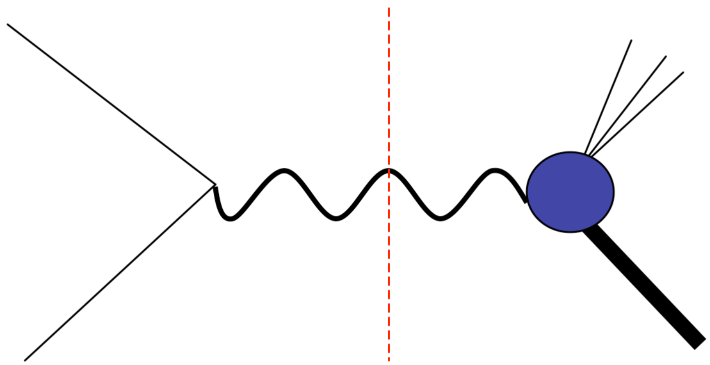
Nucleon Form Factors

- Introduction: EM form factors
- Experimental Techniques (BLAST)
- Proton Form Factor Ratio
- Neutron Electric and Magnetic Form Factors
- Summary

Ricardo Alarcon
The BLAST Collaboration
6th International Workshop on Chiral Dynamics, July 6-10, 2009 University of Bern

EM Nucleon Form Factors

• They are the *basic observables defined in the context of* a one-photon-exchange interaction.



• They contain information about the electromagnetic *structure of the proton and the neutron* in the *non-perturbative region*. **Related to spatial distribution of charge and magnetism.**

• They should provide guidance on how to connect QCD to the NN force

• Extensively studied by ~ 50 years now, through electron scattering: SLAC, Saclay, Mainz,NIKHEF, MIT-Bates, JLab, …

• They are required for knowledge of many other things:

structure of nuclei at short distances
Proton charge radius and Lamb shift
precision tests of Weak interaction at low Q^2

Nucleon Elastic Form Factors

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

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

Nucleon Elastic Form Factors

- **General definition of the nucleon form factor**

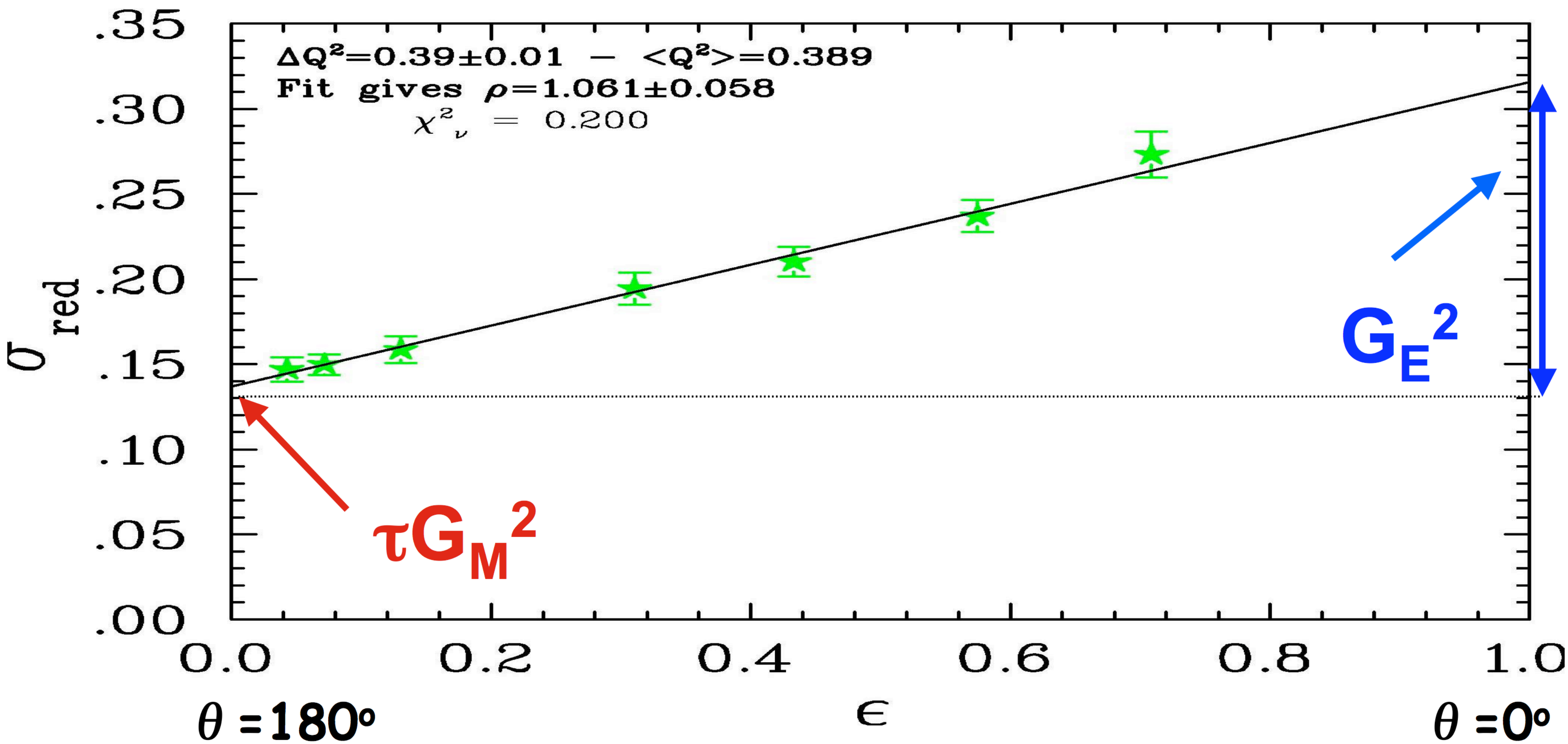
$$\langle N(P')|J^{\mu}_{\mathrm{EM}}(0)|N(P)\rangle =$$
$$\bar{u}(P')\left[\gamma^{\mu} F_1^N(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M} F_2^N(Q^2)\right] u(P)$$

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

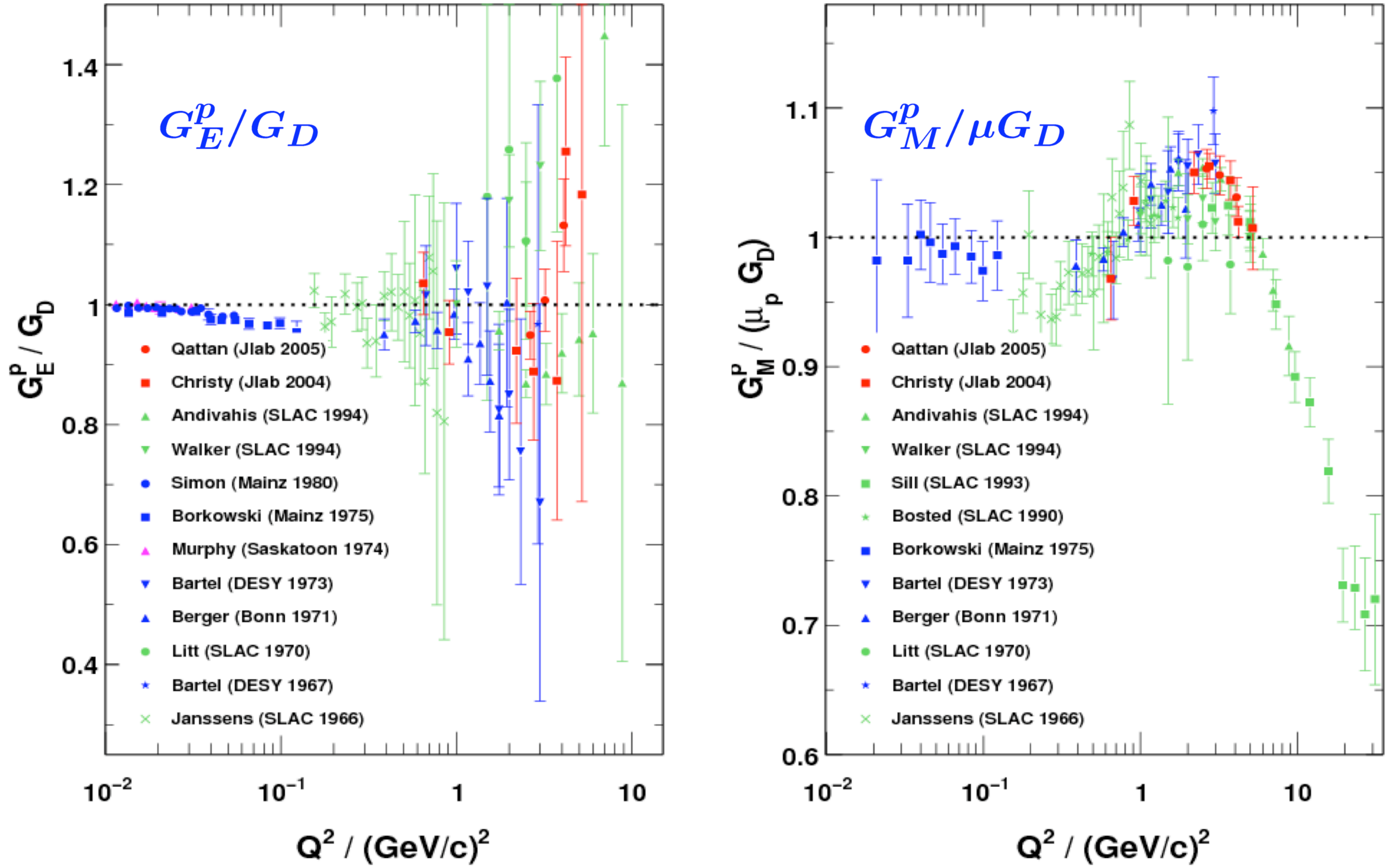
- **In One-photon exchange approximation above form factors are observables of elastic electron-nucleon scattering**

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

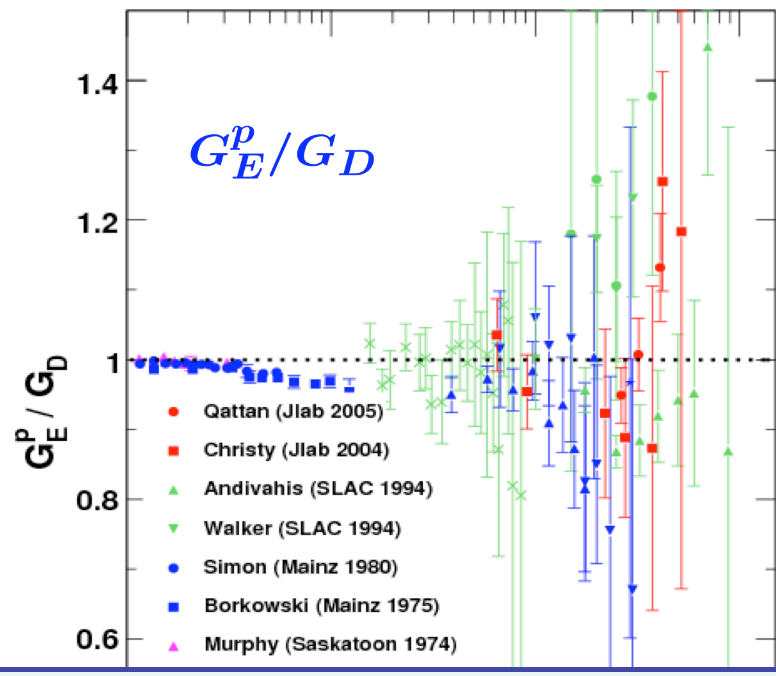
Proton Form Factors from Cross Section Measurements

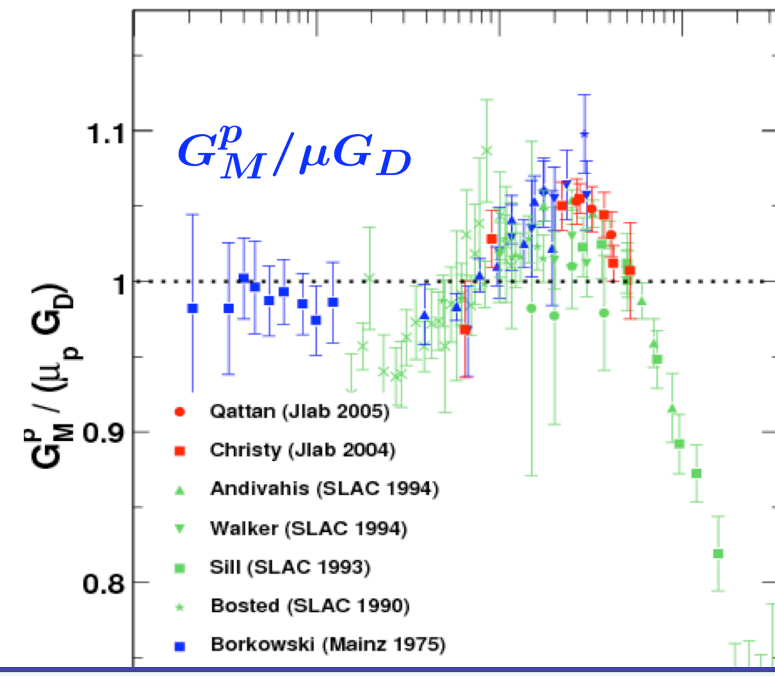


Proton Form Factors: Cross Section Measurements



Proton Form Factors: Cross Section Measurements





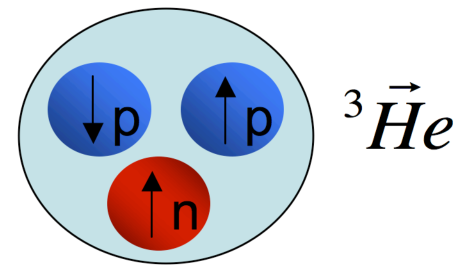
- $G(Q^2) \xleftrightarrow{\text{Fourier}} \rho(r)$ charge and magnetization density (Breit fr.)
- Dipole form factor $G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \longleftrightarrow \rho_D(r) = \rho_0\, e^{-\sqrt{0.71}r}$
- $G_E^p \approx G_M^p/\mu_p \approx G_M^n/\mu_n \approx G_D$ within 10% for $Q^2 < 10$ (GeV/c)^2

Nucleon Form Factors and Polarization

- **Polarized beam + polarized target:**

Donnelly + Raskin, Ann. Phys. 169 (1986)247

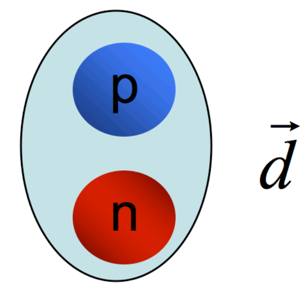
$$A = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}} \propto \frac{a(\theta^*)G_M^2 + b(\theta^*)G_M G_E}{\sigma_{unpol}}$$



$\vec{p}(\vec{e}e'p)$ → proton G_E/G_M

$\vec{d}(\vec{e}e'n)$ → neutron electric ff

$\vec{d}(\vec{e},e')$ $^3\vec{He}(\vec{e}e')$ → neutron magnetic ff



- **Polarized beam + polarization of recoil nucleon:**

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E_e + E_e')}{2M_p}\tan\frac{\theta_e}{2}$$

$d(\vec{e}e'\vec{n})$ neutron electric ff

$p(\vec{e}e'\vec{p})$ proton G_E/G_M

Akhiezer+Rekalo, Sov.JPN 3 (1974) 277
Arnold,Carlson+Gross, PRC 21 (1980) 1426

Recoil Polarization Technique

- Pioneered at MIT-Bates
- Pursued in Halls A and C, and MAMI A1
- In preparation for Jlab @ 12 GeV

V. Punjabi et al.,
Phys. Rev. C71 (2005) 05520

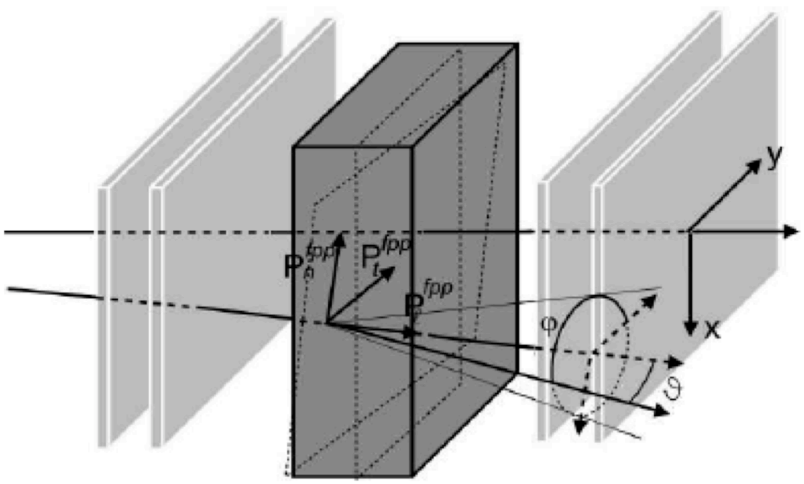


FIG. 9: Schematic of the polarimeter chambers and analyzer, showing a non-central trajectory; ϑ is the polar angle, and φ is the azimuthal angle from the y-direction counterclockwise.

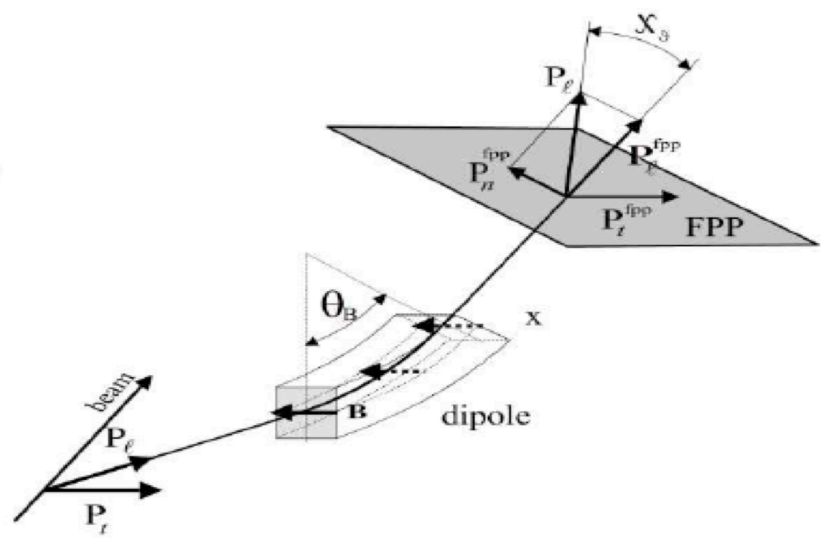
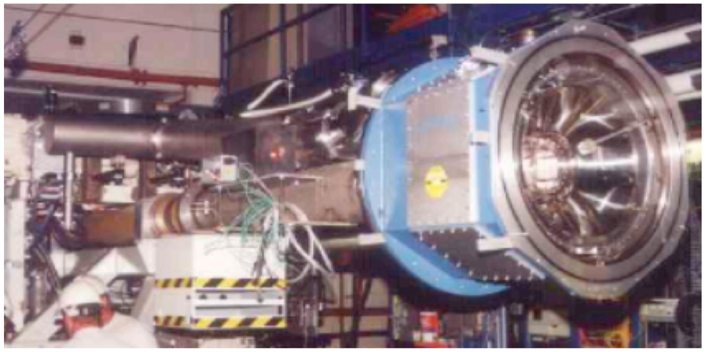


FIG. 15: Schematic drawing showing the precession by angle χ_θ of the P_ℓ component of the polarization in the dipole of the HRS.

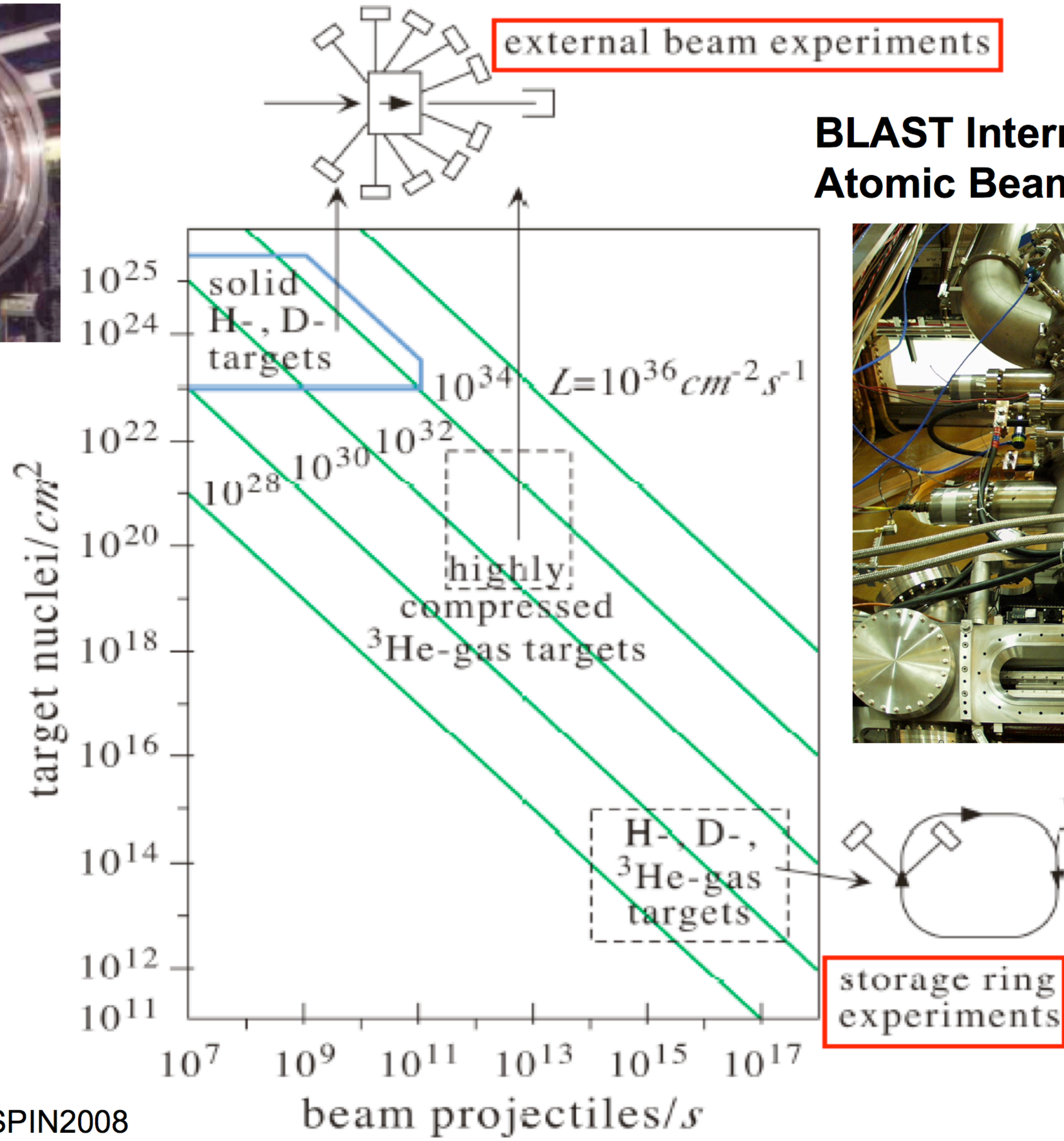
Focal-plane polarimeter
Secondary scattering of polarized proton from unpolarized analyzer

Spin transfer formalism to account for spin precession through spectrometer

Polarized Targets

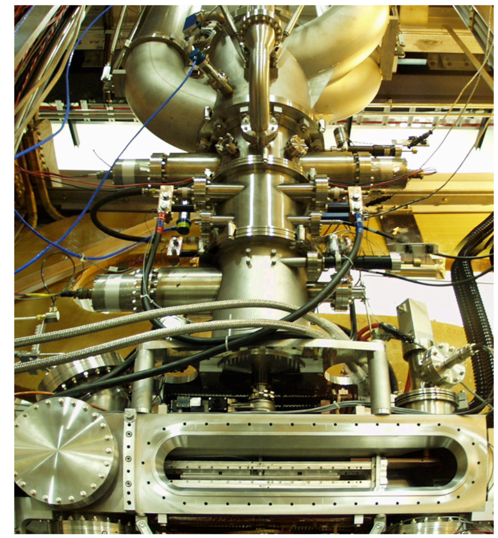


UVA / "SLAC"-Target:
Dynamic Nuclear Polarization



from W. Meyer, SPIN2008

BLAST Internal Target:
Atomic Beam Source



Limited luminosity for polarized hydrogen/deuterium targets,

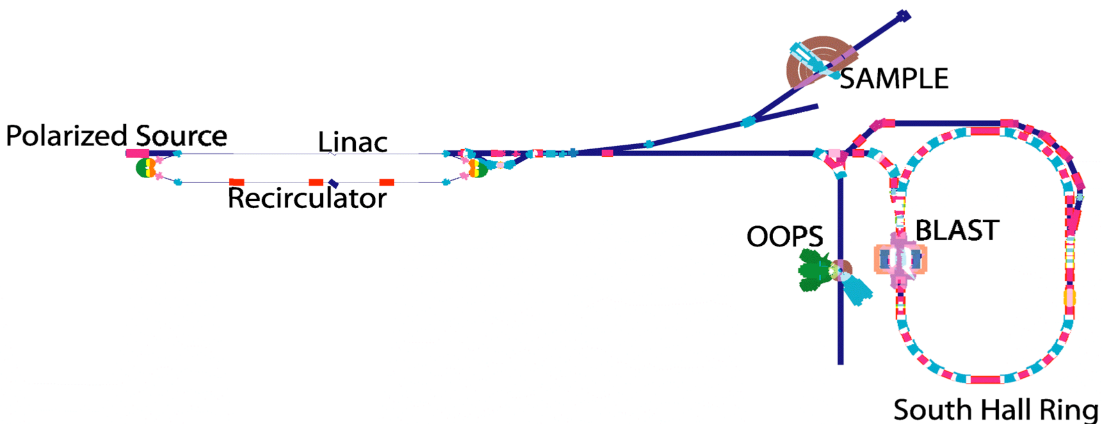
Very precise at low to moderately high Q^2

Low Q^2: BLAST at MIT-Bates

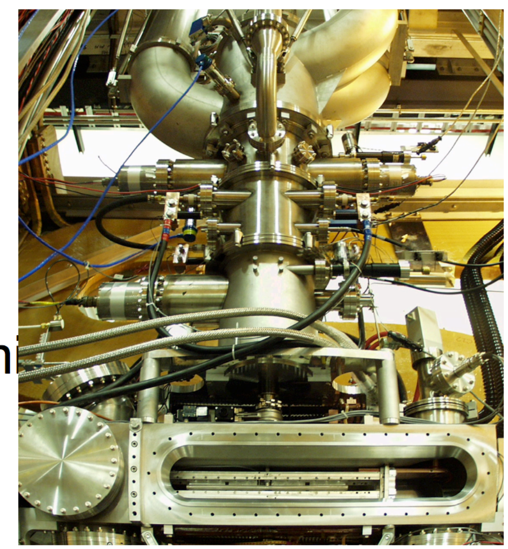
Bates Large Acceptance Spectrometer Toroid

- Symmetric, large acceptance, general purpose detector
  Detection of $e^{\pm}$, $\pi^{\pm}$, p, d, n

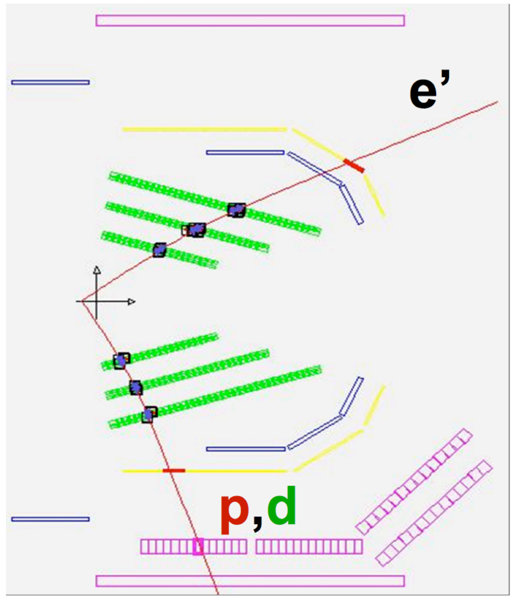
- Longitudinally polarized electrons in SHR
  850 MeV, 200 mA, P_e = 65%

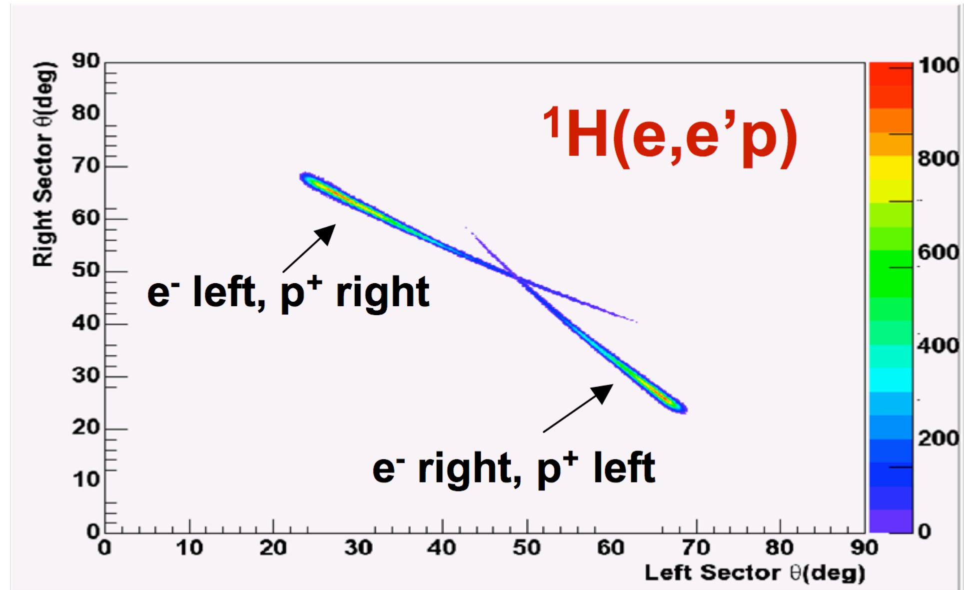


- Highly polarized internal gas target of pure H and D (Atomi
  Beam Source)
  6×10^{13} atoms/cm^2, $L = 6 \times 10^{31}/(\text{cm}^2\text{s})$, $P_{H/D}$ = 80%



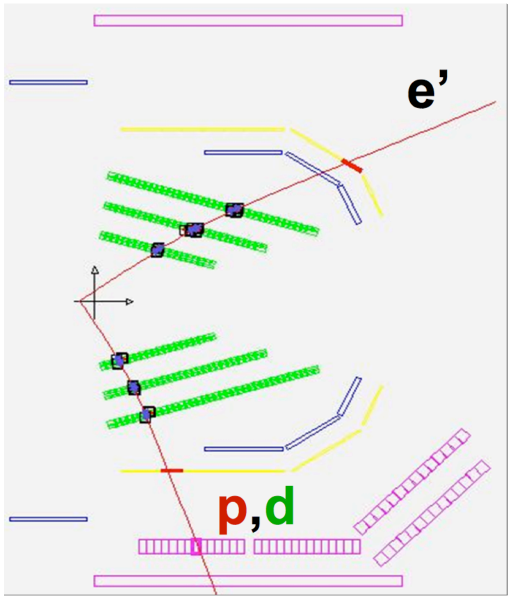
Identification of Elastic Events

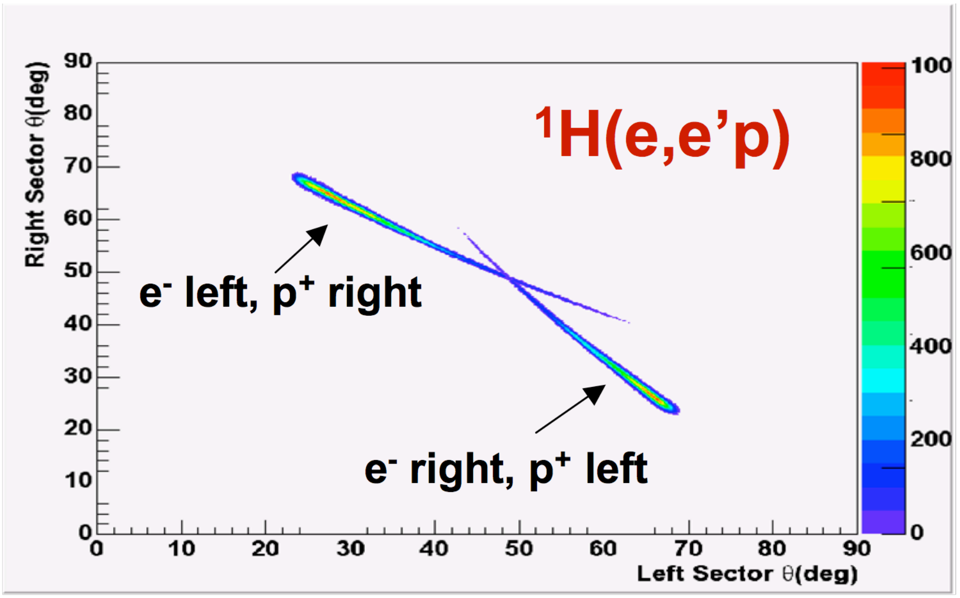




Identification of Elastic Events

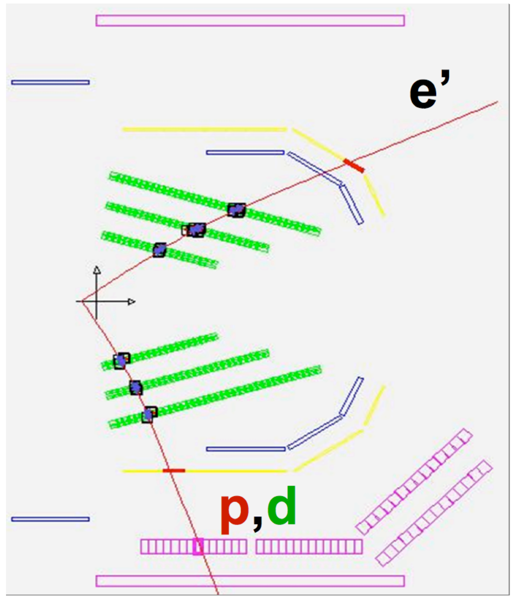
- Charge +/-
- Coplanarity
- Kinematics

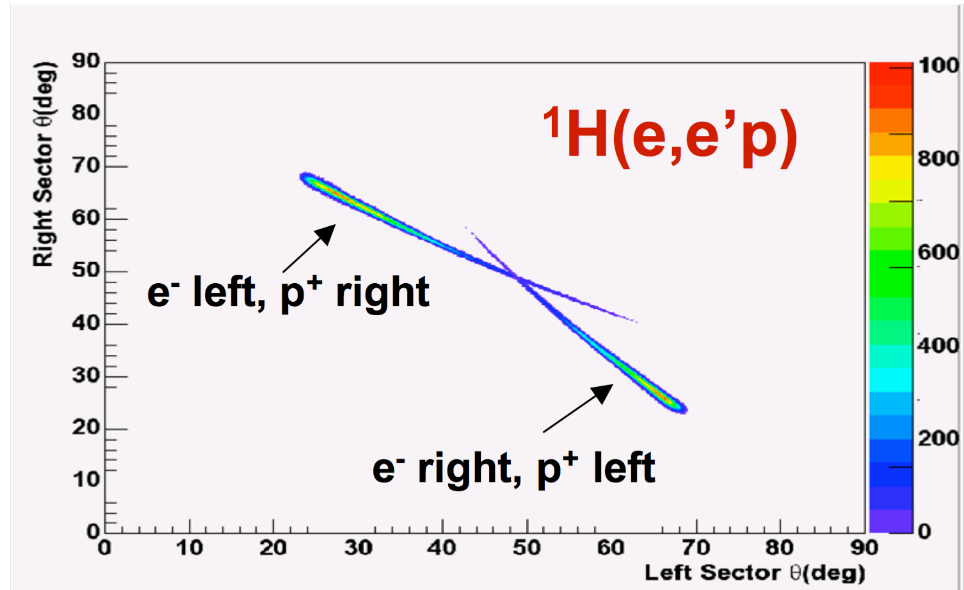


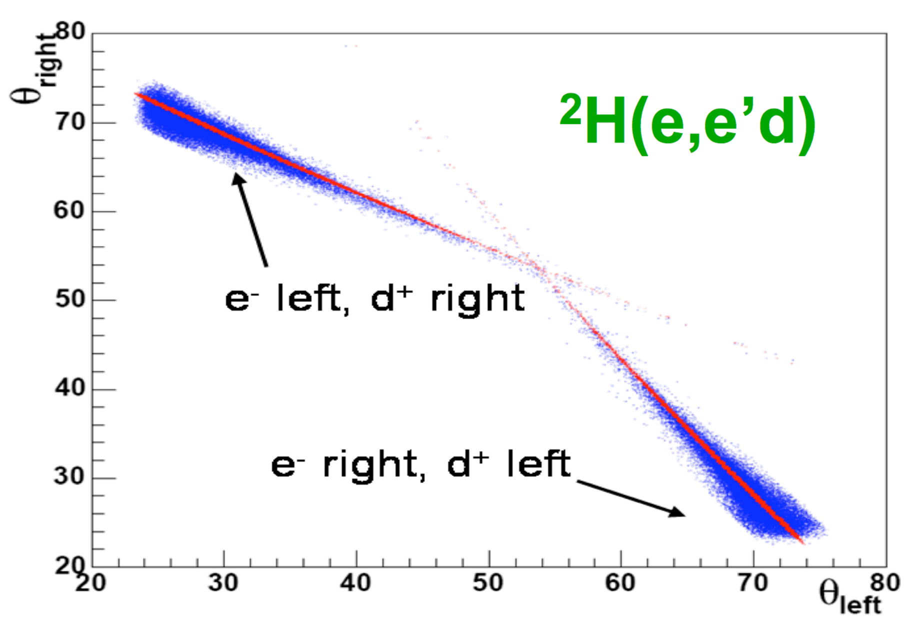


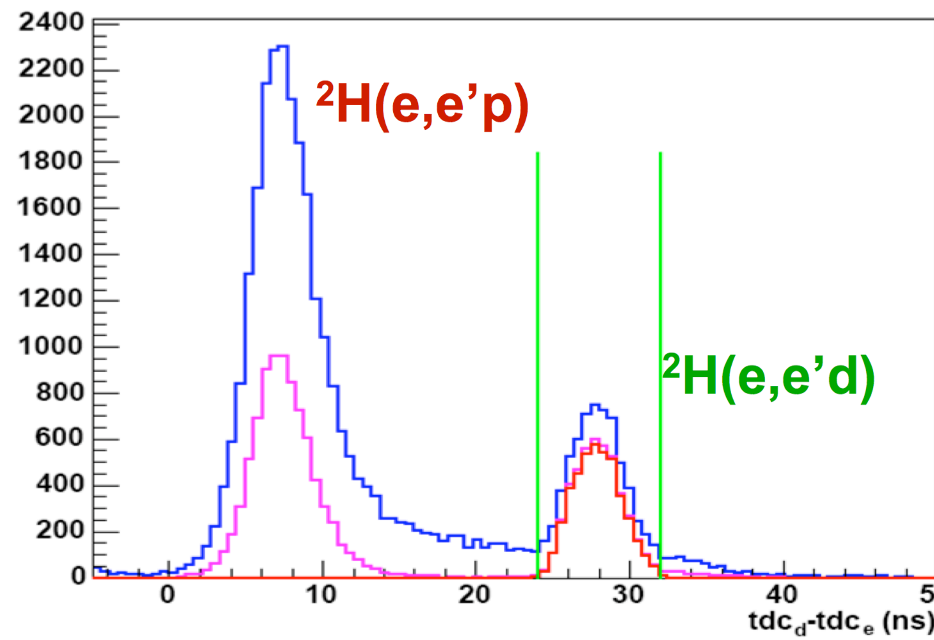
Identification of Elastic Events

- Charge +/-
- Coplanarity
- Kinematics
- Timing



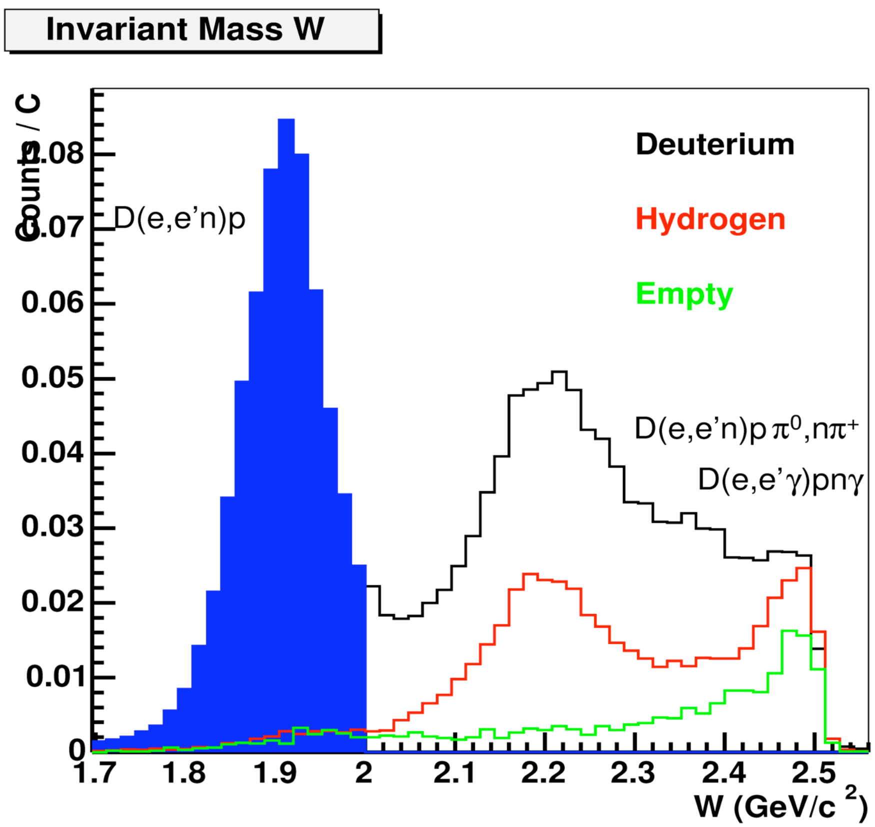


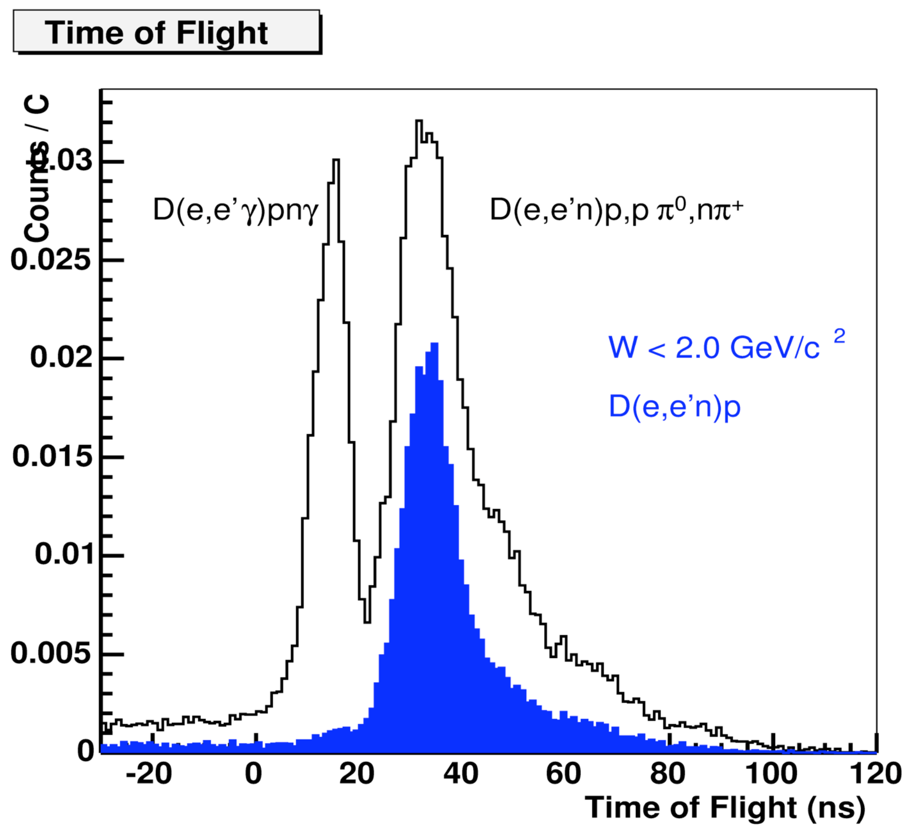




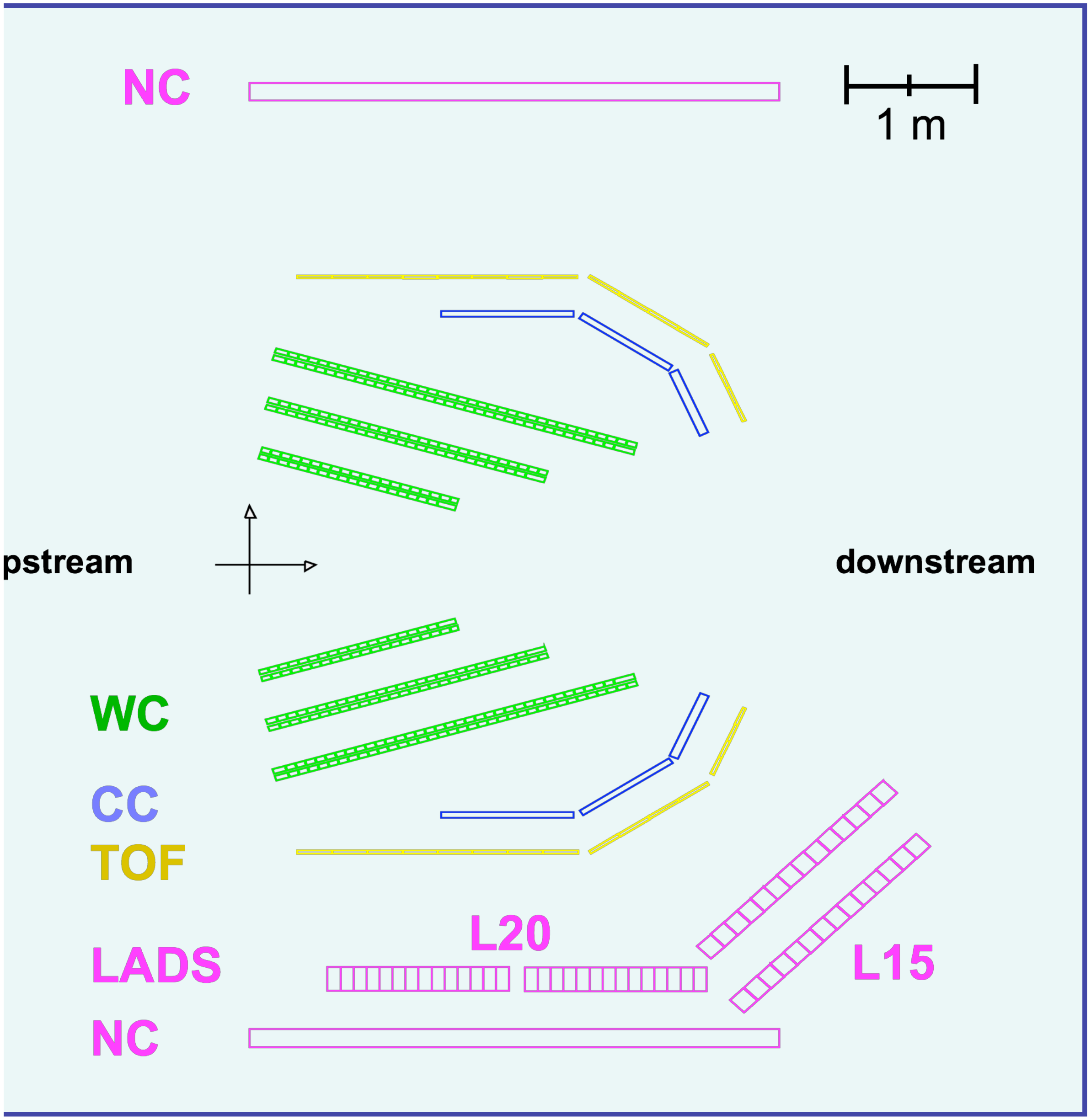
Identification of Neutron Events

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

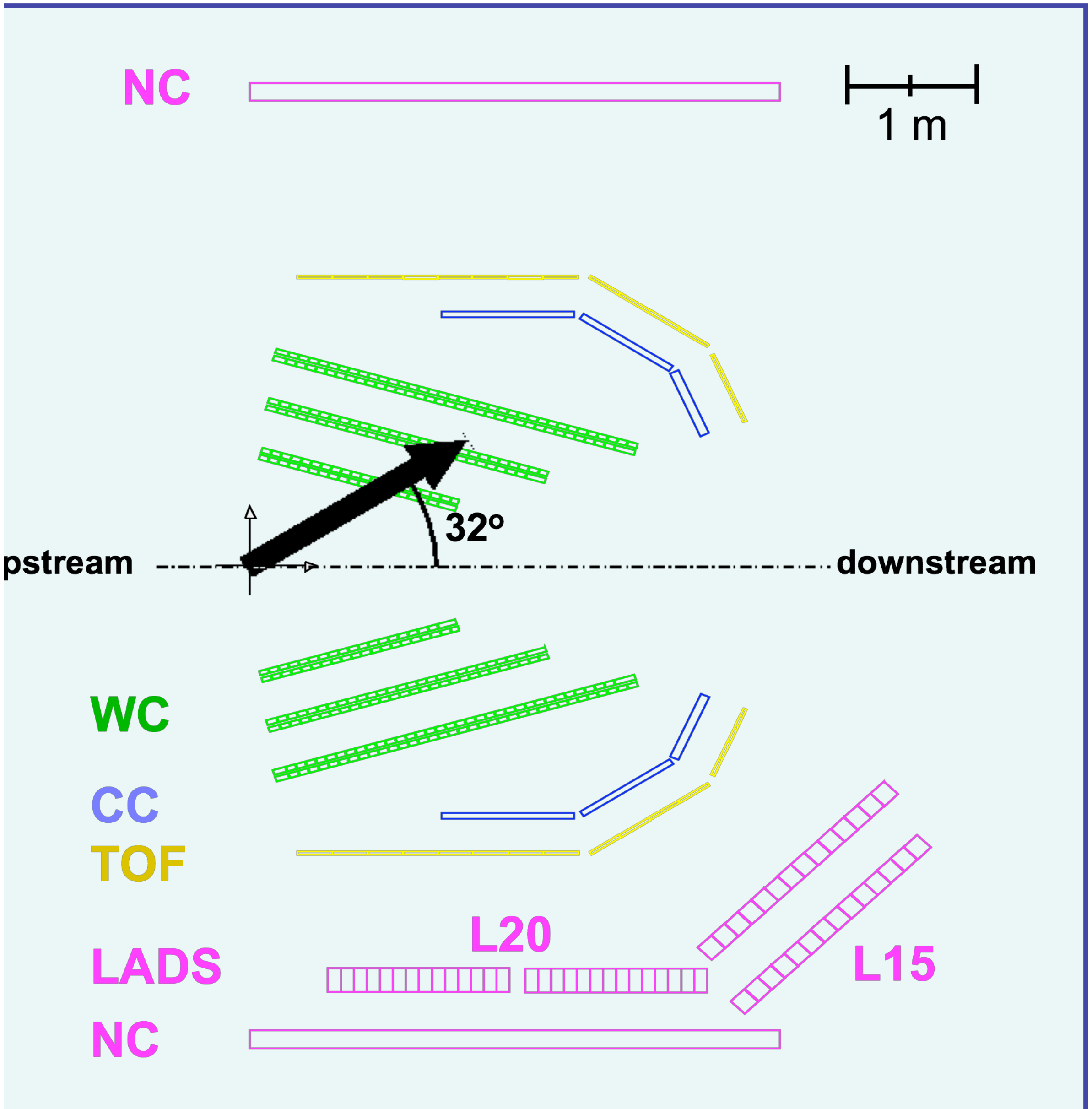




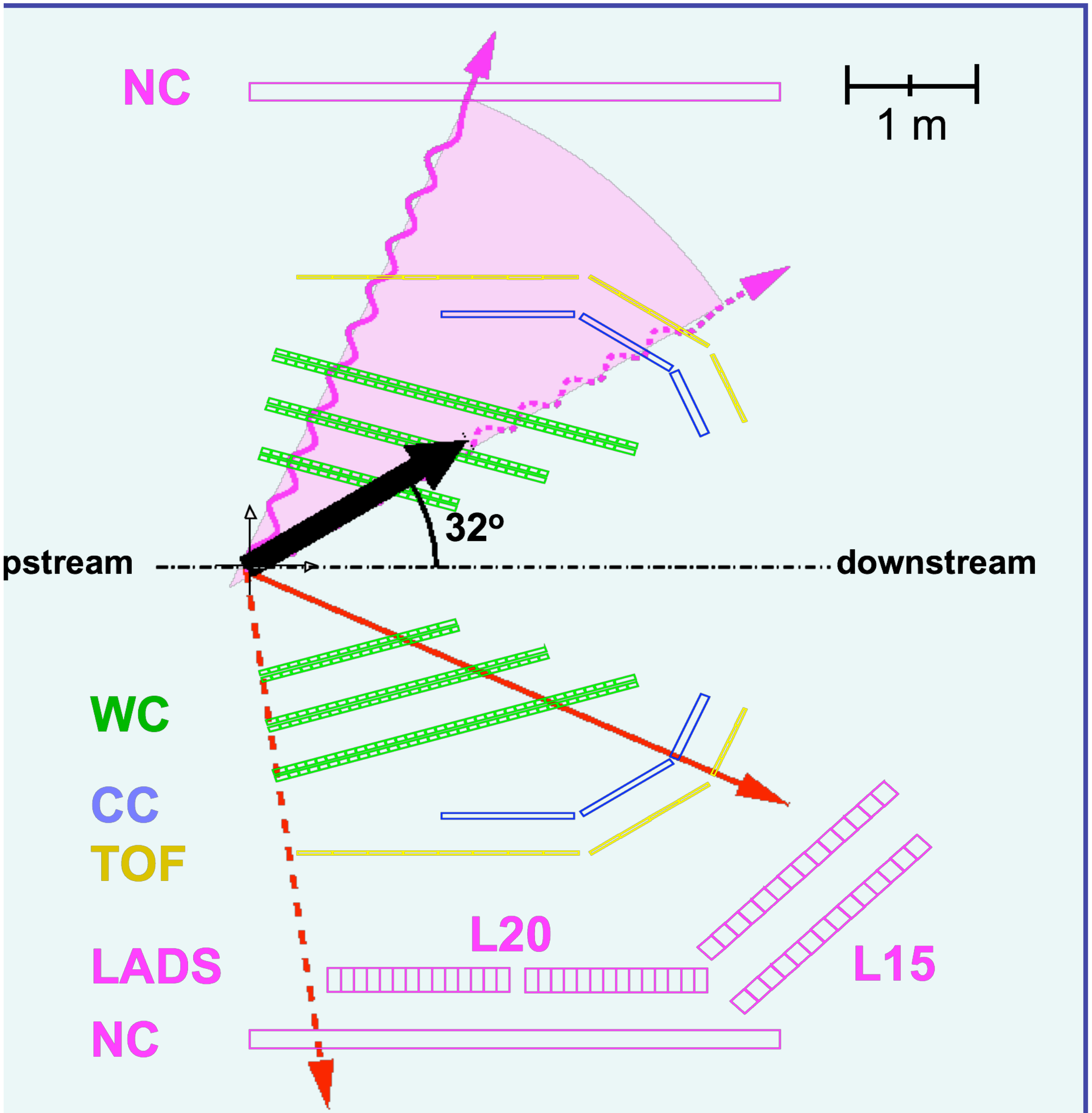
BLAST Experimental Technique



BLAST Experimental Technique



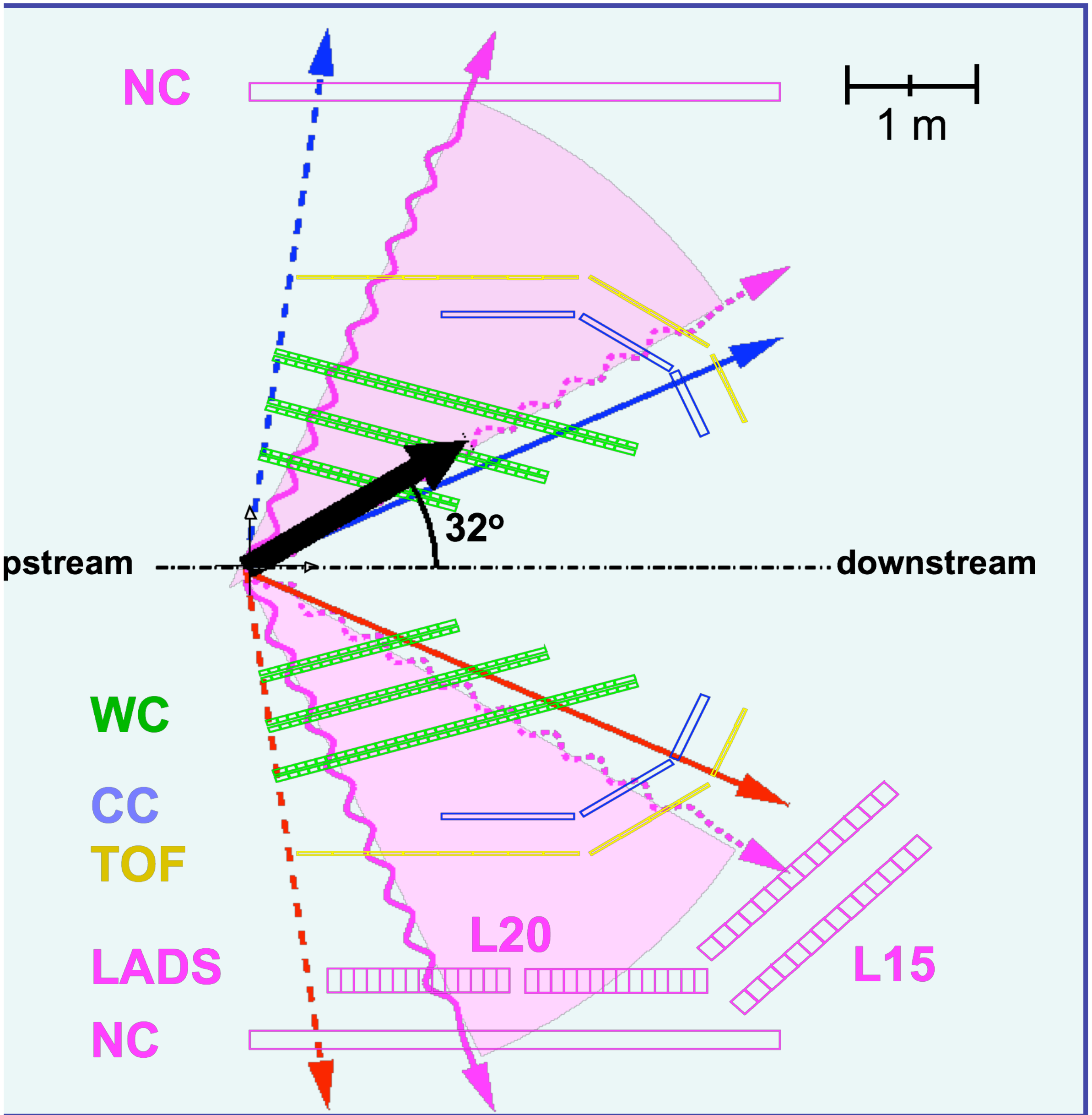
BLAST Experimental Technique



e- right $\theta^* \approx 0^o$

“spin-parallel”

BLAST Experimental Technique



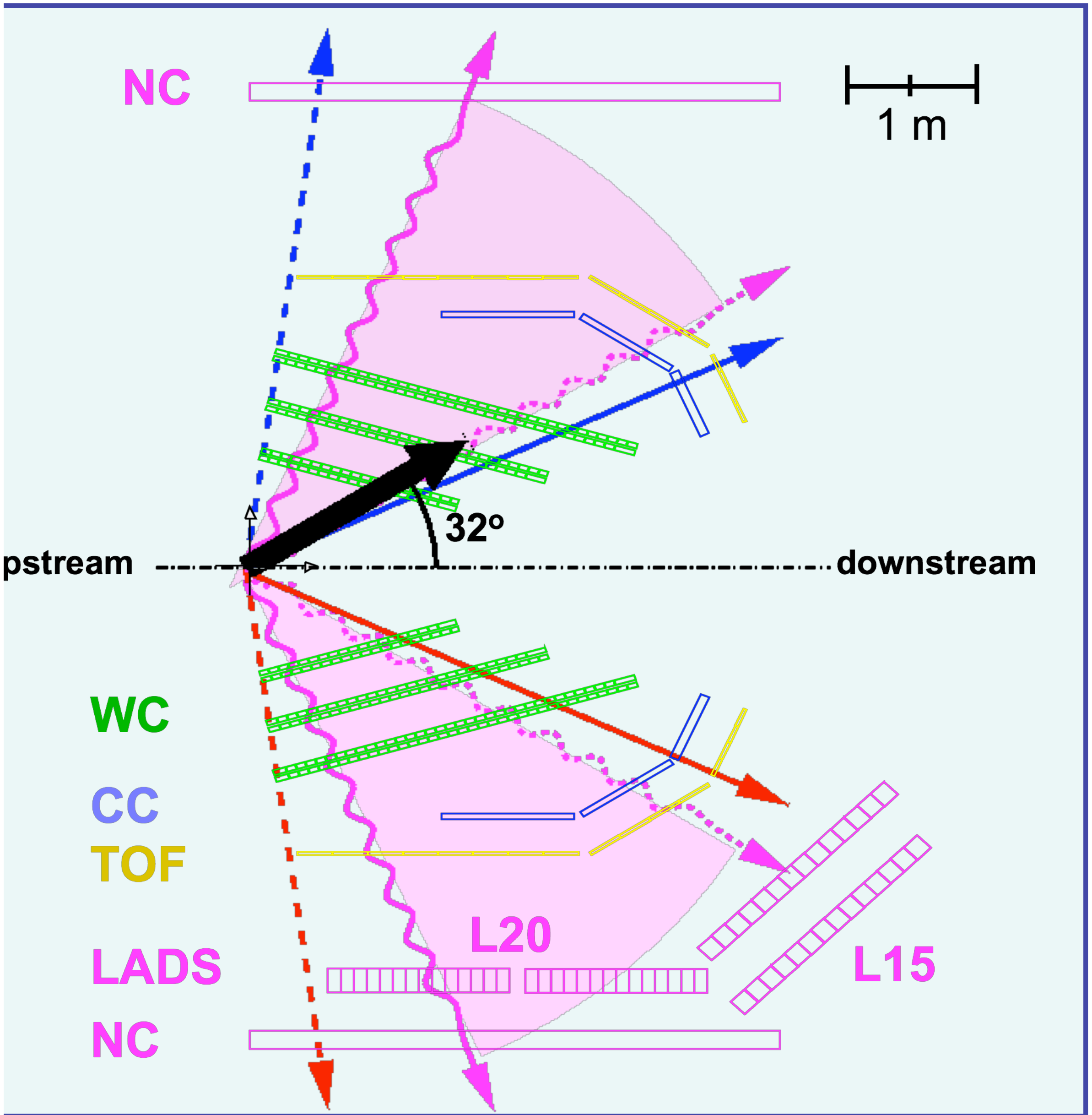
e- left $\theta^* \approx 90^o$

"spin-perpendicular"

e- right $\theta^* \approx 0^o$

"spin-parallel"

BLAST Experimental Technique



e- left $\theta^* \approx 90^o$

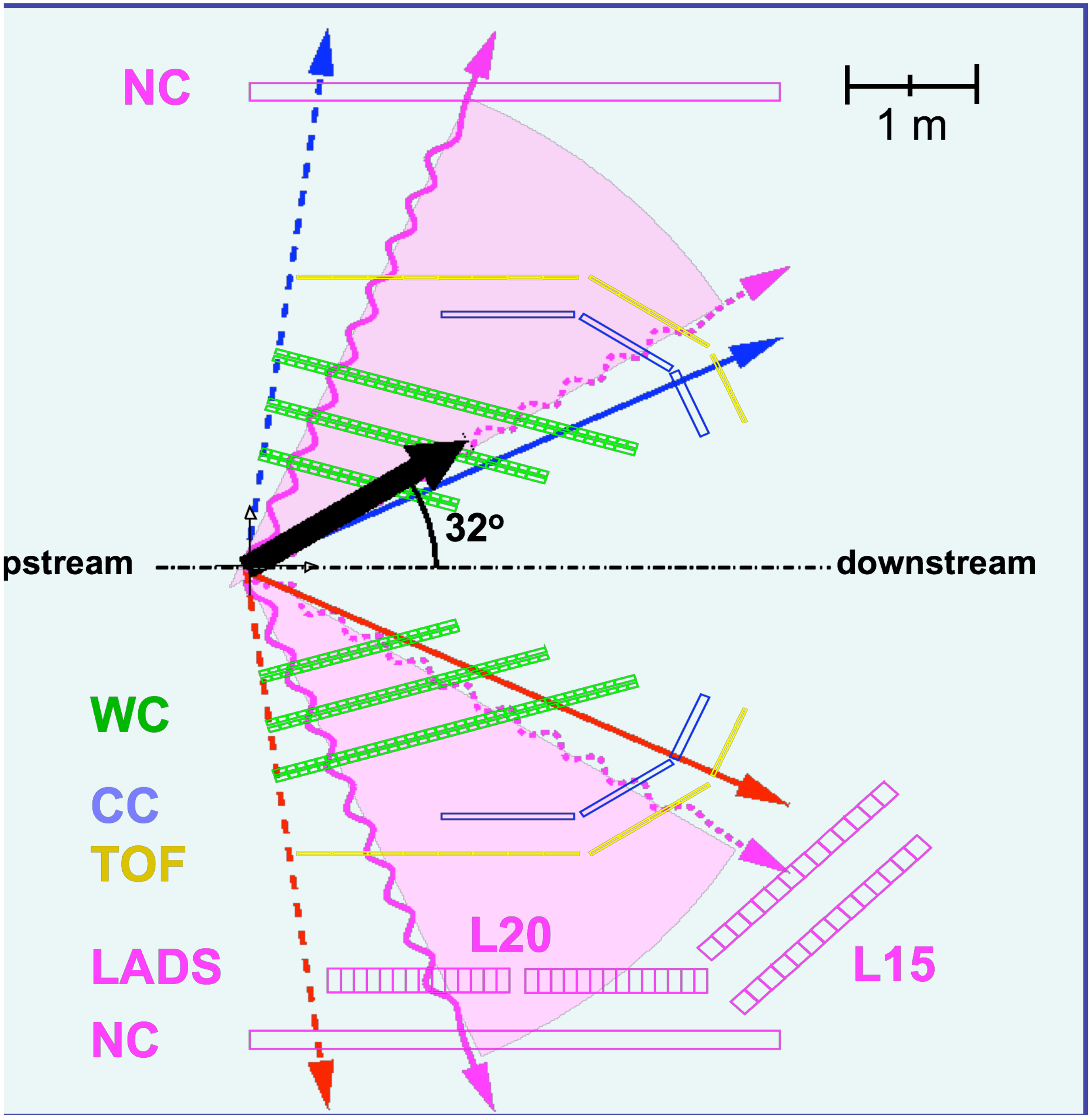
"spin-perpendicular"

e- right $\theta^* \approx 0^o$

"spin-parallel"

$$R_A \equiv \frac{A_L}{A_R} = \frac{z_L + x_L \cdot R}{z_R + x_R \cdot R}$$

BLAST Experimental Technique



e- left $\theta^* \approx 90^o$

"spin-perpendicular"

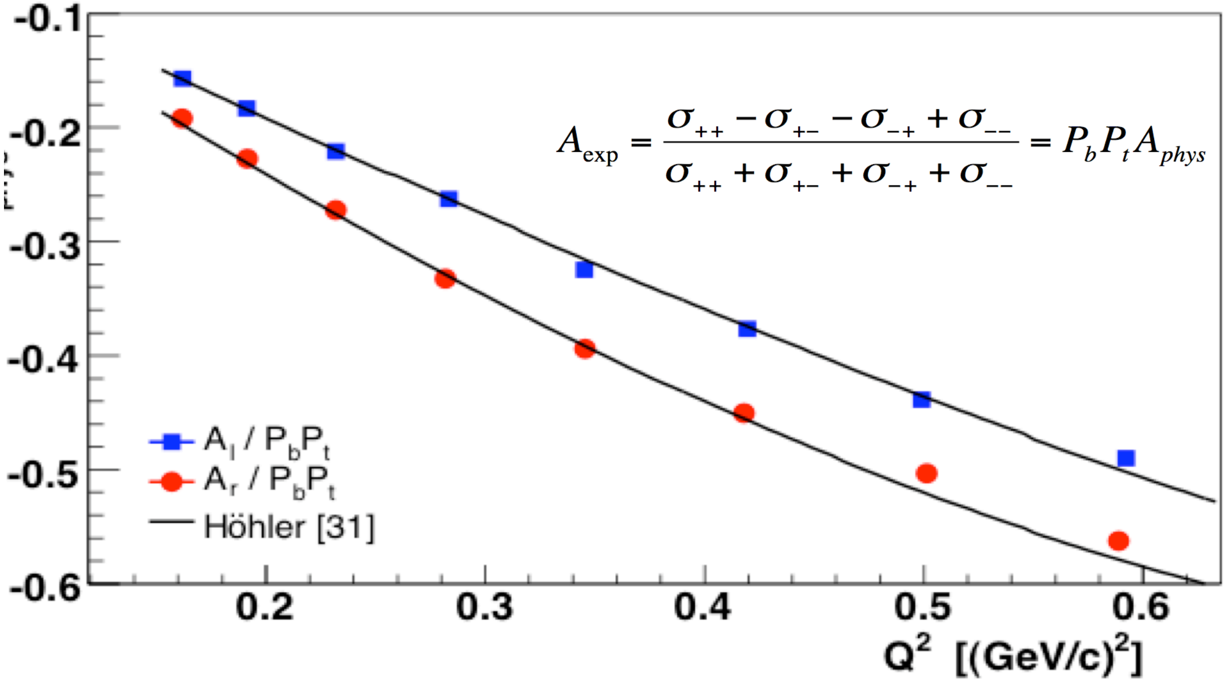
e- right $\theta^* \approx 0^o$

"spin-parallel"

$$R_A \equiv \frac{A_L}{A_R} = \frac{z_L + x_L \cdot R}{z_R + x_R \cdot R}$$

$$R = \frac{G_E^P}{G_M^p}$$

Asymmetry Results for $H(\vec{e},e'\vec{p})$



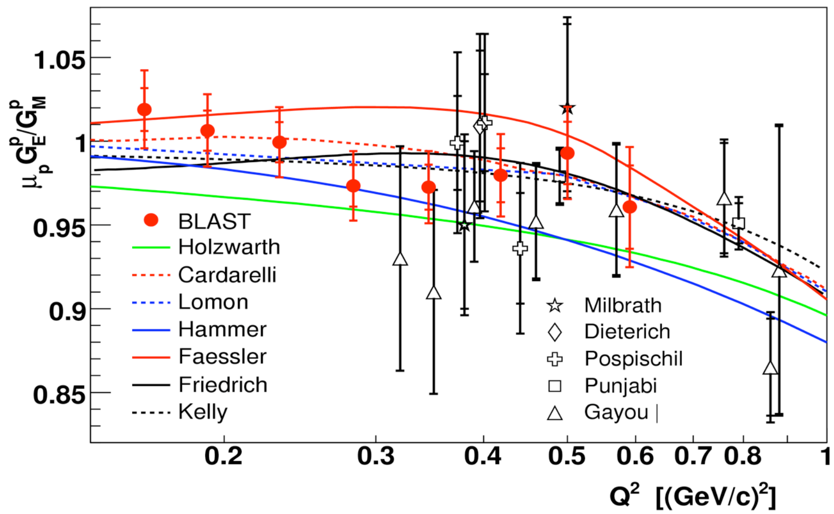
- Beam and target asymmetries also evaluated individually; no significant false asymmetries detected
- A_{phys} fit with Höhler parameterization of form factors to extract P_b P_t = 51.8 ±0.3%, 51.9% ±0.2%
  - Agreement → Confidence in target spin angle as determined from measurement of target holding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

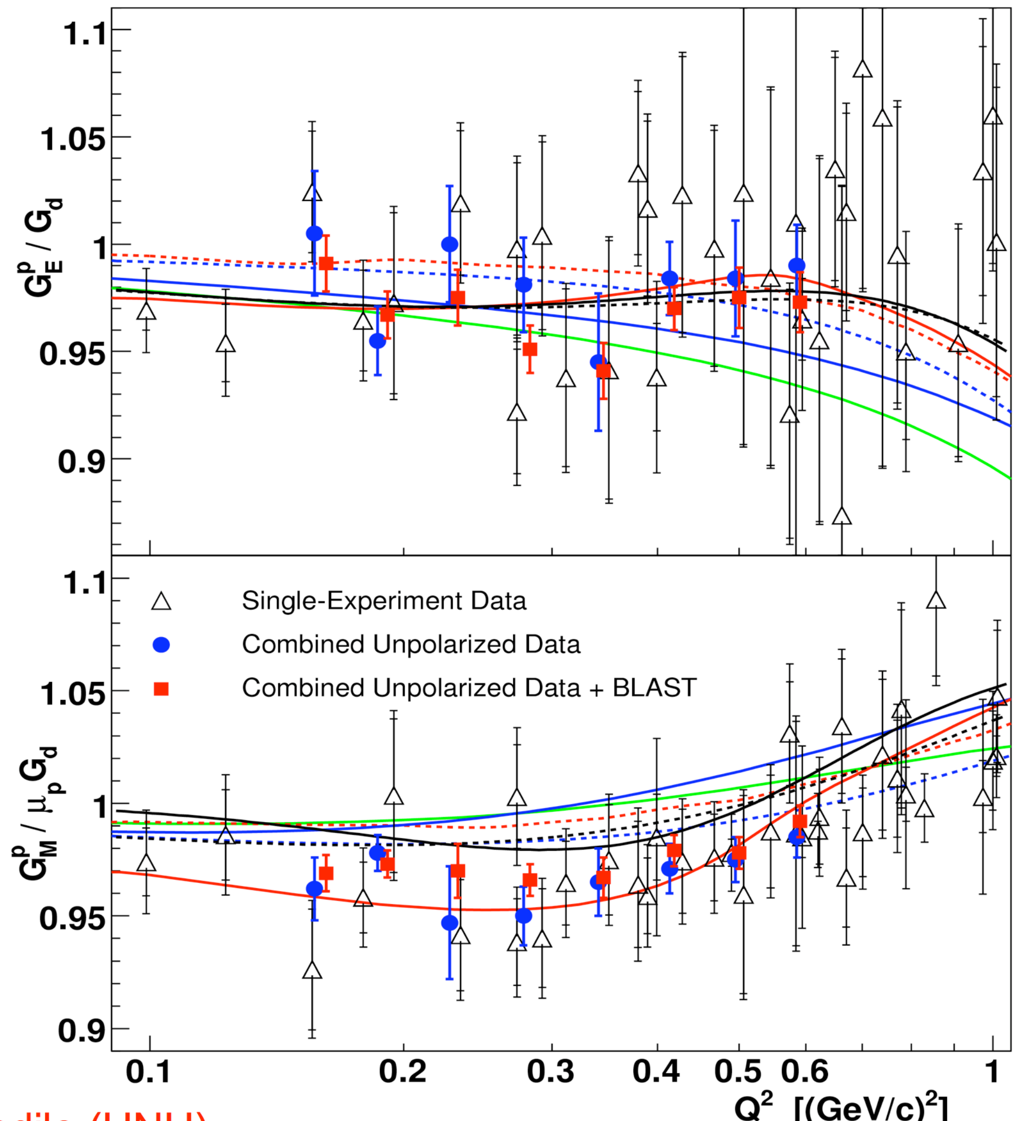
  90 pb^{-1} integrated luminosity

Data with electron detected in left and right sectors

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

C.B. Crawford et al., PRL98 (2007) 052301

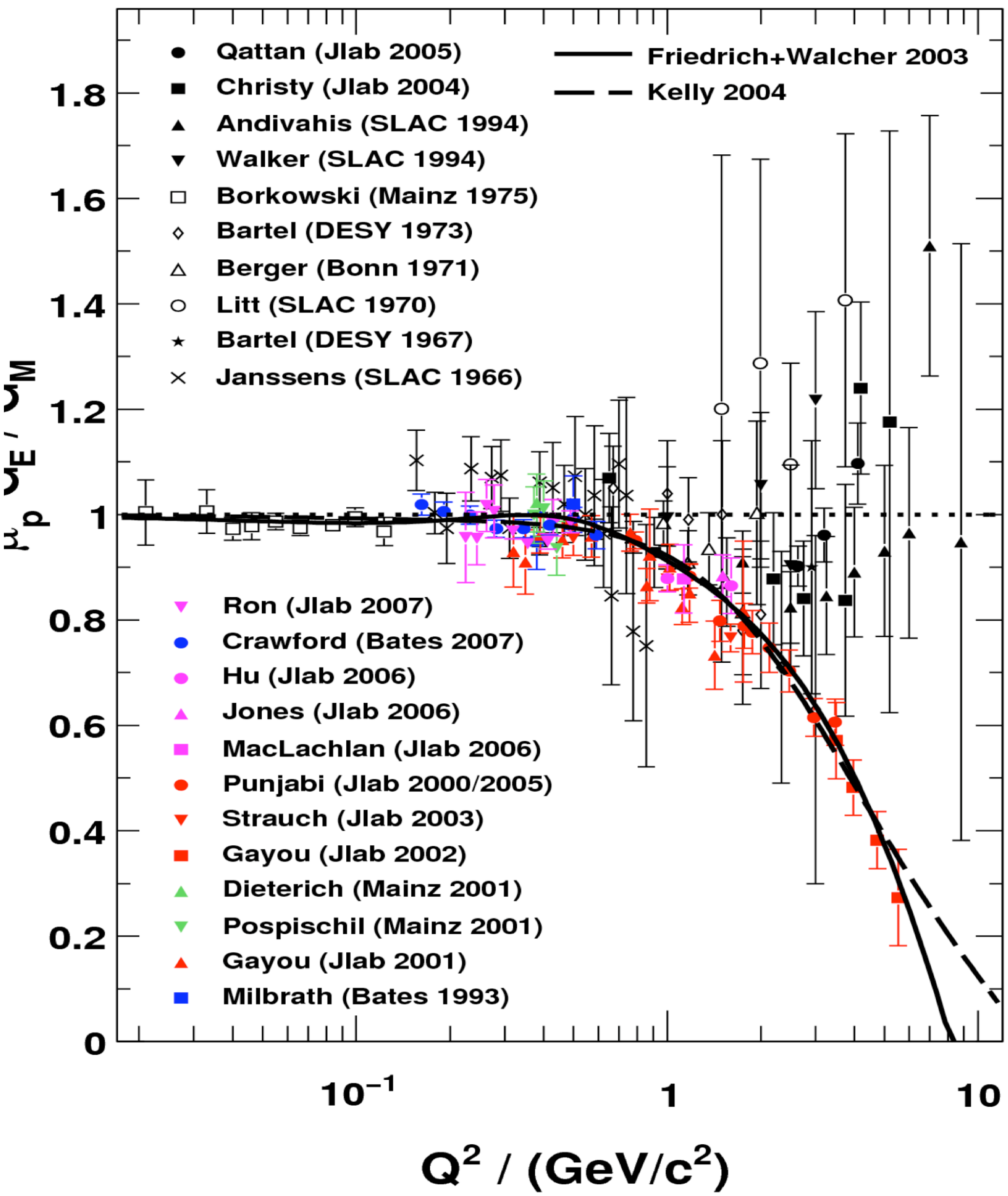




- BLAST data combined with cross sections on separation of G^p_E and G^p_M.
- Errors factor ~2 smaller.
- Deviation from dipole at low Q^2.

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

Proton Form Factor Ratio



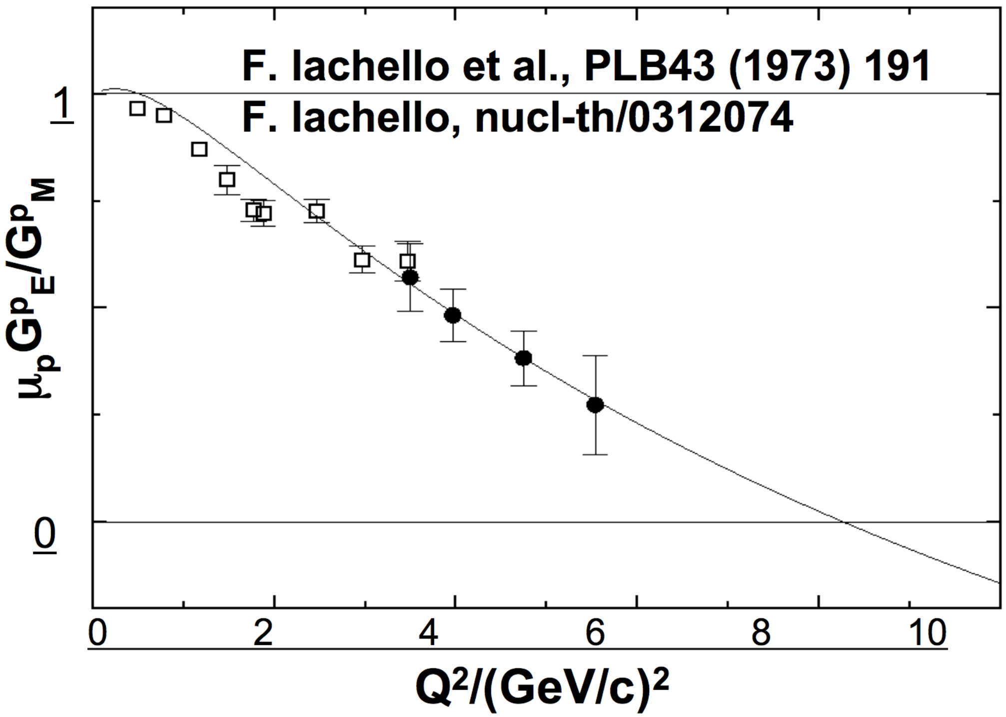
Jefferson Lab

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

Dramatic discrepancy!

>800 citations

Proton Form Factor Ratio

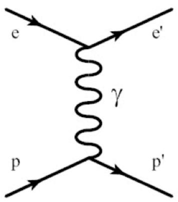


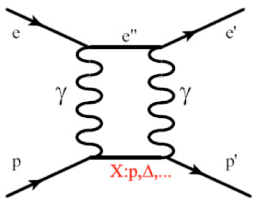
Iachello 1973: Drop of the ratio already suggested by VMD

A.V. Belitsky et al., PRL91 (2003) 092003
G. Miller and M. Frank, PRC65 (2002) 065205
S. Brodsky et al., PRD69 (2004) 076001
Quark angular momentum
Helicity non-conservation
Logarithmic scaling

Two-Photon Exchange

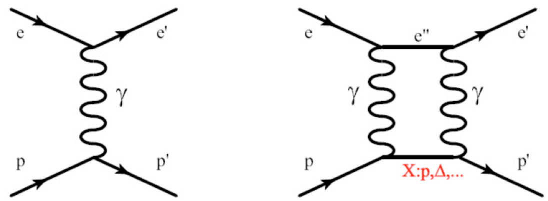
Two-photon exchange theoretically suggested
Interference of one- and two-photon amplitudes





Two-Photon Exchange

Two-photon exchange theoretically suggested
Interference of one- and two-photon amplitudes



P.A.M. Guichon and M. Vanderhaeghen, PRL91 (2003) 142303;
M.P. Rekalo and E. Tomasi-Gustafsson, EPJA22 (2004) 331:
Formalism … TPE effect could be large

P.G. Blunden, W. Melnitchouk, and J.A. Tjon,
PRC72 (2005) 034612, PRL91 (2003) 142304: Nucl. Theory … elastic ≈ half, Delta opposite

Y.C. Chen et al., PRL93 (2004) 122301: Partonic calculation, TPE large at high Q^2

A.V. Afanasev and N.P. Merenkov,
PRD70 (2004) 073002: Large logarithms in normal beam asymmetry

A.V. Afanasev, S.J. Brodsky, C.E. Carlson, Y.C. Chen, M. Vanderhaeghen,
PRD72 (2005) 013008: high Q^2, small effect on asym., larger on x-sec., TPE on R small

M. Gorchtein, PLB644 (2007) 322: Fwd. angle, dispersion ansatz, TPE sizable

Y.C. Chen, C.W. Kao, S.N. Yang, PLB652 (2007) 269: Model-independent TPE large

D. Borisyuk, A. Kobushkin, PRC74 (2006) 065203; 78 (2008) 025208: TPE effect sizable

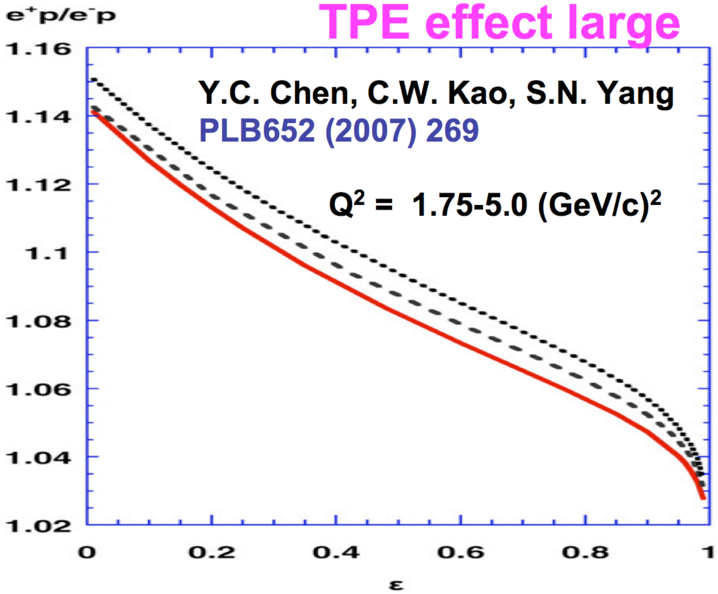
Yu. M. Bystritskiy, E.A. Kuraev, E. Tomasi-Gustafsson, PRC75 (2007) 015207:
Importance of higher-order radiative effects, TPE effect rather small!

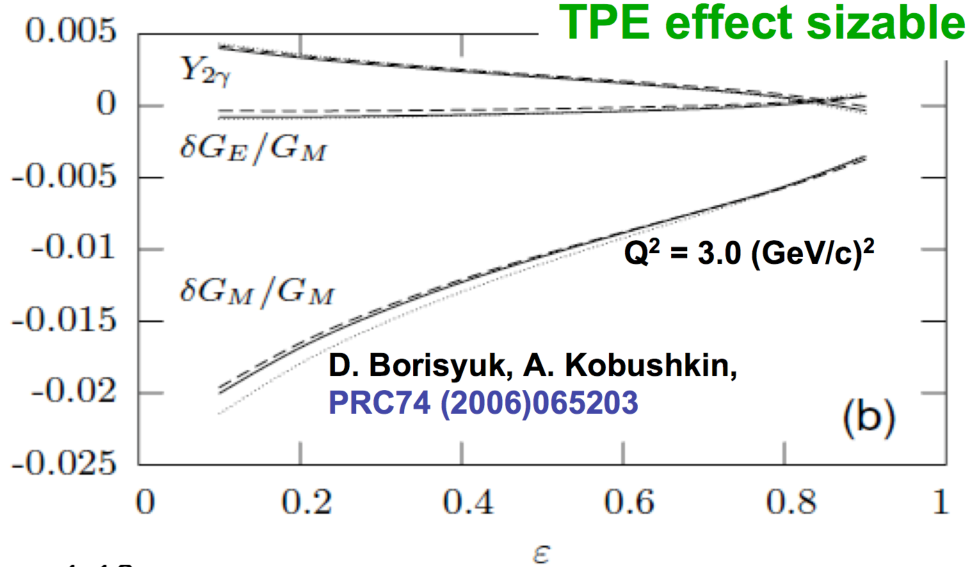
M. Kuhn, H. Weigel, EPJA38 (2008) 295: TPE in Skyrme Model

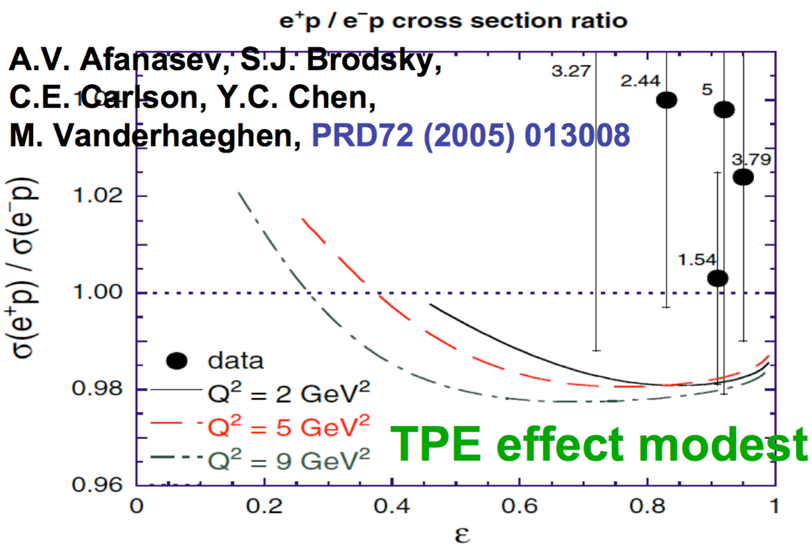
D.Y. Chen et al., PRC78 (2008) 045208: TPE for timelike form factors

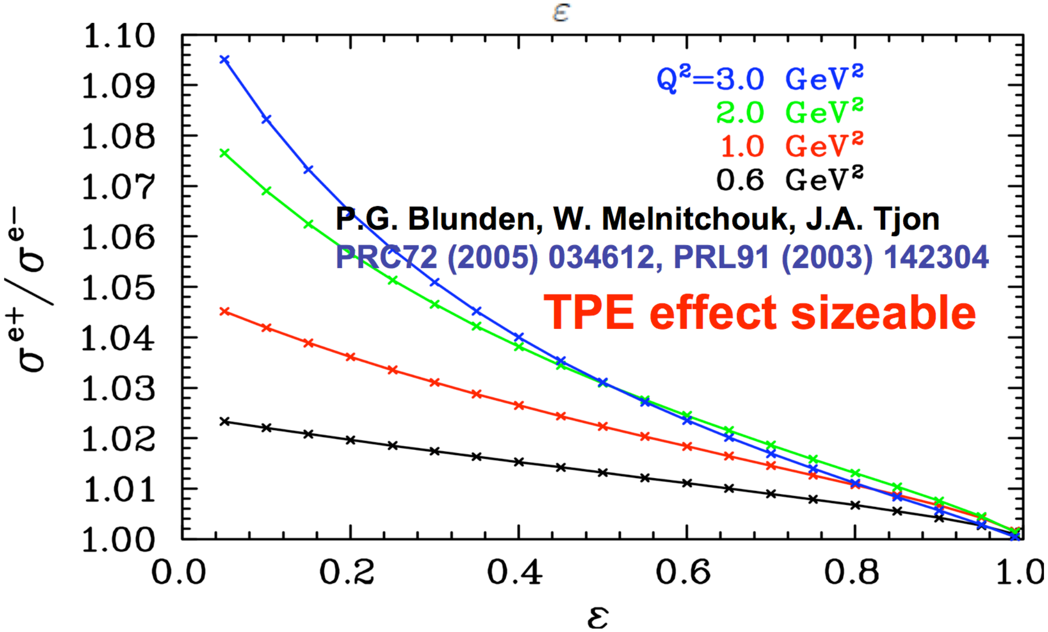
M. Gorchtein, C.J. Horowitz, PRL102 (2009) 091806: gamma-Z box

TPE Predictions for e^+/e^- Ratio



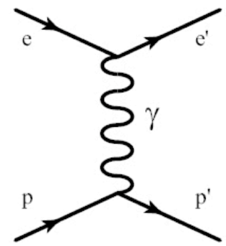


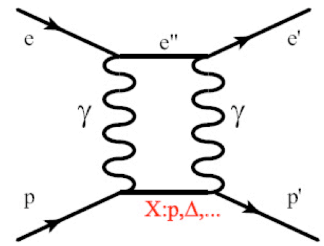




Rosenbluth re-analyzed with TPE

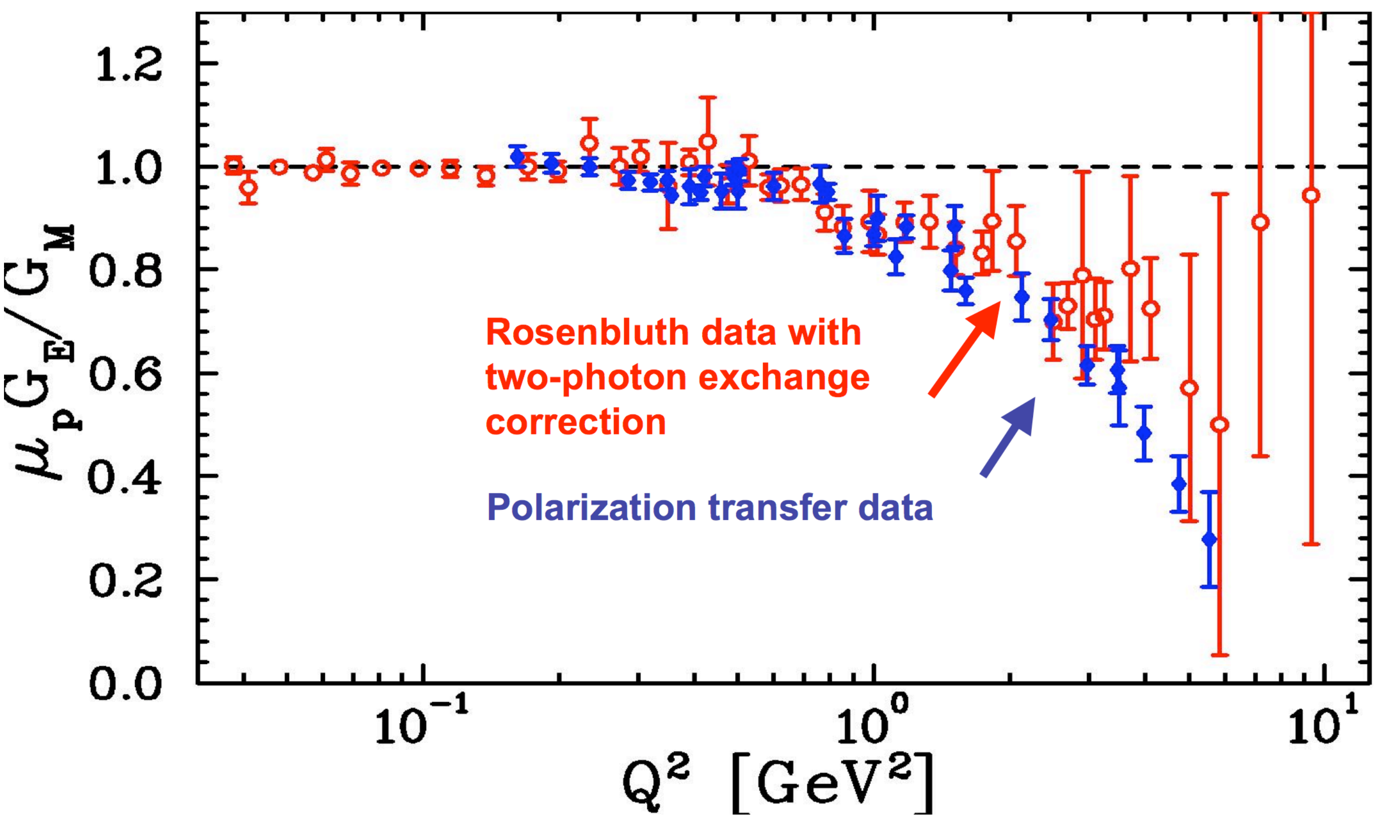
Two-photon exchange theoretically suggested



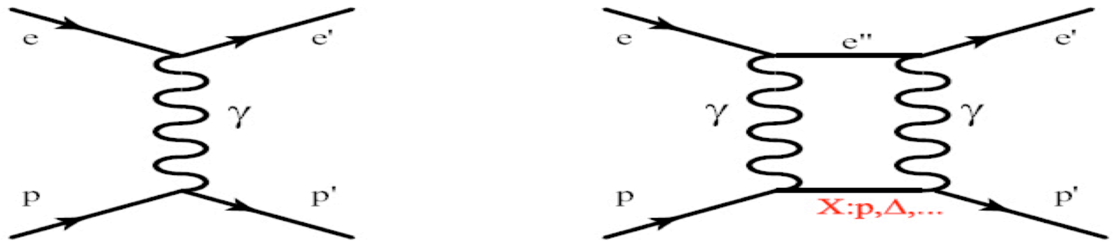


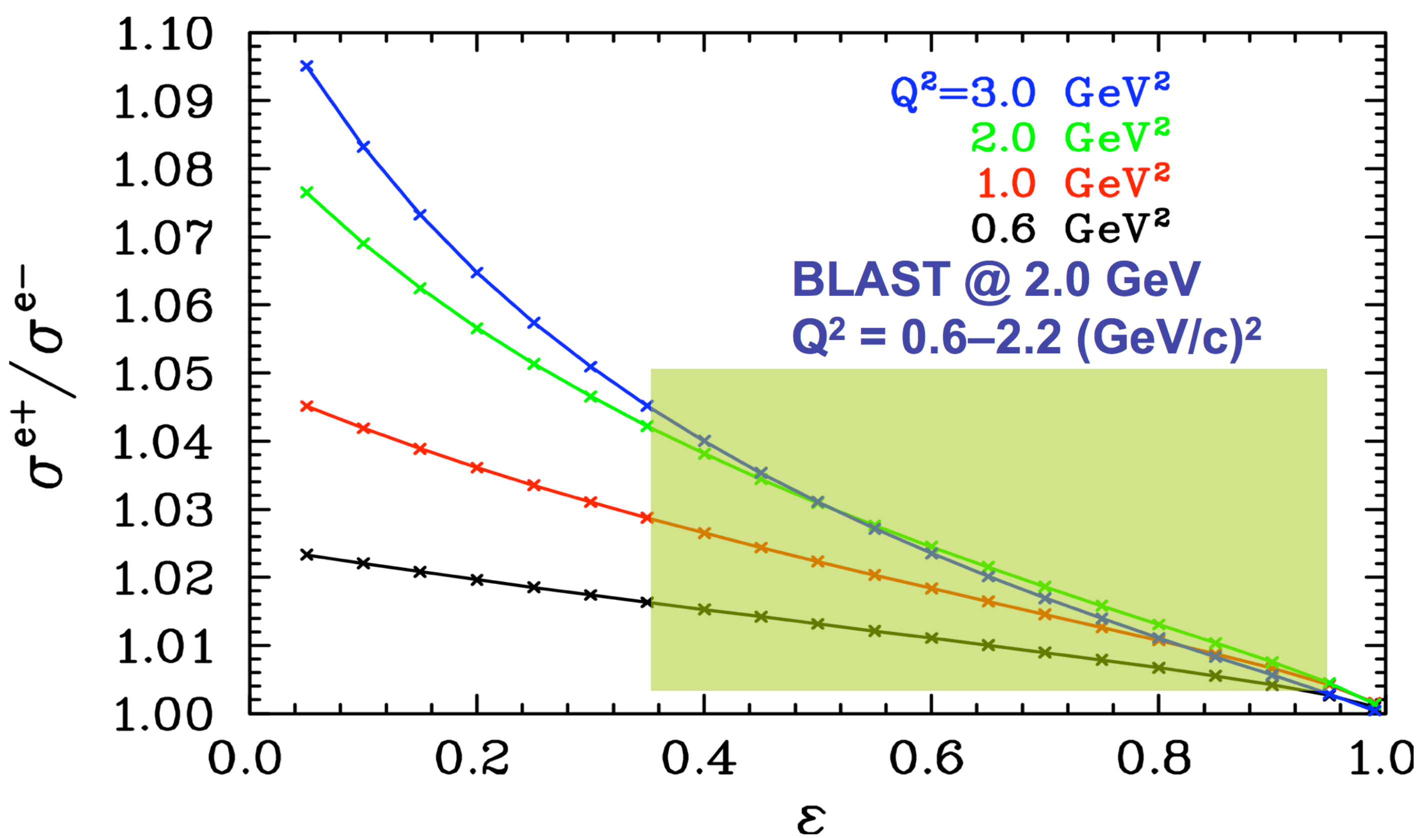
TPE can explain form factor discrepancy

J. Arrington, W. Melnitchouk, J.A. Tjon,
Phys. Rev. C 76 (2007) 035205

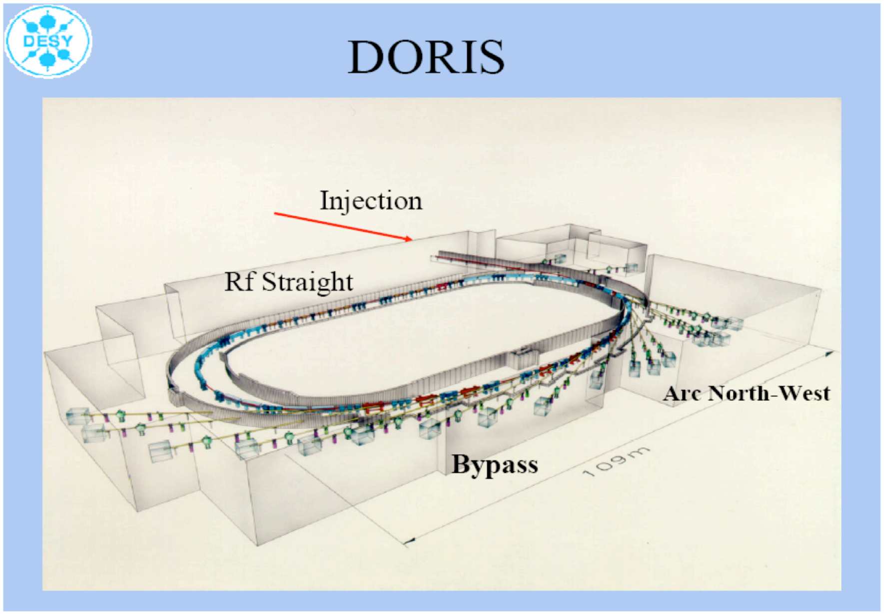


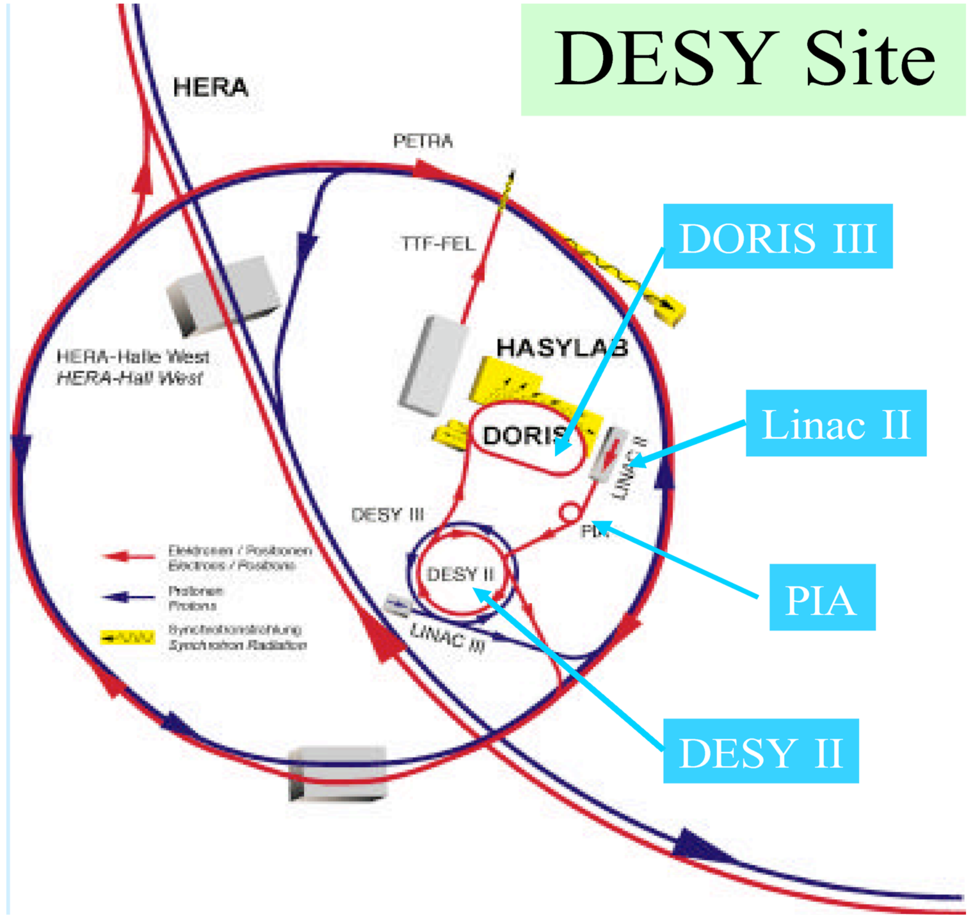
BLAST and the e^+/e^- Ratio



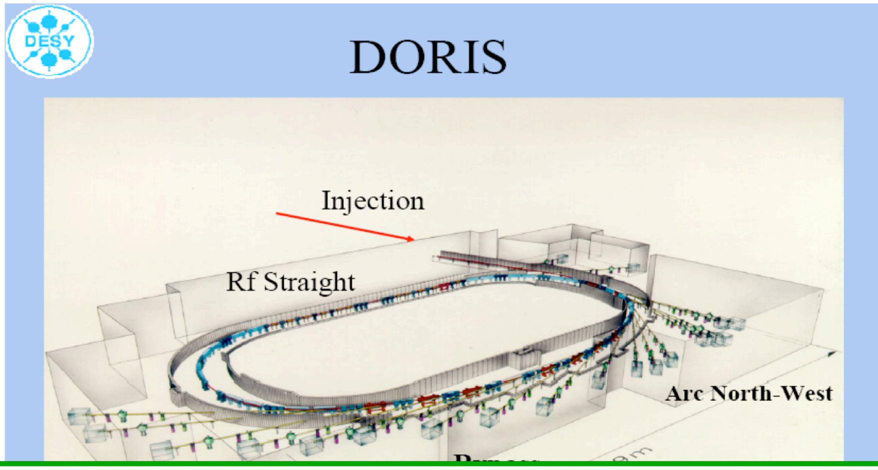


OLYMPUS: BLAST@DESY/DORIS





OLYMPUS: BLAST@DESY/DORIS



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

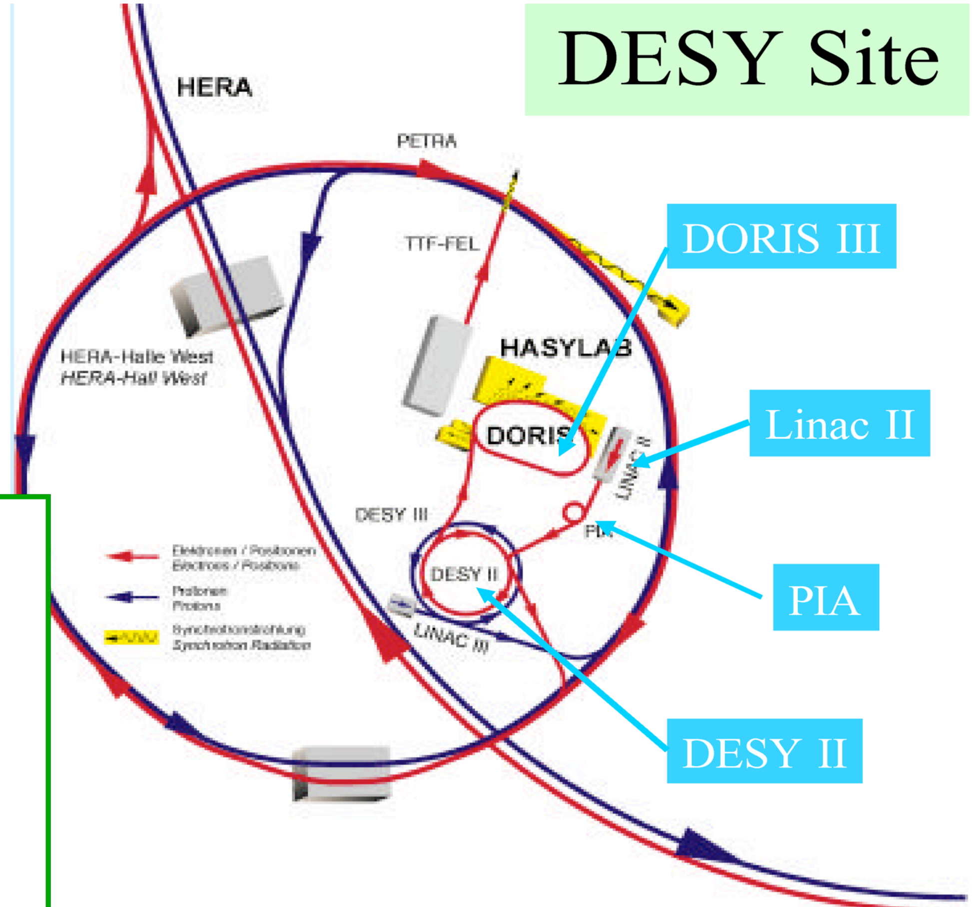
J. Arrington
Argonne National Laboratory

R. Alarcon
Arizona State University

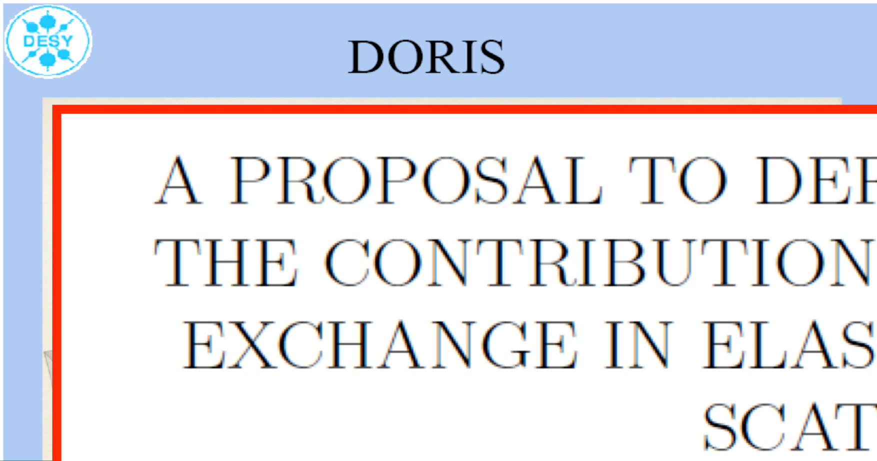
J. Calarco
University of New Hampshire

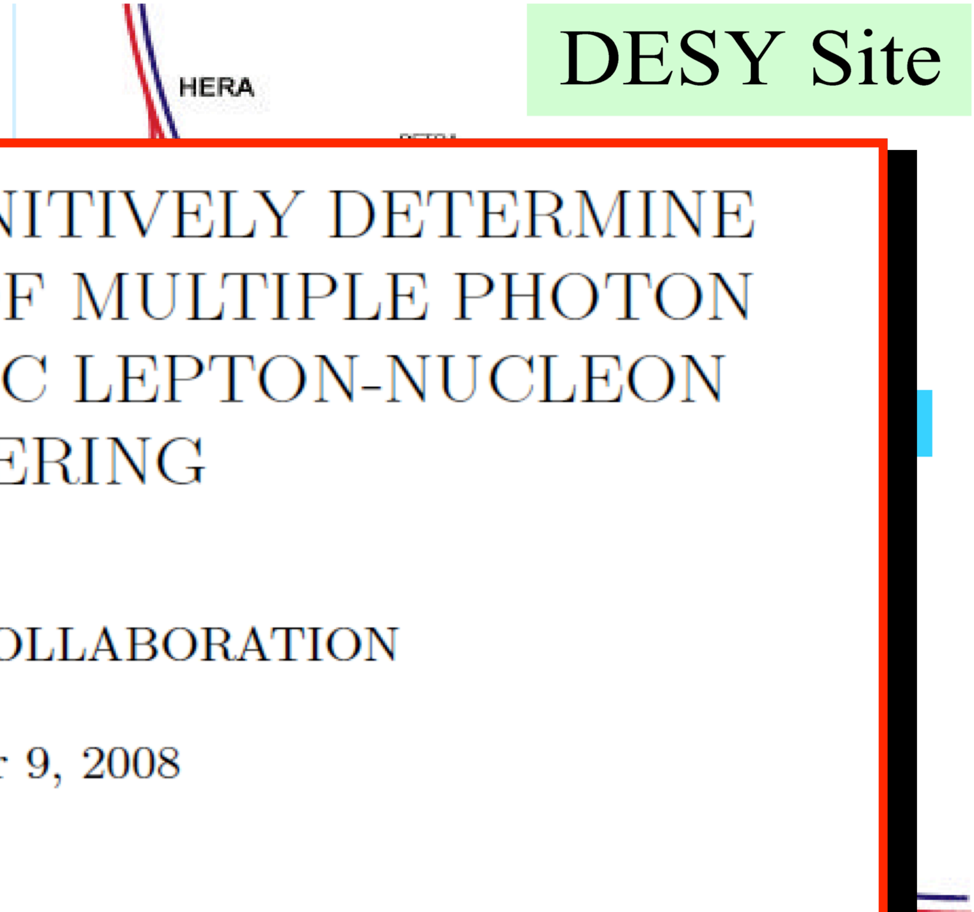
June 19, 2007

Abstract



OLYMPUS: BLAST@DESY/DORIS





A PROPOSAL TO DEFINITIVELY DETERMINE THE CONTRIBUTION OF MULTIPLE PHOTON EXCHANGE IN ELASTIC LEPTON-NUCLEON SCATTERING

THE OLYMPUS COLLABORATION

September 9, 2008

Co

J.

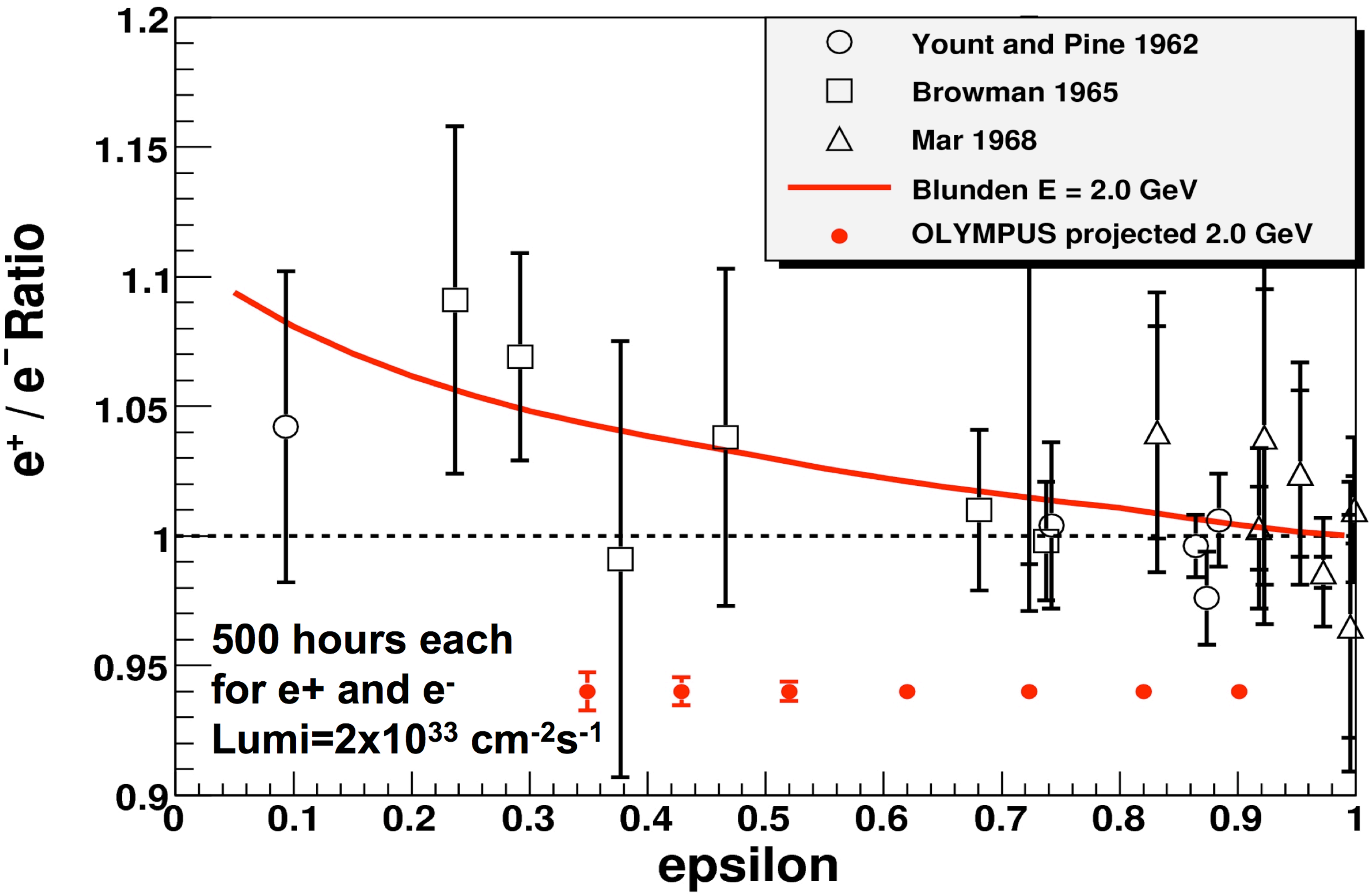
MIT

J. Calarco
University of New Hampshire

June 19, 2007

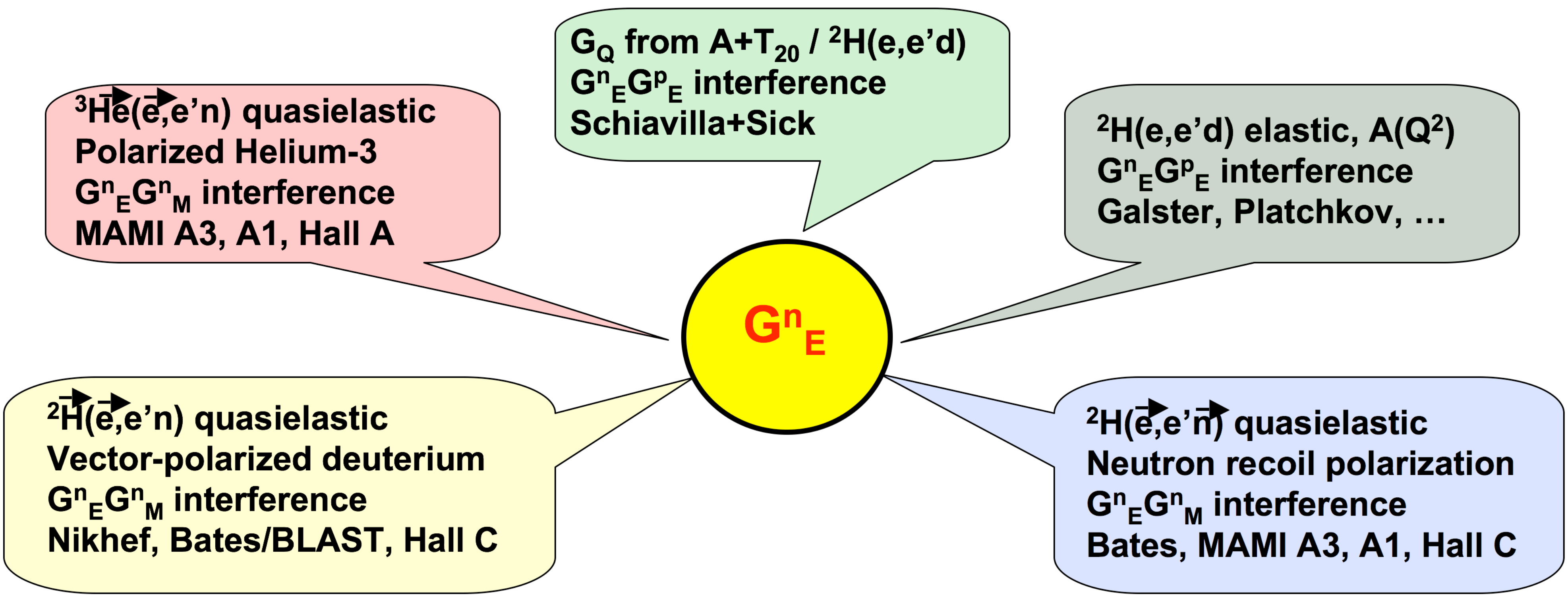
Abstract

Projected Results for OLYMPUS



G^n_E: The Neutron Charge Form Factor

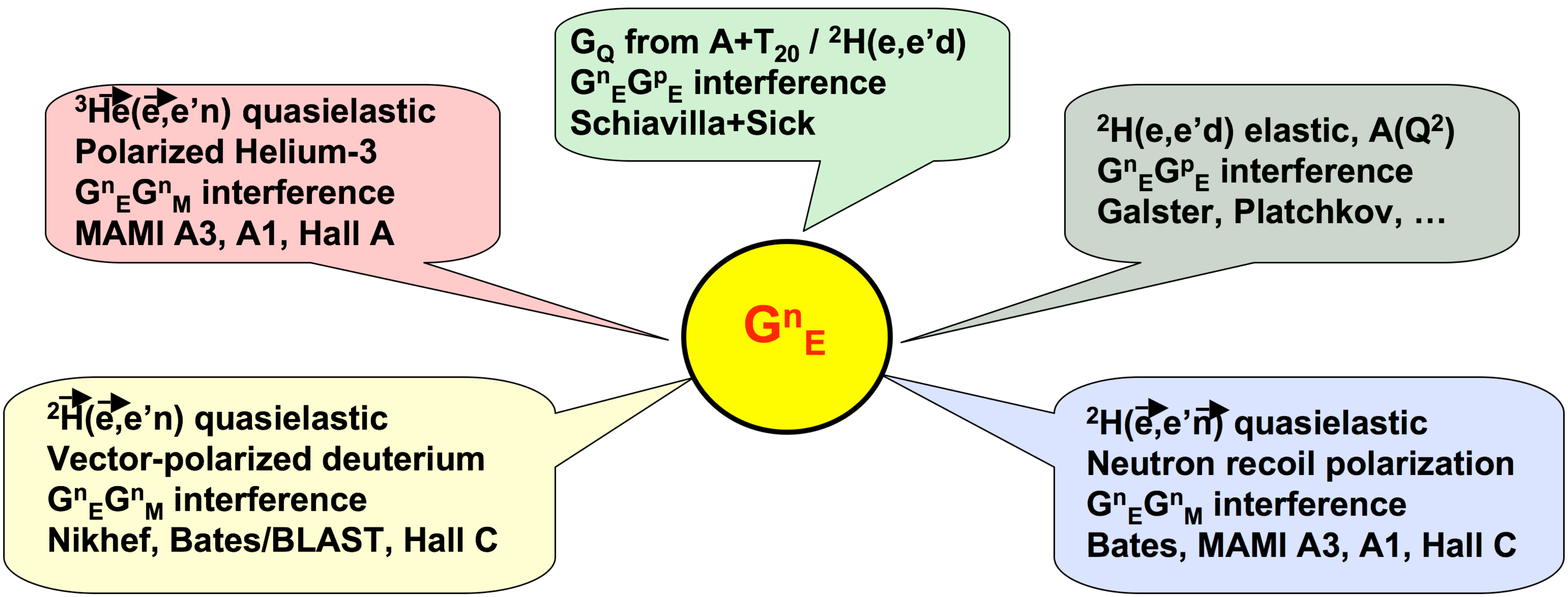
No free neutron target → elastic and quasi-elastic scattering
Nuclear corrections (FSI, MEC, …)
Smallness of G^n_E does not allow L-T sep. of d(e,e'n) or d(e,e')–d(e,e'p)



G^n_E: The Neutron Charge Form Factor

- No free neutron target → elastic and quasi-elastic scattering
- Nuclear corrections (FSI, MEC, …)
- Smallness of G^n_E does not allow L-T sep. of d(e,e'n) or d(e,e')–d(e,e'p)

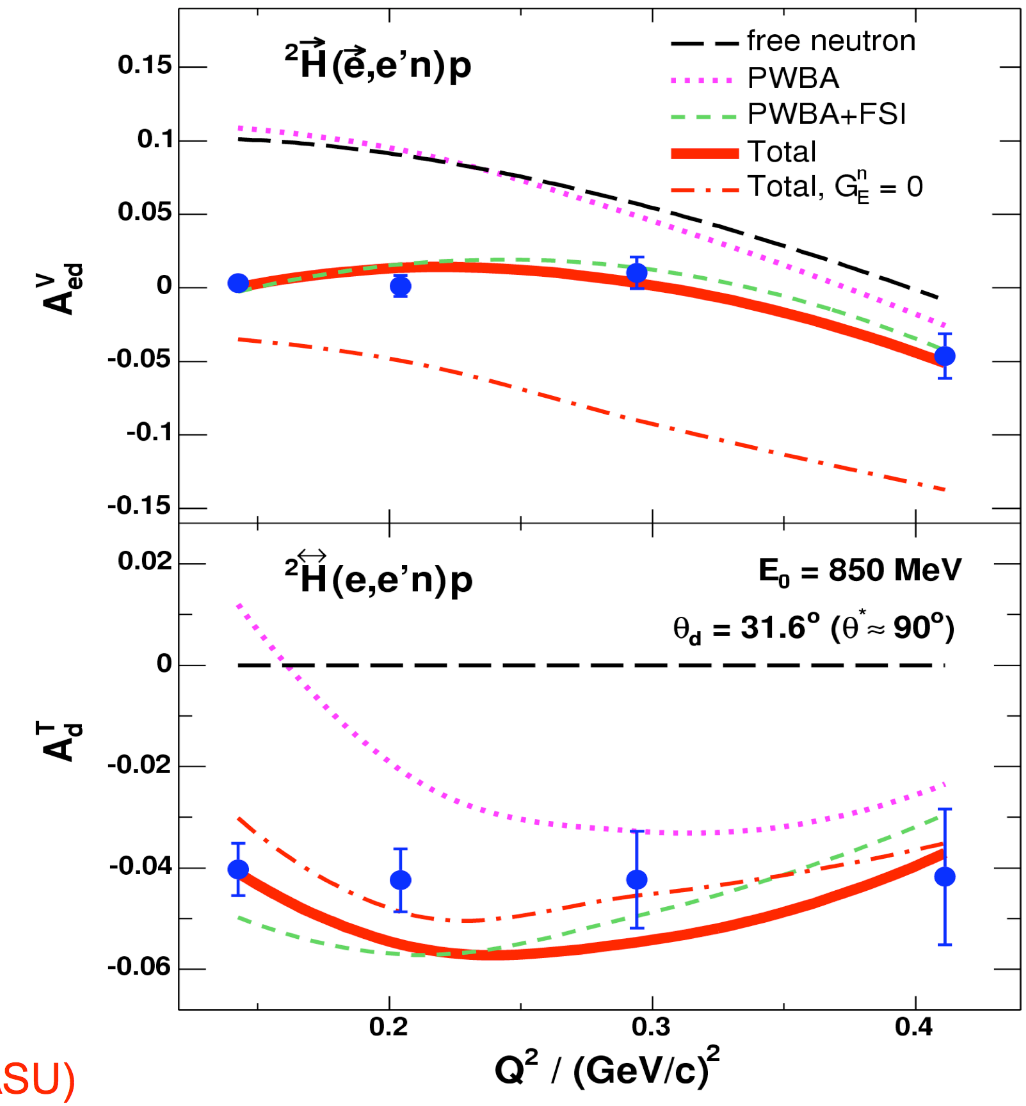
$$A^V_{ed} = \frac{a\, {G^n_M}^2 \cos\theta^* + b\, G^n_E G^n_M \sin\theta^* \cos\phi^*}{c\, {G^n_E}^2 + {G^n_M}^2} \approx a\cos\theta^* + b\,\frac{G^n_E}{G^n_M}\sin\theta^* \cos\phi^*$$



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

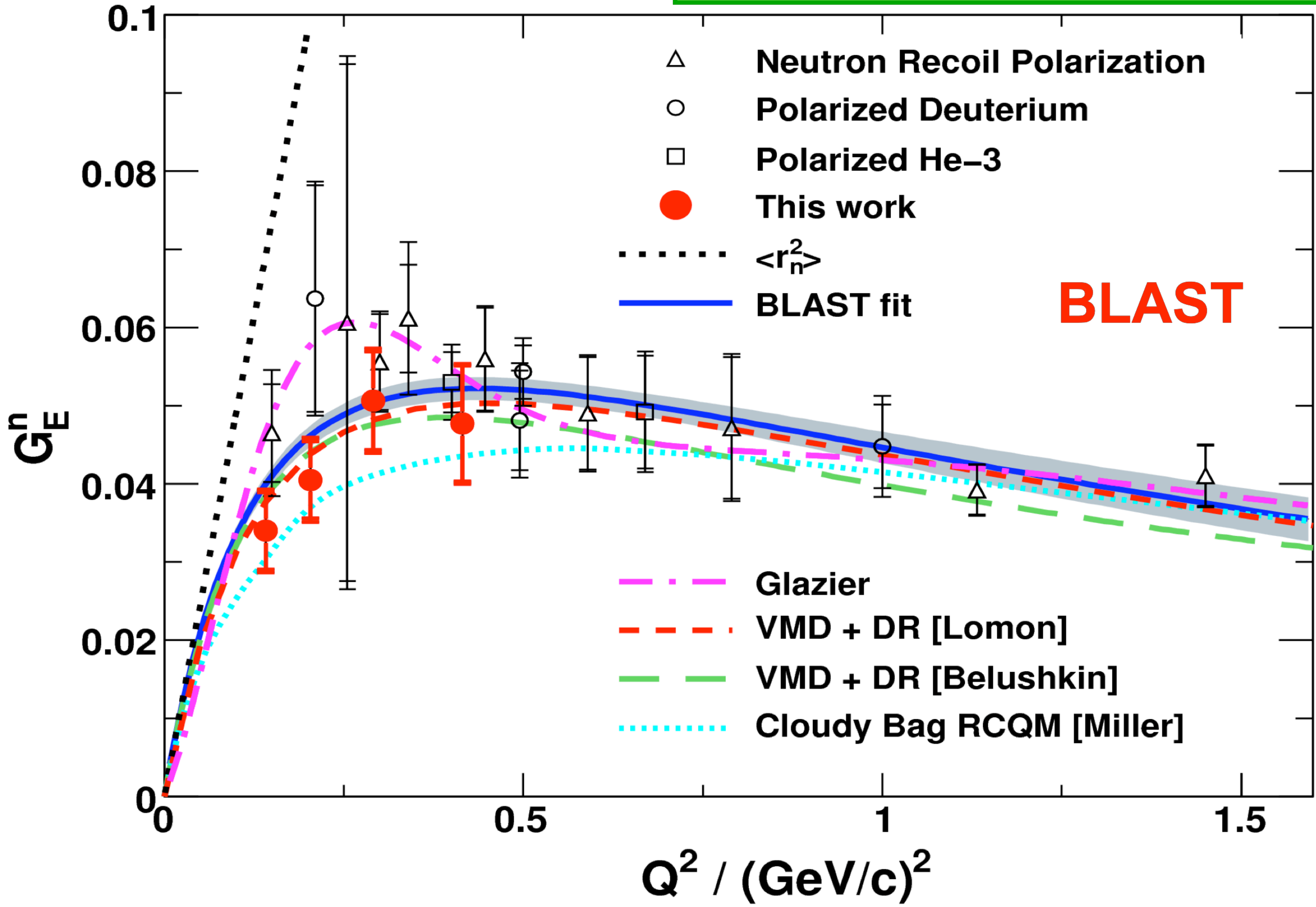
- **Use tensor asymmetry to control FSI**



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

Neutron Electric Form Factor G^n_E *

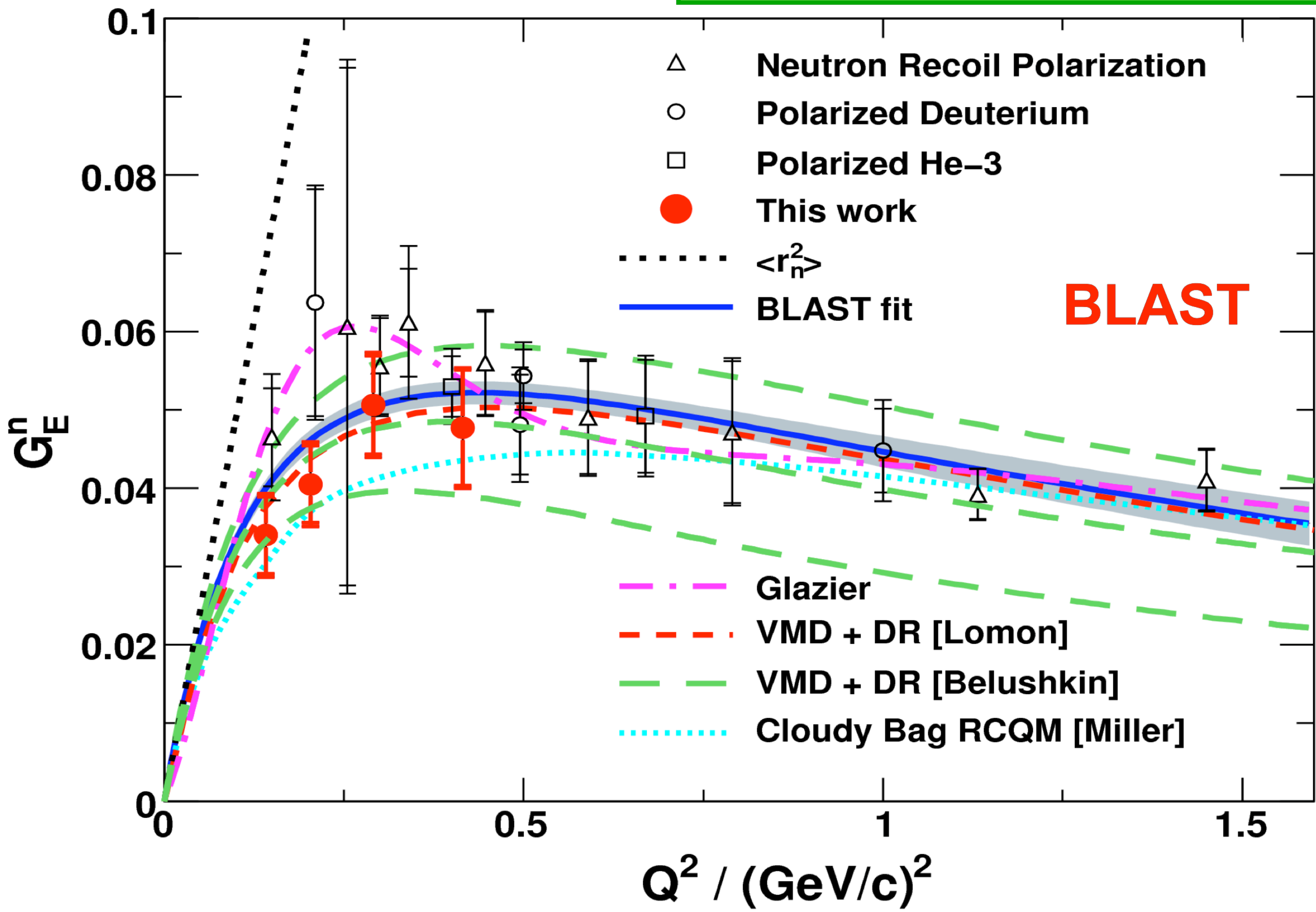
E. Geis et al., PRL101 (2008) 042501



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

Neutron Electric Form Factor G^n_E *

E. Geis et al., PRL101 (2008) 042501



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

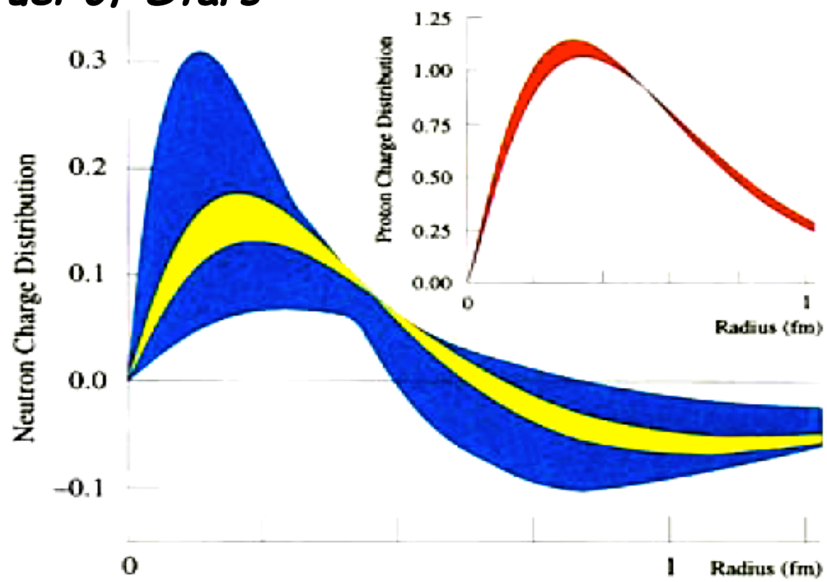
Neutron Charge Distribution

Neutron Charge Distribution

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

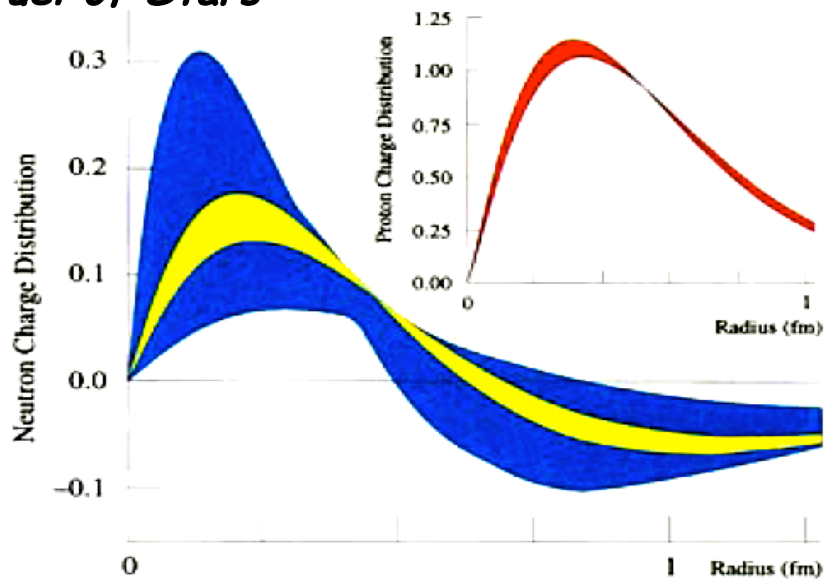
Neutron Charge Distribution

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



Neutron Charge Distribution

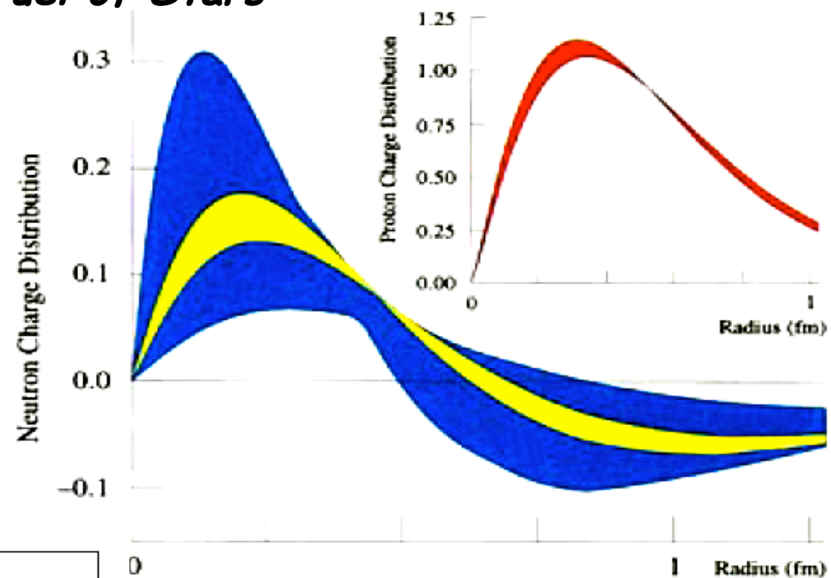
Nuclear Physics: The Core of Matter, The Fuel of Stars
National Research Council (1999)



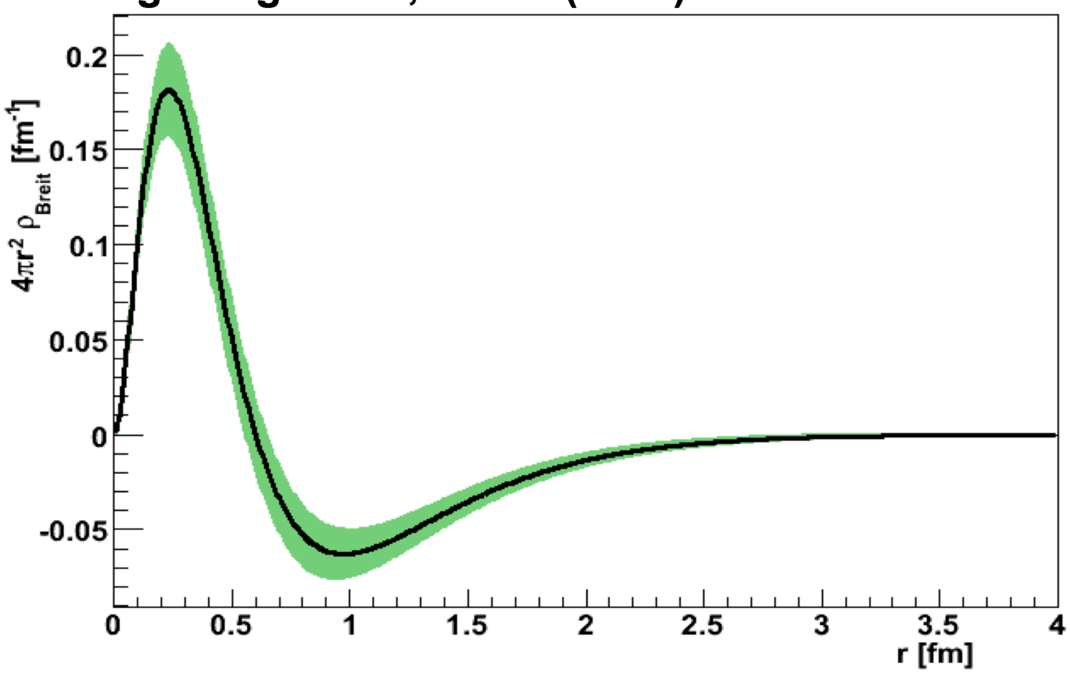
The Frontiers of Nuclear Science:
A Long Range Plan, NSAC (2008)

Neutron Charge Distribution

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



The Frontiers of Nuclear Science:
A Long Range Plan, NSAC (2008)

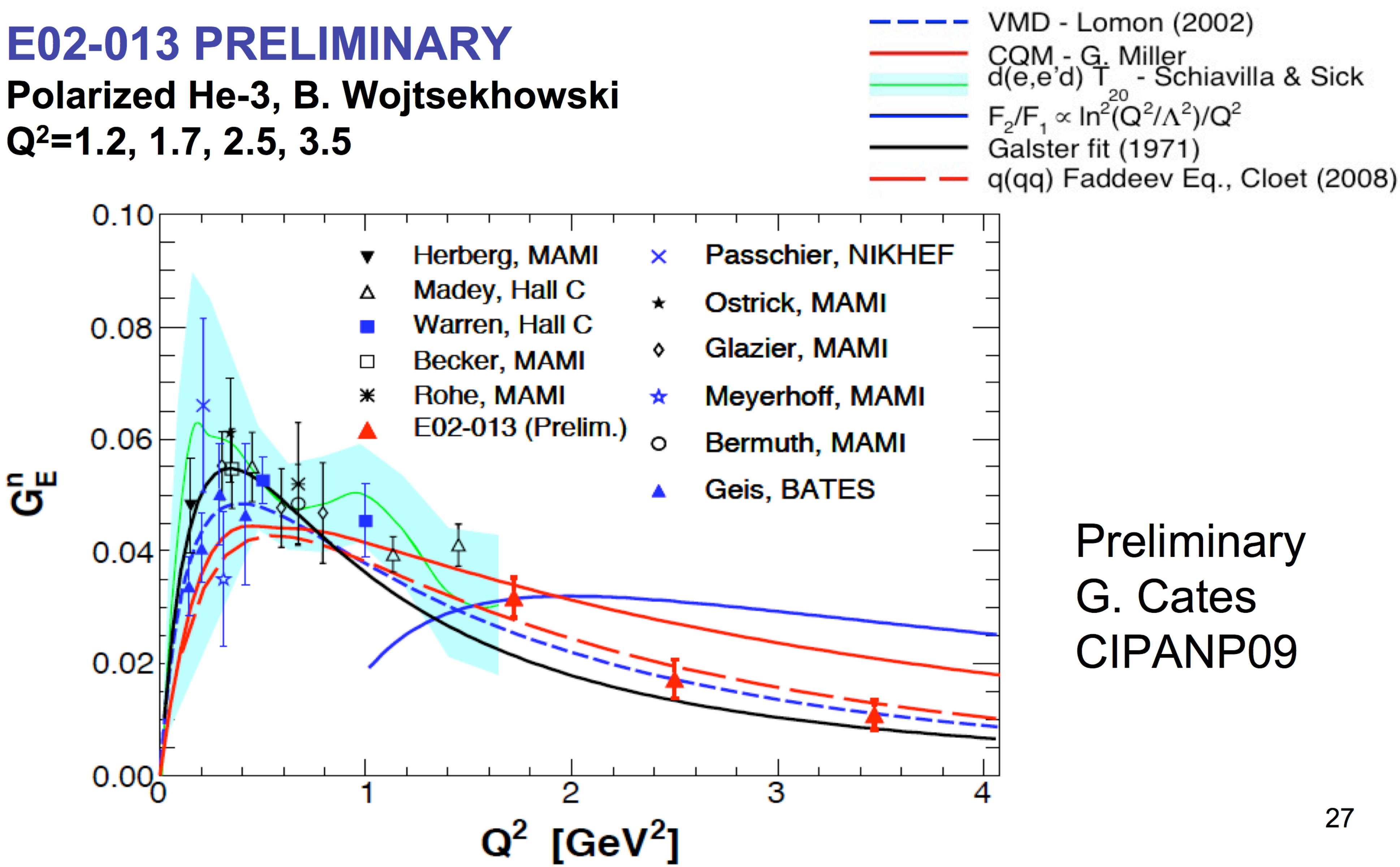


New Measurements of G^n_E

E02-013 PRELIMINARY

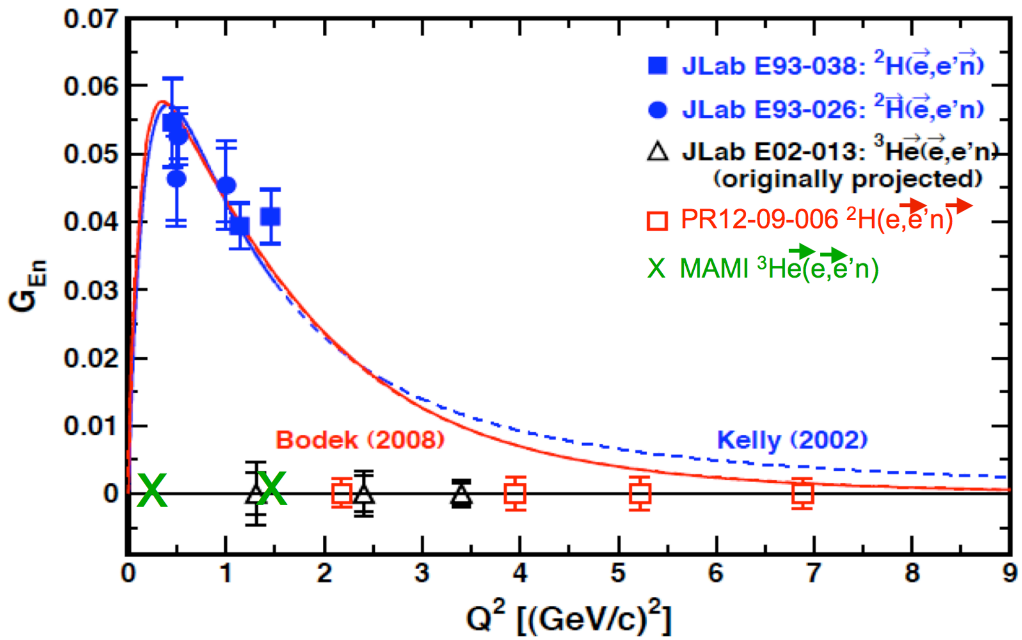
Polarized He-3, B. Wojtsekhowski

Q^2=1.2, 1.7, 2.5, 3.5



Preliminary
G. Cates
CIPANP09

Future Measurements of G^n_E



PAC34 (2009): PR12-09-006

B.D. Anderson, J. Arrington, S. Kowalski, R. Madey, B. Plaster, A. Yu. Semenov et al.

Hall C: SHMS + NPOL

Up to **Q^2 = 7 (GeV/c)^2**

Superseeding PR04-110

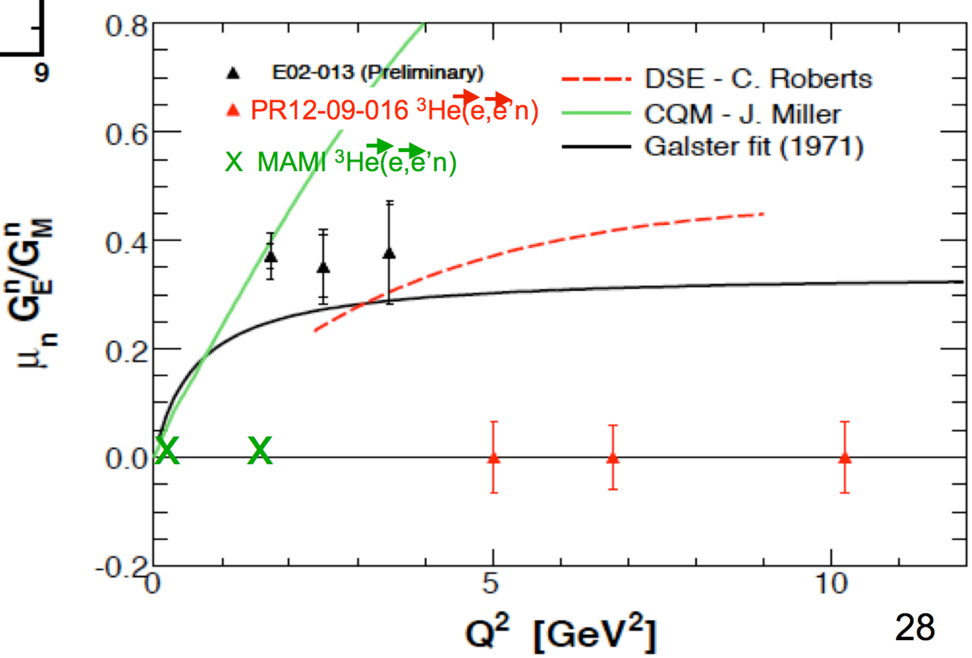
PAC34 (2009): PR12-09-016

B. Wojtsekhowski, G. Cates, S. Riordan et al.

Hall A: Polarized He-3

Up to **Q^2 = 10 (GeV/c)^2**

MAMI-A1
Polarized He-3
Q^2=0.25, 1.50 (GeV/c)^2



G^n_M in Absence of Free Neutron Target

No free neutron target → elastic and quasi-elastic scattering
Nuclear corrections (FSI, MEC, …)
Neutron efficiency

$^3\vec{He}(\vec{e},e')$ quasielastic, inclusive
Polarized He-3
Bates, Hall A
Issues: P_n, FSI
a>>1, b>c

$$A_{T'} = \frac{1 + a\,{G^n_M}^2}{b + c\,{G^n_M}^2}$$

d(e,e')-p(e,e') difference
d(e,e' !p), d(e,e'n)
Issues: large nucl. corr.
Need to know n-efficiency

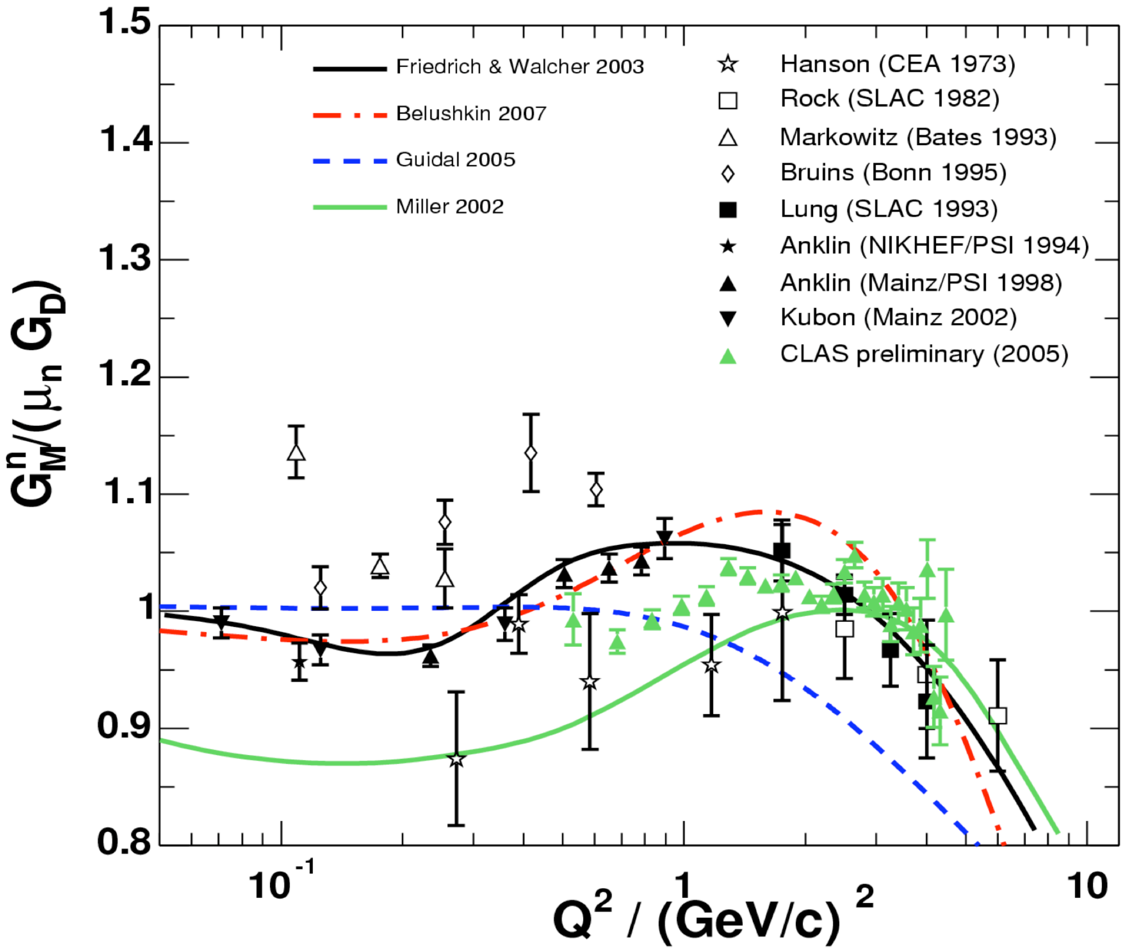
G^n_M

$^2\vec{H}(\vec{e},e')$ quasielastic, inclusive
Vector-polarized deuterium
Bates/BLAST
IncAs (LOI-09-003)
Issues:
Know G^p_E/G^p_M, G^p_M

$$\frac{A_\perp}{A_\parallel} \approx \frac{\kappa \frac{G^p_E}{G^p_M}}{1 + \left(\frac{G^n_M}{G^p_M}\right)^2}$$

$\frac{^2H(e,e'n)}{^2H(e,e'p)}$ ratio quasielastic
SLAC, Bates, Nikhef, MAMI, Hall B
Issues: Know G^p_M
Need to know n-efficiency

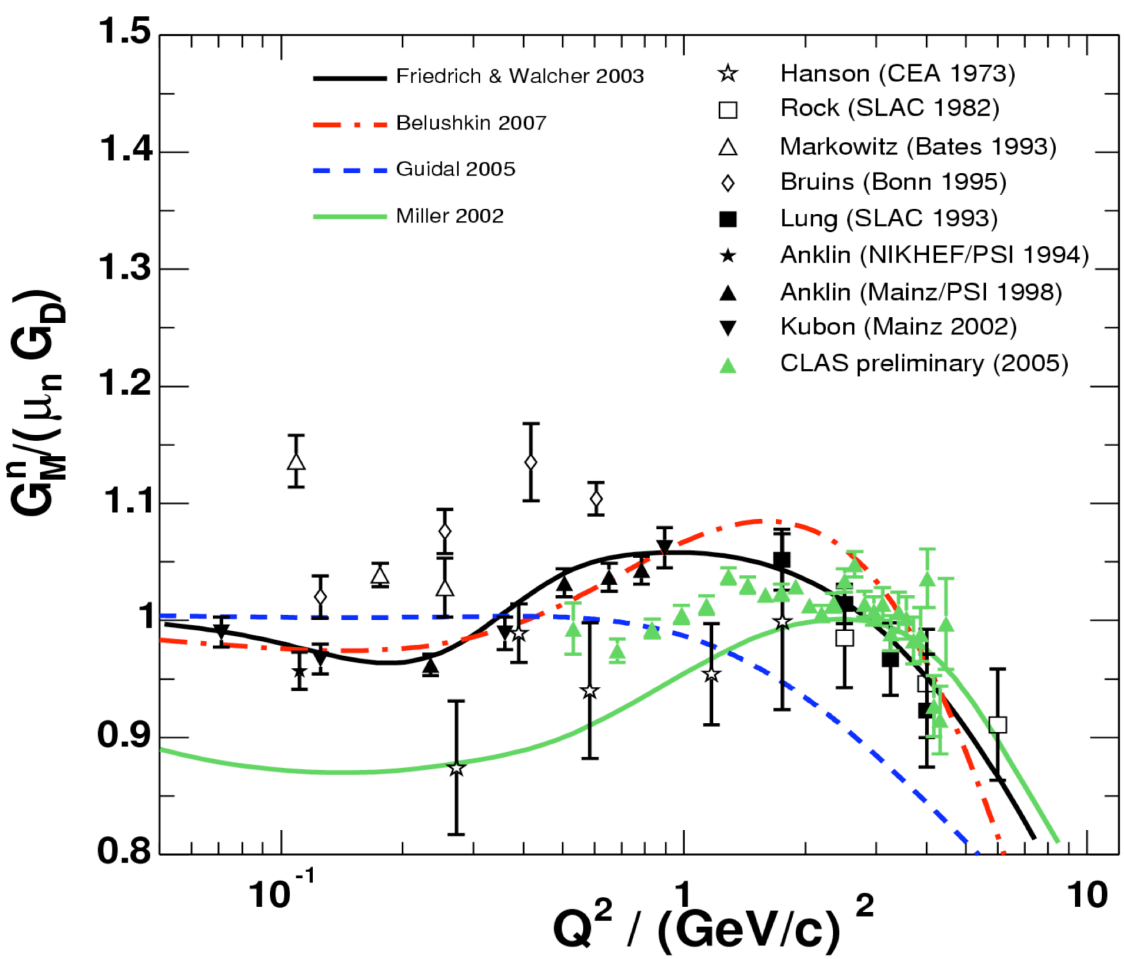
Neutron Magnetic Form Factor G^n_M*



$$\frac{d(e,e'n)}{d(e,e'p)}$$

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

Neutron Magnetic Form Factor G^n_M*



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

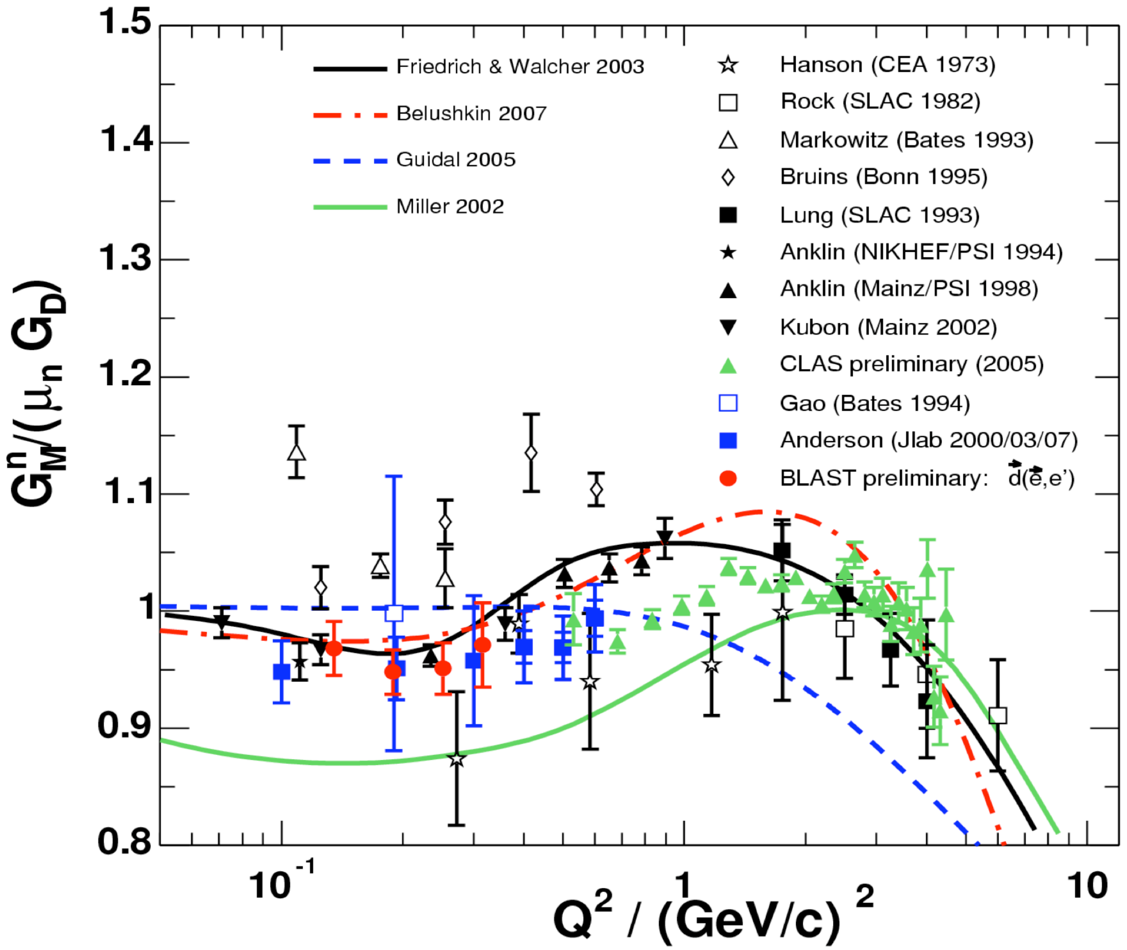
quasielastic $\dfrac{d(e,e'n)}{d(e,e'p)}$

- **+ CLAS preliminary**

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

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

Neutron Magnetic Form Factor G^n_M*



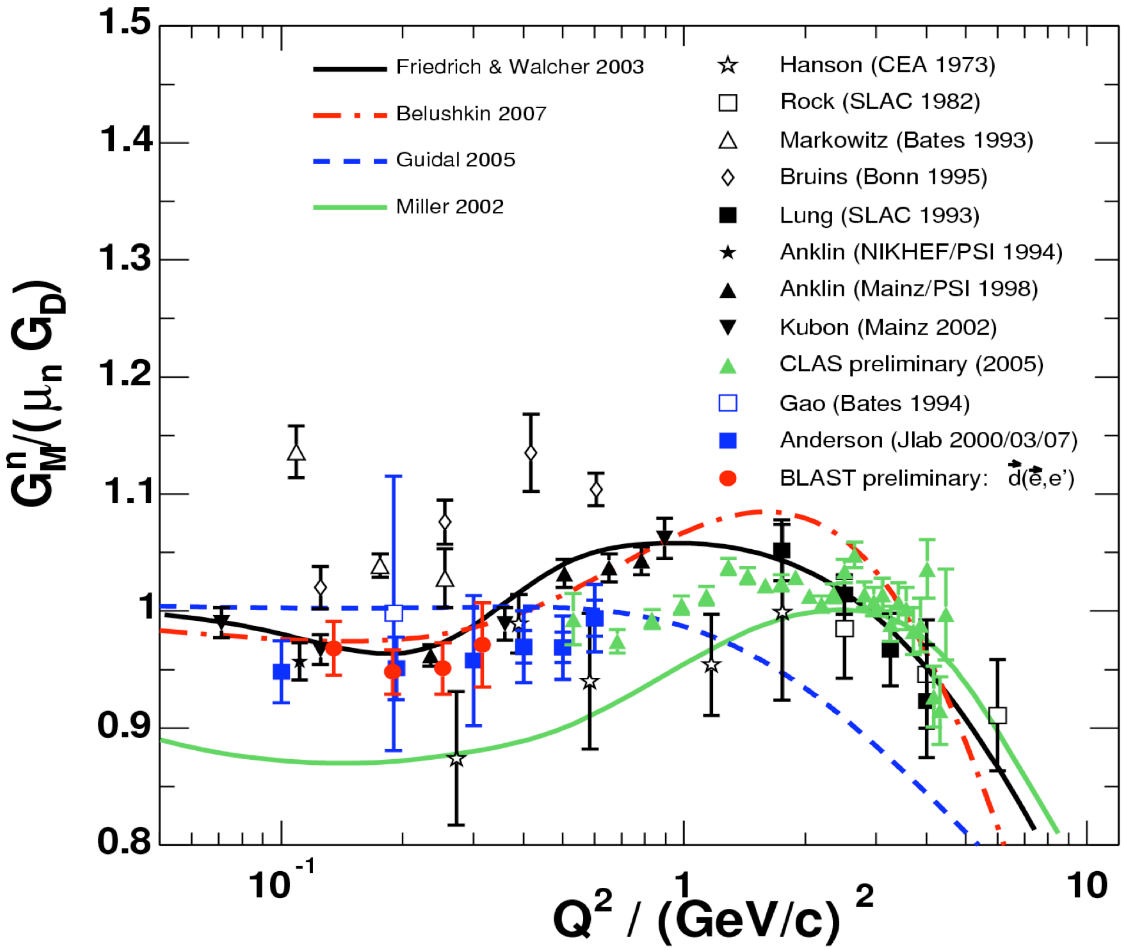
- **Pre-polarization era**
- G^n_M world data from unpolarized experiments
- Cross section ratio

quasielastic $\frac{d(e,e'n)}{d(e,e'p)}$

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

*Ph.D. work of N. Meitanis (MIT) and B. 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 $\frac{d(e,e'n)}{d(e,e'p)}$

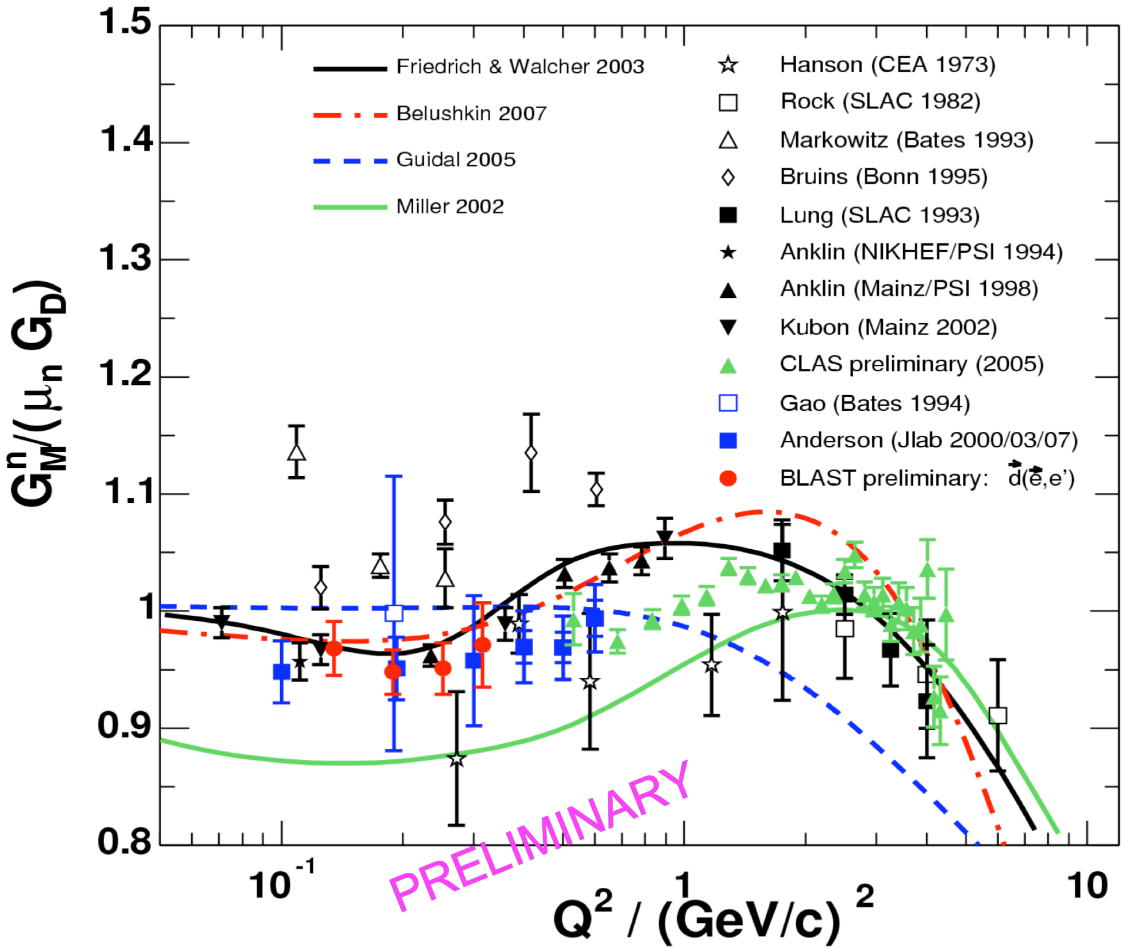
- **+ CLAS preliminary**

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

+ BLAST preliminary

*Ph.D. work of N. Meitanis (MIT) and B. 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 preliminary**

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

  + BLAST preliminary

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

Summary

- **Nucleon electromagnetic elastic form factors**
- **Tremendous progress during last decade**
- **High precision, low systematic uncertainties through polarization experiments**
- **Worldwide activity at its peak**

- **Progress in past decade:**
  - **High-Q^2 surprise in G^p_E/G^p_M; strong impact on theoretical picture Evidence for two-photon exchange effects. Experimental verification is needed (OLYMPUS).**
  - **New precise picture of G^n_E for Q^2<1.5 $(GeV/c)^2$, G^n_M <5 $(GeV/c)^2$**
  - **Evidence for structure beyond G_{Dipole} at low Q^2 in all form factors**
  - **VMD description very successful**

- **Many new experiments underway or proposed**