Polarization Observables in Quasielastic (*e,e'p*) and (*e,e'n*) on the *Deuteron*

J.R. Calarco, Univ. of New Hampshire

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Outline

- Wave functions in the deuteron
- Effect of the *D-state*
- Signature of the *D-state* in QE (*e,e'p*)
- Inclusive QES and G_M^n
- Extraction of G_E^n from QE (*e,e'n*)

The Deuteron

- Only bound state of the NN system
- The "hydrogen atom" of nuclear physics
- Sensitive to the NN potential
- Known to be sensitive to spin-spin interaction … J = 1 state is bound while J = 0 is not
- Known to be sensitive to the tensor interaction … bound J = 1 state must contain both L = 0 and L = 2 components because μ_d is not quite equal to $\mu_p + \mu_n$ and Q_d is small but not 0

Deuteron Wave Functions

- NN interaction conserves only total angular momentum
- Spin-1 nucleus contains L = 0, 2 admixture state:

$$\Psi^{m_d}(\vec{r}) = R_0(r) Y_{110}^{m_d}(\Omega_r) + R_2(r) Y_{112}^{m_d}(\Omega_r)$$

- Tensor component must be present to allow L = 2
- Fourier transform into momentum space:

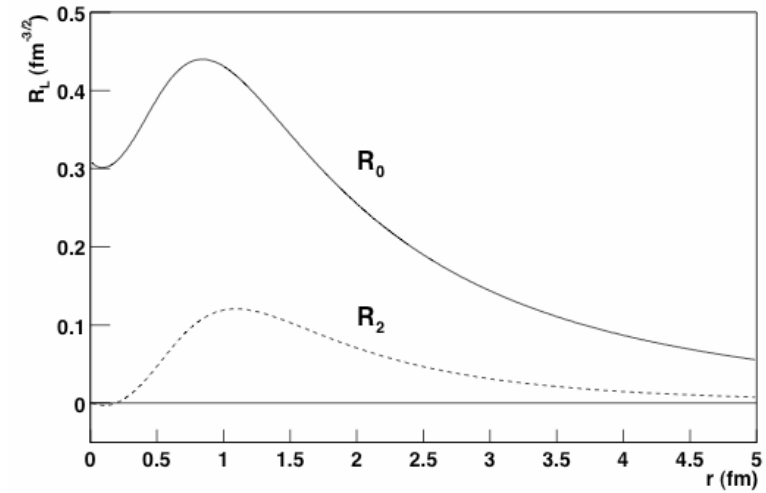
$$\vec{r} \equiv \vec{r}_p - \vec{r}_n \quad \rightarrow \quad \vec{p} \equiv \frac{1}{2}(\vec{p}_p - \vec{p}_n)$$

$$R_0(r) \rightarrow \tilde{R}_0(p)$$

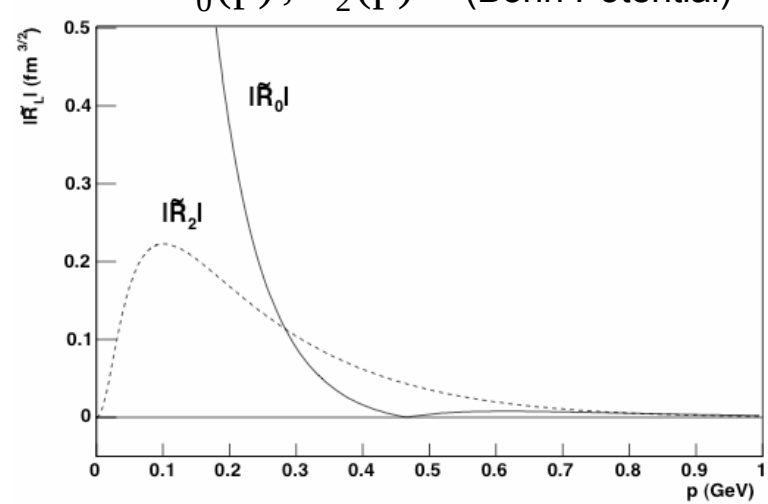
$$R_2(r) \rightarrow \tilde{R}_2(p)$$

- L = 2 component is dominant at p ~ 0.3GeV

$R_0(r), R_2(r)$ (Bonn Potential)



$\tilde{R}_0(p), \tilde{R}_2(p)$ (Bonn Potential)



Deuteron Density Functions

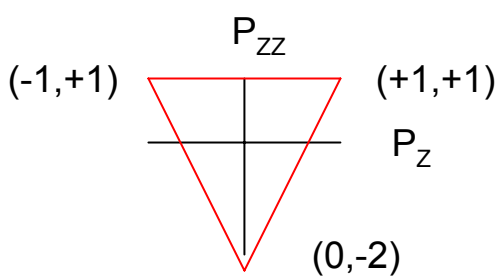
- Calculate the density functions:

$$\rho^{m_d}(\vec{r}') = \Psi^{m_d}(\vec{r})^* \Psi^{m_d}(\vec{r})$$

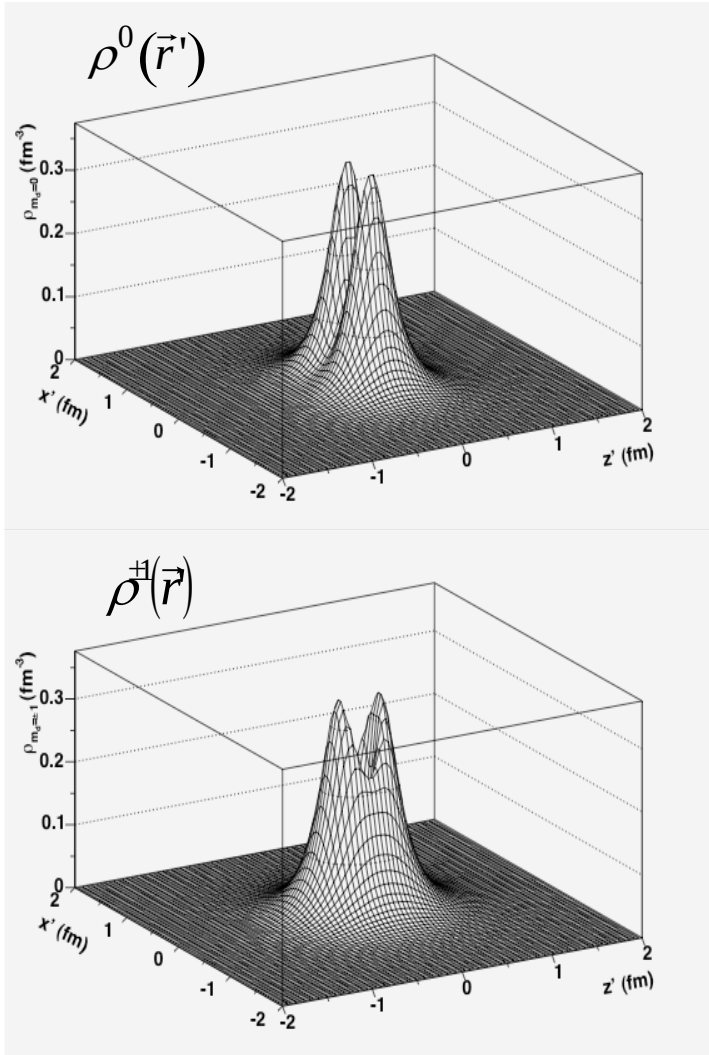
- One-to-one correspondence between m_d and the (P_Z, P_{ZZ}) polarization states:

$$m_d = \pm 1 \rightarrow \rho_{\pm 1} = 1 \rightarrow (P_Z, P_{ZZ}) = (\pm 1, +1)$$

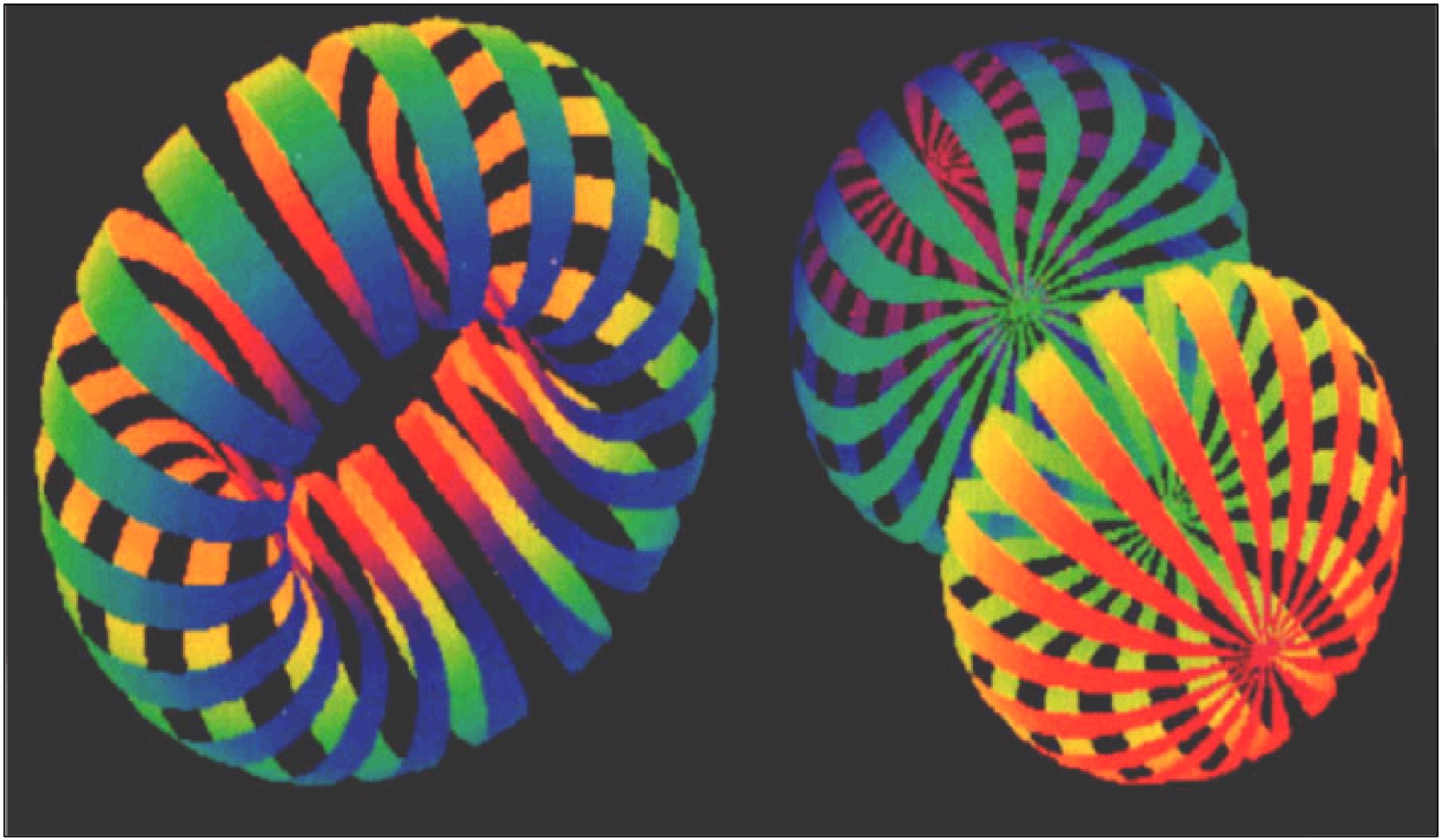
$$m_d = 0 \rightarrow \rho_0 = 1 \rightarrow (P_Z, P_{ZZ}) = (0, -2)$$



- In the absence of a tensor NN component, these plots are spherical and identical
- Famous "donut" and "dumbbell" shapes



Donuts and Dumbbells



Deuteron Density Functions

Calculate density functions:

$$\rho^{m_d}(\vec{r}') = \Psi^{m_d}(\vec{r})^* \Psi^{m_d}(\vec{r})$$

$$\rho^0(\vec{r}') = \frac{4}{\pi}\left[C_0(r) - 2C_2(r)P_2(\cos\theta)\right]$$

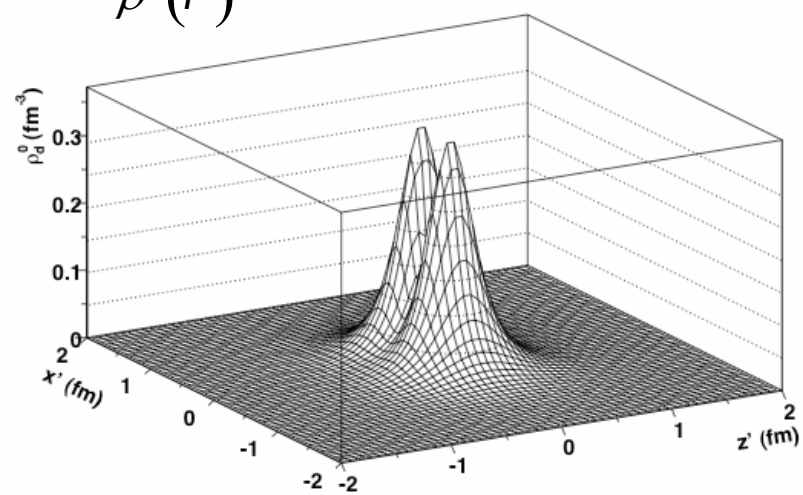
$$\rho^{\pm 1}(\vec{r}') = \frac{4}{\pi}\left[C_0(r) + C_2(r)P_2(\cos\theta)\right]$$

Straightforward form:

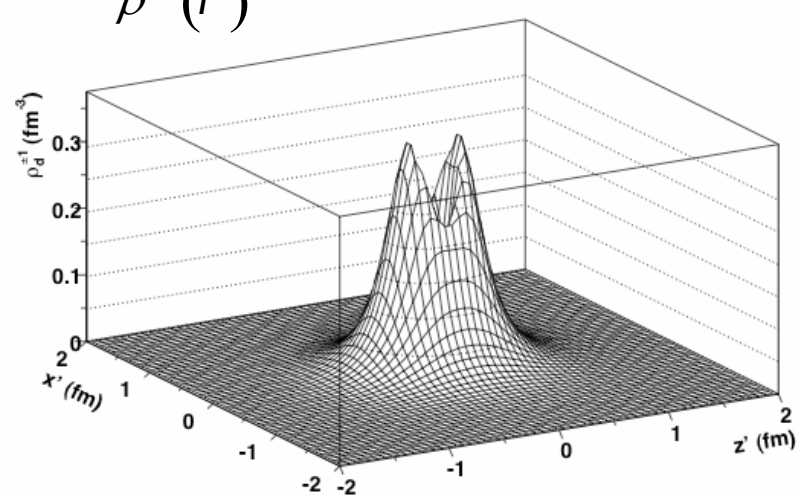
$$C_0(r) \equiv R_0(r)^2 + R_2(r)^2$$

$$C_2(r) \equiv R_2(r)\left(\sqrt{2}R_0(r) - \frac{1}{2}R_2(r)\right)$$

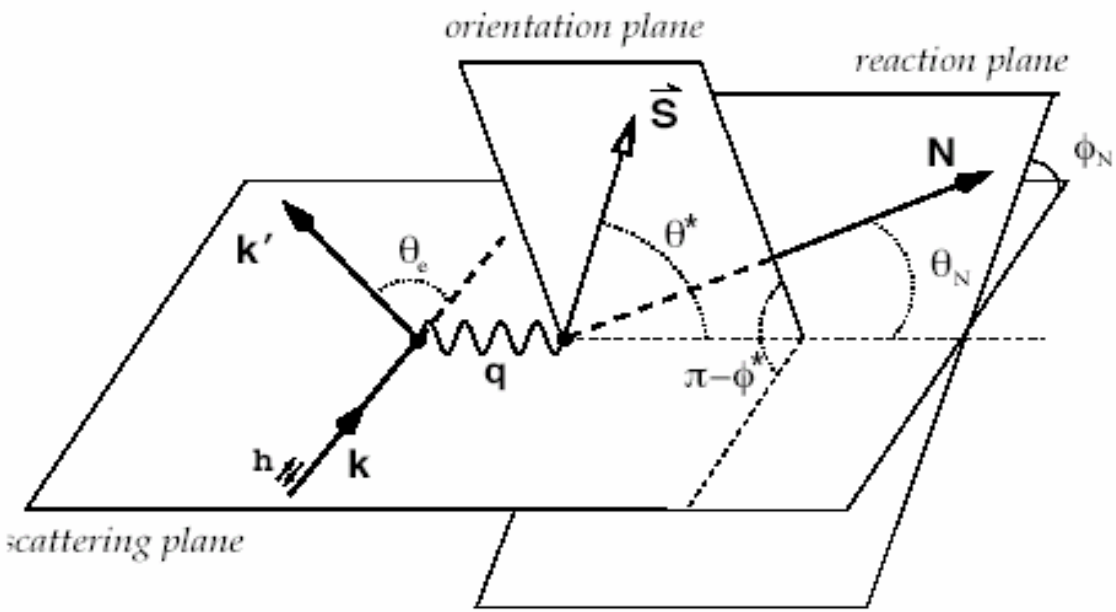
$\rho^0(\vec{r}')$



$\rho^{\pm 1}(\vec{r}')$



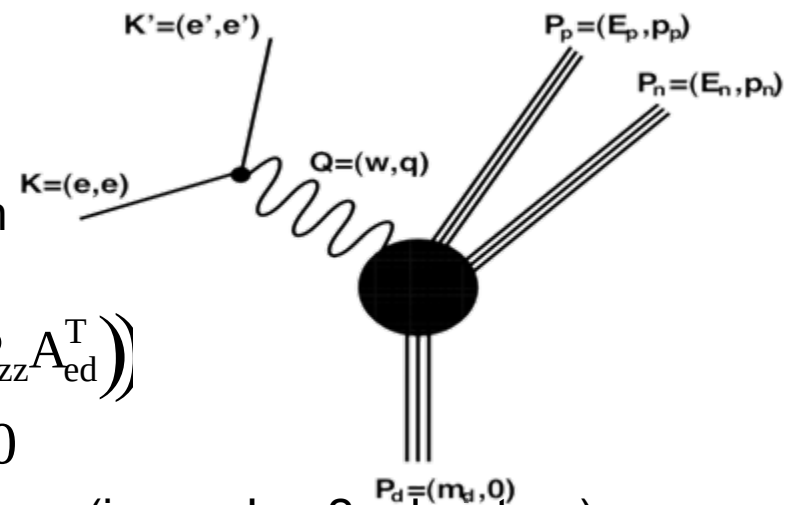
General Kinematics for Polarized *e* Scattering on a Polarized Target



Deuteron Electrodisintegration

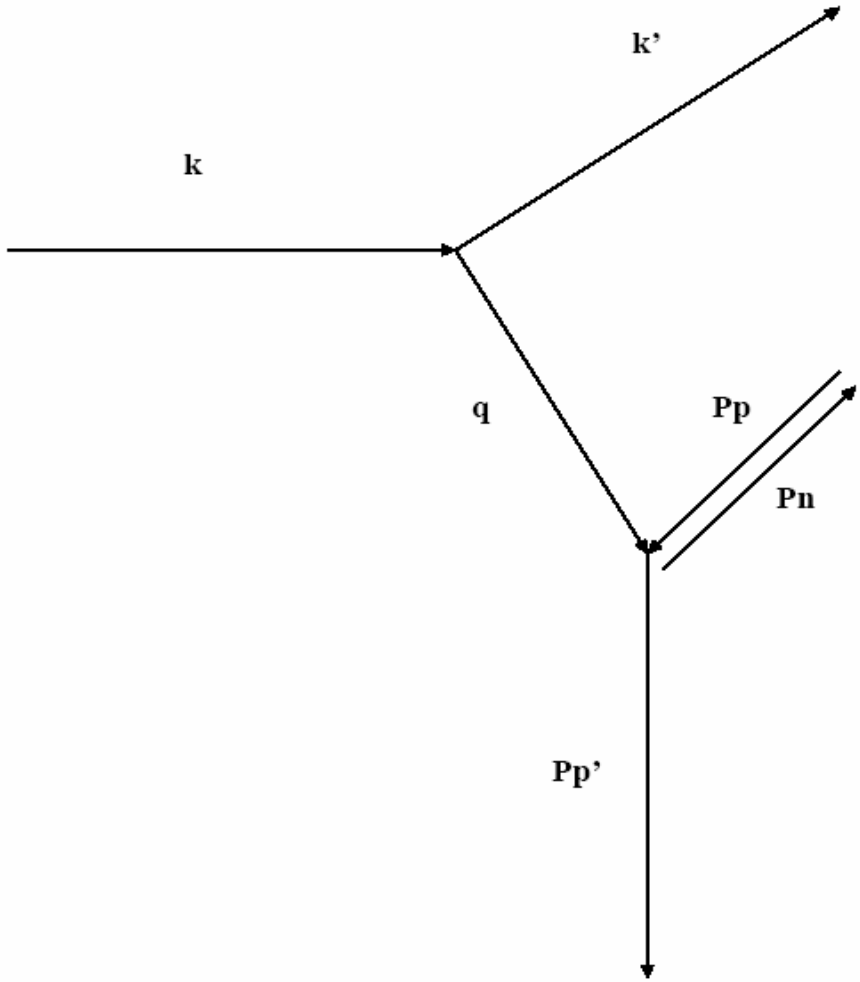
- Loosely-bound deuterium readily breaks up electromagnetically into two nucleons
  - e + d $\rightarrow$ e' + p + n
- Most generally, the $\vec{d}(\vec{e}, e' N)N$ cross section can be written as

$$S(h, P_z, P_{zz}) = S_0\left(1 + P_z A_d^V + P_{zz} A_d^T + h\left(A_e + P_z A_{ed}^V + P_{zz} A_{ed}^T\right)\right)$$



- In the Born approximation, $A_e = A_d^V = A_{ed}^T = 0$
- A_d^T vanishes in the L = 0 model for the deuteron (i.e. no L = 2 admixture)
  - Measure of L = 2 contribution and thus tensor NN component
  - Reaction mechanism effects (MEC, IC, RC) convoluted with tensor contribution
- A_{ed}^V provides a measure of reaction mechanisms and L = 2 admixture
  - -- Useful for extraction of G^n_e
  - -- Beam-vector polarization product (h•Pz) obtained from analysis

Kinematics for QES



- Electron momenta k, k'
- Momentum Transfer q=k–k'
- Proton initial momentum $P_p = -P_n$ (P_d=0)
- Measure P_p' , k , k'
- $P_p = P_p' - q = -P_n$, the
- "Missing Momentum"

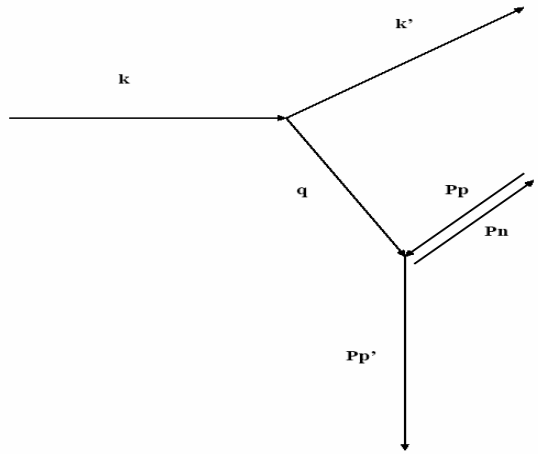
Tensor Asymmetry in PWIA

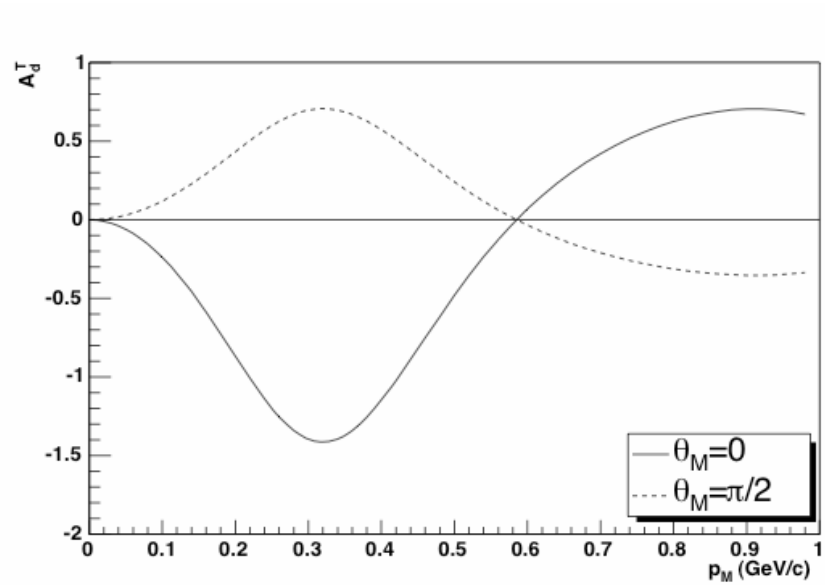
- In PWIA, ATd is a function of only the "missing momentum":

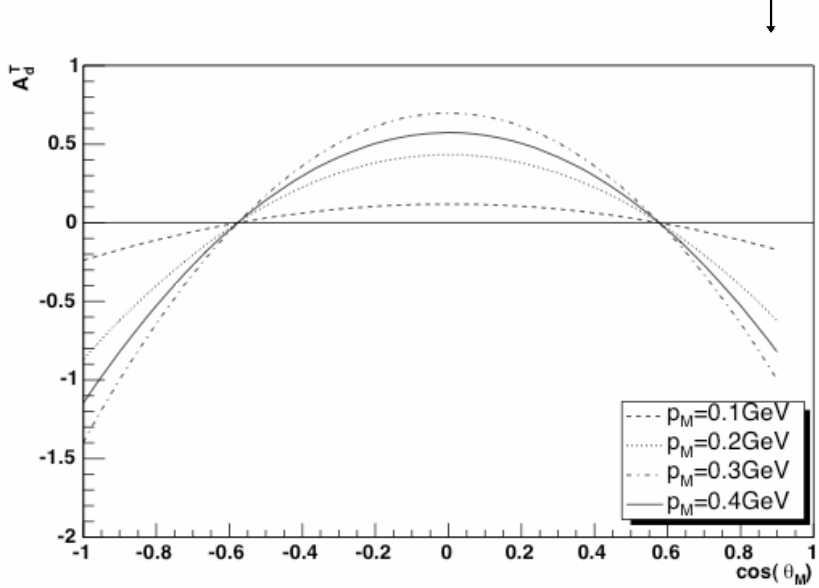
  $\mathbf{P}_M = \mathbf{P}_p = -\mathbf{P}_n = \mathbf{P'}_p - \mathbf{q}$

- A^T_d has a straightforward form:

$$A_d^T(\vec{p}_M) = -\frac{2\tilde{R}_2(p_M)\left(\tilde{R}_0(p_M) + \sqrt{\frac{1}{8}}\tilde{R}_2(p_M)\right)}{\tilde{R}_0(p_M)^2 + \tilde{R}_0(p_M)^2} P_2(\cos\theta_M)$$





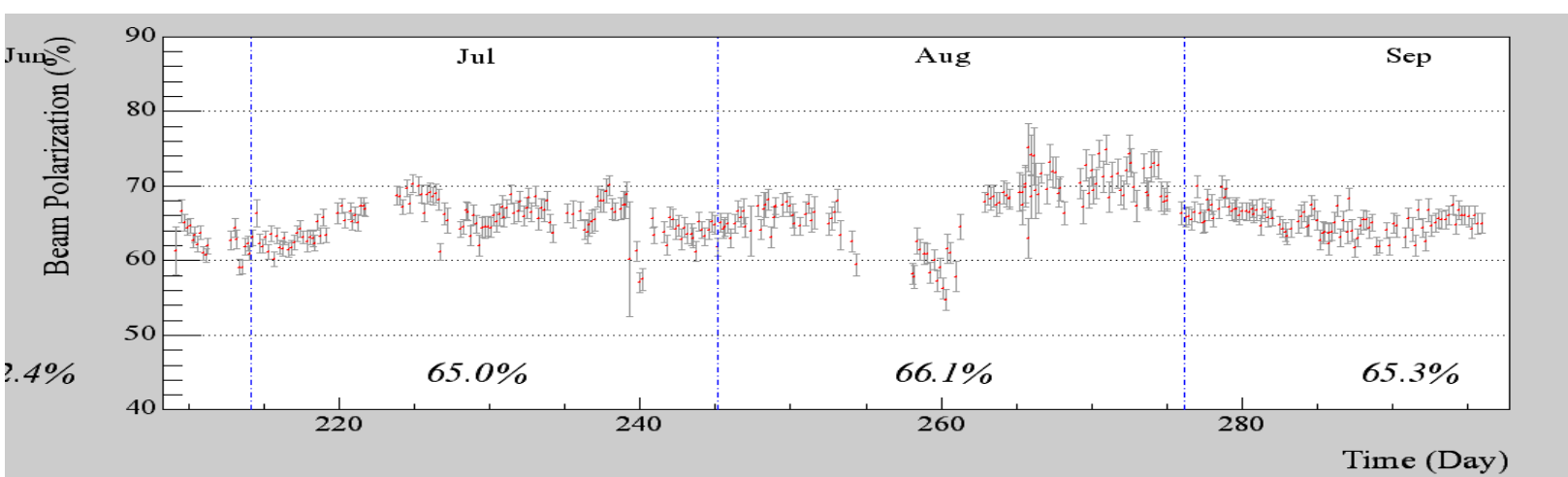


Beam and Target Performance

- Beam fills to 225mA with 25min lifetime, average polarization = 65% ± 4%
- Deuterium polarization in tri-state mode
  - (Vector, Tensor) :

    $(-P_z, +P_{zz})$ $(+P_z, +P_{zz})$ ← 3-state mode

    $(0, -2P_{zz})$
- Flow = 2.2×10^{16} atoms/s, Density = 6.0×10^{13} atoms/cm^2
- Luminosity = 4.0×10^{31} /cm^2/s @ 140mA
- Target polarizations from data analysis: P_z = 88% ± 4%, P_{zz} = 65% ± 2%

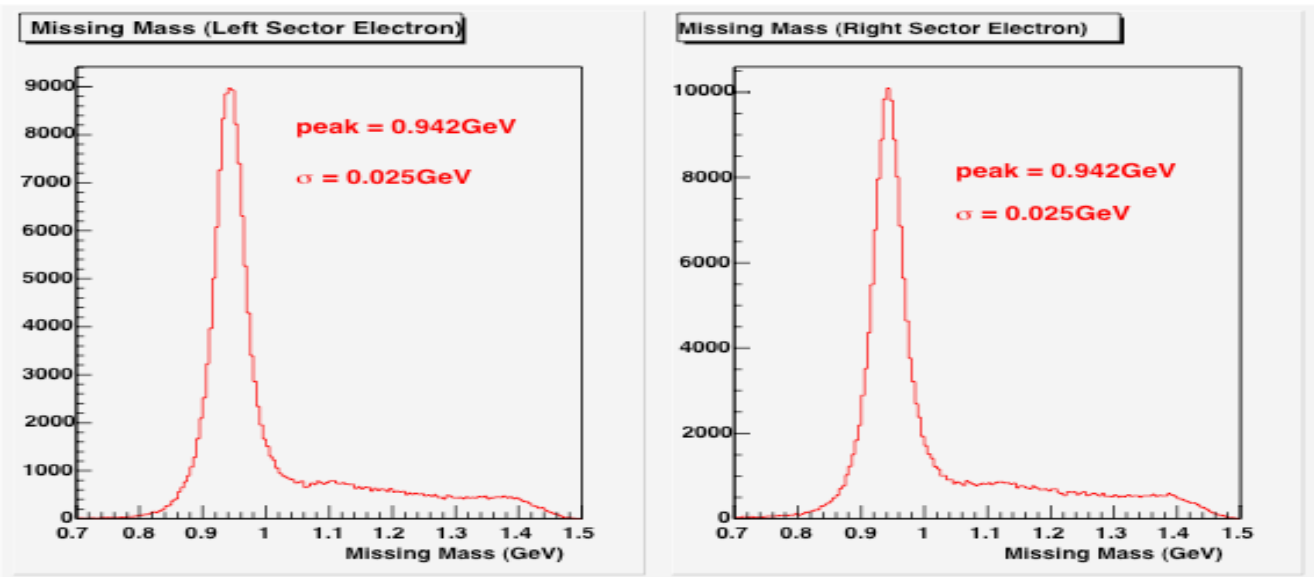


Missing Mass

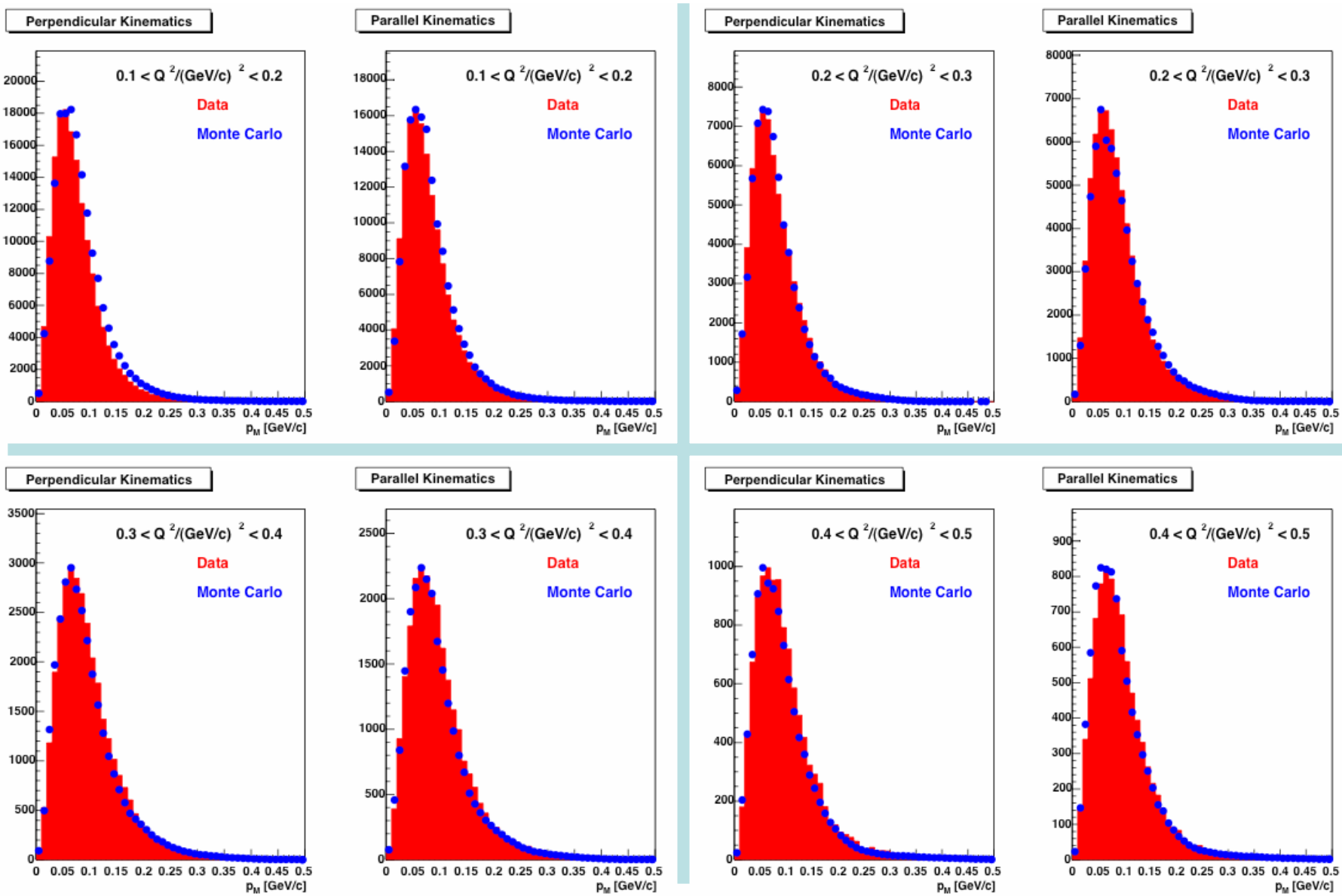
- Only the e^- and p^+ are measured
  - actually measure d(e,e'p)X and thus need cuts to ensure that X = n
- Define "missing" energy, momentum, and mass:

$$E_M \equiv m_d + \omega - E_p \quad , \quad \vec{p}_M \equiv \vec{q} - \vec{p}_p \quad , \quad m_M \equiv \sqrt{E_M^2 - p_M^2}$$

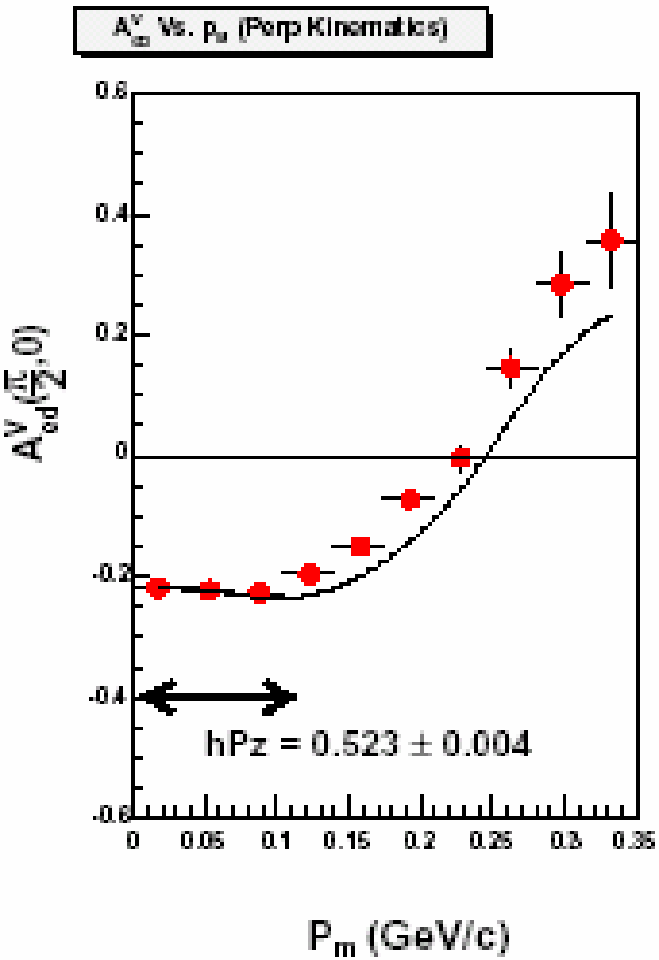
- Demanding that $m_M = m_n$ helps ensure that X = n
- Momentum magnitude corrections greatly improve m_M spectra

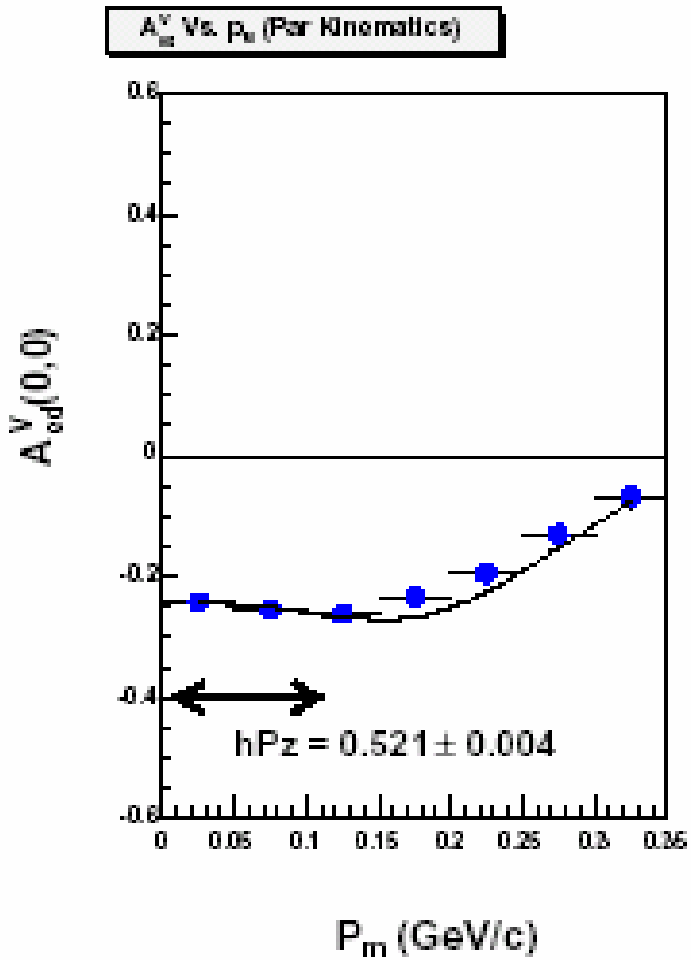


Missing Momentum Magnitude, p_M

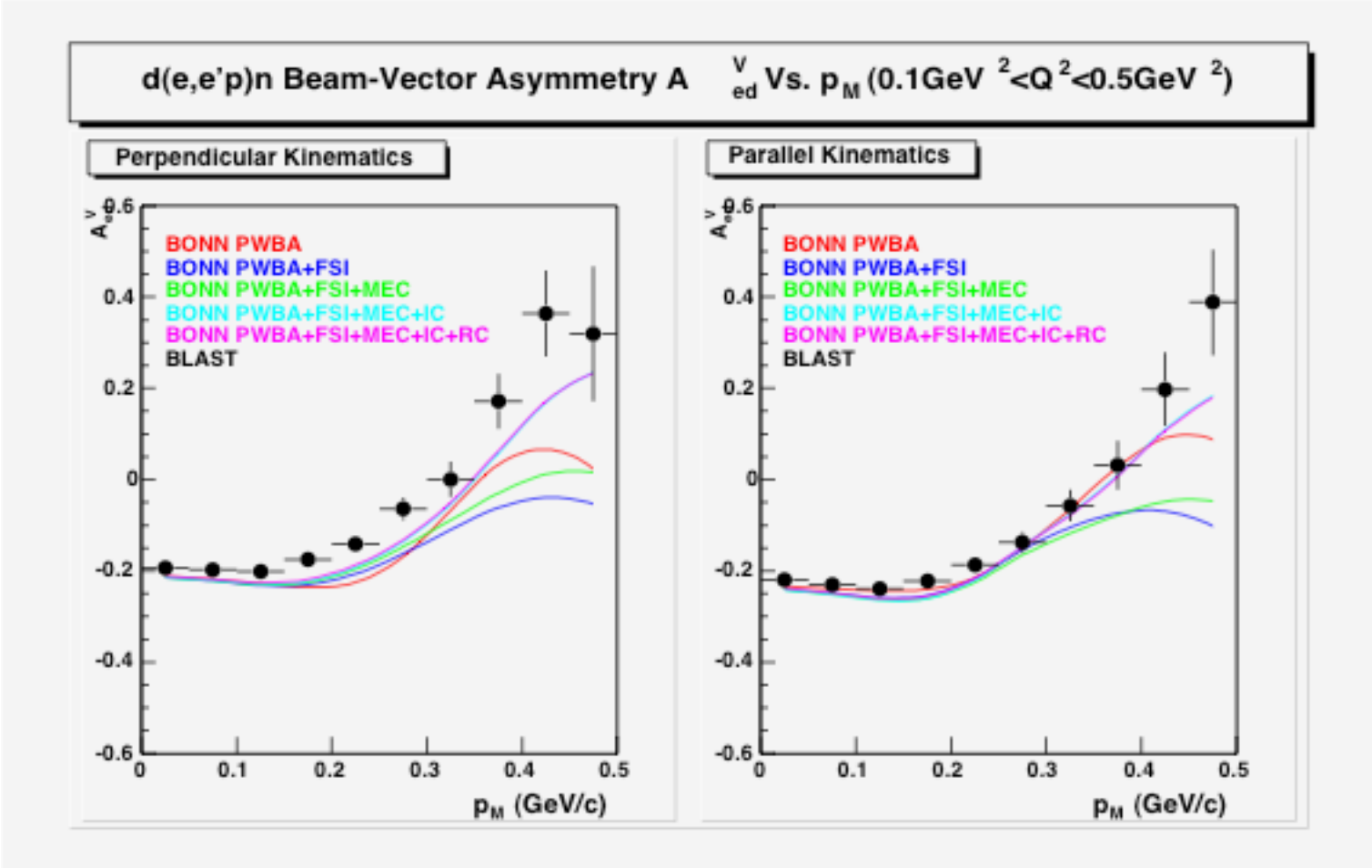


Determination of hP_z



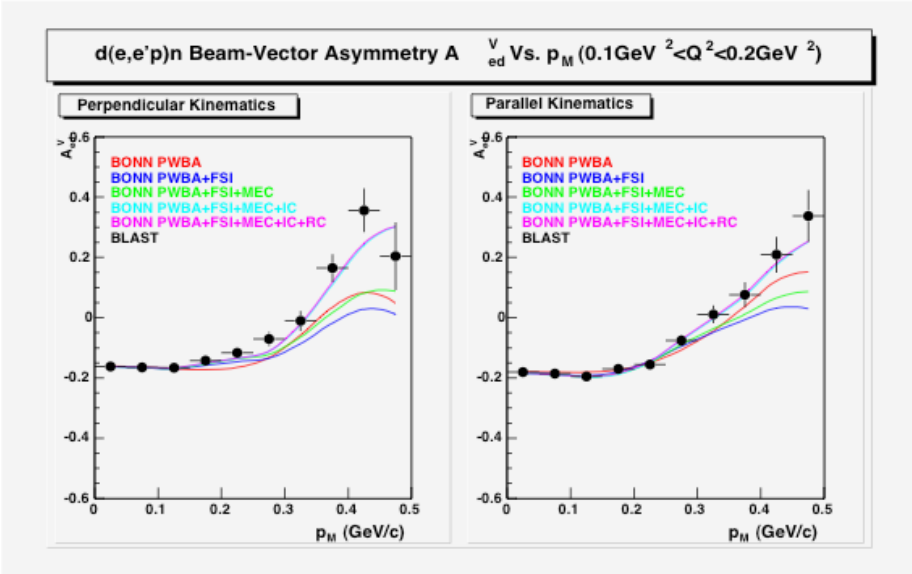


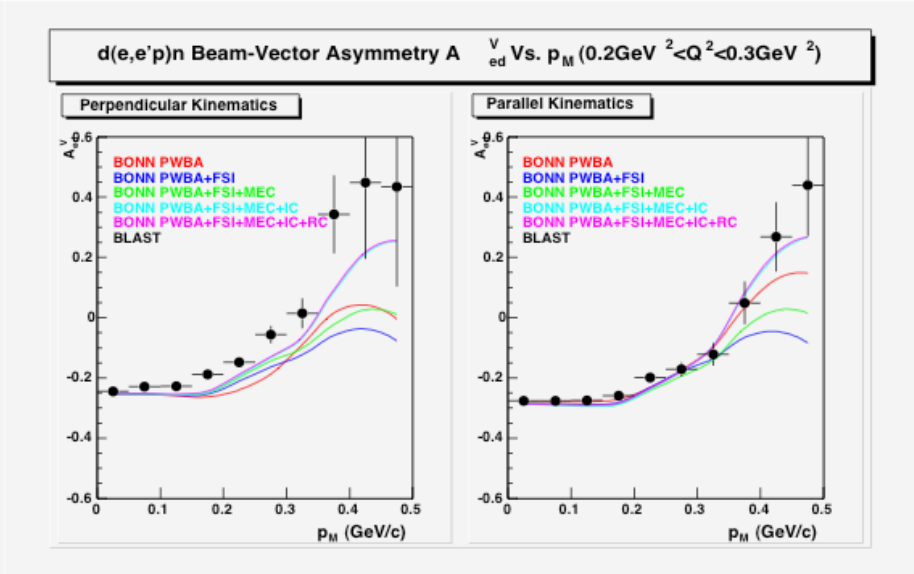
Beam-Vector Asymmetry for *D(e,e'p)* QES

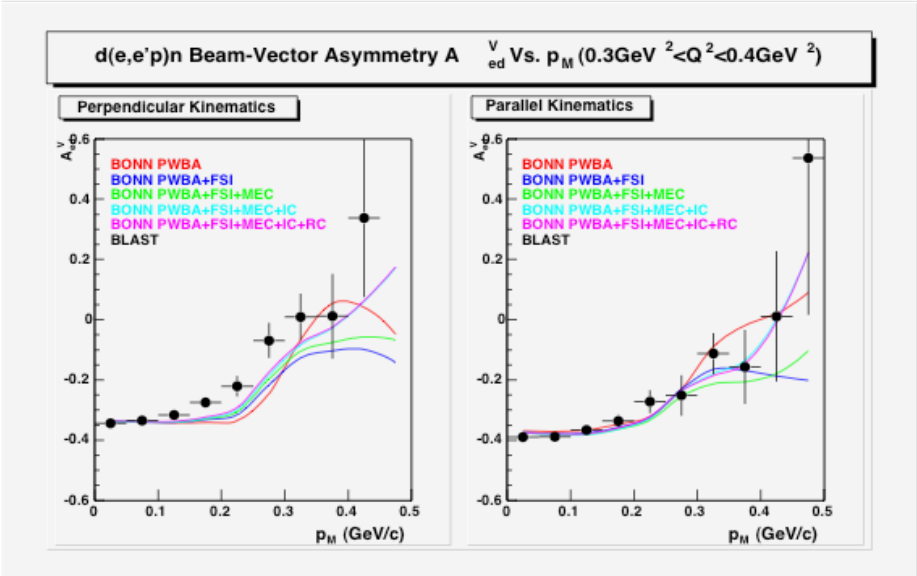


In absence of D-state, A^V_{ed} remains negative and roughly constant.

Beam-Vector Asymmetry (cont.)

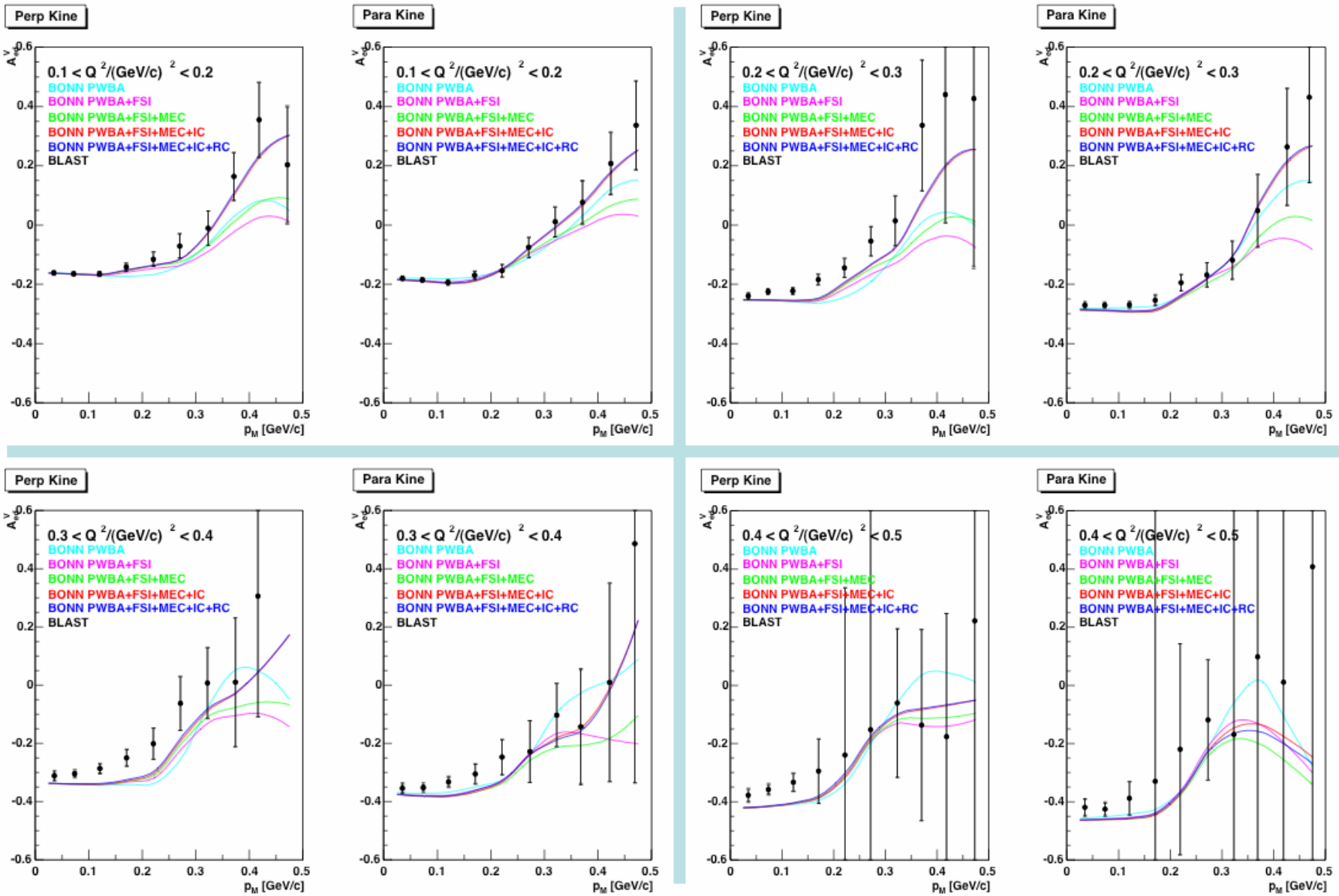




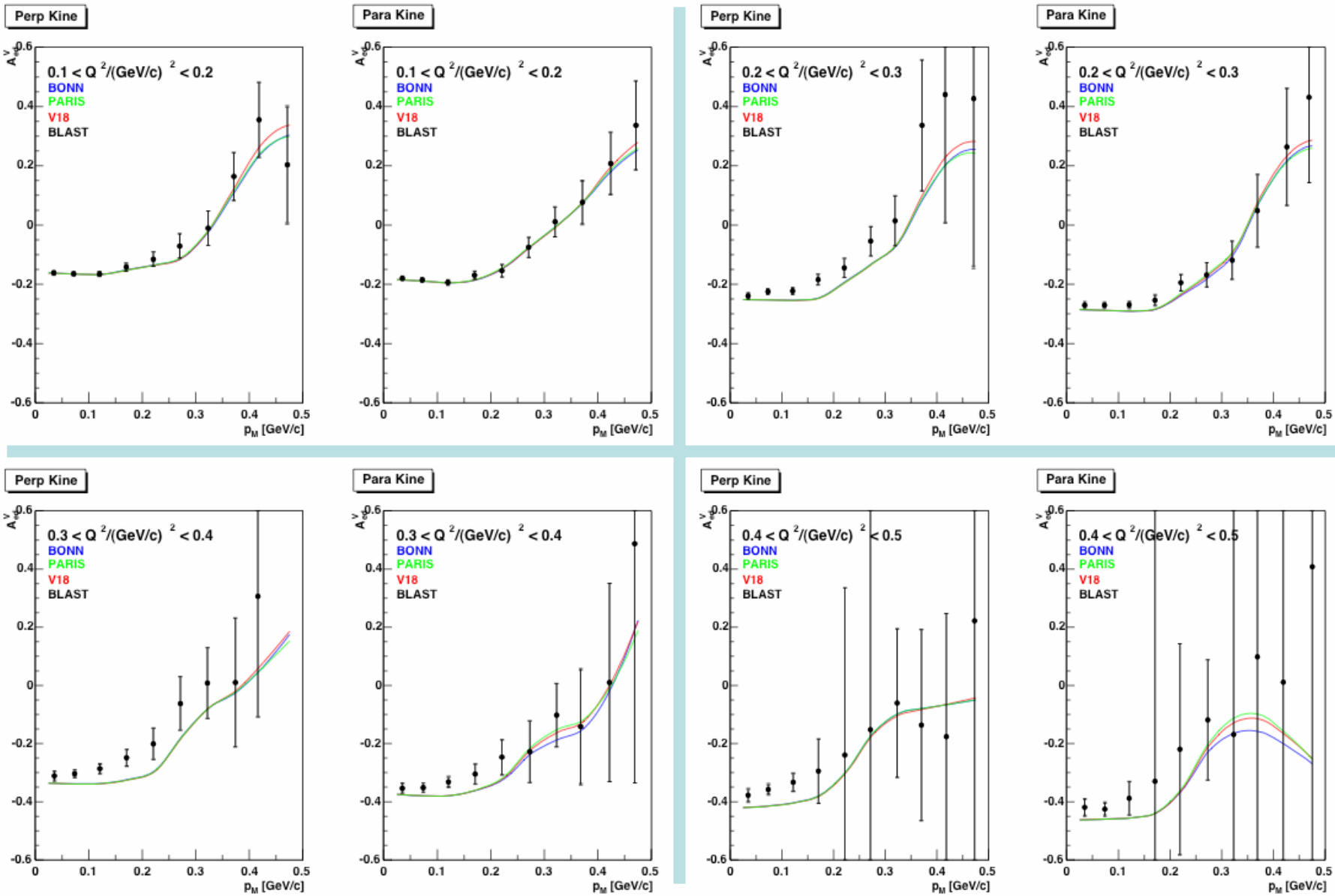


A^V_{ed} is sensitive to reaction mechanisms including MEC, IC, RC

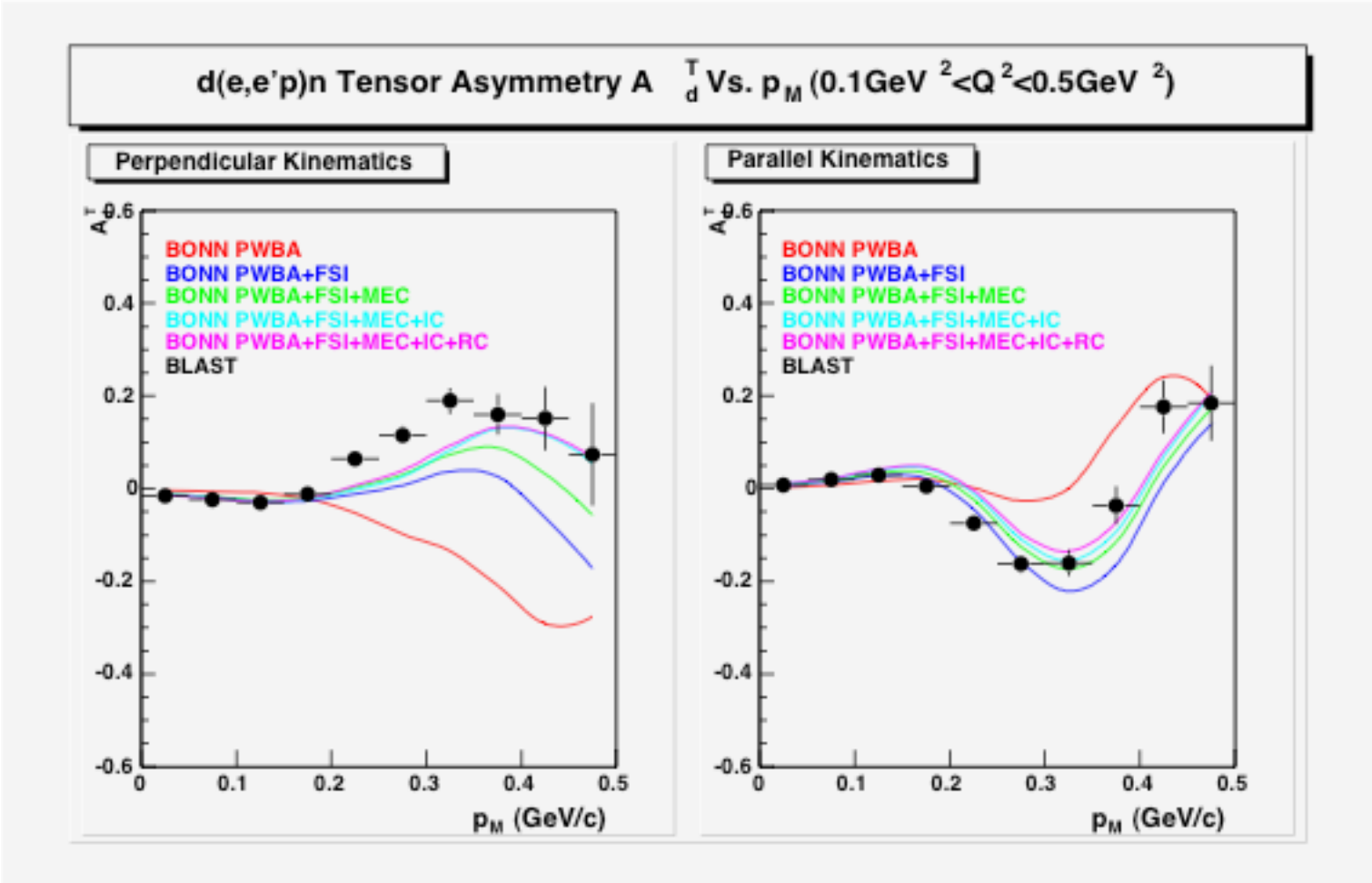
Beam-Vector Asymmetry Vs p_M



Beam-Vector Asymmetry Vs p_M

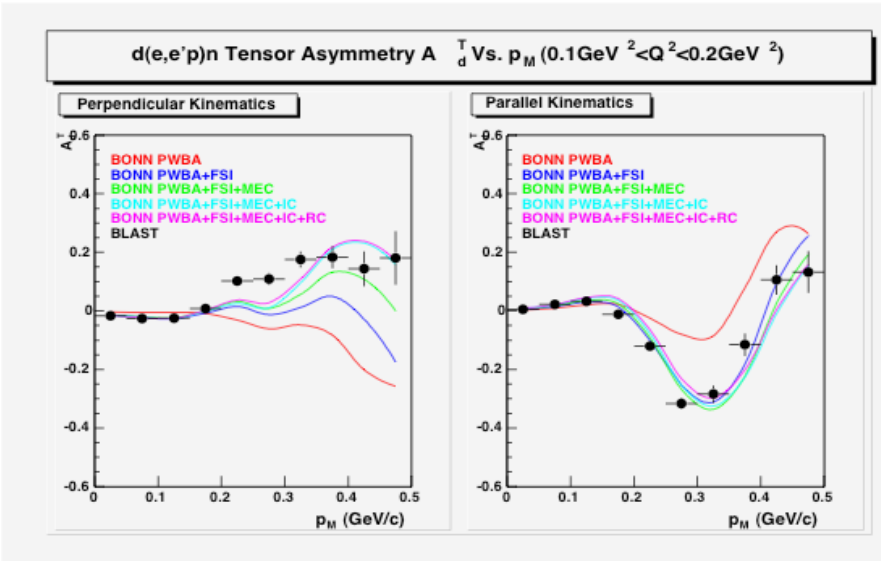


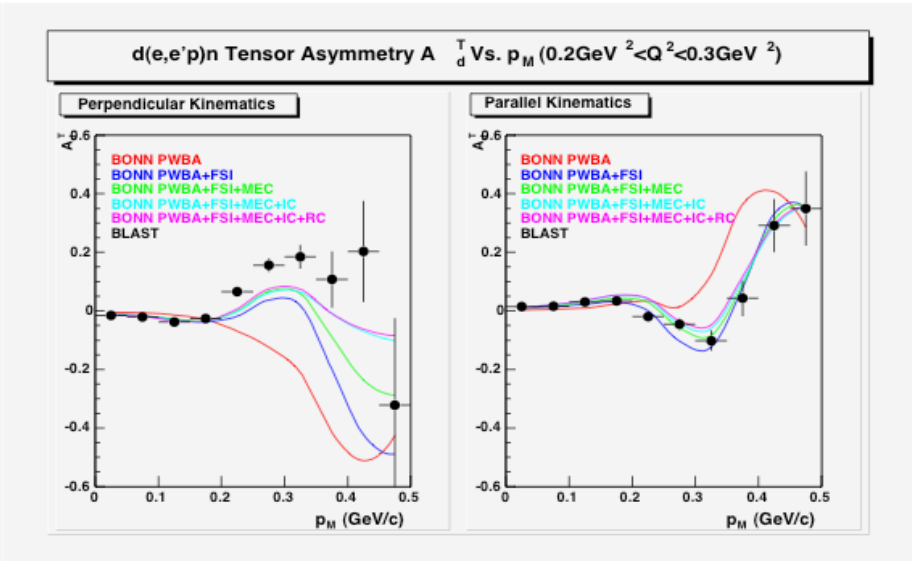
Tensor Asymmetry Results

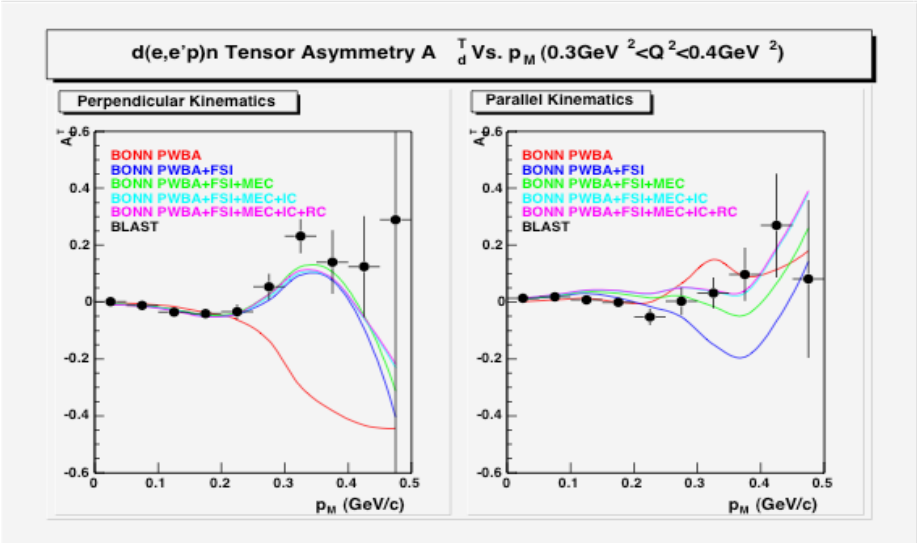


$A^T_d \rightarrow 0$ in low P_m limit where the S-state is dominant over the D-state but shows sensitivity to the D-state and reaction mechanisms at high P_m.

Tensor Asymmetry (cont.)

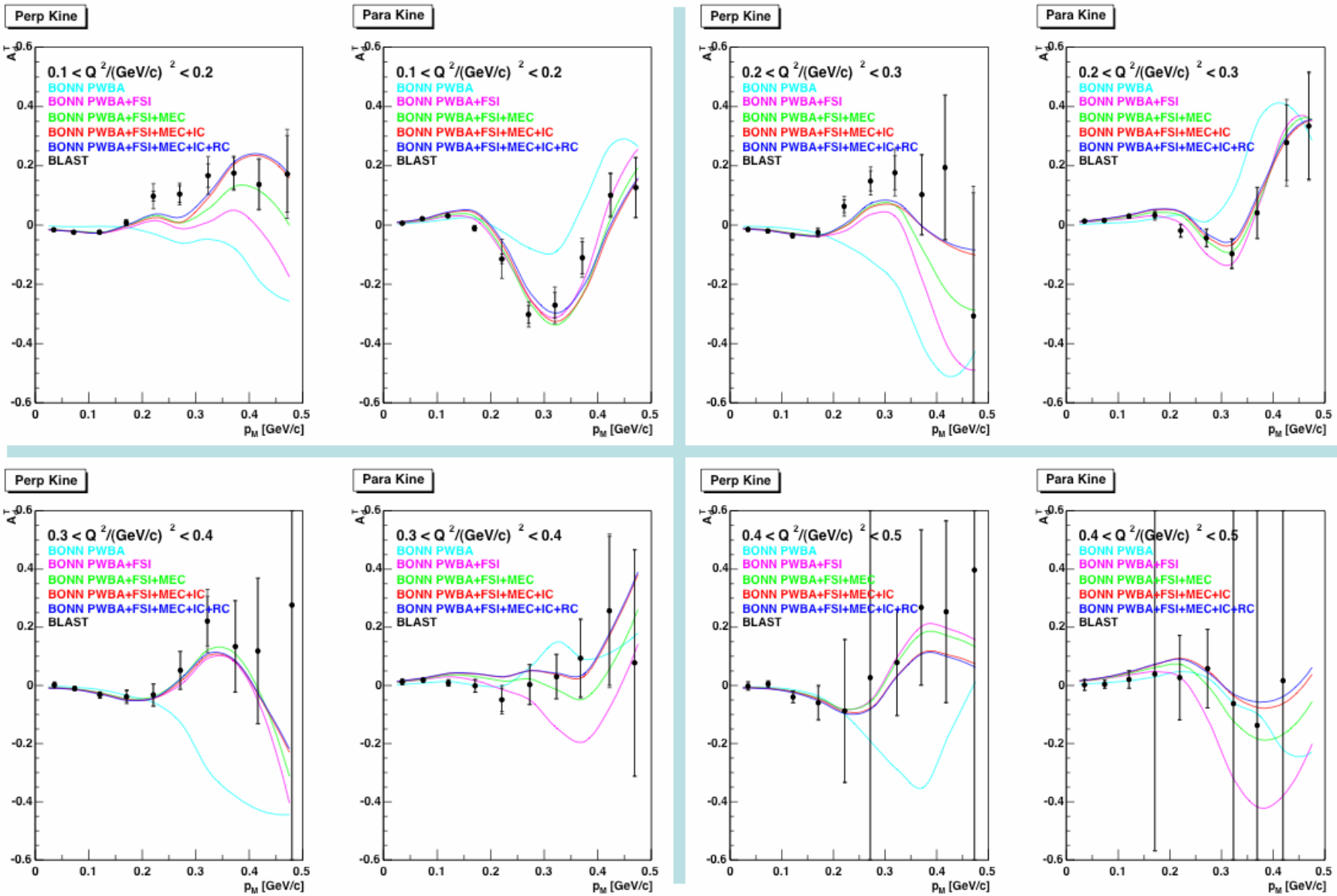




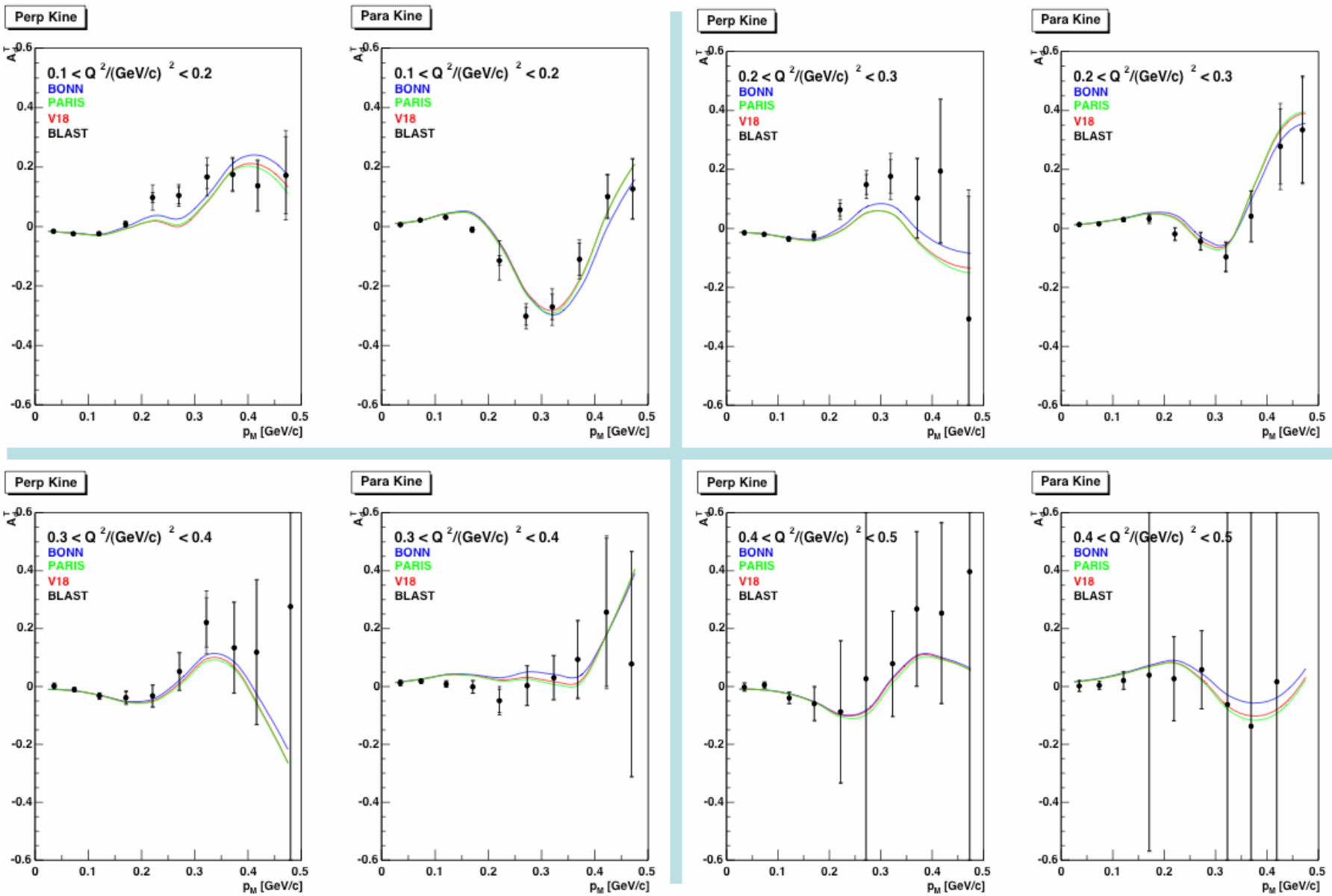


A^T_d sensitivity to reaction mechanisms varies with Q^2.

Tensor Asymmetry Vs p_M

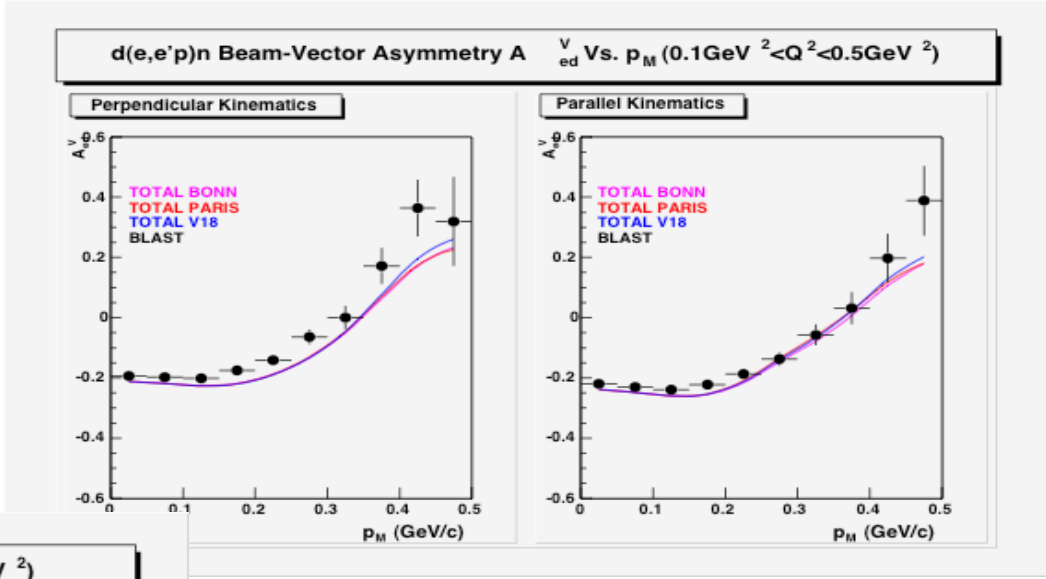


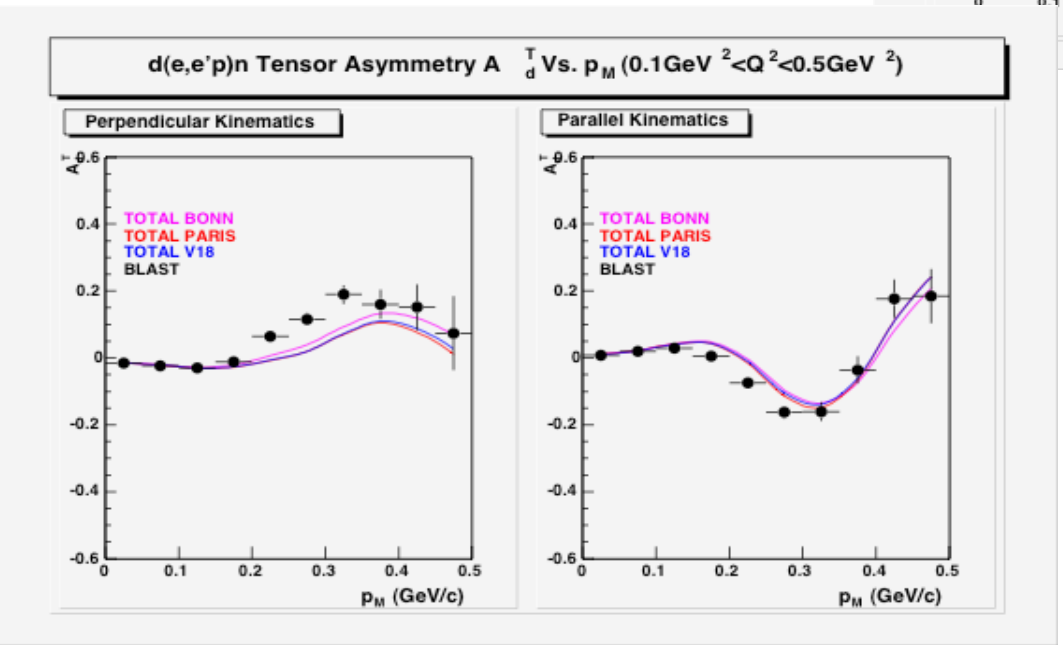
Tensor Asymmetry Vs p_M



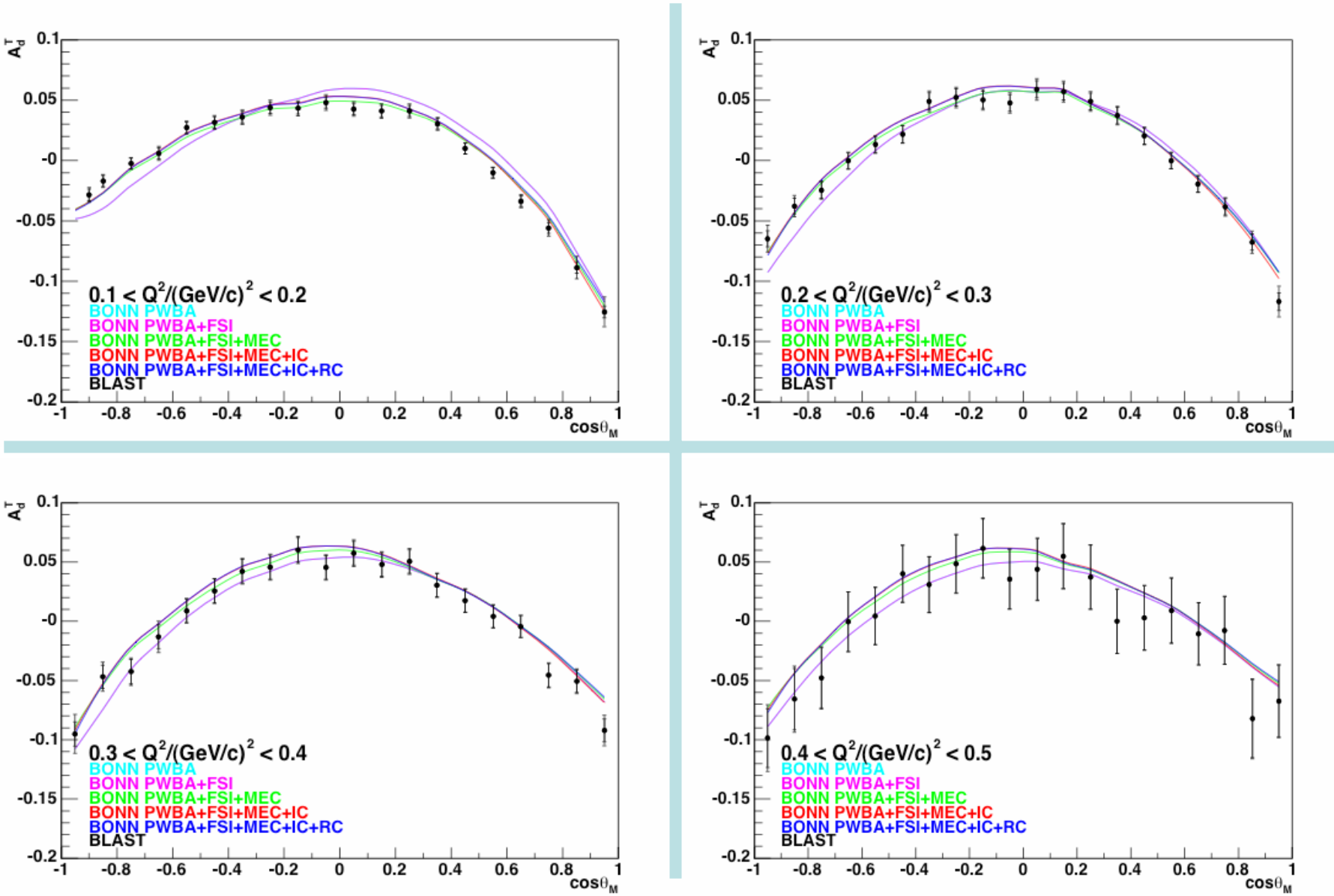
Potential Dependence

- Monte Carlo for Bonn, Paris, and V18 potentials compared to BLAST data
- Potential dependence **small compared to MEC and IC** contributions





Tensor Asymmetry Vs cos θ_M



Extraction of G_M^n from inclusive $D(e,e')$

Electron-Nucleon Elastic Scattering

Unpolarized target: Rosenbluth cross section

$$\left(\frac{d\sigma}{d\Omega}\right)^{unpol} = \sigma_{Mott} f_{recoil}^{-1} \left[\frac{G_E^{P\,2} + G_M^{P\,2}}{1+\tau} + 2\tau G_M^{P\,2} \tan^2\left(\theta_e/2\right)\right]$$

Mott cross section: (spin ½ electron, spinless+structureless nucleon)

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2 \cos^2\left(\frac{\theta}{2}\right)}{4E^2 \sin^4\left(\frac{\theta}{2}\right)\left(1+2(E/m_N)\sin^2\left(\frac{\theta}{2}\right)\right)}$$

Polarized target:

$$\frac{d\sigma}{d\Omega} = S\left[\rho_L f_L + \rho_T f_T + \rho_{LT} f_{LT} + \rho_{TT} f_{TT} + h(\rho'_{LT} f'_{LT} + \rho'_T f'_T)\right]$$

Electron-Nucleon Elastic Scattering

Forming asymmetries:

$$A_{\vec{e}\vec{N}} \equiv \frac{\left(\frac{d\sigma}{d\Omega_{e'}}\right)^{+} - \left(\frac{d\sigma}{d\Omega_{e'}}\right)^{-}}{\left(\frac{d\sigma}{d\Omega_{e'}}\right)^{+} + \left(\frac{d\sigma}{d\Omega_{e'}}\right)^{-}} = h\frac{\left(\rho'_{LT} f'_{LT} + \rho'_{T} f'_{T}\right)}{\rho_L f_L + \rho_T f_T}$$

Asymmetry in terms of Sachs form factors:

$$A_{\vec{e}\vec{N}} = -hP_z \frac{4\sqrt{2\tau}\rho'_{LT} G_E G_M \sin\theta^* \cos\phi^* + \rho'_T G_M^2 \cos\theta^*}{2\sqrt{2\tau}\rho_L G_E^2 + \rho_T G_M^2}$$

(θ^*, φ^*) : Angles between the target polarization and the momentum transfer vector.

θ^* = 0 deg. : parallel kinematics

θ^* = 90 deg. : perpendicular kinematics.

Inclusive Electron-Deuteron Quasi-elastic Scattering

Only electron detected.

Cross section derived from integral of exclusive structure functions over n-p phase space.

10 Structure Functions remaining after integration.

$$\sigma(h, P_1^d, P_2^d) = \sigma_o \left[1 + P_1^d \alpha_d^V + P_2^d \alpha_d^T + h(P_1^d \alpha_{ed}^V + P_2^d \alpha_{ed}^T) \right]$$

Beam-target vector asymmetry

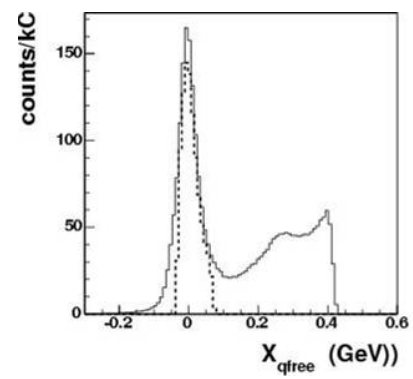
This asymmetry exhibits sensitivity to G_M^n in the inclusive electro-disintegration reaction of polarized electrons and polarized deuterium.

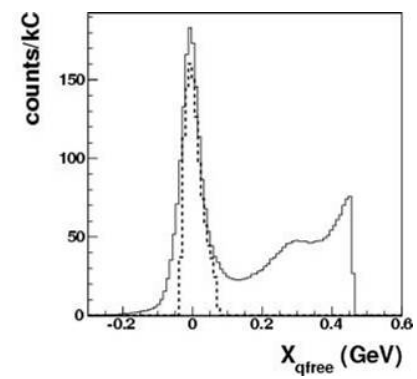
NEW MEASUREMENT.

Inclusive Electron Selection

1. Particles with inbending Wire-Chamber Track (negative charge).
2. Correlated TOF – Cerenkov signals.
3. Invariant mass cuts: essentially limit events to QE regime.

$$X_{qfree} \equiv \sqrt{M_N^2 + 2\omega M_N - Q^2} - M_N = 0$$





4. The data were divided into four Q^2 bins.

Q^2 bin	Q^2 Range $((GeV/c)^2)$	$< Q^2 >$ $((GeV/c)^2)$
1	0.100 - 0.163	0.135
2	0.163 - 0.225	0.189
3	0.225 - 0.288	0.252
4	0.288 - 0.350	0.316

Inclusive Electron Selection

Data from 3 triggers

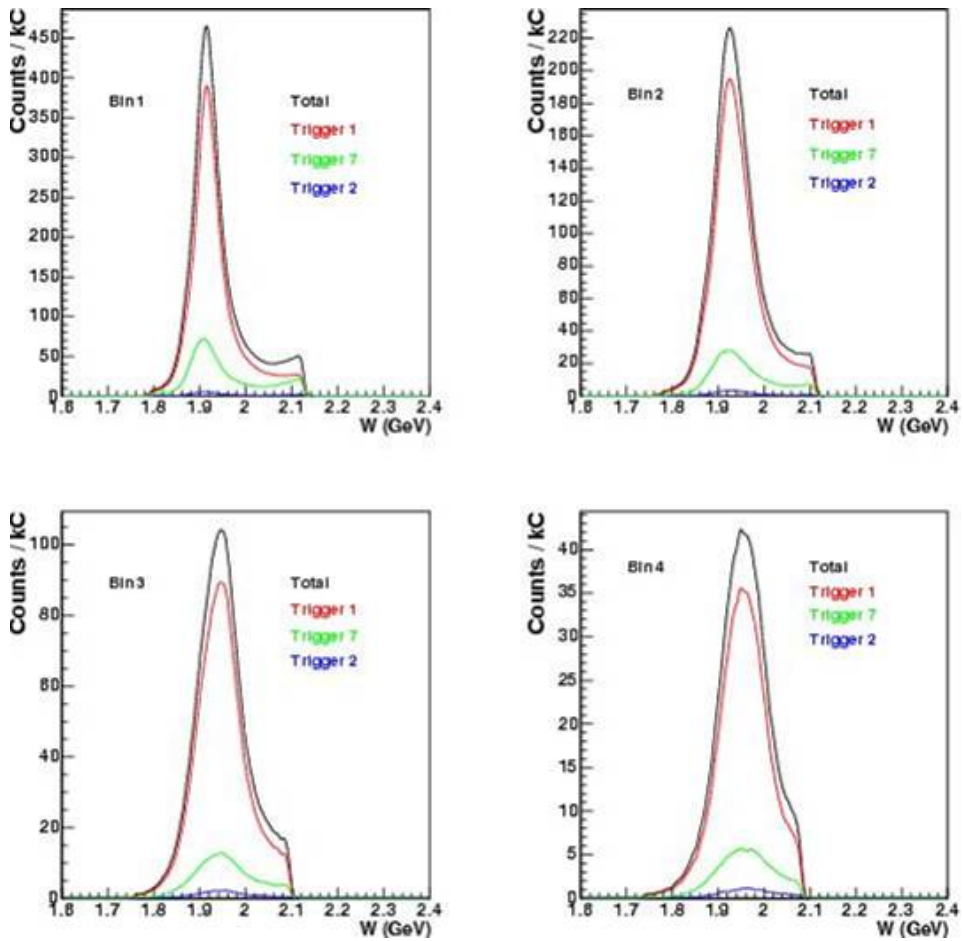
Trigger 1 : (e,e'p), (e,e'd)

Trigger 2: (e,e'n)

Trigger 7: (e,e') singles

prescaled by 3

INCLUSIVE: ADD TRIGGERS



NOTE:

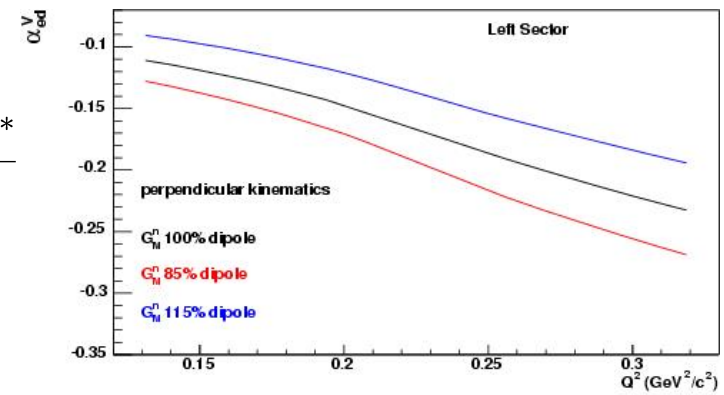
In forming the inclusive cross section, the individual detection efficiencies cancel out when trigger 7 is taken into account.

Electron detection efficiency is not crucial when forming asymmetries.

Sensitivity to G_M^n

ASYMMETRIES

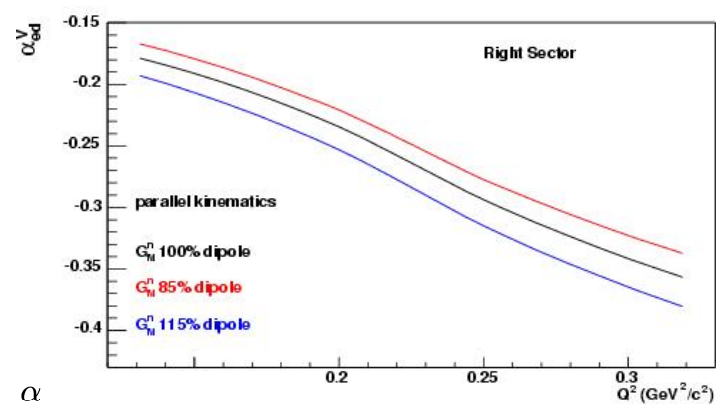
$$A_{\vec{e}\vec{N}} = -hP_z \frac{4\sqrt{2\tau}\rho'_{LT} G_E G_M \sin\theta^* \cos\phi^* + \rho'_T G_M^2 \cos\theta^*}{2\sqrt{2\tau}\rho_L G_E^2 + \rho_T G_M^2}$$



Polarized deuteron:

Incoherent sum of pol. neutron and pol. proton

$$\alpha_{\parallel} \approx \frac{\left(1 + \left(G_M^n/G_M^p\right)^2\right)}{b + c\left(1 + \left(G_M^n/G_M^p\right)^2\right)}$$

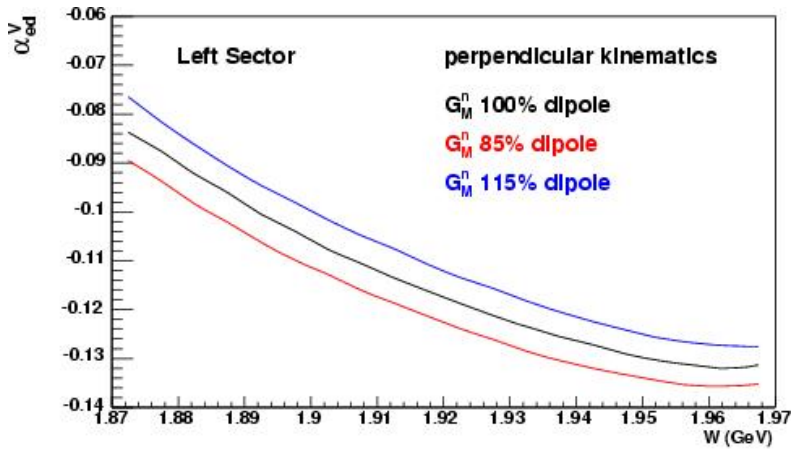


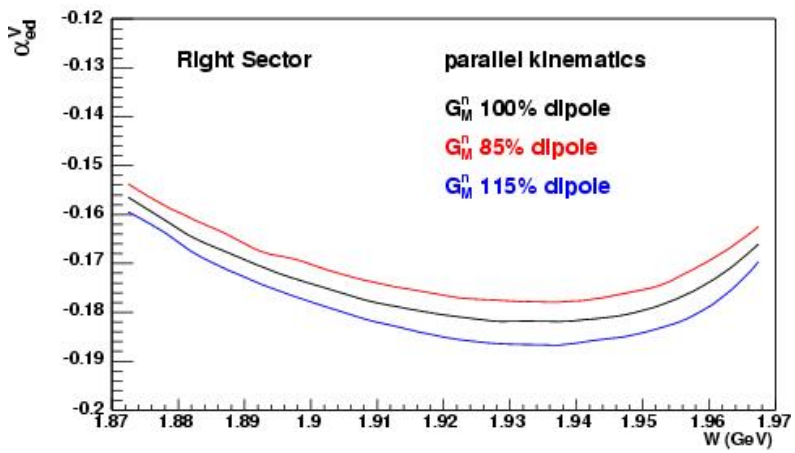
$$\alpha_{\perp} \approx \frac{c_1 G_E^p G_M^p + c_2 G_E^n G_M^n}{c_3 {G_E^n}^2 + c_4 {G_E^p}^2 + c_5 {G_M^n}^2 + c_6 {G_M^p}^2} \approx \frac{\alpha}{\beta + \gamma\left(1 + \left(G_M^n/G_M^p\right)^2\right)}$$

NOTE: Asymmetries vary with opposite sign in the two sectors. This can be exploited in a linear combination of the two.

Sensitivity to G_M^n

Same sensitivity across W spectrum.



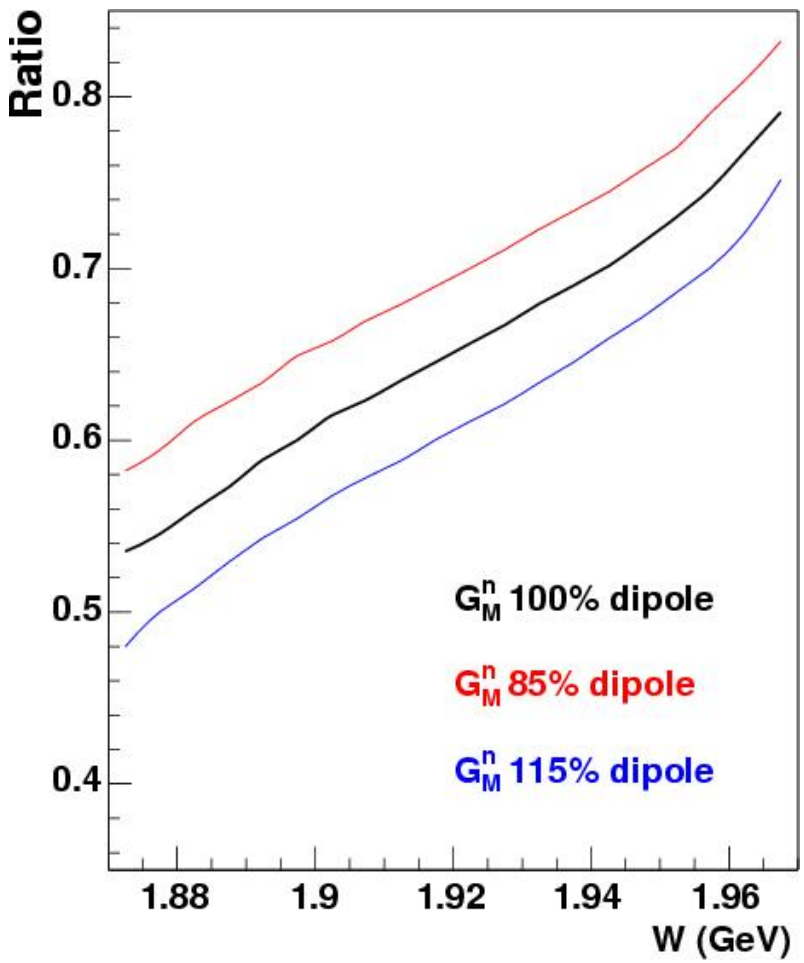


Sensitivity to G_M^n

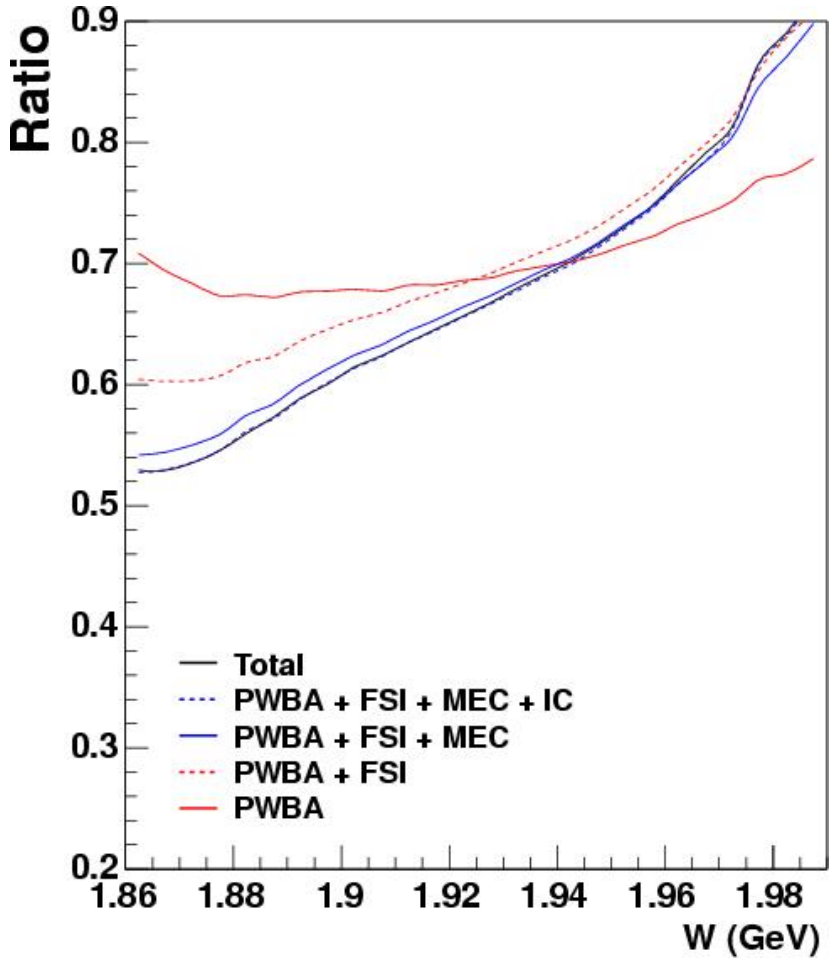
RATIO OF ASYMMETRIES

$$\Re \approx \frac{\alpha_\perp}{\alpha_\parallel} \approx \frac{c\frac{G_E^p}{G_M^p}}{1+\left(\frac{G_M^n}{G_M^p}\right)^2}$$

The ratio enhances sensitivity to the form factor. The form factor enters the ratio squared.



Calculation by H. Arenhovel



A model of Deuteron structure using the Bonn potential.

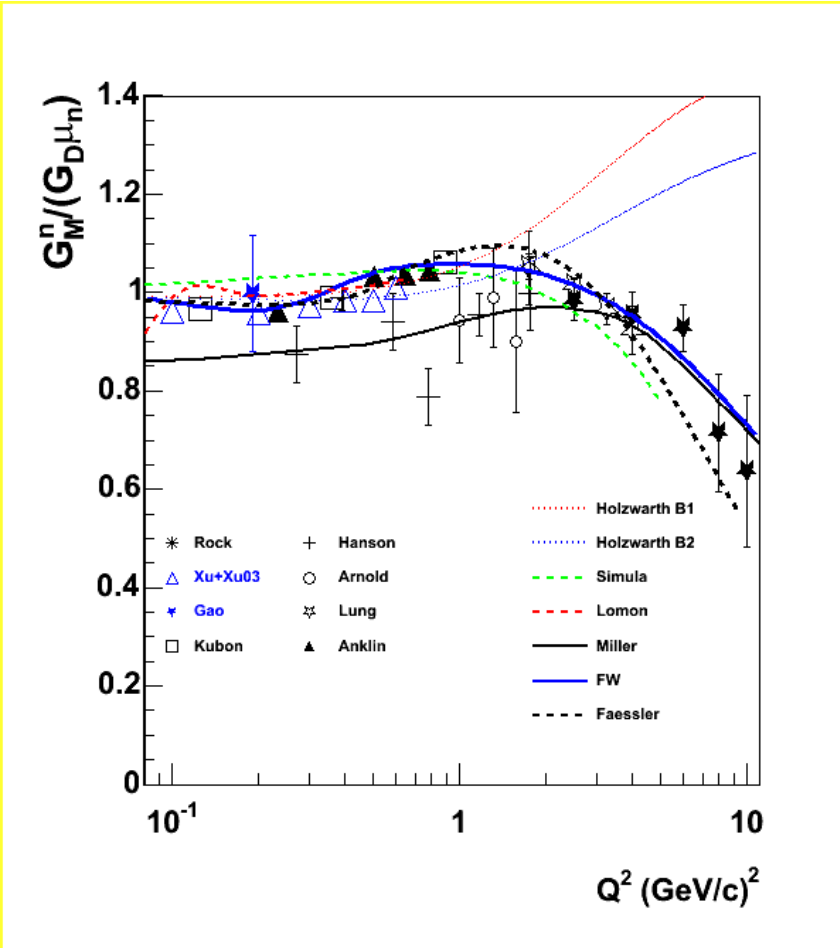
Incorporated in Monte Carlo.

Friedrich & Walcher form factors for proton, Galster form factor for GEn.

Incorporates:

1. Final State Interactions (FSI)
2. Meson Exchange Currents (MEC)
3. Isobar Configurations (IC)
4. Relativistic Corrections (RC)

World's Data for G_M^n



THEORETICAL CALCULATIONS

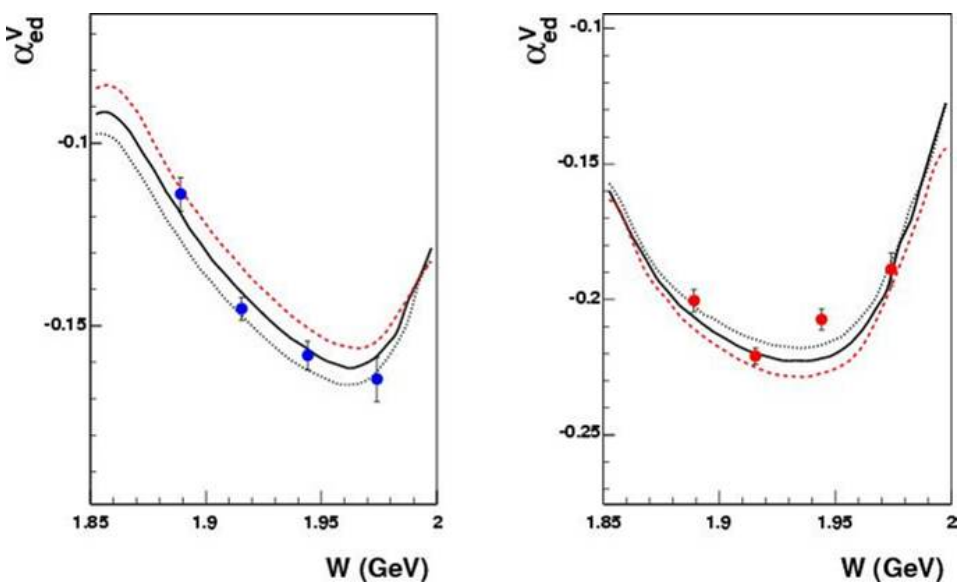
- Holzwarth B1, B2: Soliton
- Simula: CQM
- Lomon: VMD model
- Miller: Cloudy Bag model
- FW: Friedrich & Walcher par.
- Faessler: ChPT

Extraction of G_M^n

The following analysis process was performed for each data set independently:

1. Divide the data into the Q2 bins and form the asymmetries in both perpendicular and parallel kinematics.

   Within each Q2 bin, divide the data in W bins.
   Correct the asymmetries for empty target background.



$Q^2 = 0.189\ (GeV/c)^2$

Extraction of G_M^n

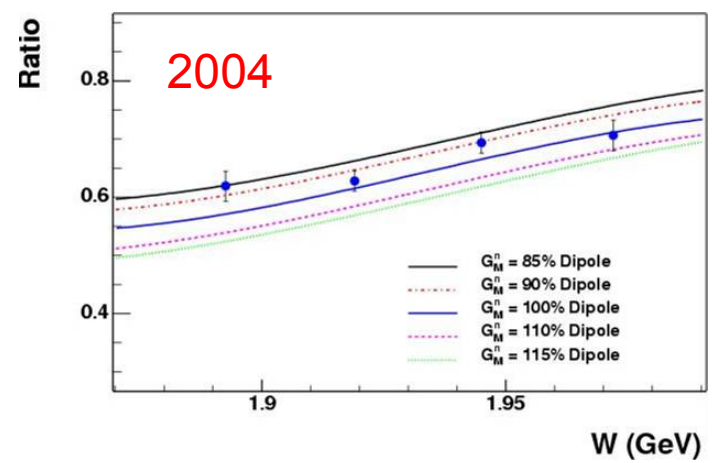
2. Divide the asymmetries to form the ratio.

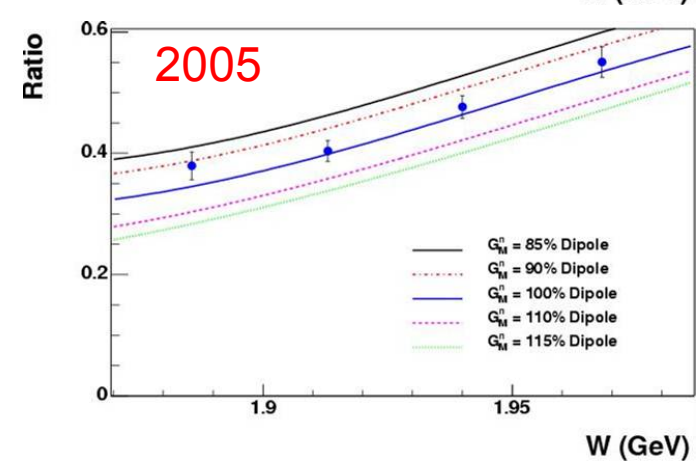
$$\Re \approx \frac{\alpha_\perp}{\alpha_\parallel} \approx \frac{c\frac{G_E^p}{G_M^p}}{1+\left(\frac{G_M^n}{G_M^p}\right)^2}$$

3. Vary G_M^n value wrt the dipole form factor in the Monte Carlo.

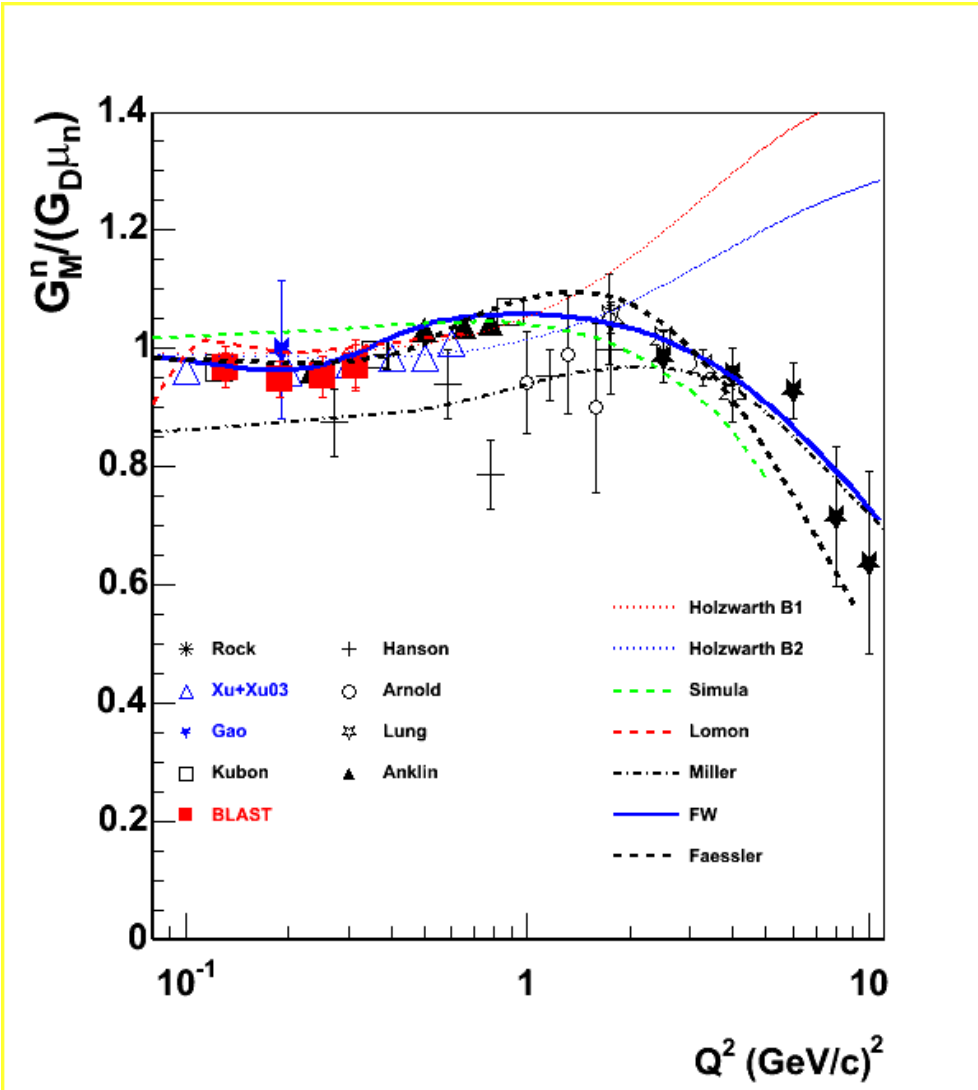
4. Obtain χ^2 for each calculation.

$Q^2 = 0.189\ (\mathrm{GeV}/c)^2$





Final Results



Combined results			
$< Q^2\,((GeV/c)^2) >$	G_M^n	ΔG_M^n (stat)	ΔG_M^n (syst)
0.135	0.968	0.023	0.025
0.189	0.948	0.019	0.025
0.252	0.951	0.022	0.025
0.316	0.971	0.036	0.025

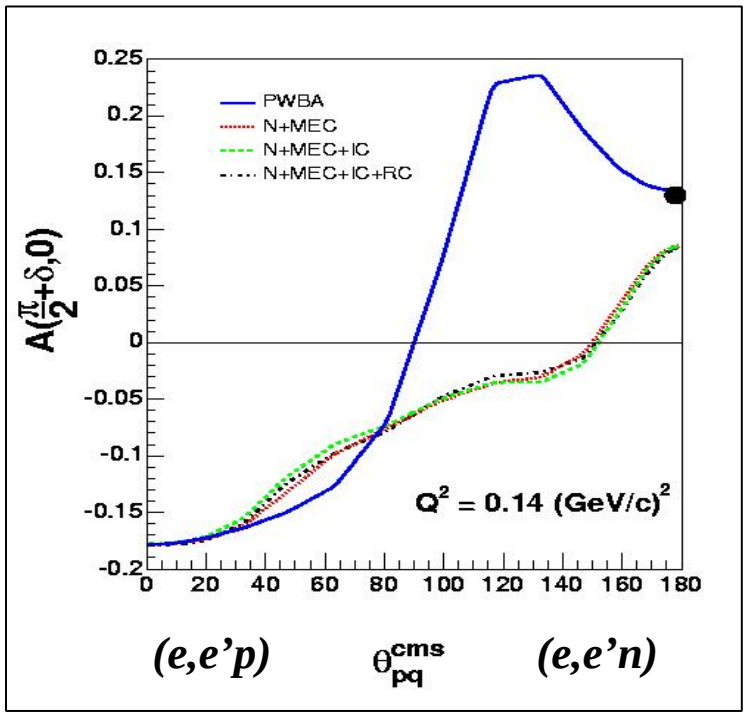
1. New measurement technique.
2. Includes full deuteron structure.
3. Consistent with recent polarization and other data.
4. Provides a tighter fit to form factor in the low Q2 region.

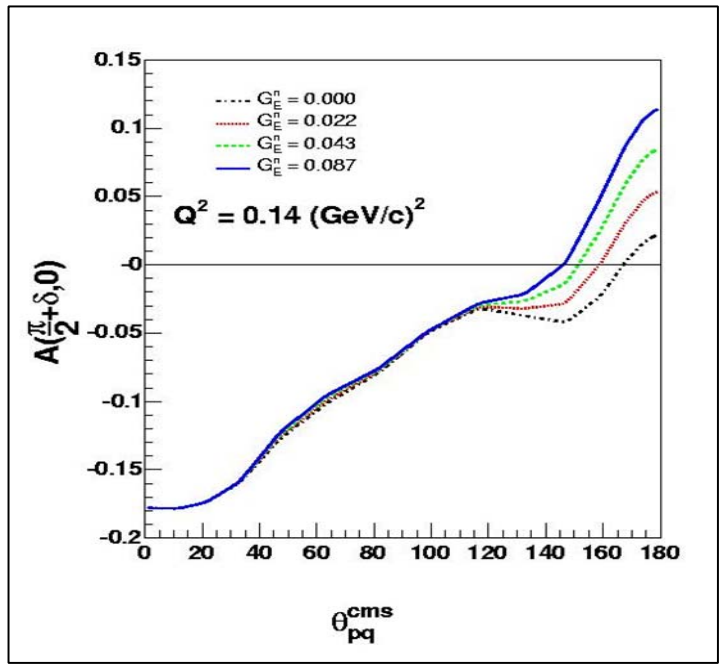
Extraction of G_e^n from exclusive $D(e,e'n)$

Sensitivity to G^n_E

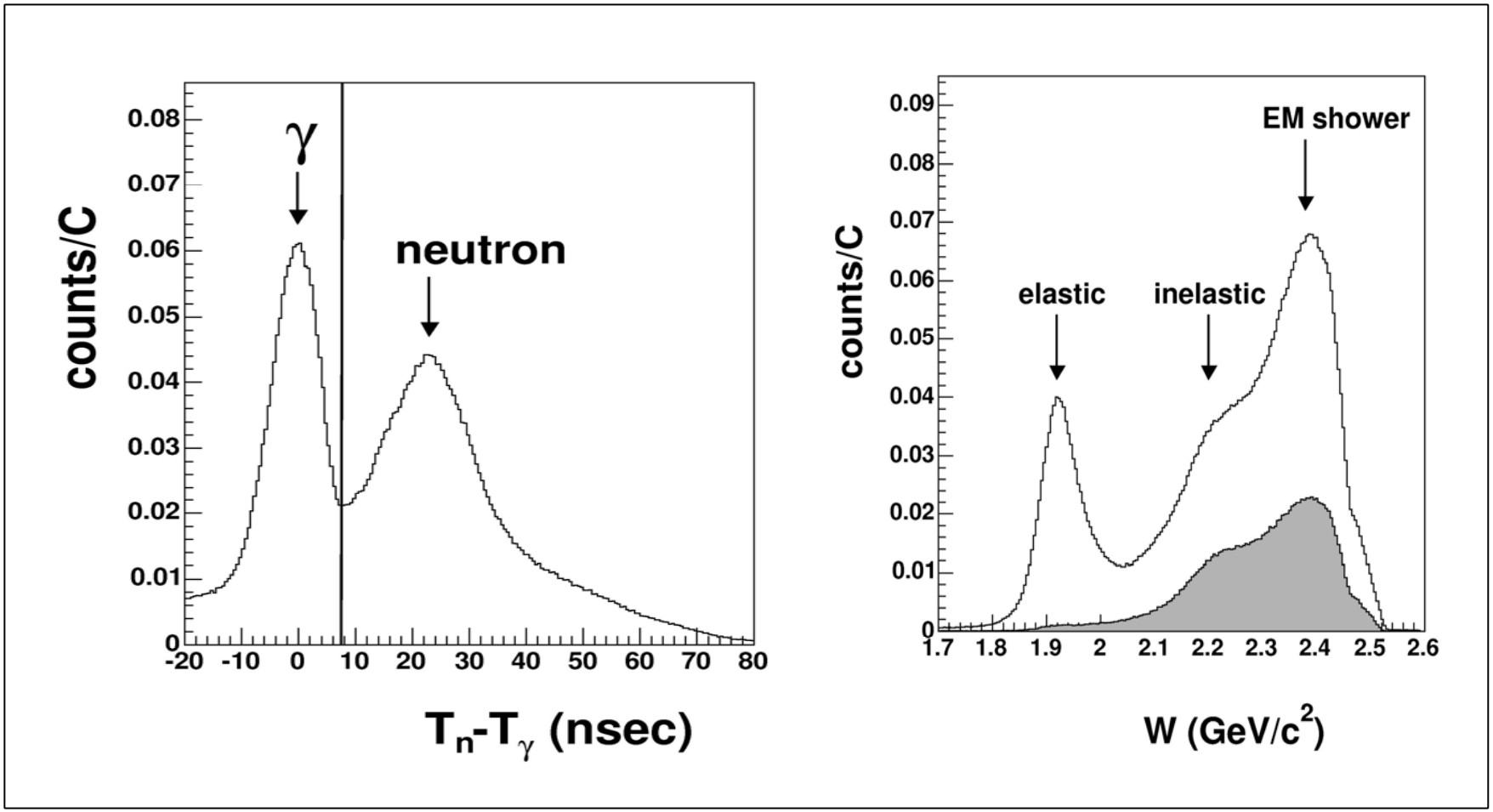
$$\frac{d^5\sigma}{d\omega d\Omega_e^{lab} d\Omega_{pq}^{cms}} = \Sigma_0 \left\{ 1 + P_d^V A_d^V + P_d^T A_d^T + h\left(A_e + \underline{P_d^V A_{ed}^V} + P_d^T A_{ed}^T\right)\right\}$$

$$A_{ed}^V(90°, 0) = -\frac{2\sqrt{2\tau}\rho'_{LT} G_E^n G_M^n}{\rho_L (G_E^n)^2 + 2\tau\rho_T (G_M^n)^2}$$

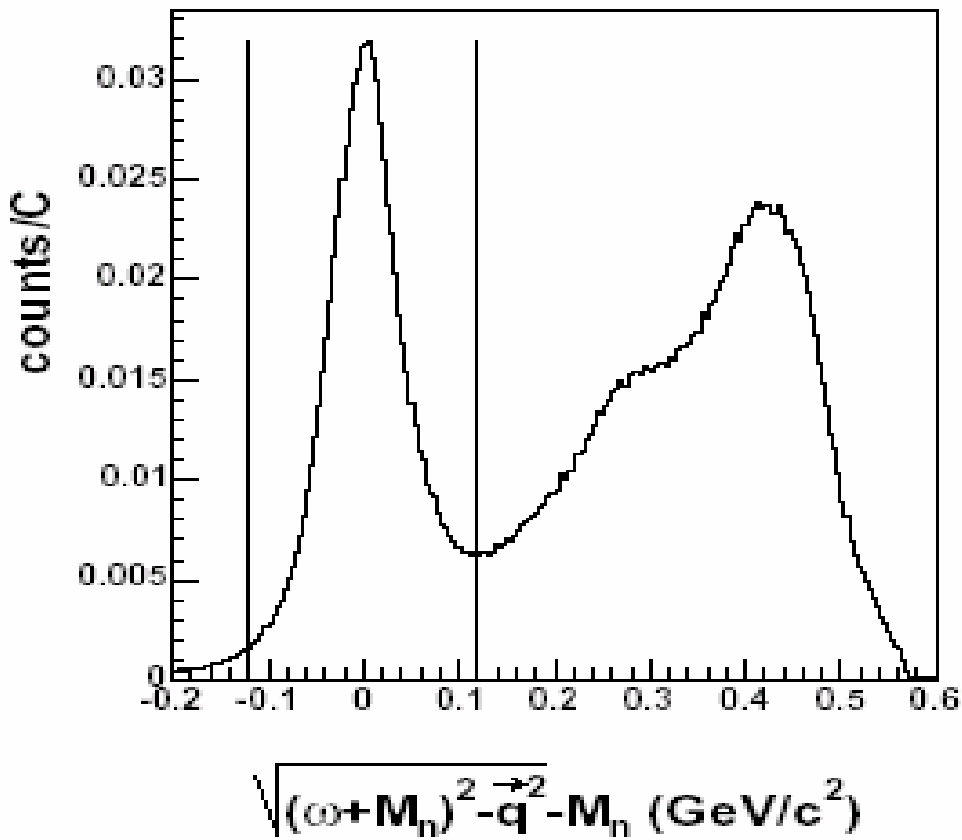




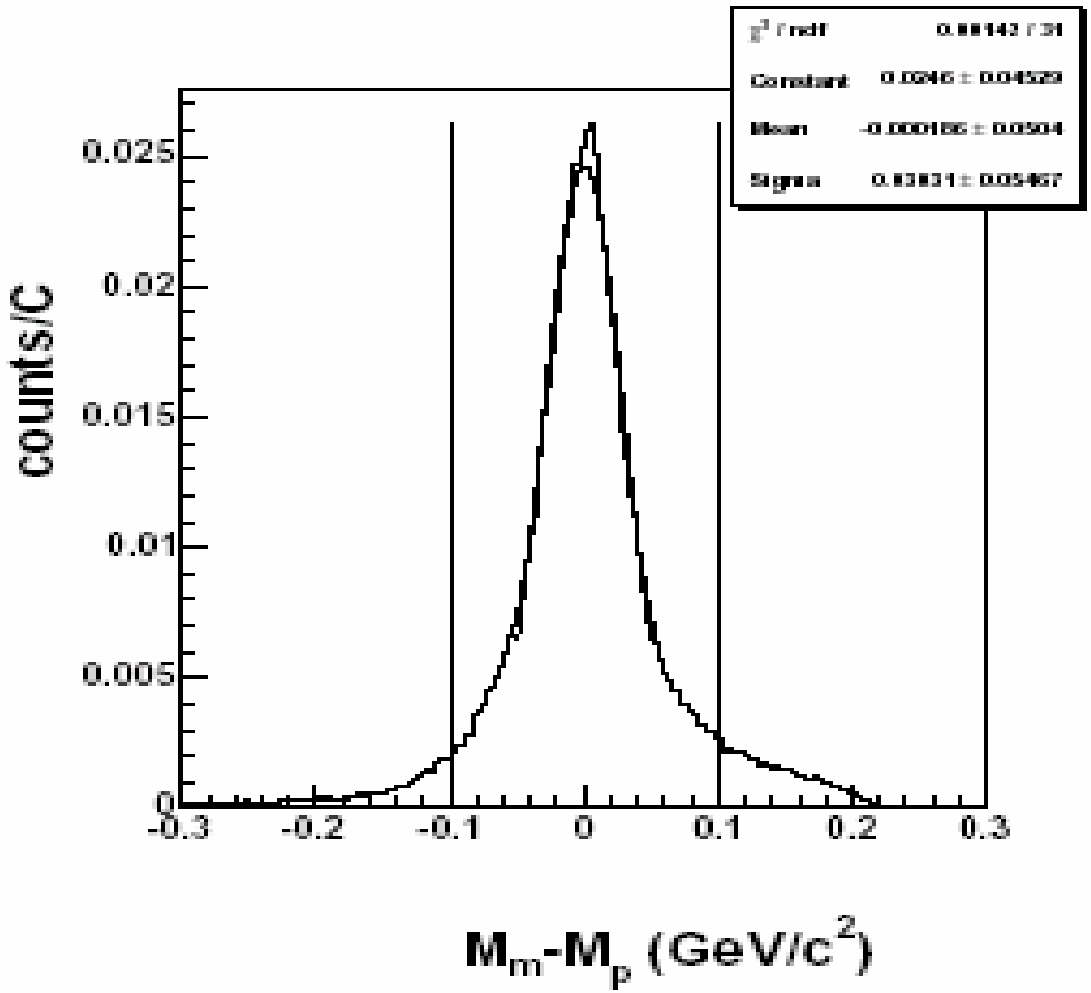
γ/n Separation in (*e,e'n*)

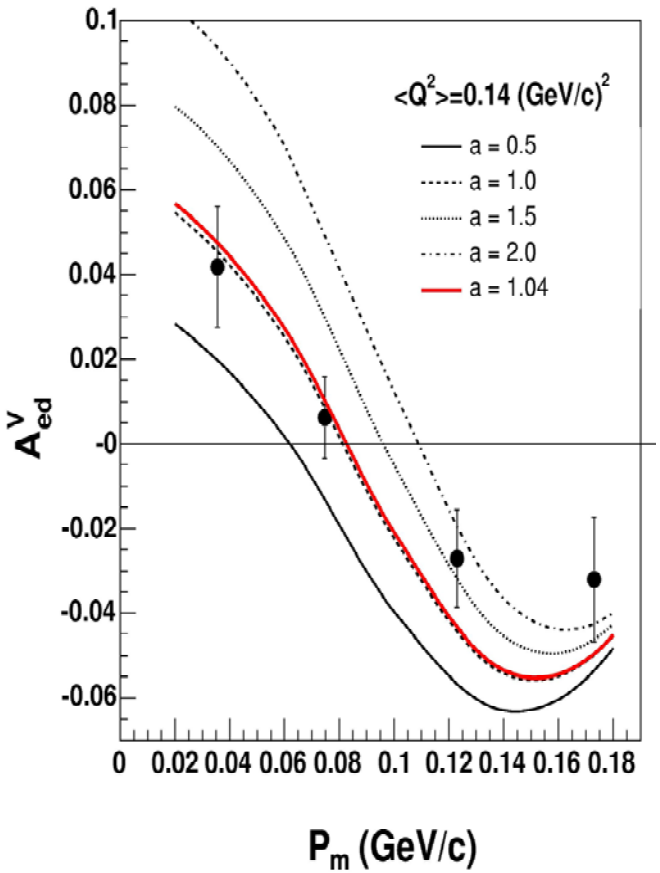


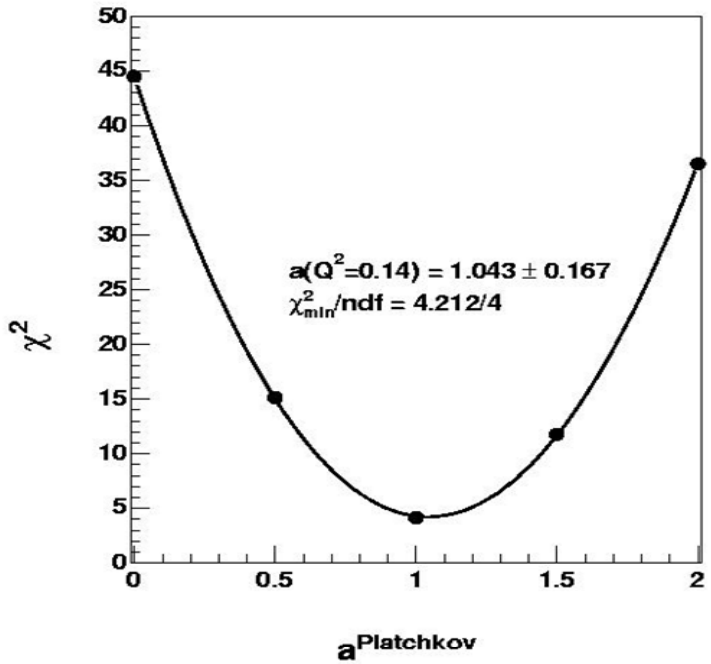
D(e,e'n) Kinematic Distribution



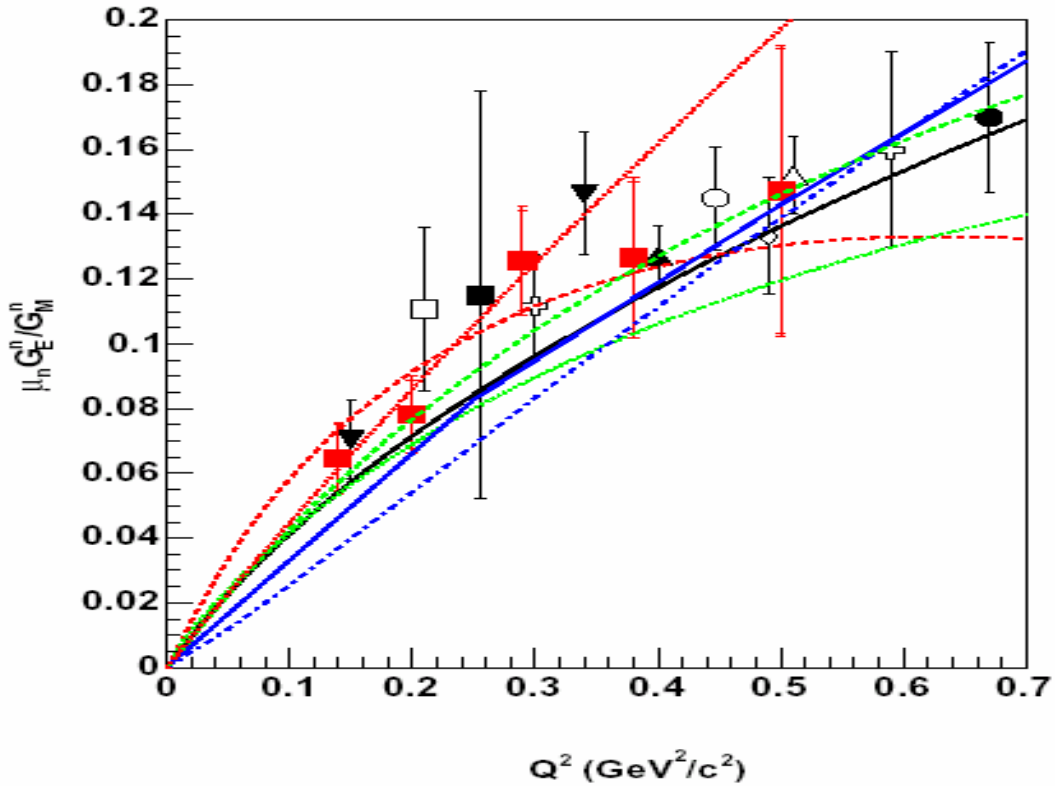
Missing Mass from *D(e,e'n) QES*



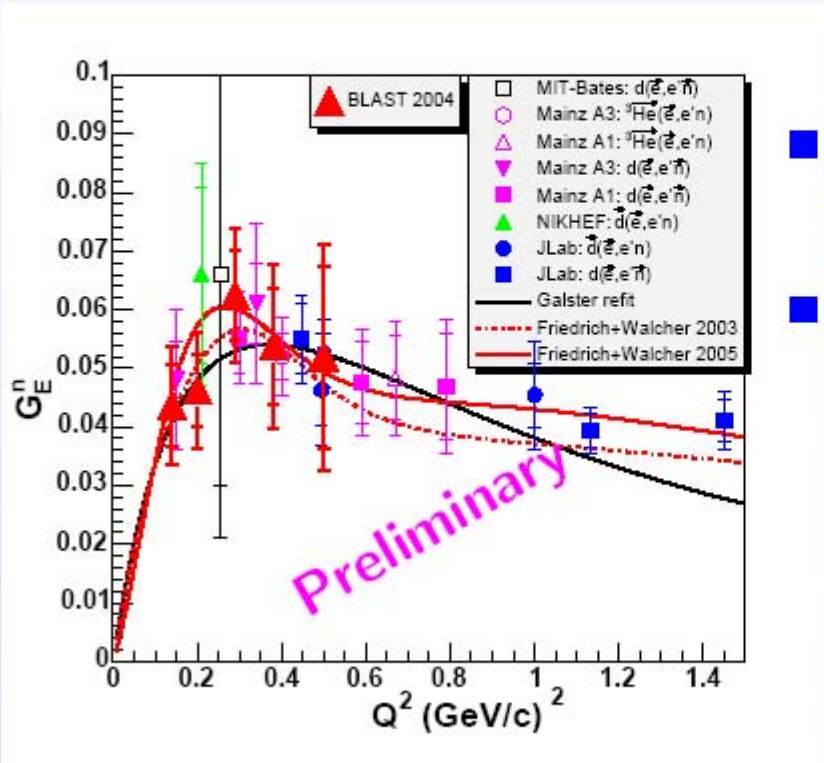

$\langle Q^2 \rangle$=0.14 (GeV/c)^2
a = 0.5
a = 1.0
a = 1.5
a = 2.0
a = 1.04
A^V_{ed}
P_m (GeV/c)


$a(Q^2=0.14) = 1.043 \pm 0.167$
χ^2_{min}/ndf = 4.212/4
χ^2
$a^{Platchkov}$

G_E/G_M for the Neutron from *D(e,e'n) QES*



Neutron Electric Form Factor

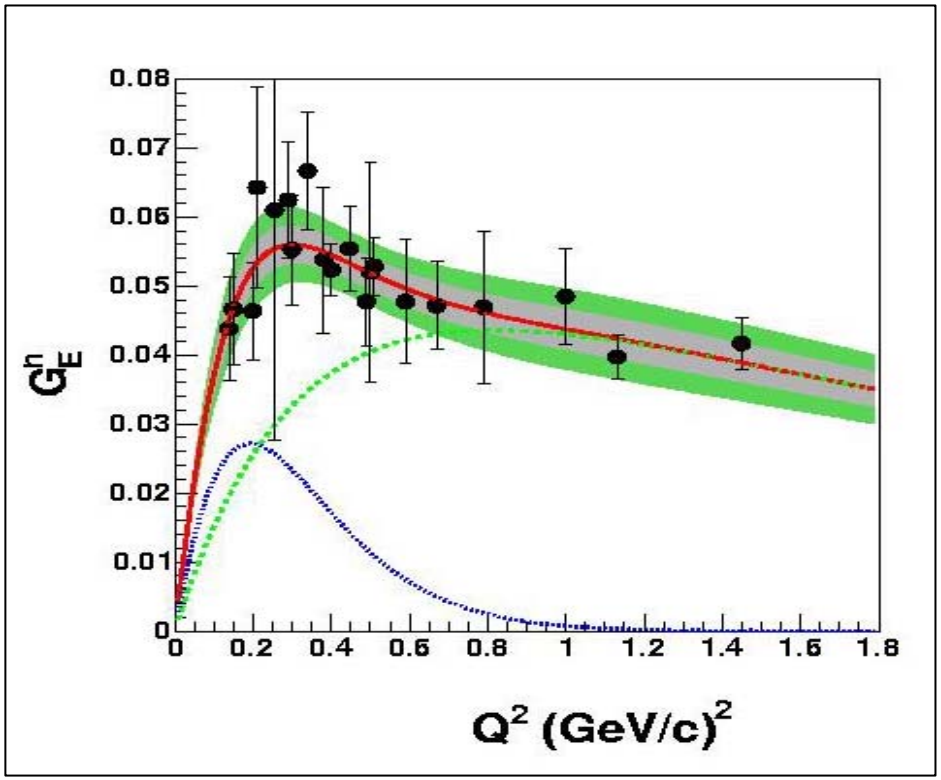


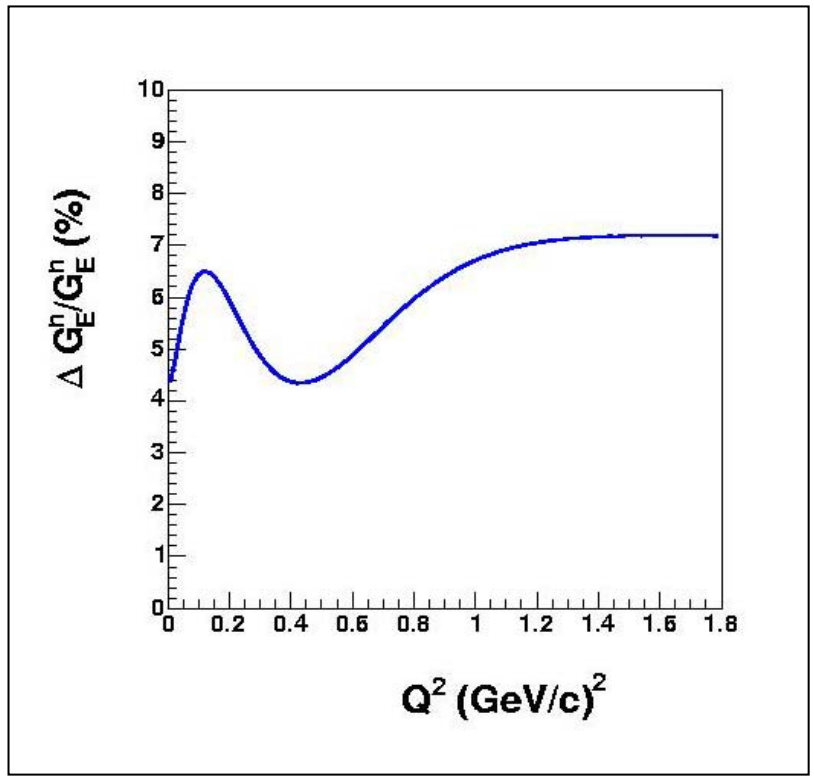
- World data on G_E^n from double pol. experiments
- Including BLAST 2004

* PH.D. work of V. Ziskin (MIT) and E. Geis (ASU)

BLAST Fit to World Polarization Data

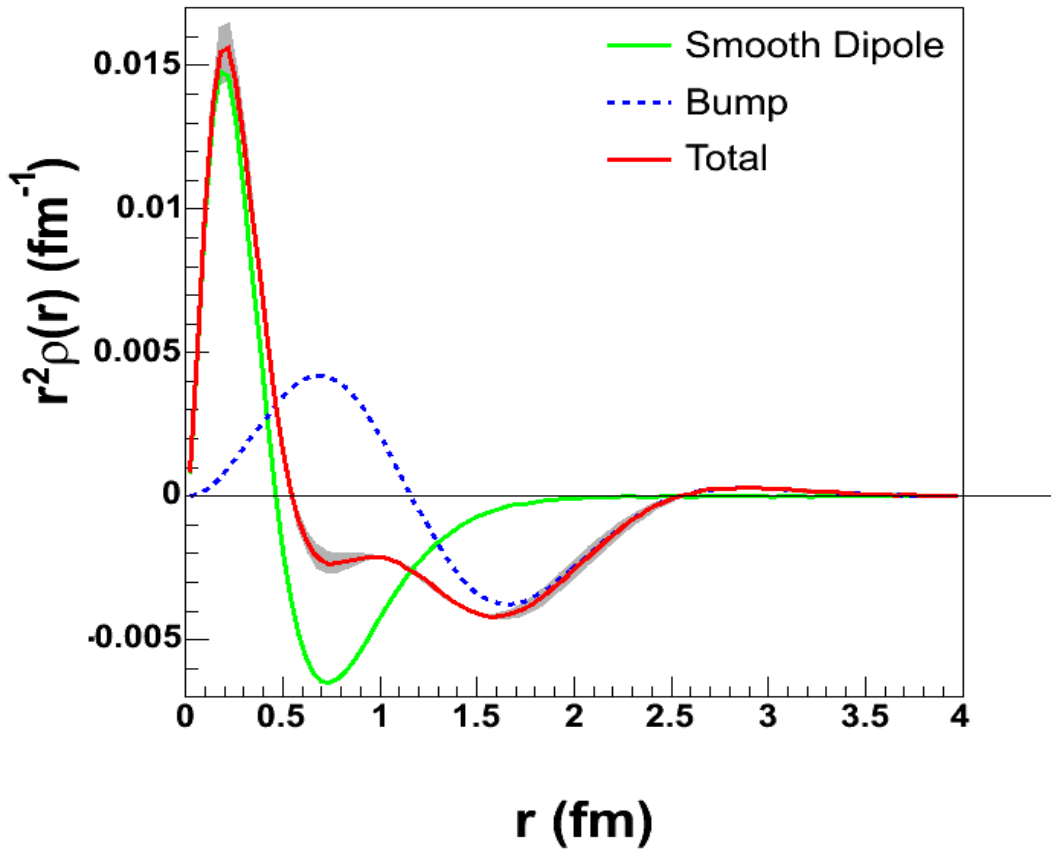
- **Remarkable consistency of all modern polarization experiments!**





Global fit determines G_E^n to better than ±7%

"Density" from the BLAST Fit



- Non-relativistic Fourier transform of the neutron form factor
- Smooth dipole corresponds to the constituent quark core
- Bump corresponds to a diffuse pion cloud

Conclusions

- Strong sensitivity in QE (*e,e'p*) to the *D-state*
- Strong sensitivity to model ingredients such as *MEC, IC, etc.*
- Not very sensitive to particular potential
- Competitive extraction of G_M^n from inclusive QES
- World class extraction of G_e^n from QE (*e,e'n*)