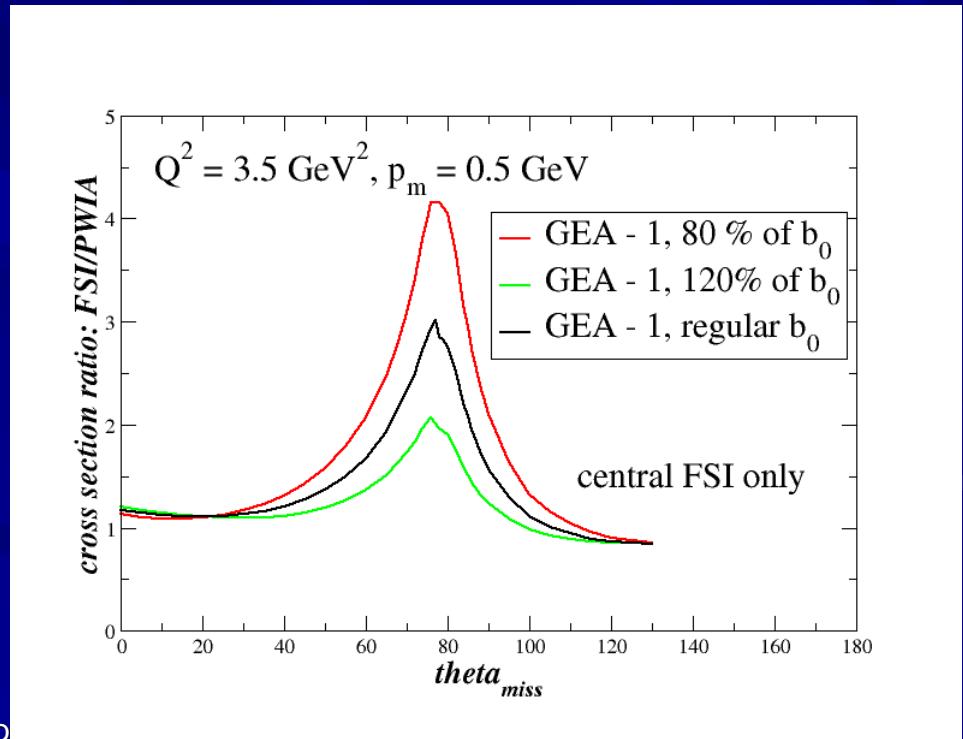
$$A(l) = \frac{k \sigma_{tot}^{NN}}{4\pi} (\rho + i) \exp(-0.5 l^2 b_o^2)$$

NN scattering parameters from:

- ⑩ Phase-shift analysis
- ⑩ Proton – nucleus Glauber analysis

New Hall A, Hall B data have very high energy transfers, phase shift analysis available up to 1.3 GeV, complete data sets?

values from pA not necessarily appropriate for deuteron, also limited to energies of 1GeV or less; fitted with only central and spin-orbit non-zero



Influence of NN parameters

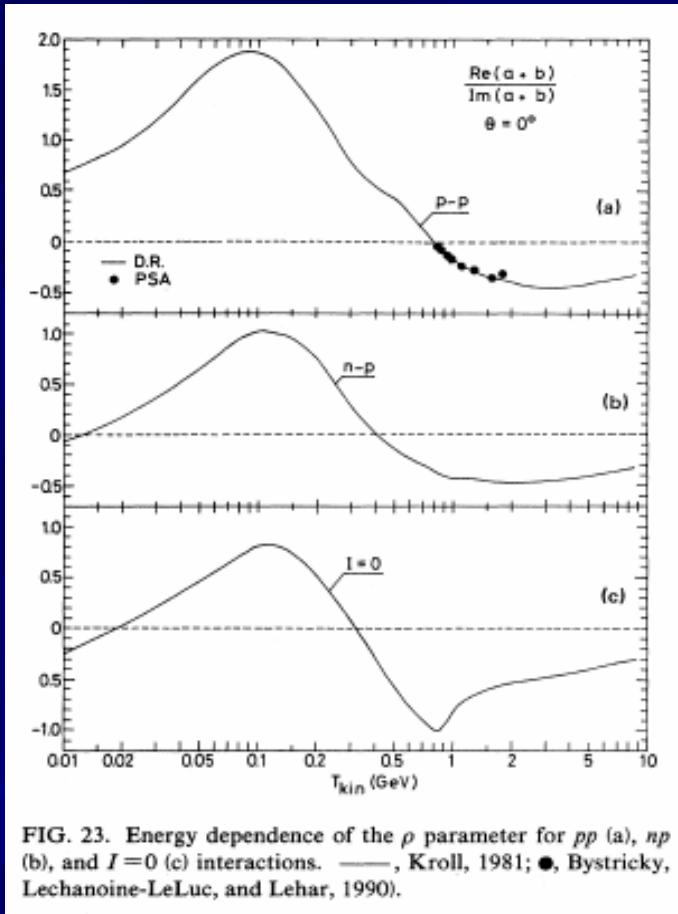
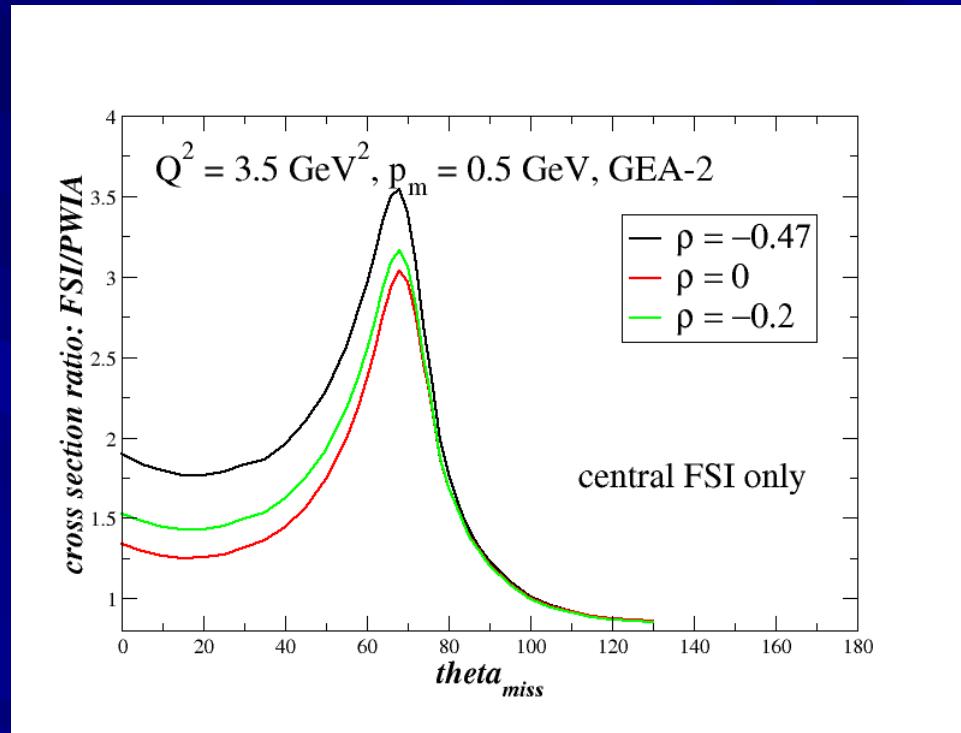


FIG. 23. Energy dependence of the ρ parameter for $p-p$ (a), $n-p$ (b), and $I=0$ (c) interactions. —, Kroll, 1981; ●, Bystricky, Lechanoine-LeLuc, and Lehar, 1990).

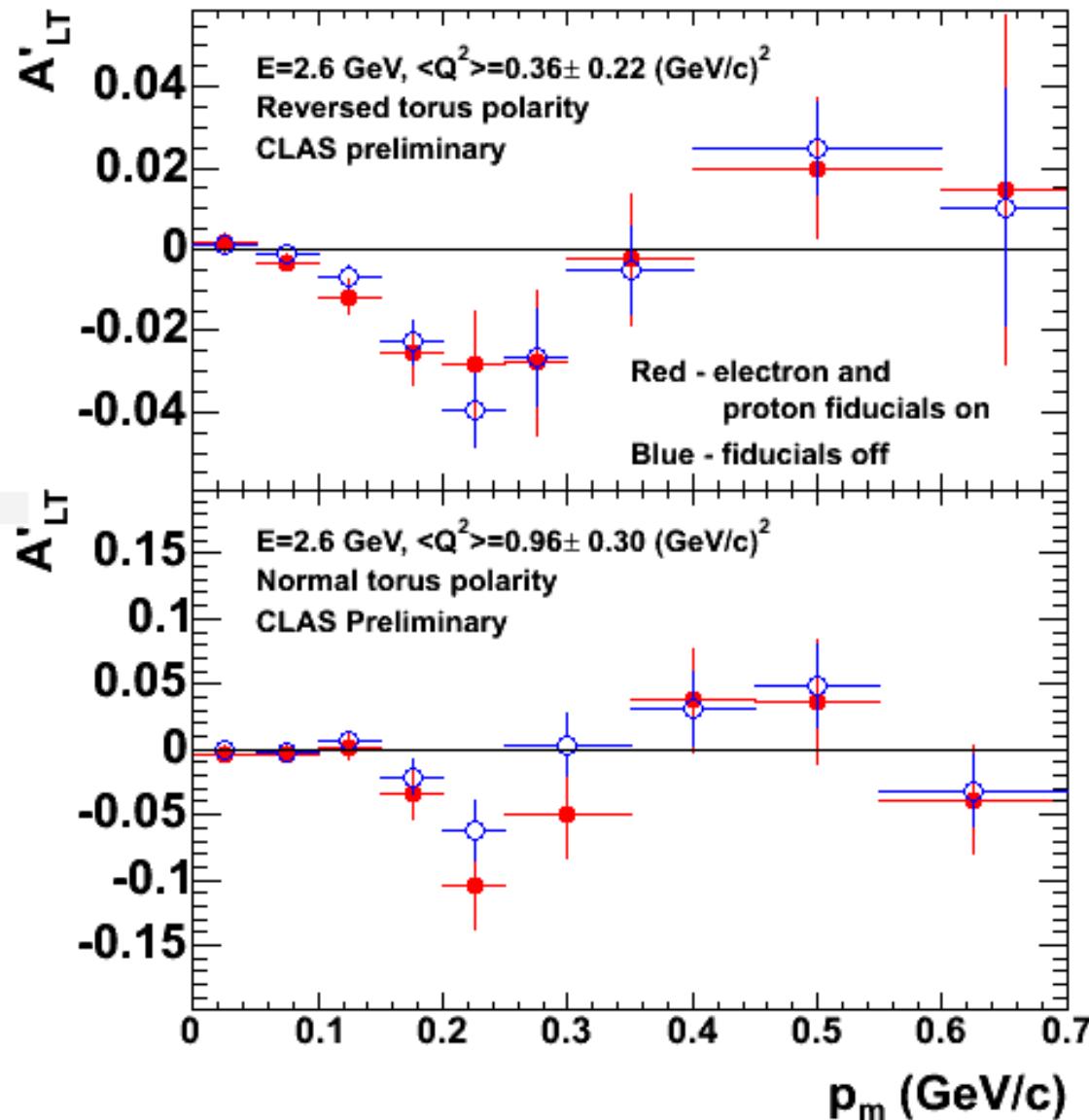
Lechanoine-Leluc & Lehar, RMP 65, 47 (1993)



The LT' Asymmetry

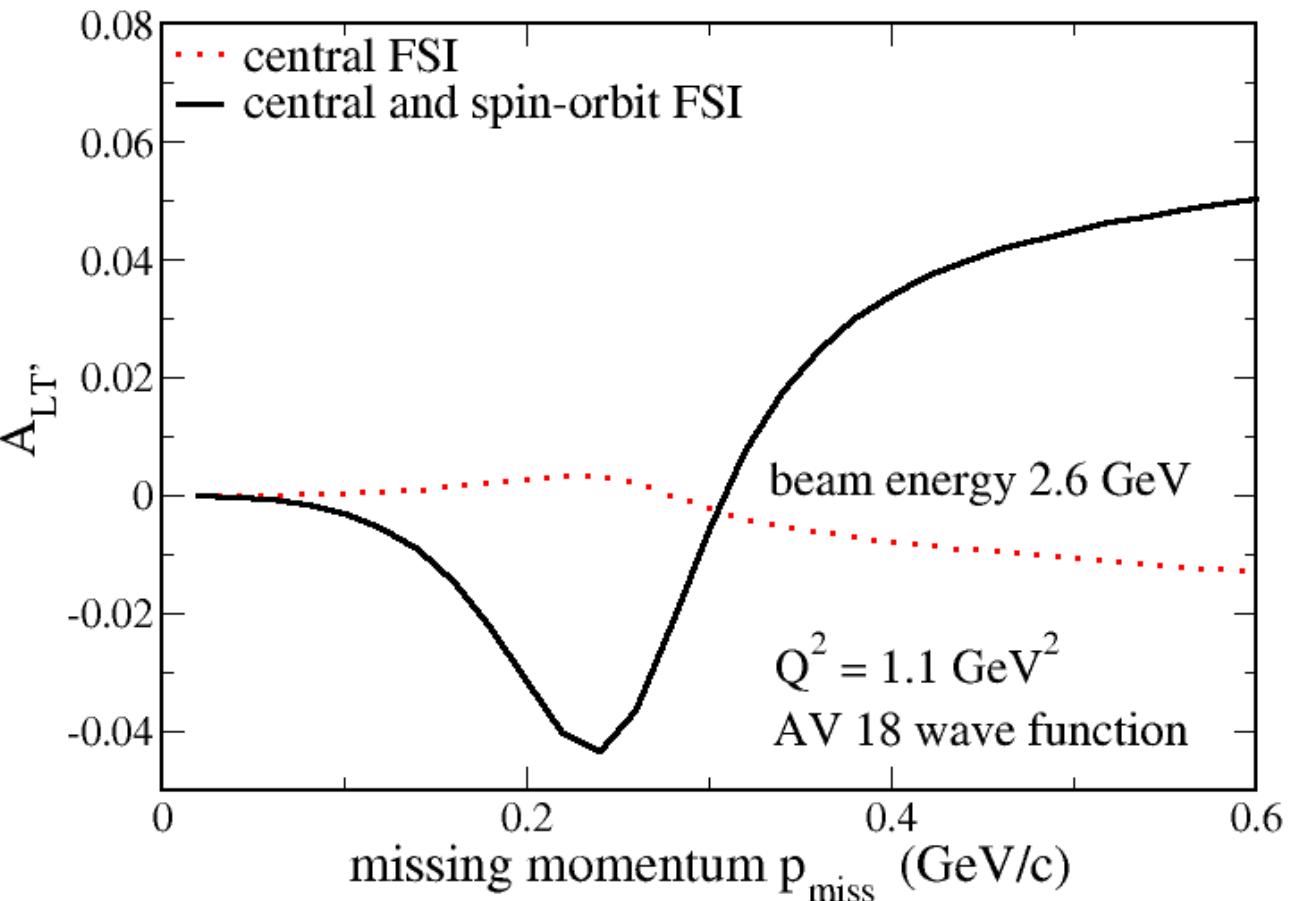
Preliminary data
from Hall B,
E5 run period,
Jerry Gilfoyle

$D(\vec{e}, e' p) n$



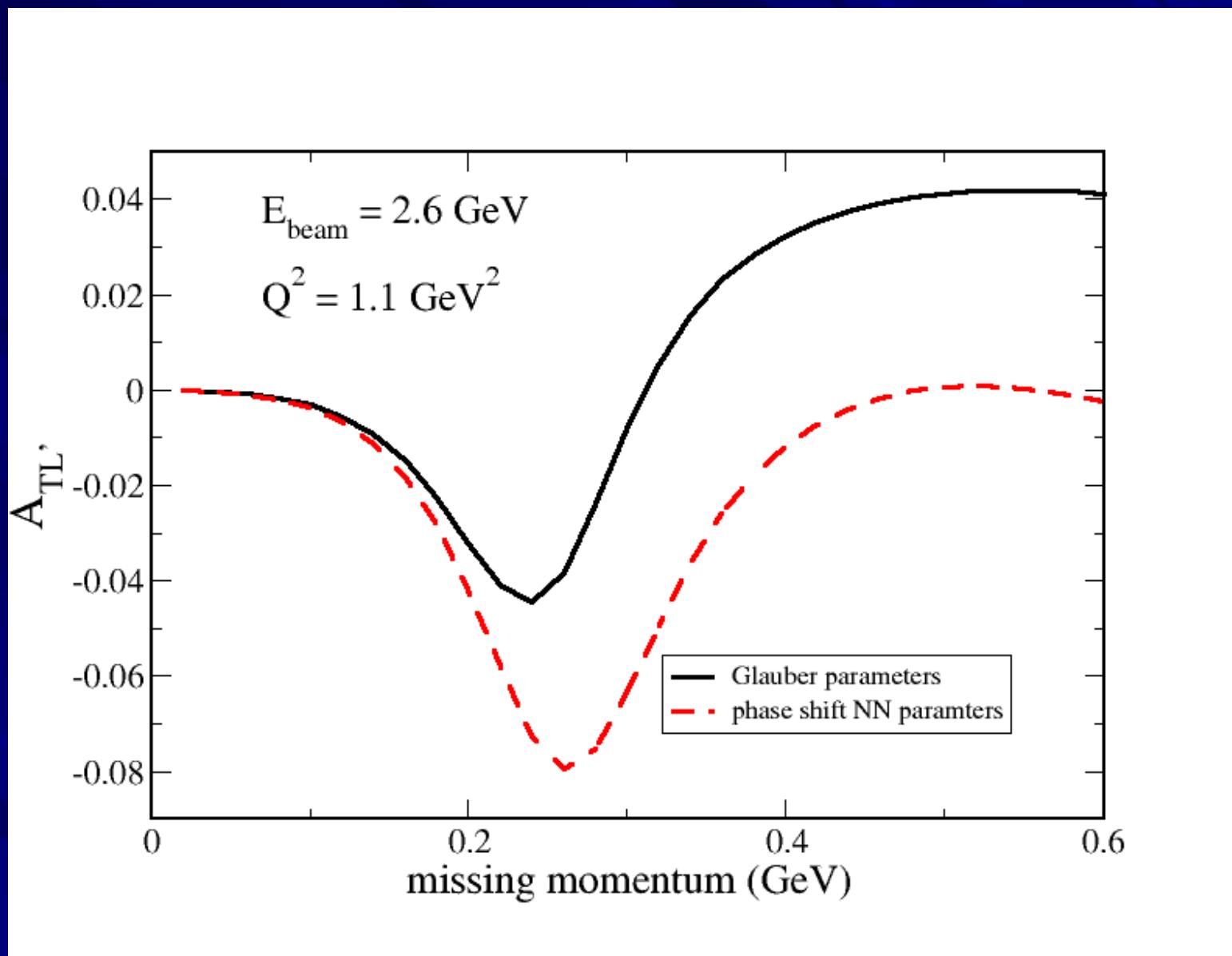
The LT' Asymmetry

$$A_{LT'} = \frac{v_{LT'} R_{LT'}}{v_L R_L + v_T R_T + v_{TT} R_{TT}}$$

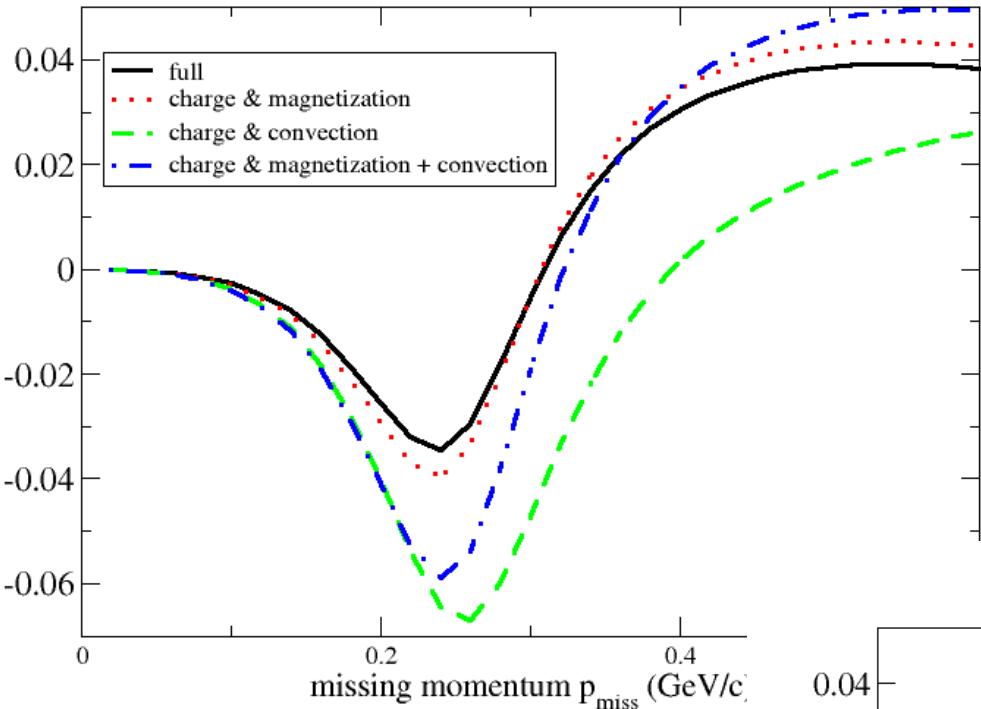


LT' Asymmetry
is zero in PWIA!

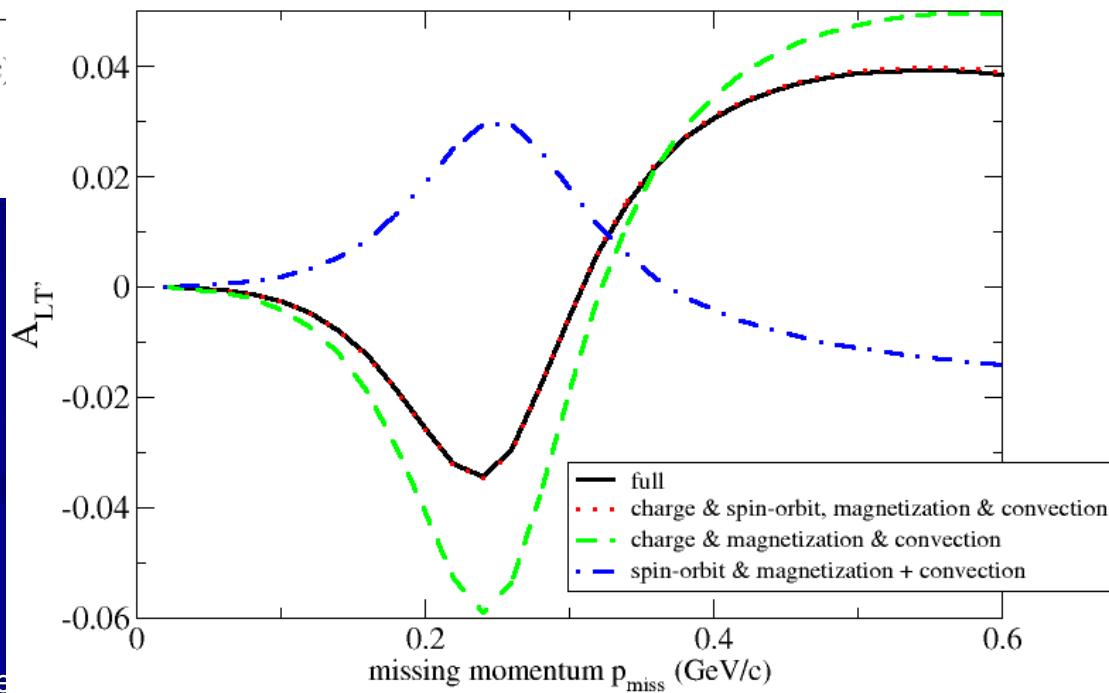
Influence of the NN parametrization



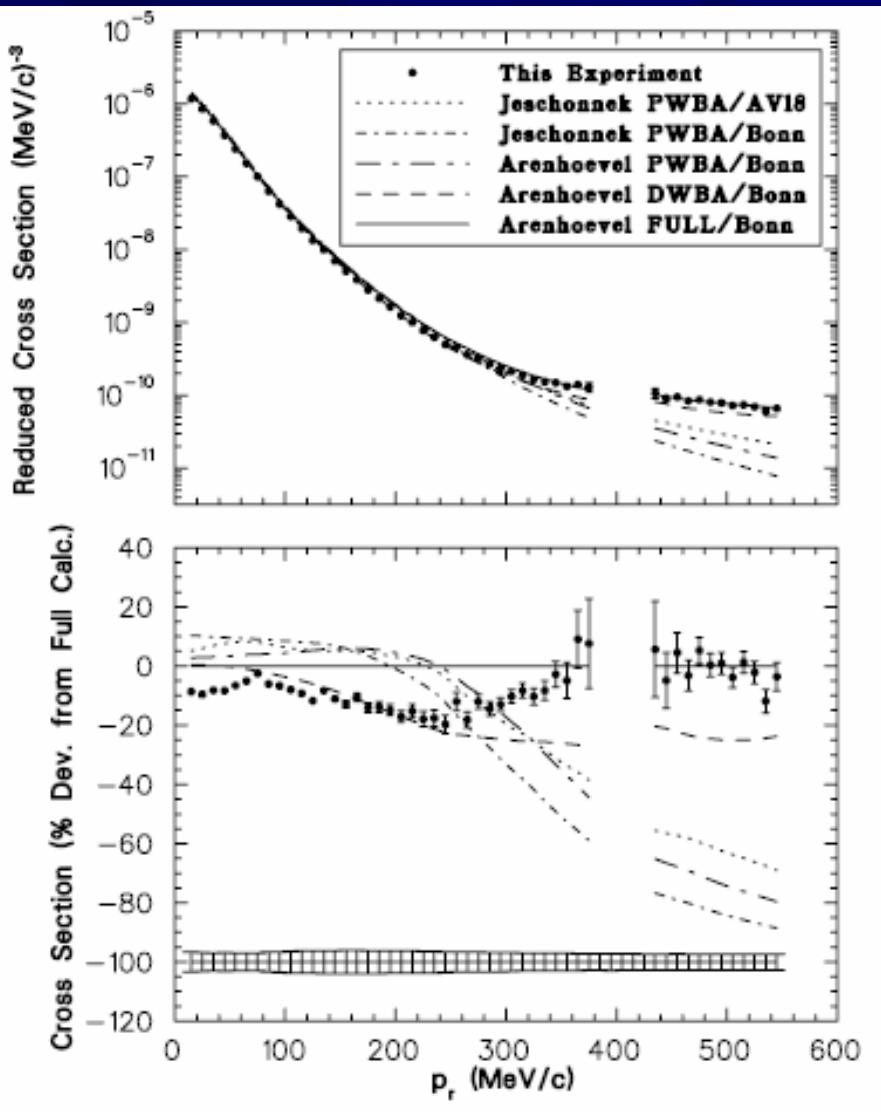
A_{LT}



What causes the dip?



The low missing momentum puzzle



From Ulmer et al, PRL 89 062301 (2002)

$$Q^2 = 0.665 \text{ GeV}/c^2, \quad x = 0.964$$

Also seen in

- Hall B data
- Saclay data, Bernheim et al, NPA 365, 349 (1981)
- Blomqvist PLB 424, 38 (1998)
- ${}^3\text{He}(e, e'p){}^2\text{H}$ data

Deuteron Benchmark Project - Goals

■ Time line

- Finish PWIA comparison by end of July
- Finish FSI comparison by October

■ Expected Results

- Agree on what is relevant
- Agree on a set of inputs
- Identify a “theory error band”

■ Web-based interface for D($e,e'p$) theory?

got deuteron?

Please send calculations to jeschonnek.1@osu.edu
or sargsian@fiu.edu

Determining the Neutron Magnetic Form Factor

- Traditional approach: inclusive measurement on deuteron, helium: large theoretical corrections
- Modern approach: ratio of $(e,e'p)$ and $(e,e'n)$ data: small theoretical corrections

$$R_{data} \frac{R_{PWIA}^{theo}}{R_{full}^{theo}} = R_{PWIA}^{exp} = \frac{\sigma_{en}^{elastic,exp}}{\sigma_{ep}^{elastic,exp}}$$

Low Q^2 measurements at Mainz; high Q^2 data from Hall B, E5 (Will Brooks et al.)

Determining the Neutron Magnetic Form Factor

Theoretical correction factor:

$$\frac{R_{PWIA}^{theo}}{R_{full}^{theo}}$$

Q^2	ratio
1	0.99980
2	0.99972
3	0.99969
4	0.99967
5	0.99961

Using AV 18, MMD form factor parametrization

For $Q^2 = 5 \text{ GeV}^2$: **Bonn: 0.99958 Paris: 0.99961 CD Bonn: 1.00037**

$$\begin{aligned}\text{dipole} + G_E^n &= 0: 0.99962 \\ \text{dipole} + \text{Galster} &: 0.99961\end{aligned}$$