Jefferson Lab Seminar, January 9, 2009

Results from the BLAST Experiment at MIT-Bates

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BLAST to be LAST?

Overview

- **Motivation or: Why BLAST?**
  Electromagnetic structure of nucleons and light nuclei
  with **spin-dependent electron scattering**
  from internal polarized targets **at low Q^2**

- **Some Results or: Why BLAST was a BLAST!**

  Nucleon Form Factors:
  Proton and neutron electric and magnetic form factors

  Deuteron Structure:
  Charge, quadrupole, and magnetic form factor
  Polarized quasi-elastic electrodisintegration

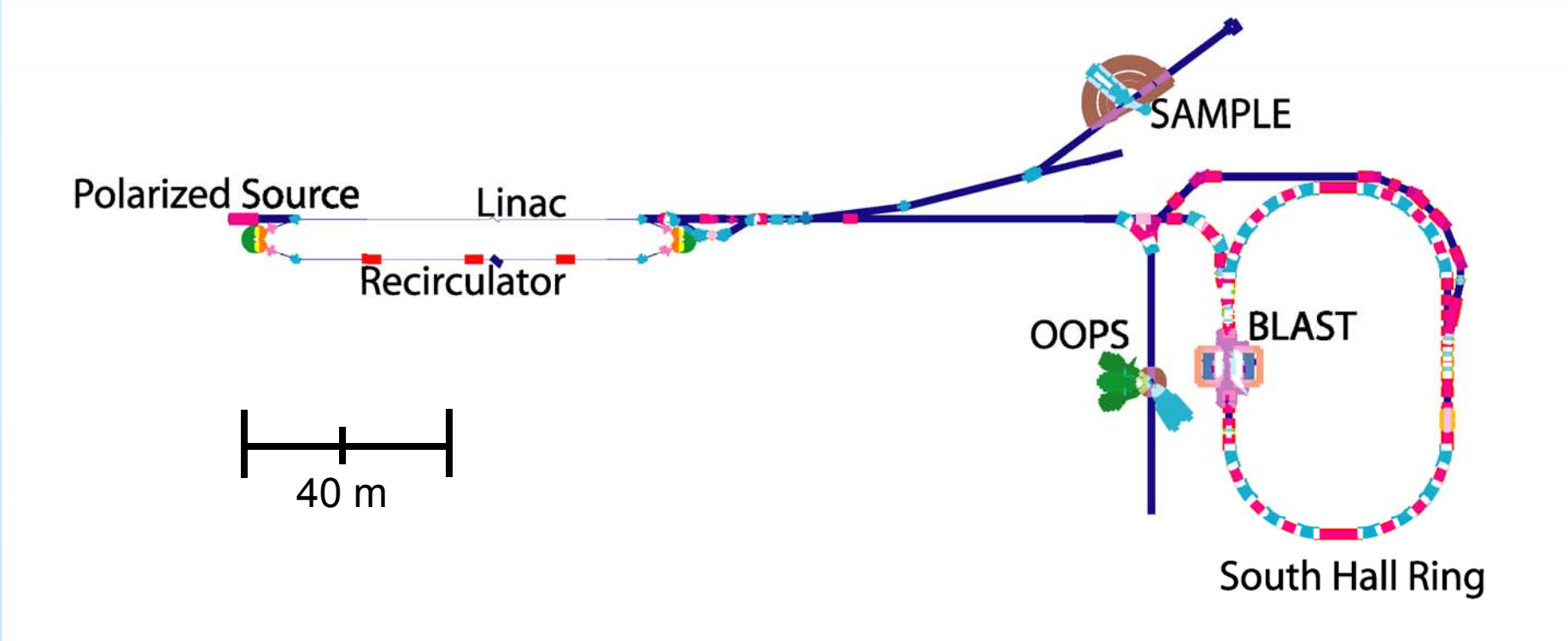
  Pion electroproduction:
  N-Delta transition in inclusive and exclusive response

EM Studies with Polarized H and D

- Exploit **single and double polarization observables** to keep **systematic errors low**
- Exploit **internal target in storage ring** to provide **highly polarized, isotopically pure (background free) target**
- Exploit **large angular and energy acceptance** to provide **simultaneous measurement of all reaction channels** over complete Q^2 range
- Exploit **field free region at target** to allow orientation of **target polarization in any direction** → Toroid

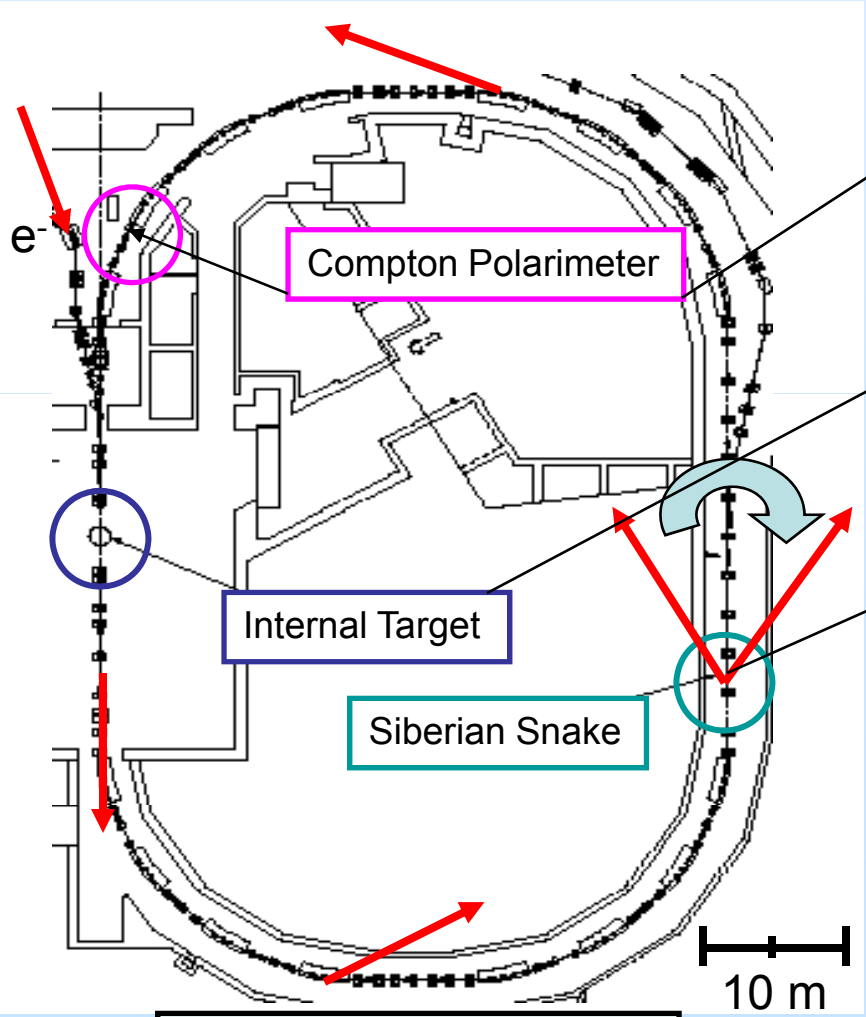
→ **Bates Large Acceptance Spectrometer Toroid**

MIT-Bates Linear Accel. Center



- **Beam:** Stored (SHR) 850 MeV, 200 mA, P_e = 65%
- **Target:** Internal (ABS) 6 x $10^{31}/(cm^2 s)$, $P_{H/D}$ = 80%
- **Detector:** **B**ates **L**arge **A**cceptance **S**pectrometer **T**oroid

MIT-Bates South Hall Ring

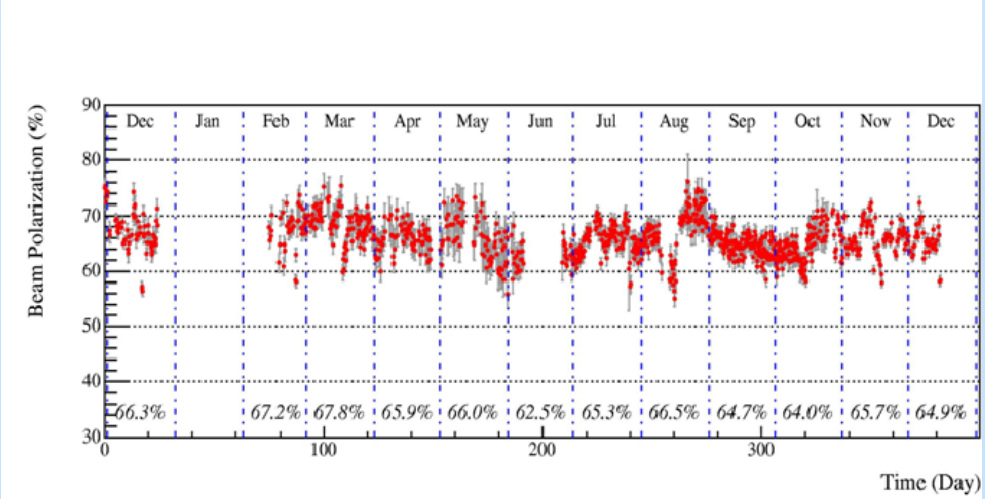


Monitoring of electron beam polarization

Injection with longitudinal spin at internal target

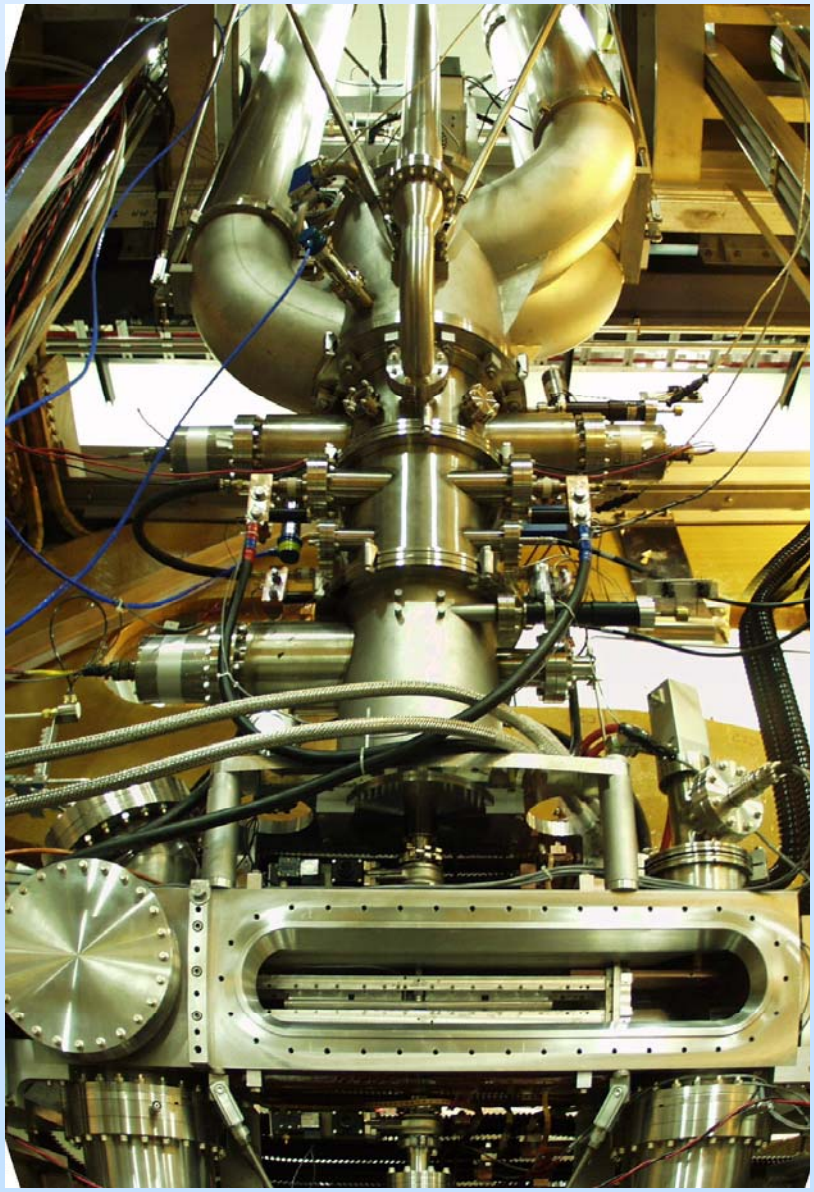
Siberian snake to restore longitudinal polarization

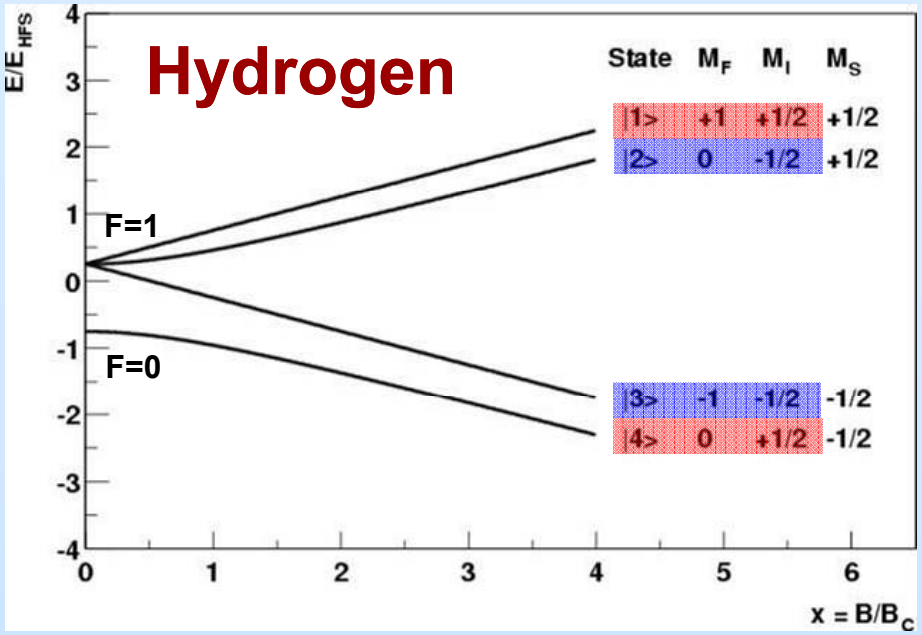
In-plane spin transport



$P_e = 0.65 \pm 0.04$

Atomic Beam Source (ABS)



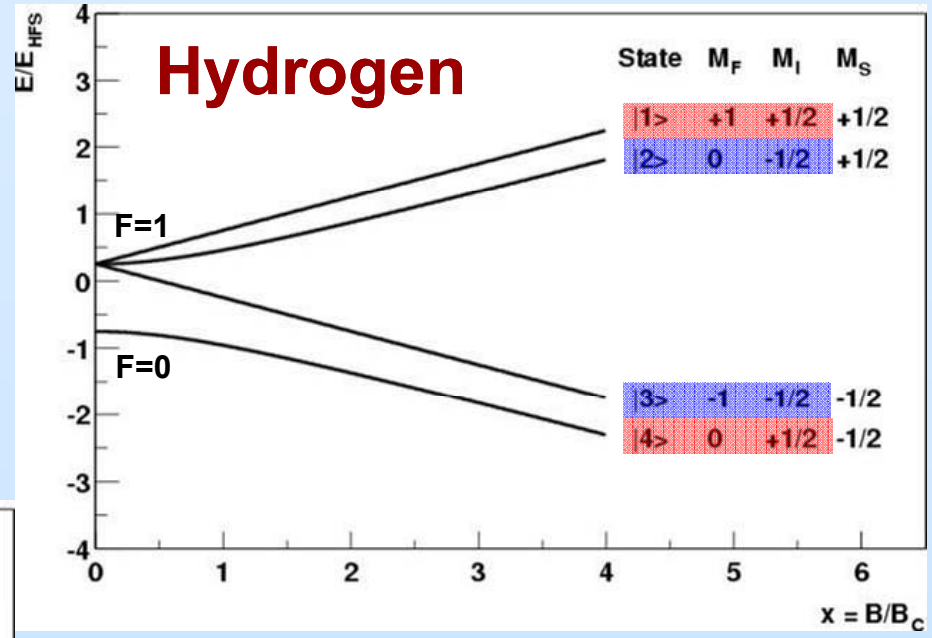


- Separately prepare m_I = **+½**, **-½** (**hydrogen**) and

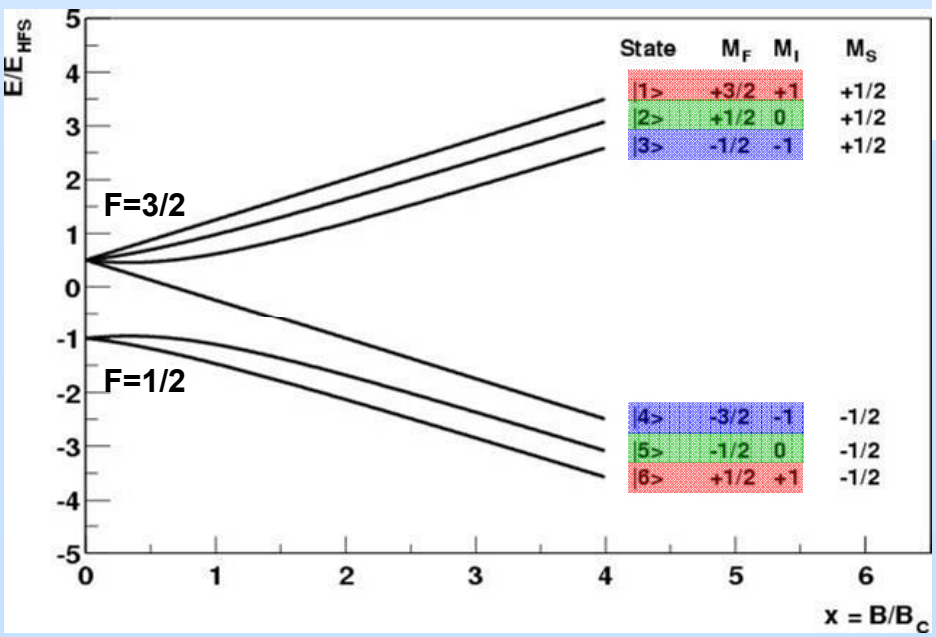
  with sextupoles and RF transitions

- Switch between states every 5 minutes

Atomic Beam Source (ABS)



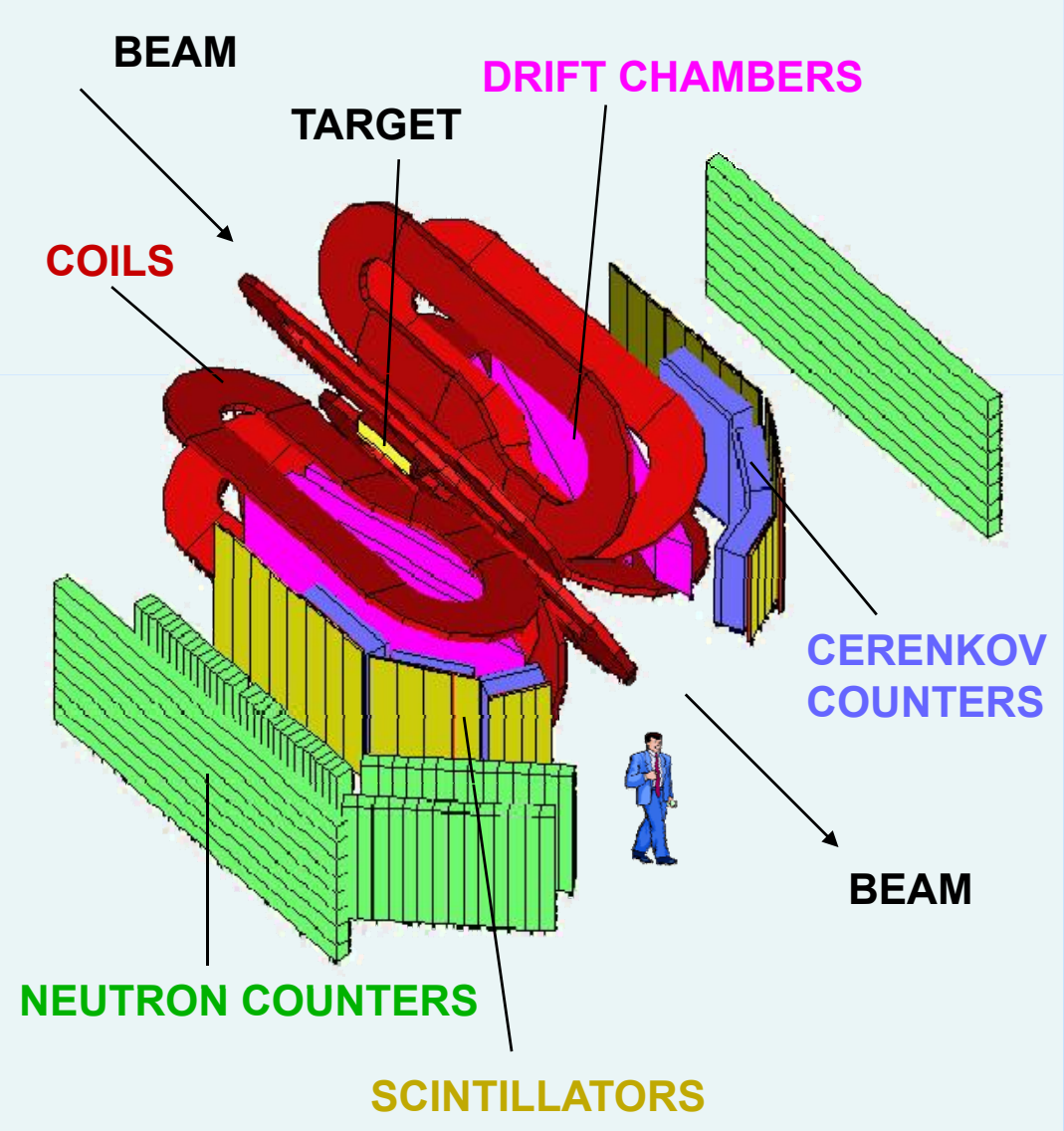
Deuterium



- Separately prepare m_I = **+½**, **-½** (**hydrogen**) and m_I = **+1**, **0**, **-1** (**deuterium**) with sextupoles and RF transitions
- Switch between states every 5 minutes

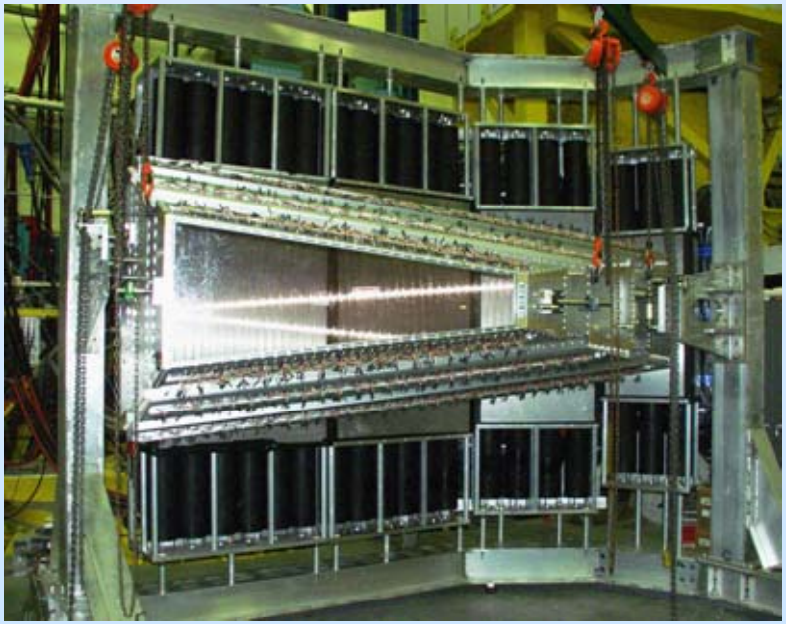
The BLAST Detector

- **Left-right symmetric**
- **Large acceptance:**
  $0.1 < Q^2/(GeV/c)^2 < 0.8$
  $20^o < \theta < 80^o$, $-15^o < \phi < 15^o$
- **COILS** $B_{max} = 3.8$ kG
- **DRIFT CHAMBERS**
  Tracking, PID (charge)
  $\delta p/p=3\%$, $\delta\theta = 0.5^o$
- **CERENKOV COUNTERS**
  e/π separation
- **SCINTILLATORS**
  Trigger, ToF, PID (π/p)
- **NEUTRON COUNTERS**
  Neutron tracking (ToF)



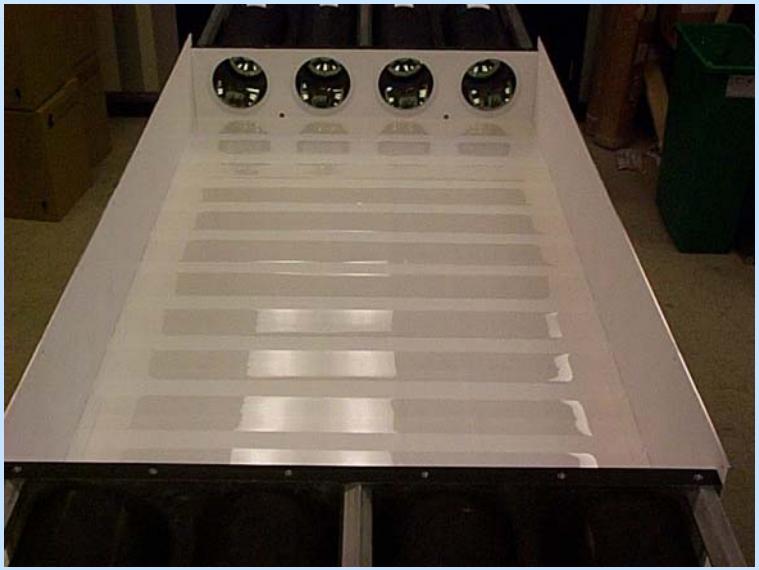
The BLAST Detector

Bates



MIT

UNH

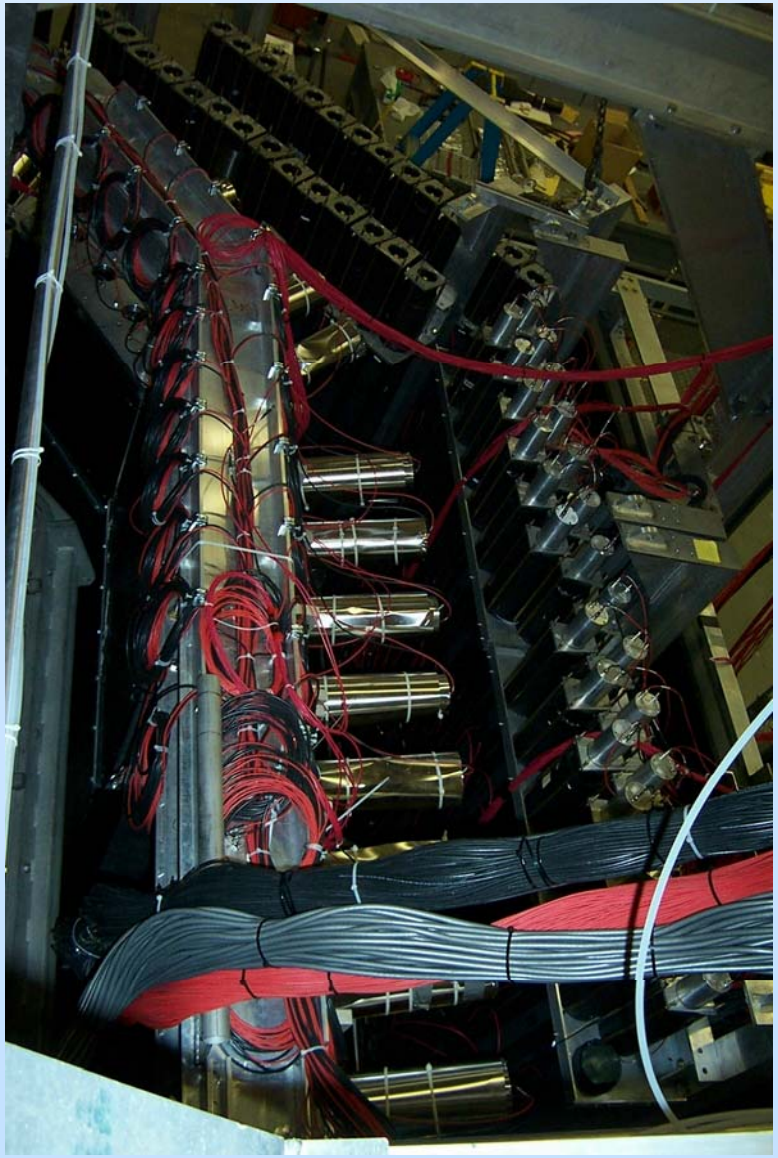


ASU

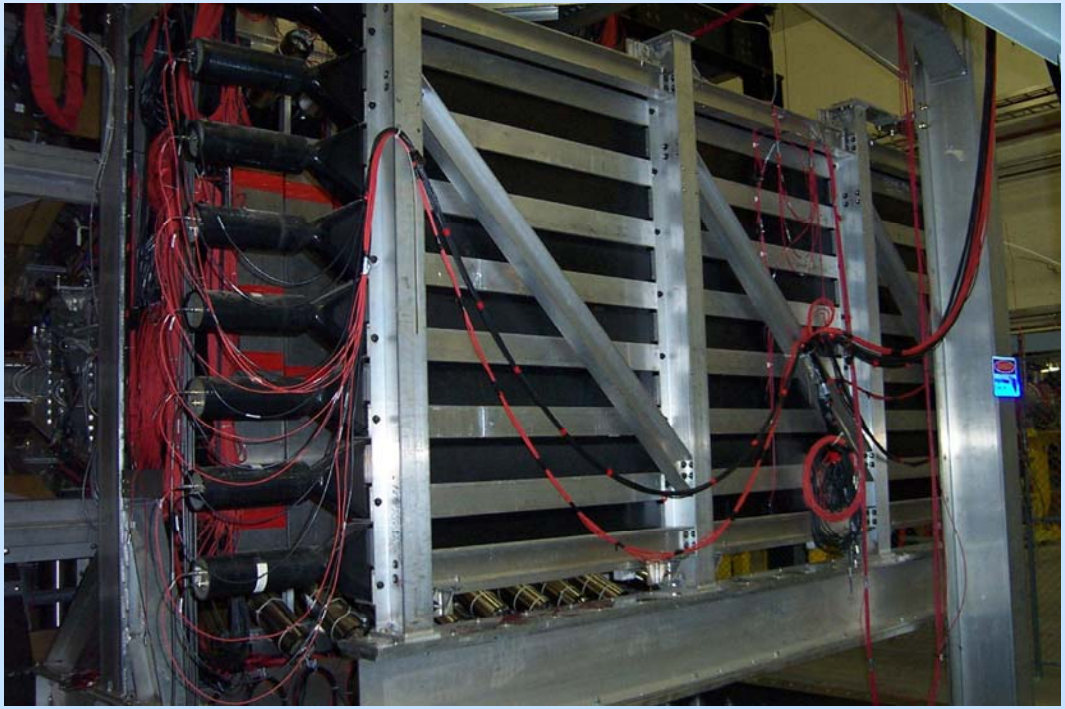
The BLAST Detector

Neutron Detectors

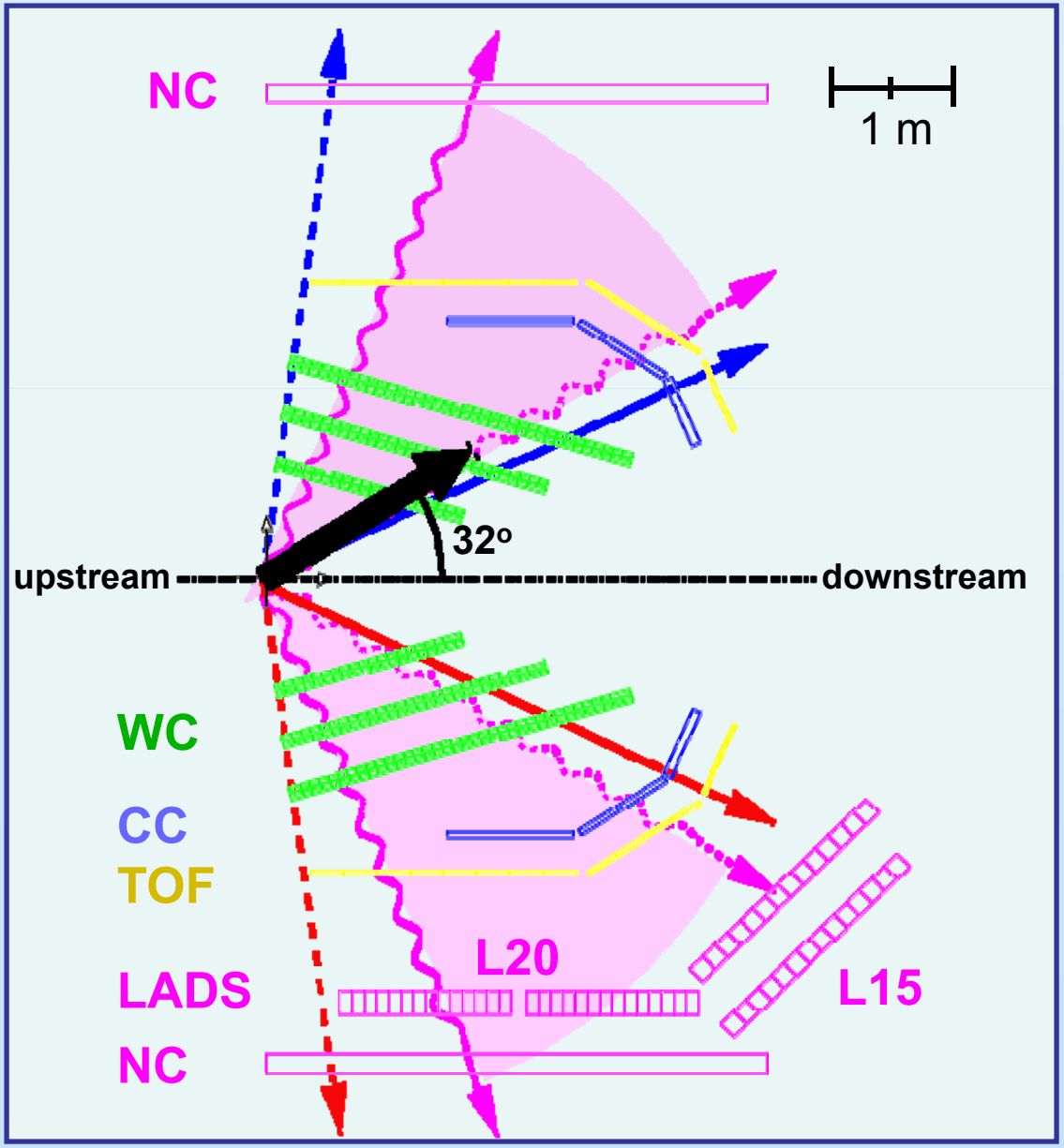
Bates



Ohio University



Target Spin Orientation



Freedom of in-plane spin angle

32° (2004) / 47° (2005)

e- left → $\theta^* \approx 90^o$

"spin-perpendicular"

e- right → $\theta^* \approx 0^o$

"spin-parallel"

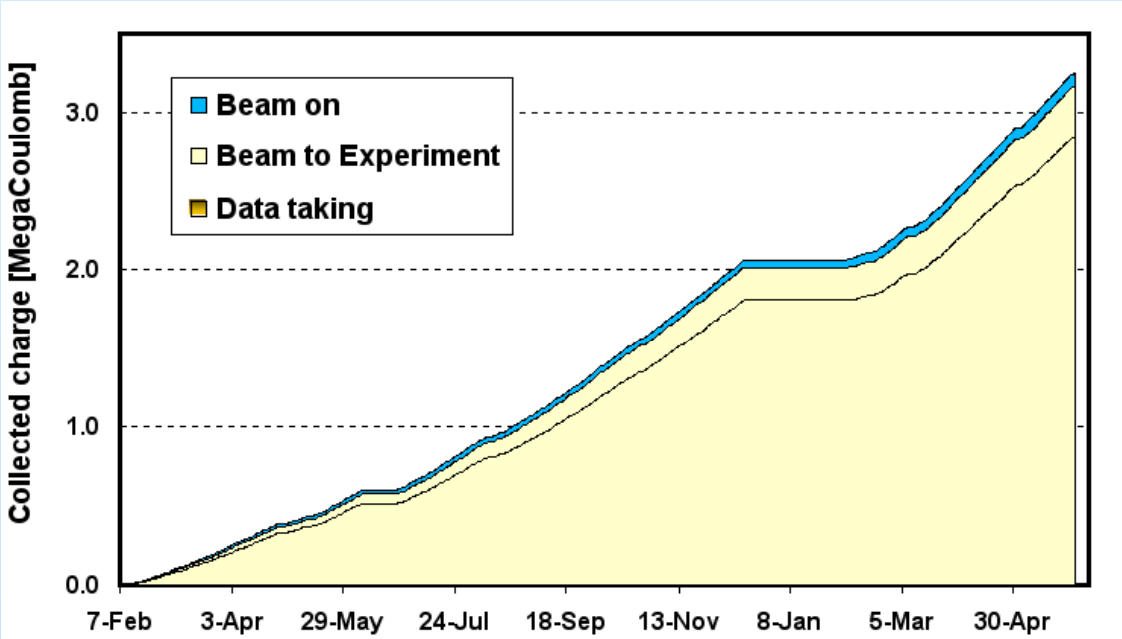
BLAST Data Collection

- **> 3 MC** accumulated charge for **Hydrogen** and **Deuterium** 2004/05

- **Hydrogen 2004**
  $\theta_d = 47^o$, 290 kC (**90 pb^{-1}**)
  $P_z = 82\%$

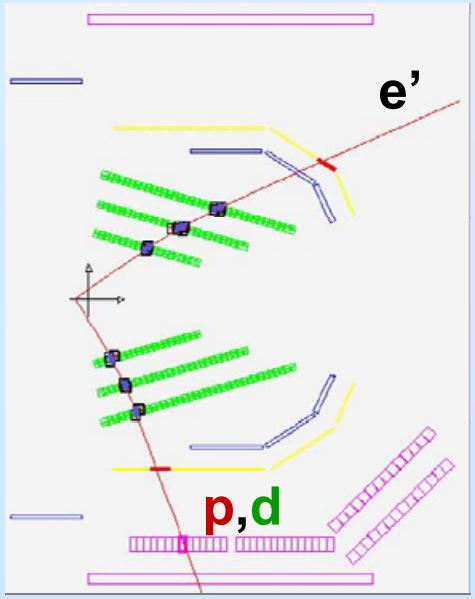
- **Deuterium 2004**
  $\theta_d = 32^o$, 450 kC (**169 pb^{-1}**)
  $P_z = 86\%$, $P_{zz} = 68\%$

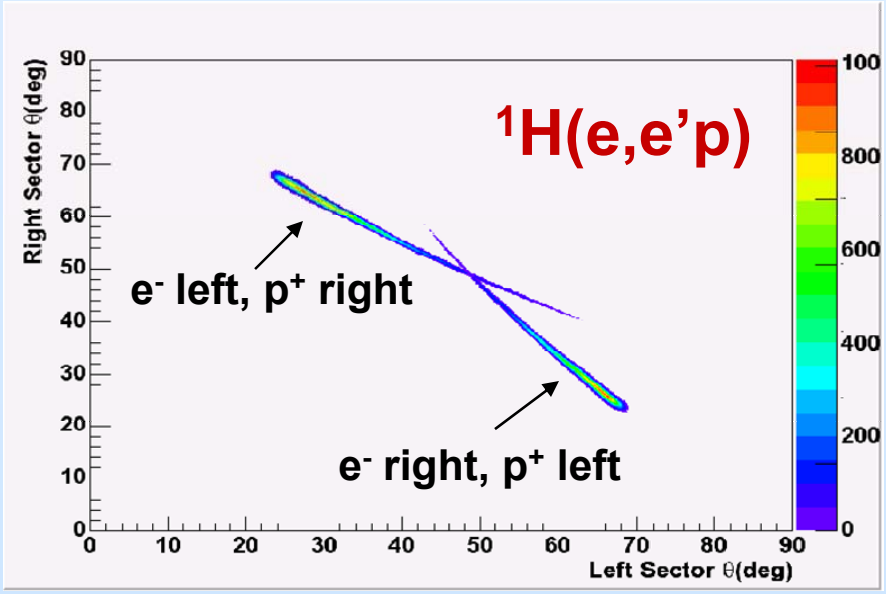
- **Deuterium 2005**
  $\theta_d = 47^o$, 550 kC (**150 pb^{-1}**)
  $P_z = 73\%$, $P_{zz} = 56\%$

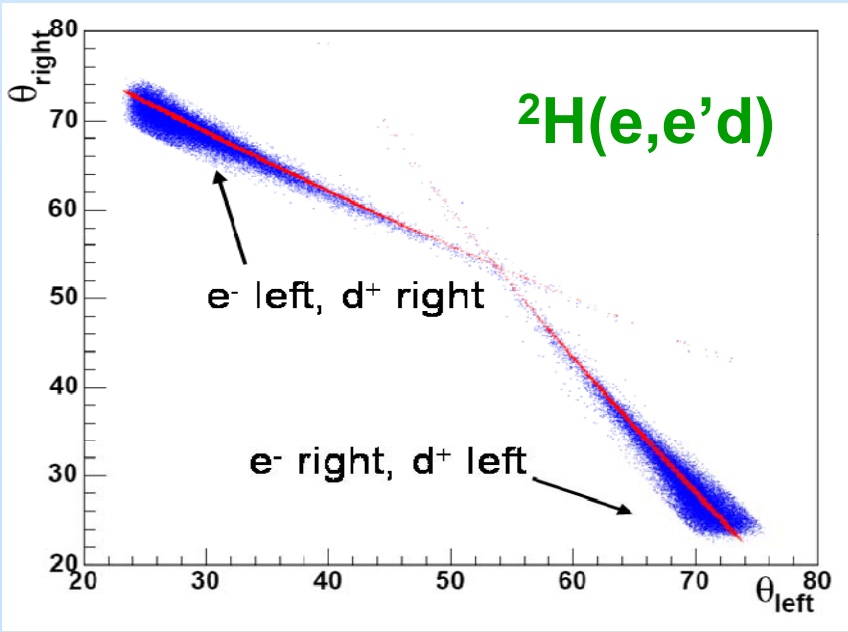


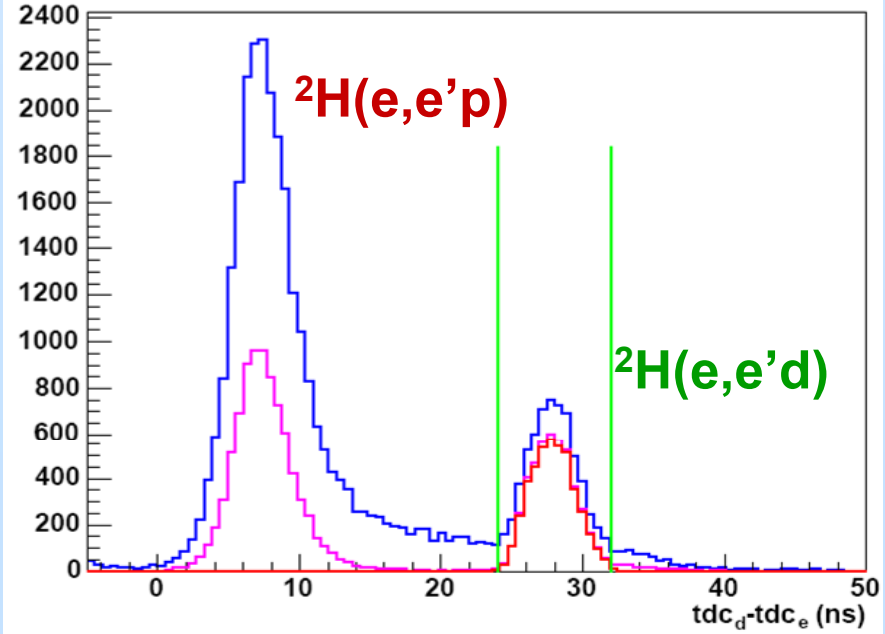
Identification of Elastic Events

- Charge +/-
- Coplanarity
- Kinematics
- Timing



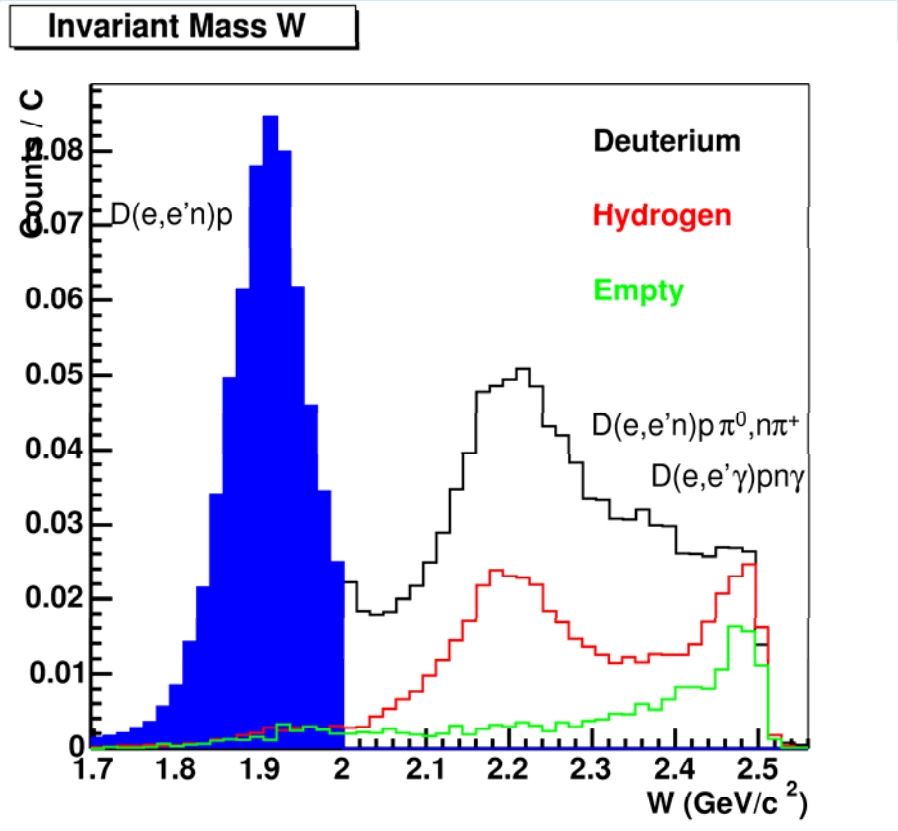


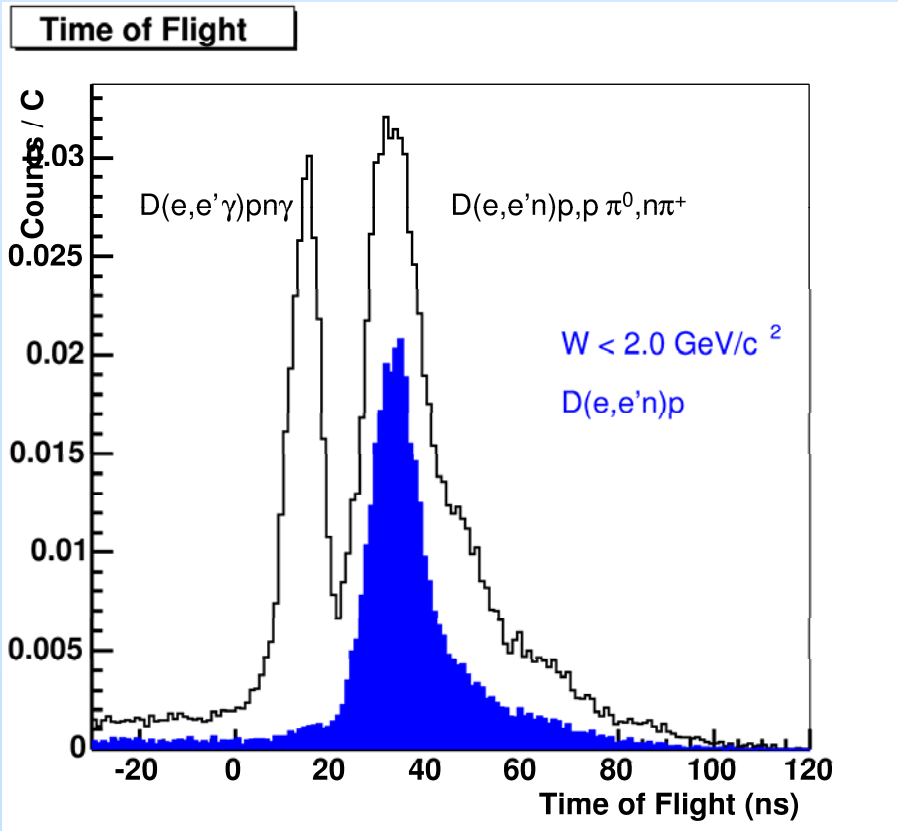




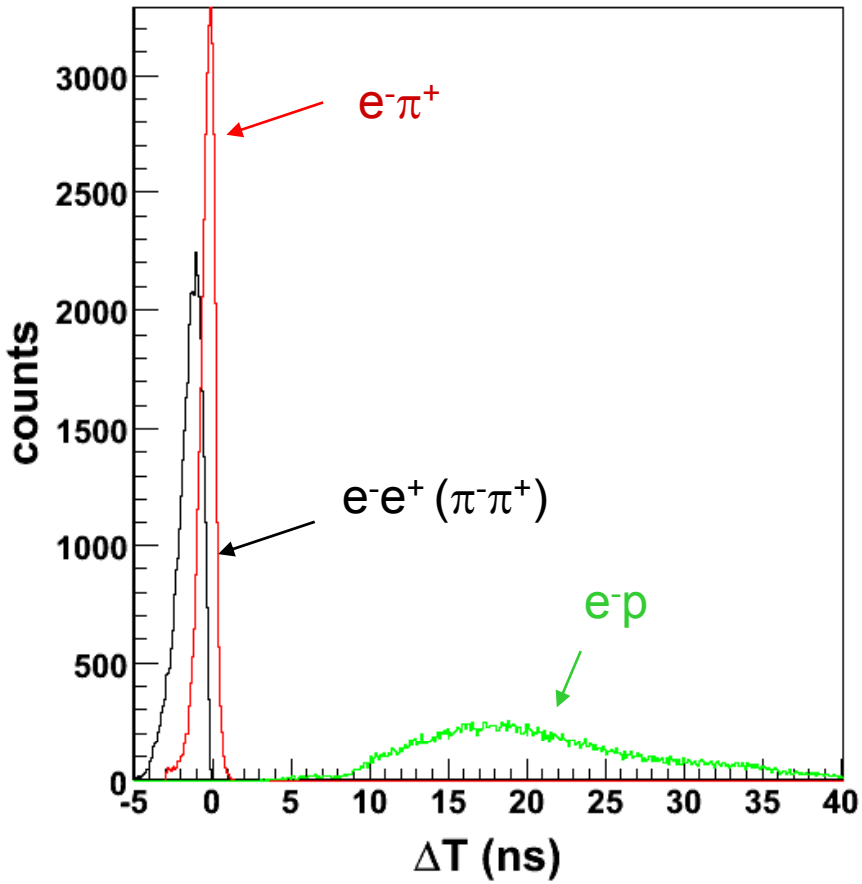
Identification of Neutron Events

- Very clean quasielastic ^{2}H(e,e'n) spectra
- Highly efficient **proton veto** (drift chambers + TOF)

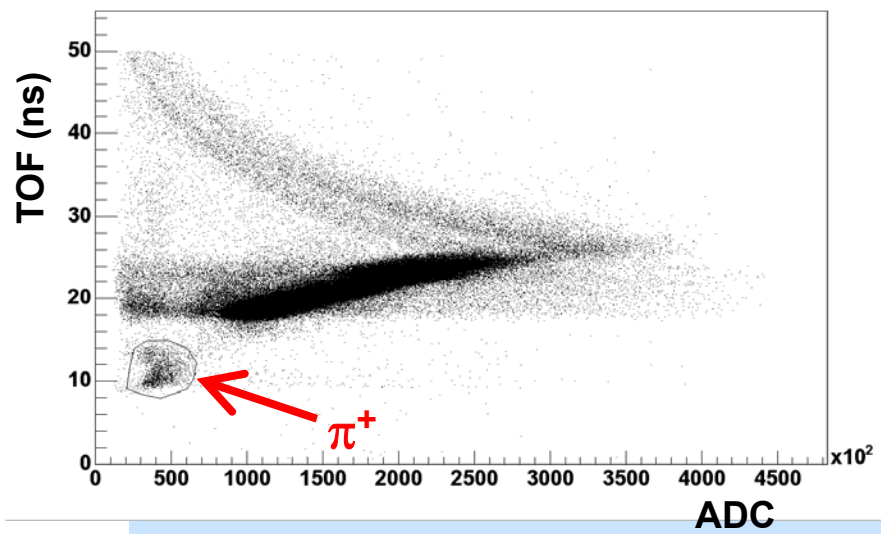




Identification of π^+ Events



Time correlation for candidate e'π^+ events, corrected for pathlength



- **Cerenkov used to discriminate π^+ / e^+ and π^- / e^- tracks.**

Nucleon Form Factors

Nucleon Elastic Form Factors

- General definition of the nucleon form factor

$$\langle N(P')|J^{\mu}_{\rm EM}(0)|N(P)\rangle = \bar{u}(P')\left[\gamma^{\mu}F_1^N(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2^N(Q^2)\right]u(P)$$

- Sachs Form Factors $G_E = F_1 - \tau F_2; \quad G_M = F_1 + F_2, \quad \tau = \frac{Q^2}{4M^2}$

- In One-photon exchange approximation above form factors are observables of **elastic electron-nucleon** scattering

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{\epsilon\, G_E^2 + \tau G_M^2}{\epsilon\,(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

Nucleon Form Factors and Polarization

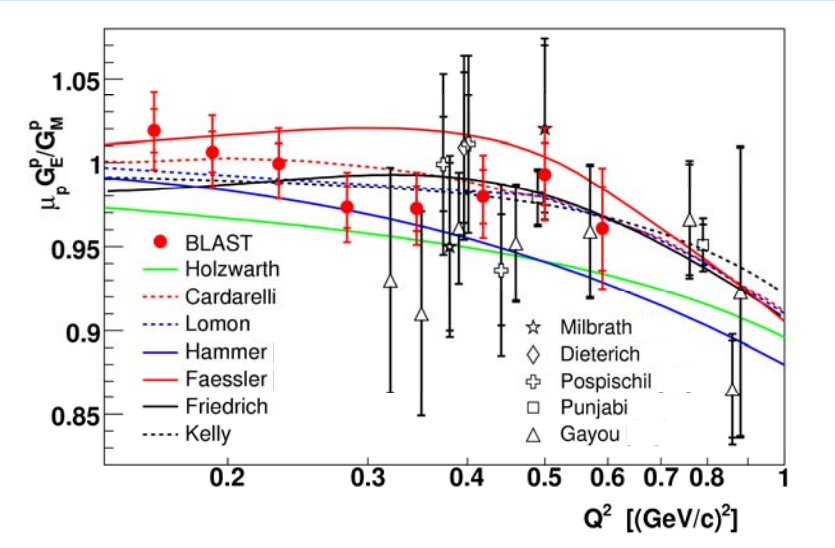
- Double polarization in elastic/quasielastic **ep** or **en** scattering:
  Recoil polarization or (vector) polarized target
  $^{1,2}H(\vec{e},e'\vec{p})$, $^{1,2}\vec{H}(\vec{e},e'p)$, $^{2}H(\vec{e},e'\vec{n})$, $^{2}\vec{H}(\vec{e},e'n)$

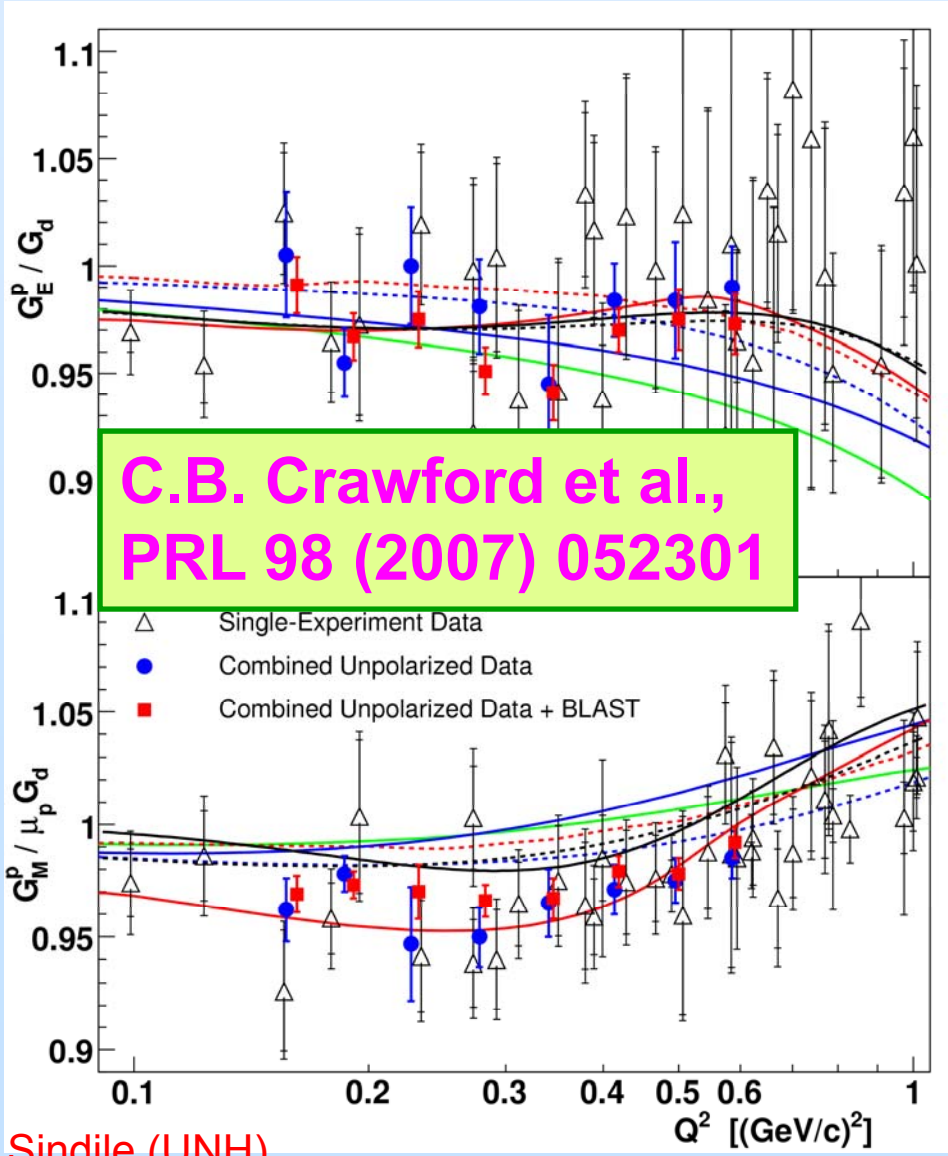
- Polarized cross section
  $$\sigma = \sigma_0 \left(1 + P_e \vec{P}_p \cdot \vec{A}\right)$$

- Double spin asymmetry = spin correlation
  $$-\sigma_0 \vec{P}_p \cdot \vec{A} = \sqrt{2\tau\epsilon(1-\epsilon)} G_E G_M \sin\theta^* \cos\phi^* + \tau\sqrt{1-\epsilon^2} {G_M}^2 \cos\theta^*$$

- Asymmetry ratio ("Super ratio") $\frac{P_\perp}{P_\parallel} = \frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}$
  independent of polarization or analyzing power

Proton Form Factor Ratio $\mu_p G^p_E / G^p_M$*





C.B. Crawford et al., PRL 98 (2007) 052301

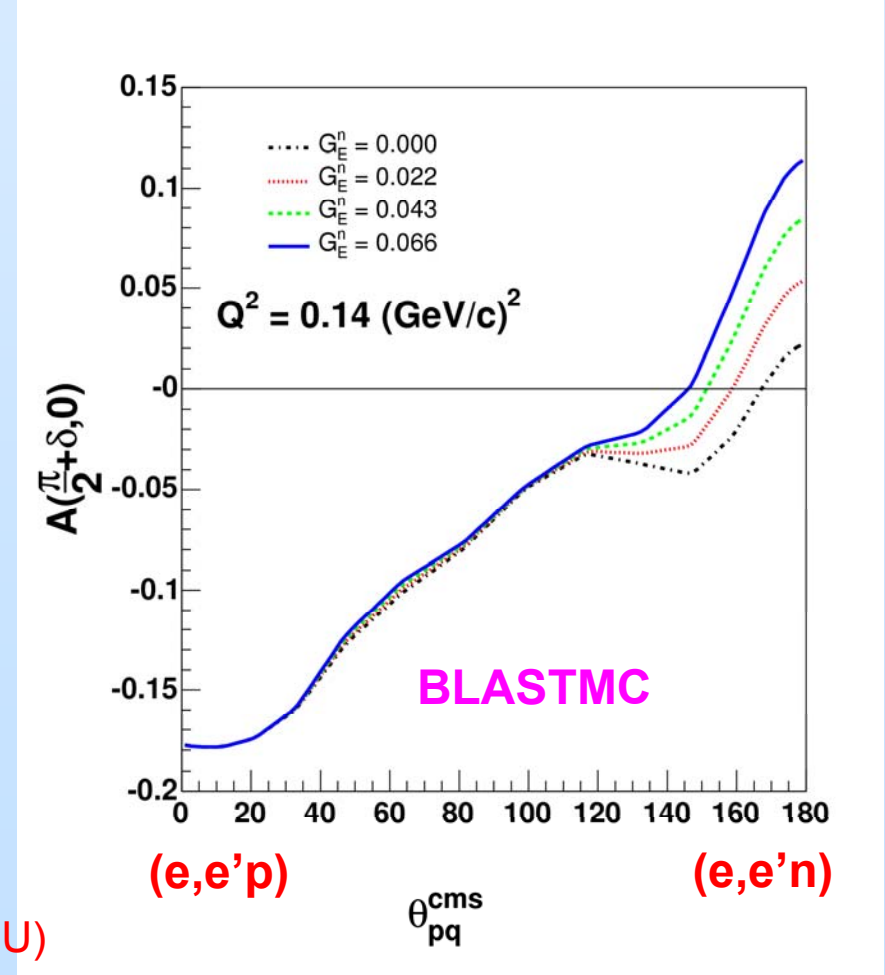
- **Impact of BLAST data combined with cross sections on separation of G^p_E and G^p_M**
- **Errors factor ~2 smaller**
- **Reduced correlation**
- **Deviation from dipole at low Q^2!**

*Ph.D. work of C. Crawford (MIT) and A. Sindile (UNH)

Extraction of G^n_E*

$$A^V_{ed} = \frac{a\, {G^n_M}^2 \cos\theta^* + b\, G^n_E G^n_M \sin\theta^* \cos\phi^*}{c\, {G^n_E}^2 + {G^n_M}^2} \approx a\cos\theta^* + b\,\frac{G^n_E}{G^n_M}\sin\theta^*\cos\phi^*$$

- Quasielastic $^2\vec{H}(\vec{e},e'n)$
- Full Montecarlo simulation of the BLAST experiment
- Deuteron electrodisintegration by H. Arenhövel
- Accounted for FSI,MEC,RC,IC
- Spin-perpendicular beam-target vector asymmetry A^V_{ed} shows high sensitivity to G^n_E
- Compare measured A^V_{ed} with **BLASTMC**, vary G^n_E

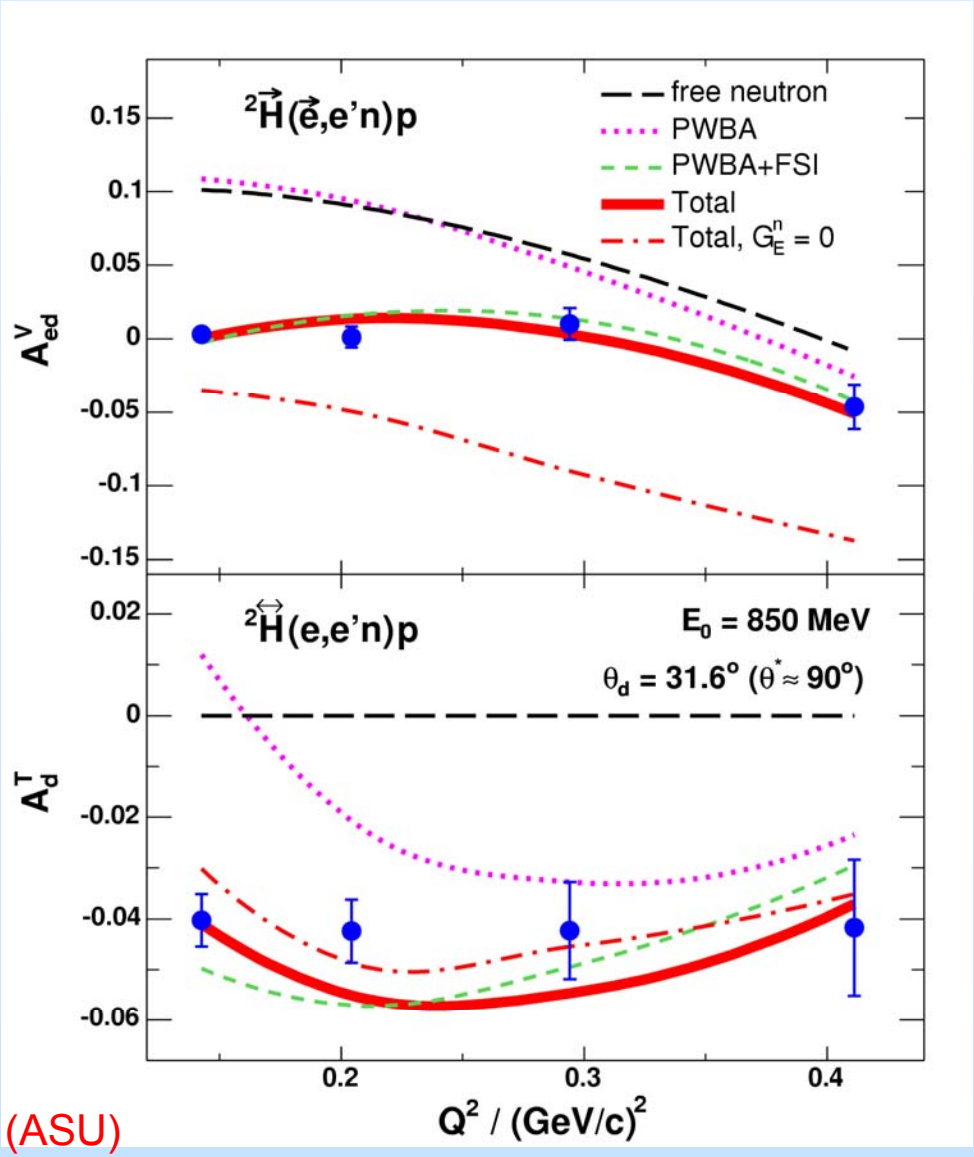


*Ph.D. work of V. Ziskin (MIT) and E. Geis (ASU)

How well is the FSI effect known?

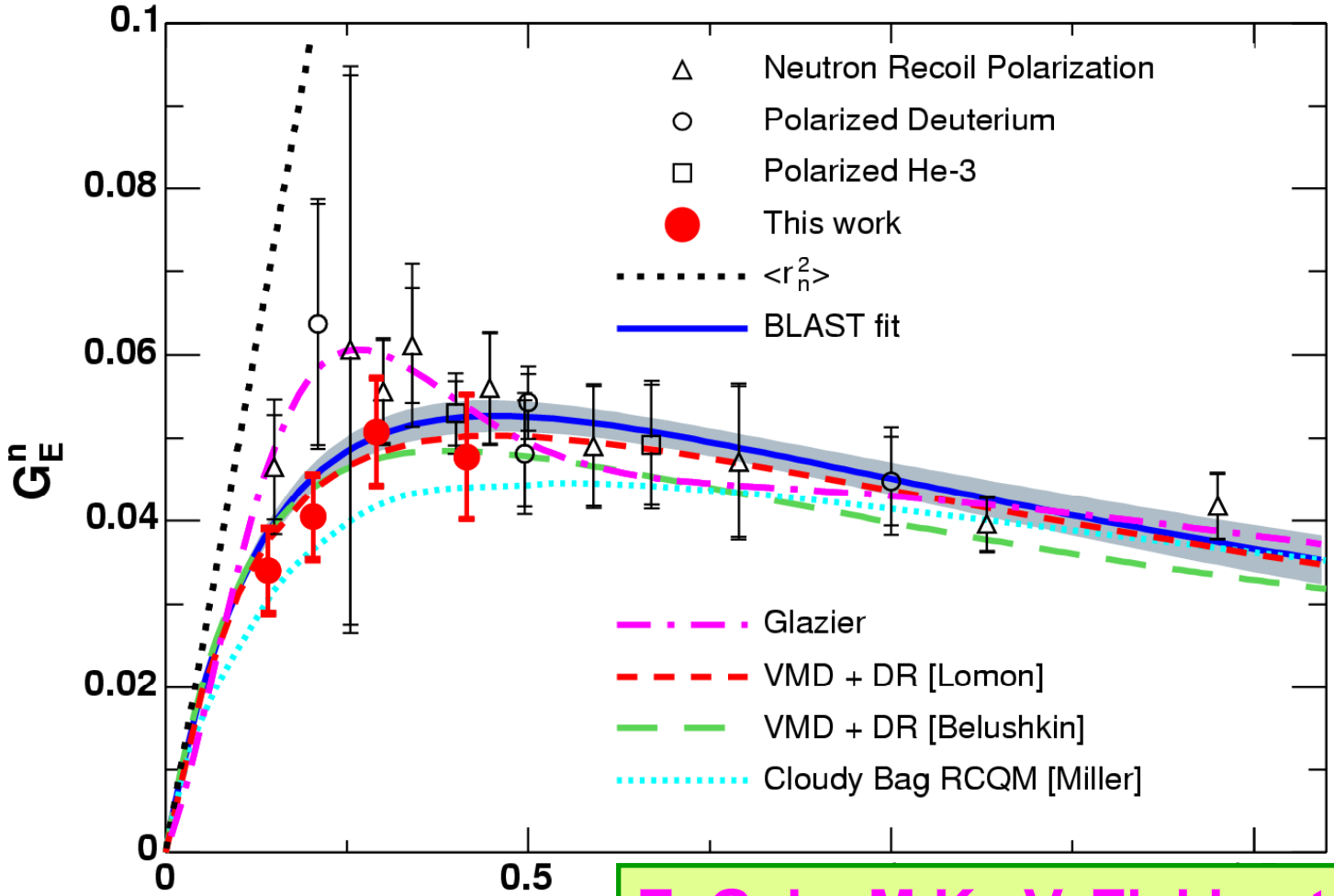
- Quasielastic $^2\vec{H}(\vec{e},e'n)$
- Full Montecarlo simulation of the BLAST experiment
- Deuteron electrodisintegration by H. Arenhövel
- Accounted for FSI,MEC,RC,IC
- Spin-perpendicular beam-target vector asymmetry A^V_{ed} shows high sensitivity to G^n_E

- **Use tensor asymmetry to control FSI**



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

Neutron Electric Form Factor G^n_E*



E. Geis, M.K., V. Ziskin et al., PRL 101 (2008) 042501

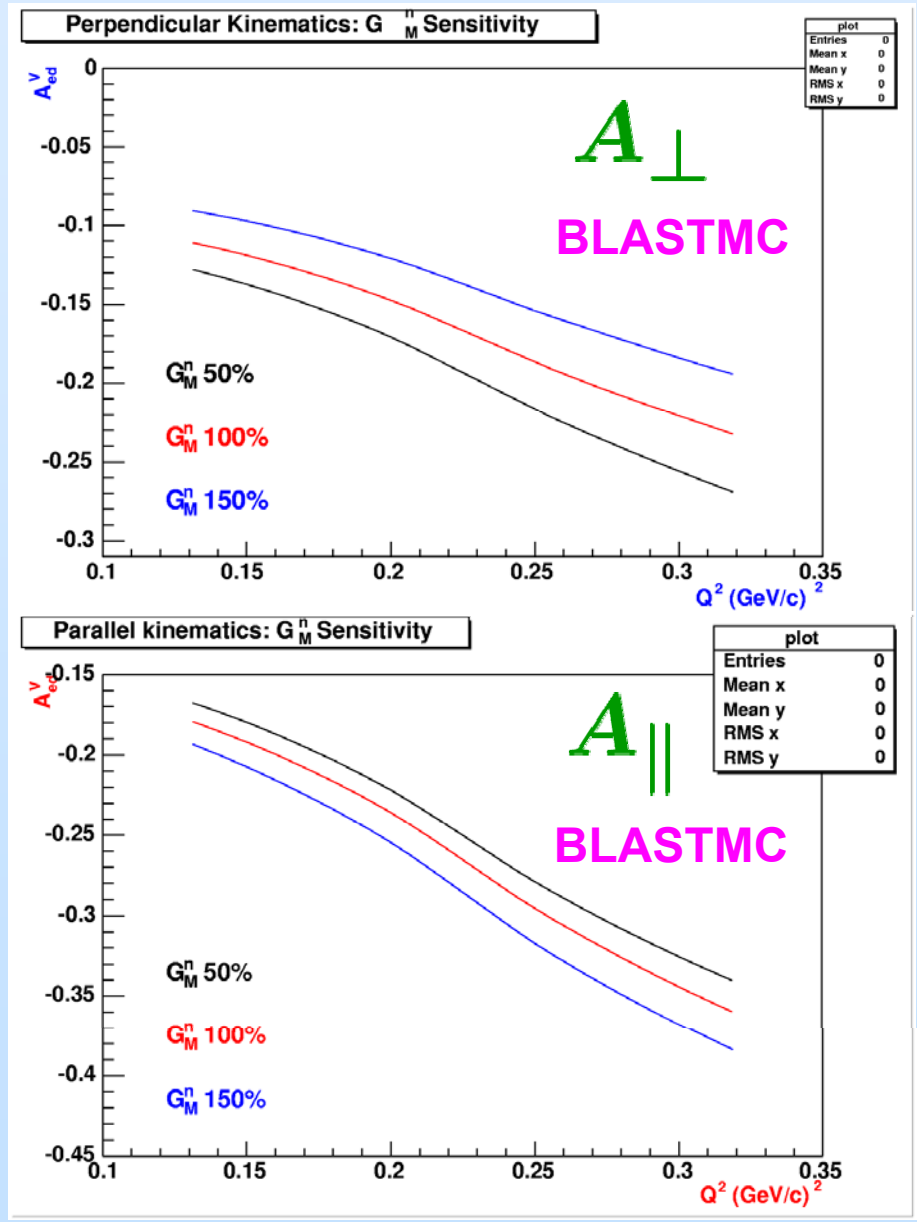
*Ph.D. work of V. Ziskin (MIT) and E.

Extraction of G^n_M

- Quasielastic $^2\vec{H}(\vec{e},e')$ inclusive
- Full Montecarlo simulation of the BLAST experiment
- Deuteron electrodisintegration by H. Arenhövel
- Accounted for FSI,MEC,RC,IC
- Beam-target vector asymmetry A^V_{ed} spin-parallel + perpendicular show sensitivity to G^n_M
- PWIA:

$$A_\perp \approx \frac{c\,(G_E^p/G_M^p)}{a + b\left(1 + (G_M^n/G_M^p)^2\right)}$$

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

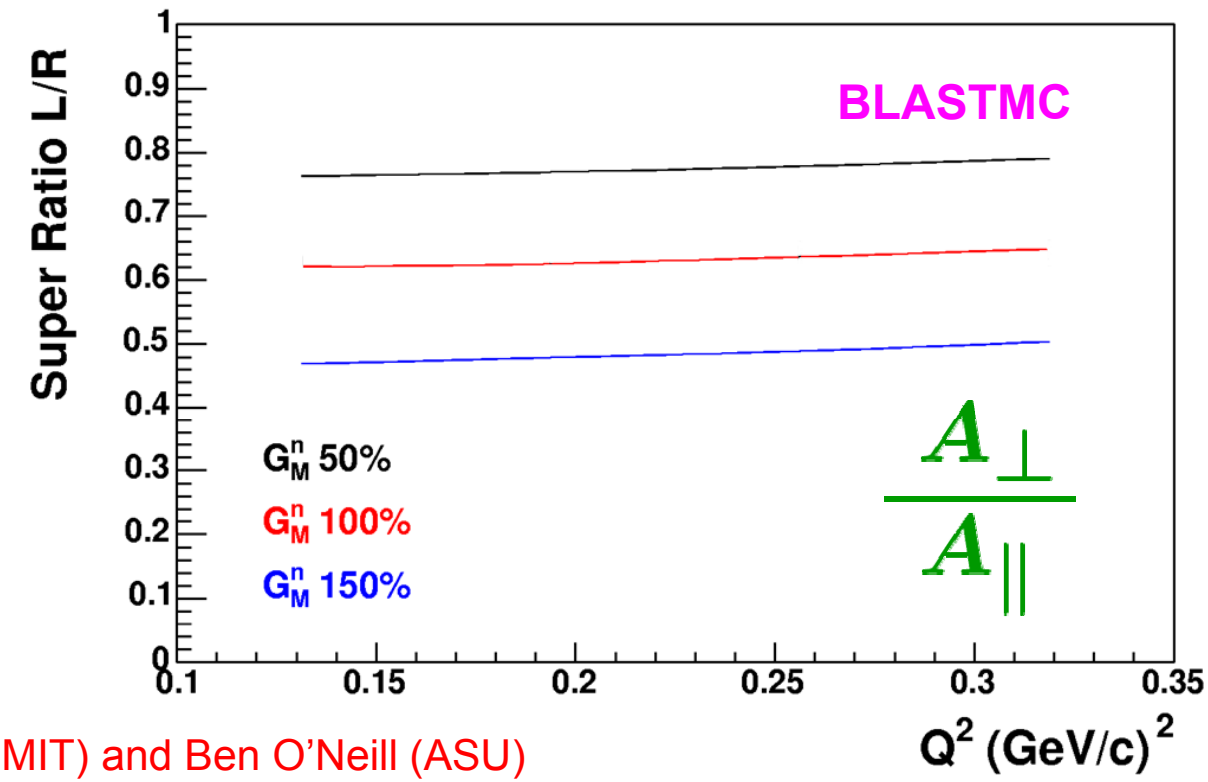


Extraction of G^n_M *

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

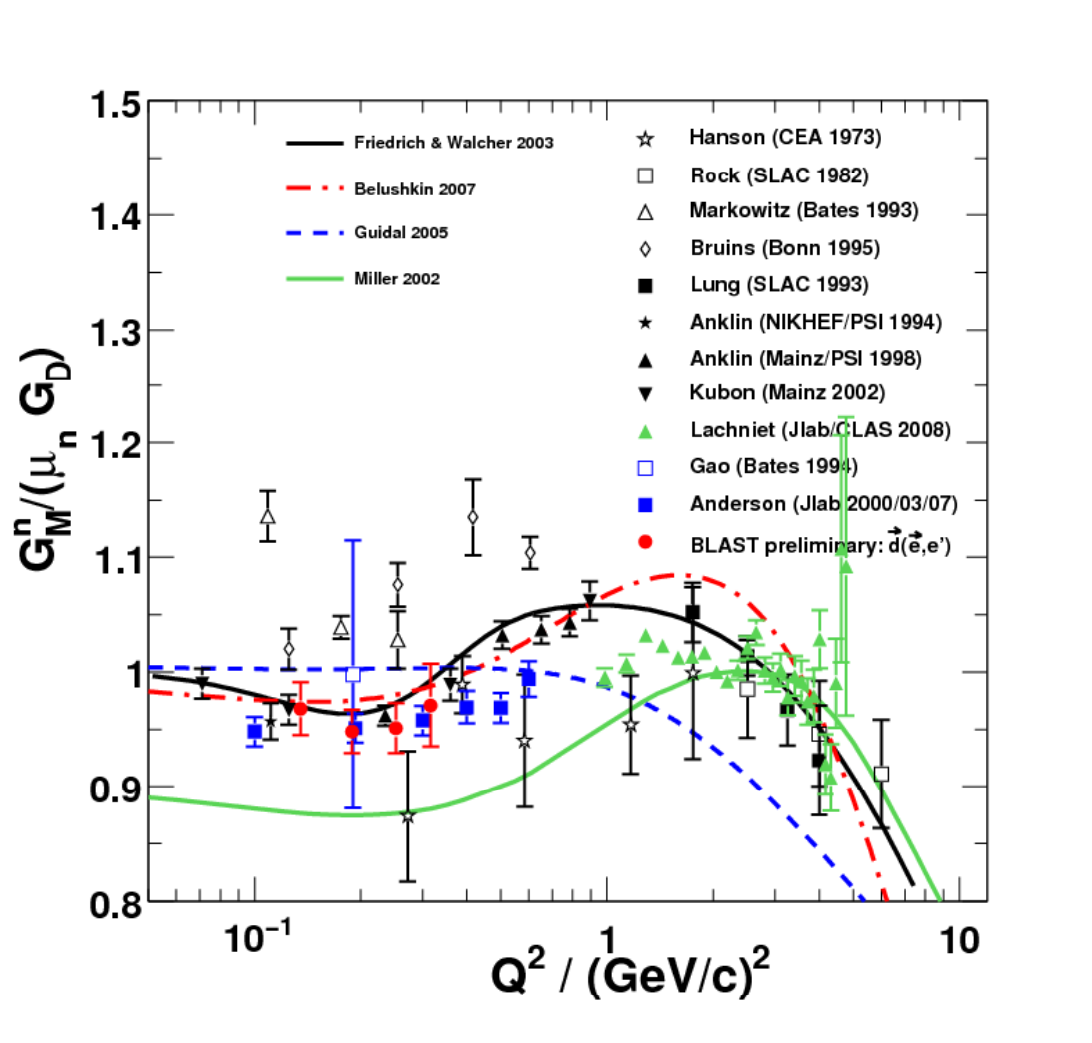
Enhanced sensitivity in super ratio

Independent of polarization



*Ph.D. work of N. Meitanis (MIT) and Ben O'Neill (ASU)

Neutron Magnetic Form Factor G^n_M



- **Pre-polarization era**
- G^n_M world data from unpolarized experiments
- Cross section ratio

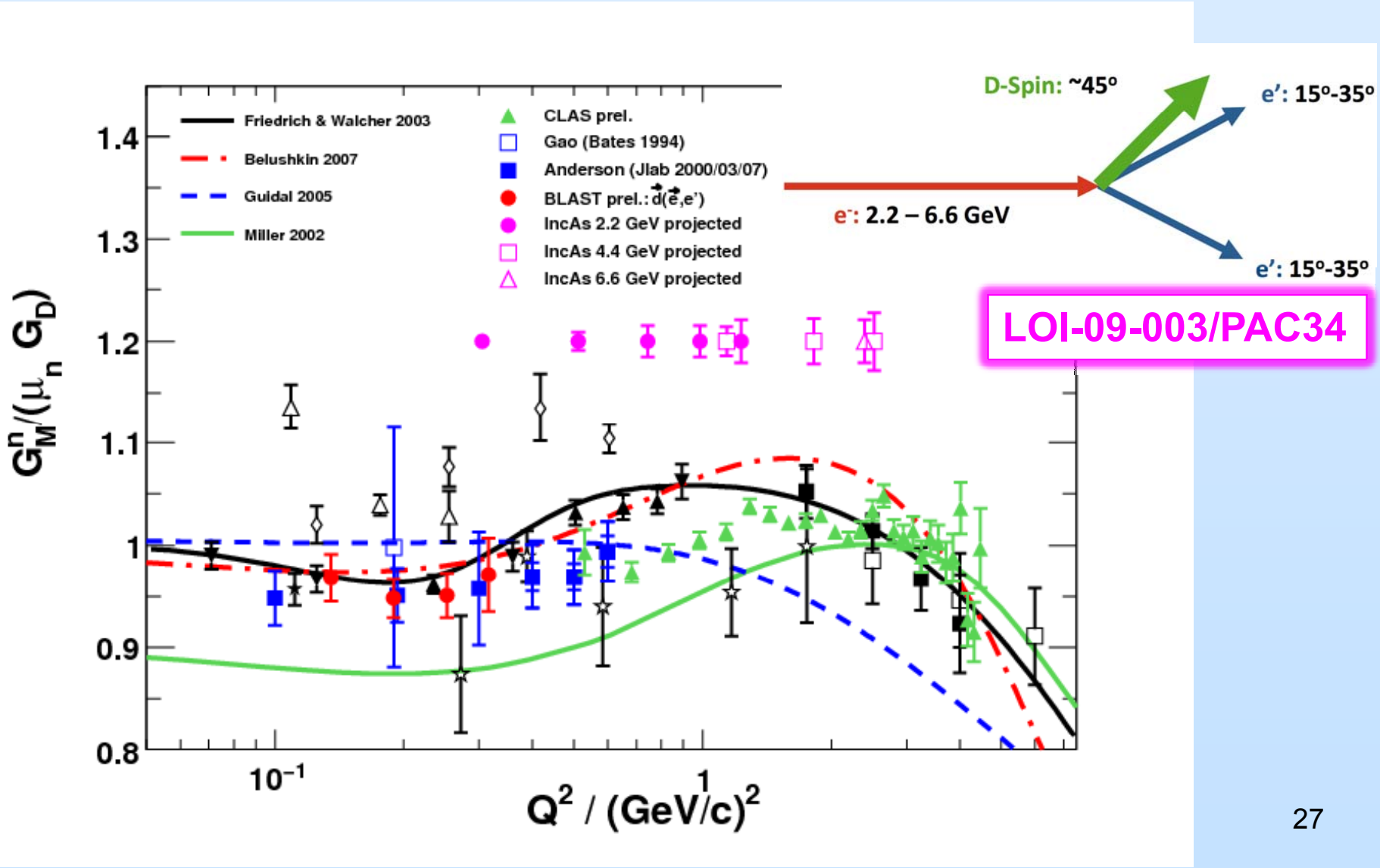
  quasielastic $\frac{d(e,e'n)}{d(e,e'p)}$
- **+ CLAS 2008**

- **Polarization era**
- G^n_M world data **+ ^{3}He**

  + BLAST preliminary

*Ph.D. work of N. Meitanis (MIT) and B. O'Neill (ASU)

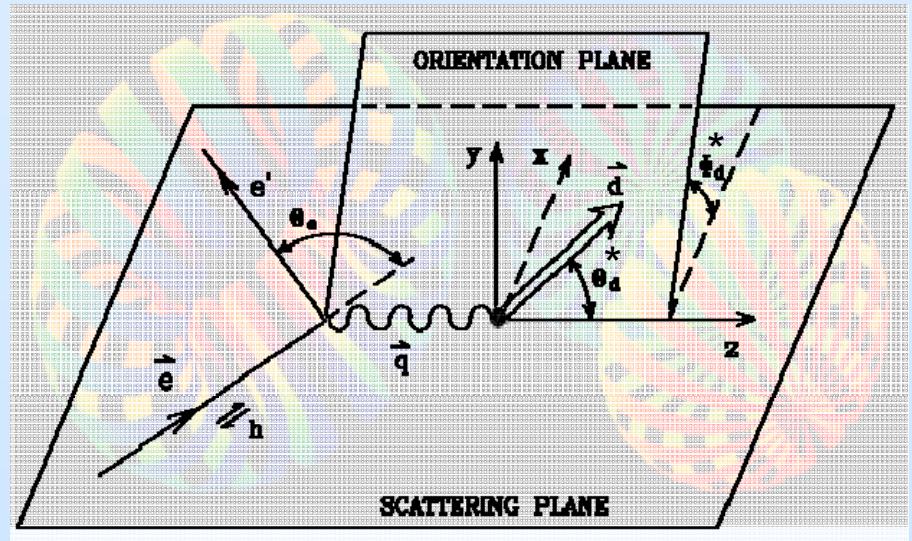
IncAs: Inclusive Asymmetries



Deuteron Structure

Elastic Electron-Deuteron Scattering

- Spin 1 ↔ three elastic form factors
  G^d_C, G^d_Q, G^d_M
- Quadrupole moment
  $M^2_d Q_d = G^d_Q(0) = 25.83$
- G^d_Q ↔ Tensor force, D-wave



- Unpolarized elastic cross section

$$\sigma_0 = \sigma_{\text{Mott}} \left(A + B \tan^2(\theta_e/2)\right) := \sigma_{\text{Mott}} S_0$$

$$A(Q^2) = {G^d_C}^2 + \tfrac{8}{9}\eta^2 {G^d_Q}^2 + \tfrac{2}{3}\eta {G^d_M}^2$$

$$B(Q^2) = \tfrac{4}{3}\eta(1+\eta){G^d_M}^2; \quad \eta = Q^2/(4M_D^2)$$

- Polarized cross section

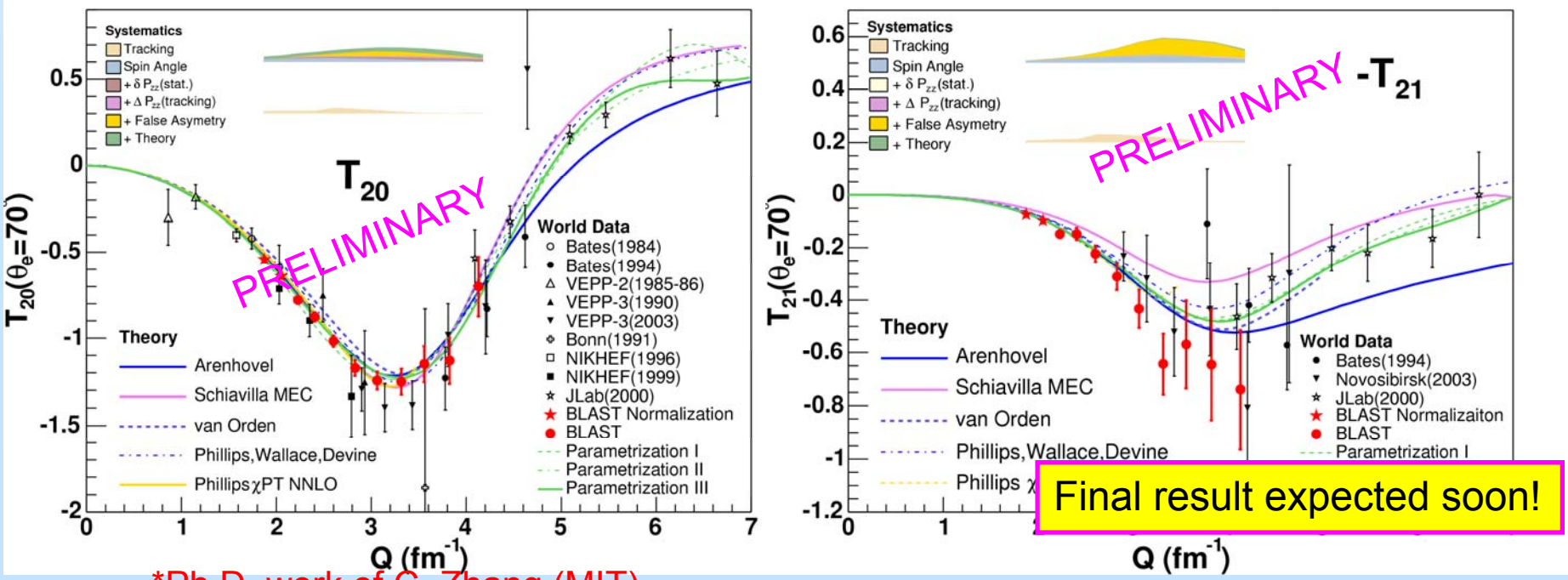
$$\sigma = \sigma_0 \left(1 + P_{zz} A^T_d + h P_z A^V_{ed}\right)$$

Tensor Analyzing Powers T_{20}, T_{21} *

$$A_d^T = \frac{1}{\sqrt{2}}\left(\frac{3}{2}\left(\cos^2\theta_d - 1\right)T_{20} - \sqrt{\frac{3}{2}}\sin 2\theta_d \cos\phi_d T_{21} + \sqrt{\frac{3}{2}}\sin^2\theta_d \cos 2\phi_d T_{22}\right)$$

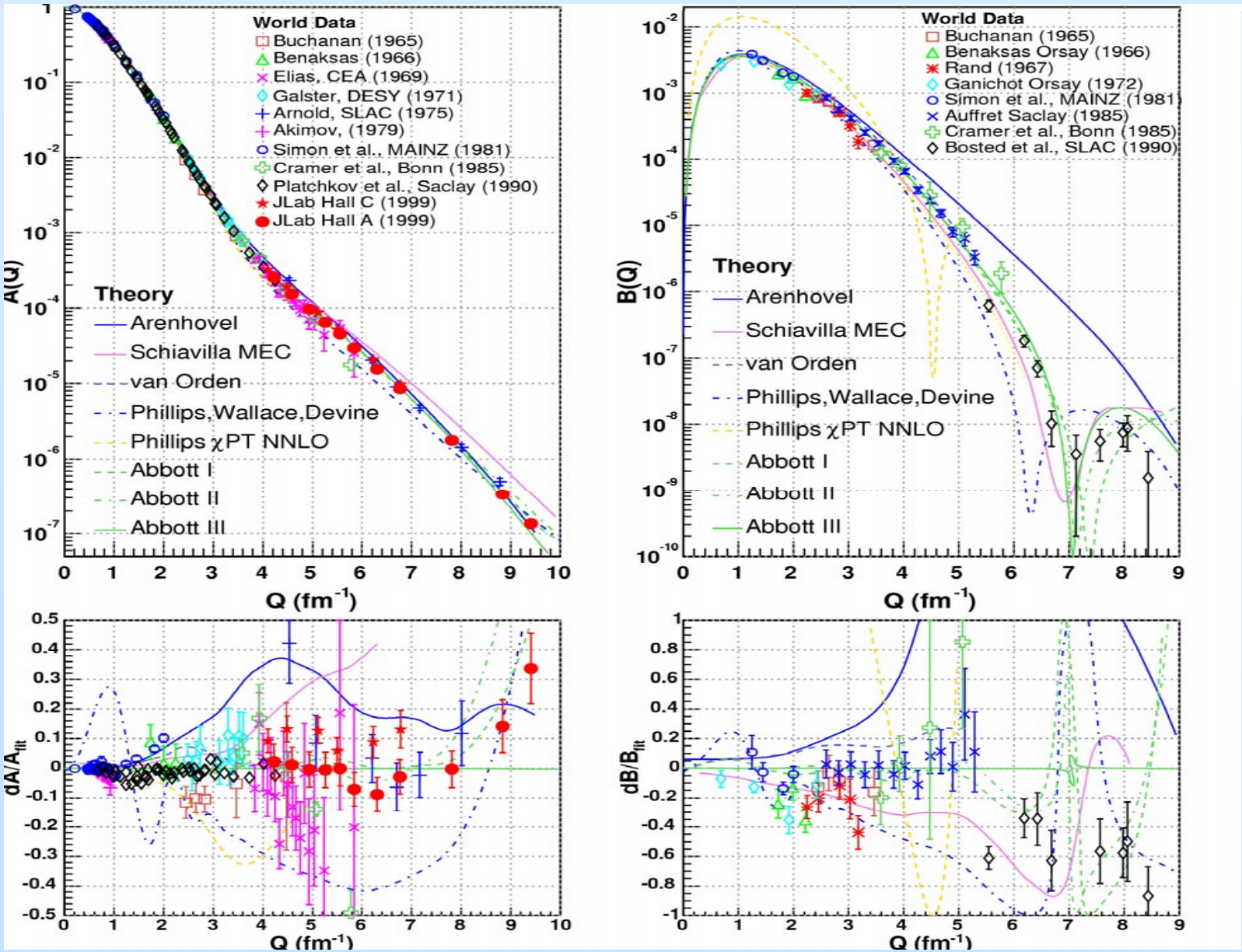
$$T_{20}(Q^2,\theta_e) = \frac{1}{\sqrt{2}S_0}\left[\frac{8}{3}\eta\, G_C^d G_Q^d + \frac{8}{9}\eta^2 {G_Q^d}^2 + \frac{1}{3}\eta\left(1 + 2\left(1+\eta\right)\tan^2\frac{\theta_e}{2}\right){G_M^d}^2\right]$$

$$T_{21}(Q^2,\theta_e) = \frac{1}{\sqrt{3}S_0}2\eta\sqrt{\eta + \eta^2\sin^2\frac{\theta_e}{2}}\sec\frac{\theta_e}{2}\, G_M^d G_Q^d$$

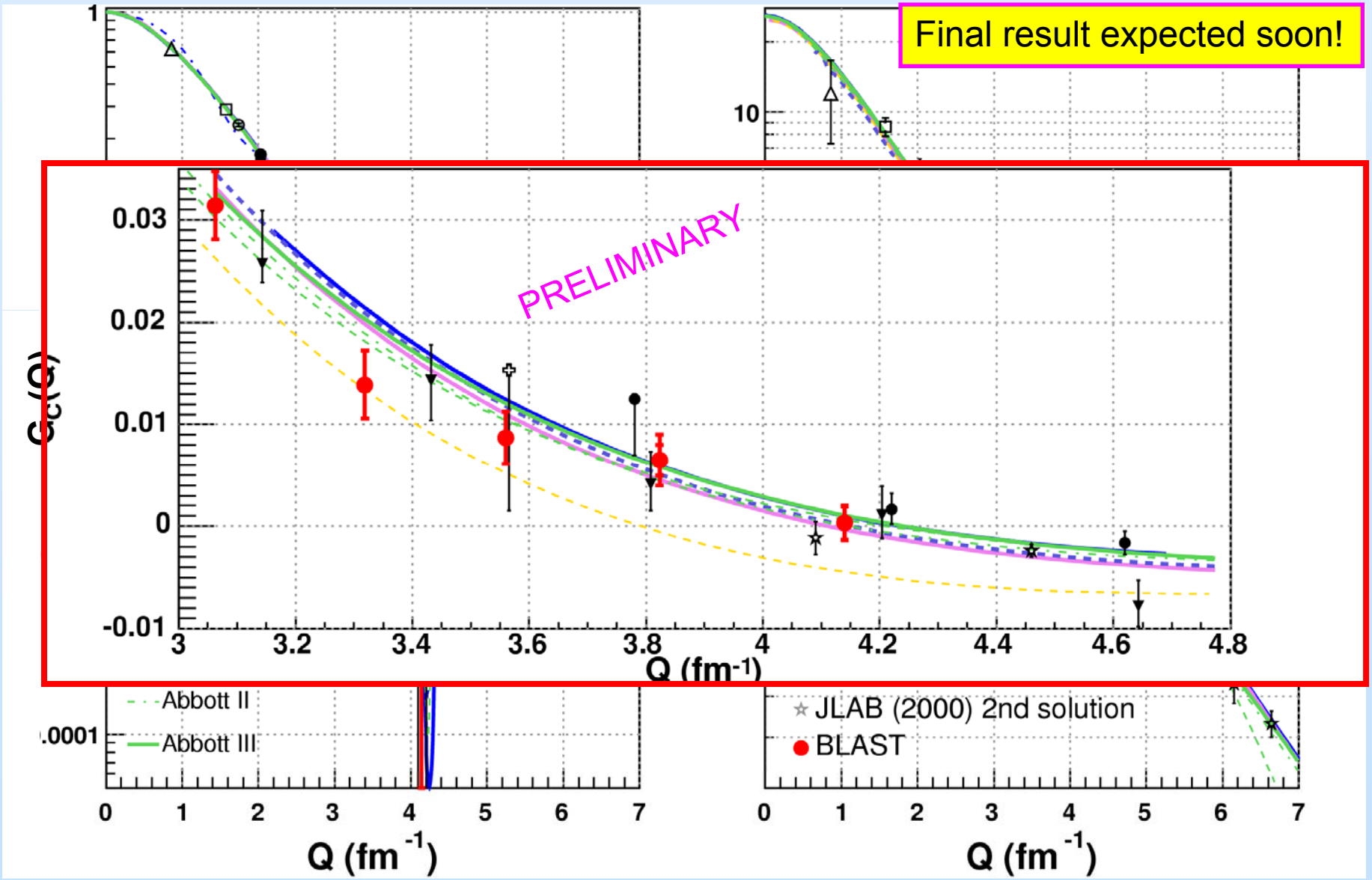


*Ph.D. work of C. Zhang (MIT)

A and B


World Data
Buchanan (1965)
Benaksas (1966)
Elias, CEA (1969)
Galster, DESY (1971)
Arnold, SLAC (1975)
Akimov, (1979)
Simon et al., MAINZ (1981)
Cramer et al., Bonn (1985)
Platchkov et al., Saclay (1990)
JLab Hall C (1999)
JLab Hall A (1999)
Theory
Arenhovel
Schiavilla MEC
van Orden
Phillips,Wallace,Devine
Phillips χPT NNLO
Abbott I
Abbott II
Abbott III
A(Q)
Q (fm^{-1})
dA/A$_{fit}$
World Data
Buchanan (1965)
Benaksas Orsay (1966)
Rand (1967)
Ganichot Orsay (1972)
Simon et al., MAINZ (1981)
Auffret Saclay (1985)
Cramer et al., Bonn (1985)
Bosted et al., SLAC (1990)
Theory
Arenhovel
Schiavilla MEC
van Orden
Phillips,Wallace,Devine
Phillips χPT NNLO
Abbott I
Abbott II
Abbott III
B(Q)
Q (fm^{-1})
dB/B$_{fit}$

G_C and G_Q*



*Ph.D. work of C. Zhang (MIT)

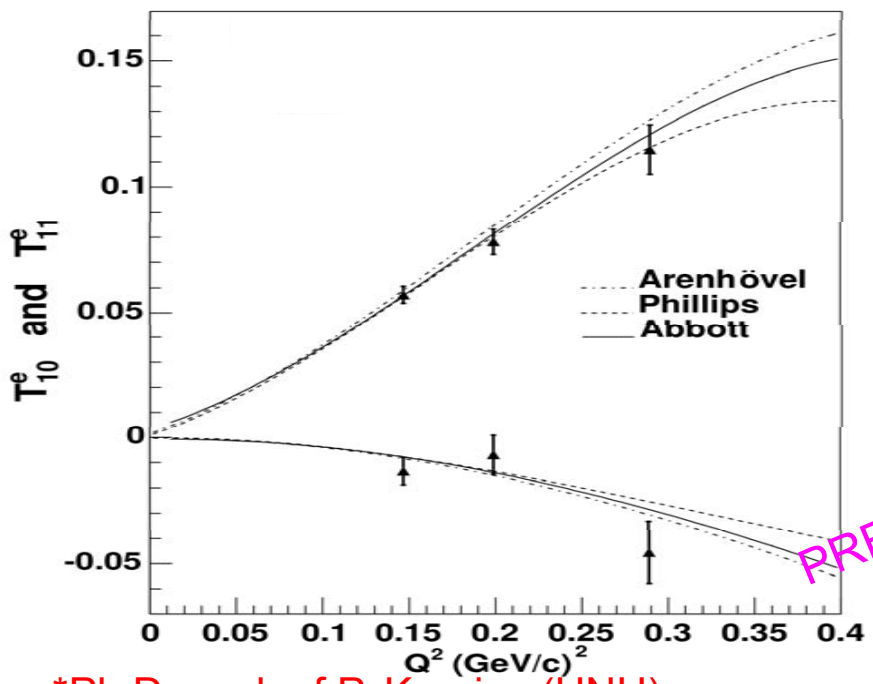
Vector-pol. Elastic ed Scattering

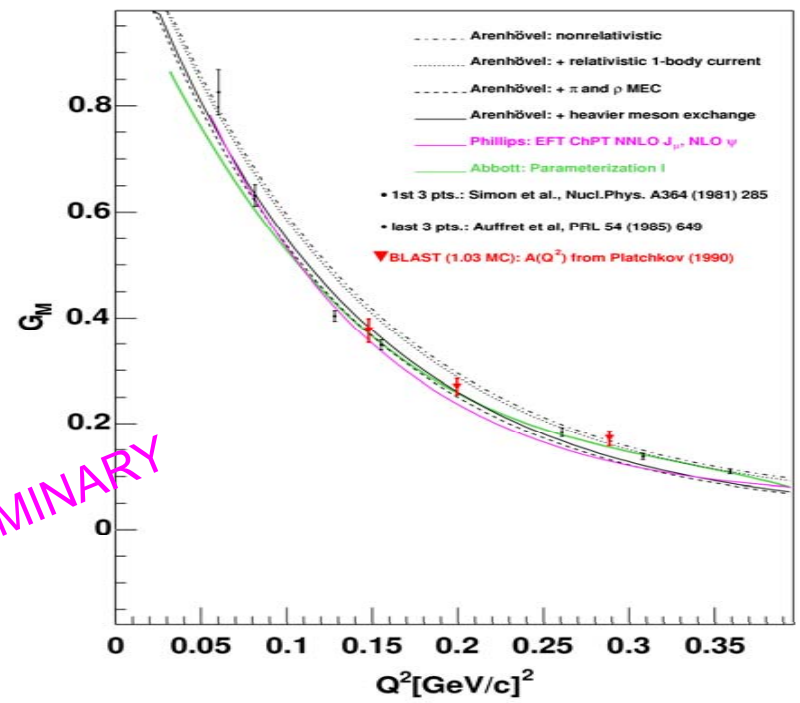
$$A_{ed}^{V} = \sqrt{3}\left(\frac{1}{\sqrt{2}}\cos\theta_d\, T_{10}^{e} - \sin\theta_d \cos\phi_d\, T_{11}^{e}\right)$$

Final result expected soon!

$$T_{10}^{e}(Q^2,\theta_e) = -\frac{\sqrt{2}}{\sqrt{3}S_0}\eta\sqrt{(1+\eta)\left(1+\eta\sin^2\frac{\theta_e}{2}\right)}\sec\frac{\theta_e}{2}\tan\frac{\theta_e}{2}\, {G_M^d}^2$$

$$T_{11}^{e}(Q^2,\theta_e) = \frac{2}{\sqrt{3}S_0}\sqrt{\eta(1+\eta)}\tan\frac{\theta_e}{2}\, G_M^d\left(G_C^d + \frac{1}{3}\eta G_Q^d\right)$$



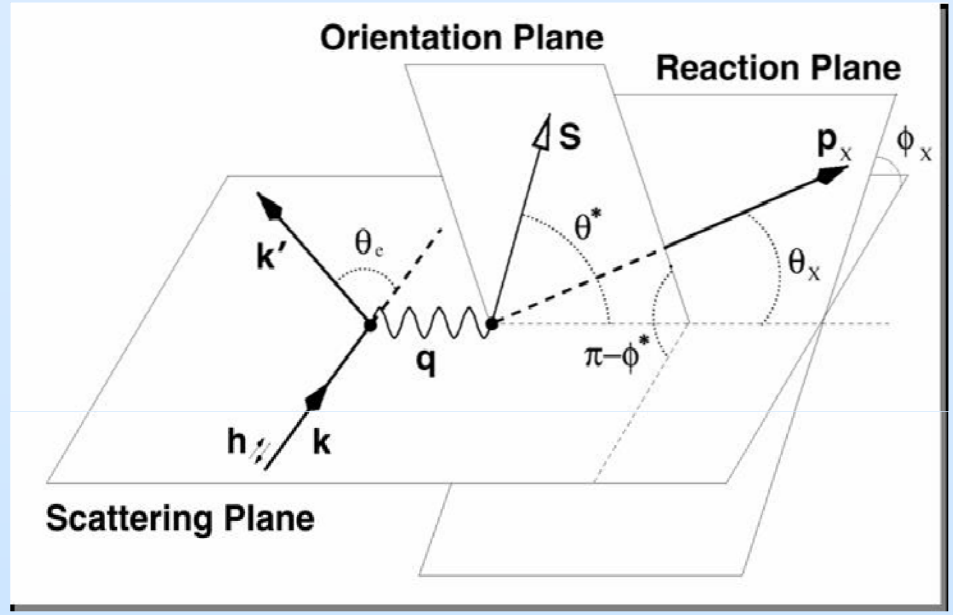


PRELIMINARY

*Ph.D. work of P. Karpius (UNH)

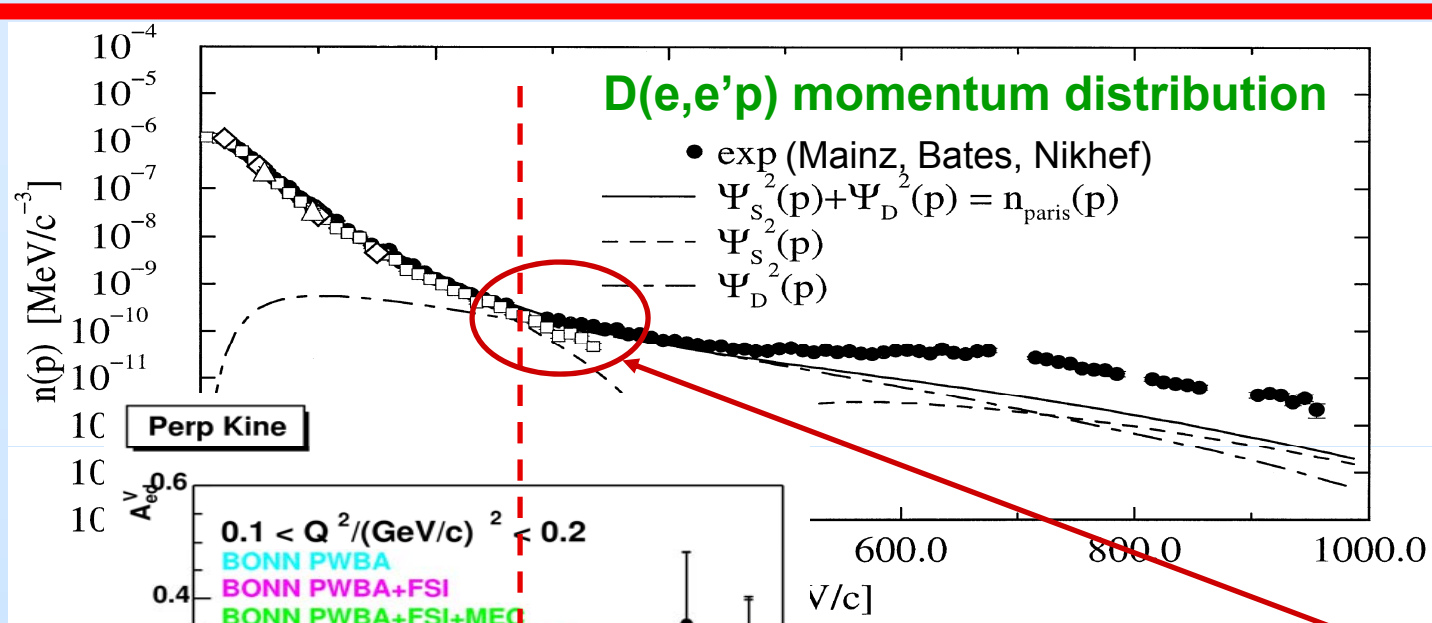
Deuteron Electrodisintegration

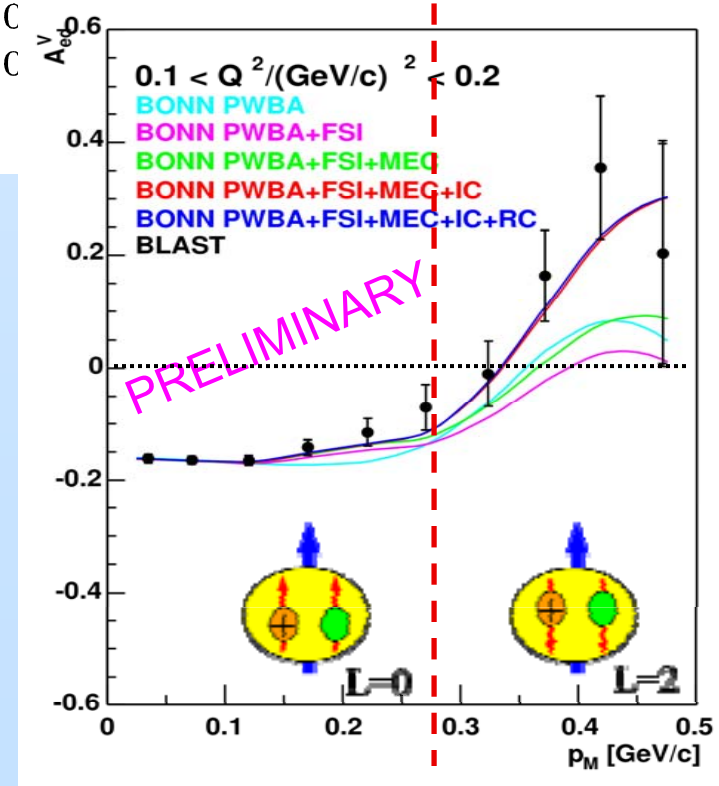
- **Quasielastic breakup**
  e + d → e' + p + n
- **D(e,e'p), PWIA:**
  $\vec{p}_m = \vec{q} - \vec{p}_p = -\vec{p}_{p,I}$
- $$\frac{\sigma}{\sigma_0} = (1 + P_{zz} A_d^T + h P_z A_{ed}^V)$$



- **Beam-vector asymmetry (PWIA):**
  $$A_{ed}^V(p,n) = \frac{a\cos\theta^* + b\left(G_E^{p,n}/G_M^{p,n}\right)\sin\theta^*\cos\phi^*}{1 + c\left(G_E^{p,n}/G_M^{p,n}\right)^2}$$
- **Nucleon spins parallel →** $A_{ed}^V\,(p_{miss})$ **changes sign**

Deuteron Electrodisintegration *





- D-wave dominant at p_m>300 MeV/c
- FSI,MEC,IC subtle effects in cross section < 450 MeV/c

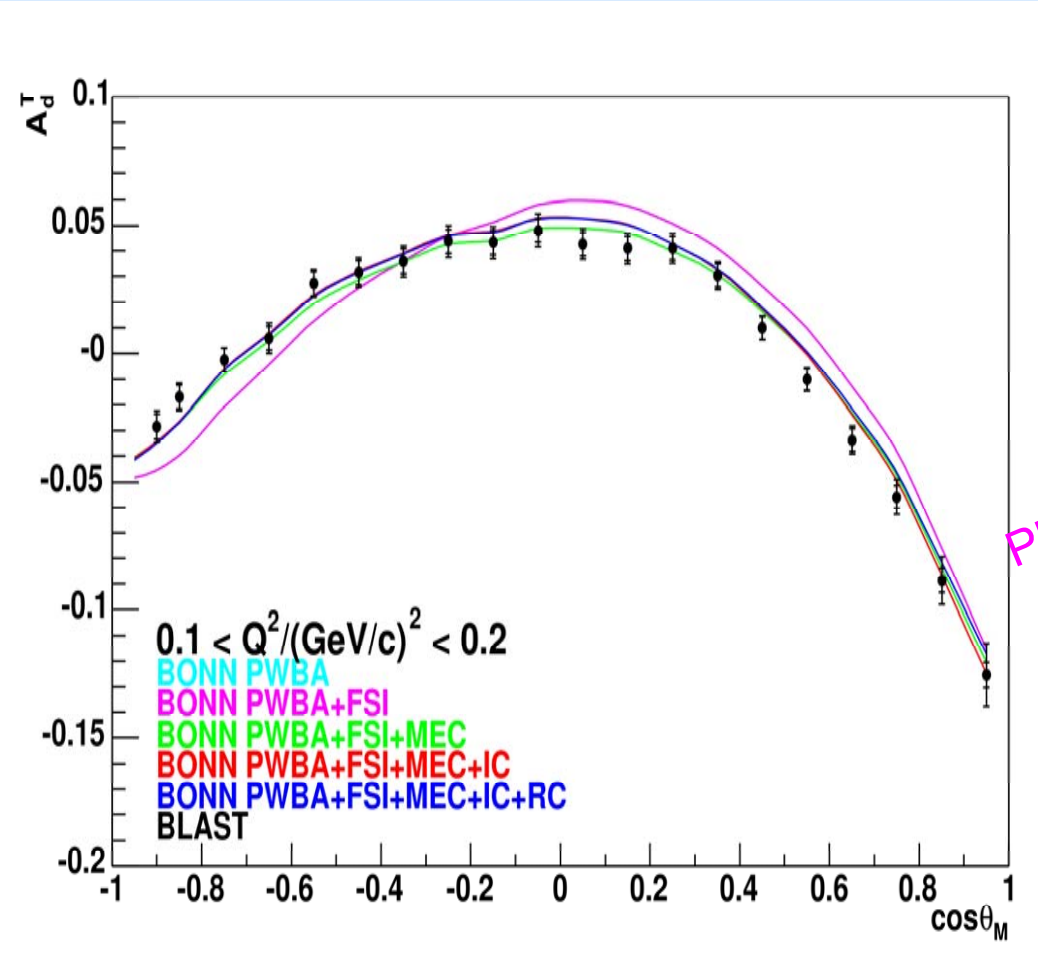
$\vec{D}(\vec{e},e'p)$ beam-vector asymmetry

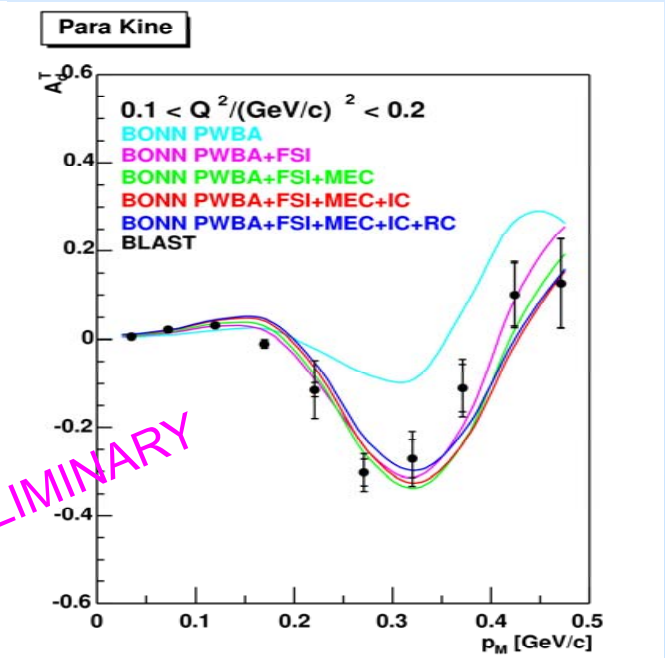
Observing expected sign change!

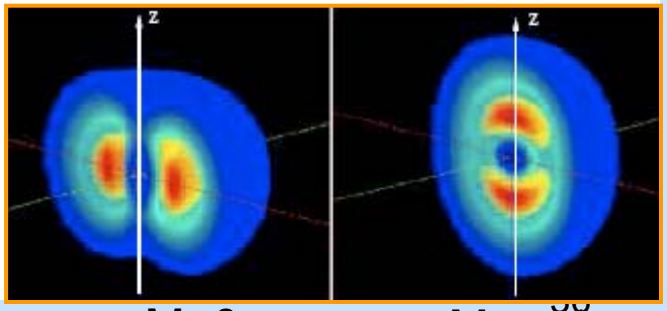
*Ph.D. work of A. Maschinot and A. DeGrush (MIT)

Quasielastic Tensor Asymmetry *

$$A_d^T = \frac{\frac{1}{2}(\rho^+ + \rho^-) - \rho^0}{\rho^+ + \rho^- + \rho^0} = \frac{C_2}{C_0} P_2(\cos\theta) = \frac{R_2(p)\left(\sqrt{2}R_0(p) - \frac{1}{2}R_2(p)\right)}{R_0(p)^2 + R_2(p)^2}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$







M=0 M=±1

*Ph.D. work of A. Maschinot and A. DeGrush (MIT)

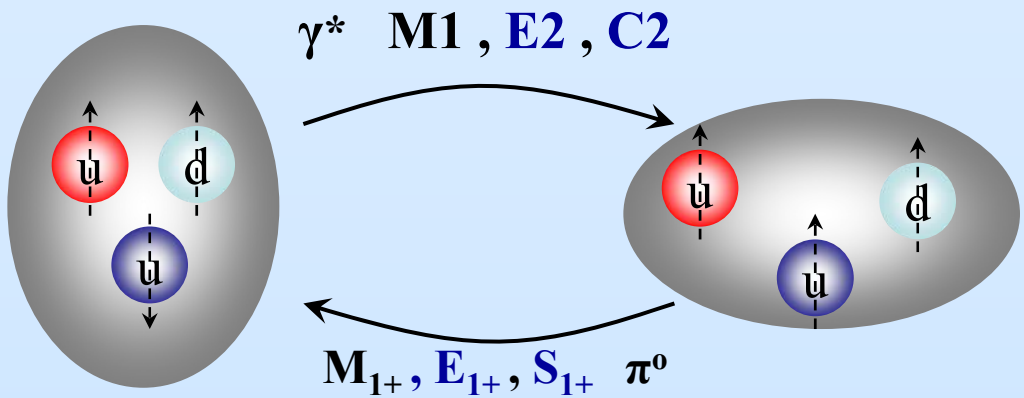
Pion Production from H & D

N-Δ transition and deformation

p(qqq)

$I = \frac{1}{2} \quad J = \frac{1}{2}$

938 MeV



Δ(qqq)

$I = \frac{3}{2} \quad J = \frac{3}{2}$

1232 MeV

Spherical $\Rightarrow$ M1

Deformed $\Rightarrow$ M1 , E2 , C2

Role of pion cloud

Deformation signal

$$\mathrm{CMR} = \mathrm{Re}\left(\frac{S_{1+}^{3/2}}{M_{1+}^{3/2}}\right)$$

$$\mathrm{EMR} = \mathrm{Re}\left(\frac{E_{1+}^{3/2}}{M_{1+}^{3/2}}\right)$$

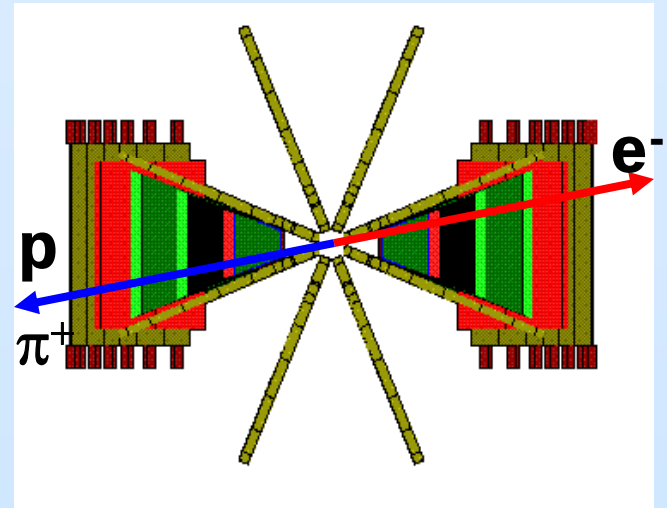
$\vec{H}(\vec{e},e')\Delta^+$, $\vec{H}(\vec{e},e'\pi^+)n$, $\vec{H}(\vec{e},e'p)\pi^0$

$$\Delta^+ \rightarrow p + \pi^0$$
$$\Delta^+ \rightarrow n + \pi^+$$

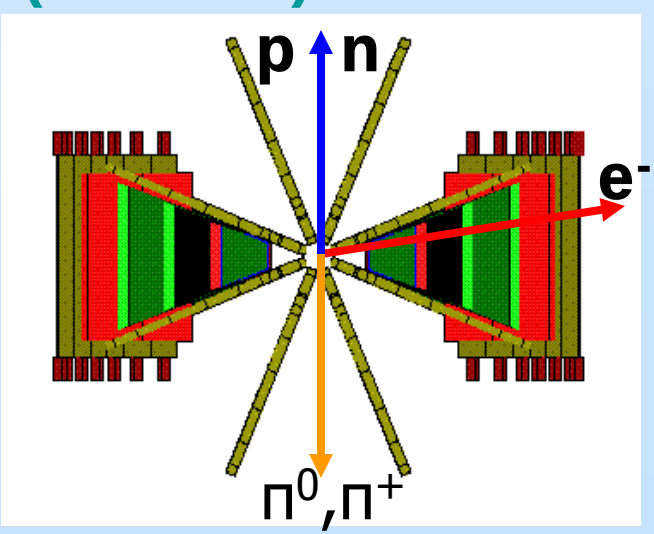
•**Trigger 1: (Charged)**

$\vec{p}(\vec{e},e'p)\,\pi^0$

$\vec{p}(\vec{e},e'\pi^+)n$

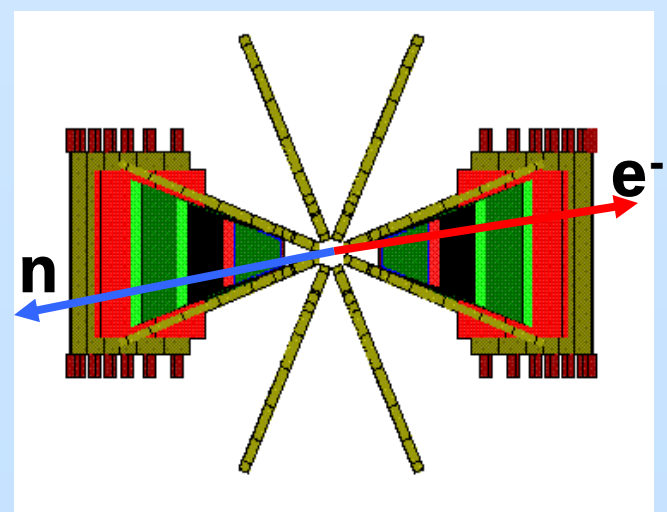


•**Trigger 7: (Inclusive)** $\vec{p}(\vec{e},e')$



•**Trigger 2: (Neutral)**

$\vec{p}(\vec{e},e'n)\pi^+$



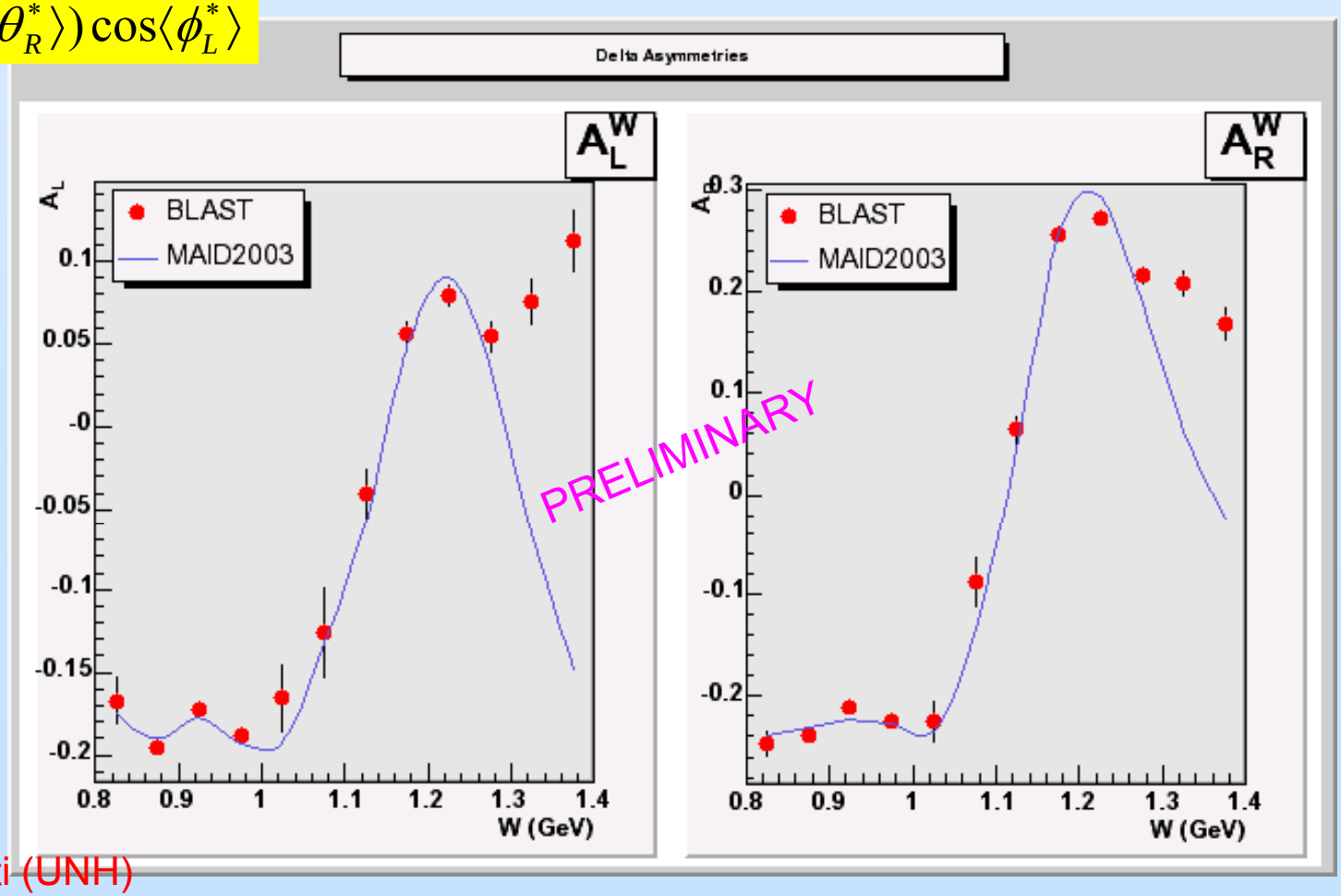
$\vec{H}(\vec{e},e')\Delta^+$ inclusive*

$$A_{TT'} = \frac{A_L \sin\langle\theta_R^*\rangle + A_R \sin\langle\theta_L^*\rangle}{\sin(\langle\theta_L^*\rangle + \langle\theta_R^*\rangle)}$$

$$A_{TL'} = \frac{A_L \cos\langle\theta_R^*\rangle - A_R \sin\langle\theta_L^*\rangle}{\sin(\langle\theta_L^*\rangle + \langle\theta_R^*\rangle)\cos\langle\phi_L^*\rangle}$$

$$A = \frac{A_{meas}}{h \cdot P_Z} = A_{TT'} \cos\theta^* + A_{TL'} \sin\theta^* \cos\phi^*$$

500k ev. / 299 kC
+ 3.7M elastic



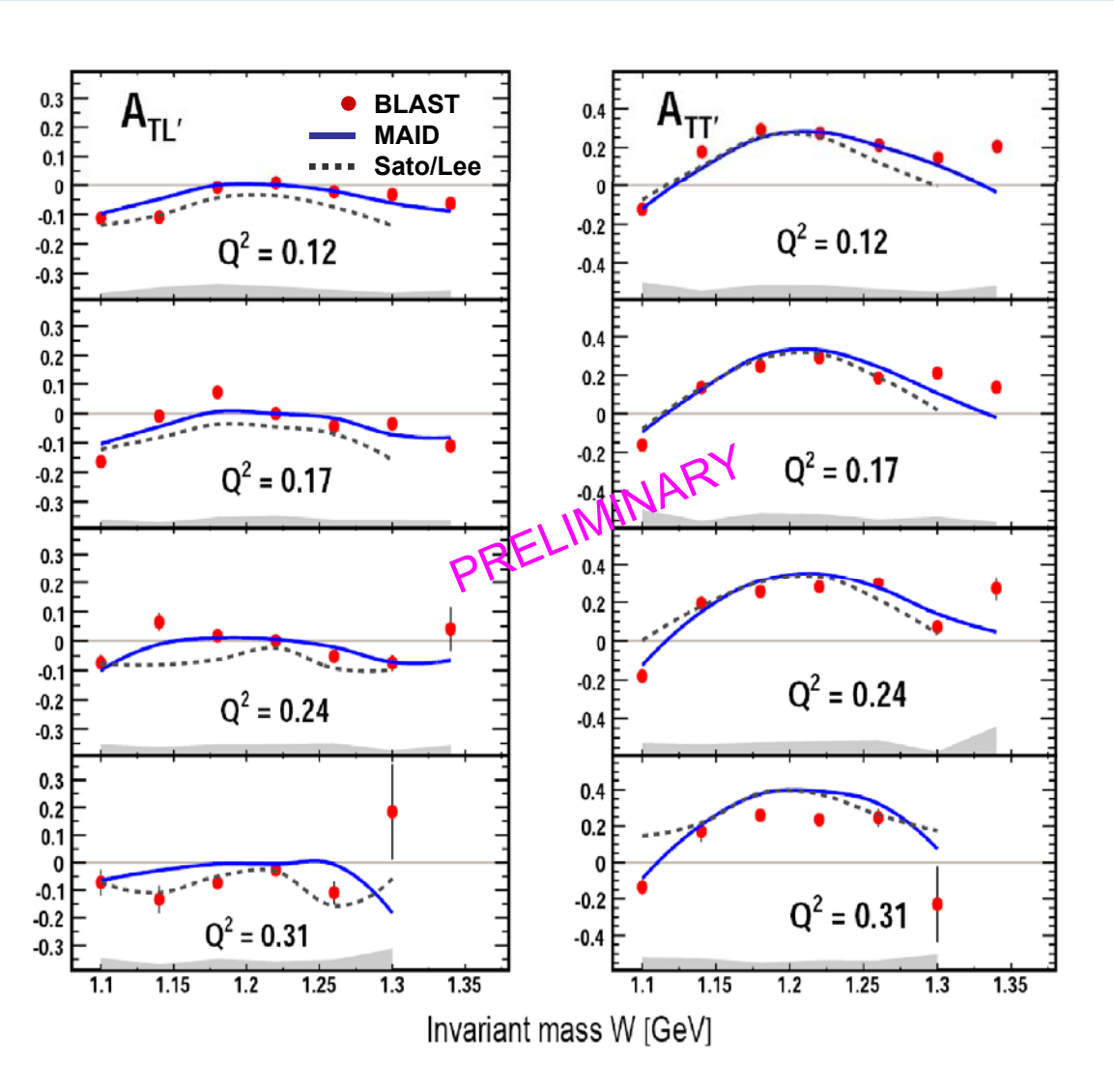
*Ph.D. work of O. Filoti (UNH)

$\vec{H}(\vec{e},e')\Delta^+$ inclusive*

$$A_{TT'} = \frac{A_L \sin\langle\theta_R^*\rangle + A_R \sin\langle\theta_L^*\rangle}{\sin(\langle\theta_L^*\rangle + \langle\theta_R^*\rangle)}$$

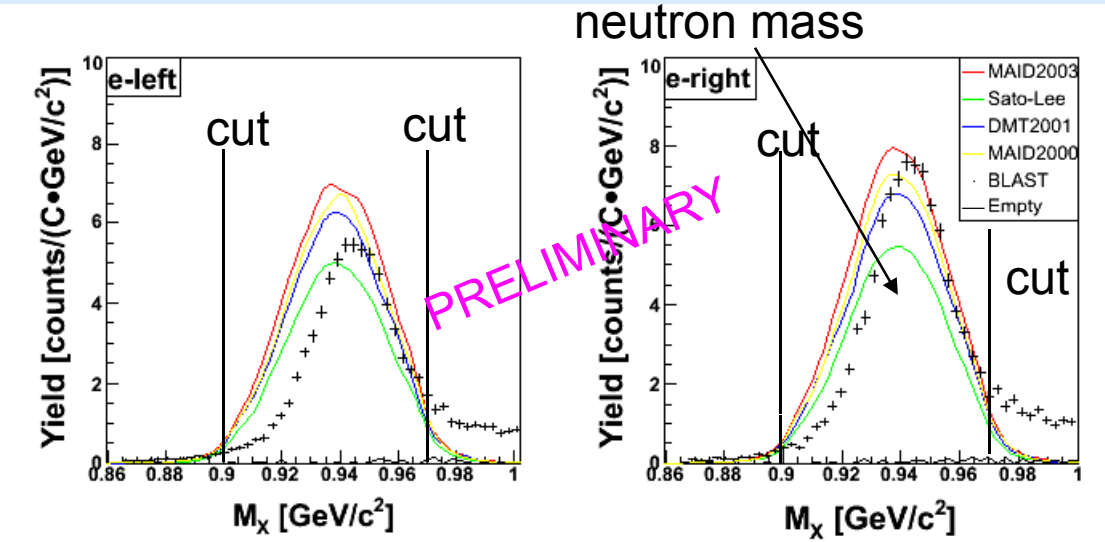
$$A_{TL'} = \frac{A_L \cos\langle\theta_R^*\rangle - A_R \sin\langle\theta_L^*\rangle}{\sin(\langle\theta_L^*\rangle + \langle\theta_R^*\rangle)\cos\langle\phi_L^*\rangle}$$

500k ev. / 299 kC
+ 3.7M elastic



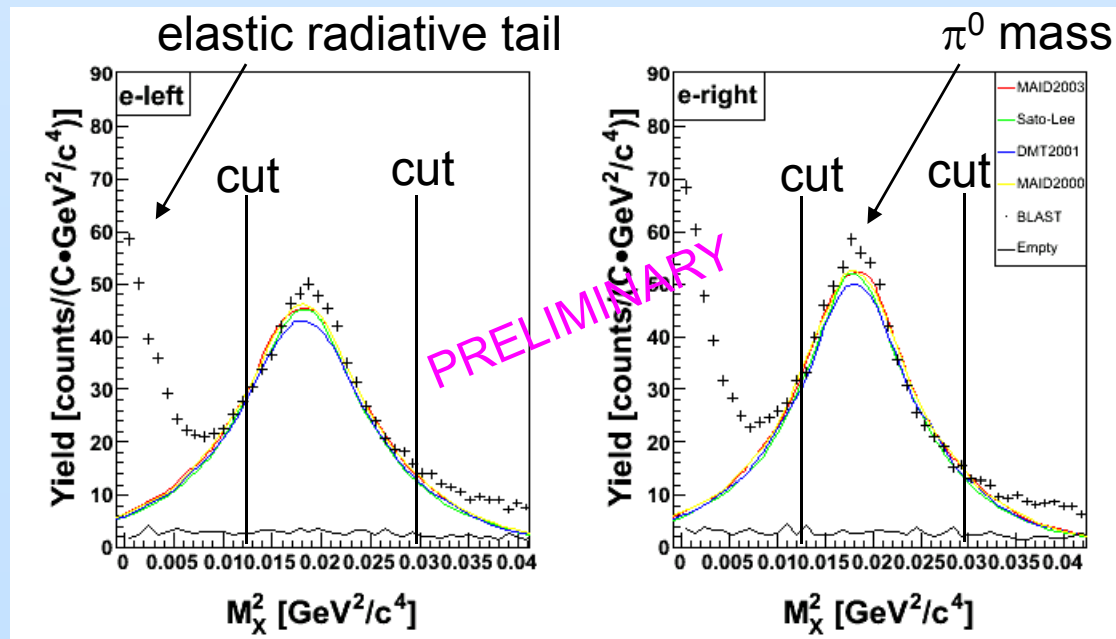
*Ph.D. work of O. Filoti (UNH)

$\vec{H}(\vec{e},e'\pi^+)n$ and $\vec{H}(\vec{e},e'p)\pi^0$ exclusive *



π^+ channel

- 40k ev. / 299 kC

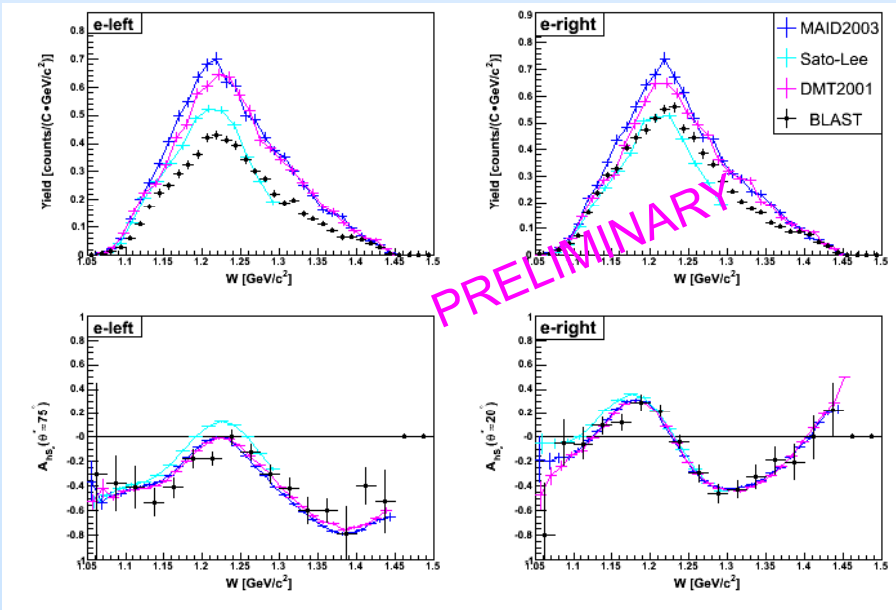


π^0 channel

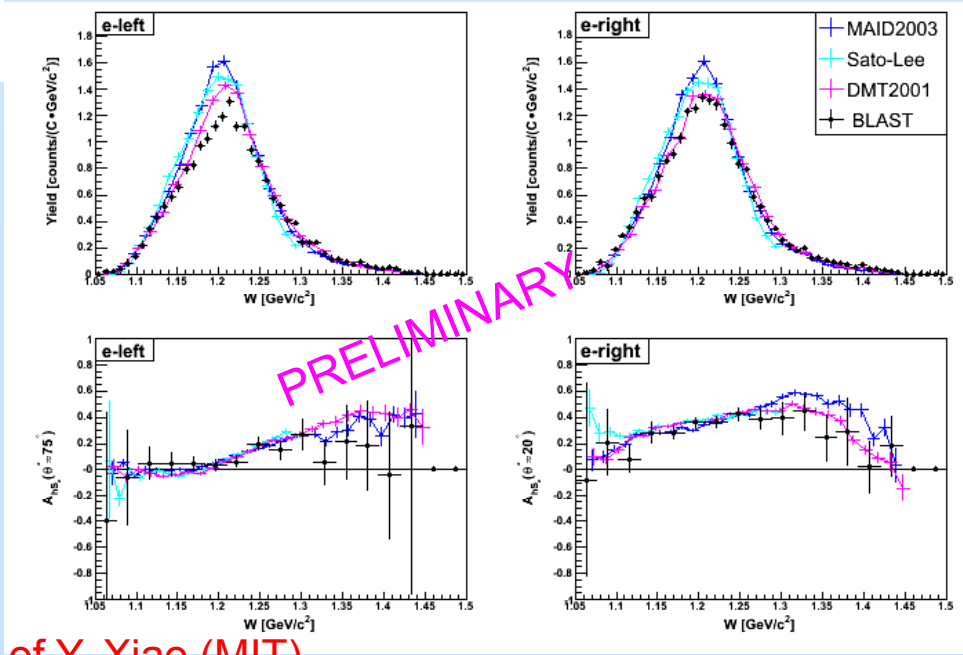
- 101k ev. / 299 kC

*Analysis by A. Shinozaki (MIT);
Ph.D. work of Y. Xiao (MIT)

$\vec{H}(\vec{e},e'\pi^+)n$ and $\vec{H}(\vec{e},e'p)\pi^0$ exclusive *



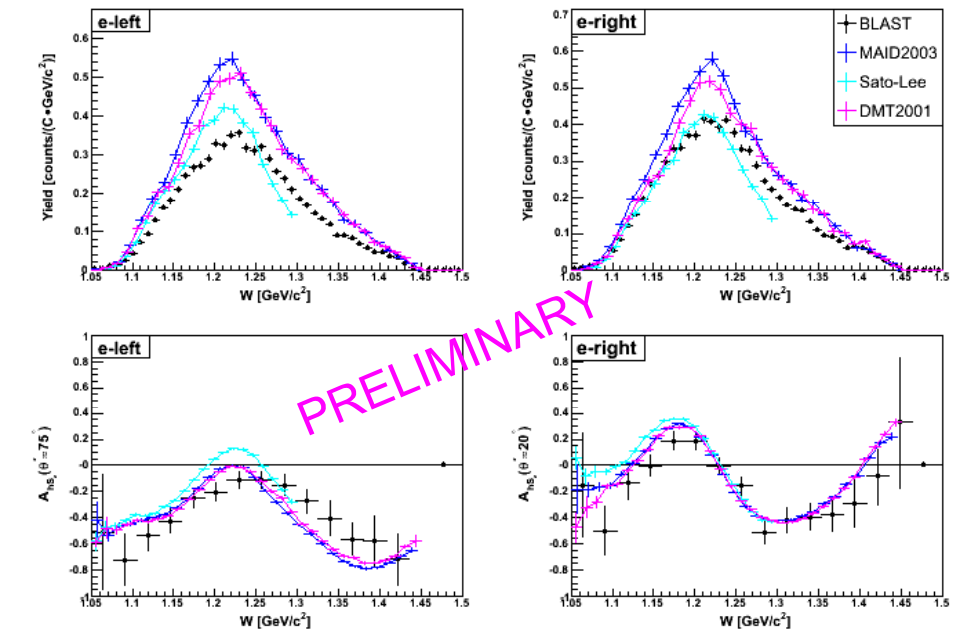
π^+ channel



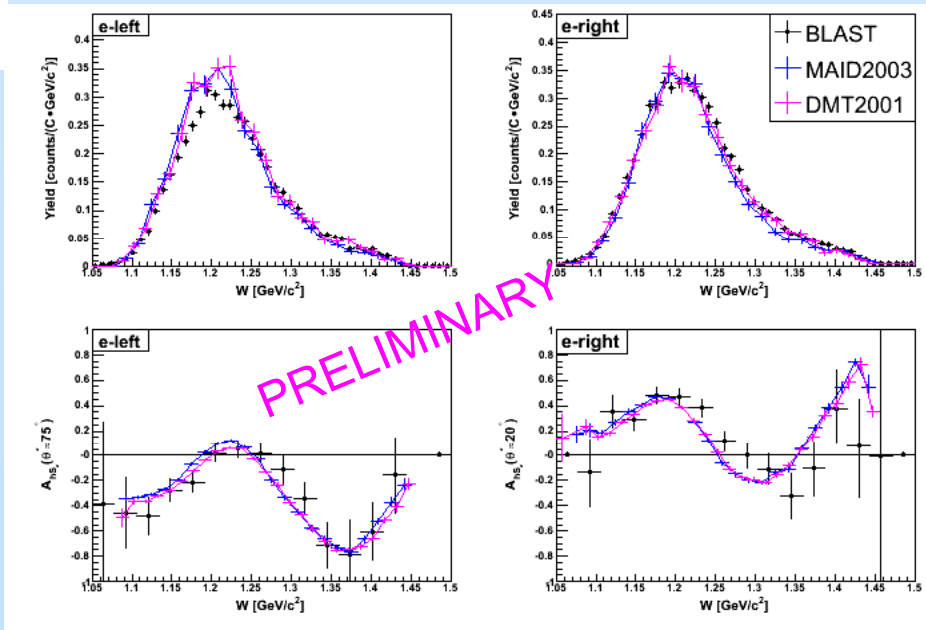
π^0 channel

*Analysis by A. Shinozaki (MIT); Ph.D. work of Y. Xiao (MIT)

$\vec{D}(\vec{e},e'\pi^{\pm})$nn,pp Double Asymmetries*



D(e,e'π^+) channel
Models: π^+ from free p

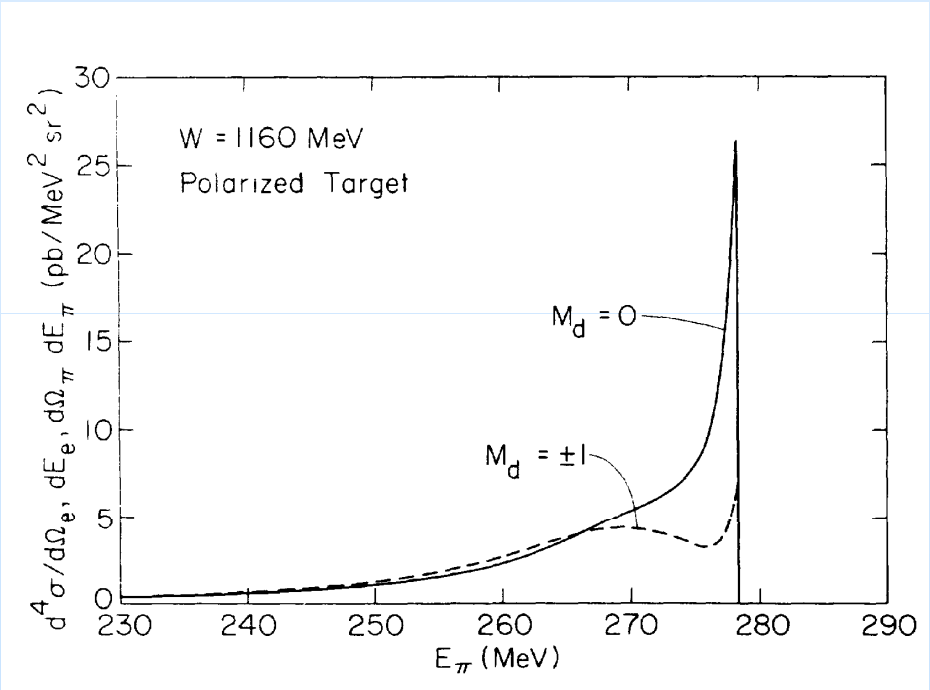


D(e,e'π^-) channel
Models: π^- from free n

*Analysis by A. Shinozaki (MIT)

Pion Electroproduction from Deuterium

R.J. Loucks, V.R. Pandharipande, R. Schiavilla, PRC49 (1994) 342

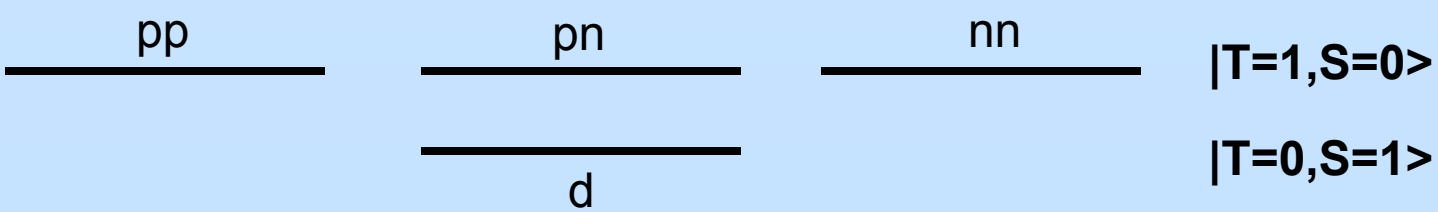


Strong FSI effect to explain quenching of ~80% in ratio of $d(e,e'\pi^+)nn$ / $p(e,e'\pi^+)n$ observed at Saclay

R. Gilman et al., PRL64 (1989) 622

Large tensor asymmetry (<0) predicted for scattering into quasibound singlet 2N state

Two-nucleon term scheme:

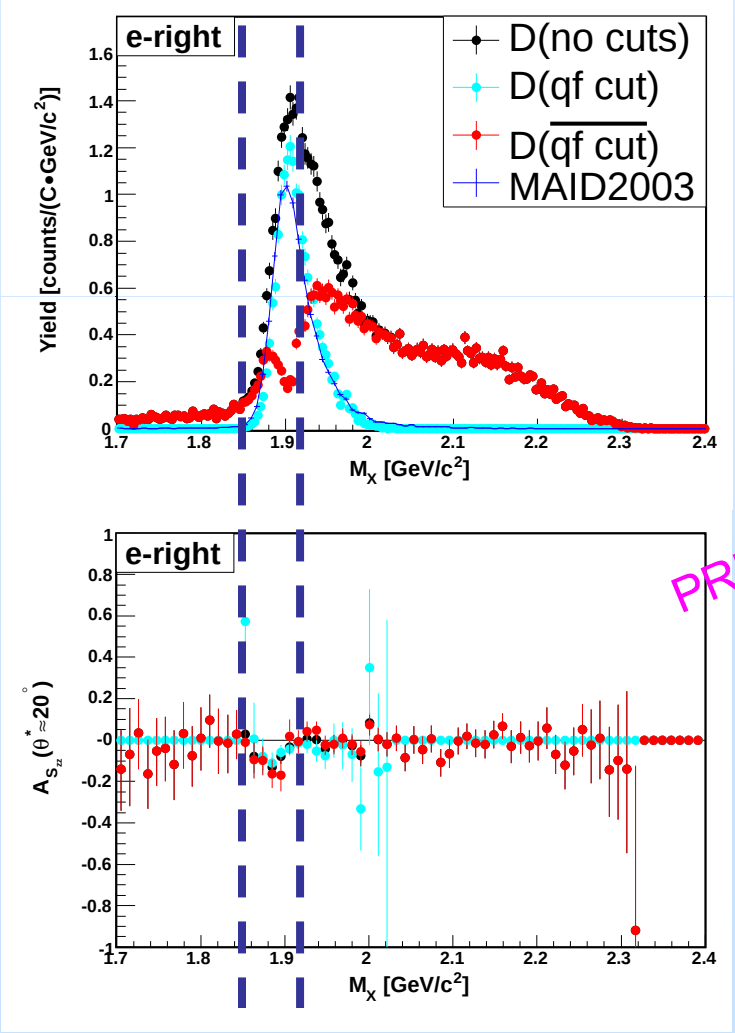


|T=1,S=0>

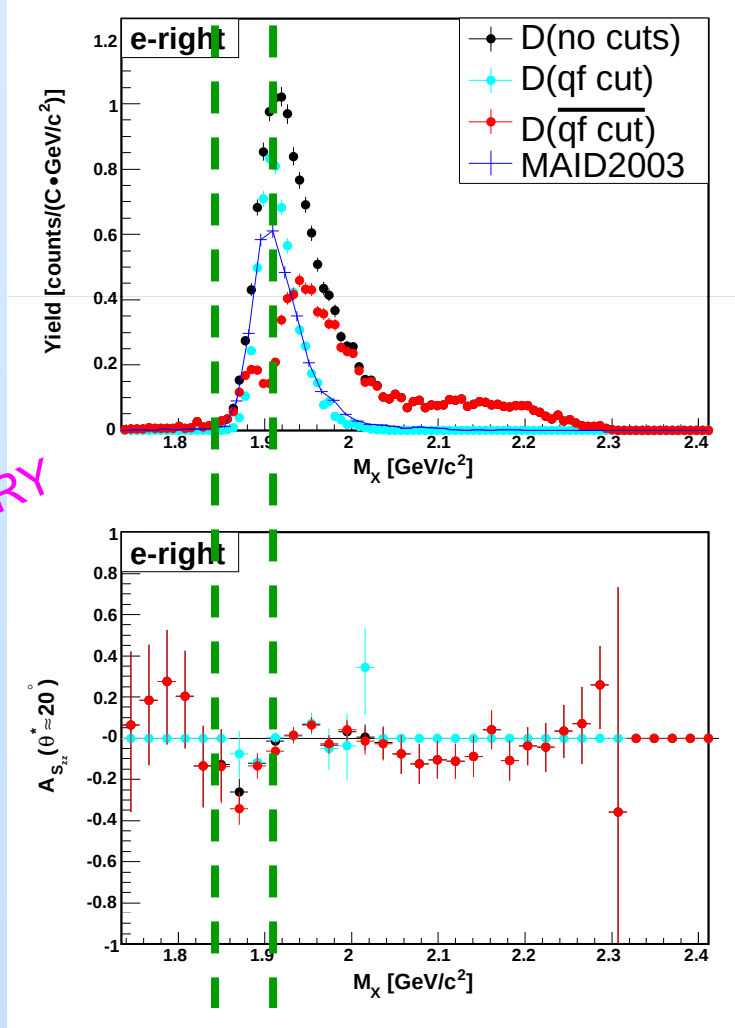
|T=0,S=1>

D(e,e'$\pi^{\pm}$)nn,pp Tensor Asymmetries*

d(e,e'π^{+})nn



d(e,e'π^{-})pp

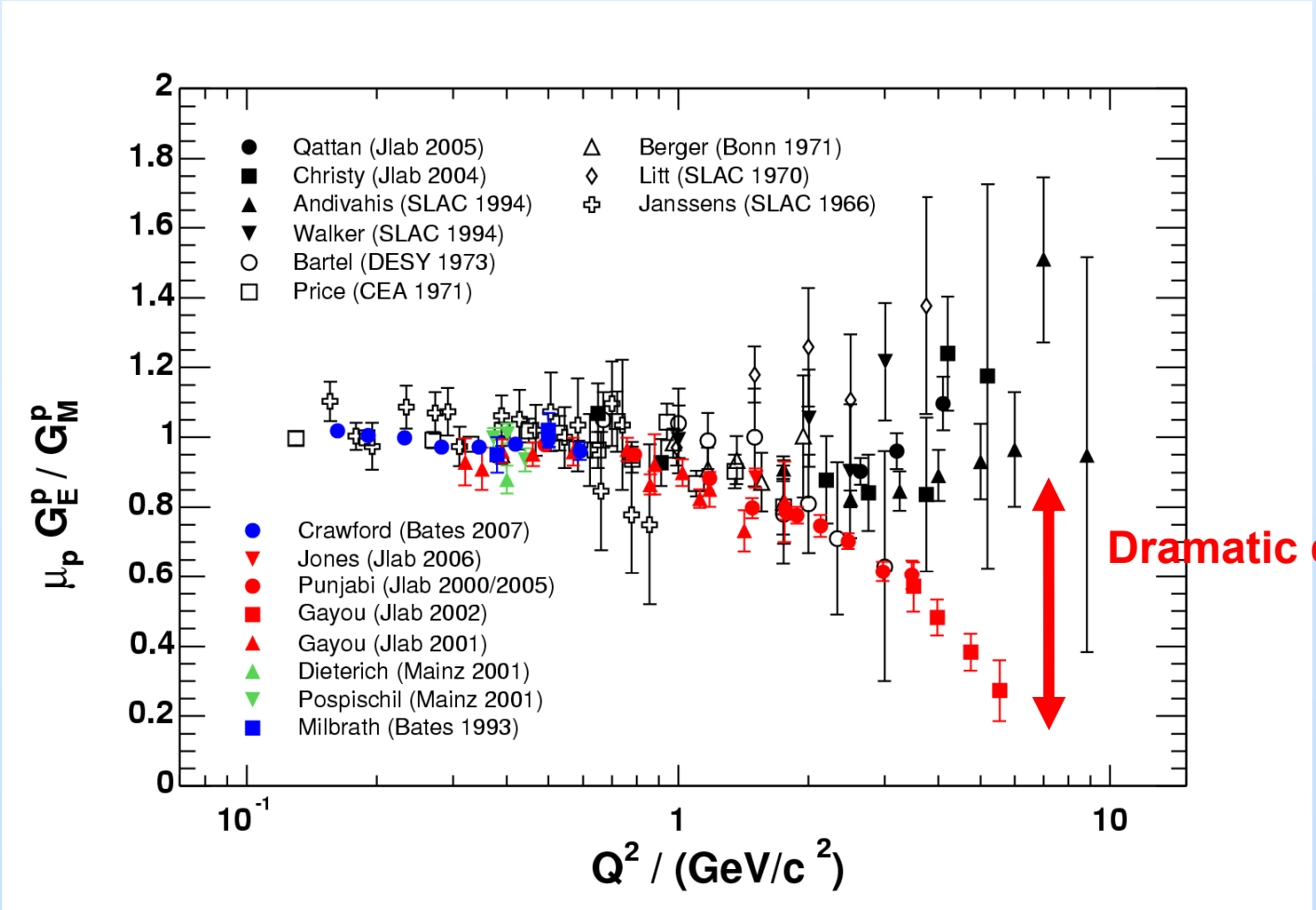


PRELIMINARY

*Analysis by A. Shinozaki (MIT)

Future of BLAST: OLYMPUS

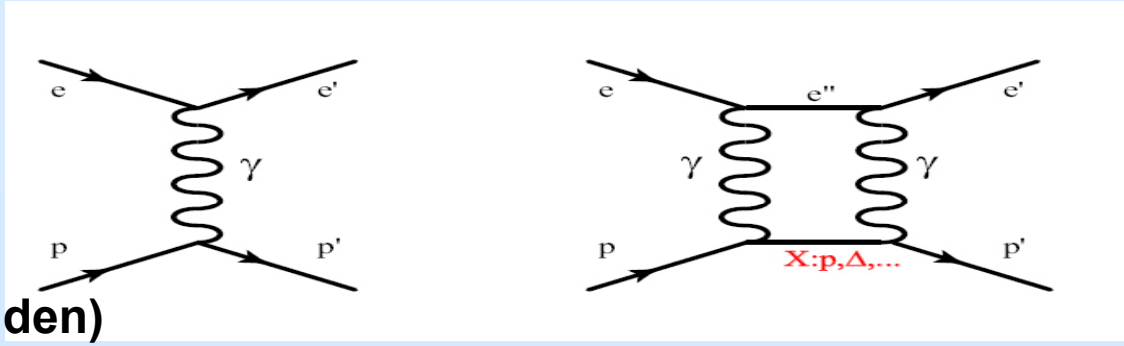
Proton Form Factor Ratio



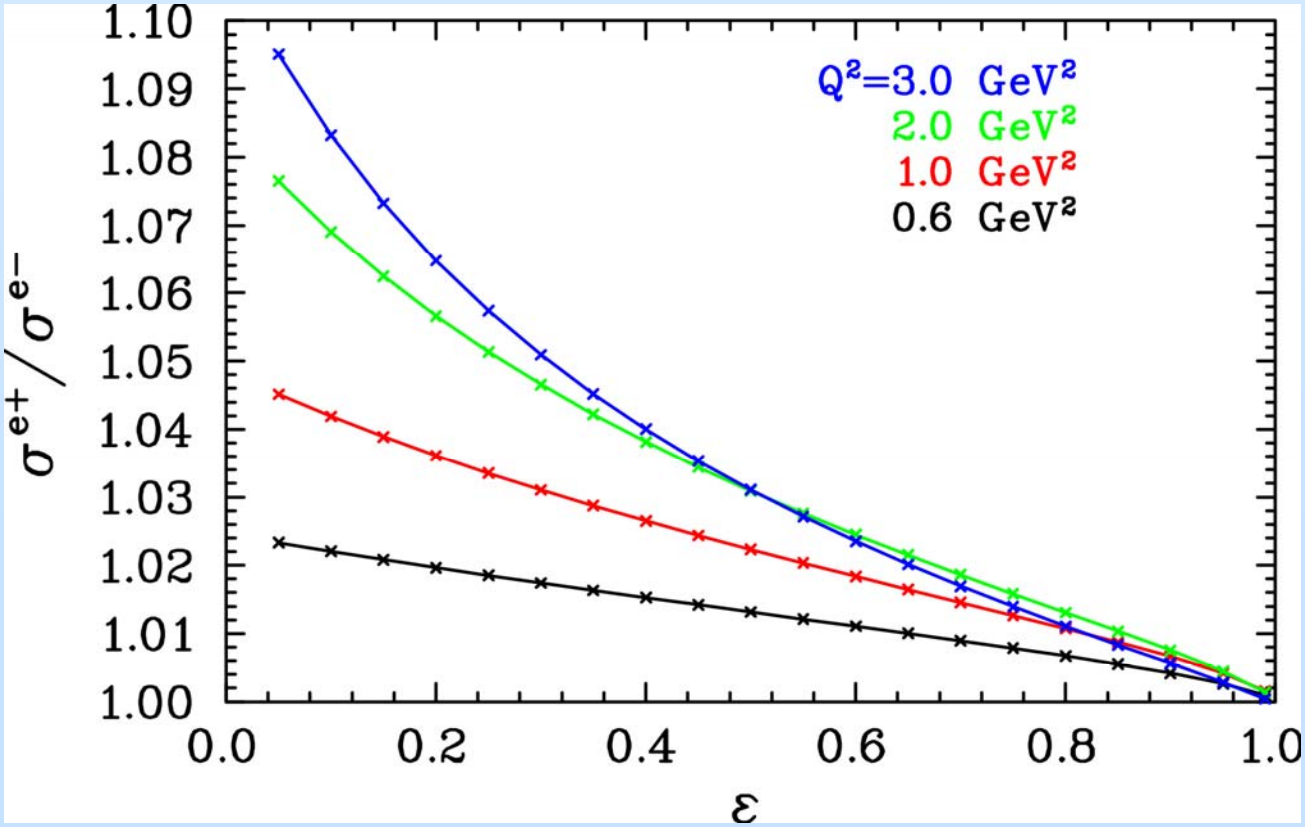
Jefferson Lab

- **All Rosenbluth data from SLAC and Jlab in agreement**
- **Dramatic discrepancy between Rosenbluth and recoil polarization technique**
- **Multi-photon exchange considered best candidate**

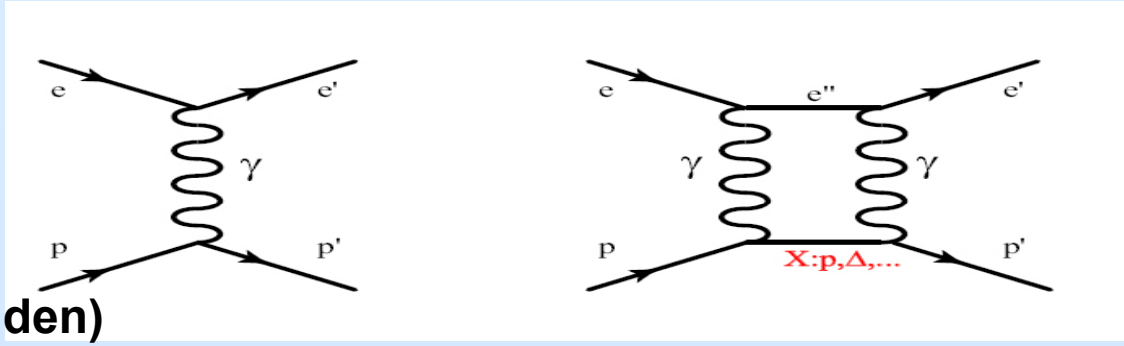
Two-photon exchange



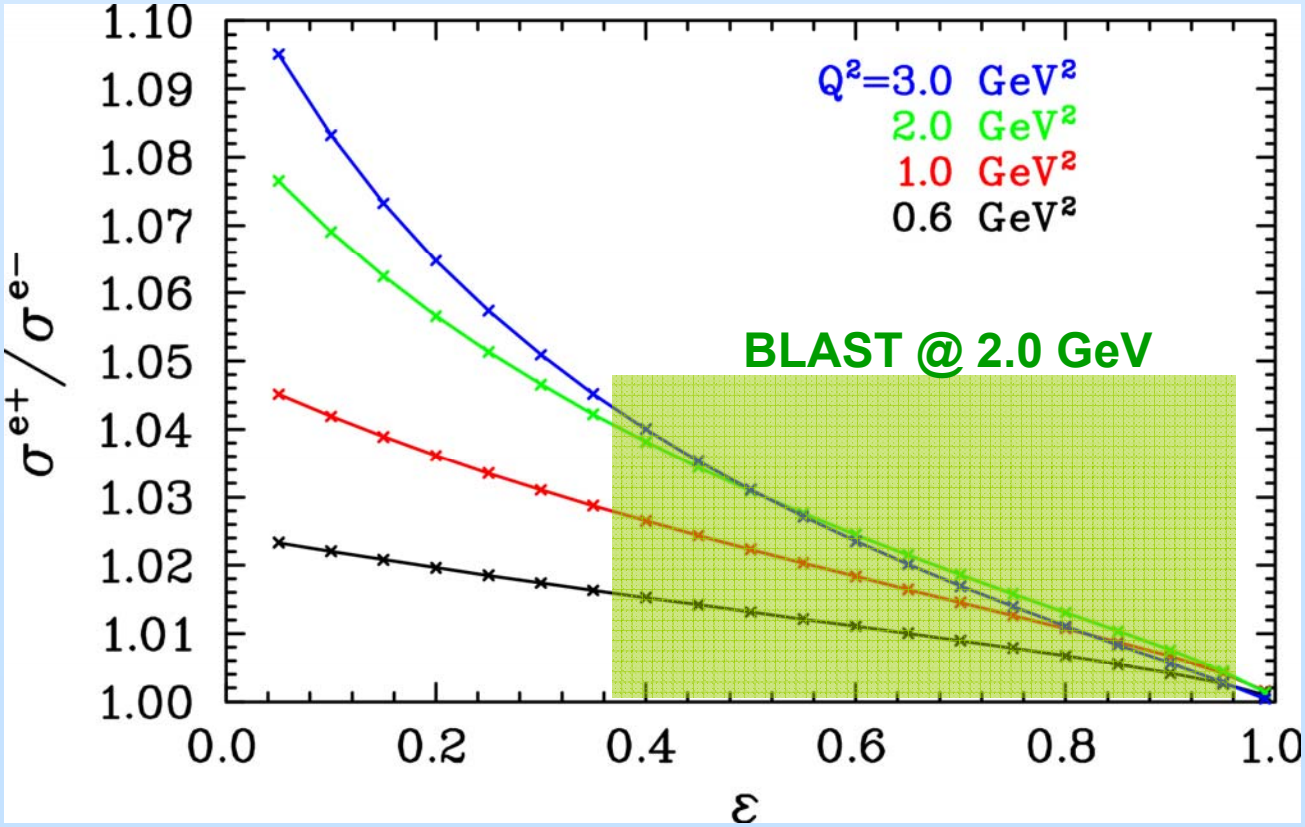
Elastic electron-proton to positron-proton ratio (P. Blunden)



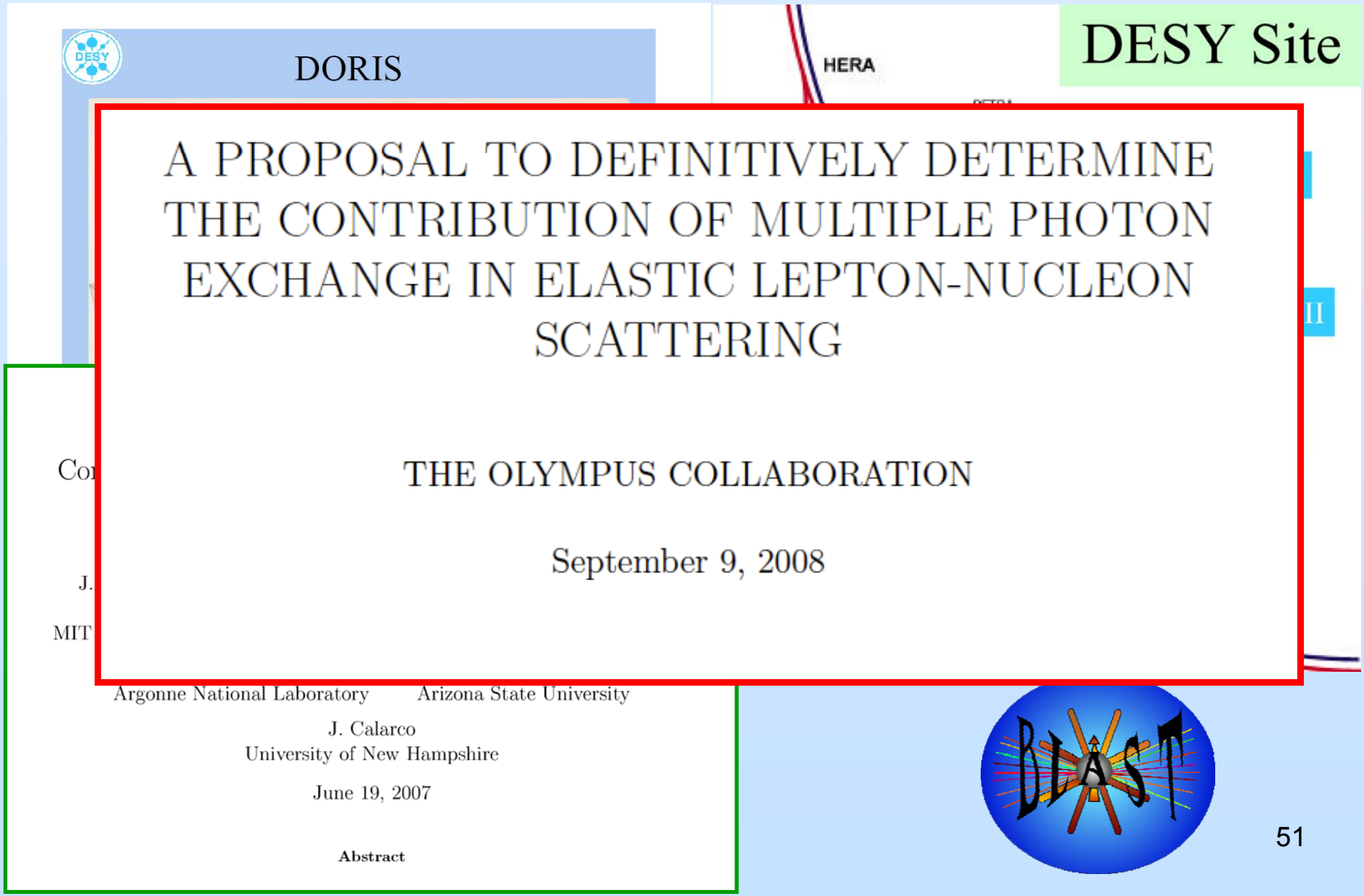
Two-photon exchange



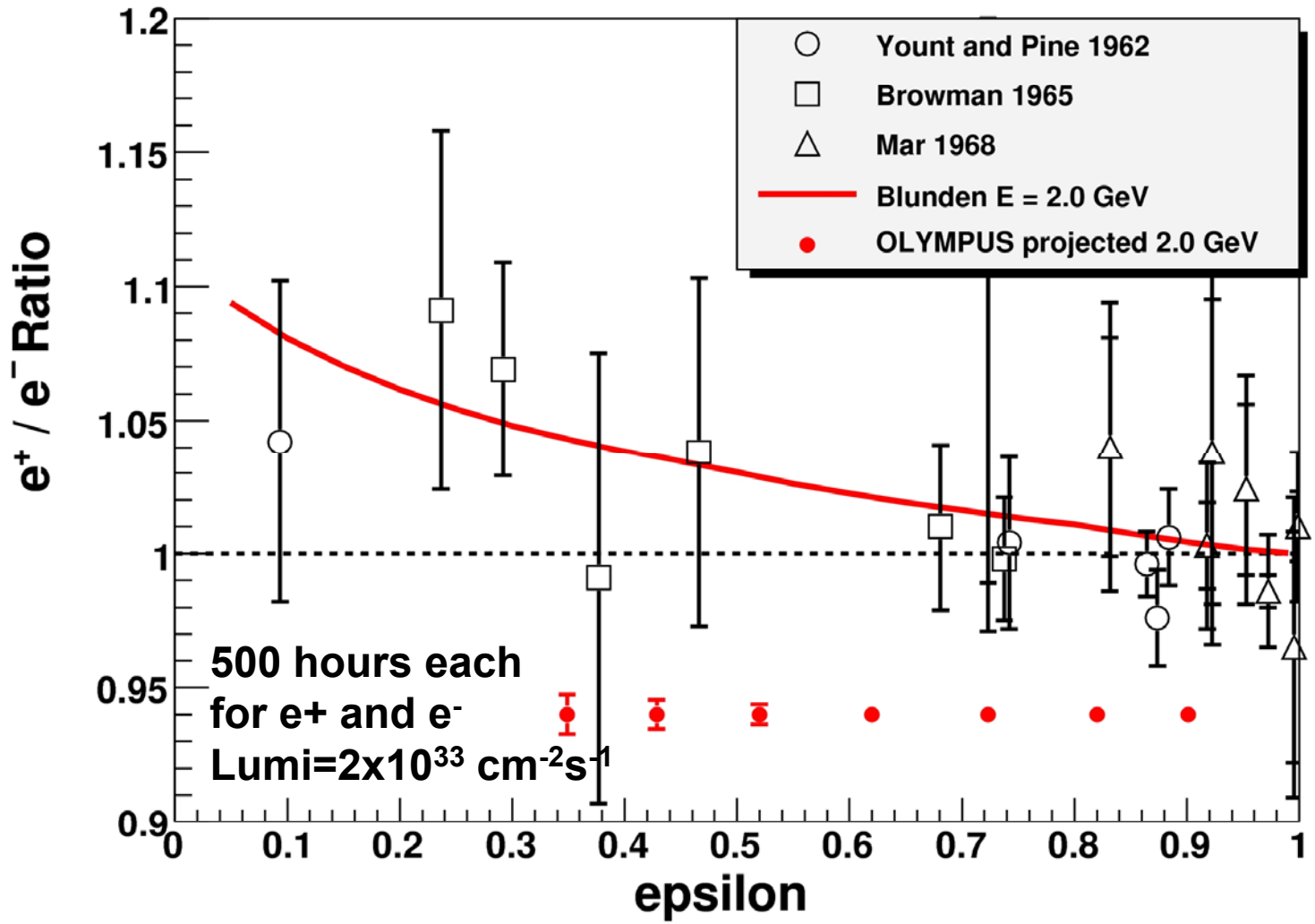
Elastic electron-proton to positron-proton ratio (P. Blunden)



Two-photon exchange



Projected Results for OLYMPUS



OLYMPUS

pO**sitron-proton and**

eL**ectron-proton elastic scattering to test the**

hY**pothesis of**

Multi-

Photon exchange

Using

DoriS

2008 – Full proposal
2009/10 – Transfer of BLAST
2011/12 – OLYMPUS Running

Summary

- **Proton, neutron**, and **deuteron** spin observables with **BLAST**
- High precision, excellent control of systematics
- **Nucleon structure:**
  - Consistent and precise determination of elastic **nucleon form factors** at low momentum transfer
- **Deuteron structure:**
  - Precision measurement of T_{20} allows to separate G^d_C and G^d_Q
  - First measurement of T_{11} allows to determine G^d_M at low Q^2
  - Electrodisintegration probing D-state
- **Pion production** from **H** and **D**
  - N-Δ single and double spin asymmetries
  - Double and tensor asymmetries from deuterium
- **OLYMPUS @ DESY:** Precise determination of two-photon exchange

Collaboration

- **BLAST A GREAT SUCCESS!!!**
- **First class single and double polarization data on H and D in elastic, quasielastic and Delta region**
- **Produced 9 Ph.D.'s, + 3 to come, and 3 Junior Faculty**

T. Akdogan[f], R. Alarcon[a], J. Althouse[c], H. Arenhövel[e], W. Bertozzi[f], E. Booth[b], T. Botto[f], H.J. Bulten[k], J. Calarco[i], B. Clasie[f], C. Crawford[l], C. D'Andrea[c], A. Degrush[f], K. Dow[f], D. Dutta[d], M. Farkhondeh[f], R. Fatemi[f], O. Filoti[j], W. Franklin[f], H. Gao[d], E. Geis[a], S. Gilad[f], A. Goodhue[c], W. Haeberli[l], D. Hasell[f], W. Hersman[i], M. Holtrop[i], E. Ilhoff[f], P. Karpius[j], J. Kelsey[f], M. Kohl[f], H. Kolster[f], S. Krause[f], T. Lee[i], A. Maschinot[f], J. Matthews[f], K. McIlhany[h], N. Meitanis[f], R. Milner[f], A. Mosser[h], J. Pavel[e], H.R. Poolman[k], R. Prince[a], J. Rapaport[g], R. Redwine[f], J. Seely[f], A. Shinozaki[f], A. Sindile[j], S. Širca[f], T. Smith[c], S. Sobczynski[f], B. Tonguc[a], C. Tschalaer[f], E. Tsentalovich[f], W. Turchinetz[f], J.F.J. van den Brand[k], J. van der Laan[f], T. Wise[i], Y. Xiao[f], W. Xu[d], C. Zhang[f], V. Ziskin[f], T. Zwart[f]

[a] *Arizona State University, Tempe, AZ 85287*
[b] *Boston University, Boston, MA 02215*
[c] *Dartmouth College, Hanover, NH 03755*
[d] *Duke University, Durham, NC 27708-0305*
[e] *Johannes Gutenberg-Universität, 55099 Mainz, Germany*
[f] *Massachusetts Institute of Technology, Cambridge, MA 02139 and Bates Linear Accelerator Center, Middleton, MA 01949*
[g] *Ohio University, Athens, OH 45701*
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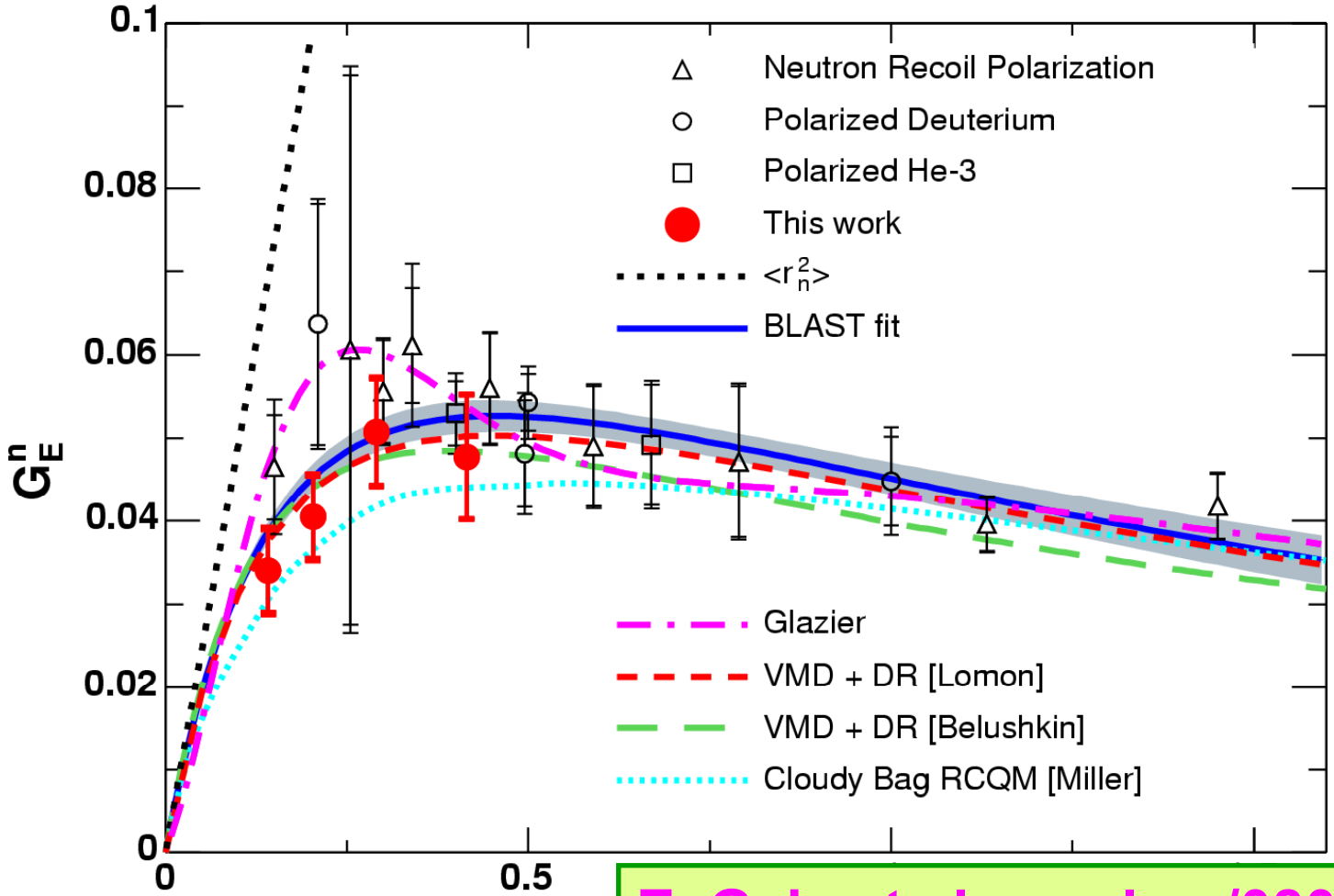
[i] *University of New Hampshire, Durham, NH 03824*
[j] *University of Wisconsin, Madison, WI 53706*
[k] *Vrije Universiteit and NIKHEF, Amsterdam, The Netherlands*

BACKUP slides

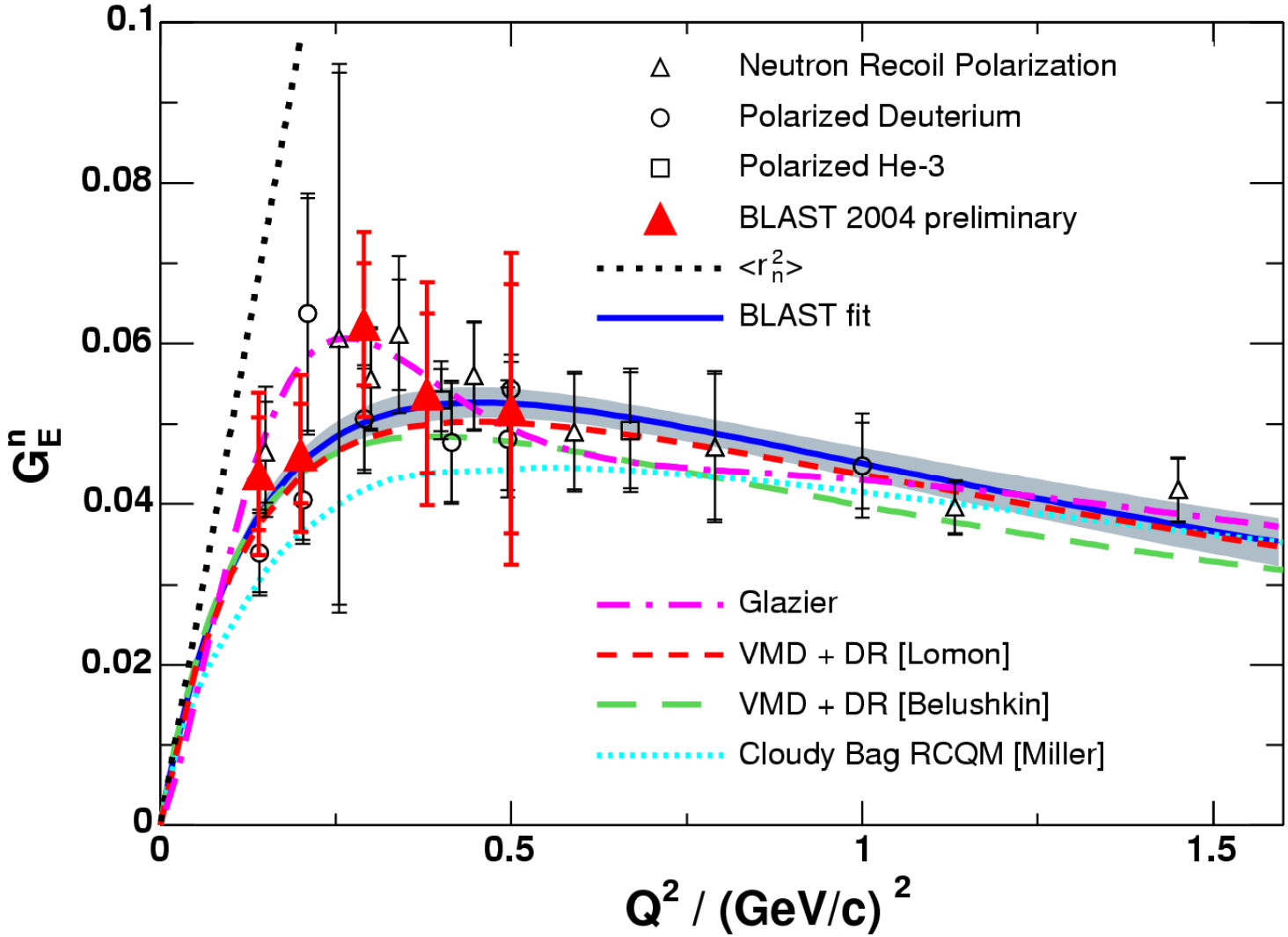
Neutron Electric Form Factor G^n_E*



E. Geis et al., nucl-ex/0803.3872v2
Submitted to Phys. Rev. Lett.

*Ph.D. work of V. Ziskin (MIT) and E.

Neutron Electric Form Factor G^n_E*



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

Pion Production Asymmetries

1. Dilution factors are determined from elastic analysis and the compton polarimeter

$$A_{S_z}^{\text{exp.}} = P_e A_h, \; A_{S_z}^{\text{exp.}} = P_p A_{Sz}, \; A_{hS_z}^{\text{exp.}} = P_e P_p A_{hS_z}, \; P_e \approx 68\%, \; P_p \approx 81\%$$

2. Single Asymmetry, A_h.

$$A_h = \frac{1}{P_e}\frac{R_+ - R_-}{R_+ + R_-}, \quad R_h = \frac{Y_h}{Q_h}$$

3. Single Asymmetry, $A_{Sz.}$

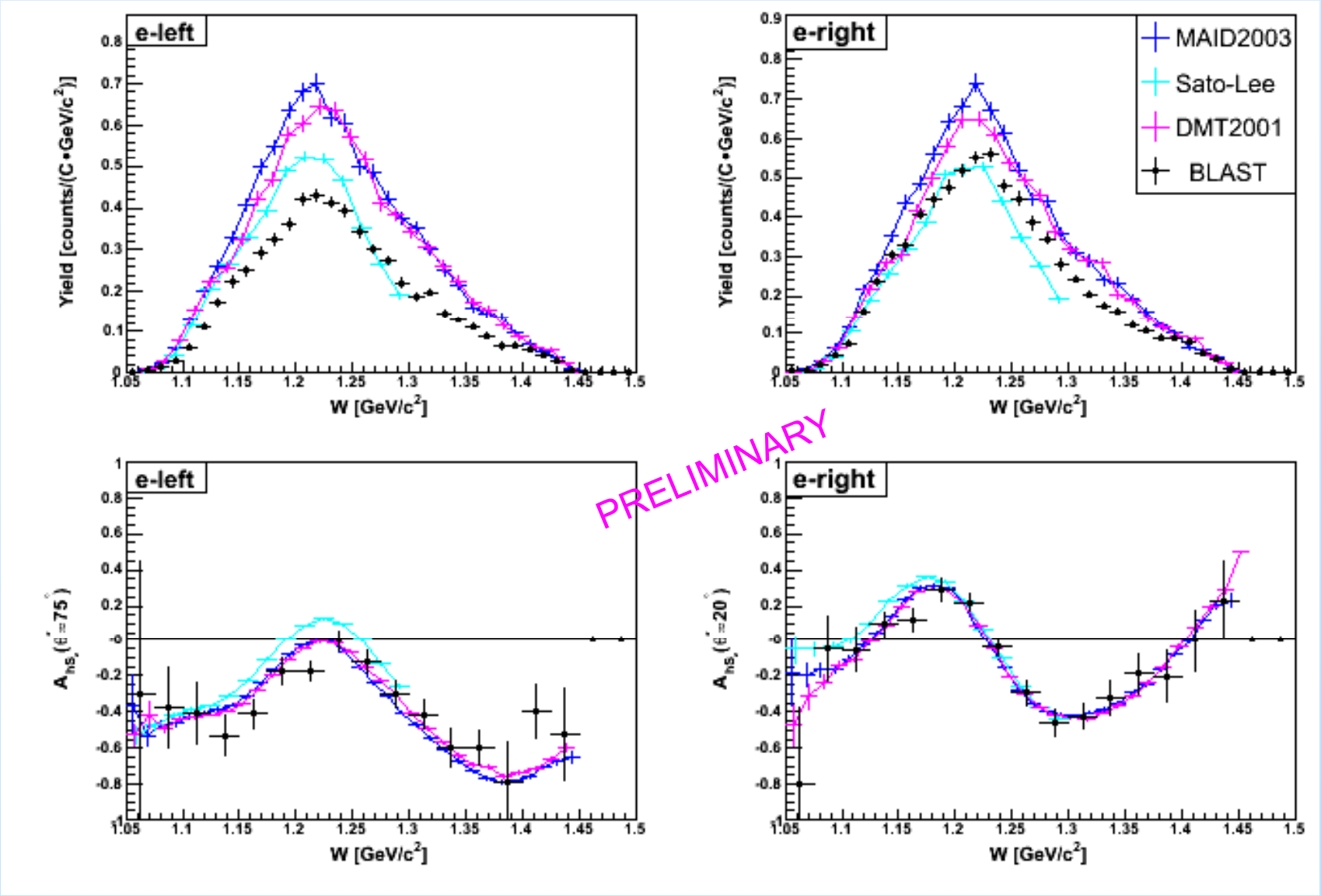
$$A_{S_z} = \frac{1}{P_p}\frac{R_+ - R_-}{R_+ + R_-}, \quad R_{S_z} = \frac{Y_{S_z}}{Q_{S_z}}$$

4. Double Asymmetry, A_{hSz}

$$A_{hS_z} = \frac{1}{P_e P_p}\frac{(R_{++} + R_{--}) - (R_{+-} + R_{-+})}{(R_{++} + R_{--}) + (R_{+-} + R_{-+})}, \quad R_{hS_z} = \frac{Y_{hS_z}}{Q_{hS_z}}$$

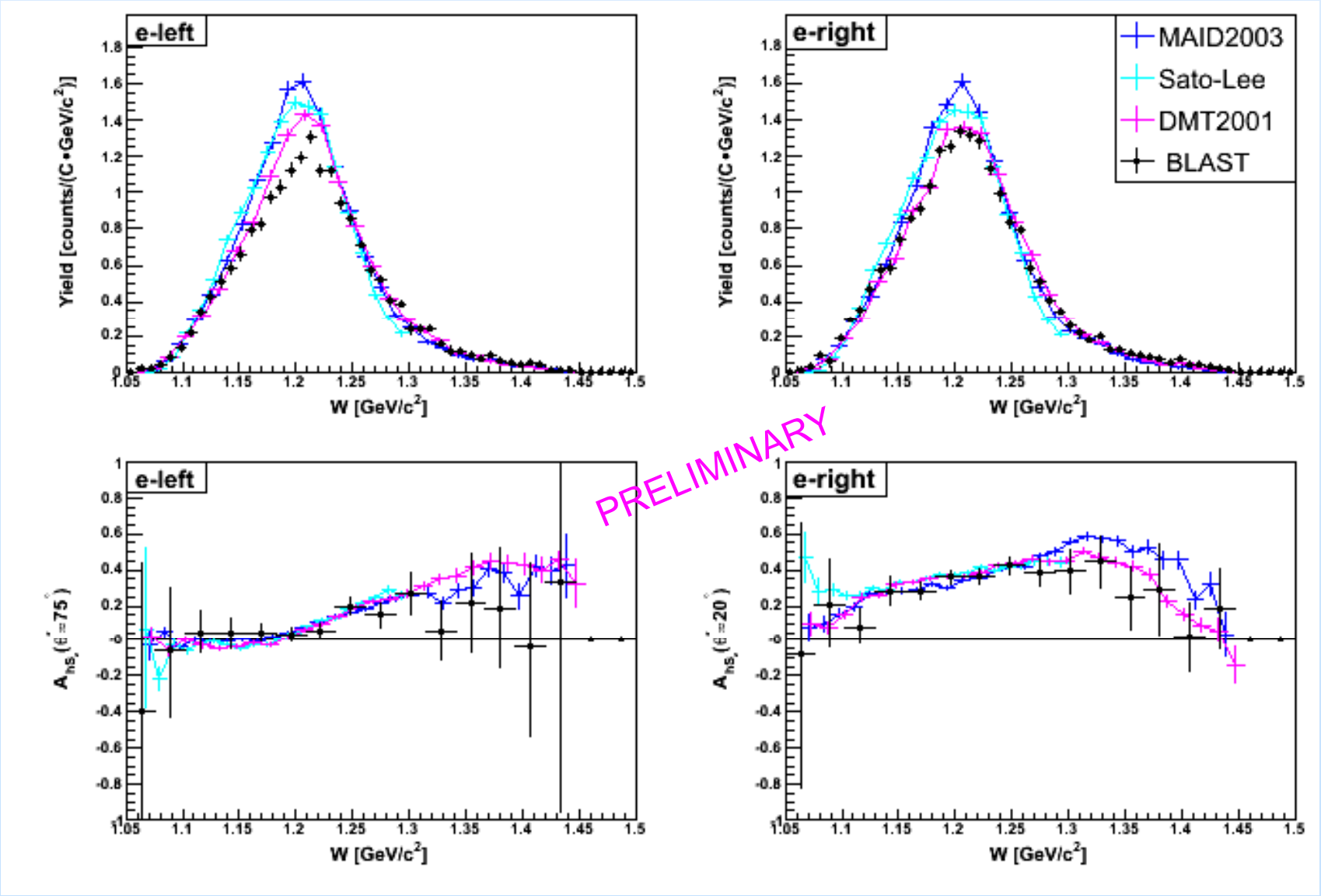
Y : event yield
Q: electron charge
h: electron helicity
S_z: target spin state

$\vec{H}(\vec{e},e'\pi^+)n$ Double Asymmetry *



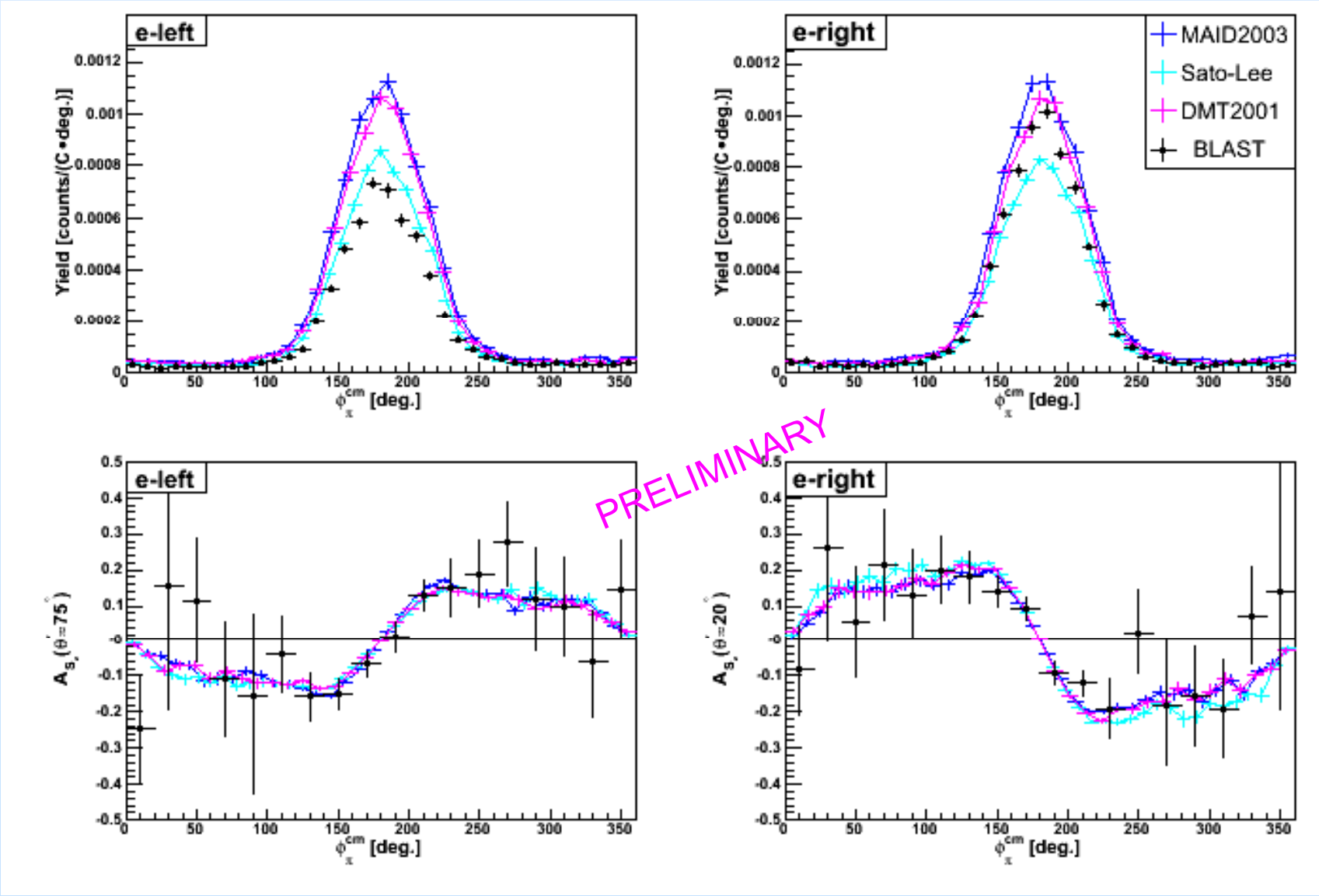
*Analyses by A. Shinozaki (MIT); Ph.D. work of Y. Xiao (MIT)

$\vec{H}(\vec{e},e'p)\pi^0$ Double Asymmetry*



*Analyses by A. Shinozaki (MIT); Ph.D. work of Y. Xiao (MIT)

$\vec{H}(e,e'\pi^+)n$ Target Asymmetry *



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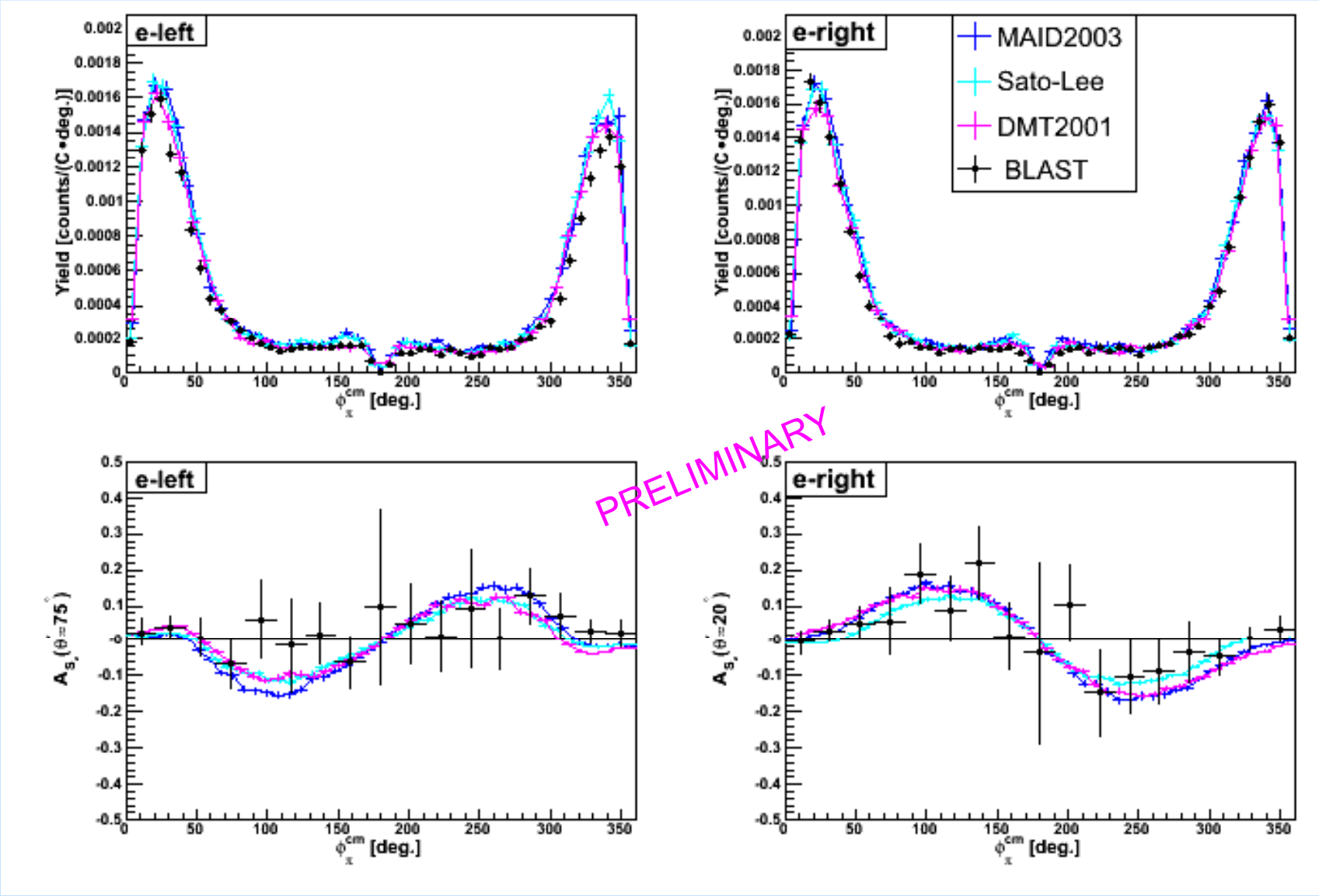
$\vec{H}(\vec{e},e'p)\pi^0$ Target Asymmetry *



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