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Structure of the proton, neutron, and deuteron from scattering of polarized electrons by polarized gas targets

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Bates Large Acceptance Spectrometer Toroid

- Electromagnetic structure of nucleons and light nuclei studied with **spin-dependent electron scattering** from internal polarized targets **at $Q^2 < 1$ (GeV/c)^2**

- **Longitudinally polarized electron beam** ($h = \pm1$)
- **Polarized (windowless) internal target in storage ring: isotopically pure, background free**
- **Detector with large angular and energy acceptance: simultaneous measurement of all reaction channels** over complete Q^2 range
- Exploit existence of **field-free region at target** to allow orientation of **target polarization in any direction**
- Exploit measurement of **single and double polarization observables** to keep **systematic errors low**

BLAST Physics Program

Nucleon Form Factors:

Proton and neutron electric and magnetic form factors

Deuteron Structure:

Charge, quadrupole, and magnetic form factors

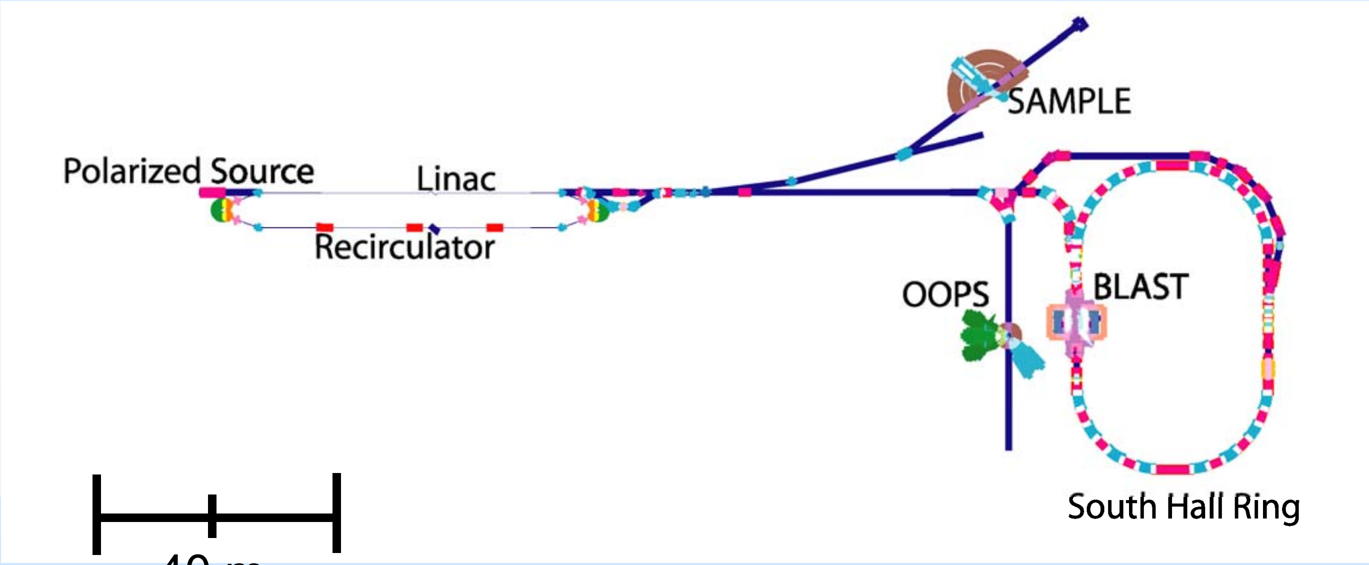
Tensor polarization observables

Polarized quasi-elastic electrodisintegration

Pion electroproduction:

$N \rightarrow \Delta(1232)$ transition in inclusive and exclusive processes

MIT-Bates Linear Accelerator Center

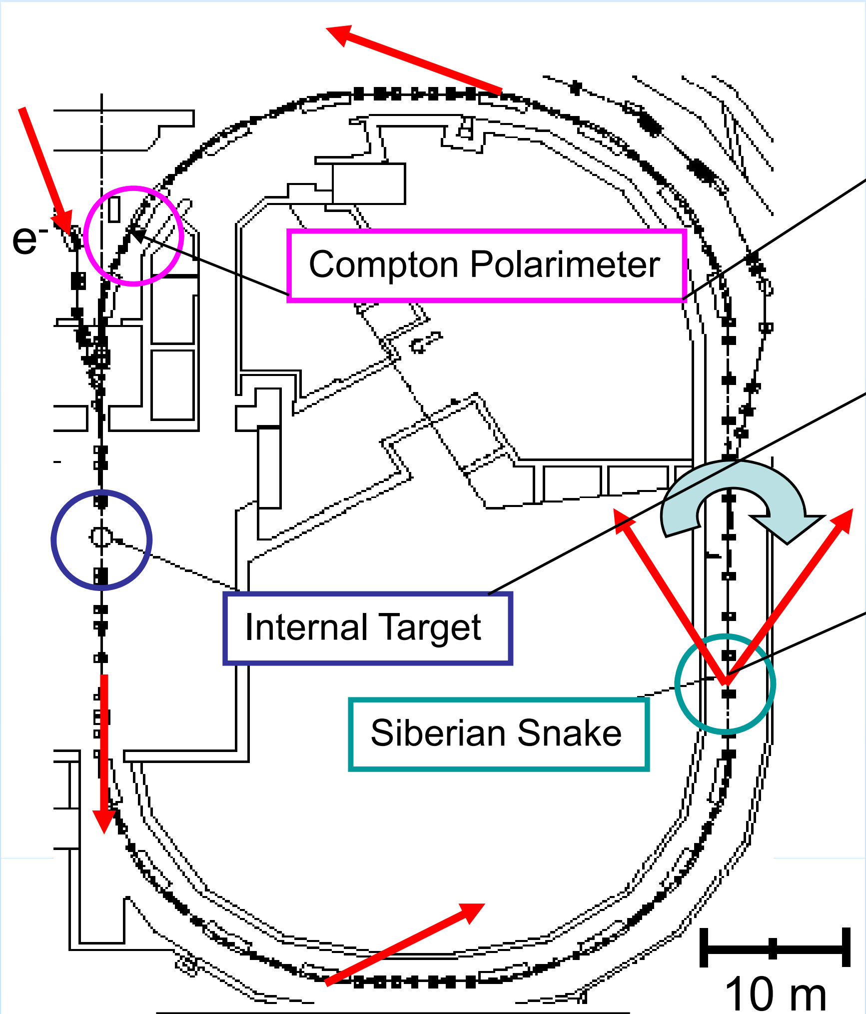


- **Stored Beam:** 850 MeV, >200 mA, $P_e \approx 65\%$ (strained GaAs)
- **Internal Target:** Polarized hydrogen, vector/tensor polarized deuterium

  Flow 2.2×10^{16} atoms/s
  Density 6×10^{13} atoms/cm^2
  Luminosity $6 \times 10^{31} cm^{-2} s^{-1}$
  Polarization $P_{H/D} \approx 80\%$
- **Detector:** **B**ates **L**arge **A**cceptance **S**pectrometer **T**oroid

  Left-right symmetric
  $\theta = 20^o - 80^o$, $\phi = -15^o - +15^o$
  $0.1 < Q^2 < 0.8$ (GeV/c)^2
  Simultaneous detection of $e^{\pm}$, $\pi^{\pm}$, *p*, *n*, *d*

MIT-Bates South Hall Ring

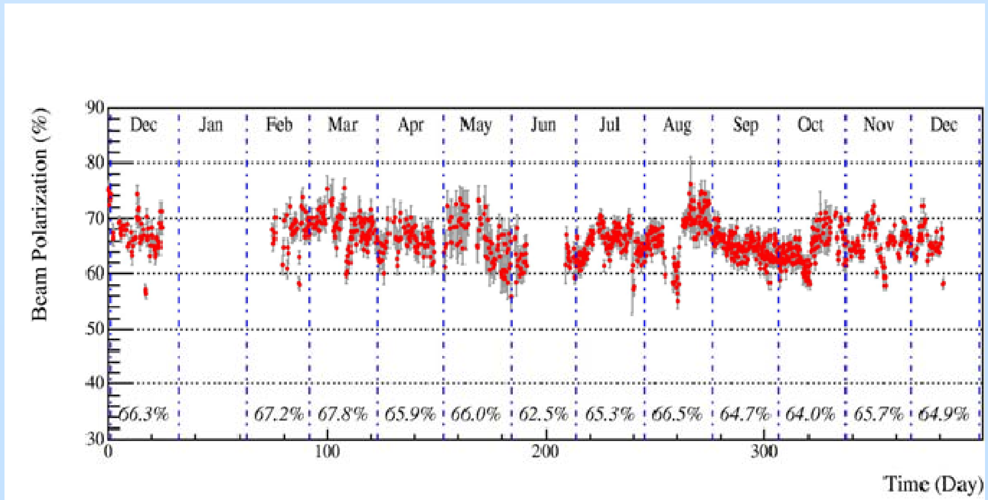


In-plane spin transport

Monitoring of electron beam polarization

Injection with longitudinal spin at internal target

Siberian snake to restore longitudinal polarization

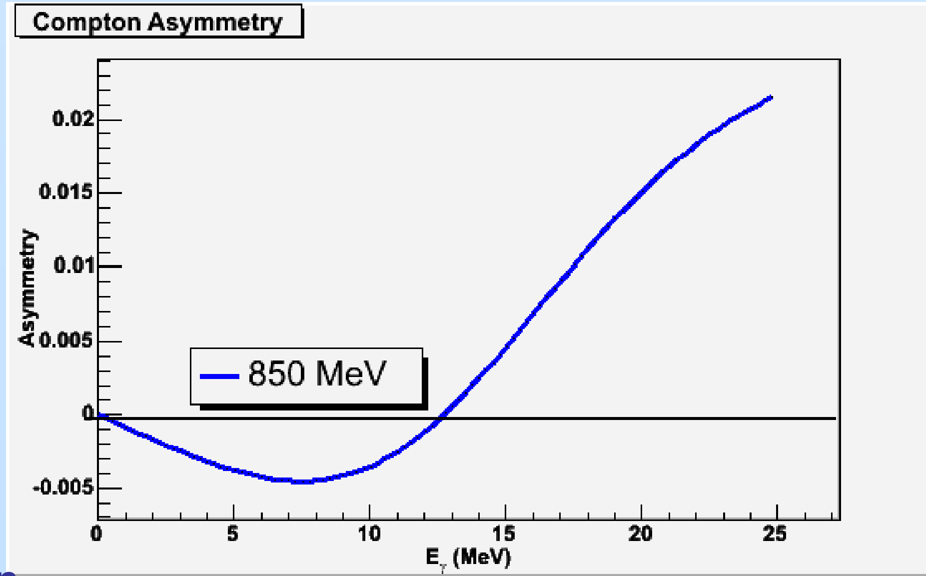


$P_e = 0.65 \pm 0.04$

Compton Polarimetry

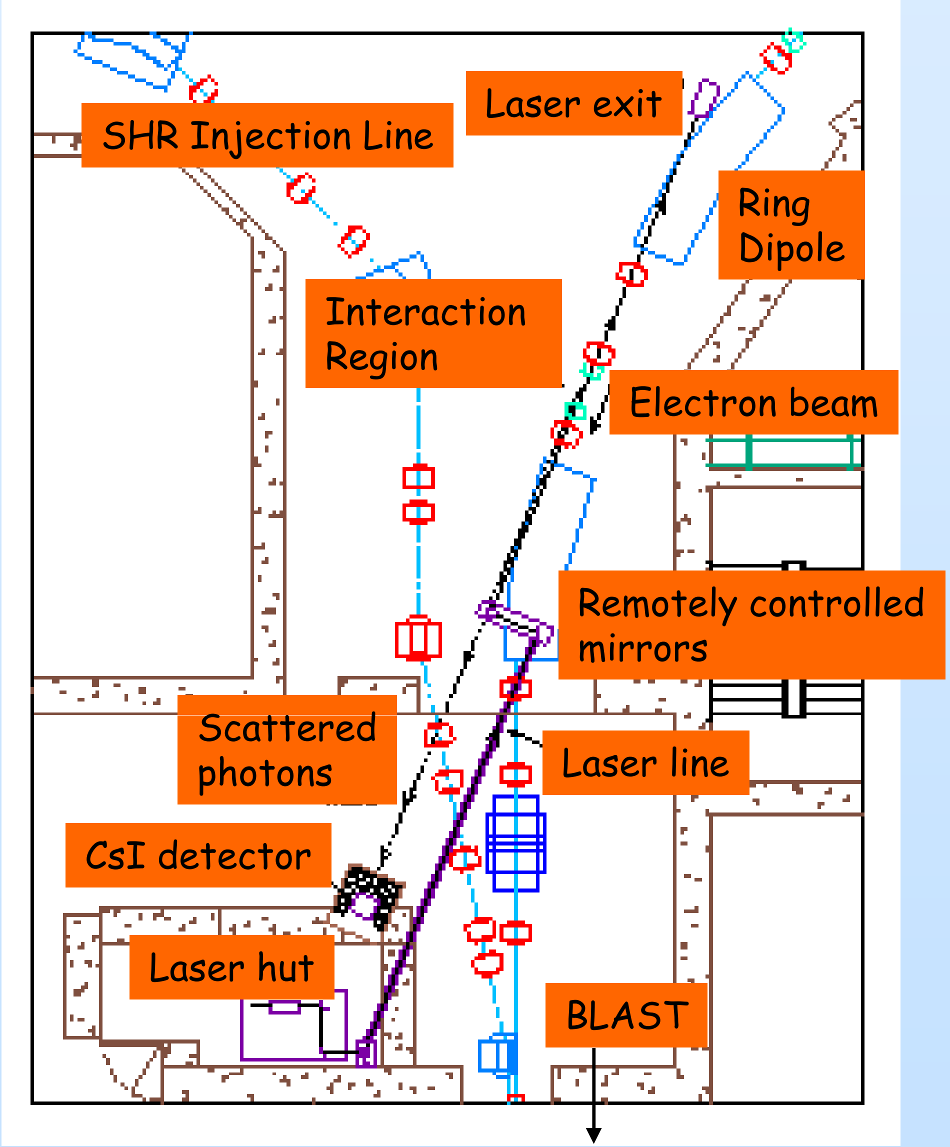
- Compton ($\gamma + e^-$) scattering in highly relativistic frame
  - Angular distribution compressed into narrow kinematic cone
  - Photon frequencies shifted from visible to gamma region
  - ➢ Detect backscattered photons with compact detector at ~180°
- Compton scattering cross section
  - Well known theoretically
  - Depends on photon helicity and electron spin
  - ➢ Can extract electron beam polarization by measuring asymmetries in scattering rates for circularly polarized laser light

- $d\sigma/dE_\gamma = (d\sigma_0/dE_\gamma)[1 + P_\lambda P_e A_z(E_\gamma)]$
  - $(d\sigma_0/dE_\gamma)$ is unpolarized cross section (Klein-Nishina)
  - E_γ is energy of back-scattered photon
  - P_λ is circular polarization of incident photons ($\lambda = \pm 1$)
  - P_e is longitudinal polarization of electron beam
  - $A_z(E_\gamma)$ is longitudinal asymmetry function



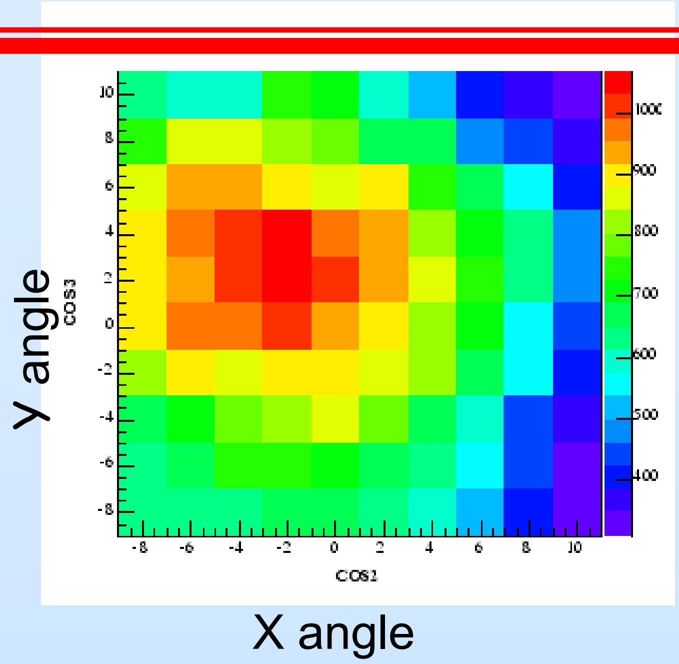
Compton Polarimeter*

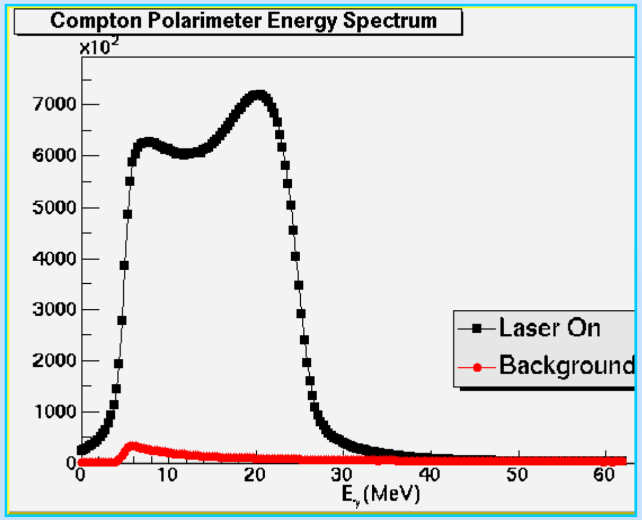
- Design Considerations
  - Based on NIKHEF Compton polarimeter
  - Located upstream of BLAST target to reduce background
  - Measures longitudinal projection of electron polarization
  - Back-scattered gamma trajectory defined by electron momentum
- Polarimeter Layout
  - Laser in shielded hut; 18 m optical path
  - Interaction with electron beam in 4 m straight section
  - Remotely movable mirrors
  - CsI gamma detector 10 m from interaction region



*W. Franklin, T. Akdoğan, JLM, T. Zwart *et al.*

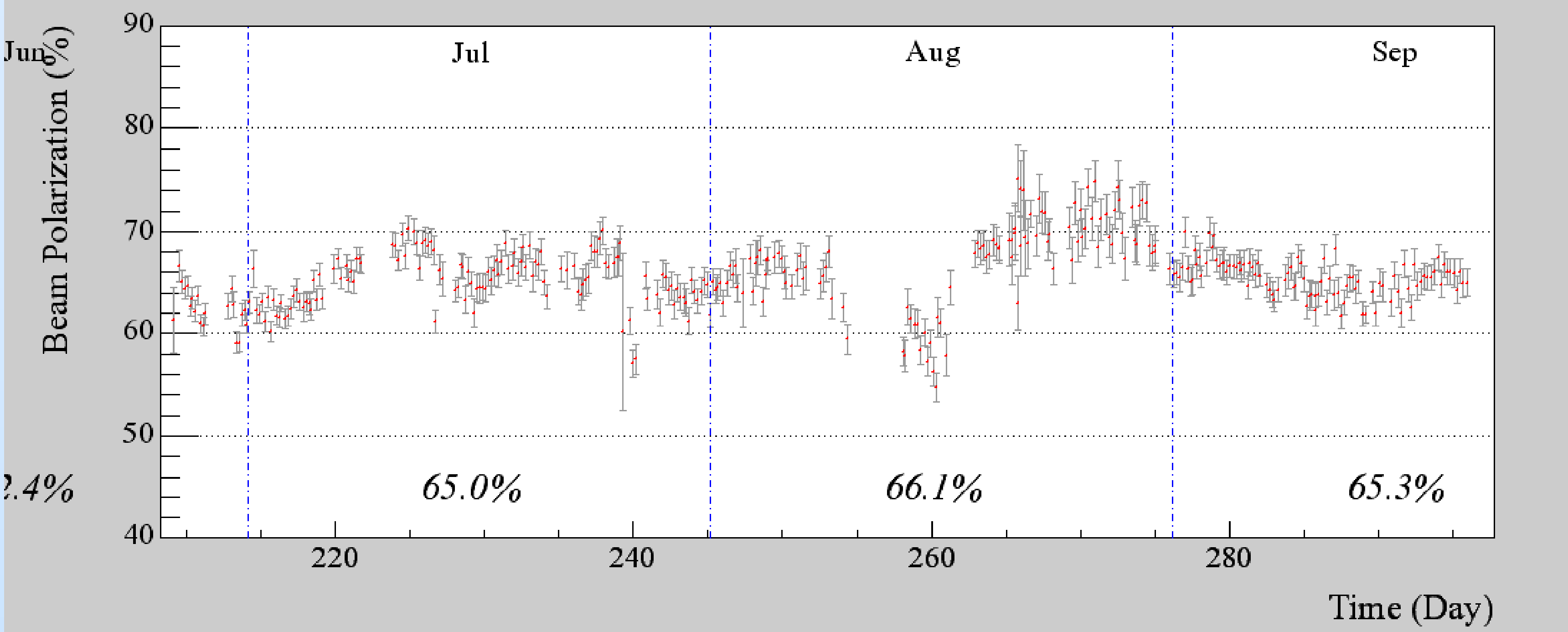
Laser system





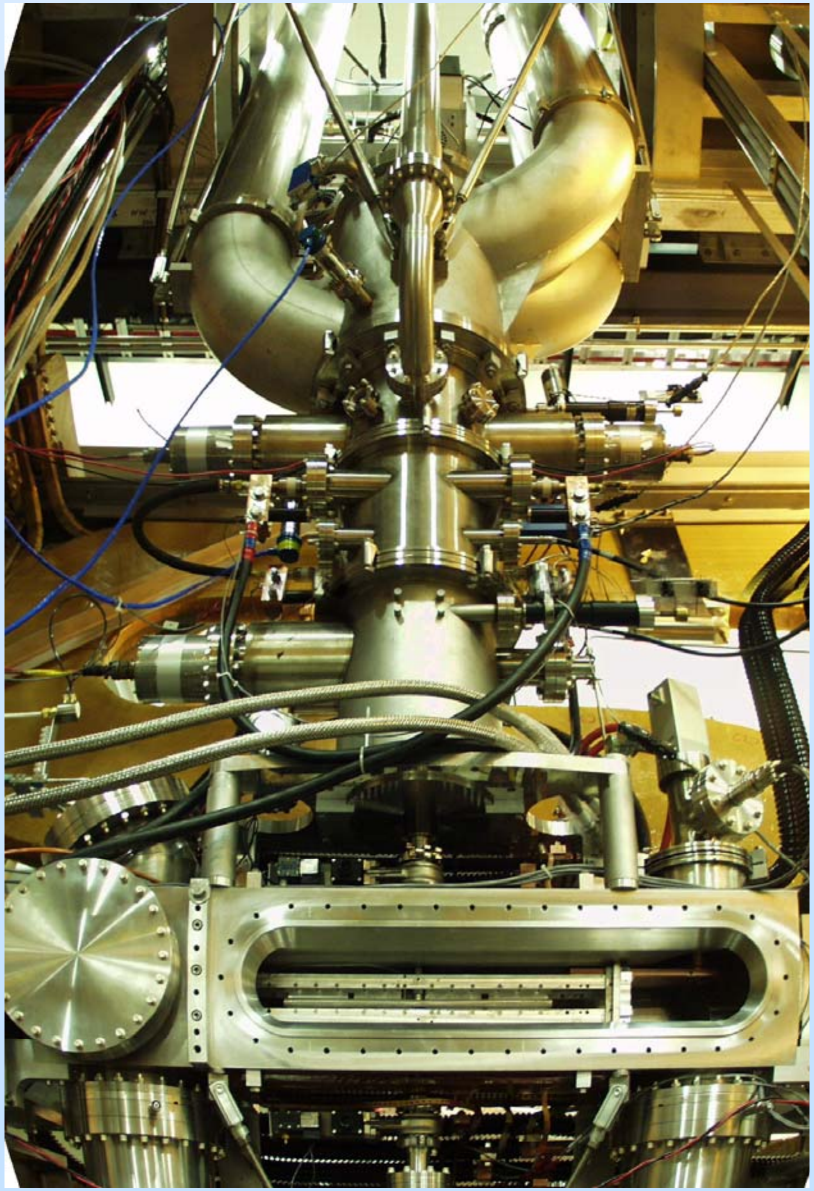
- Laser
  - Solid-state continuous-wave, very stable
  - 5W output at 532 nm (green)
- Optical Transport
  - Simple, robust lens arrangement for transport to IR and focusing
  - Mechanical chopper wheel (rotating at 9 Hz) allowed background measurements by blocking laser beam during time intervals
  - Circular polarization state produced by Pockels Cell for rapid helicity reversal (during background measurements)
  - Phase-compensated mirror arrangement
- Interaction Region
  - 4 degrees of freedom for laser beam scans
    - Laser beam position and angle scanned to maximize count rate
  - Laser beam intercepts stored electron beam at < 2 mrad

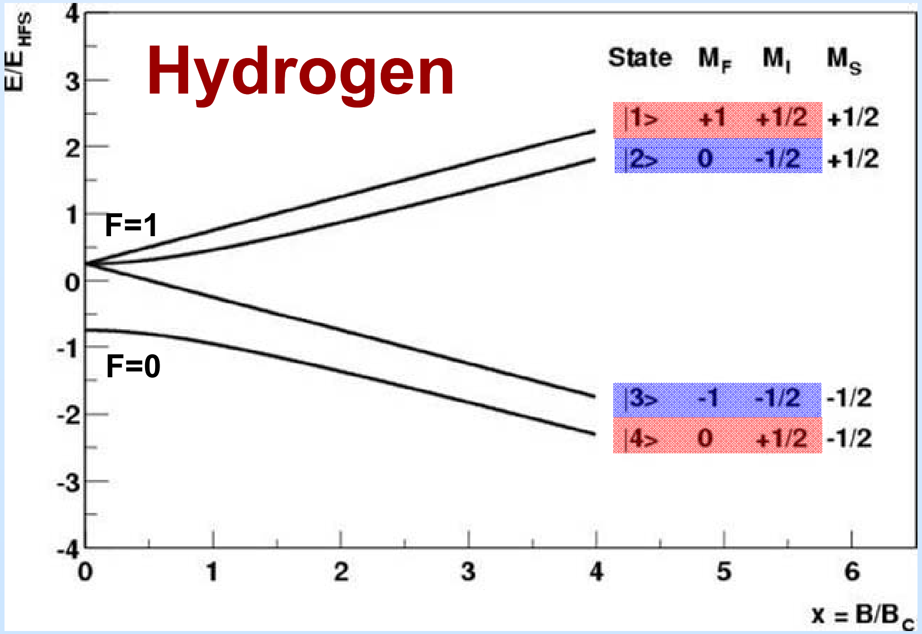
Beam Polarization as a function of time



- Polarization measurement performed for each fill of ring
- Database of polarization for BLAST experiment in blocks of ~4 hrs
- Polarization stable within few percent as a function of time
- Changes usually correlated with electron beam properties
- Mean polarization (2004): 0.654
- Long term errors dominated by systematics

Atomic Beam Source (ABS)*



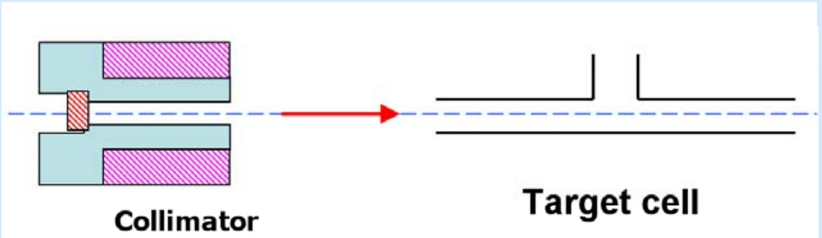


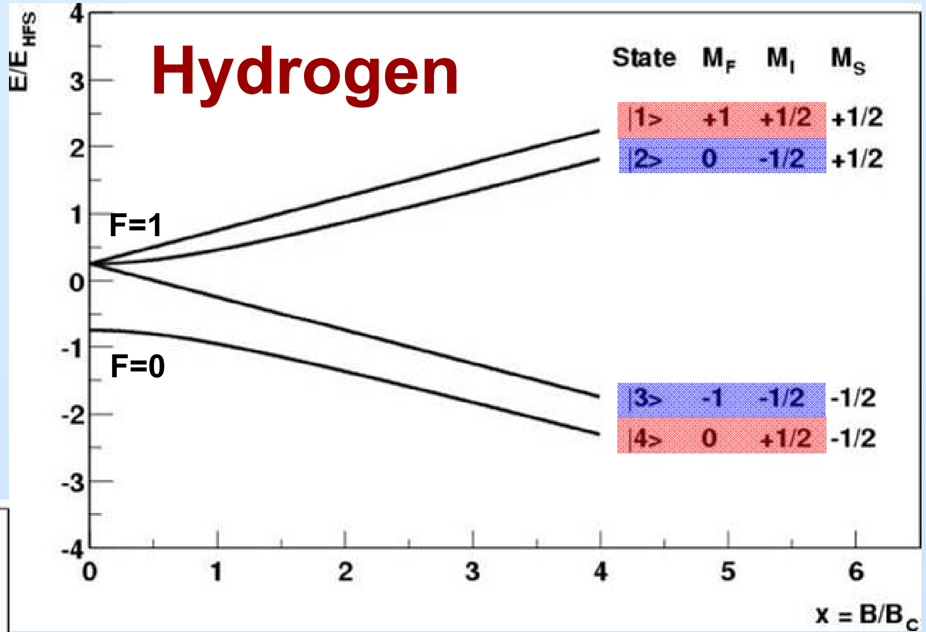
- Separately prepare m_I = **+½**, **-½** (**hydrogen**) and

  with sextupoles and RF transitions
- Switch between states every 5 minutes

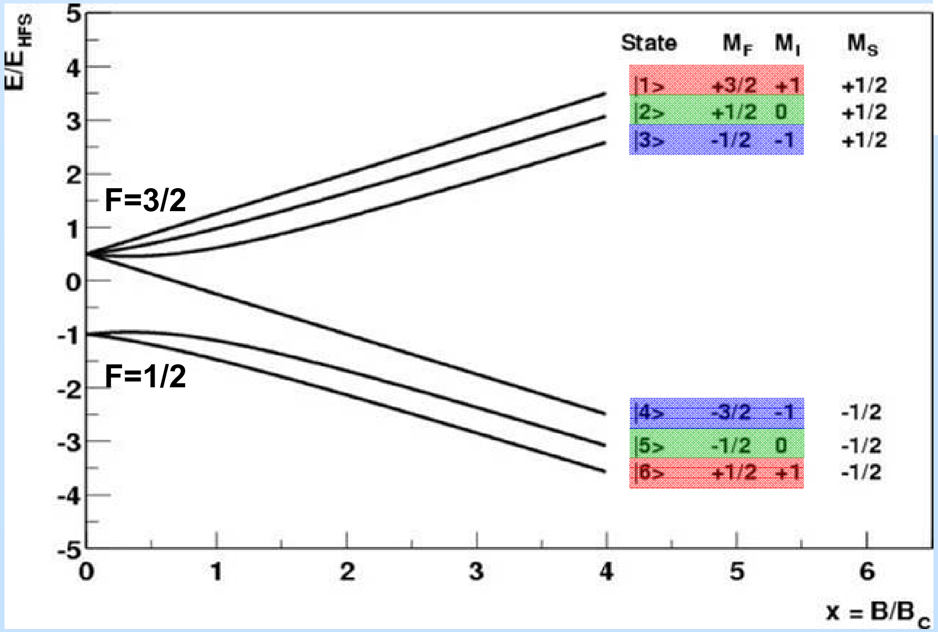
*R. Milner, students *et al*.

Atomic Beam Source (ABS)*





Deuterium

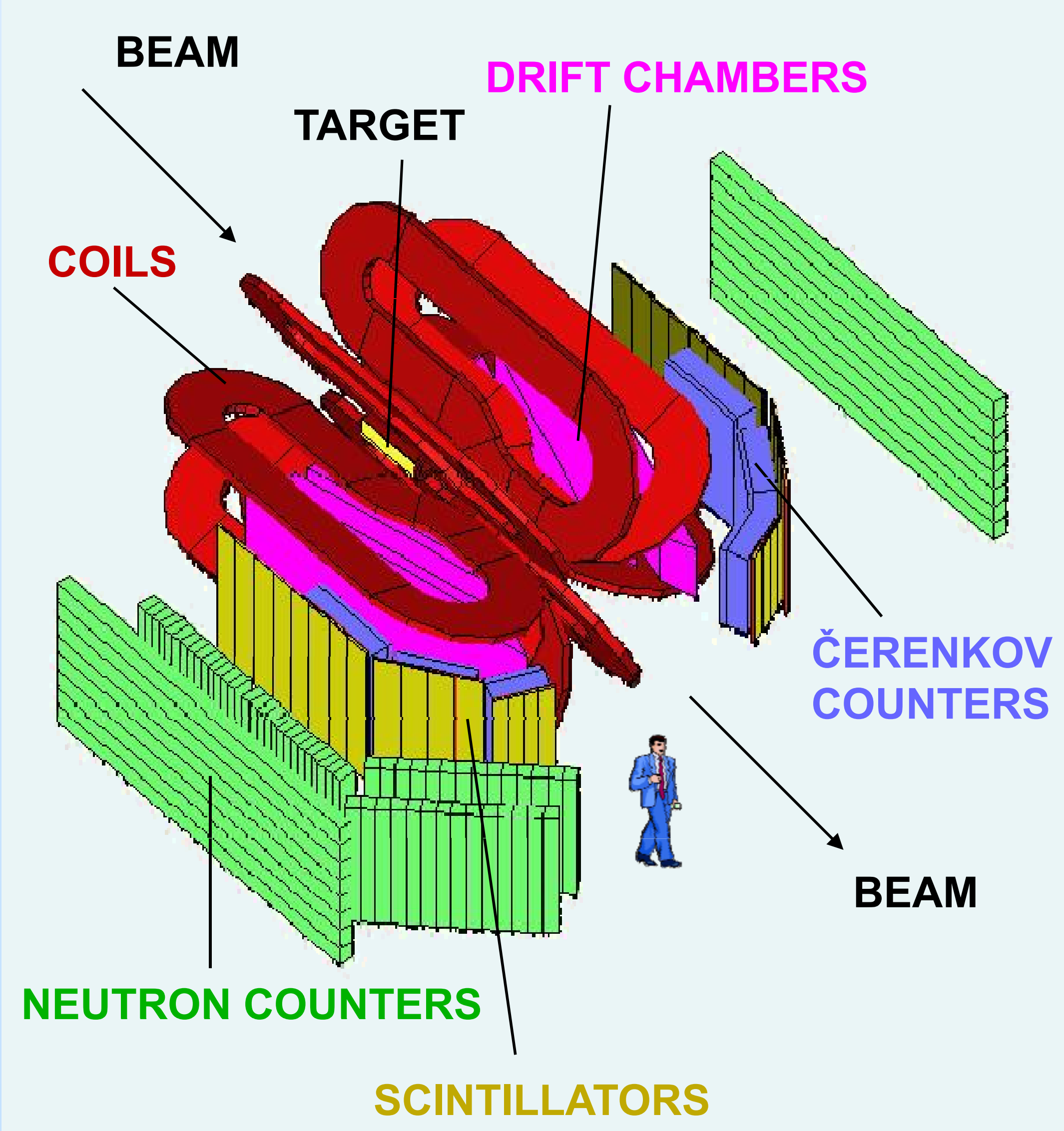


- Separately prepare m_I = +½, -½ (**hydrogen**) and m_I = **+1, 0, -1** (**deuterium**) with sextupoles and RF transitions
- Switch between states every 5 minutes

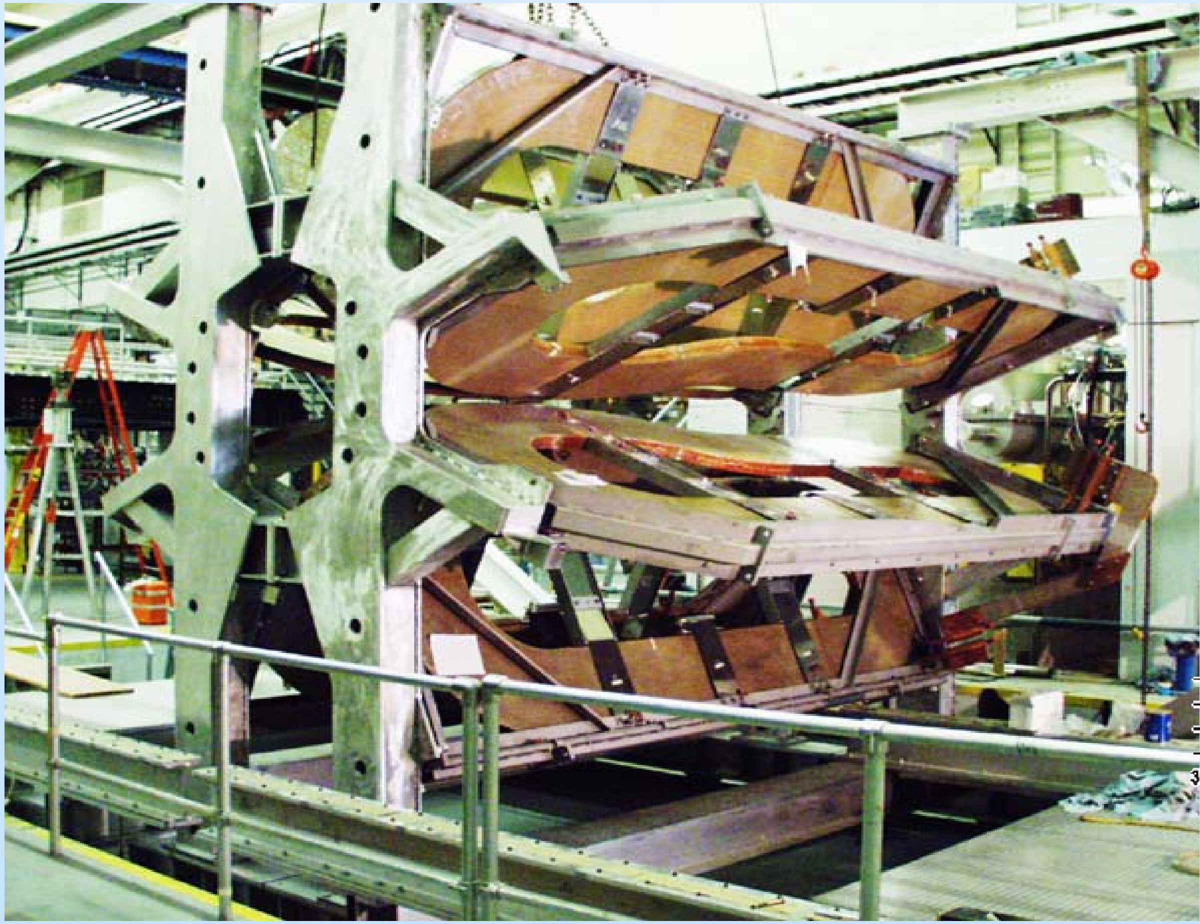
*R. Milner, students *et al*.

The BLAST Detector

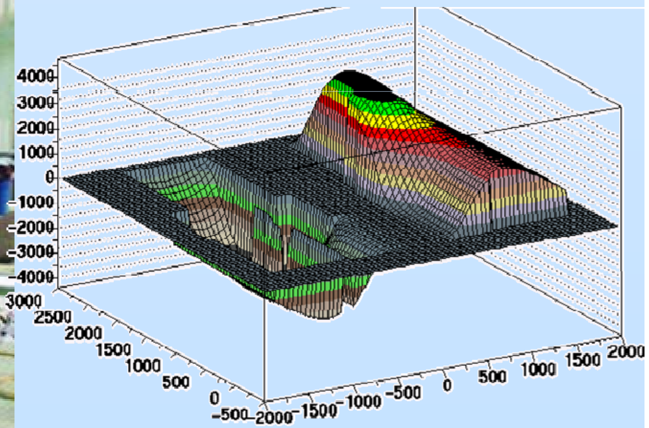
- **Left-right symmetric**
- **Large acceptance:**
  $0.1 < Q^2/(\mathrm{GeV}/c)^2 < 0.8$
  $20^o < \theta < 80^o$, $-15^o < \phi < 15^o$
- **COILS** $B_{max} = 3.8$ kG
- **DRIFT CHAMBERS**
  Tracking, charge selection
  $\delta p/p = 3\%$, $\delta\theta = 0.5^o$
- **ČERENKOV COUNTERS**
  e/π separation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



The BLAST Toroid (Bates)*



- 8 copper coils
  to minimize gradients
  at target
- coil positions adjusted
  to minimize target field
- field mapped (3D)
  ±1% of calculated field
- 6730 A, 3700 G
  3% momentum resolution

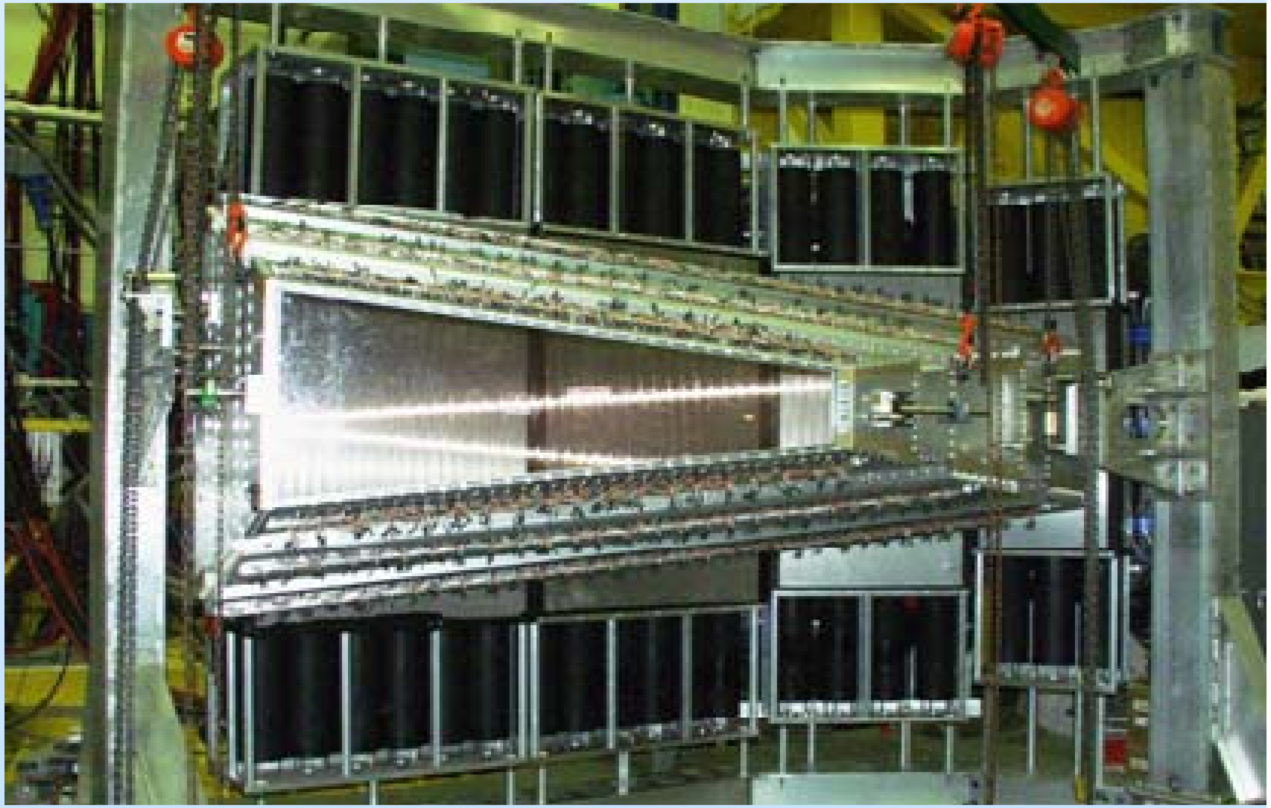


*J. Kelsey, E. Ihloff *et al.*

K. A..Dow *et al.*, Nucl.Instr. Meth. A, *in press*

Drift Chambers (MIT)*

- 954 sense wires   200µm wire resolution   signal to noise ratio 20:1

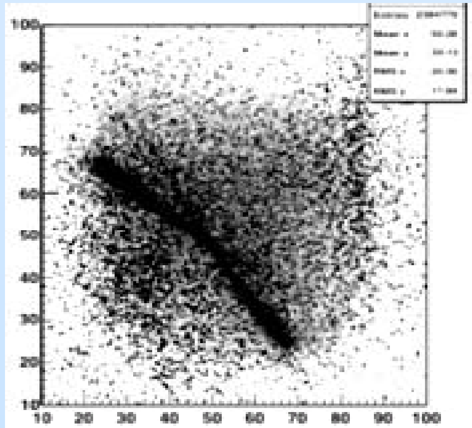


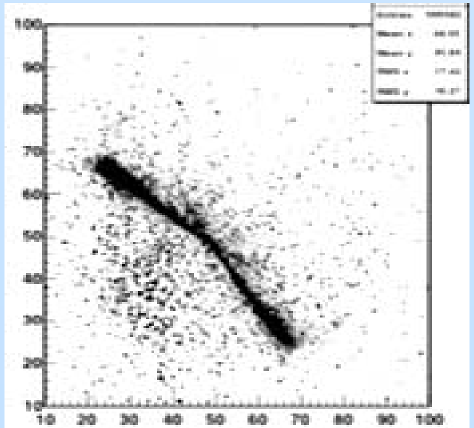
- 3 chambers per sector
  - single gas volume
  - 2 superlayers per chamber (±10° stereo)
    - 3 sense layers per superlayer
- 18 layers total tracking
  - momentum analysis
  - scattering angles
  - event vertex
  - particle charge

*D. Hasell, R. Redwine + students

Čerenkov Detectors (ASU)*

- e, π discrimination
- 1 cm thick aerogel
  n = 1.02–1.03
- 80-90% efficiency

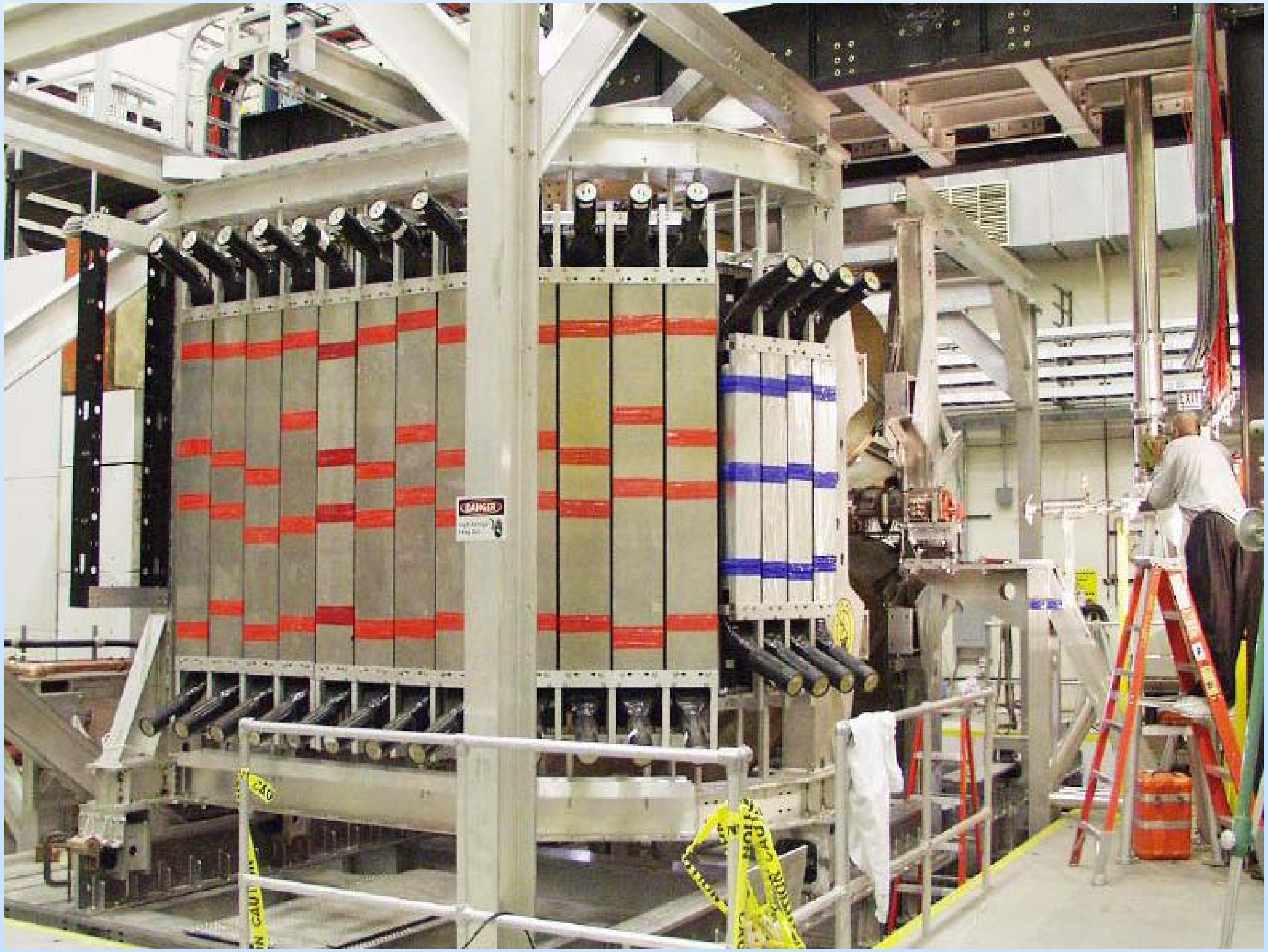


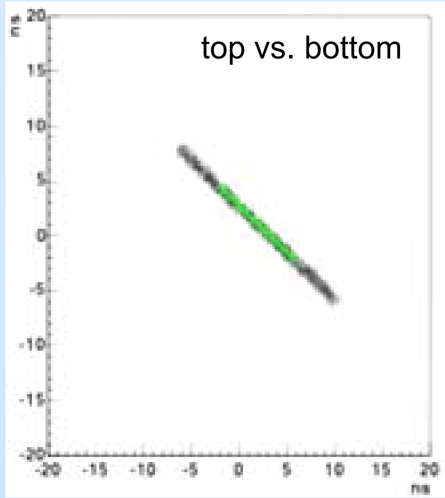


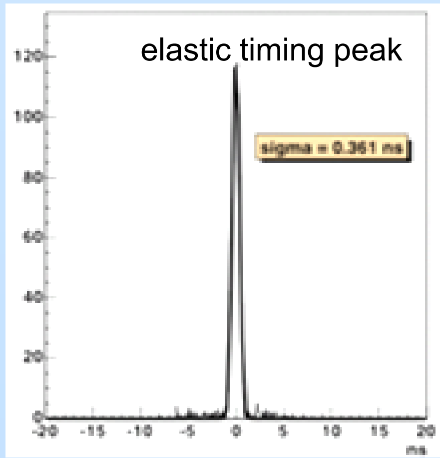
*R. Alarcon + students

Time-of-Flight Scintillators (UNH)*

350 ps timing resolution
1% velocity resolution



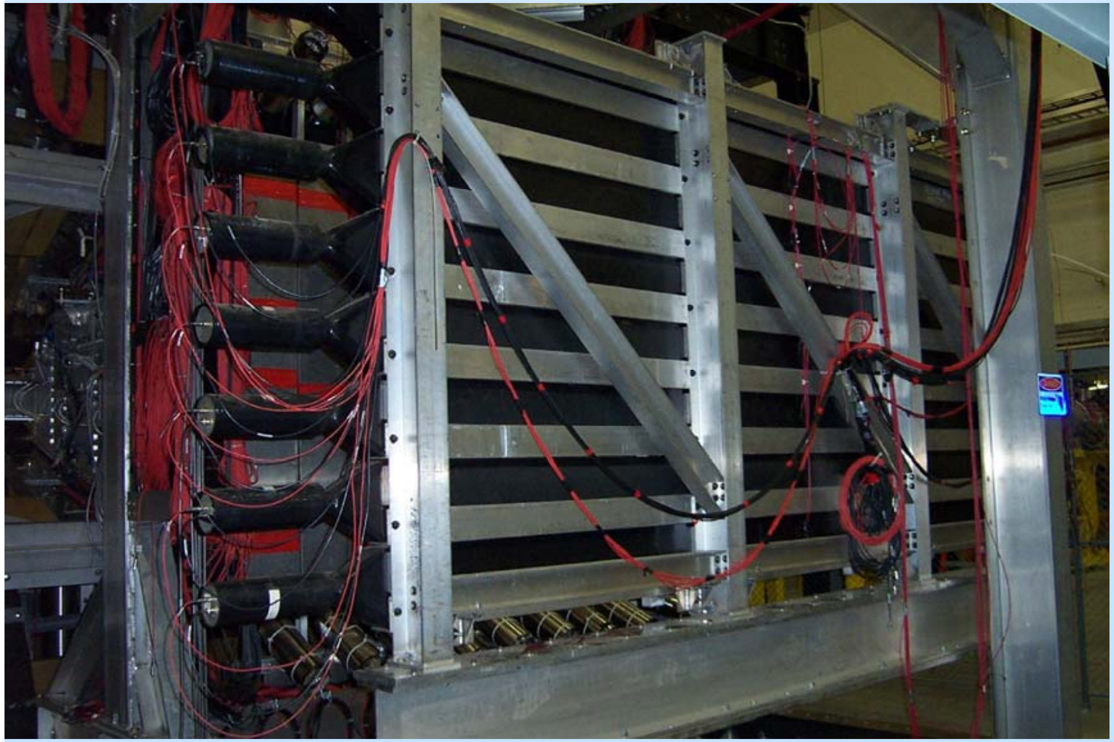


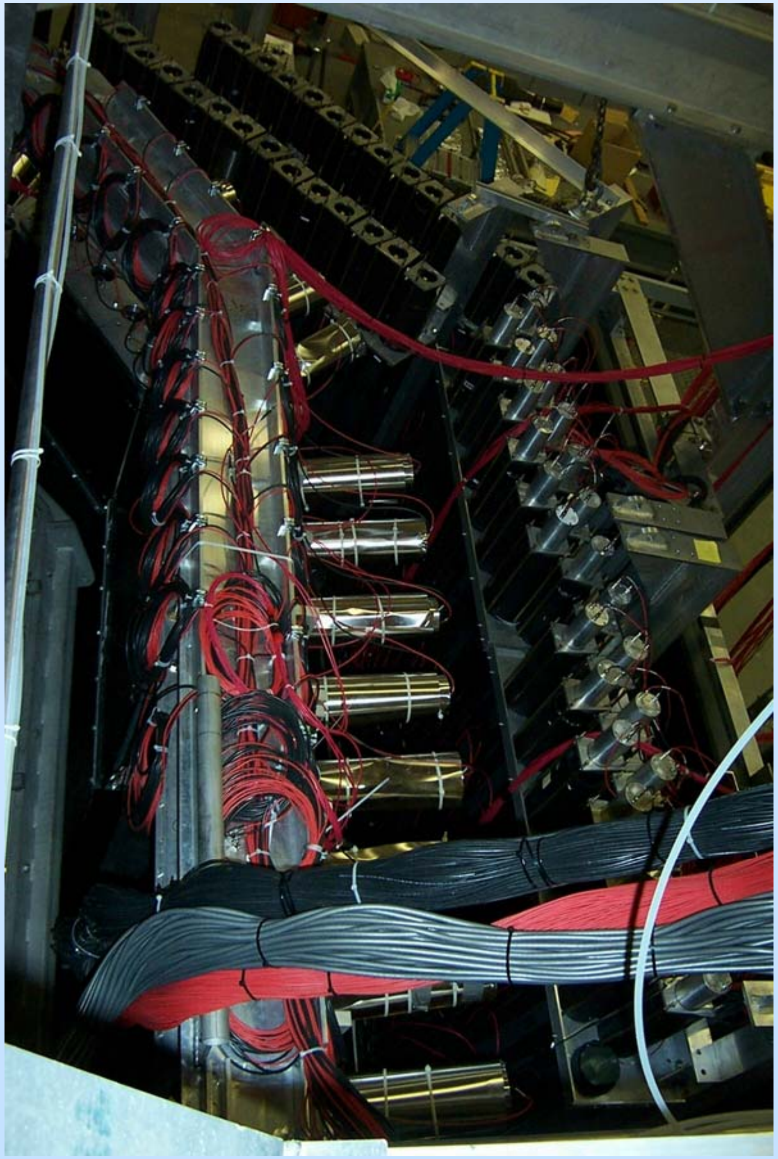


*J. Calarco + students

Neutron Scintillators (Ohio U.*, Bates**)

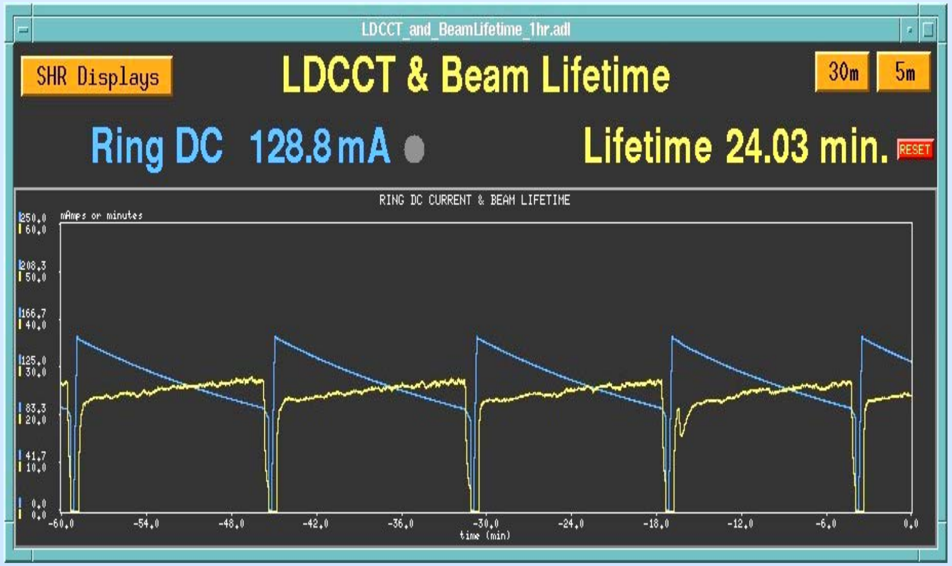
- **20% detection efficiency**
- **LADS (PSI, JLab) detectors added on beam-right for increased sensitivity in G_e^n measurement**
- **TOF scintillators, drift chambers provided good charged particle veto**

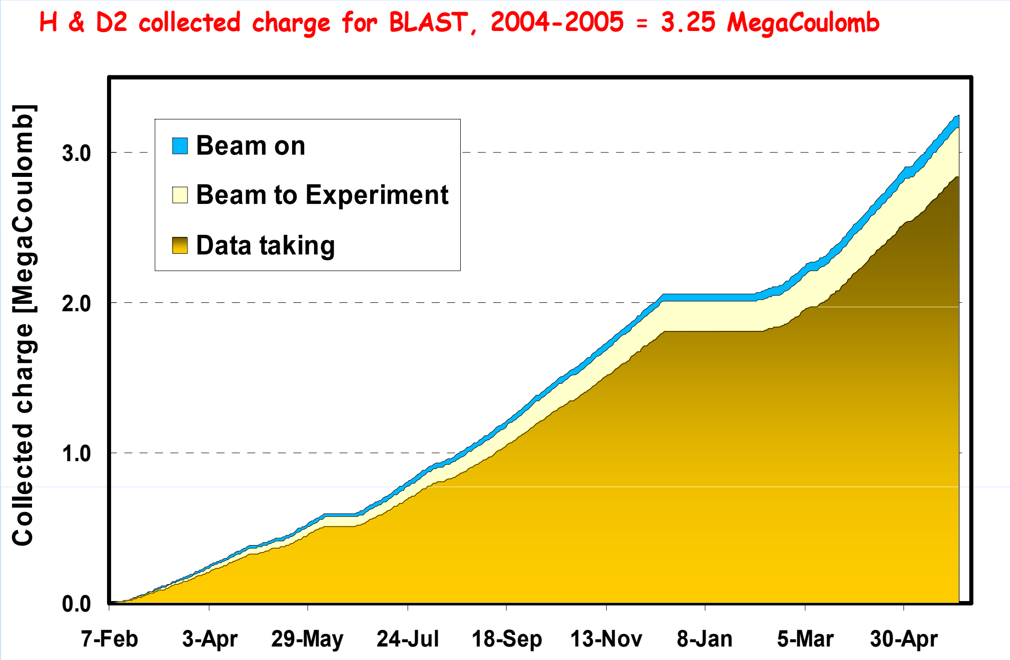




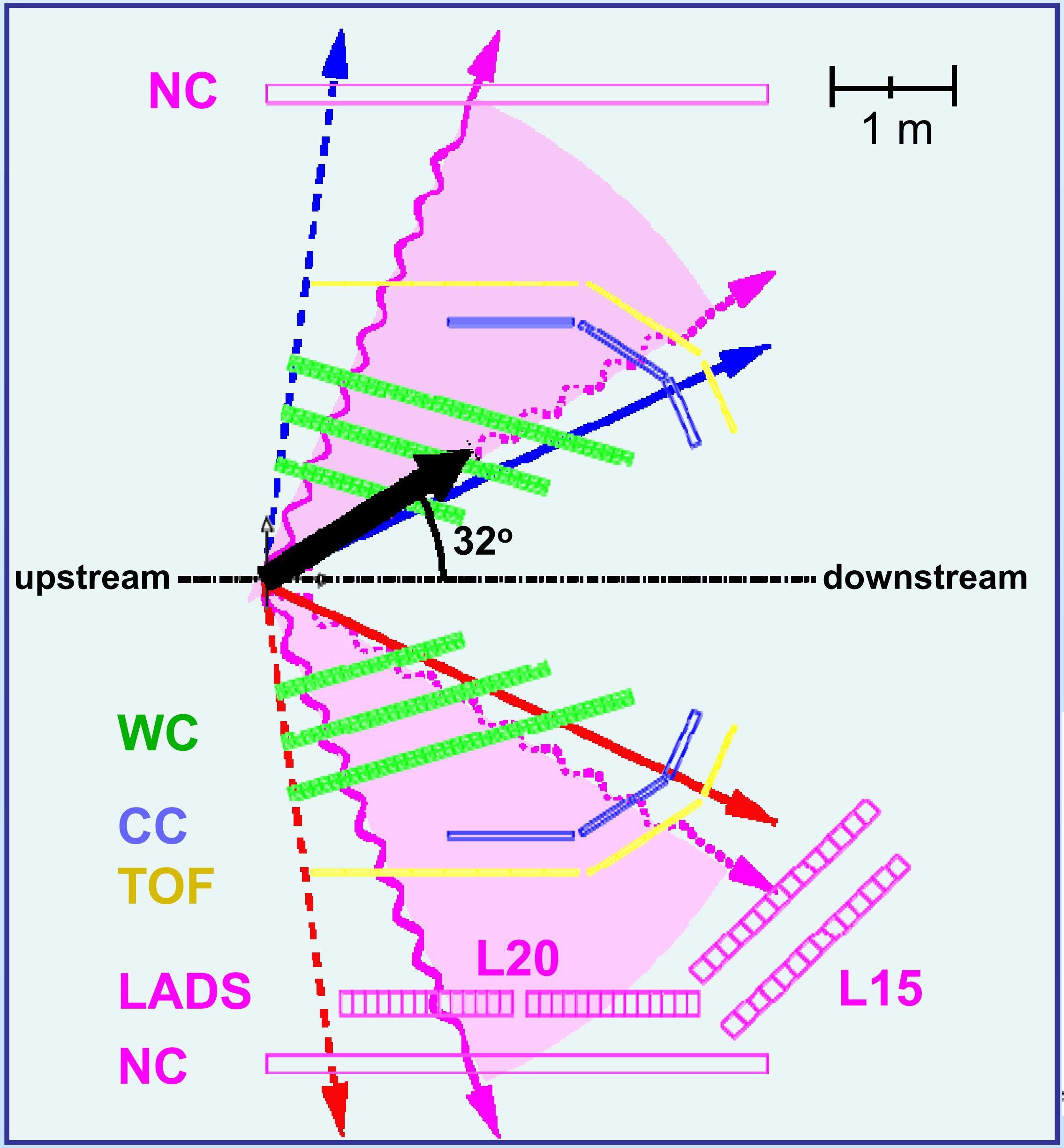
*J. Rapaport, **M, Kohl

BLAST Data Collection





Target Spin Orientation



ABS allows free choice of target spin angle in horizontal plane

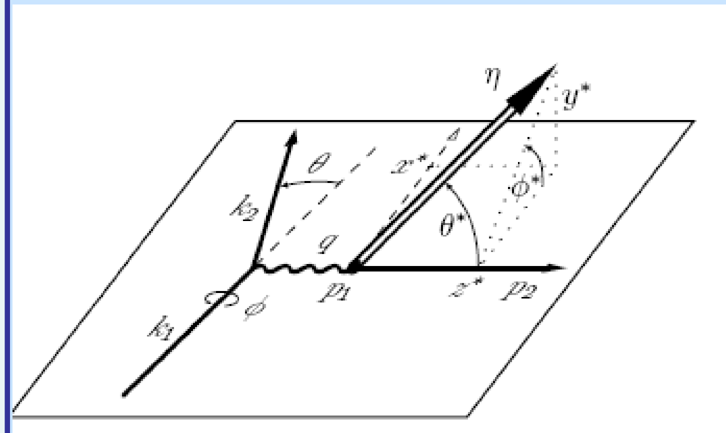
[32° (2004) / 47° (2005)]

e- left → $\theta^* \approx 90°$

Target spin perpendicular to momentum transfer $\vec{q}$

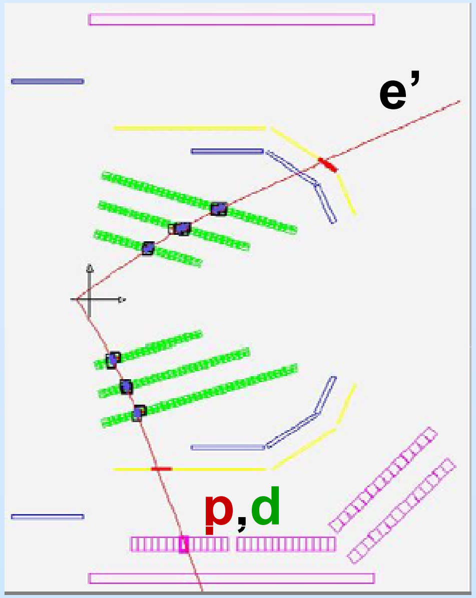
e- right → $\theta^* \approx 0°$

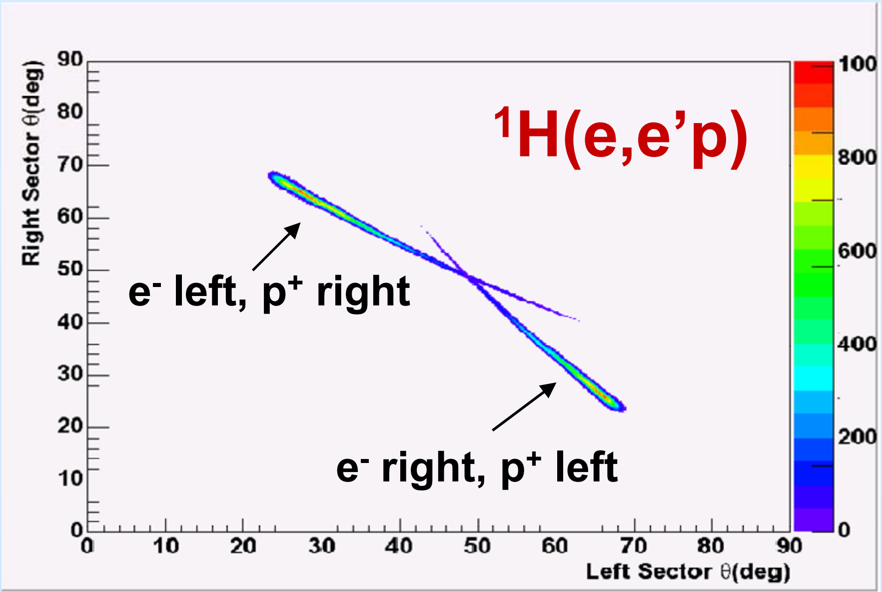
Target spin parallel to momentum transfer $\vec{q}$

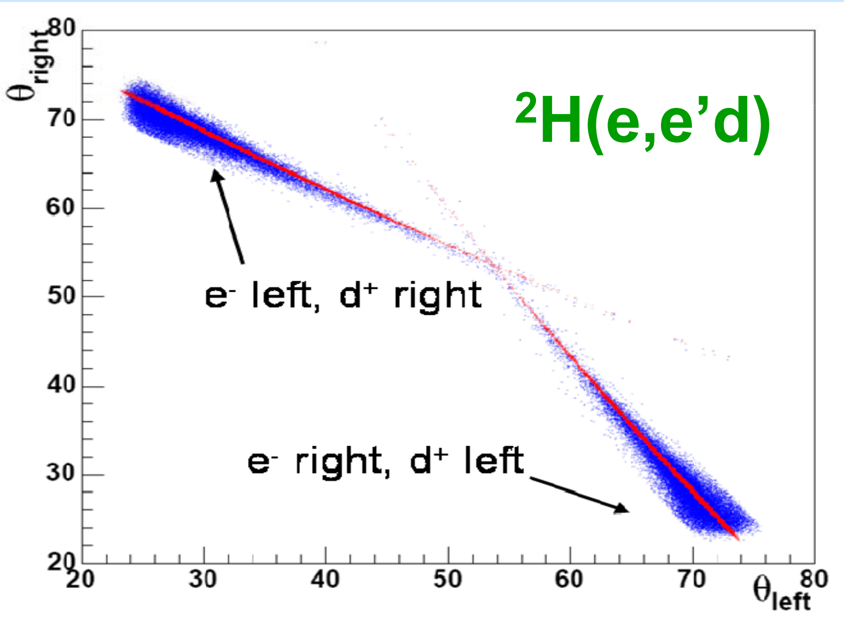


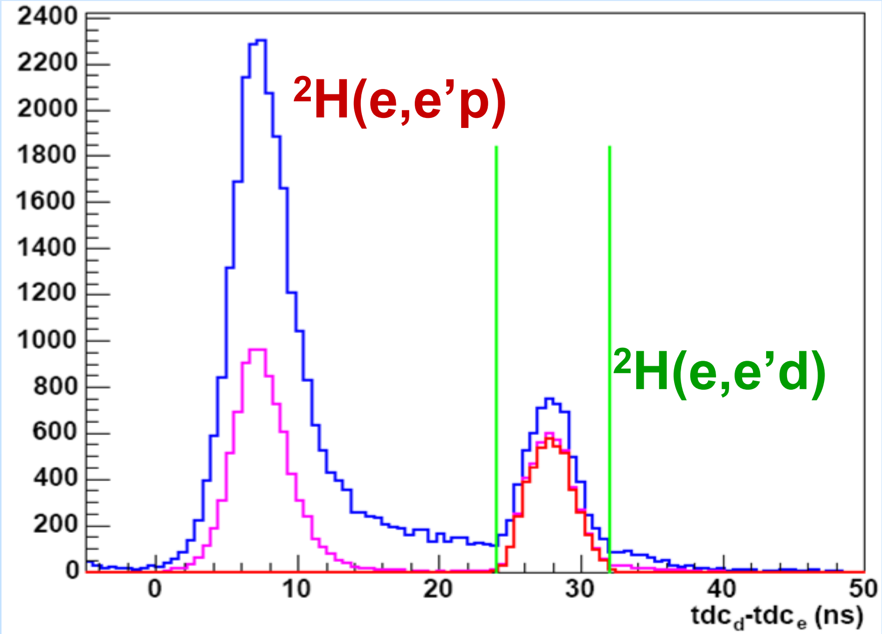
Identification of Elastic Events

- Charge +/-
- Coplanarity
- Kinematics
- Timing



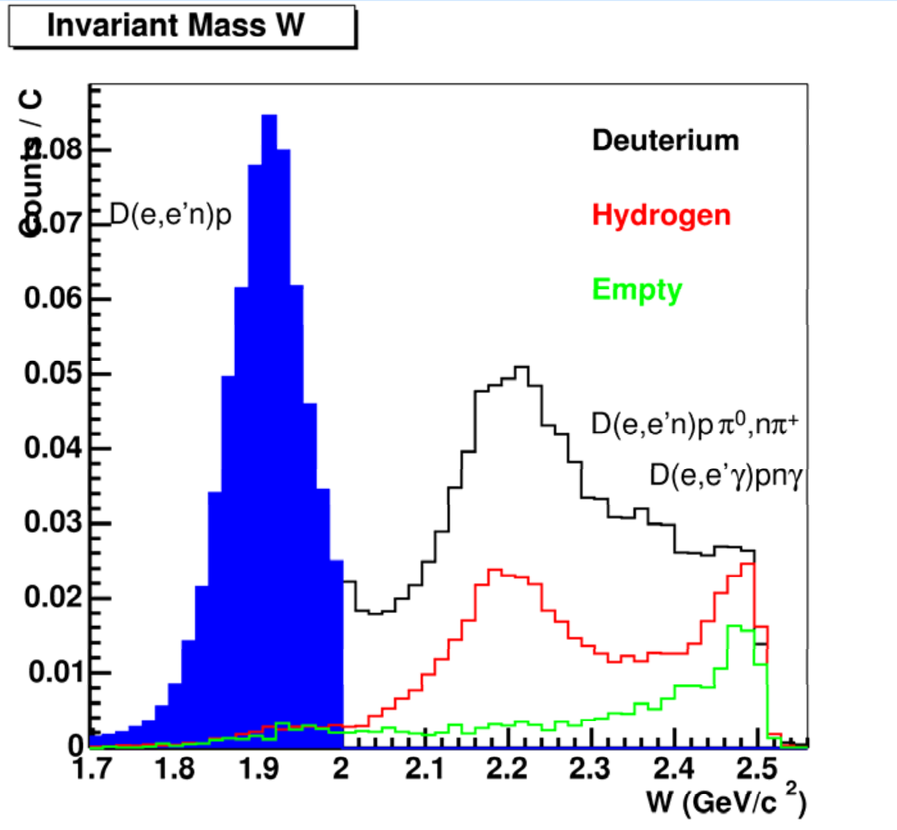


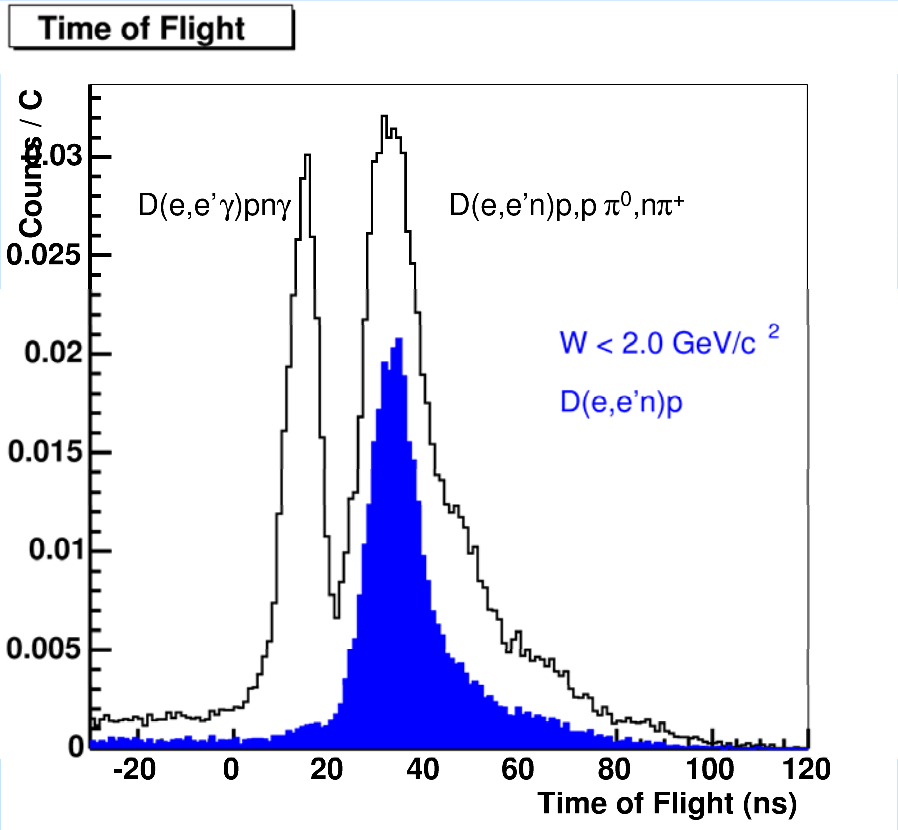




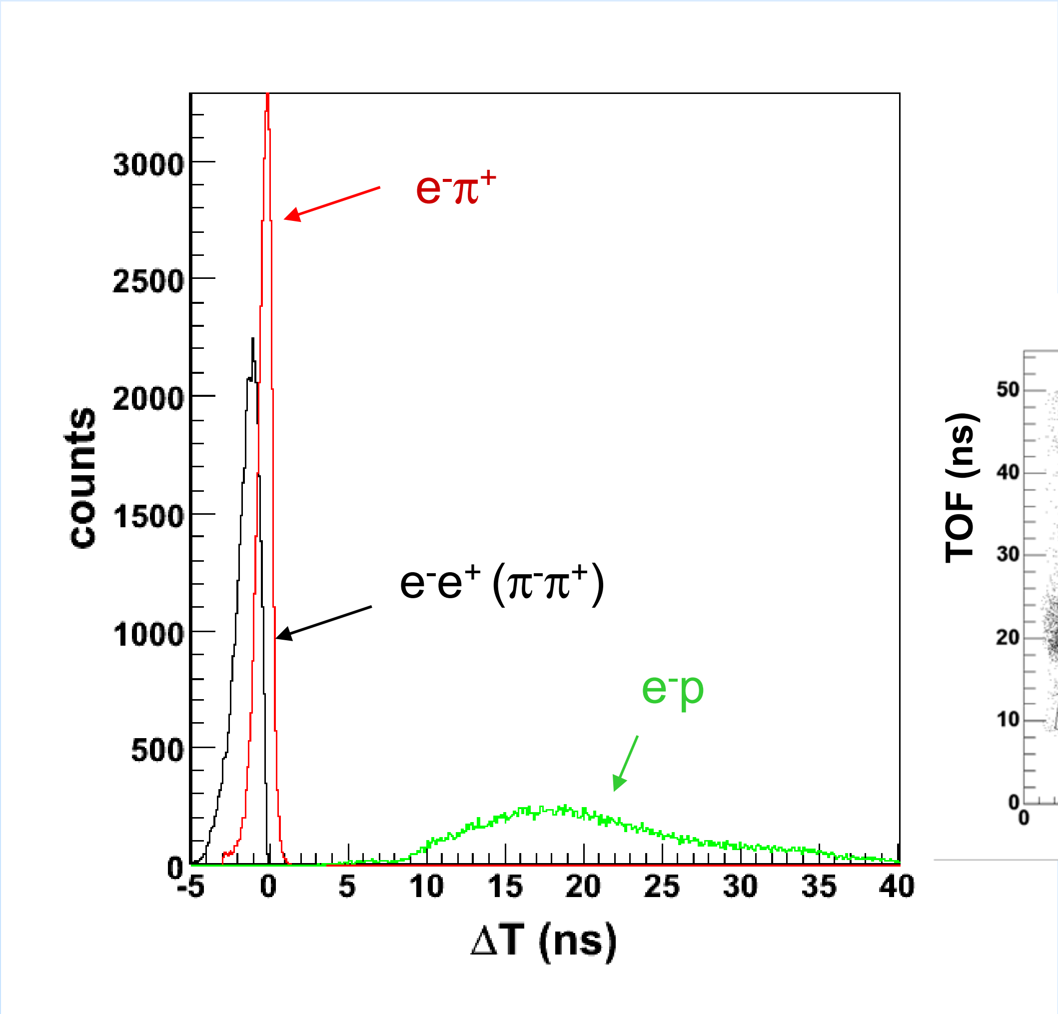
Identification of Neutron Events

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

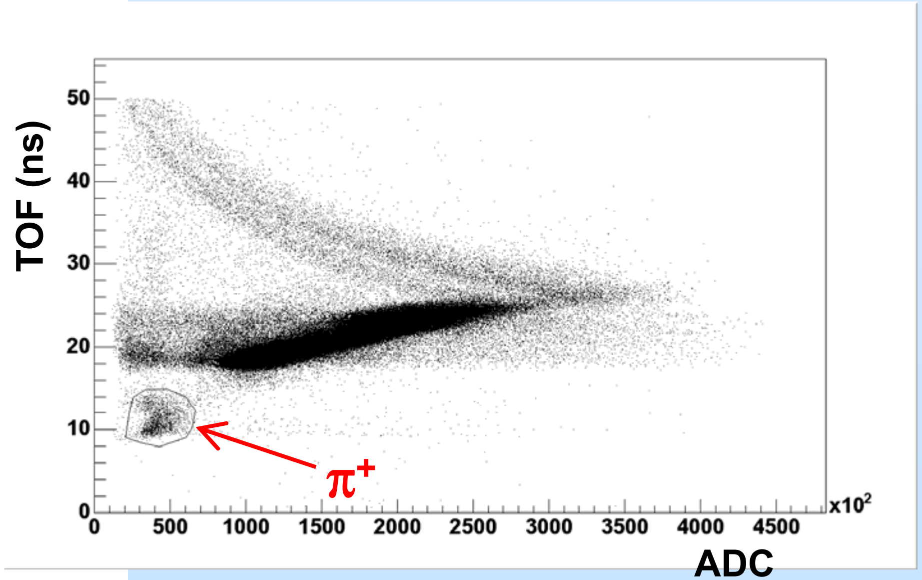




Identification of π^+ Events



Time correlation for candidate e′ π events, corrected for path-length



Cerenkov detector information discriminates π^+ / e^+ and π^- / e^- events.

Nucleon Elastic Form Factors

- General definition of the nucleon form factor

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

- 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 the one-photon exchange approximation the above form factors are observables of **elastic electron- nucleon** scattering

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$
$$= \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

Polarization and Nucleon Form Factors

- Double polarization observables in elastic *ep* scattering:
  with recoil polarization or **polarized target**

  $^{1}\mathrm{H}(\vec{e},e'\vec{p})$, $^{\vec{1}}\mathrm{H}(\vec{e},e'p)$

- Polarized cross section

$$\sigma = \sigma_0 \left(1 + P_e \vec{P}_t \cdot \vec{A}\right)$$

- Double spin asymmetry

$$\frac{\vec{P}_t}{P_t} \cdot \vec{A} = -\frac{\sqrt{2\tau\epsilon(1-\epsilon)}G_E G_M \tilde{P}_x + \tau\sqrt{1-\epsilon^2}{G_M}^2 \tilde{P}_z}{\epsilon G_E^2 + \tau G_M^2}$$

Target polarization components $\tilde{P}_x = \sin\theta^* \cos\phi^*$, $\tilde{P}_z = \cos\theta^*$

- Measured asymmetry = $A_{exp} = P_e P_t A_{phys}$
- Scattered electron can be detected in either the left (A_L) or the right (A_R) sector of BLAST
- **"Super-ratio" $(A_L/A_R)_{exp} = (A_L/A_R)_{phys}$, independent of P_e and P_t**

Extraction of G_E/G_M from super-ratio

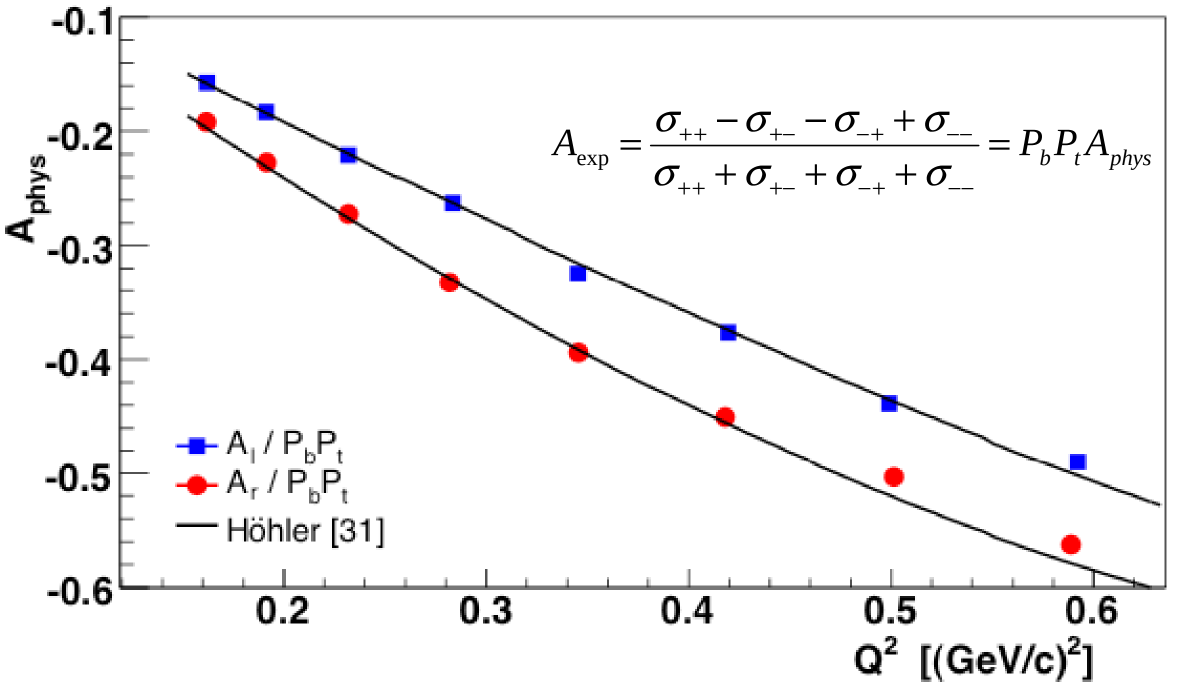
Recall that electron in left (right) sector corresponds to target spin perpendicular: $\theta^* = 90^o$ (parallel: $\theta^* = 0^o$) to $\vec{q}$

$$\frac{A_L}{A_R} =\propto \frac{z_L + x_L\, G_E/G_M}{z_R + x_R\, G_E/G_M} \approx \frac{A_{perp}}{A_{par}} \propto \frac{G_E}{G_M}$$

$x_{L,R}$, $z_{L,R}$ are kinematic factors

(~sin θ^* cos ϕ^*, ~cos θ^*)

Asymmetries in $\vec{H}(\vec{e}, e'p)$



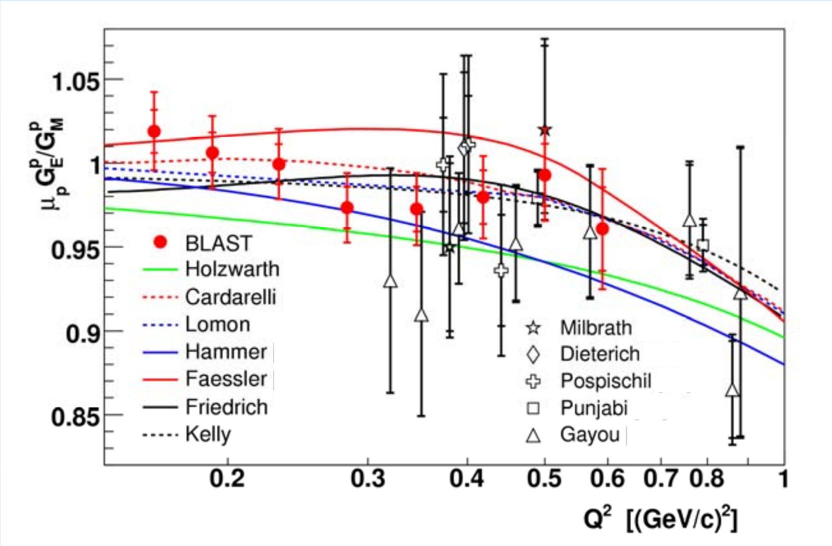
$$A_{\exp} = \frac{\sigma_{++} - \sigma_{+-} - \sigma_{-+} + \sigma_{--}}{\sigma_{++} + \sigma_{+-} + \sigma_{-+} + \sigma_{--}} = P_b P_t A_{phys}$$

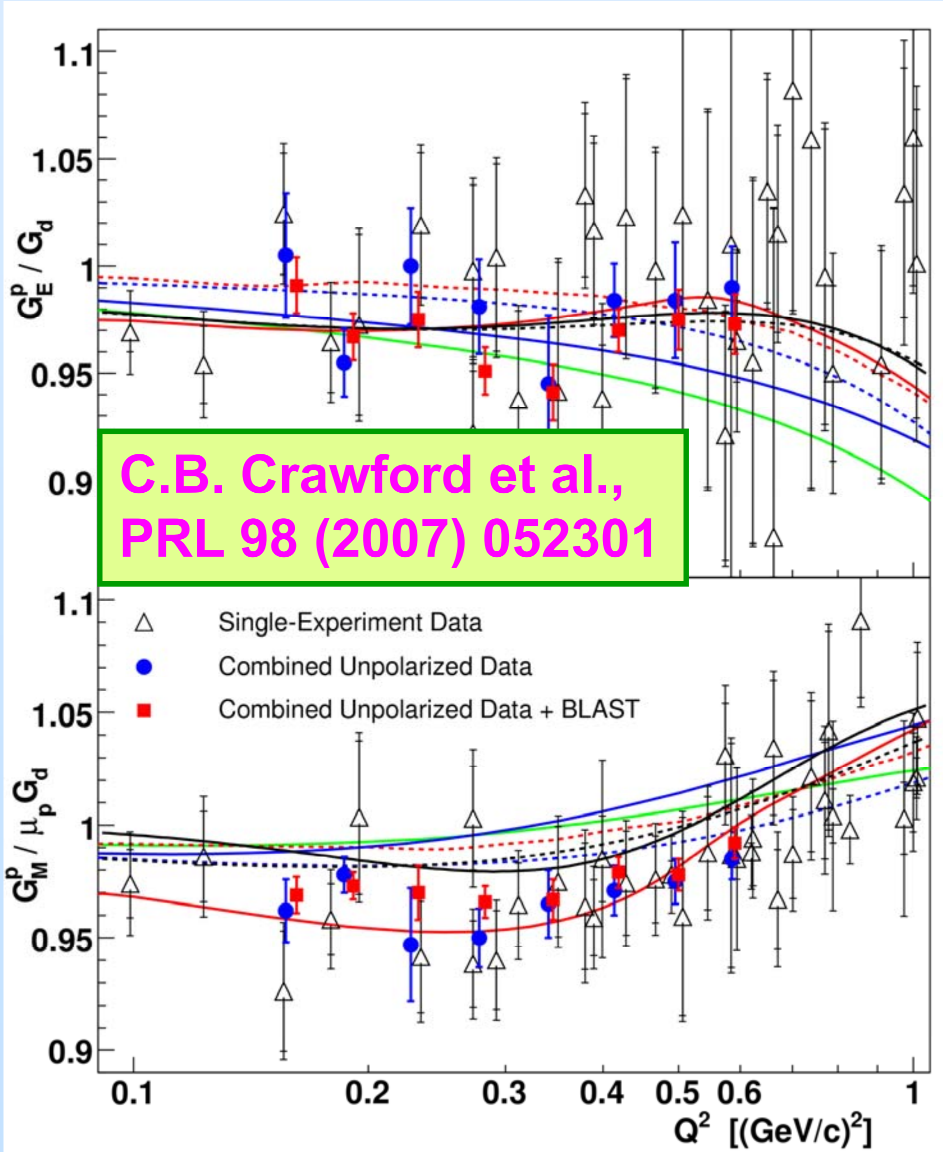
Data with electron detected in left and right sectors

- Beam and target asymmetries also evaluated individually; no significant false asymmetries detected
- A_{phys} fit with Höhler parameterization of form factors to extract $P_b\, P_t$ = 51.8 ±0.3%, 51.9% ±0.2%
  - Agreement $\rightarrow$ Confidence in target spin angle as determined from measurement of target holding field angle
- Value of target spin angle agrees with that determined from analysis of T_{20} in $e\,\overleftrightarrow{d}$ scattering
- Radiative corrections small
- 300 kC integrated e^- flux;

  90 pb^{-1} integrated luminosity

Proton Form Factor Ratio $\mu_p G^p_E / G^p_M$ (from A_L / A_R) *



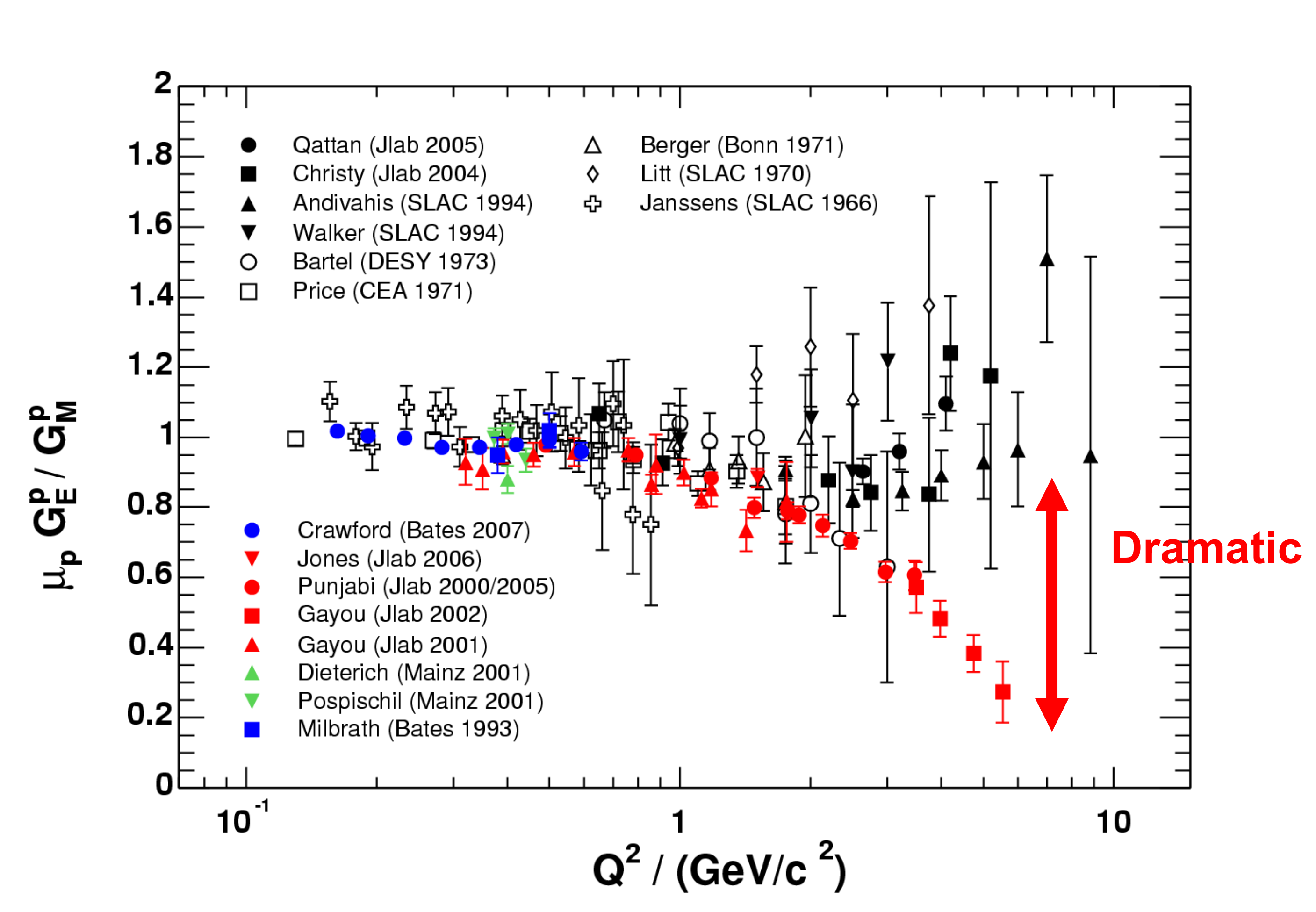


- Impact of BLAST data combined with cross sections on separation of G^p_E and G^p_M
- Errors factor ~2 smaller
- Reduced correlation
- Deviation from dipole at low Q^2!

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

Proton Form Factor Ratio

Jefferson Lab

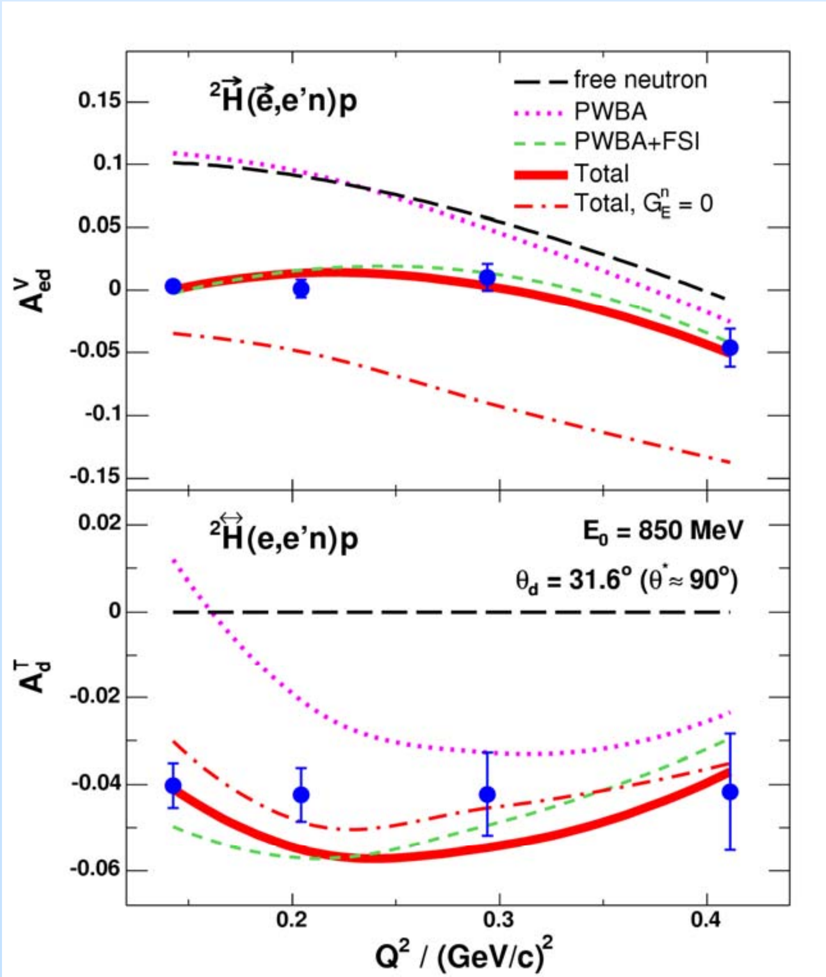


- All Rosenbluth data from SLAC and JLab in agreement
- Dramatic discrepancy between results of Rosenbluth and recoil polarization
- Multi-photon exchange considered probable explanation

Extraction of G^n_E from Quasielastic $^2\vec{H}(\vec{e},e'n)$ *

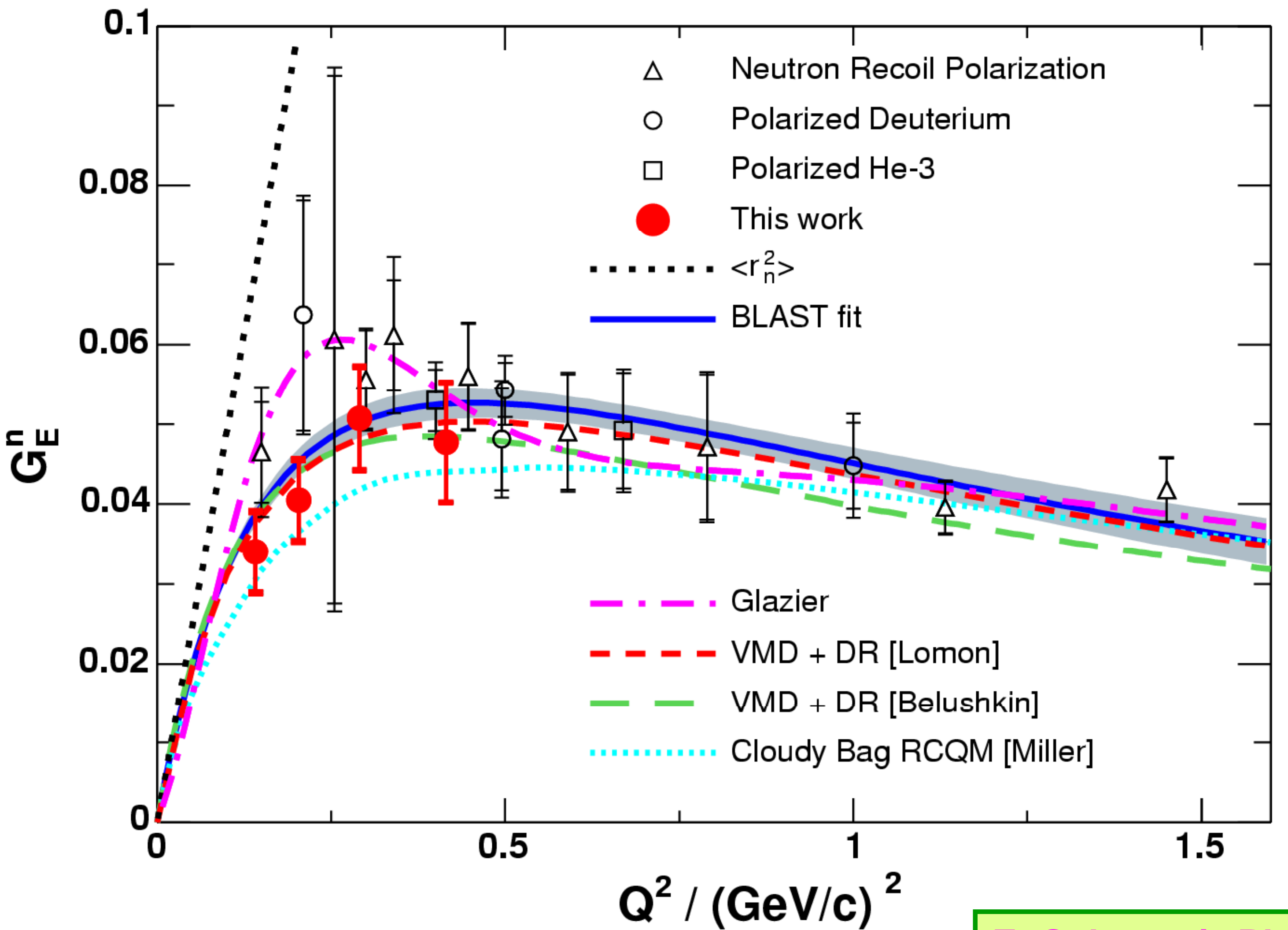
$$A^V_{ed} = \frac{a\, {G^n_M}^2 \cos\theta^* + b\, G^n_E G^n_M \sin\theta^* \cos\phi^*}{c\, {G^n_E}^2 + {G^n_M}^2} \approx a\cos\theta^* + b\,\frac{G^n_E}{G^n_M}\sin\theta^* \cos\phi^*$$

- Must account for FSI, MEC ,RC, IC
- Perform full Monte Carlo simulation of BLAST acceptance using deuteron electrodisintegration model of H. Arenhövel
- Spin-perpendicular beam-target vector asymmetry A^V_{ed} shows high sensitivity to G^n_E
- Compare measured A^V_{ed} with simulation, with G^n_E as a free parameter
- Use measured 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 *et al*., Phys. Rev. Lett. 101, 042501 (2008)

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

Systematic Uncertainties in G^n_E

Source of Systematic Error	Contribution
Target Polarization Angle, θ^S	5%
Product of Beam and Target Polarization, hP_z	1.2%
Reconstruction, $(Q^2, p_m, \theta^{np}_{cms})$	1%
Cut Dependence, $\|M_m - M_p\| \leq n\sigma$	1.5%
Uncertainty of G^n_M	1.5%
Radiative Corrections	0.7%
False Asymmetries	1%
Total	5.8%

Extraction of G^n_M from inclusive quasielastic $^2\vec{H}(\vec{e},e')$

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

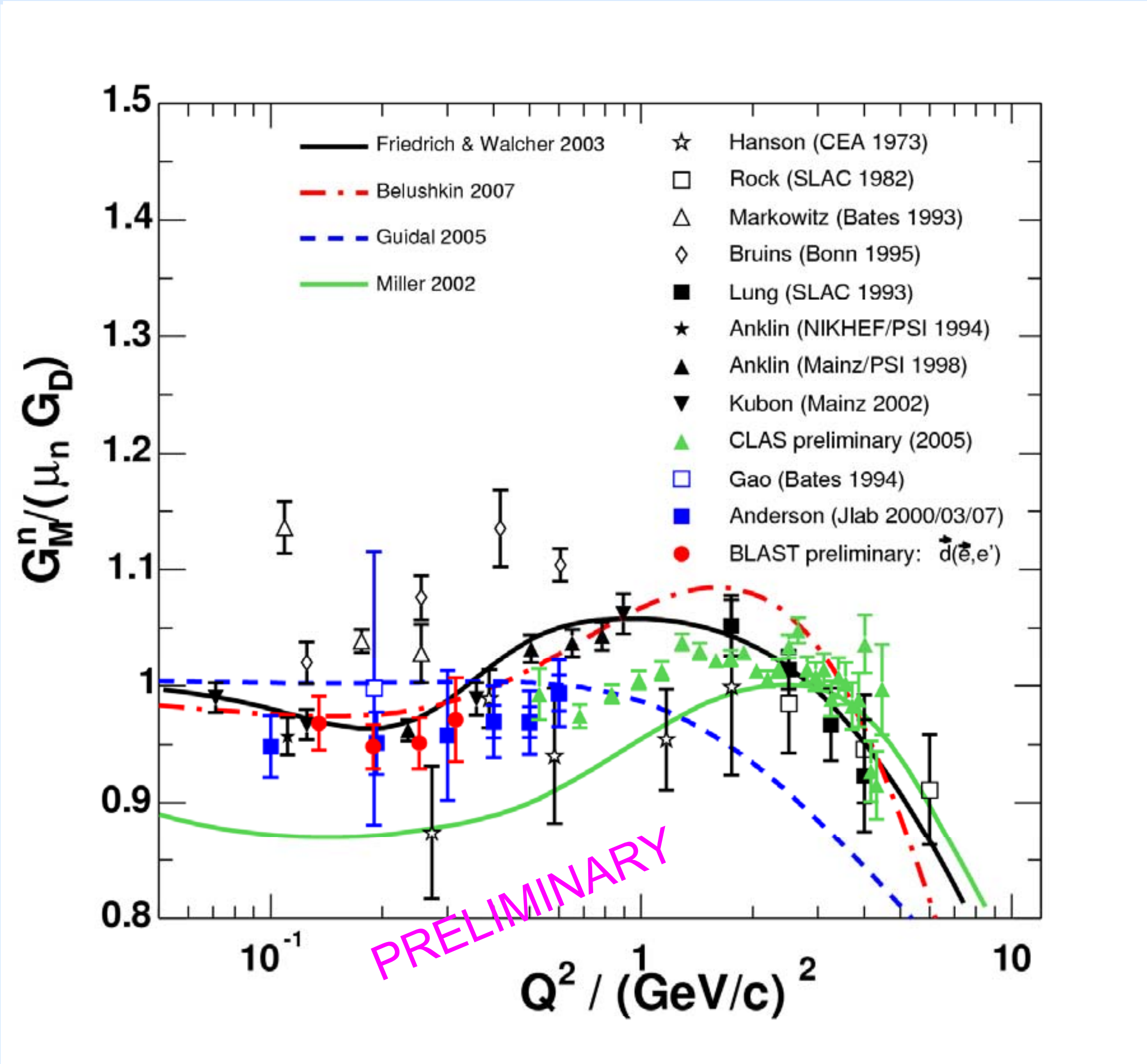
- Must account for FSI, MEC, RC, IC

- Perform full Monte Carlo simulation of BLAST acceptance using deuteron electrodisintegration model of H. Arenhövel

- Beam-target vector asymmetry A^V_{ed} in both spin-parallel and spin- perpendicular kinematics shows sensitivity to G^n_M

- Enhanced sensitivity in super-ratio

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 preliminary**

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

  + BLAST preliminary

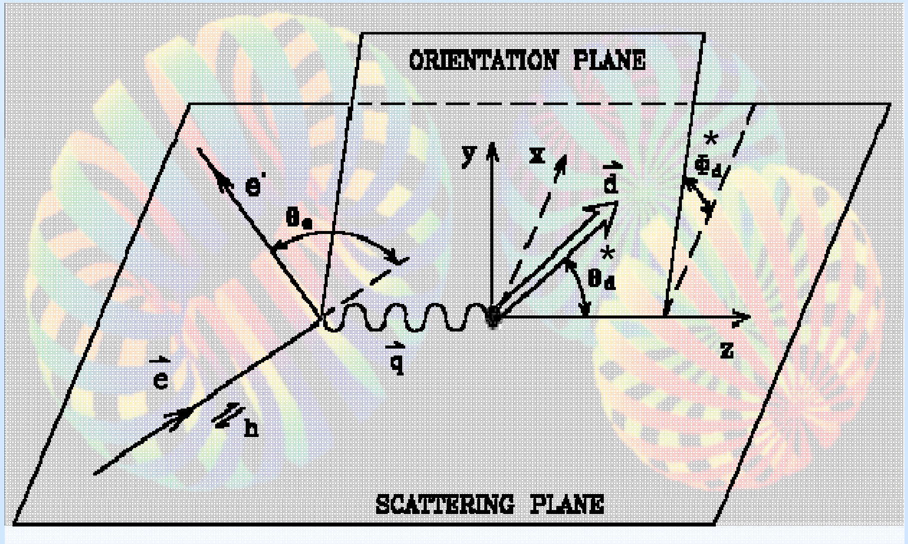
*Ph.D. work of N. Meitanis (MIT) and B. O'Neill (ASU)

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

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

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

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

- Polarized cross section

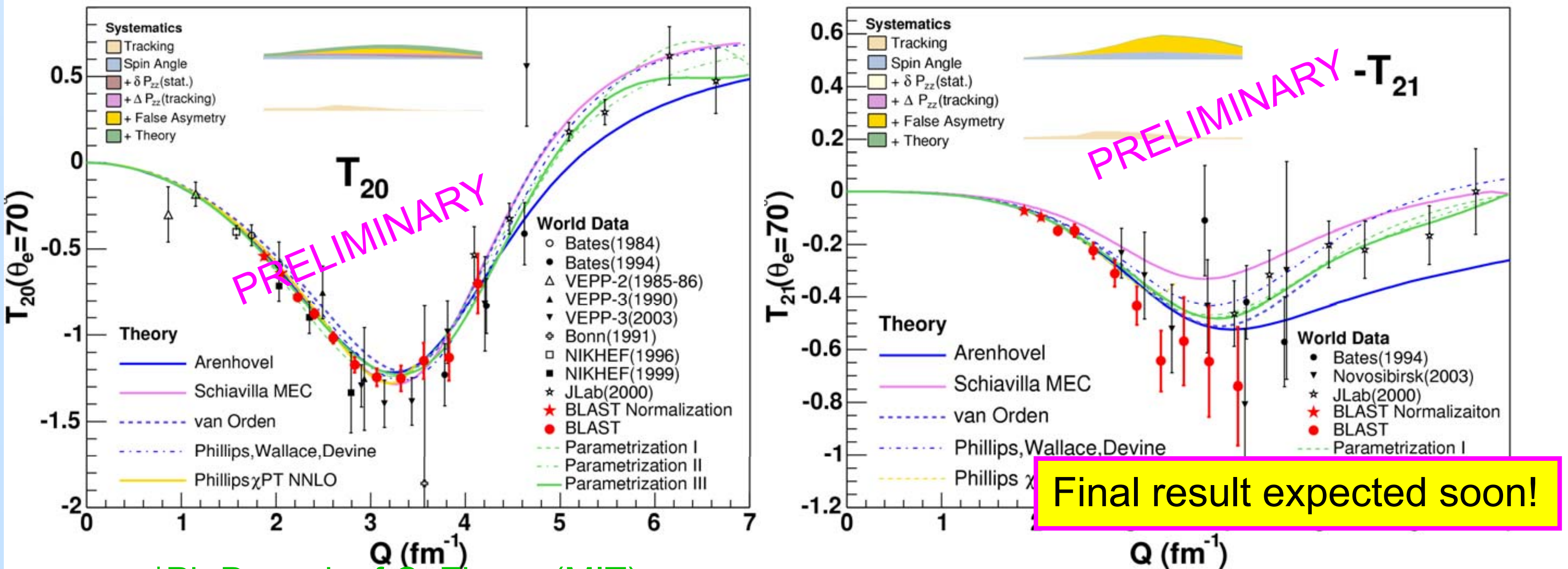
$$\sigma = \sigma_0 \left(1 + P_{zz} A^T_d + h P_z A^V_{ed}\right)$$

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

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

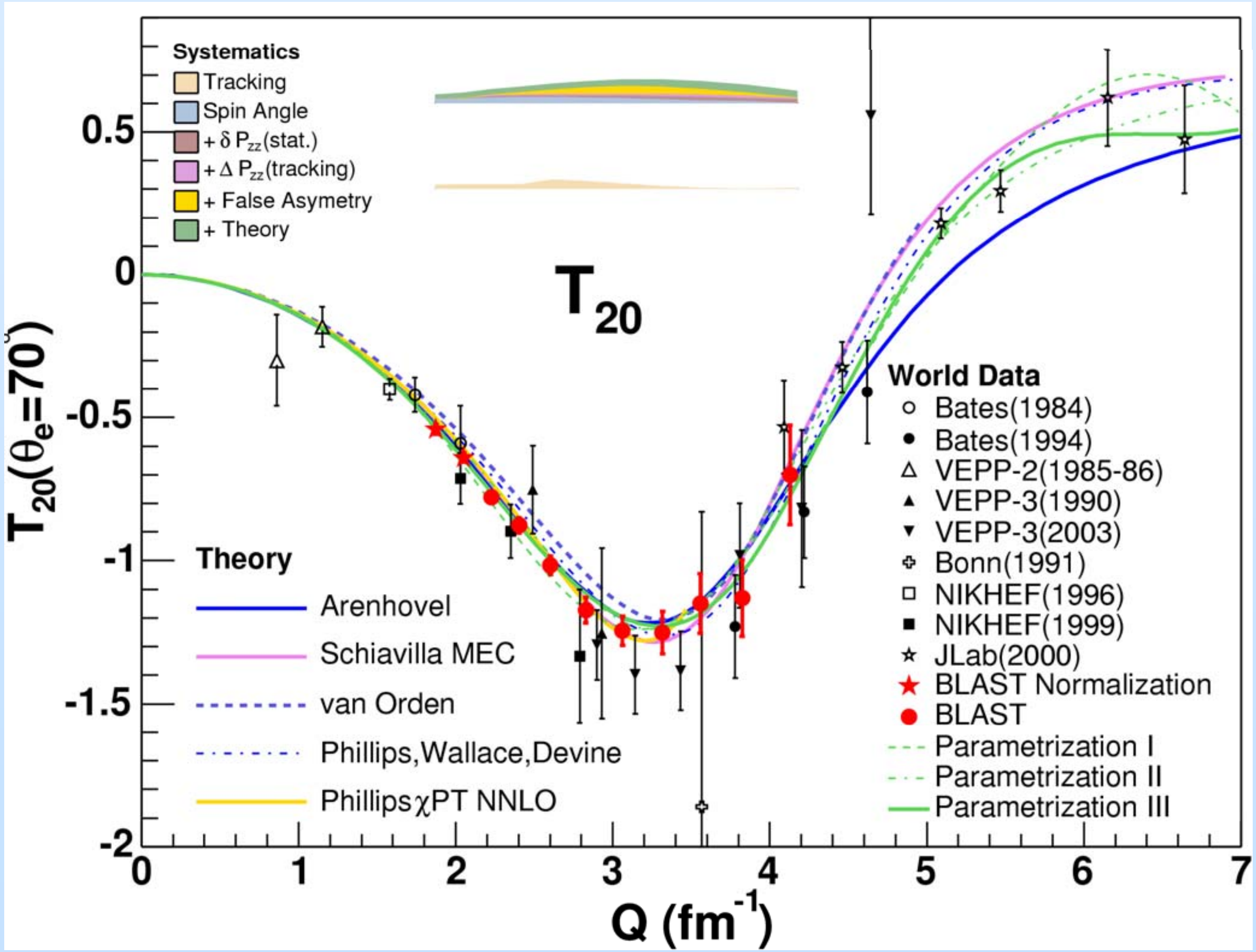
$$T_{20}(Q^2,\theta_e) = \frac{1}{\sqrt{2}S_0}\left[\frac{8}{3}\eta\, G_C^d G_Q^d + \frac{8}{9}\eta^2 {G_Q^d}^2 + \frac{1}{3}\eta\left(1 + 2\left(1+\eta\right)\tan^2\frac{\theta_e}{2}\right) {G_M^d}^2\right]$$

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



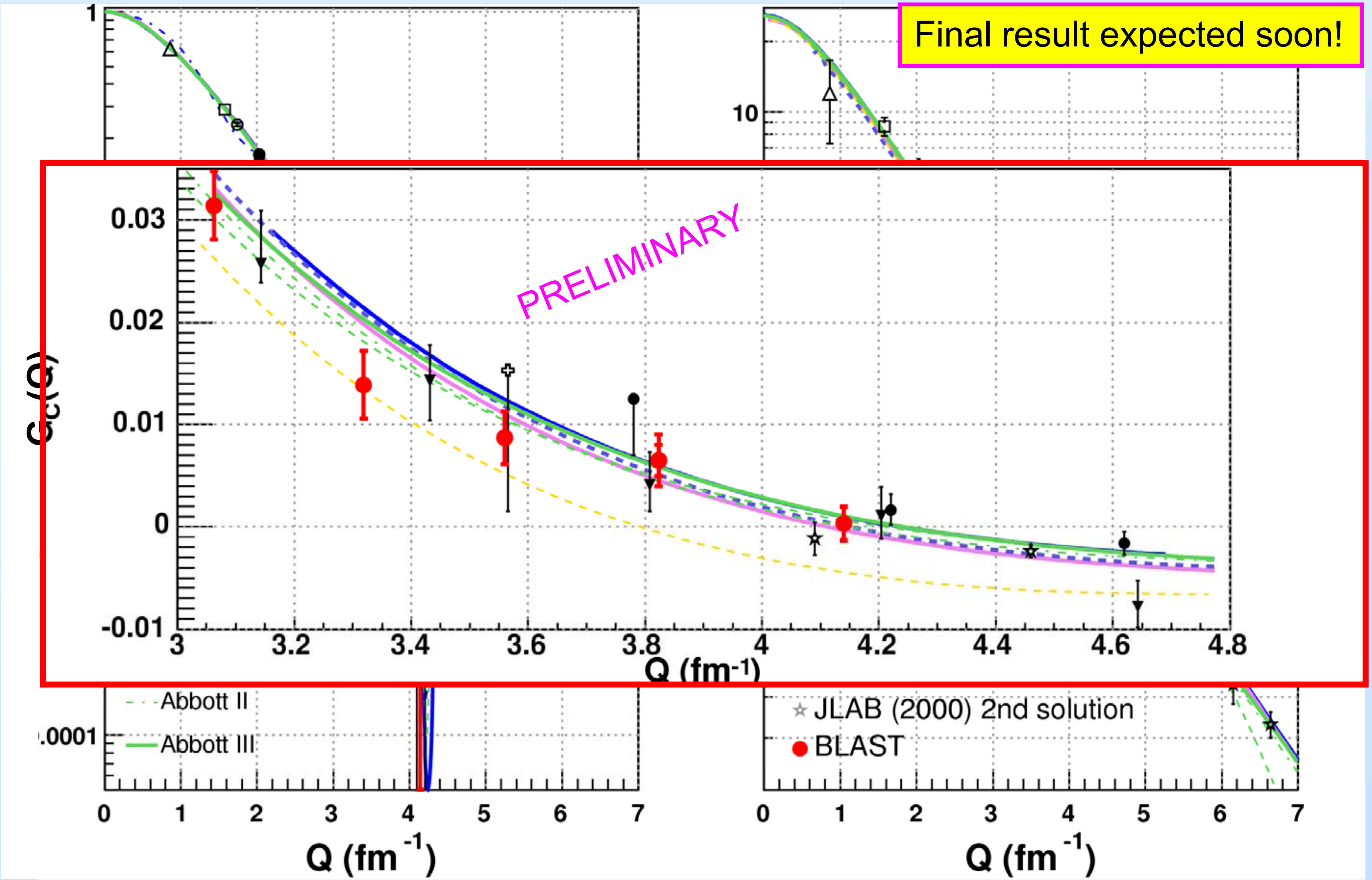
*Ph.D. work of C. Zhang (MIT)

Preliminary T_{20} data*



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

G_C and G_Q*



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

Other results on the deuteron

- Vector-polarized elastic ed scattering
  - $A^V_{ed} \rightarrow T_{10}, T_{11}$
    - Ph.D. work of P. Karpius (UNH)
- Electrodisintegration $\vec{D}(\vec{e},e'p)$
  - Beam-vector asymmetry as function of p_{miss}
    - Effect of *d*-state: A^V changes sign (seen in data)
  - Quasielastic tensor asymmetry
    - Ph.D. work of A. Maschinot and A. DeGrush (MIT)

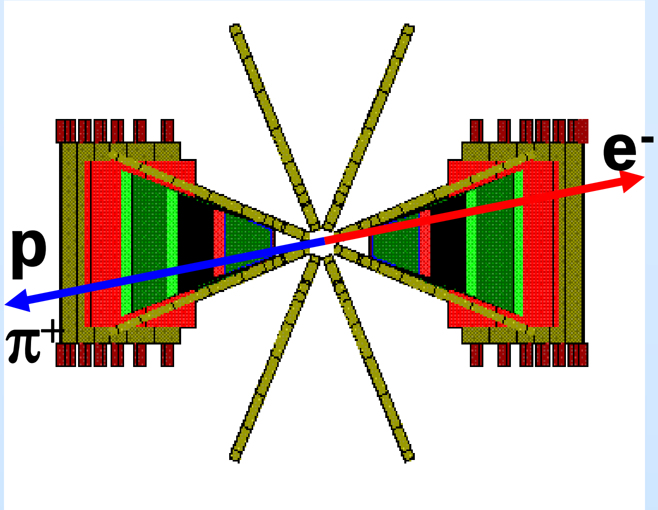
$\vec{H}(\vec{e},e')\Delta^+$, $\vec{H}(\vec{e},e'\pi^+)n$, $\vec{H}(\vec{e},e'p)\pi^0$

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

- **Trigger 1: (Charged)**

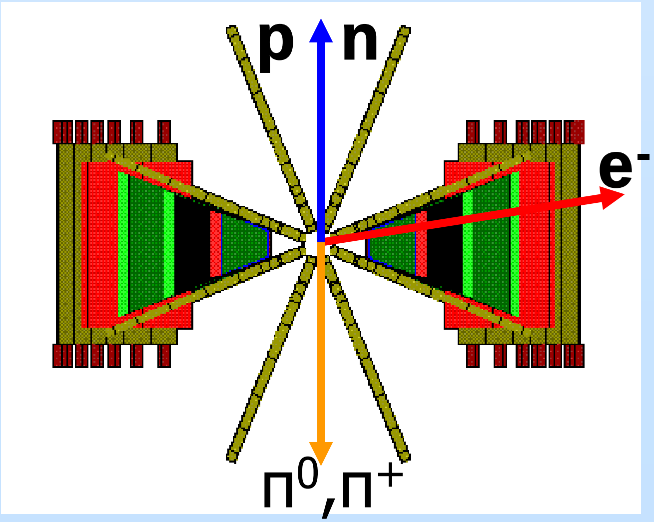
$\vec{p}(\vec{e},e'p)\,\pi^0$

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



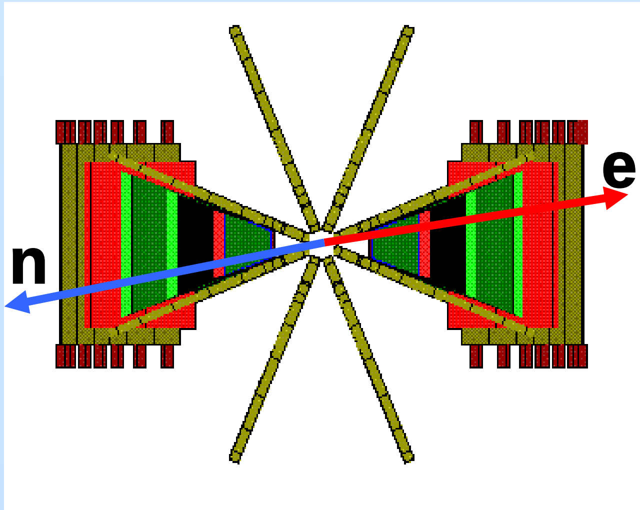
- **Trigger 7: (Inclusive)**

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



- **Trigger 2: (Neutral)**

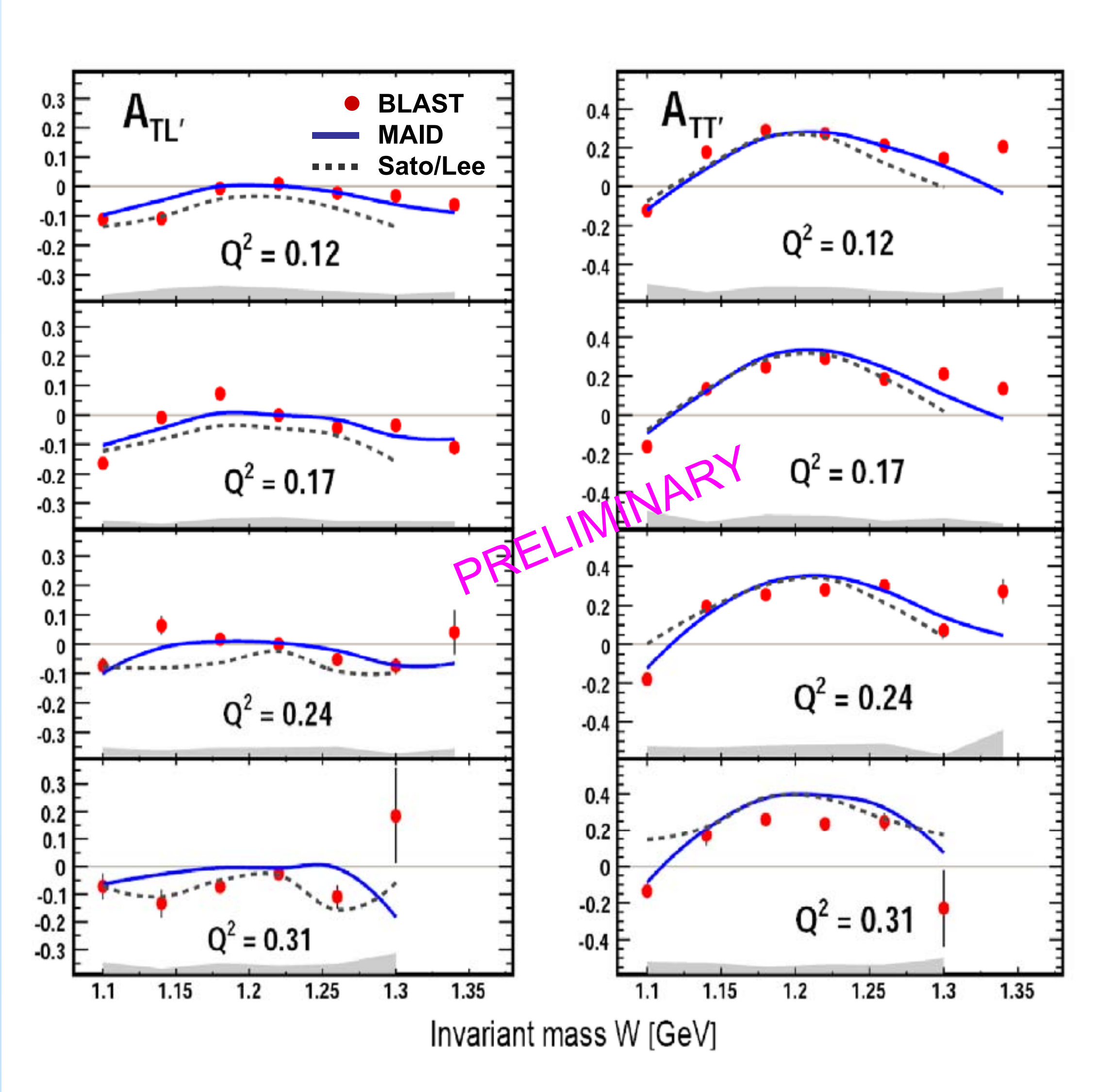
$\vec{p}(\vec{e},e'n)\pi^+$



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

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

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



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

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_{S_z}.

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

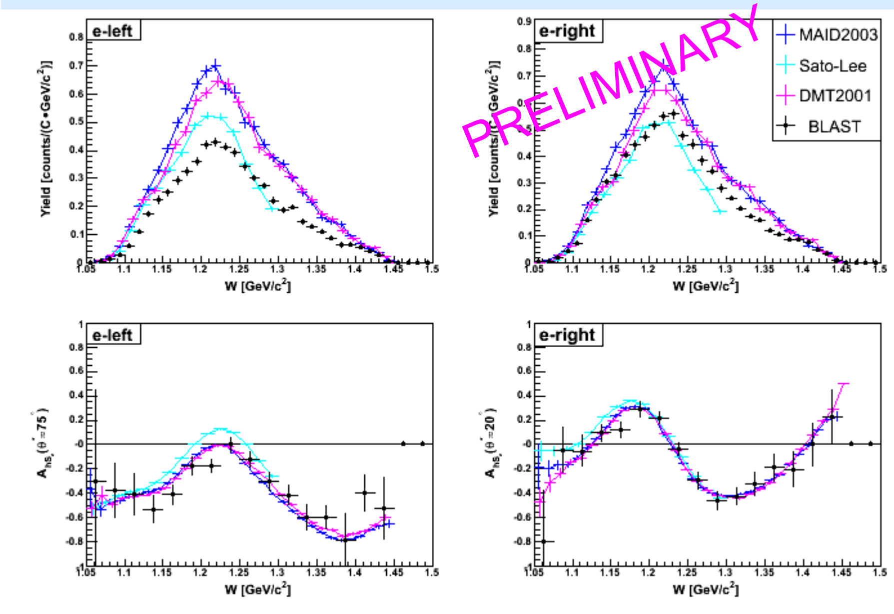
4. Double Asymmetry, A_{hS_z}

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

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

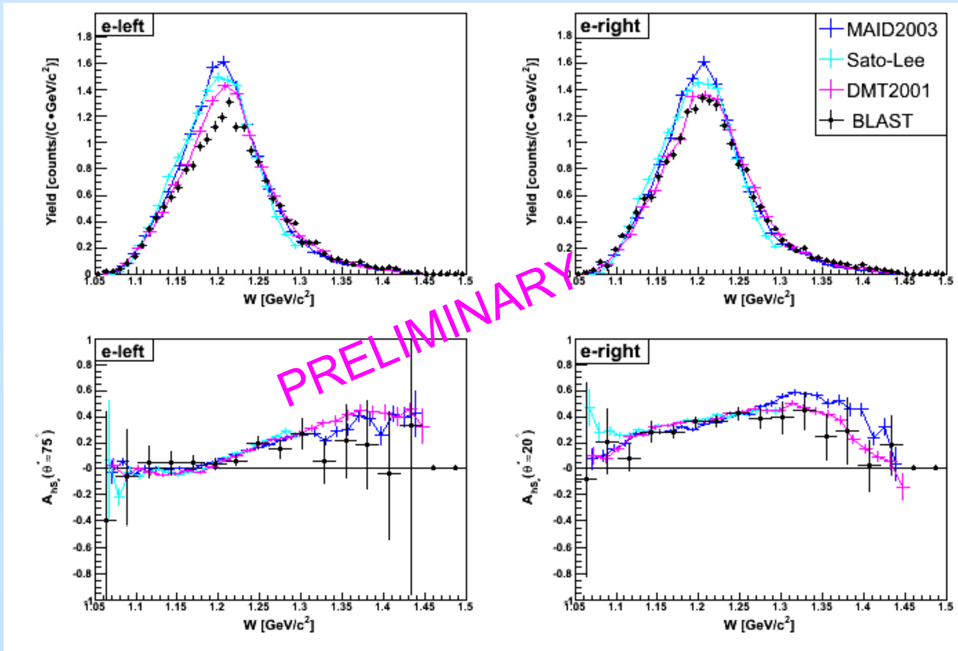
$\vec{H}(\vec{e},e'\pi^+)n$ and $\vec{H}(\vec{e},e'p)\pi^0$ exclusive *

Double Asymmetry A_{hS_z}



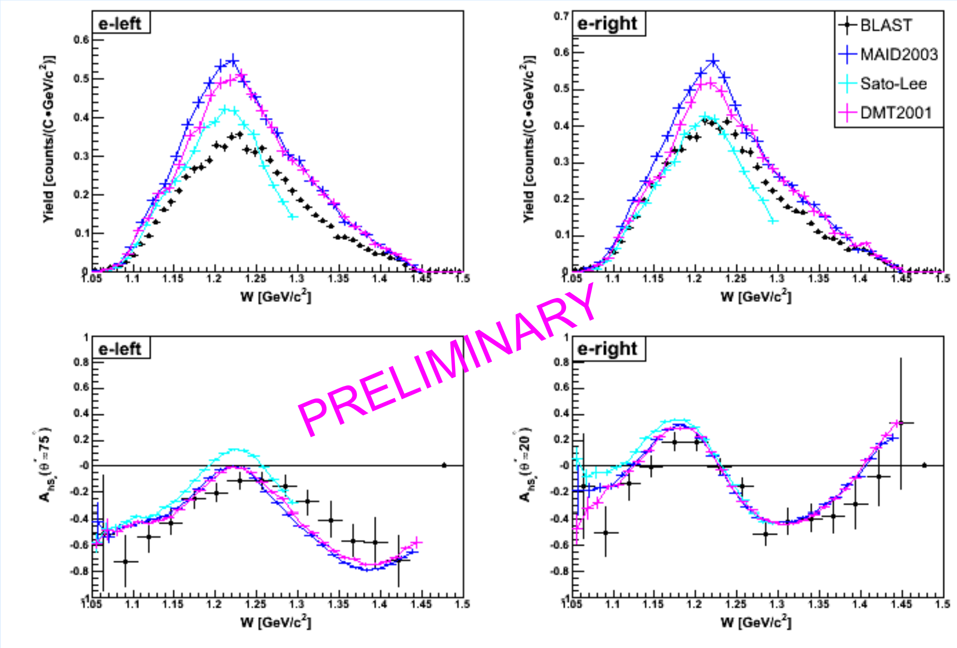
π^+ channel

π^0 channel

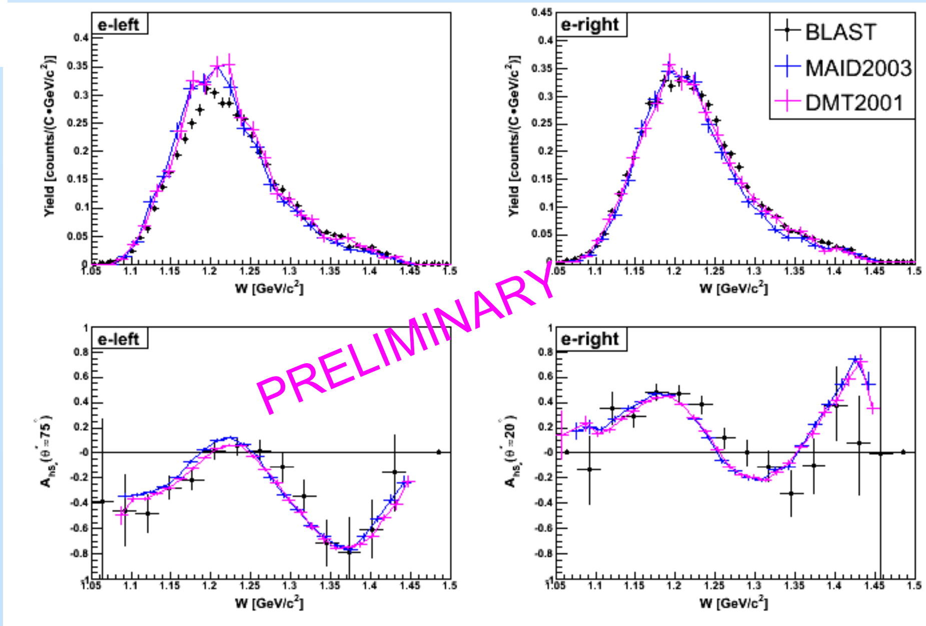


*Analysis by A. Shinozaki (MIT); Ph.D. work of Y. Xiao (MIT)

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



$D(e,e'\pi^{+})$ channel
Models: π^{+} from free p



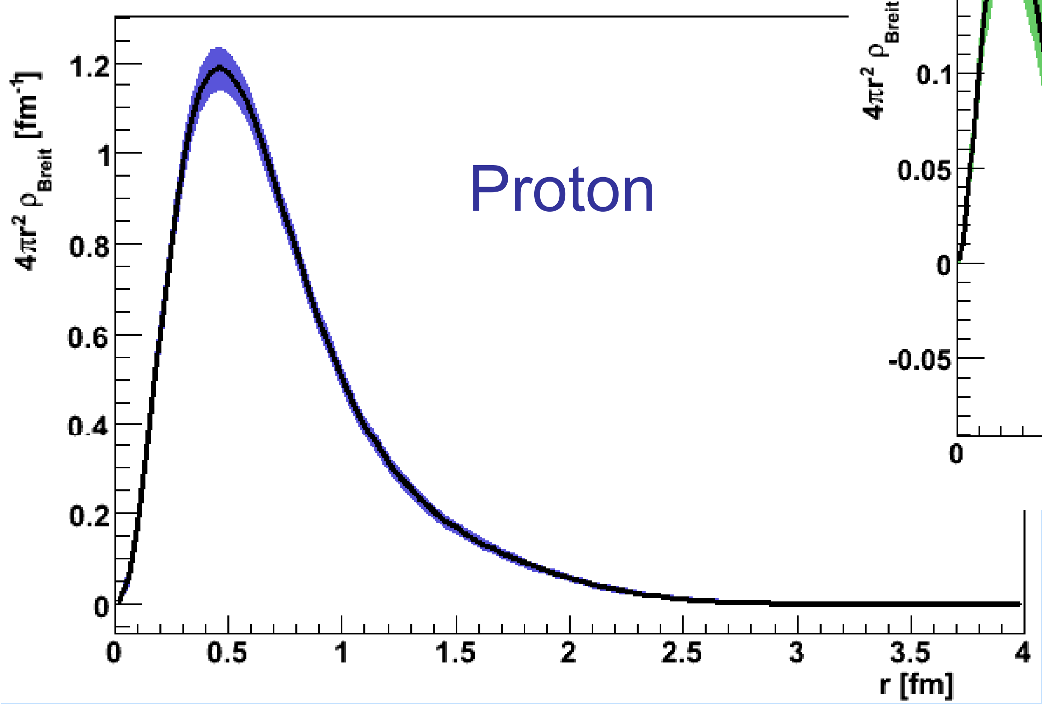
$D(e,e'\pi^{-})$ channel
Models: π^{-} from free n

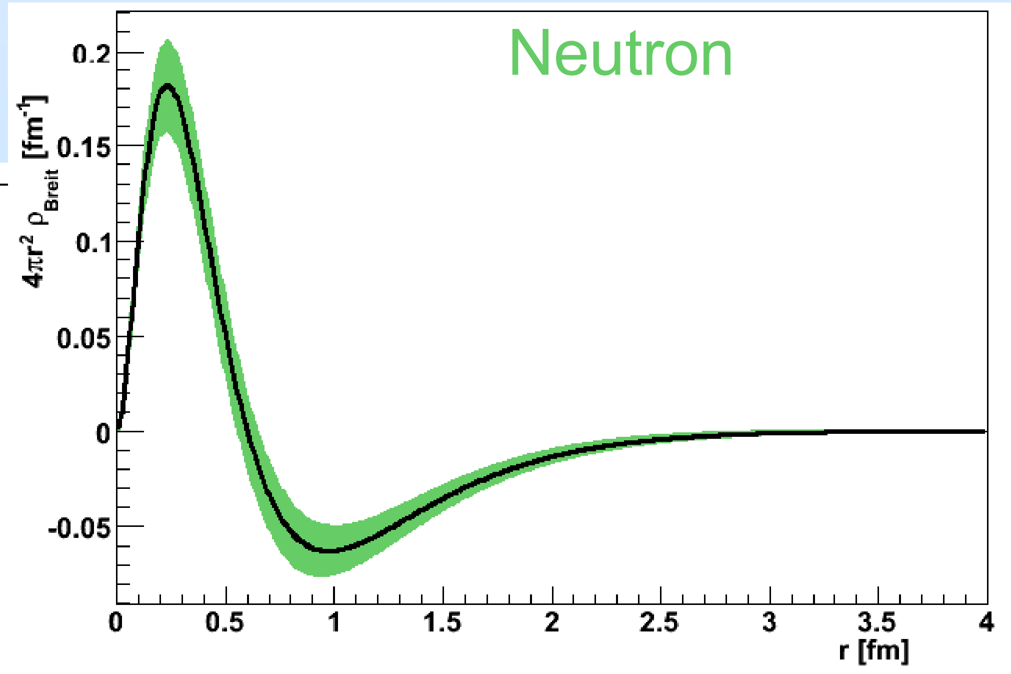
*Analysis by A. Shinozaki (MIT)

Charge distributions

$$4\pi r^2 \rho^{p,n}_{Breit}(r) \equiv \frac{2}{\pi}\int_0^\infty dr\; qr \sin qr\; G_E^{p,n}(Q^2)\Big|_{Breit}$$

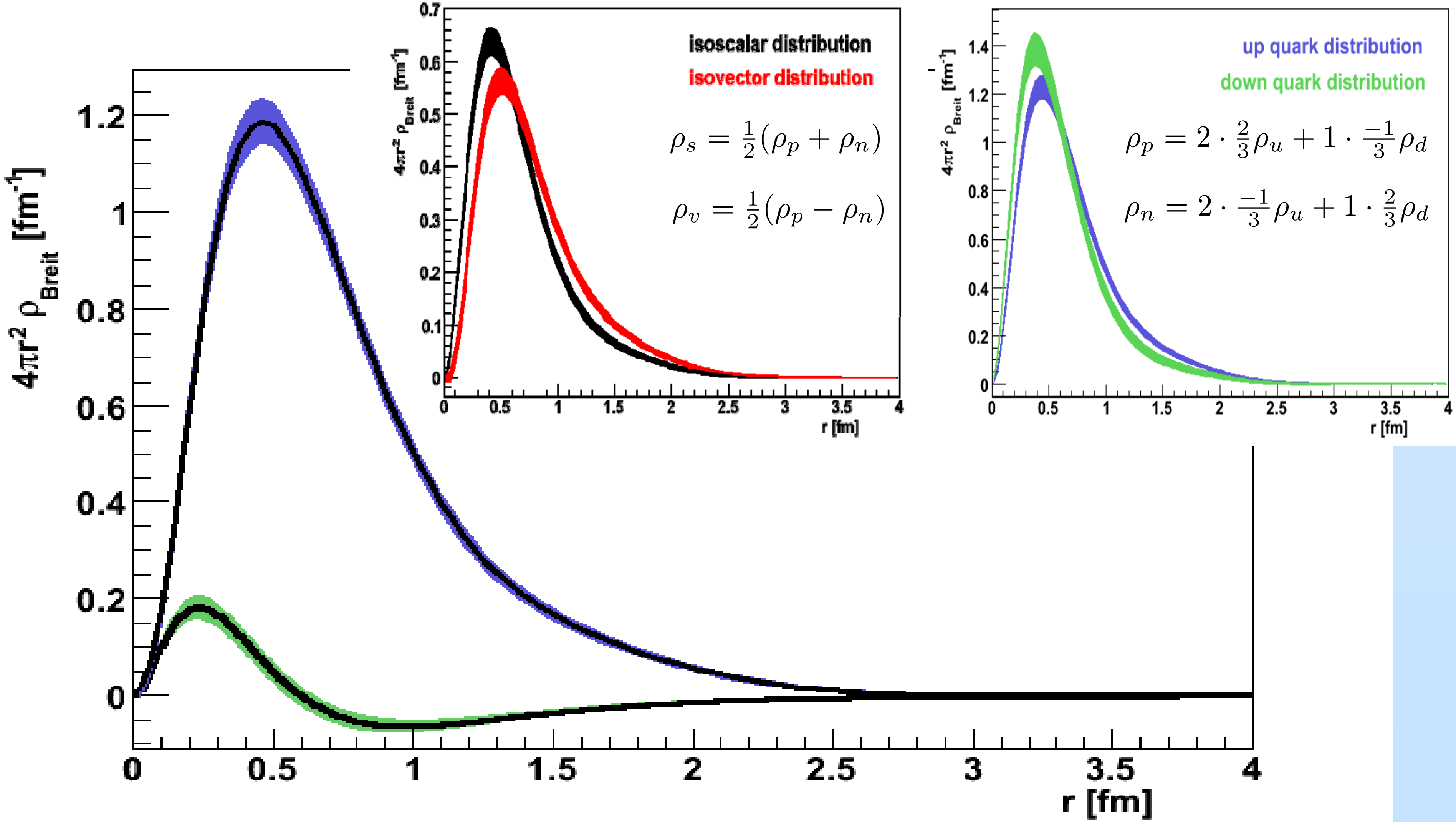
$$\sqrt{|Q^2|} = |\boldsymbol{q}|$$





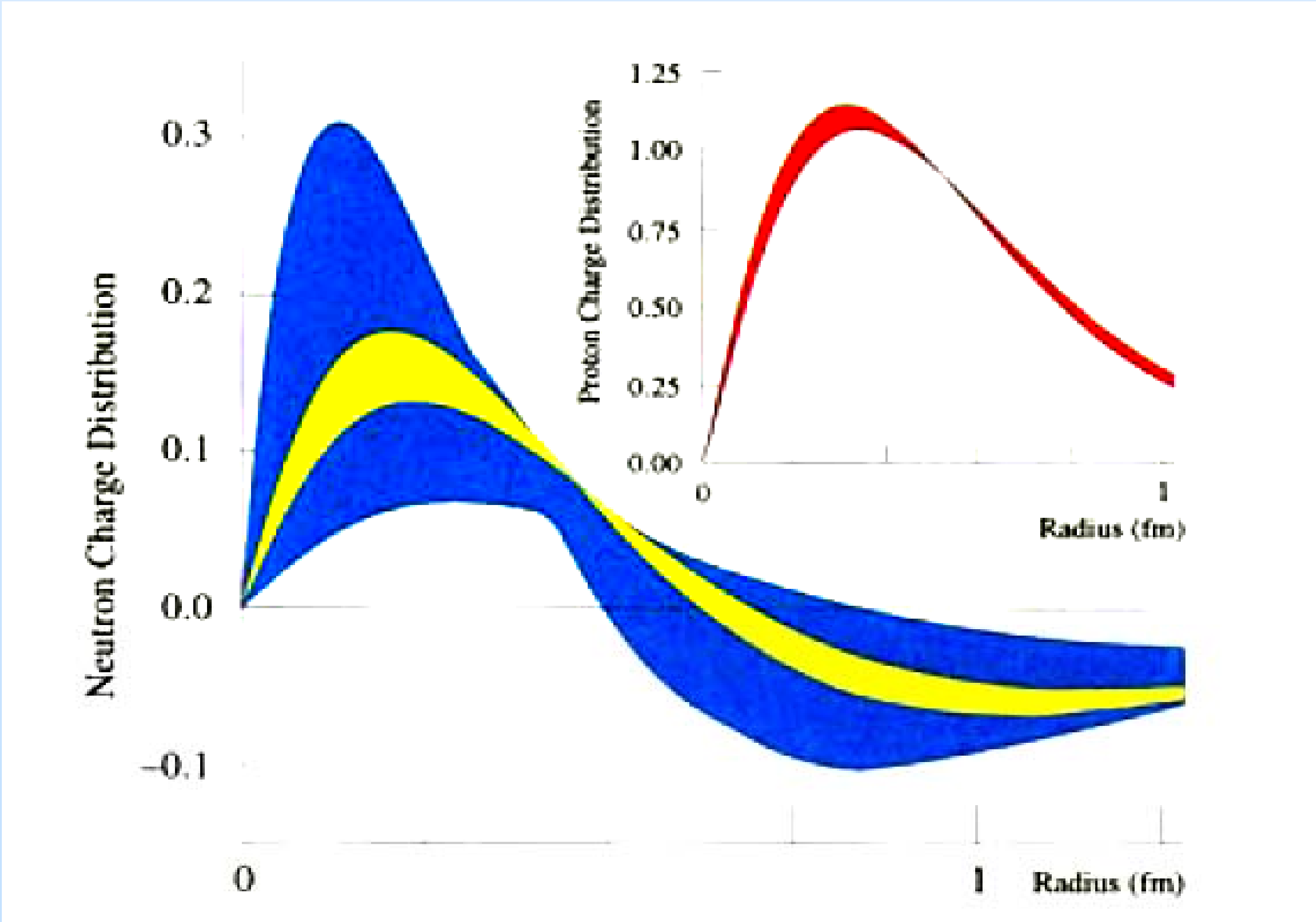
The Frontiers of Science:
A Long Range Plan (Dec 2007)

Isospin and Quark Distributions



Pre-BLAST Charge Distributions

Nuclear Physics: The Core of Matter, The Fuel of Stars
National Research Council (1999)



Summary of BLAST physics

- **Proton, neutron**, and **deuteron** spin observables measured with **polarized electron beam**

  ∗ **High precision, excellent control of systematics**

- **Nucleon structure:**
  - Consistent and precise determination of elastic **nucleon form factors** at low momentum transfer
    → **Structure at low Q^2 beyond dipole form factor**

- **Deuteron structure:**
  - Precision measurement of T_{20} allows separation of G^d_C and G^d_Q
  - First measurement of T_{11} allows determination of G^d_M at low Q^2
  - Asymmetries in electrodisintegration probe *d*-state in deuteron wave function
- **Pion production** from **H** and **D**
  - Single and double spin asymmetries in $N \rightarrow \Delta$ transition (**H**)
  - Double and tensor asymmetries in pion production on **D**

Collaboration

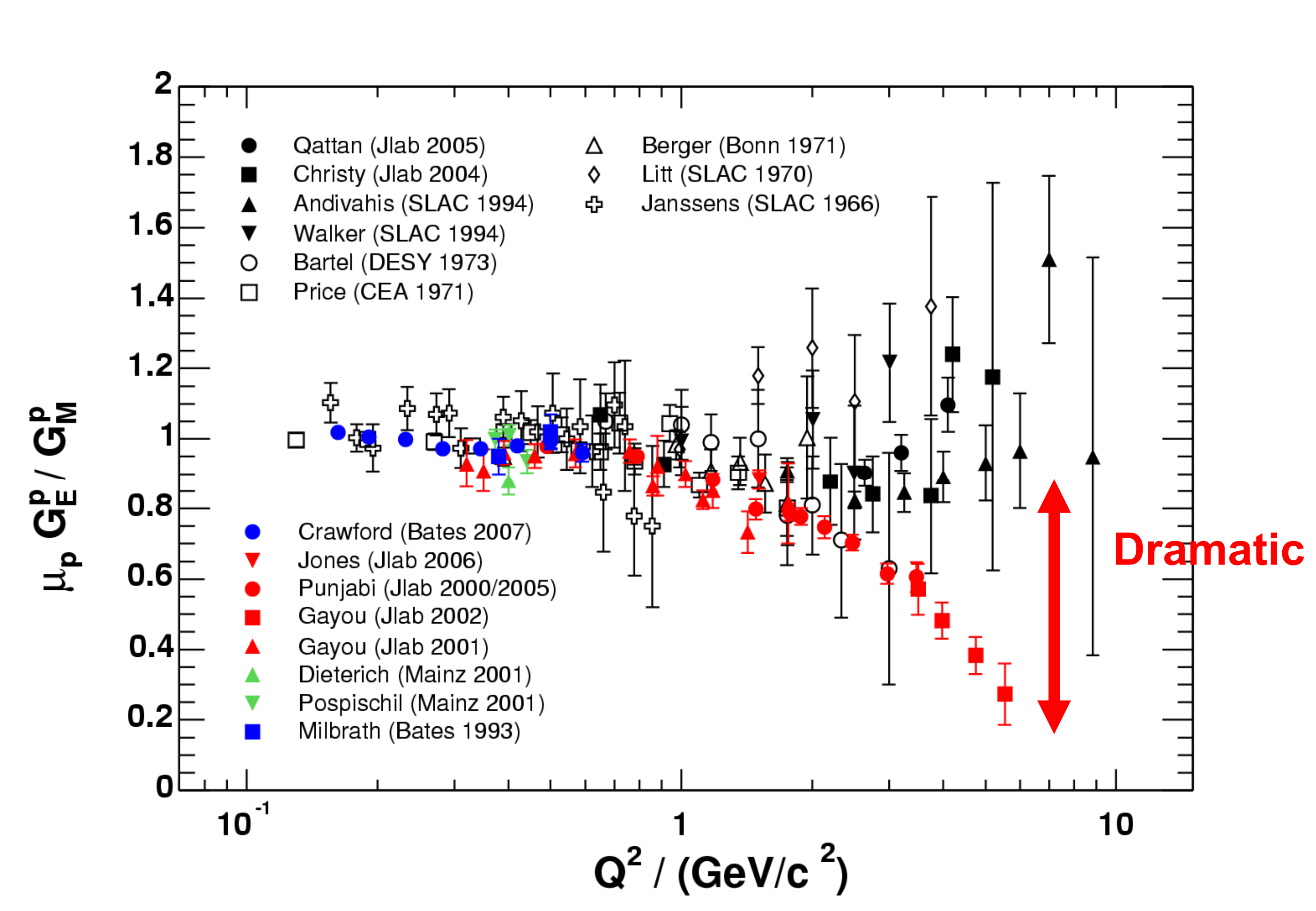
- **BLAST A GREAT SUCCESS!!!**
- **First-class single and double polarization data on H and D in elastic, quasielastic and Δ region**
- **Produced 9 Ph.D.'s + 3 more to come**

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[f], C. D'Andrea[c], A. Degrush[f], K. Dow[f], D. Dutta[d], M. Farkhondeh[f], R. Fatemi[f], O. Filoti[i], W. Franklin[f], H. Gao[d], E. Geis[a], S. Gilad[f], A. Goodhue[c], W. Haeberli[j], D. Hasell[f], W. Hersman[i], M. Holtrop[i], E. Ilhoff[f], P. Karpius[i], 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[c], H.R. Poolman[k], R. Prince[a], J. Rapaport[g], R. Redwine[f], J. Seely[f], A. Shinozaki[f], A. Sindile[i], 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[j], 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*
[h] *United States Naval Academy, Annapolis, MD 21402*
[i] *University of New Hampshire, Durham, NH 03824*
[j] *University of Wisconsin, Madison, WI 53706*
[k] *Vrije Universitaet and NIKHEF, Amsterdam, The Netherlands*

Future of BLAST?

Proton Form Factor Ratio

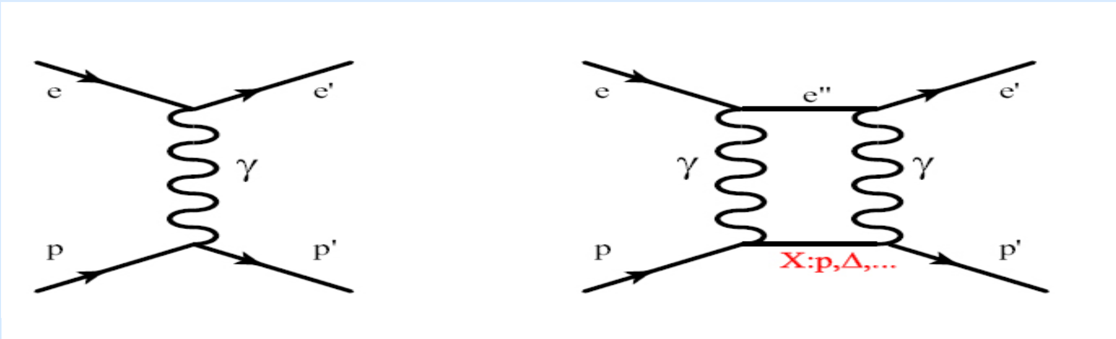


Jefferson Lab

Dramatic discrepancy!

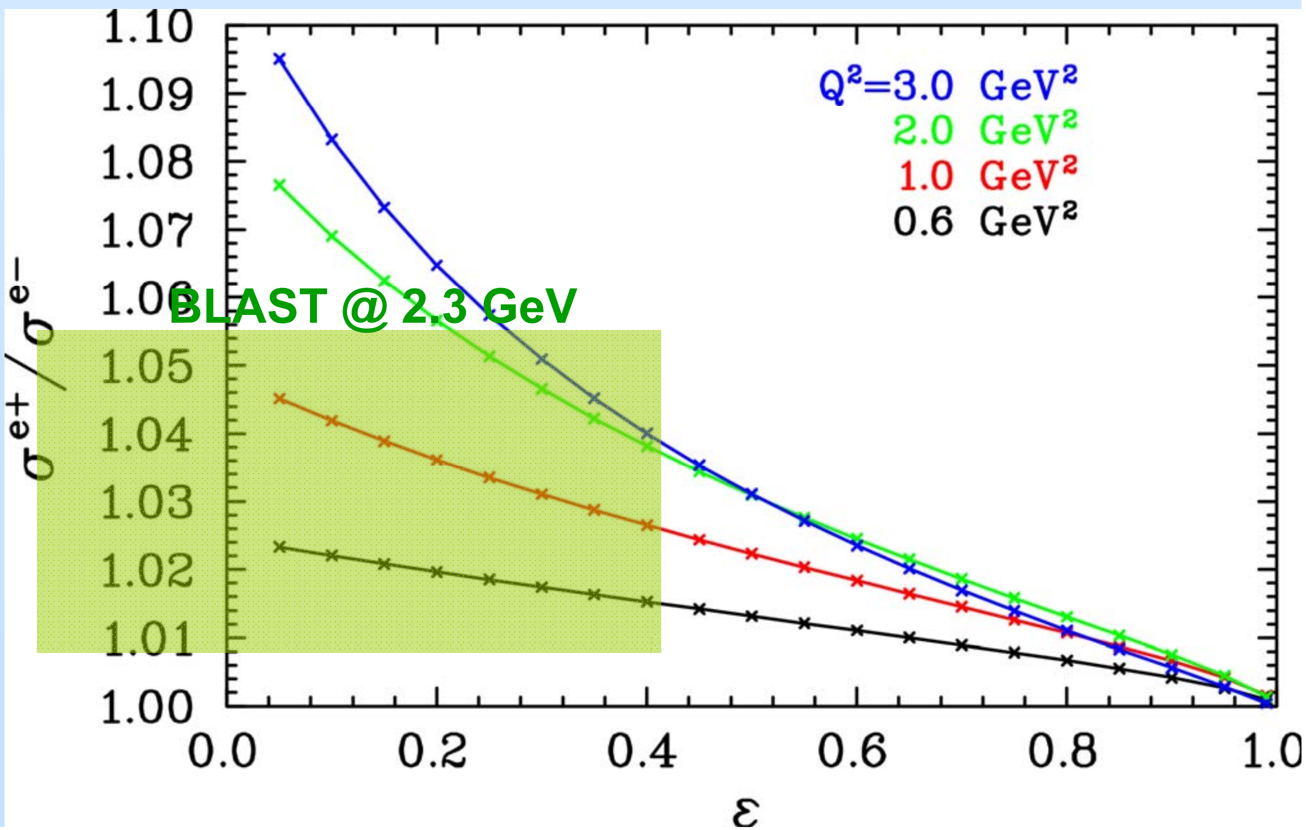
- **All Rosenbluth data from SLAC and JLab in agreement**
- **Dramatic discrepancy between results of Rosenbluth and recoil polarization**
- **Multi-photon exchange considered probable explanation**

Two-photon exchange

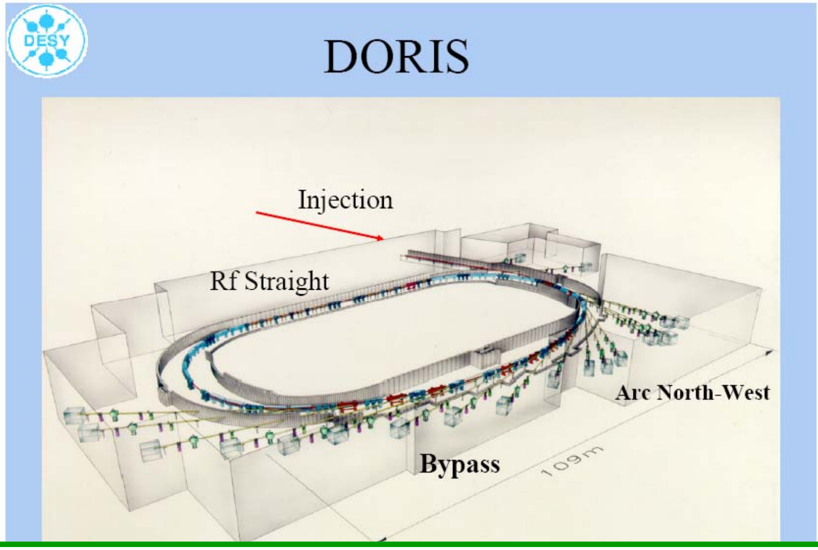


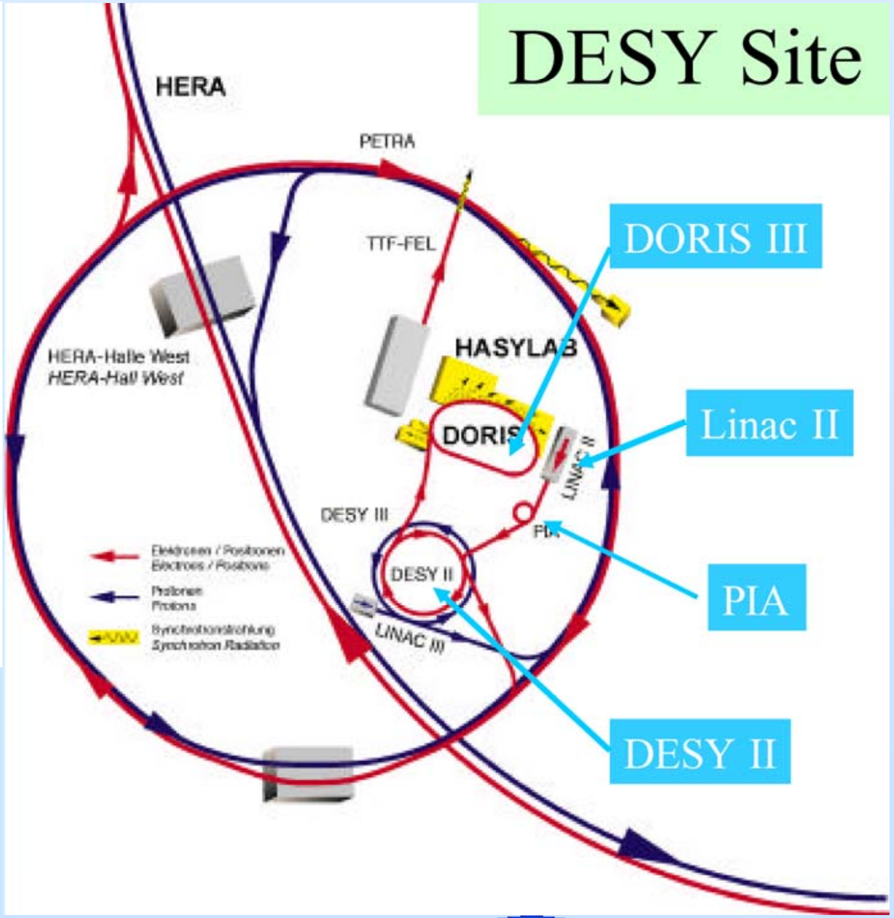
One- and two-photon amplitudes will interfere: interference term has opposite sign for e^+ and e^- scattering

Ratio of cross sections for positron-proton and electron-proton elastic scattering (P. Blunden) as a function of virtual photon polarization



Letter of intent to install BLAST in DORIS ring submitted to DESY in 2007; full proposal in Sept. 2008





An Experiment to Definitively Determine the Contributions of Multiple Photon Exchange in Elastic Lepton-Nucleon Scattering

K. Dow, W. Franklin, D. Hasell, E. Ihloff, J. Kelsey, M. Kohl, J. Matthews, R. Milner, R. Redwine, C. Tschalaer, E. Tsentalovich, B. Turchinetz, J. van der Laan, and F. Wang
MIT Laboratory for Nuclear Science and Bates Linear Accelerator Center

J. Arrington
Argonne National Laboratory

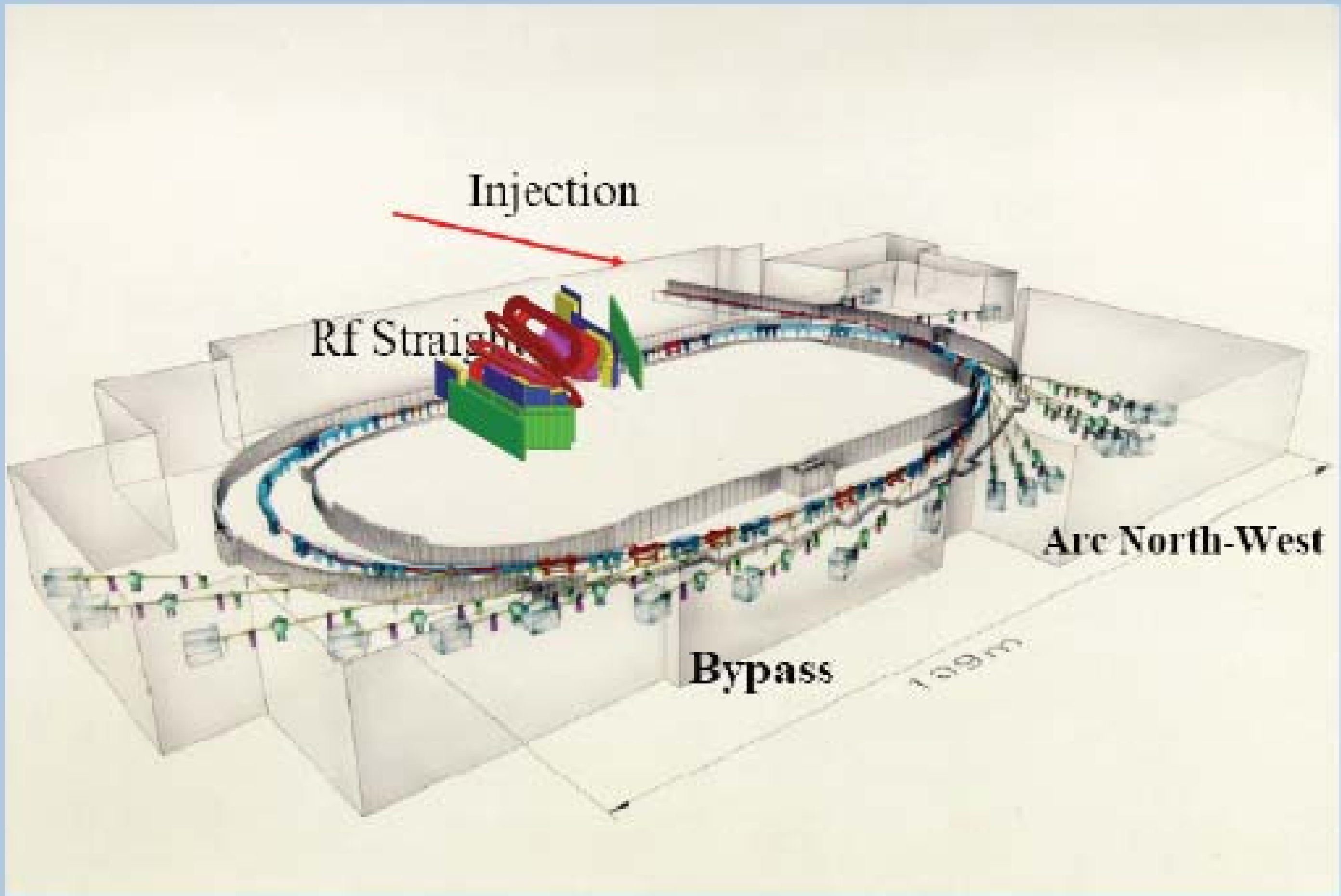
R. Alarcon
Arizona State University

J. Calarco
University of New Hampshire

June 19, 2007

Abstract

DORIS



OLYMPUS

pOsitron-proton and

eLectron-proton elastic scattering to test the

hYpothesis of

Multi-

Photon exchange

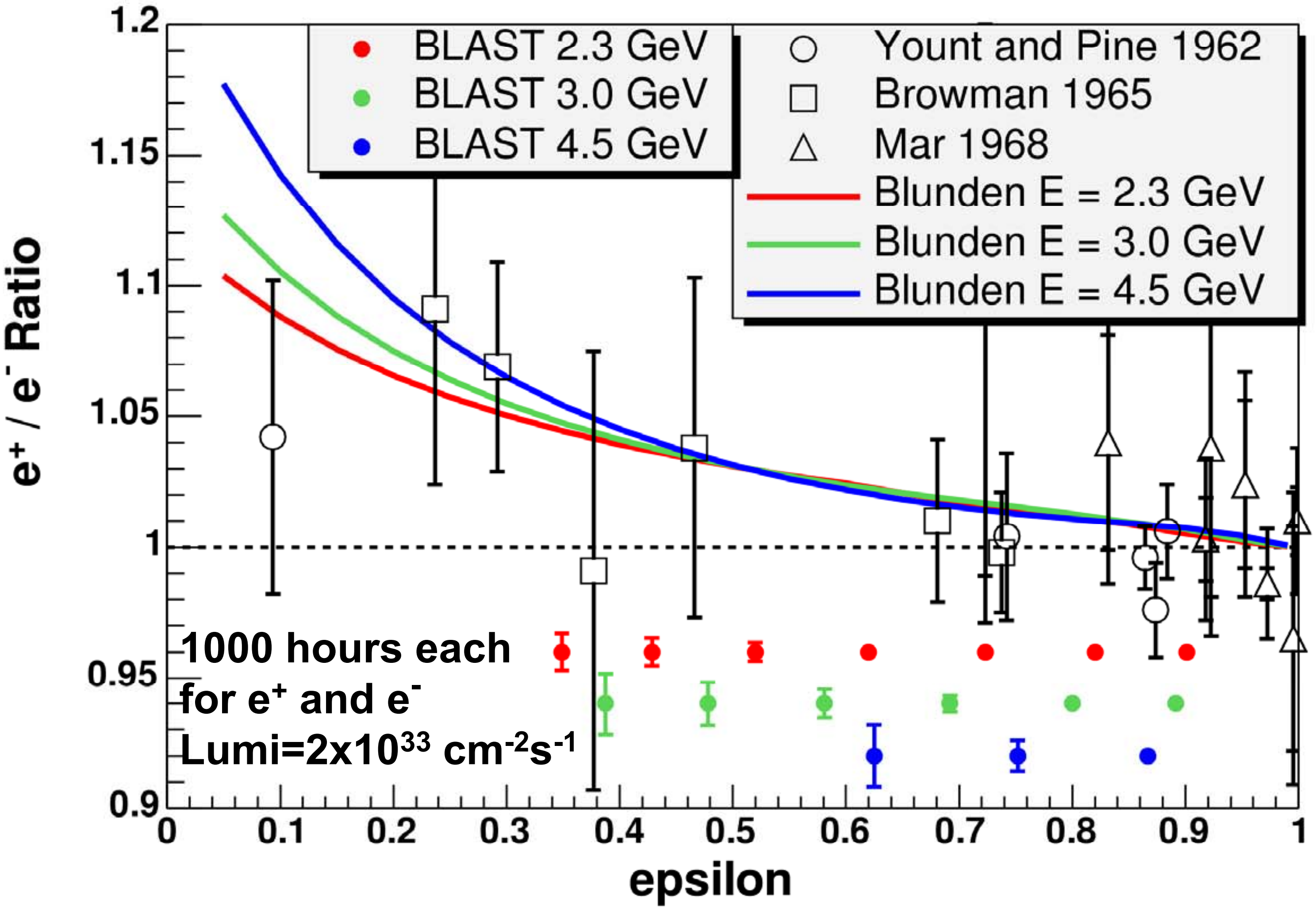
Using

DoriS

OLYMPUS

2008 – Proposal submitted
2009 – Transfer of BLAST
2010 – Engineering run

Projected Results for OLYMPUS



Control of Systematics

Super-ratio:

$$\left[\frac{N_{e^+ +}/L_{e^+ +}}{N_{e^- +}/L_{e^- +}} \cdot \frac{N_{e^+ -}/L_{e^+ -}}{N_{e^- -}/L_{e^- -}}\right]^{\frac{1}{2}} = \frac{\sigma_{e^+}}{\sigma_{e^-}}$$

Cycle of four states: e $^{\pm}$, BLAST magnetic field polarity ±
Repeat cycle many times

- **Change between electrons and positrons regularly**
- **Change BLAST polarity every day**
- **Left-right symmetry provides additional redundancy – two identical experiments simultaneously taking data**

OLYMPUS collaboration (9/2008)

- **USA**
  - Arizona State University
  - University of Colorado
  - Hampton University
  - University of Kentucky
  - Massachusetts Institute of Technology
  - University of New Hampshire
- **Germany**
  - Universität Bonn
  - DESY, Hamburg
  - Universität Erlangen-Nürnberg
  - Universität Mainz
- **Italy**
  - INFN, Bari
  - INFN, Ferrara
  - INFN, Rome
- **Russia**
  - St. Petersburg Nuclear Physics Institute
- **United Kingdom**
  - University of Glasgow

Summary

- The current dramatic discrepancy between recoil polarization and Rosenbluth measurements of the elastic form factor ratio G_E^p/G_M^p constitutes a serious challenge to our understanding of the structure of the proton.
- The widely accepted explanation in terms of multiple photon exchange demands a definitive confirmation. A precision measurement of the e^+p/e^-p cross section ratio will directly test the contribution of multiple photon effects.
- As the prediction of the magnitude of these effects is model-dependent, the experiment described here will provide a strong constraint on theoretical calculations.
- The proposed experiment takes advantage of unique features of the BLAST detector combined with an internal hydrogen gas target and the DORIS storage ring operated with both electrons and positrons.
  - The systematic uncertainties are controllable at the percent level, and with the superior luminosity that can be provided at DORIS, this experiment will not be limited in statistical precision.

Conclusion

- ~~BLAST~~ OLYMPUS has a future
- Stay tuned!

BACKUP slides

Relativistic effects involve factors of

$$\gamma_i = m_N / E_i$$

$$\gamma_f = m_N / E_f$$

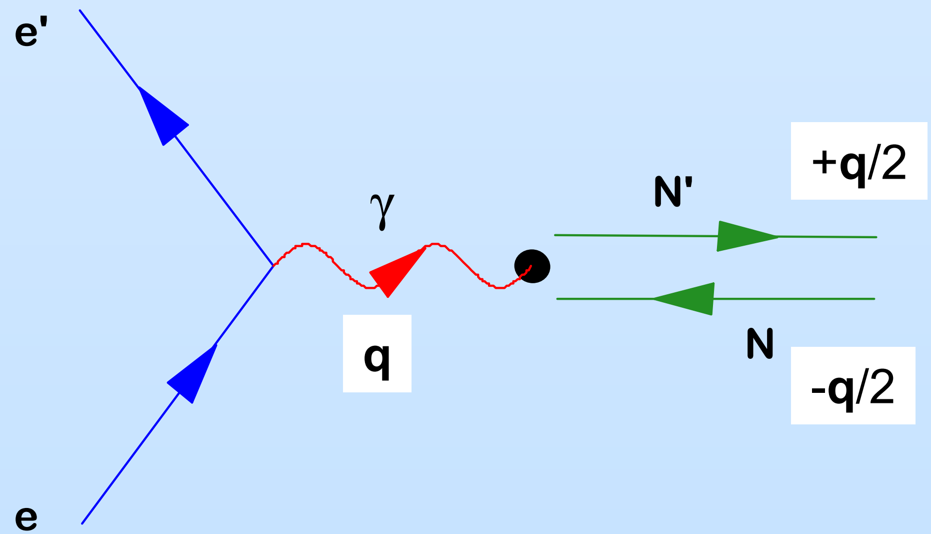
Product $\gamma_i \gamma_f$ minimized in the Breit frame where

$$\boldsymbol{p}_f = -\boldsymbol{p}_i = \boldsymbol{q}/2$$

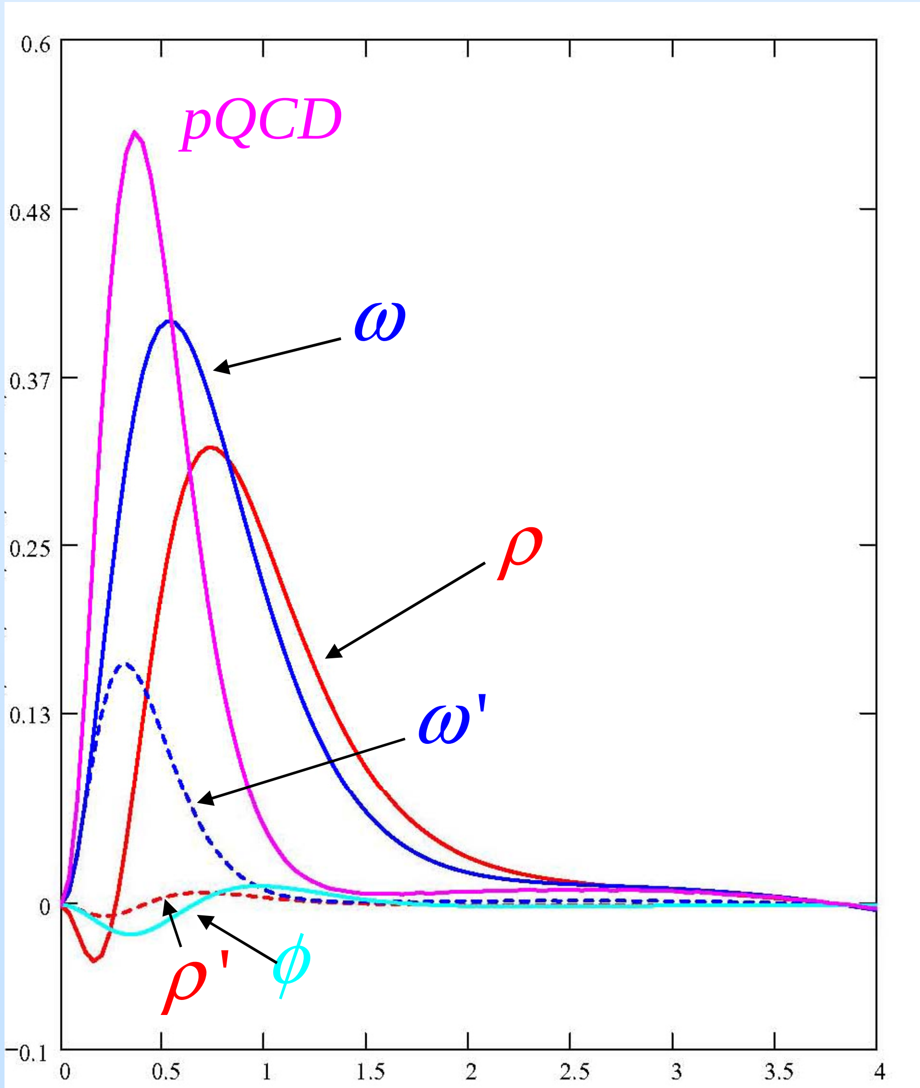
$$\omega = 0 \leftrightarrow \sqrt{|Q^2|} = |\boldsymbol{q}|$$

$$\gamma_f = \gamma_i \equiv \gamma_{Breit} = \sqrt{1+\tau}$$

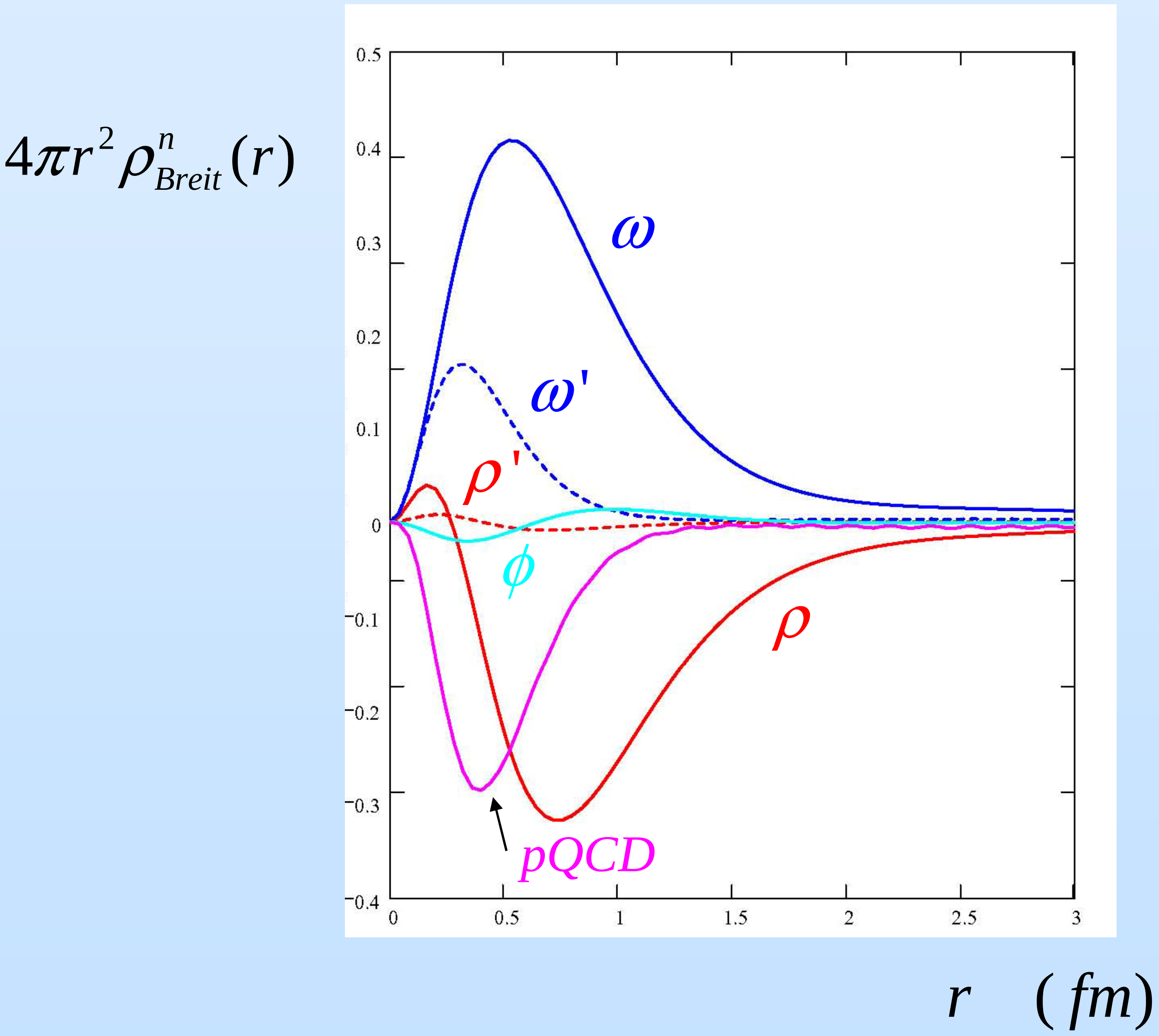
$$\tau = |Q^2| / 4m_N^2$$



$4\pi r^2 \rho^p_{Breit}(r)$



$r \quad (fm)$



4πr²ρ^n_Breit(r)
ω
ω'
ρ'
φ
ρ
pQCD
r (fm)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
0
0.5
1
1.5
2
2.5
3

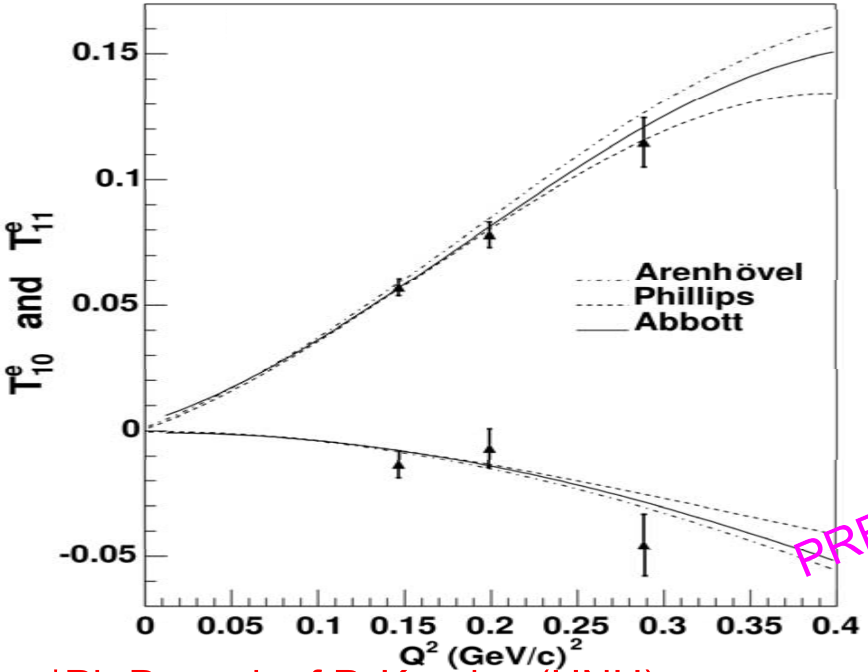
Vector-pol. Elastic ed Scattering

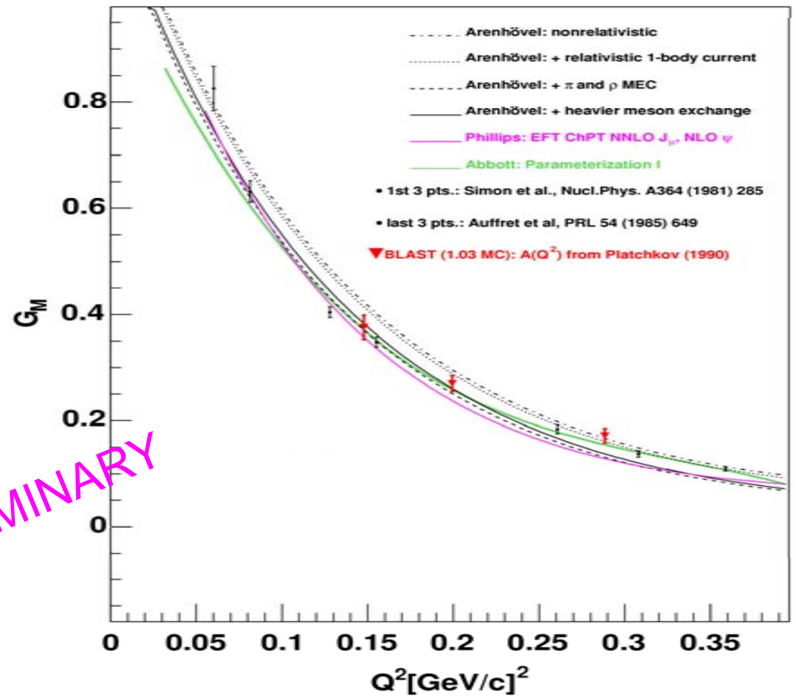
$$A_{ed}^{V} = \sqrt{3}\left(\frac{1}{\sqrt{2}}\cos\theta_d\, T_{10}^{e} - \sin\theta_d \cos\phi_d\, T_{11}^{e}\right)$$

Final result expected soon!

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

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



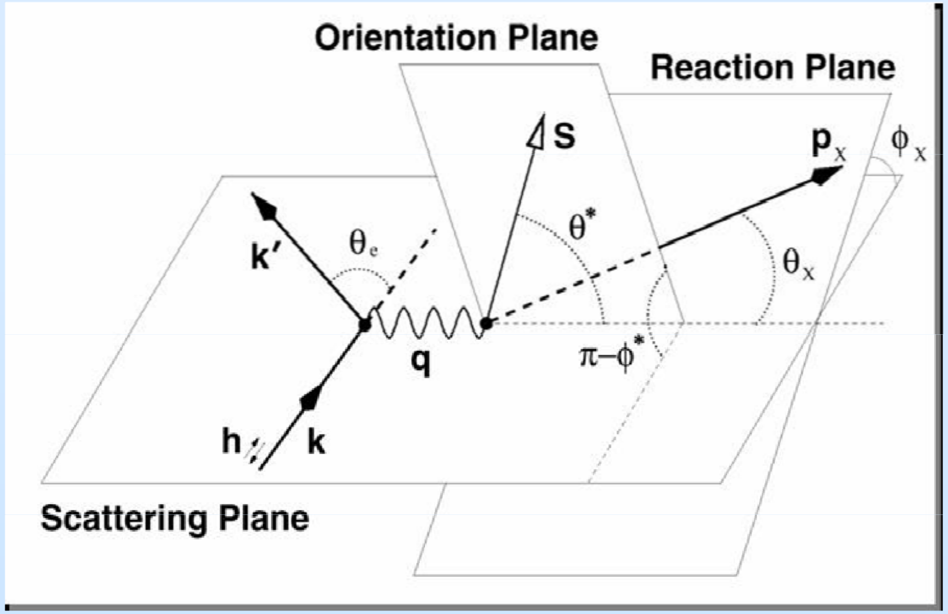


PRELIMINARY

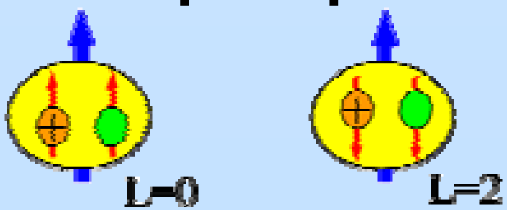
*Ph.D. work of P. Karpius (UNH)

Deuteron Electrodisintegration

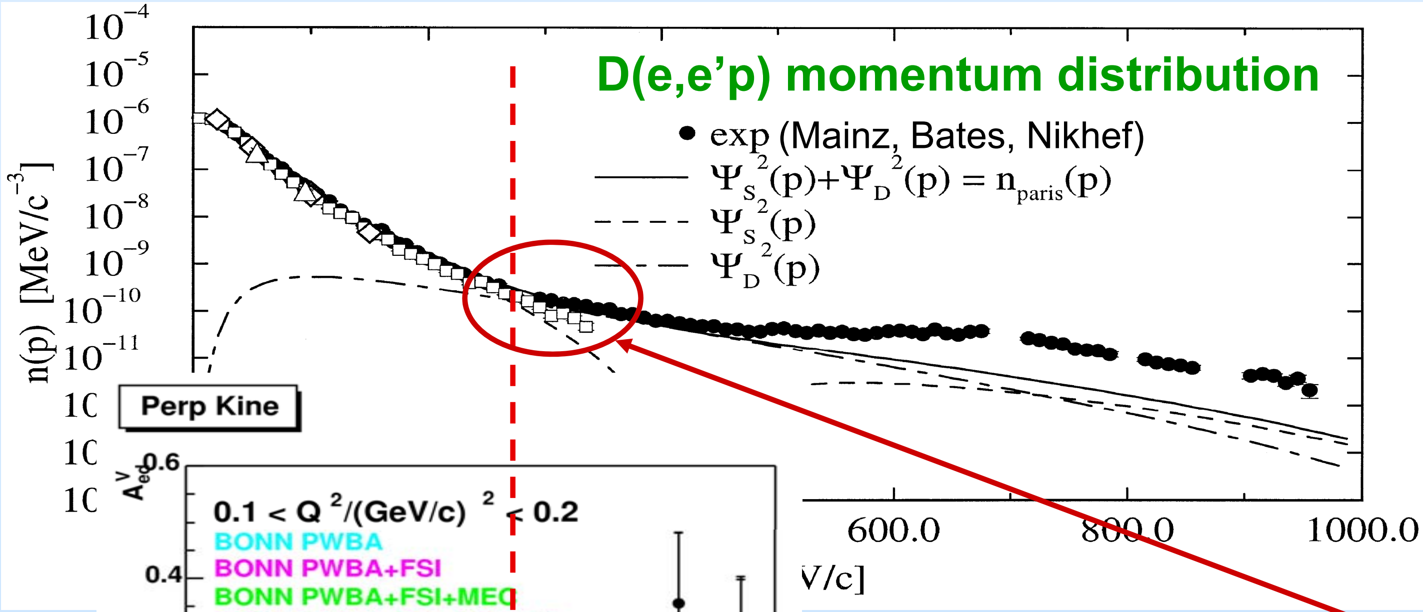
- **Quasielastic breakup**
  e + d → e' + p + n
- **D(e,e'p), PWIA:**
  $\vec{p}_m = \vec{q} - \vec{p}_p = -\vec{p}_{p,l}$

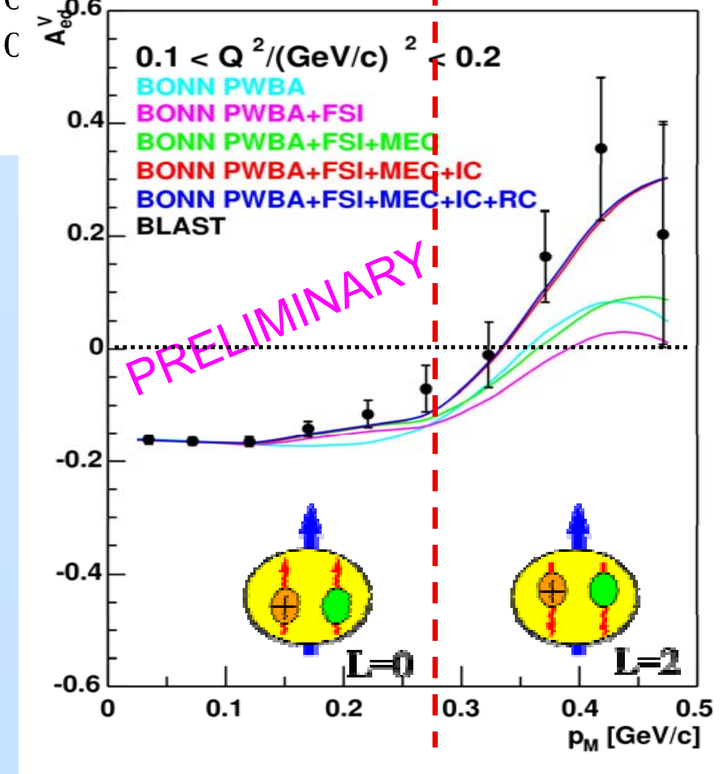


- $$\frac{\sigma}{\sigma_0} = (1 + P_{zz} A_d^T + h P_z A_{ed}^V)$$
- **Beam-vector asymmetry (PWIA):**
  $$A_{ed}^V(p,n) = \frac{a \cos\theta^* + b\,(G_E^{p,n}/G_M^{p,n}) \sin\theta^* \cos\phi^*}{1 + c\,(G_E^{p,n}/G_M^{p,n})^2}$$
- **Nucleon spins parallel** → $A_{ed}^V\,(p_{miss})$ **changes sign**



Deuteron Electrodisintegration*





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

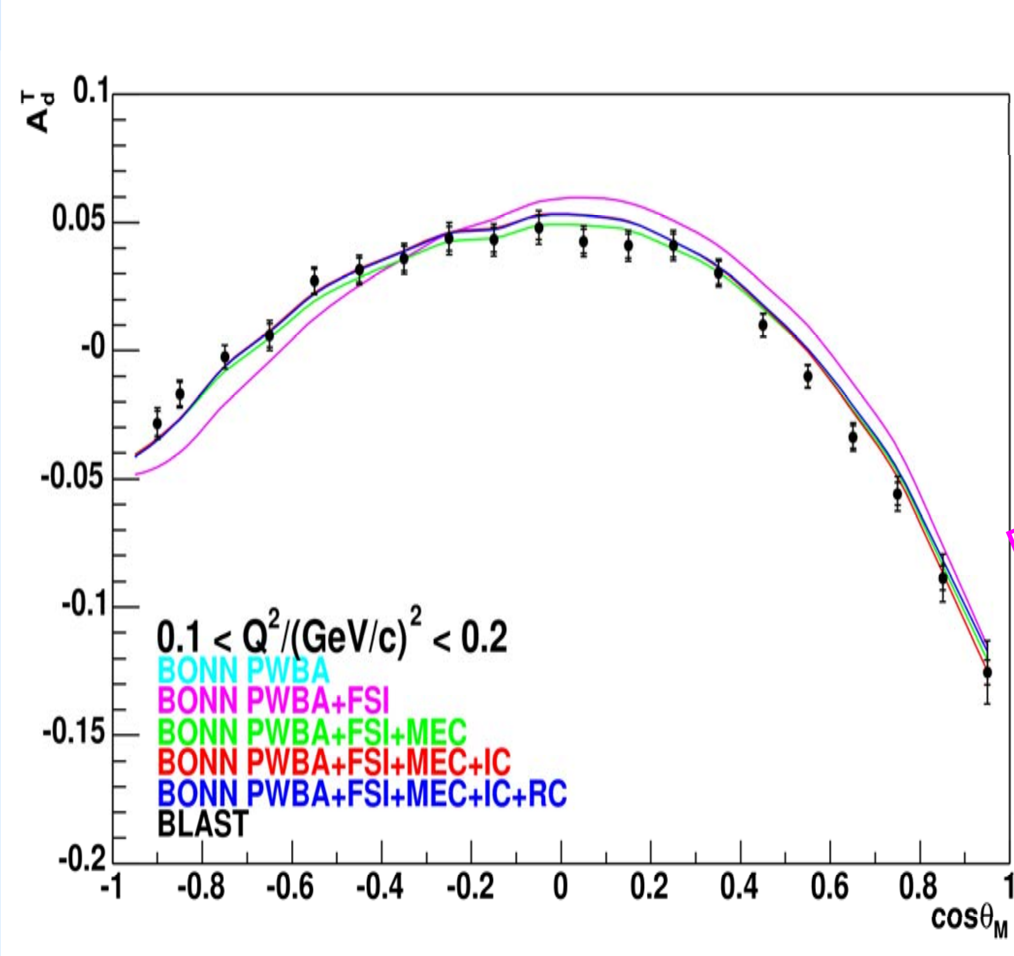
$\vec{D}(\vec{e}$,e'p) beam-vector asymmetry

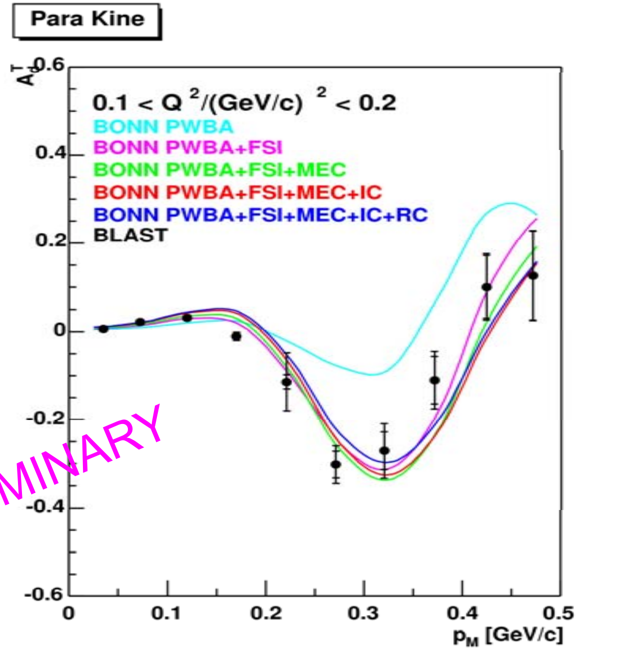
Observing expected sign change!

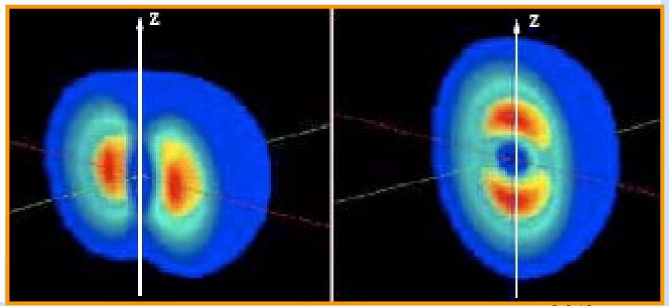
*Ph.D. work of A. Maschinot and A. DeGrush (MIT)

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

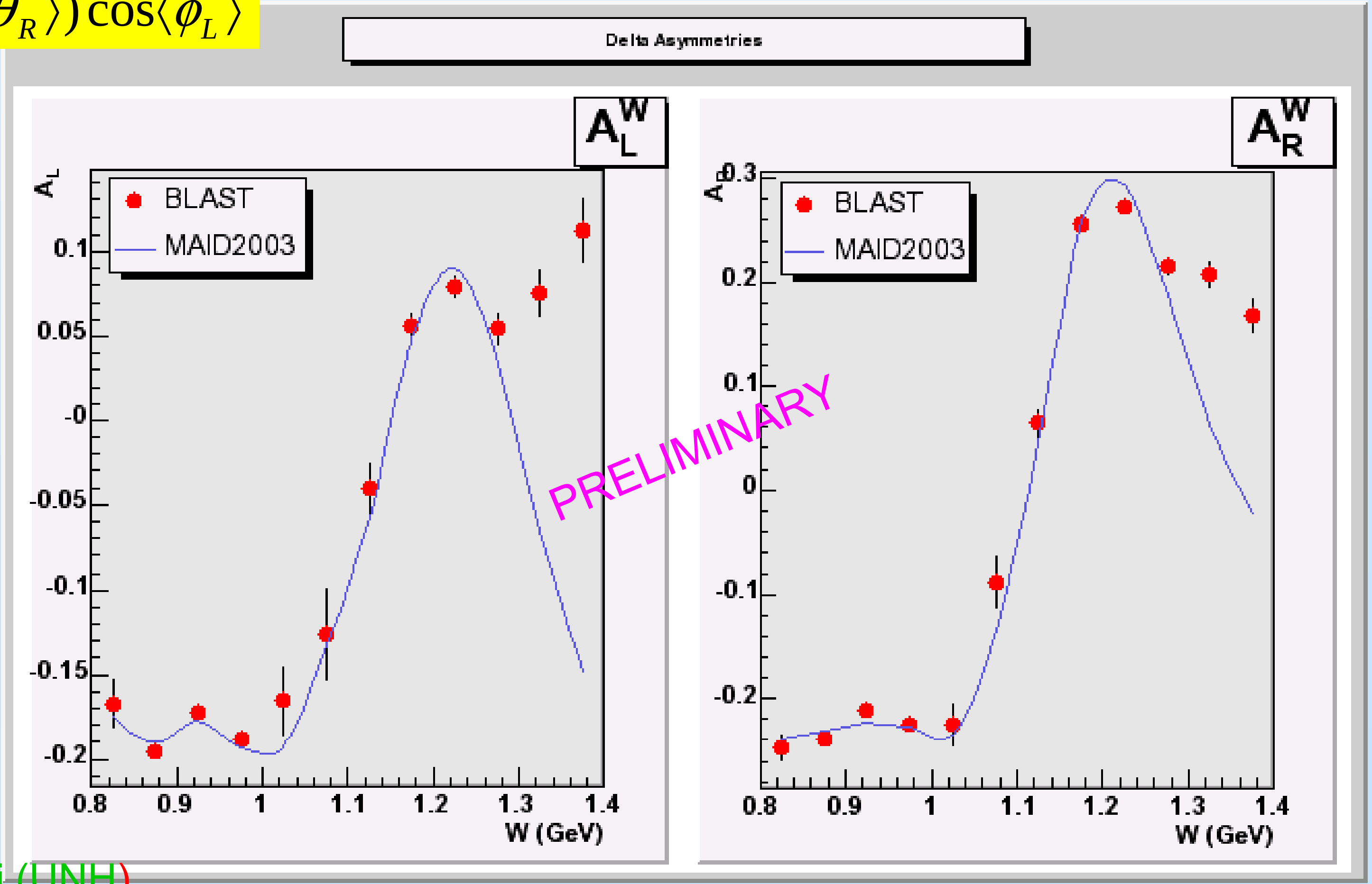
*Ph.D. work of A. Maschinot and A. DeGrush (MIT)

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

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

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

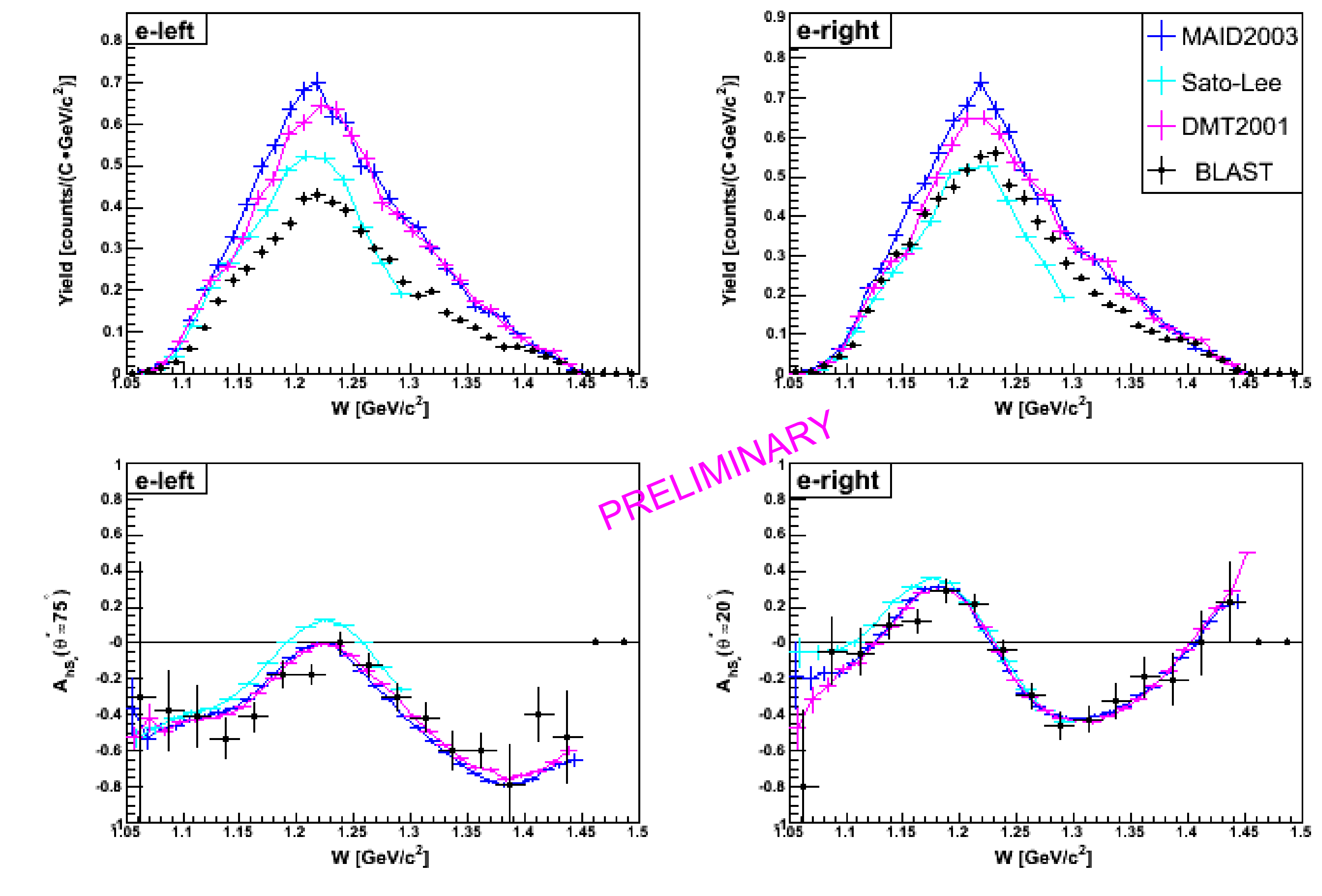
$$A = \frac{A_{meas}}{h \cdot P_Z} = A_{TT'} \cos\theta^* + A_{TL'} \sin\theta^* \cos\phi^*$$



5k ev. / 299 kC
+ 3.7M elastic

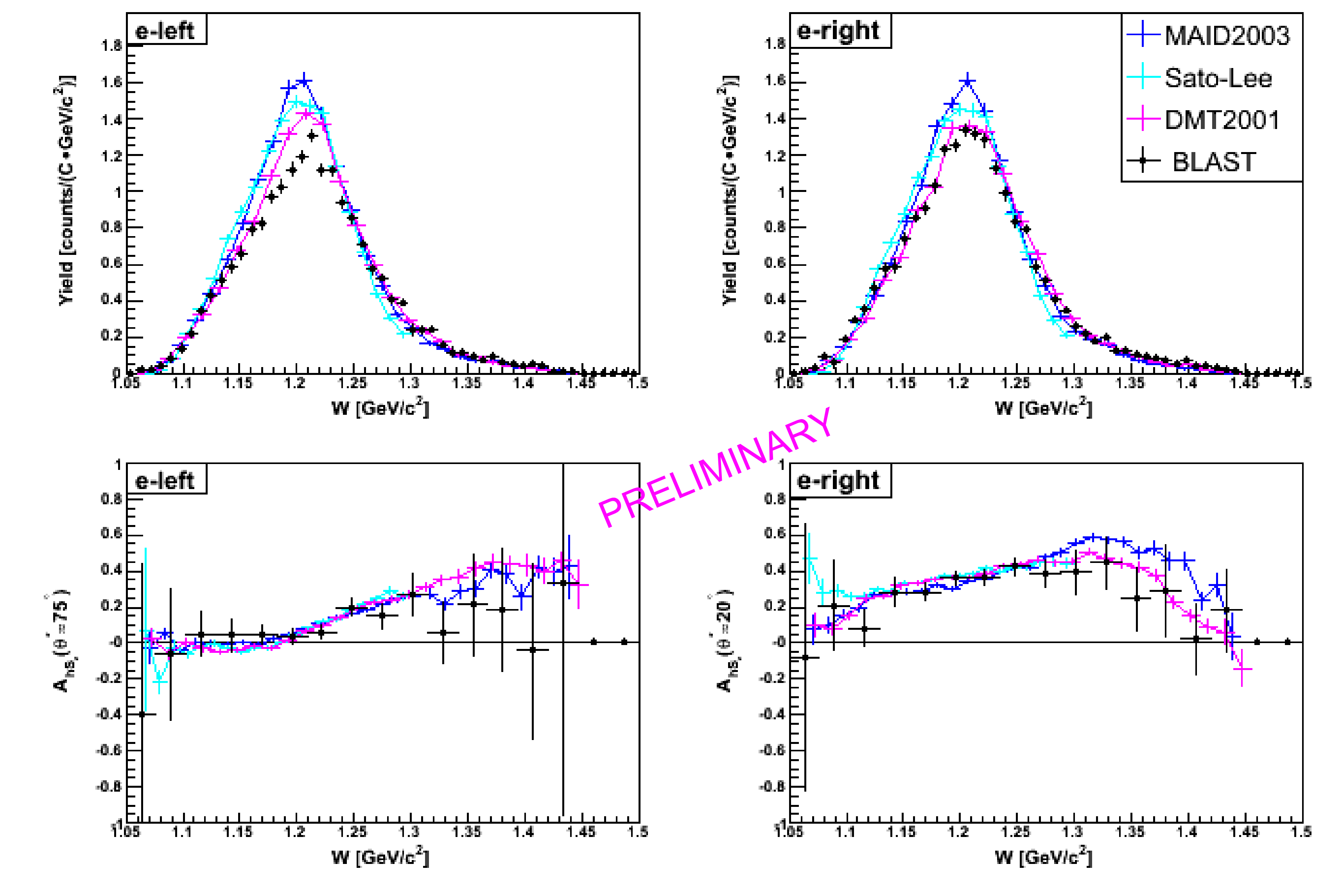
*Ph.D. work of O. Filoti (UNH)

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



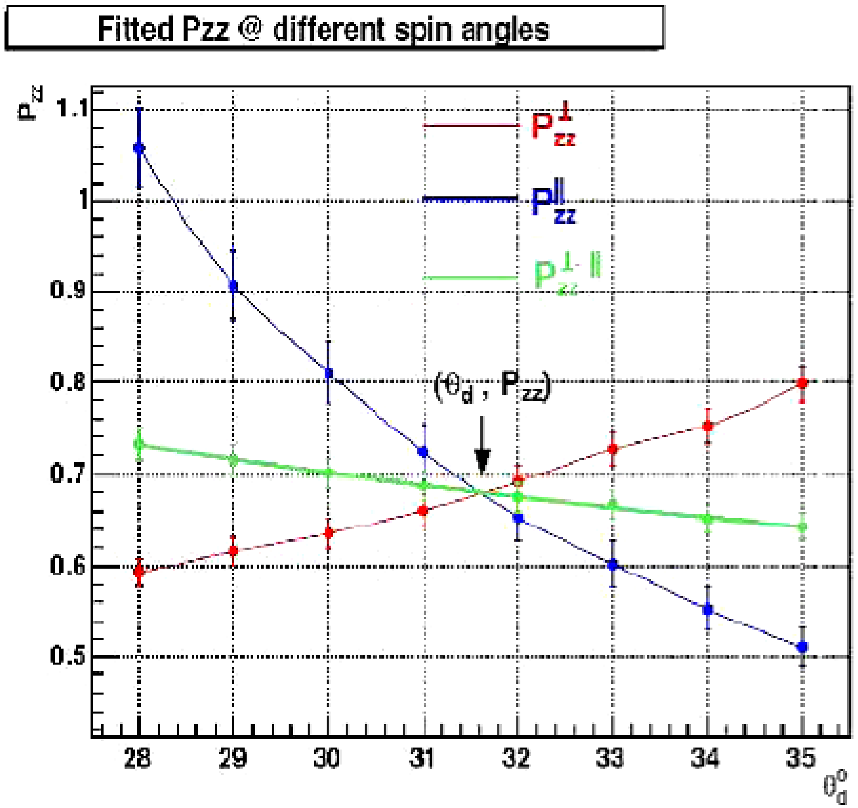
*Analyses by A. Shinozaki (MIT); Ph.D. work of Y. Xiao (MIT)

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

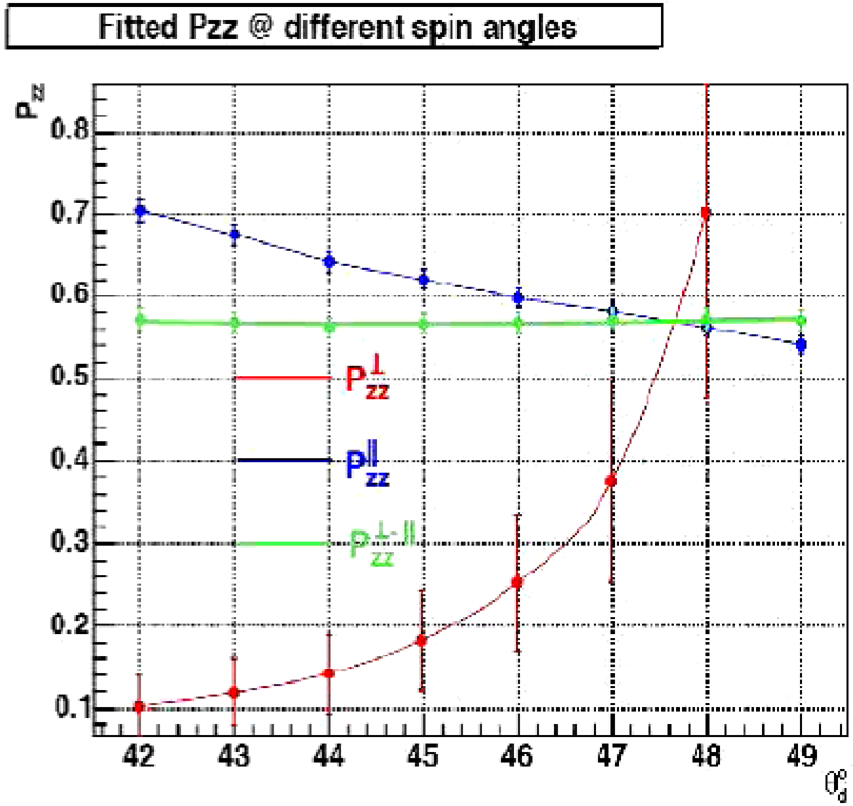


*Analyses by A. Shinozaki (MIT); Ph.D. work of Y. Xiao (MIT)

Determination of the spin angle



2005 θ_d=32±



2004 θ_d=47±