4th Int. Workshop "From Parity Violation to Hadronic Structure and more..." (PAVI09),
Bar Harbor, ME, June 22-26, 2009

Elastic Form Factor Experiments: A Serial Story

Michael Kohl

**Hampton University, VA 23668 and
Jefferson Lab, VA 23606, USA**

HAMPTON UNIVERSITY
The Standard of Excellence, An Education for Life

Jefferson Lab

Outline

Proton & Neutron electric and magnetic form factors

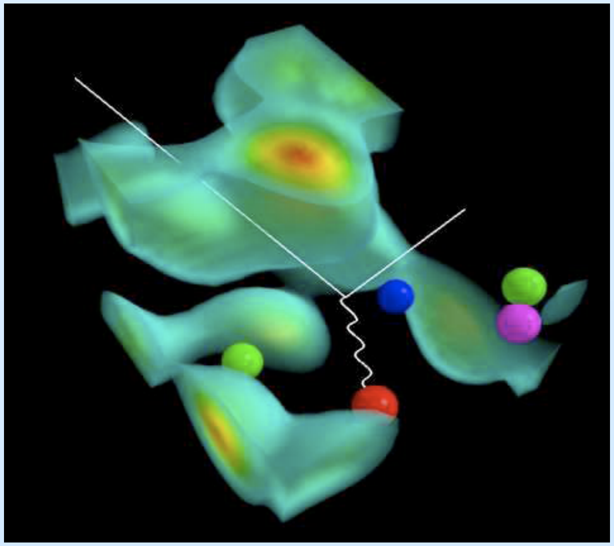
- Introduction, motivation and formalism
- Traditional and new techniques
- Overview of experimental data

Energy frontier

- High Q^2: Proton form factor ratio and two-photon exchange
- Transition to pQCD

Precision frontier

- Low Q^2: Pion cloud effect
- Deviations from dipole FF



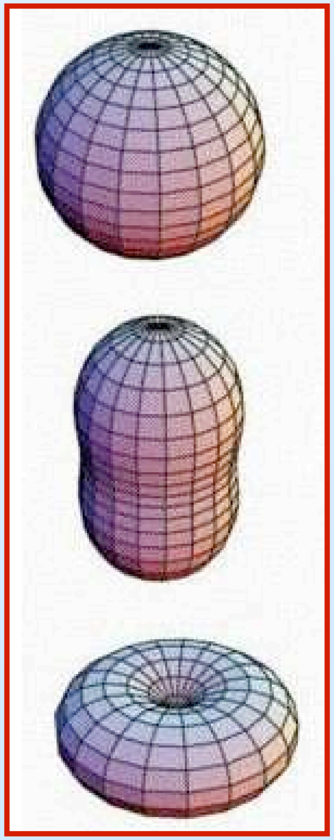
A. Thomas, W. Weise,
The Structure of the Nucleon (2001)

Nucleon Elastic Form Factors …

- Fundamental quantities
- Defined in context of single-photon exchange

- Describe internal structure of the nucleons
- Related to spatial distribution of charge and magnetism

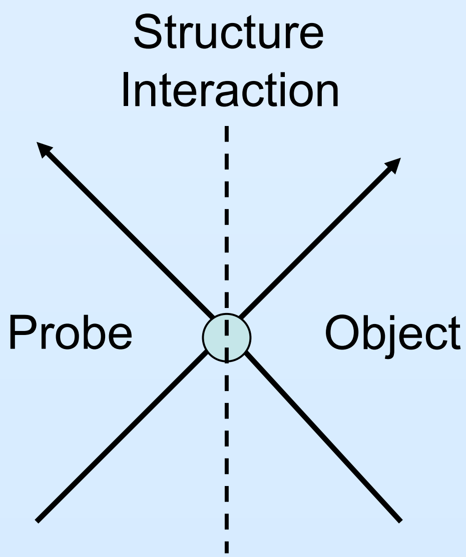
- Rigorous tests of nucleon models
- Determined by quark structure of the nucleon
- Ultimately calculable by Lattice-QCD
- Input to nuclear structure and parity violation experiments



50 years of ever increasing activity

- Tremendous progress in experiment and theory over last decade
- New techniques / polarization experiments
- Unexpected results

(Hadronic) Structure and (EW) Interaction

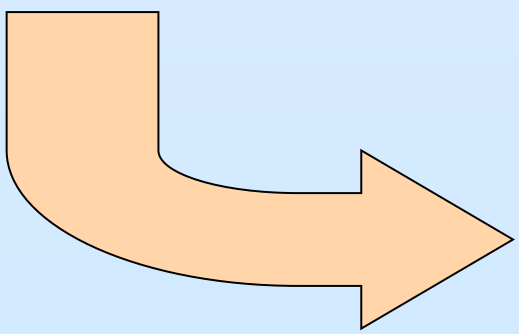


Factorization!

$$|\text{Form factor}|^2 = \frac{\sigma(\text{structured object})}{\sigma(\text{pointlike object})}$$

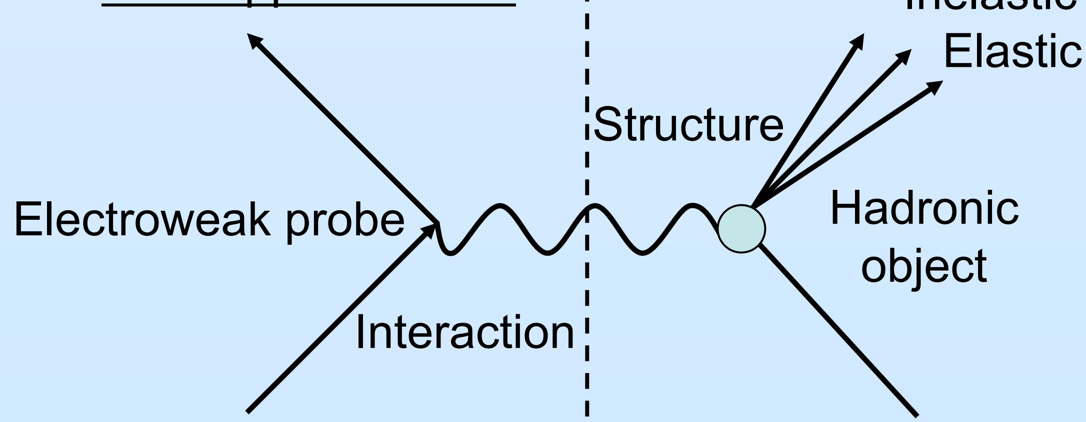
→ **Interference!**

→ **Utilize spin dependence of electromagnetic interaction to achieve high precision**



Lepton scattering

Born Approximation



The Beginnings

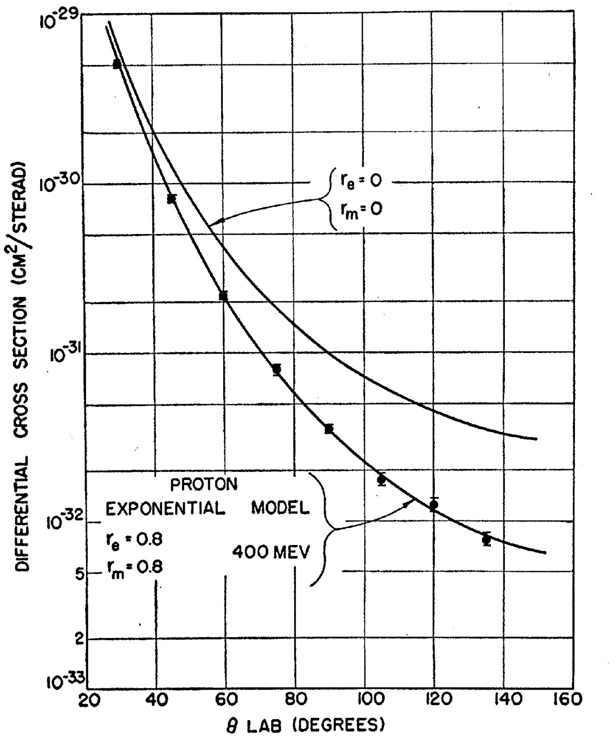


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii$=0.80\times10^{-13}$ cm.

Robert Hofstadter
Nobel prize 1961

ep-elastic
Finite size of the proton

R. Hofstadter, Rev. Mod. Phys. 56 (1956) 214

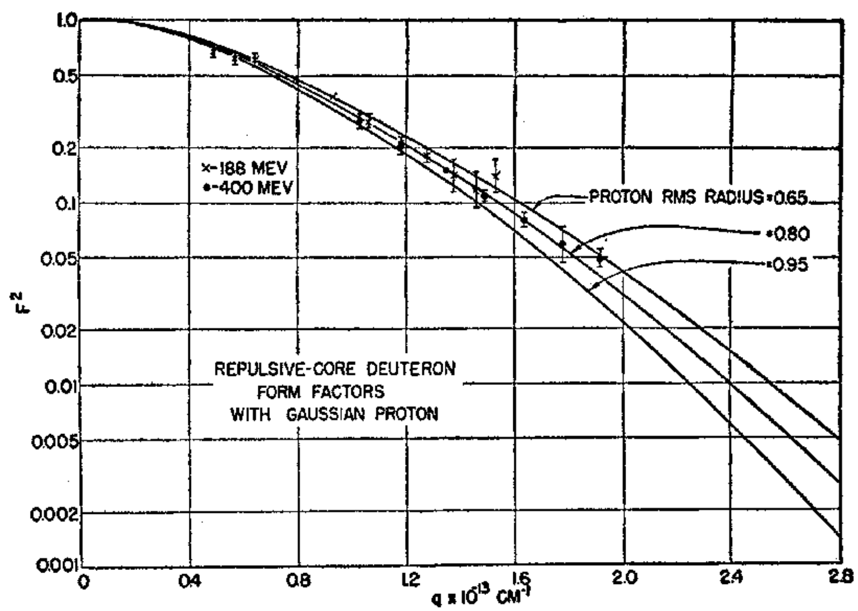


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

ed-elastic
Finite size + nuclear structure

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**

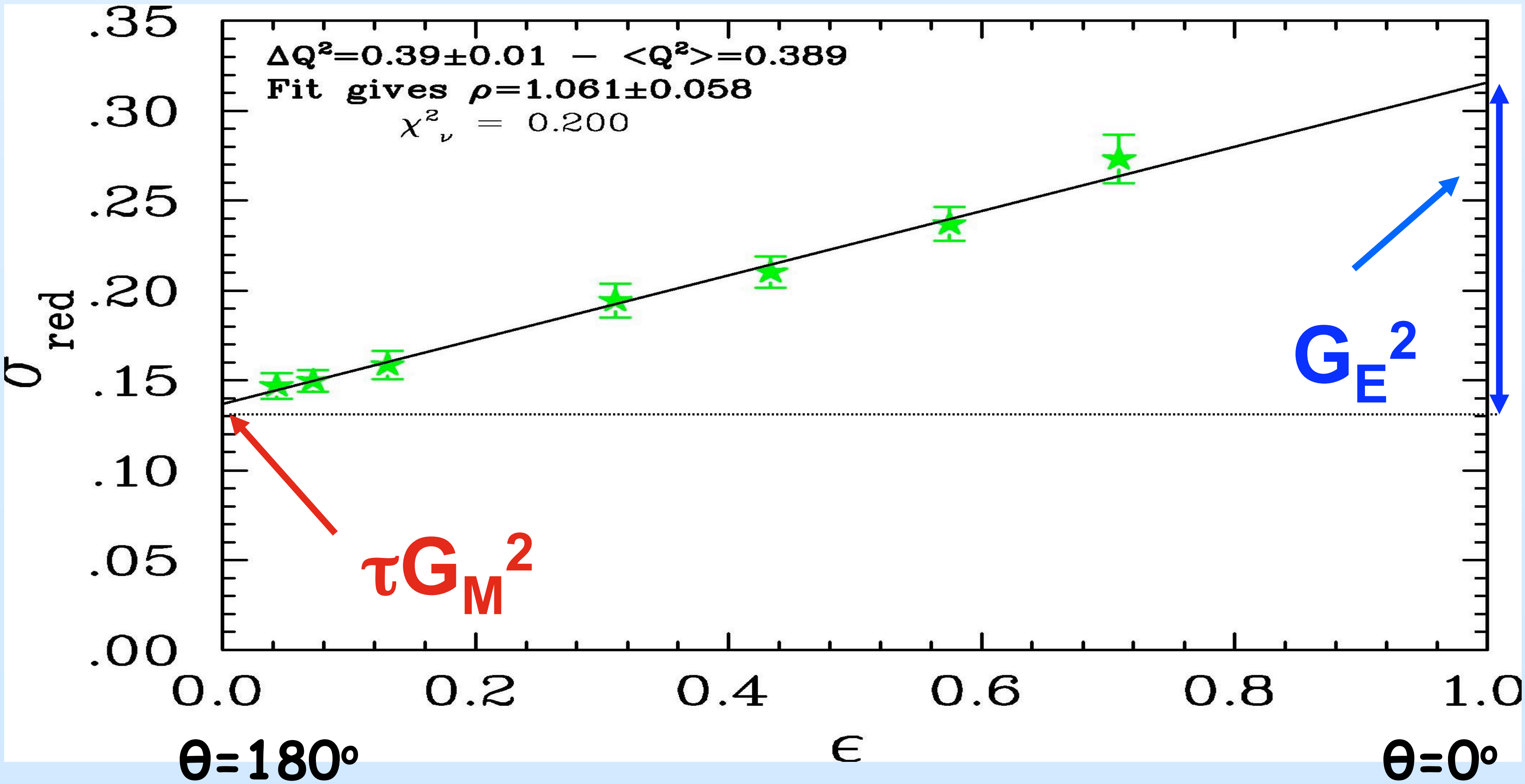
$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

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

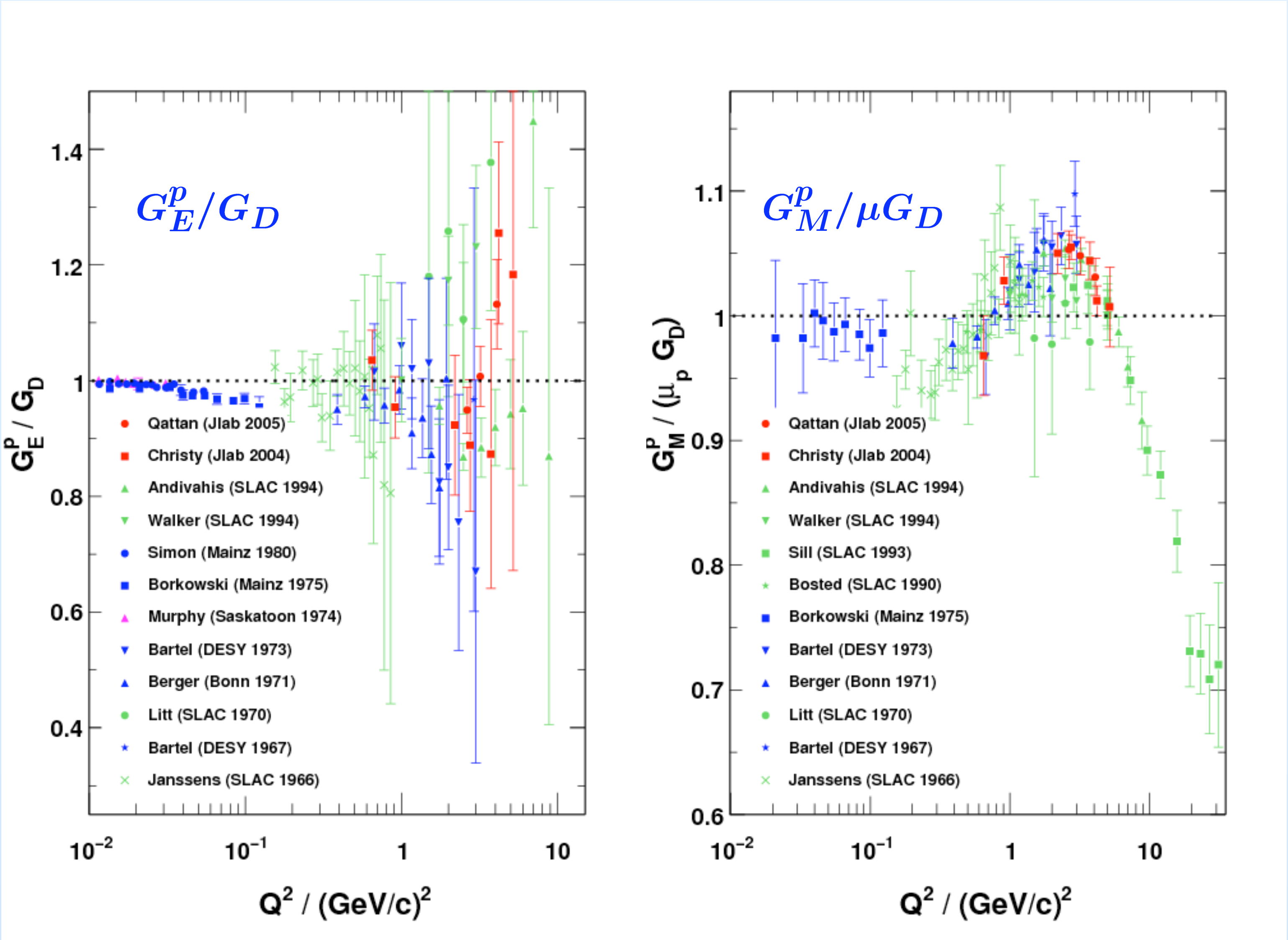
$$= \frac{\epsilon\, G_E^2 + \tau G_M^2}{\epsilon\,(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

Proton

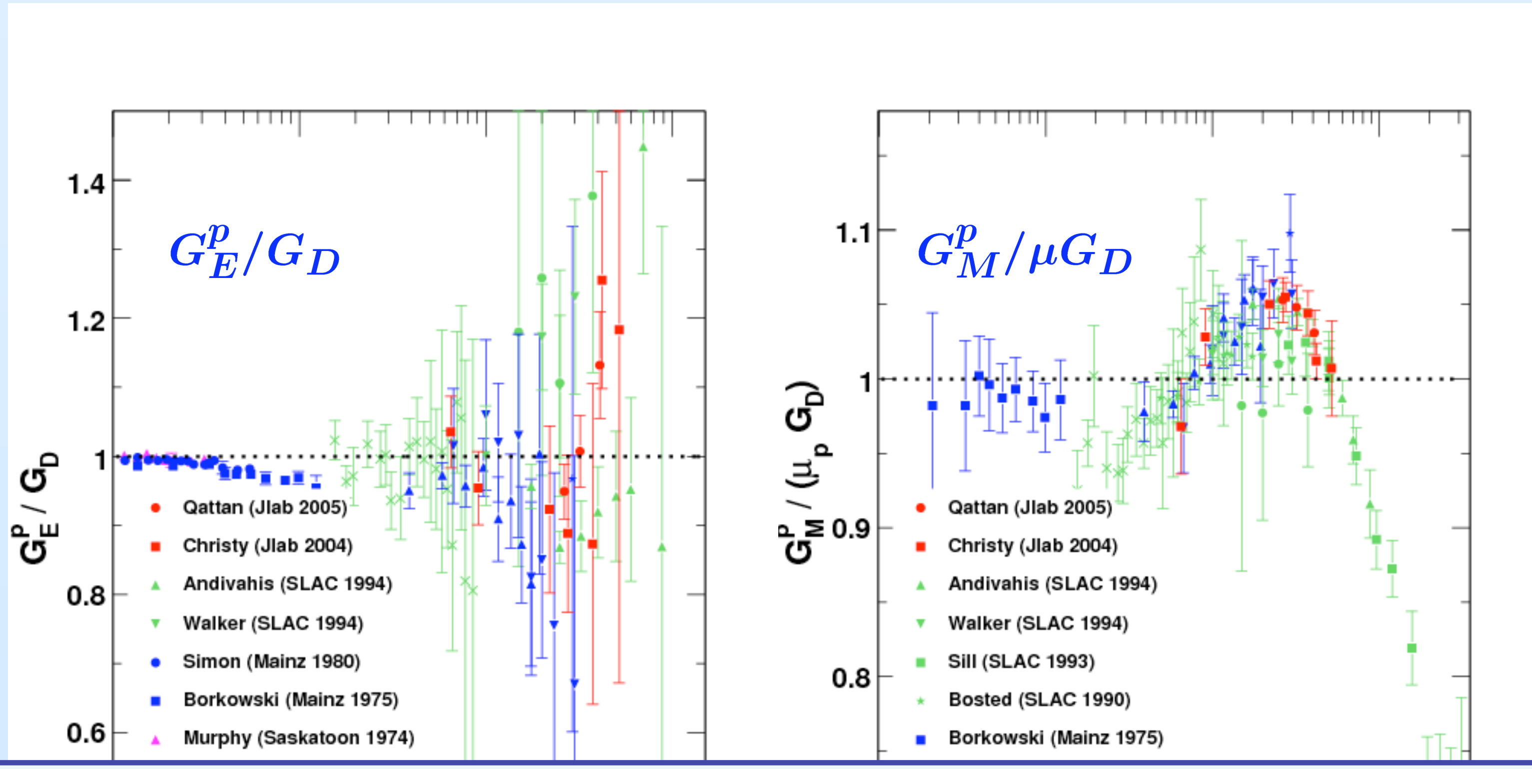
Rosenbluth Separation



G^p_E and G^p_M from Unpolarized Data



G^p_E and G^p_M from Unpolarized Data



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

Nucleon Form Factors and Polarization

- **Double polarization in elastic/quasielastic ep or en scattering: Recoil polarization or (vector) polarized target**

  $^{1,2}H(\vec{e},e'\vec{p})$, $^{1,2}\vec{H}(\vec{e},e'p)$, $^{2}H(\vec{e},e'\vec{n})$, $^{2}\vec{H}(\vec{e},e'n)$, $^{3}\vec{He}(\vec{e},e'n)$,

- **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

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

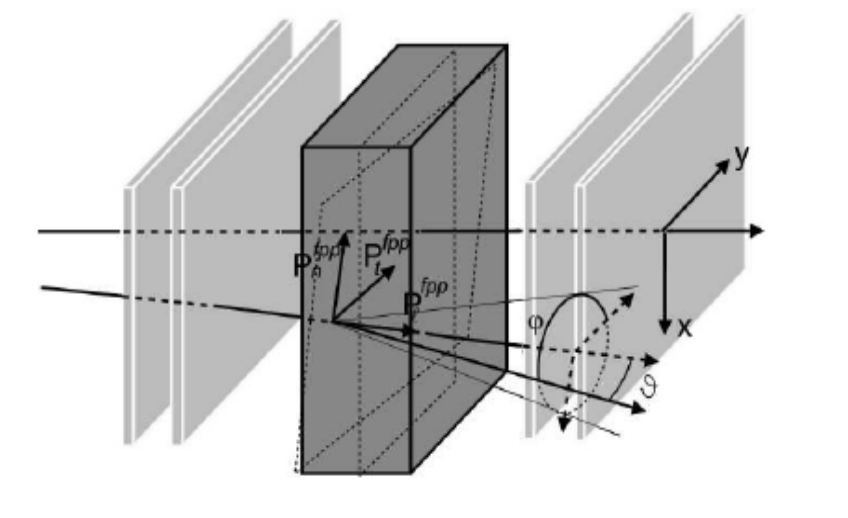


FIG. 9: Schematic of the polarimeter chambers and analyzer, showing a non-central trajectory; ϑ is the polar angle, and φ is the azimuthal angle from the y-direction counterclockwise.

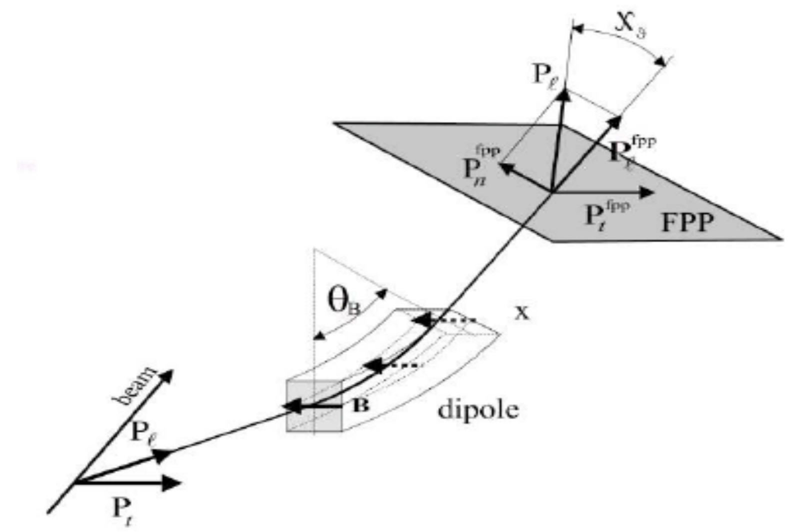


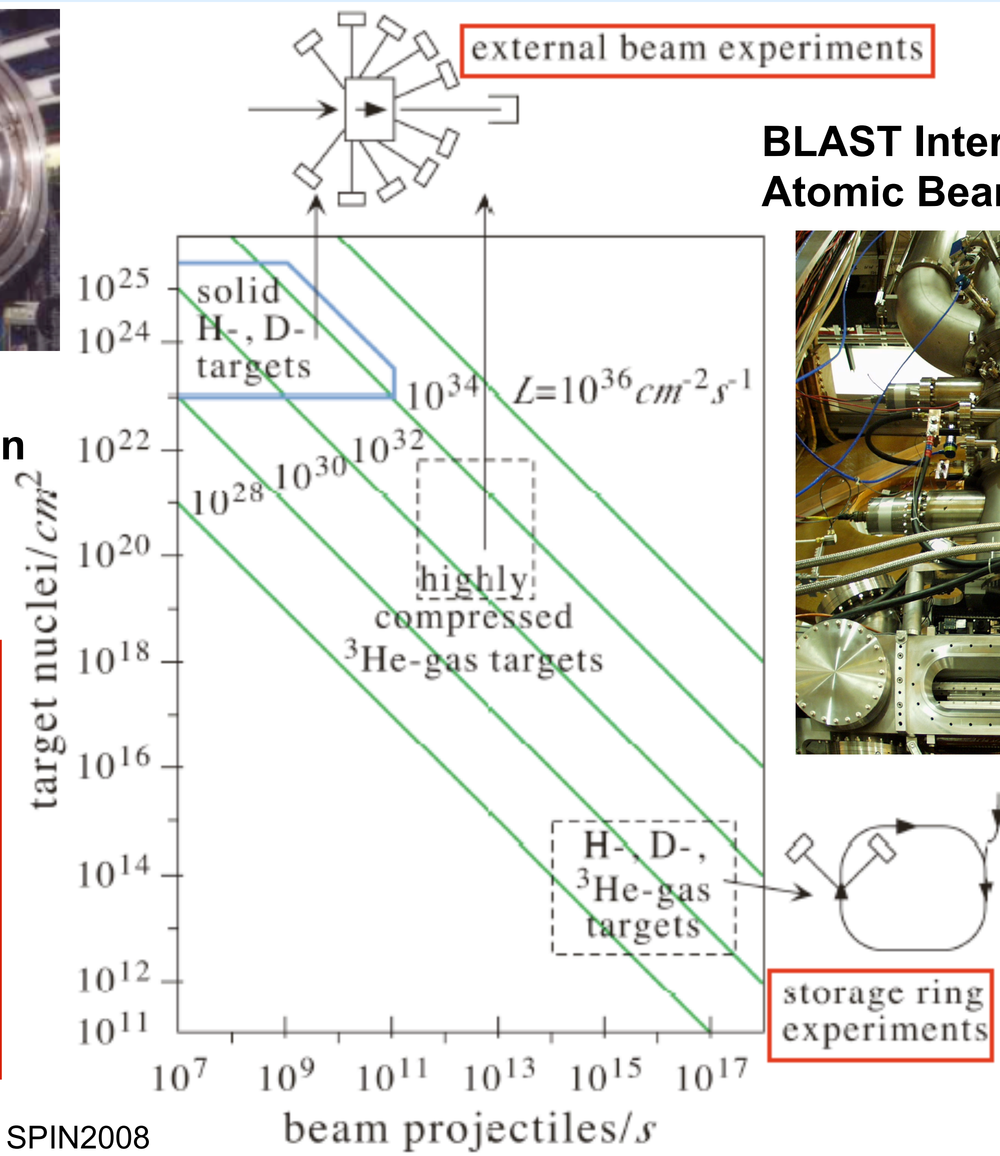
FIG. 15: Schematic drawing showing the precession by angle χ_θ of the P_ℓ component of the polarization in the dipole of the HRS.

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

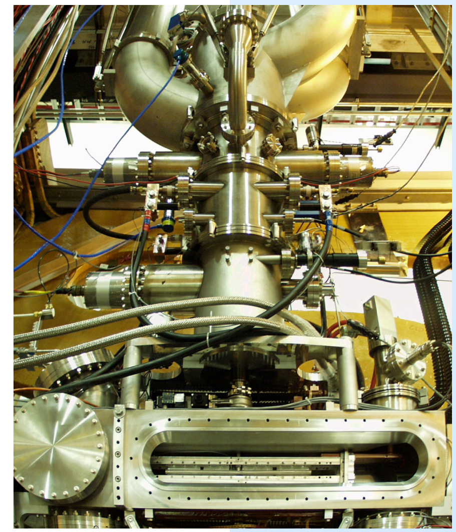
Spin transfer formalism to account for spin precession through spectrometer

Polarized Targets

UVA / "SLAC"-Target:
Dynamic Nuclear Polarization



BLAST Internal Target:
Atomic Beam Source

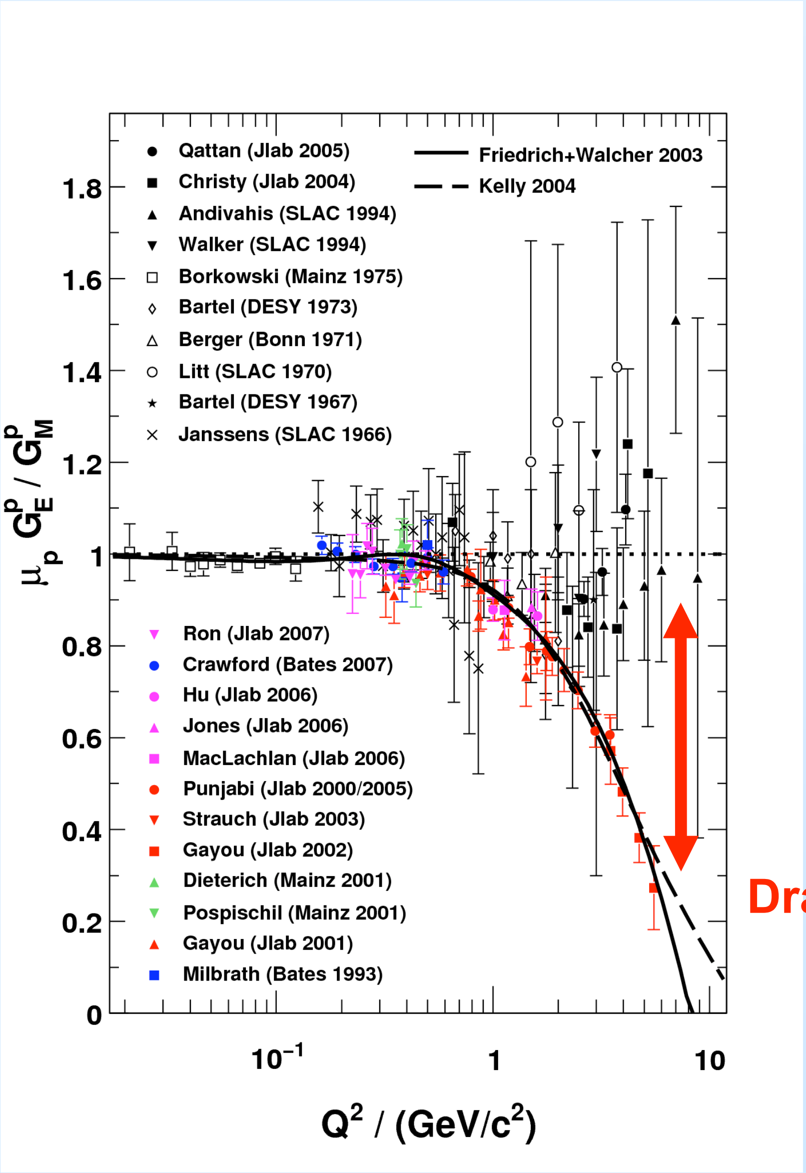


Limited luminosity for polarized hydrogen/ deuterium targets,

Very precise at low to moderately high Q^2

from W. Meyer, SPIN2008

Proton Form Factor Ratio



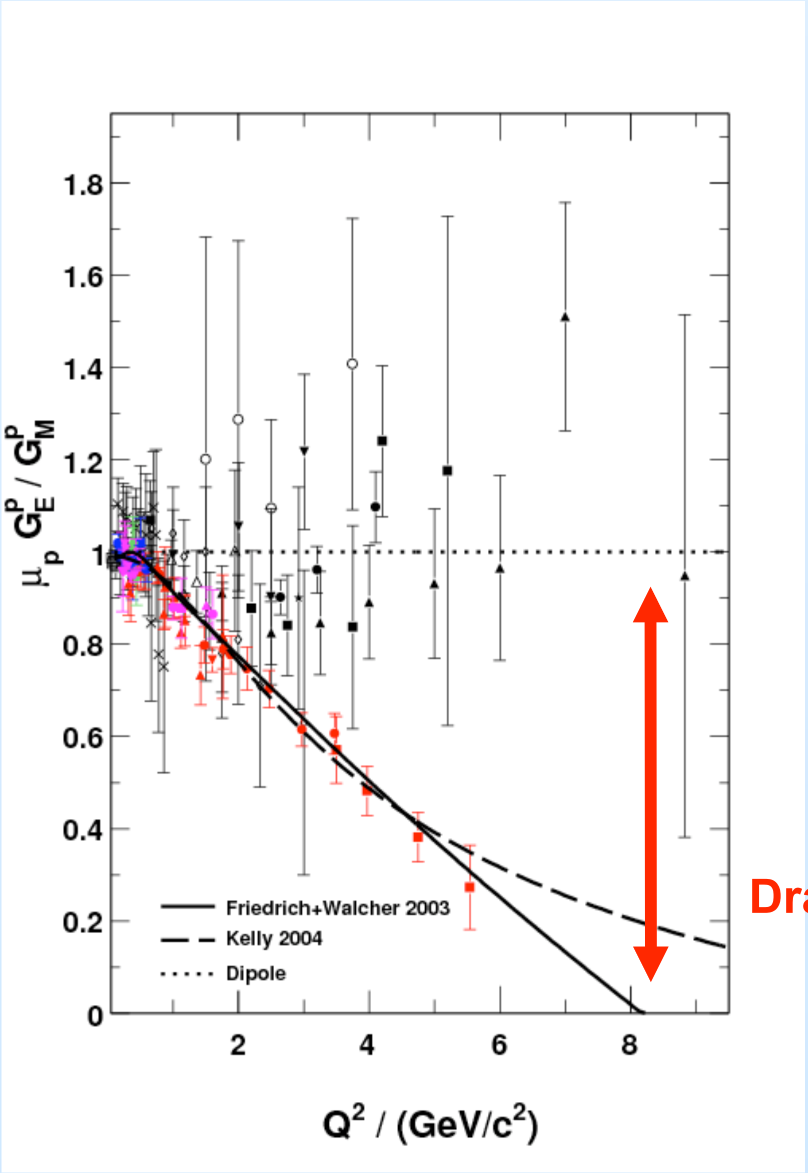
Jefferson Lab

- 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



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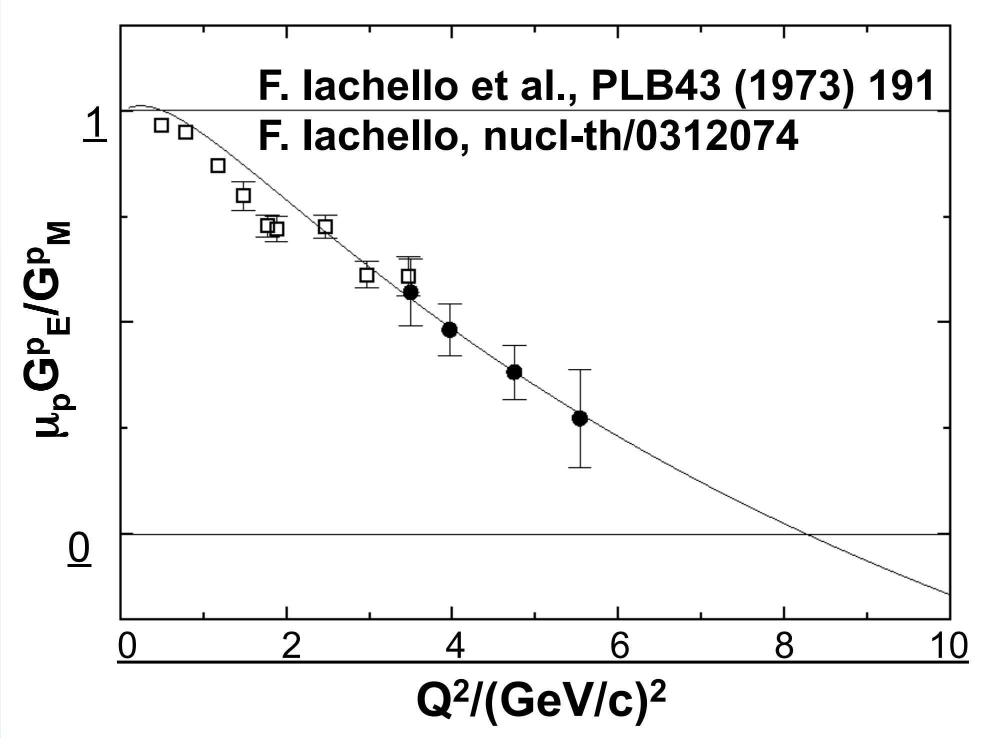
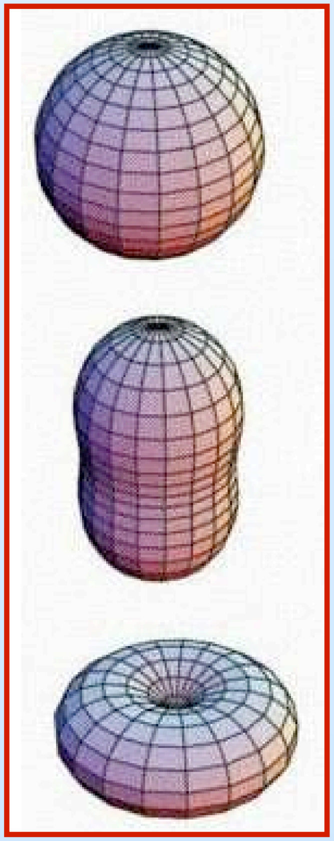


Iachello 1973:

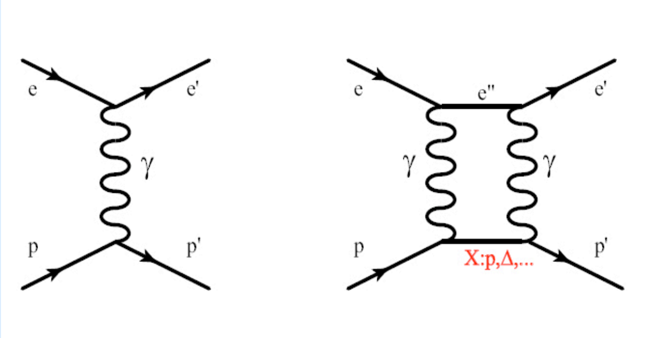
Drop of the ratio already suggested by VMD



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

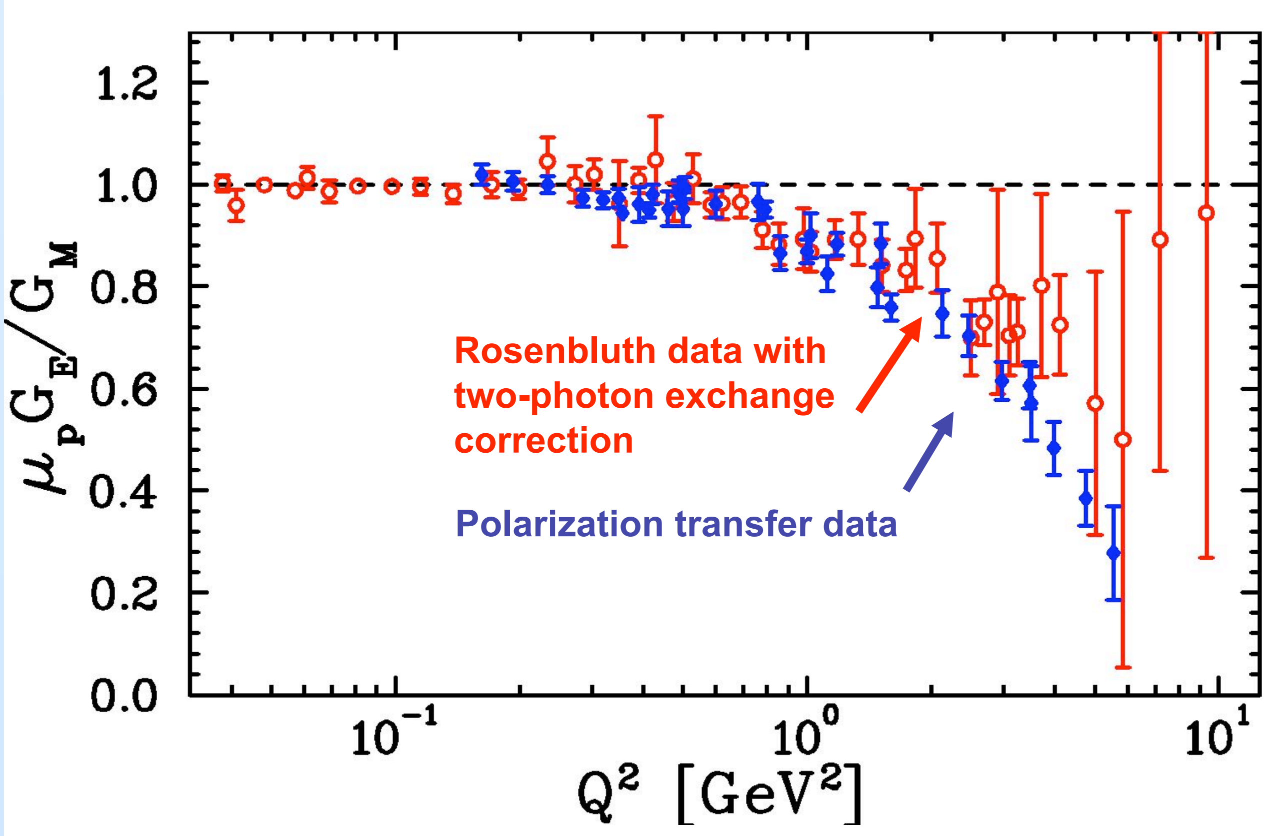
Two-Photon Exchange: Exp. Evidence

Two-photon exchange theoretically suggested



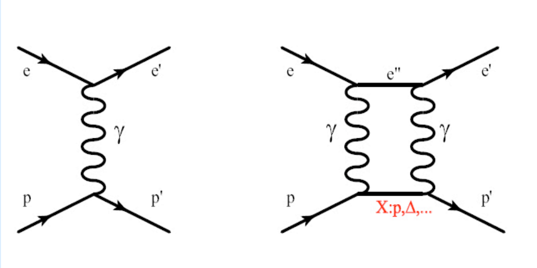
TPE can explain form factor discrepancy

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



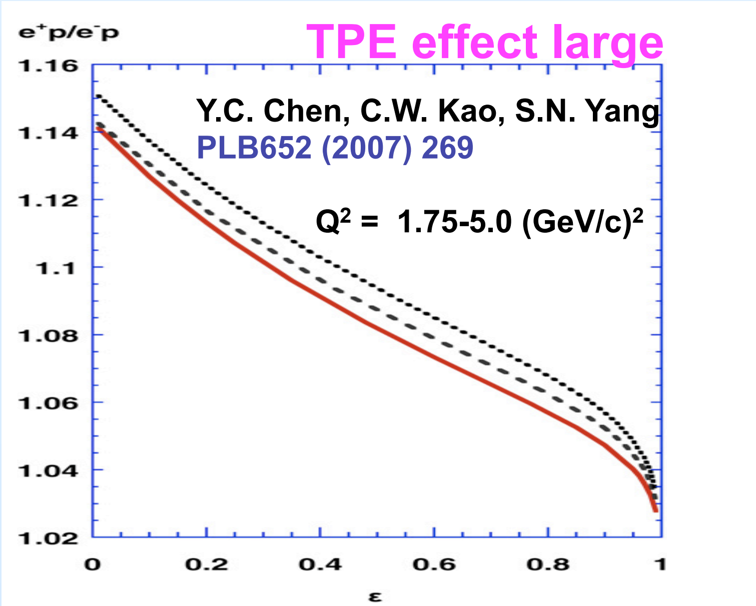
Two-Photon Exchange: A Lot of Theory

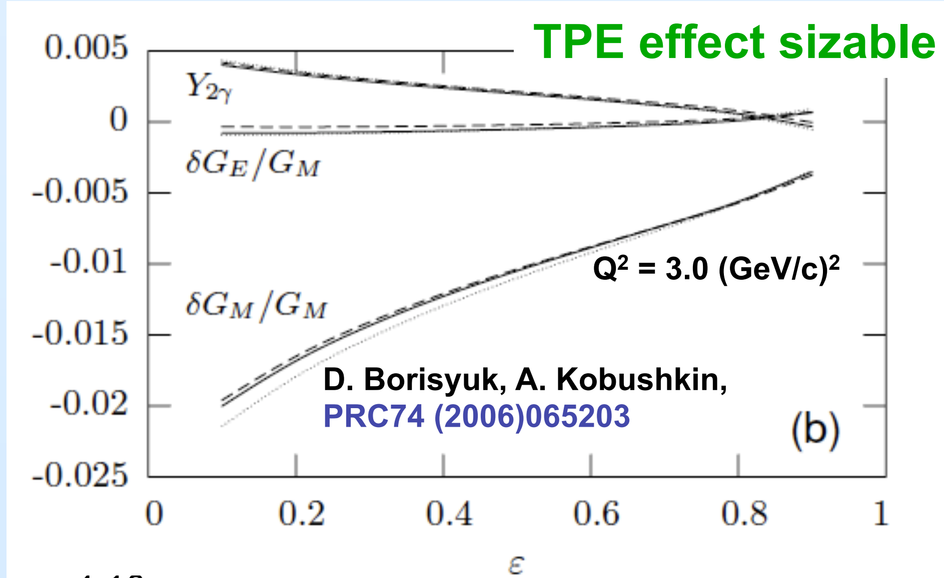
Two-photon exchange theoretically suggested
Interference of one- and two-photon amplitudes

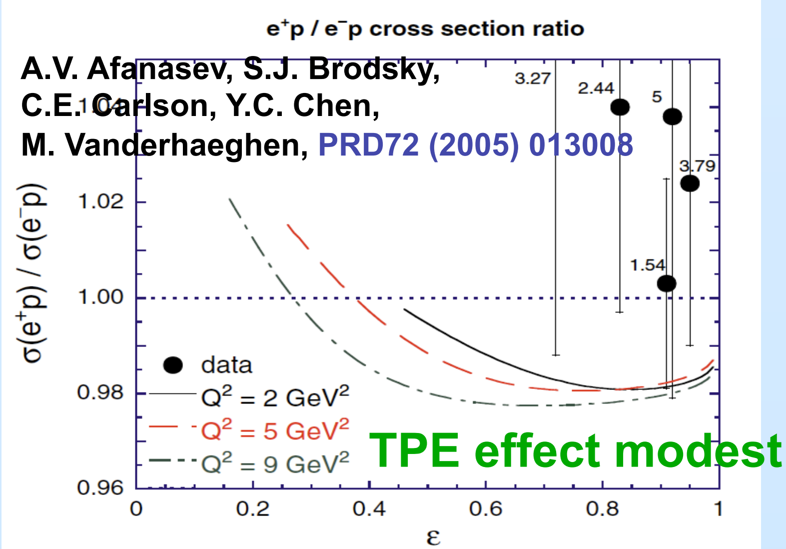


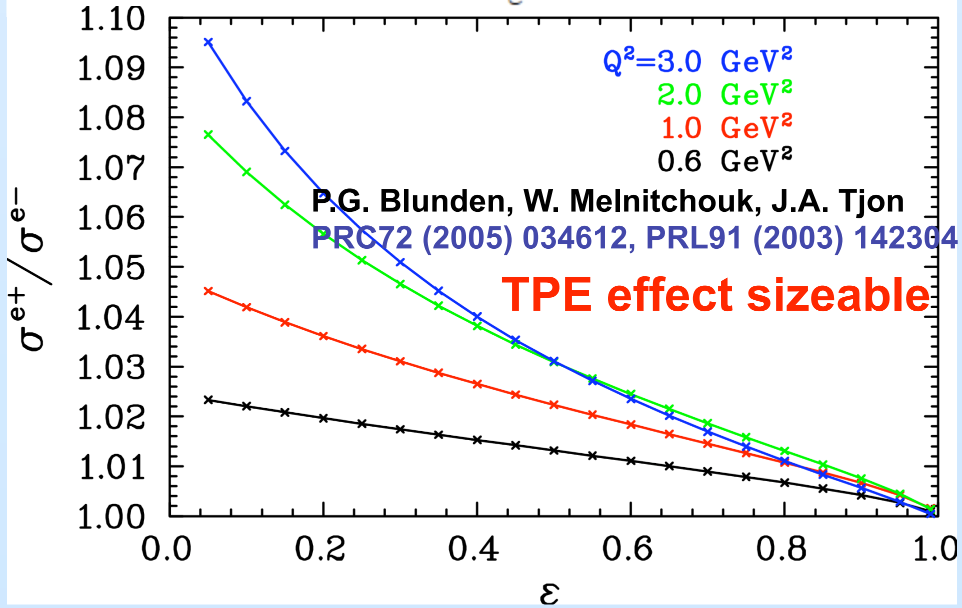
- P.A.M. Guichon and M. Vanderhaeghen, PRL91 (2003) 142303; M.P. Rekalo and E. Tomasi-Gustafsson, EPJA22 (2004) 331: Formalism … TPE effect could be large
- P.G. Blunden, W. Melnitchouk, and J.A. Tjon, PRC72 (2005) 034612, PRL91 (2003) 142304: Nucl. Theory … elastic ≈ half, Delta opposite
- Y.C. Chen 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





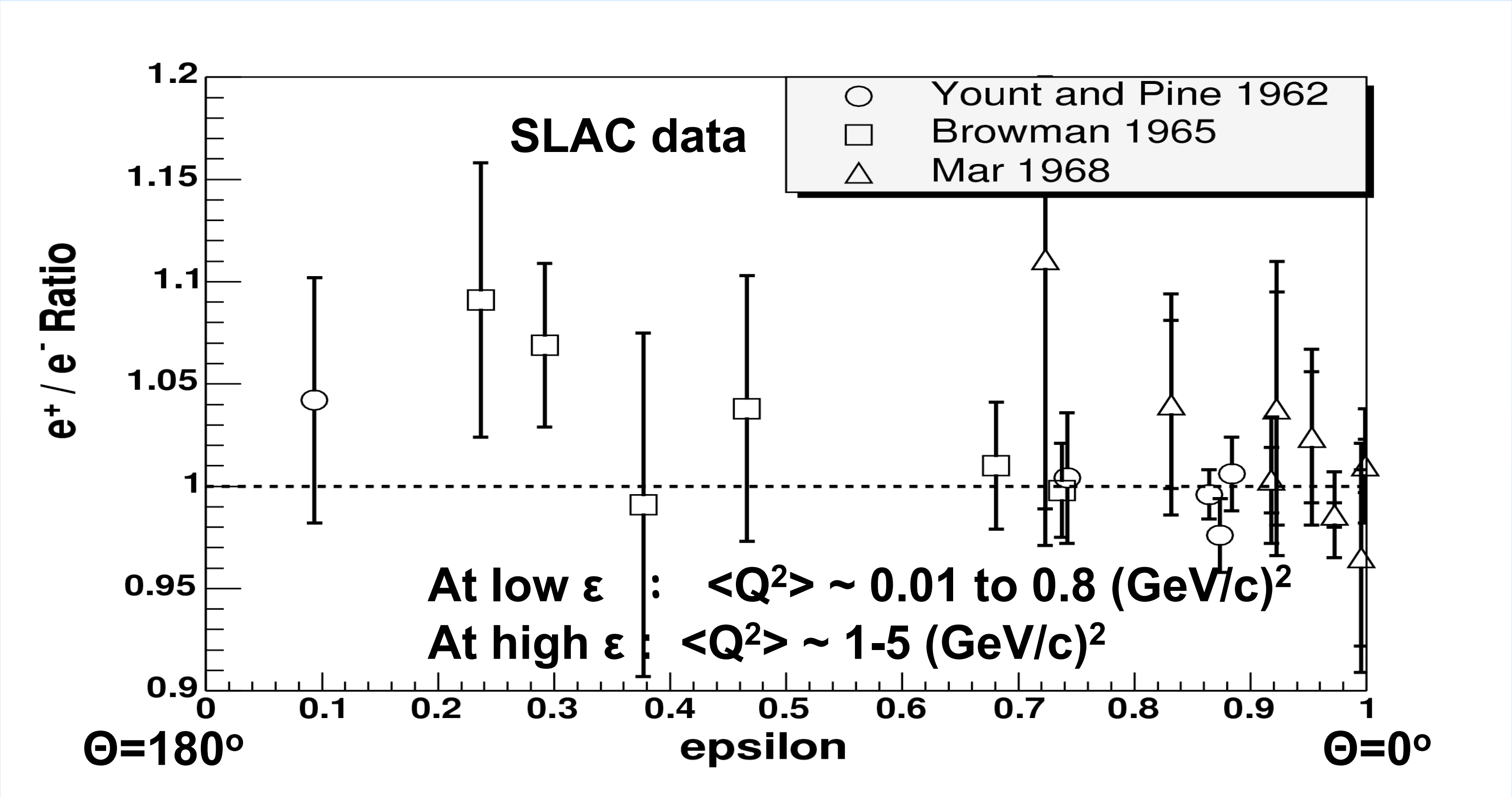




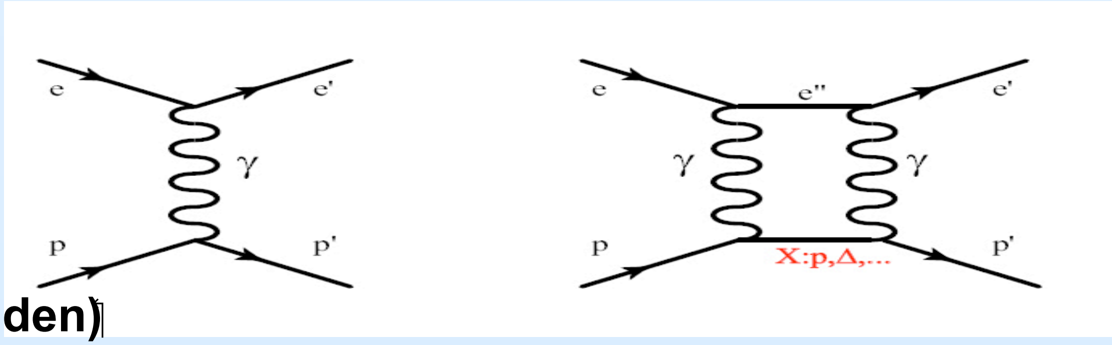
Experiments to Verify 2γ Exchange

Precision comparison of positron-proton and electron-proton elastic scattering over a sizable ε range at $Q^2 \sim$ 2-3 $(GeV/c)^2$

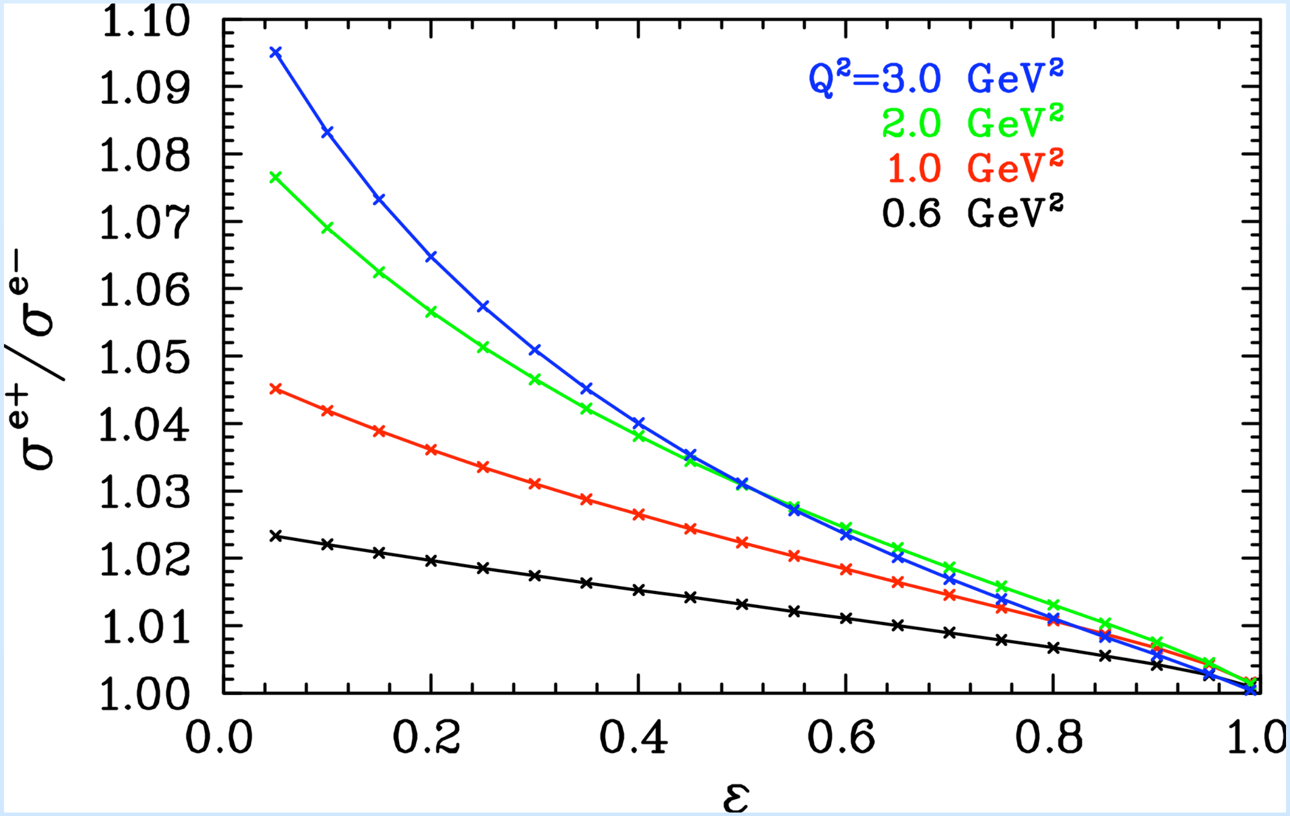
J. Arrington, PRC 69 (2004) 032201(R)



Two-Photon Exchange



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



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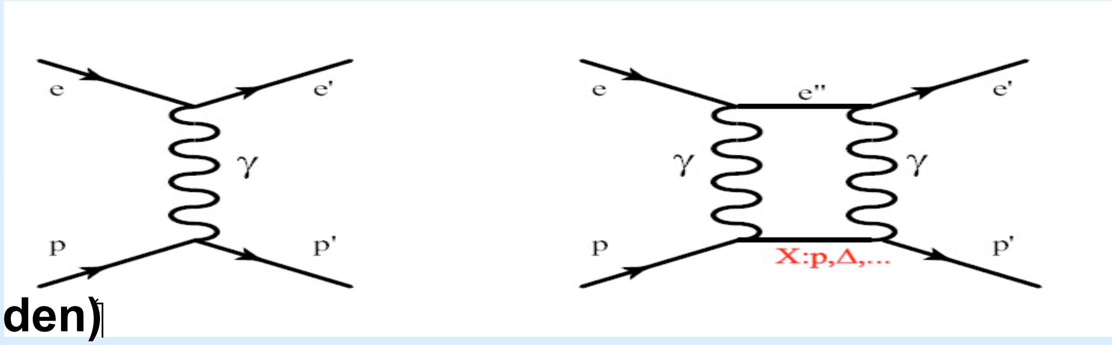

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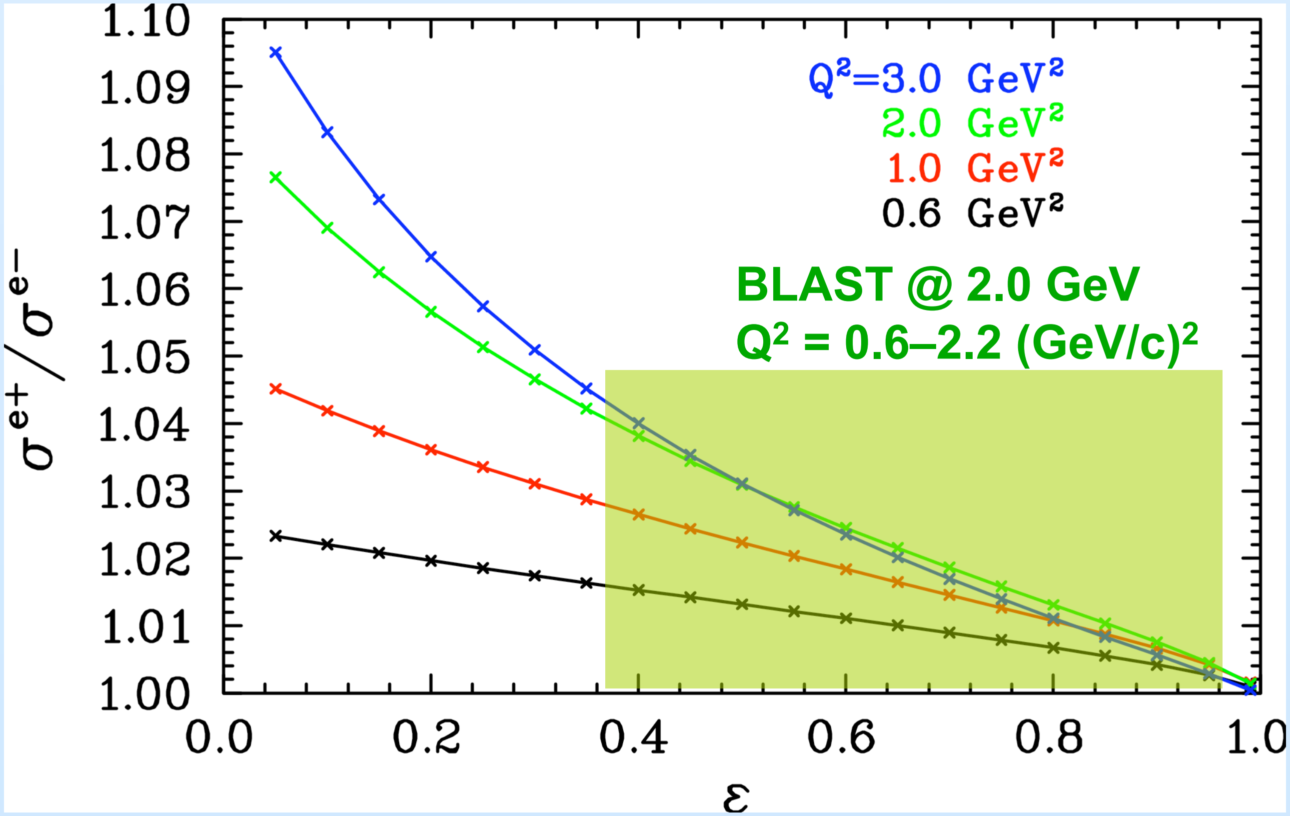
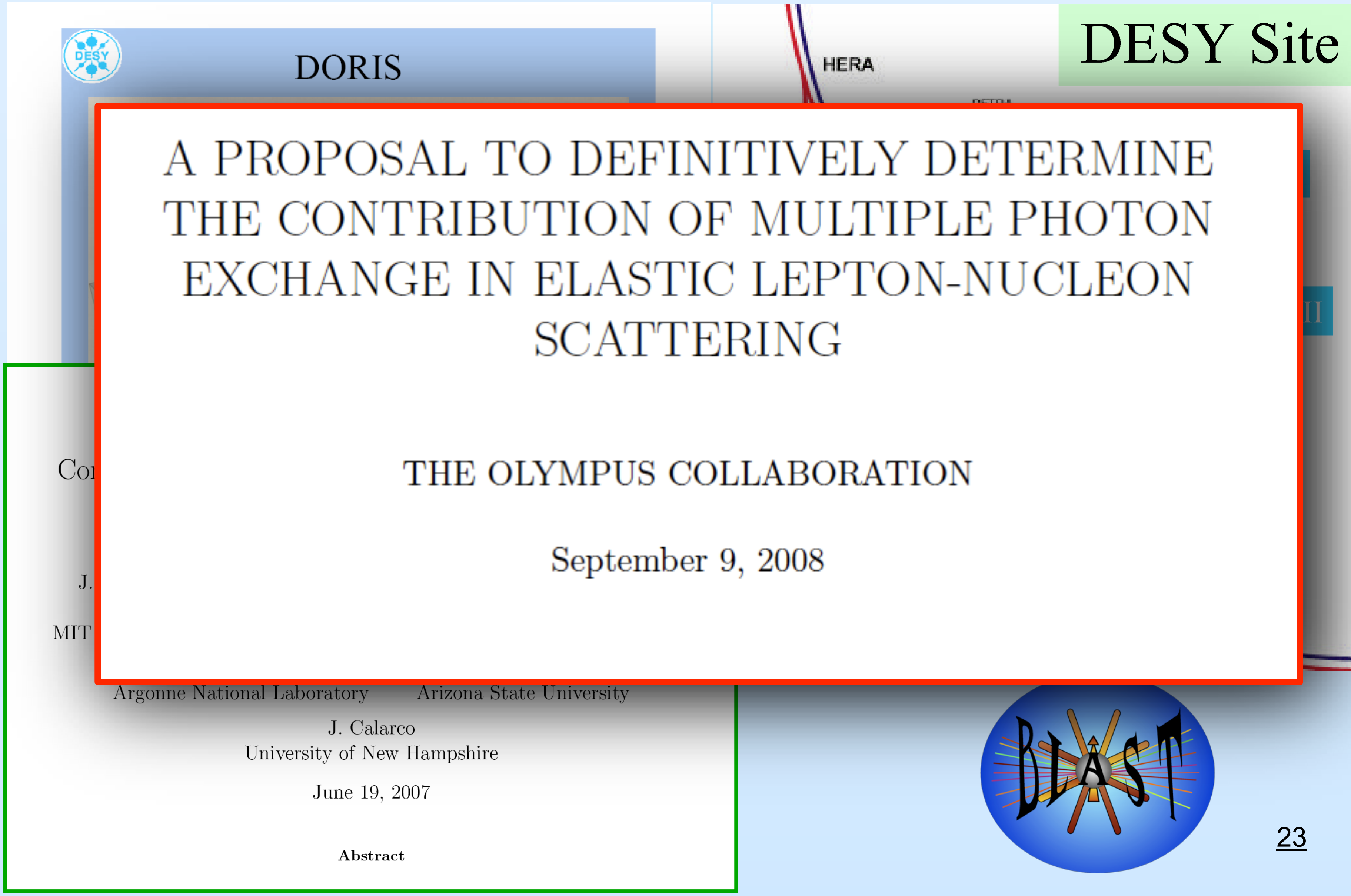


OLYMPUS: BLAST@DESY/DORIS



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

THE OLYMPUS COLLABORATION

September 9, 2008

Argonne National Laboratory   Arizona State University

J. Calarco
University of New Hampshire

June 19, 2007

Abstract

OLYMPUS

pOsitron-proton and

eLectron-proton elastic scattering to test the

hYpothesis of

Multi-

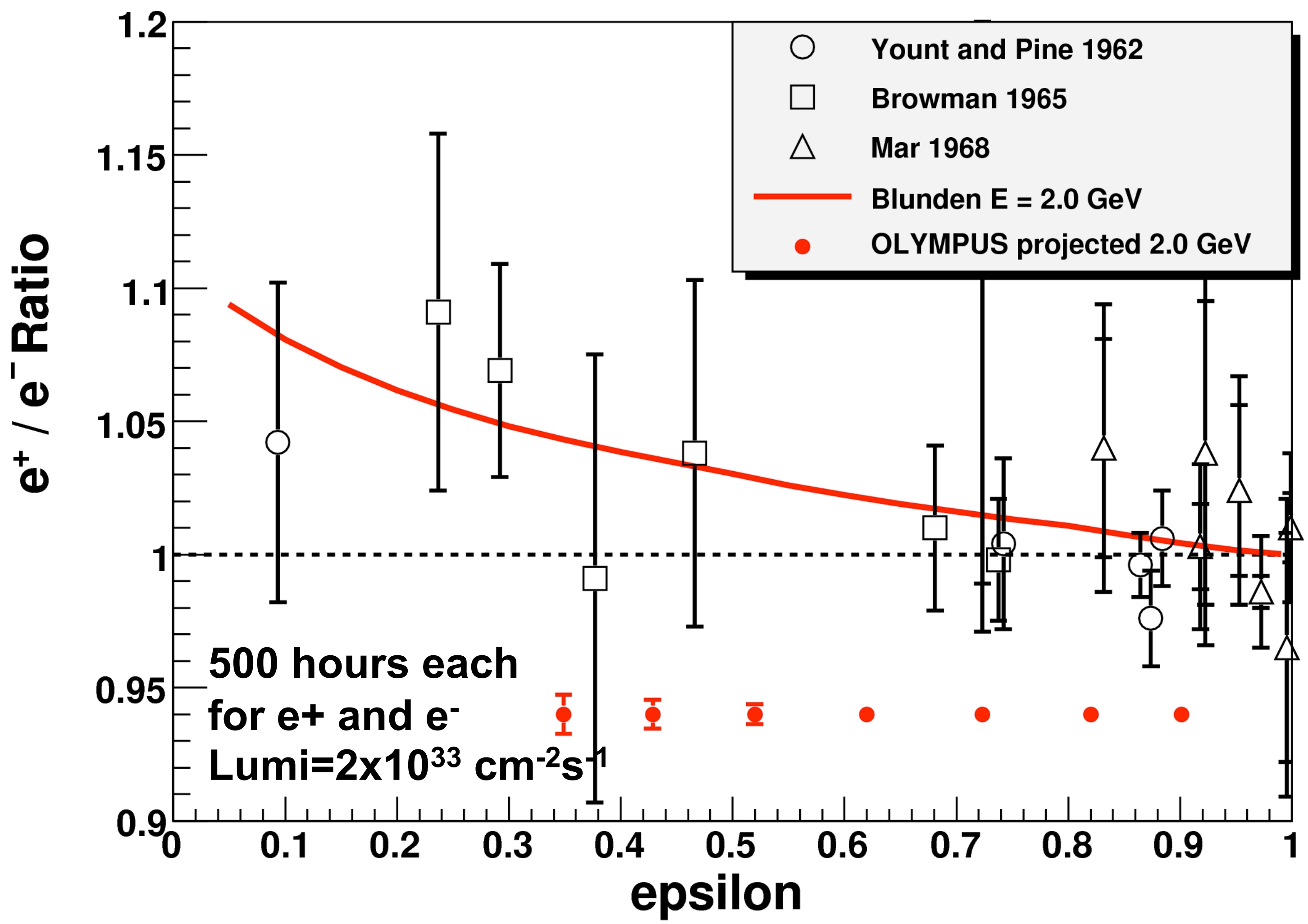
Photon exchange

Using

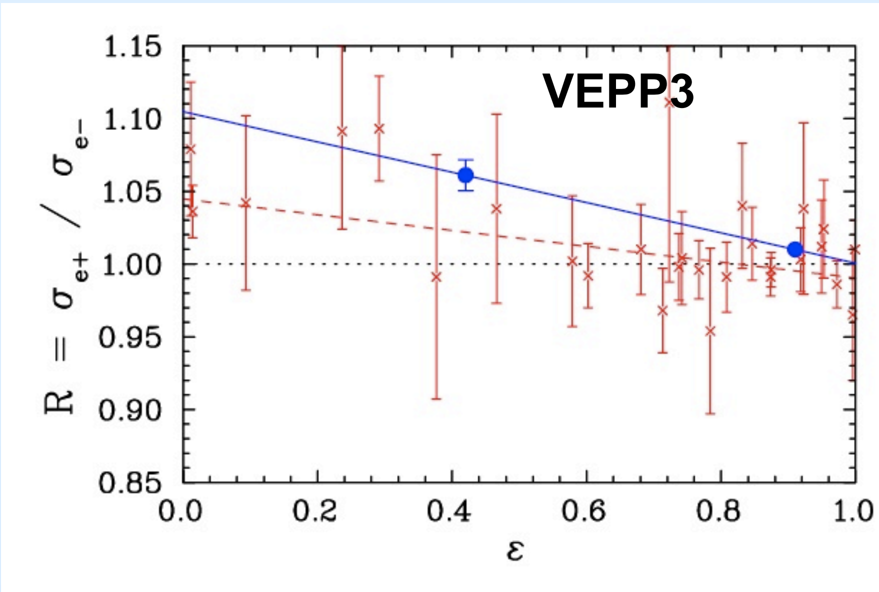
DoriS

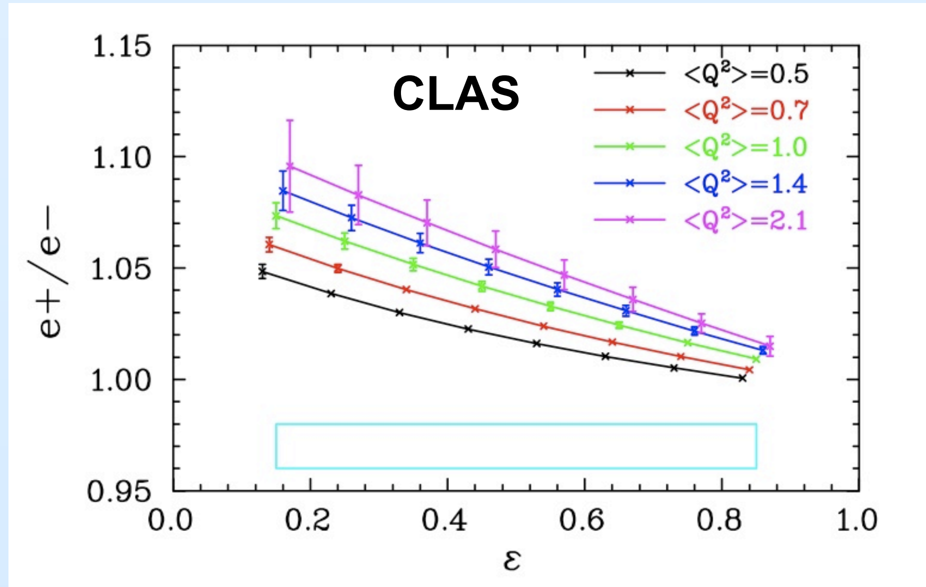
2008 – Full proposal
2010/11 – Transfer of BLAST
2012 – OLYMPUS Running

Projected Results for OLYMPUS



Other Experiments to Verify TPE





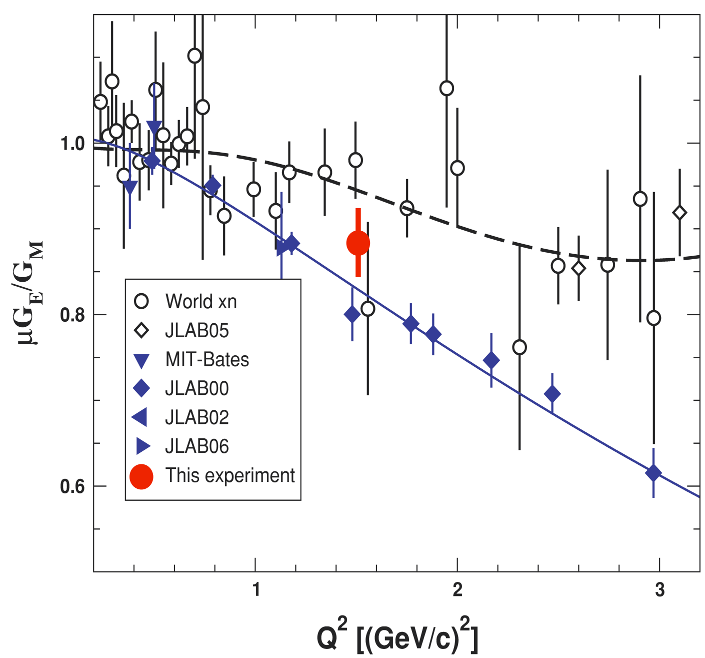
Experiment proposals to verify hypothesis:

e+/e- ratio:	**CLAS/PR04-116**	**secondary e+/e- beam**	**– 2011/12**
	Novosibirsk/VEPP-3	**storage ring / intern. target**	**– 2009**
	OLYMPUS@DESY (=BLAST@DORIS)	**storage ring / intern. target**	**– 2012**

SSA: **PR05-15 (Hall A, trans. pol target); MAMI-A4 (trans. pol. beam)**

ε-dependence: **PR04-019 (polarized), PR05-017 (unpolarized)**

Polarized Target Experiments at High Q^2



Polarized Target:
Independent verification of recoil polarization result is crucial

Polarized internal target / low Q^2: **BLAST**
Q^2<0.65 (GeV/c)^2 not high enough to see deviation from scaling

RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)^2

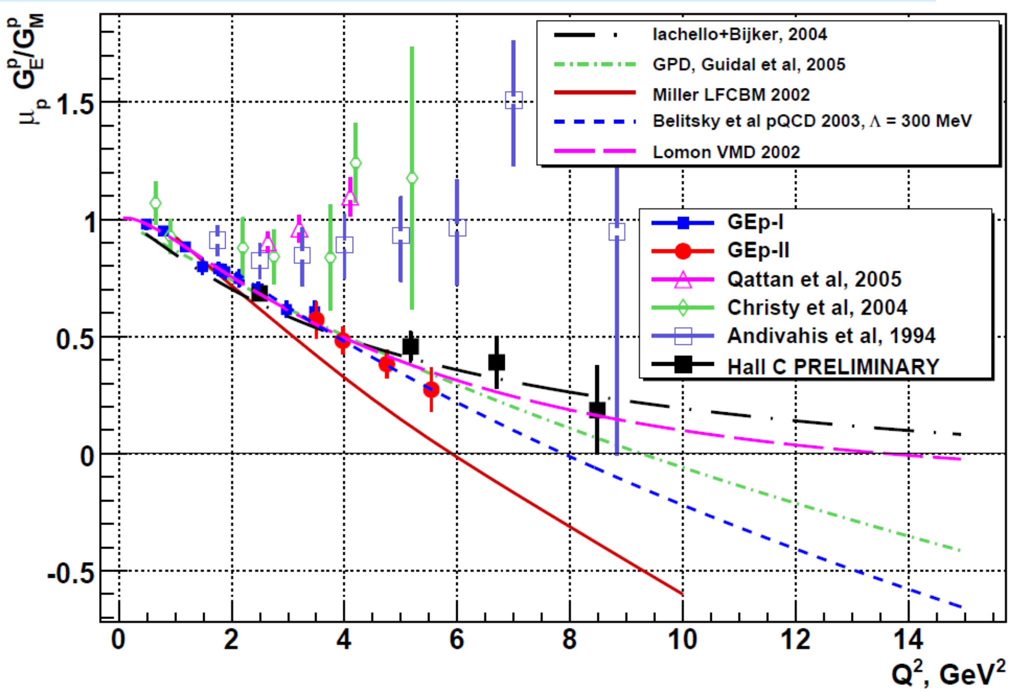
SANE/Hall C: completed March 2009
BigCal electron detector
Recoil protons in HMS parasitically
Extract G_E/G_M to <5% at Q^2≈5-6 (GeV/c)^2

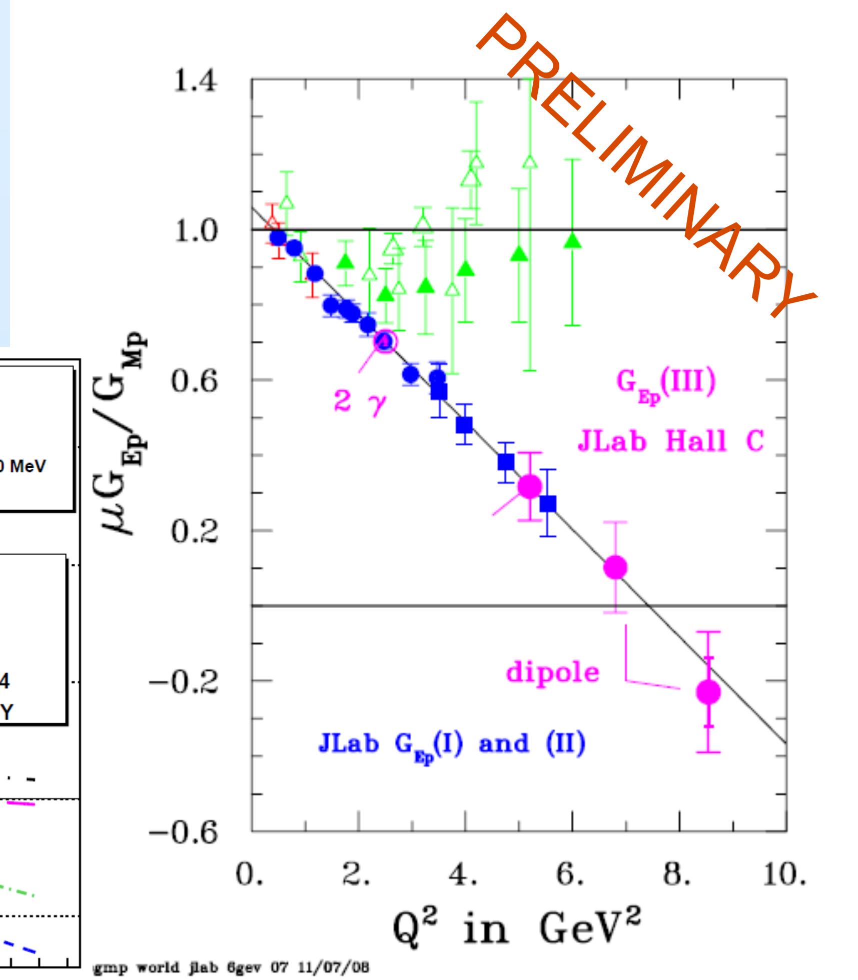
M.K. Jones et al., PRC74 (2006) 035201

New Proton Measurements at High Q^2

Extension to higher Q^2 at Jefferson Lab

- **GEp-III /Hall C: PR04-108/PR04-019**
  Completed in spring 2008
- Sign change of G_E/G_M observed
  (preliminary, C. Perdrisat @ PANIC08)
- **Or maybe not (preliminary, CIPANP09)**





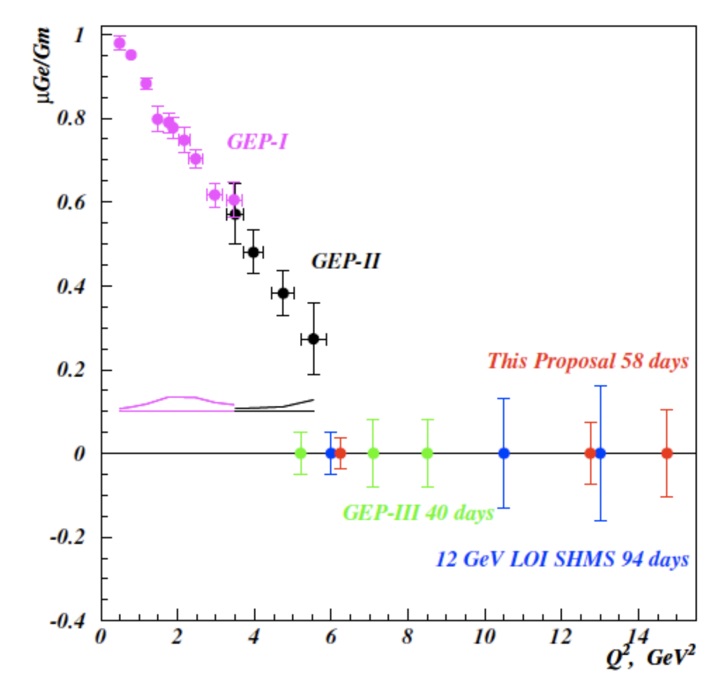
New Proton Measurements at High Q^2

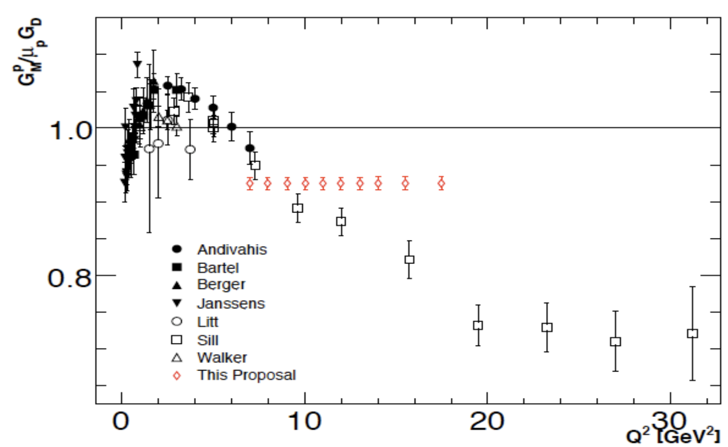
Extension to higher Q^2 at Jefferson Lab

- **GEp-III /Hall C: PR04-108/PR04-019**
  Q^2 = 5.2, 6.8, 8.5 $(GeV/c)^2$
  Completed in spring 2008
- Hall C PR05-017 Super-Rosenbluth
  Q^2 = 0.9 - 6.6 $(GeV/c)^2$
  Completed in summer 2007

Proposed experiments

- PAC32: **PR12-07-109 /Hall A (GEp-IV)**
  L. Pentchev, C.F. Perdrisat, E. Cisbani,
  V. Punjabi, B. Wojtskhowski, M. Khandaker et al.
  Q^2=13,15 $(GeV/c)^2$: Approved
- PAC32: **PR12-07-108 /Hall A (high-Q^2 x-sec.)**
  S. Gilad, B. Moffit, B. Wojtsekhowski, J. Arrington et al.
  Q^2 =7-17.5 $(GeV/c)^2$: Approved
- PAC34: **PR12-09-001 /Hall C (GEp-V)**
  E.J. Brash, M. Jones, C.F. Perdrisat, V. Punjabi et al.
  Q^2=6,10.5,13 $(GeV/c)^2$: Conditionally approved



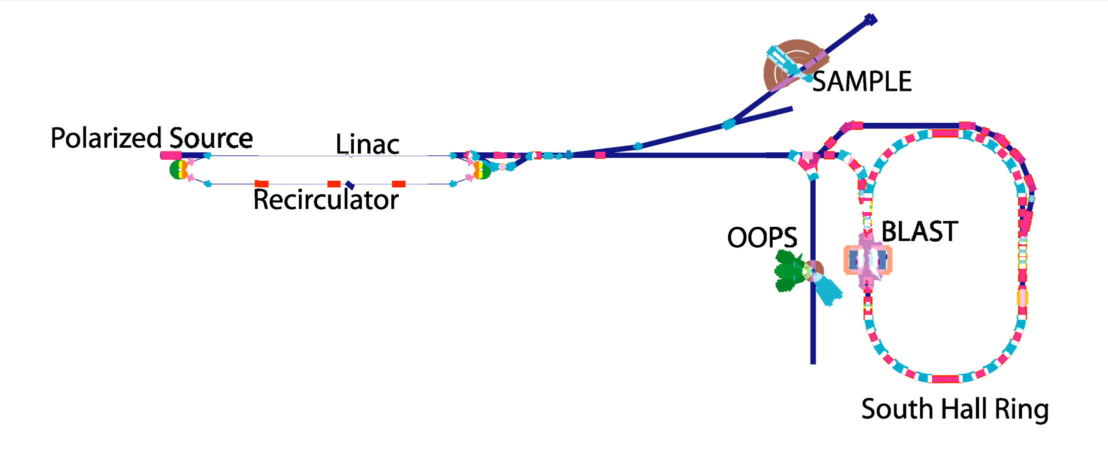


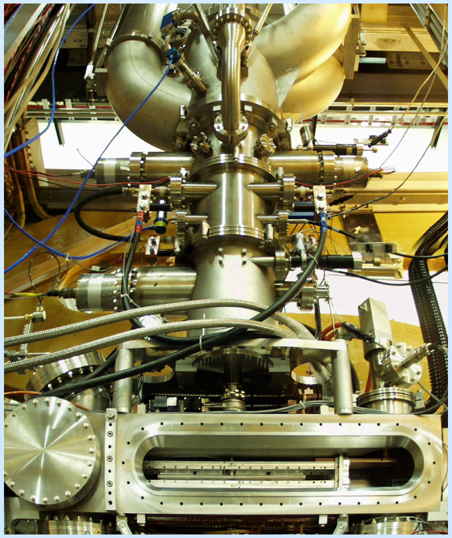
Low Q^2: BLAST at MIT-Bates

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%

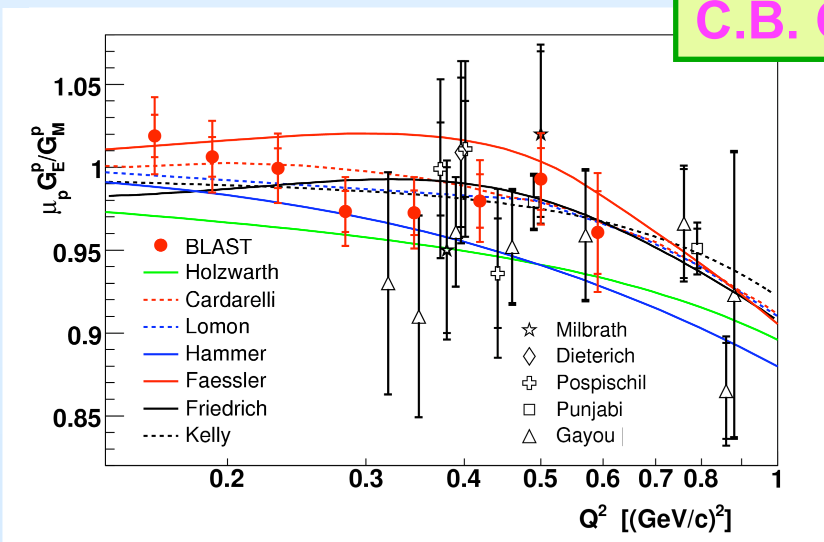


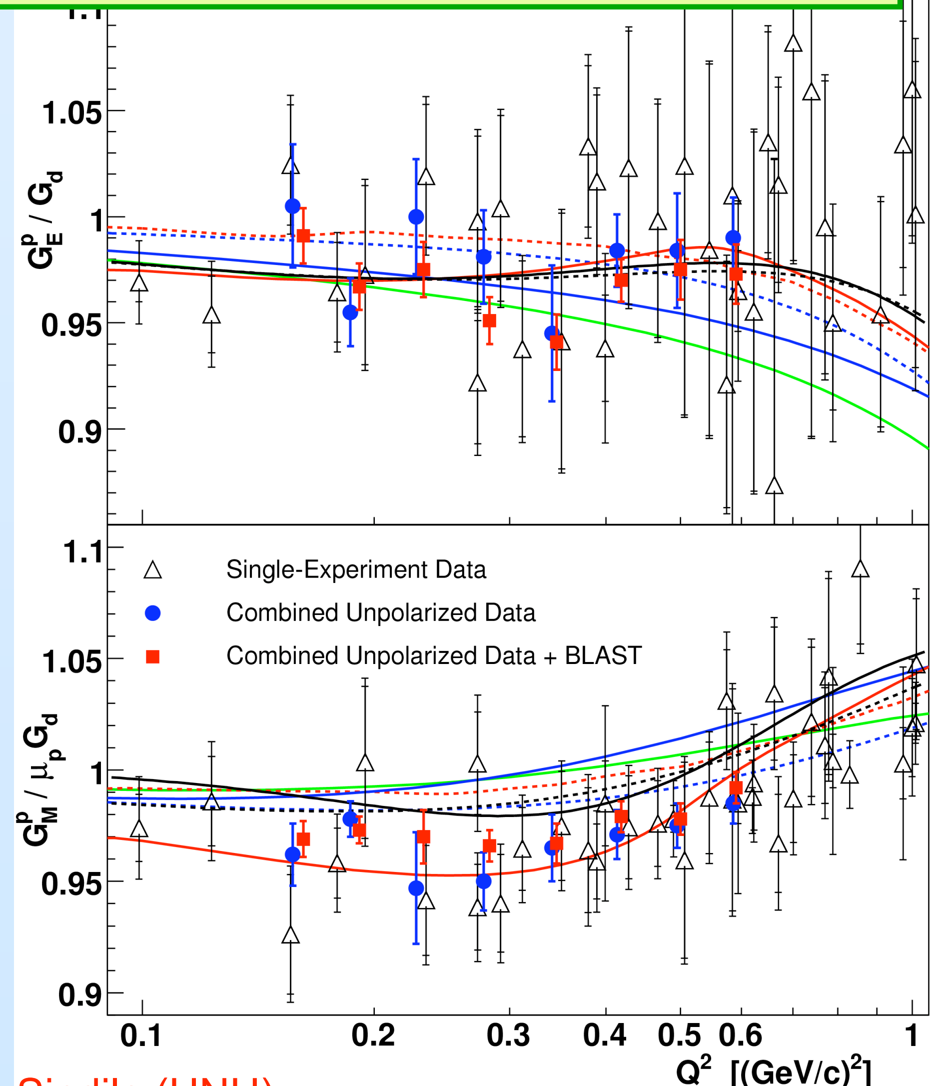


- Highly polarized internal gas target of pure H and D (Atomic Beam Source)
  6×10^{13} atoms/cm^2, $L = 6 \times 10^{31}$/(cm^{2}s), $P_{H/D}$ = 80%

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

C.B. Crawford et al., PRL98 (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!**

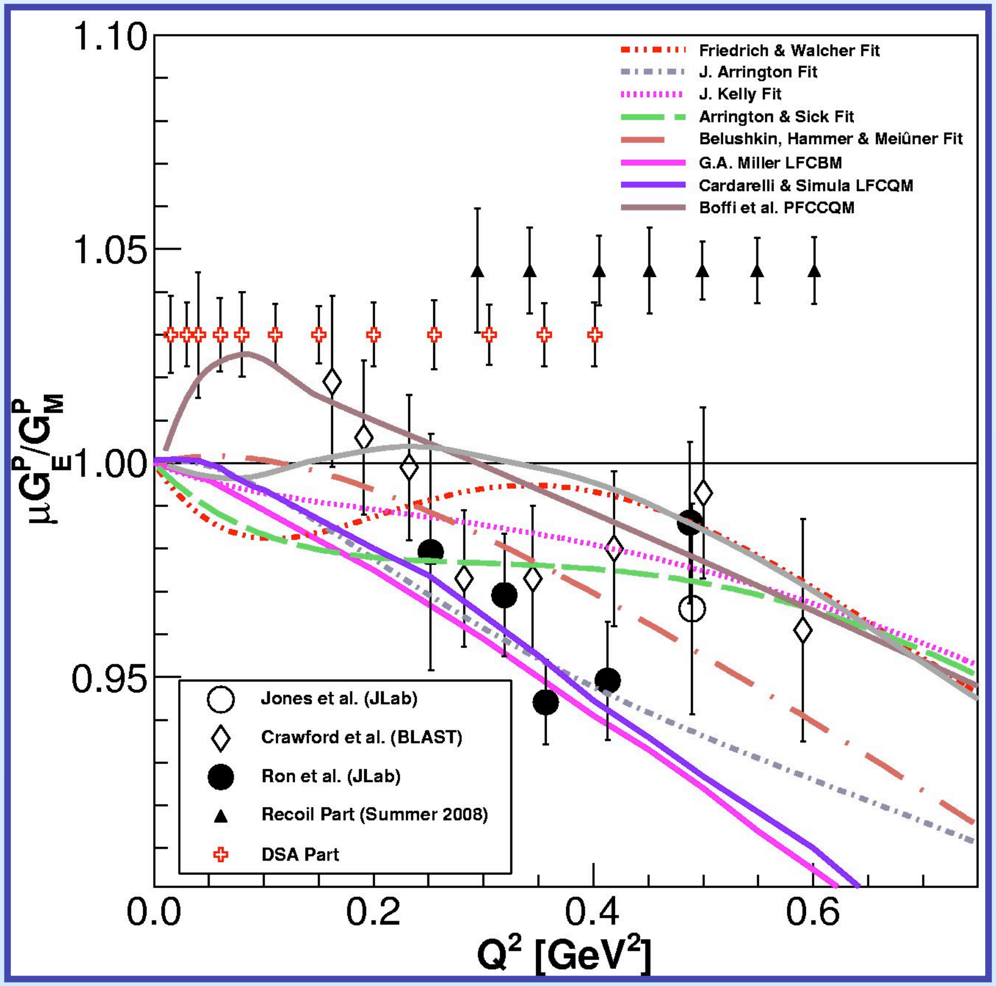
*Ph.D. work of C. Crawford (MIT) and A. Sindile (UNH)

New Proton Measurements at Low Q^2

Hall A PR07-004, 08-007 (PAC31/33)

- **Recoil polarization, completed 2008**
- **Polarized target, cond. approved**

LEDEX PR05-004,
G. Ron et al., PRL99 (2007) 202002



New Proton Measurements at Low Q^2

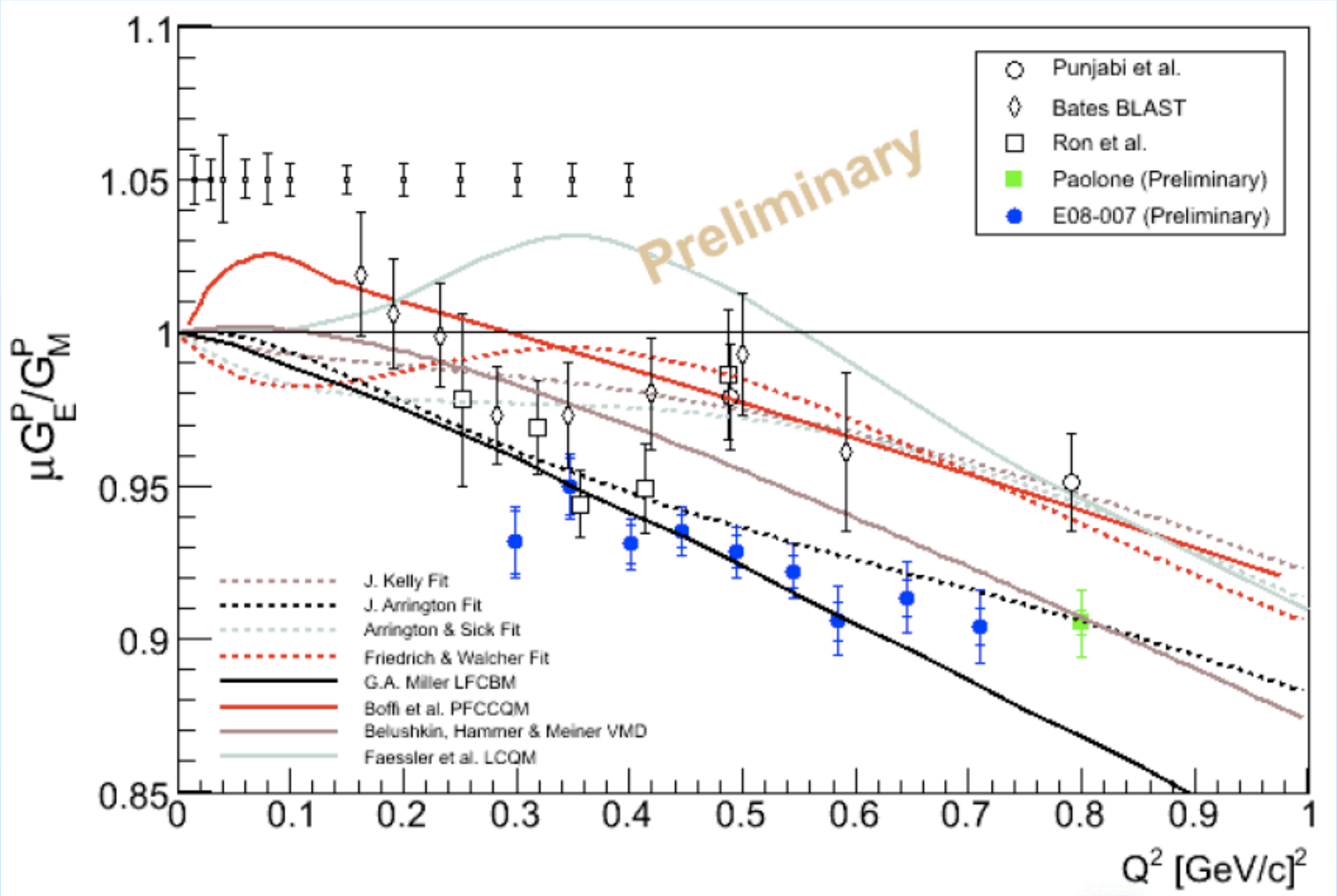
Hall A PR07-004, 08-007 (PAC31/33)

•Recoil polarization, completed 2008

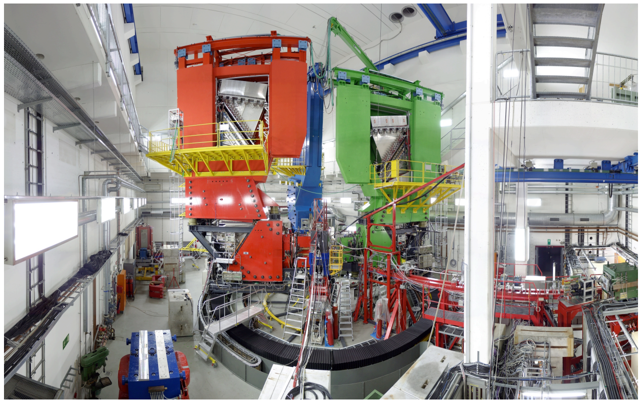
•Polarized target, cond. approved

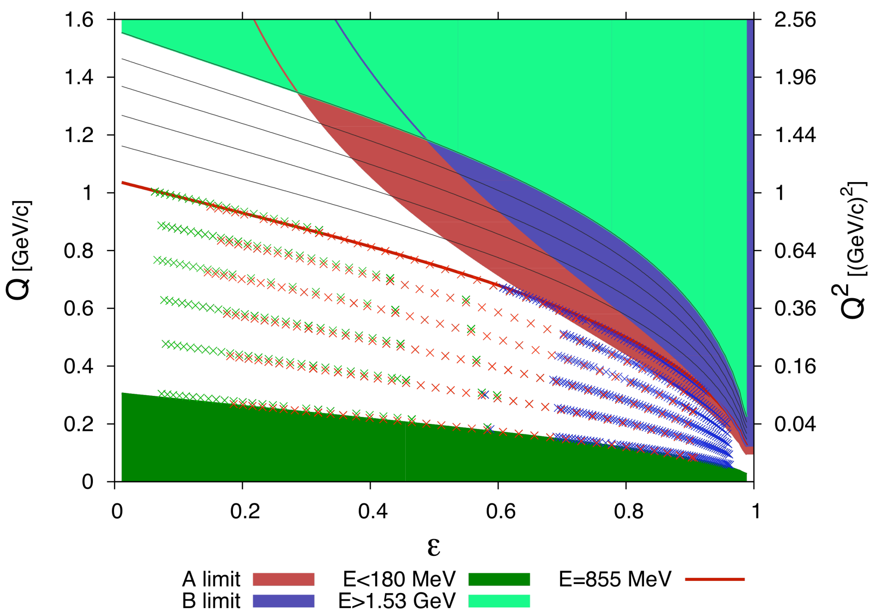
X. Zhan, CIPANP09
LEDEX reanalysis
E08-007 prel. release

2-sigma difference lower than BLAST



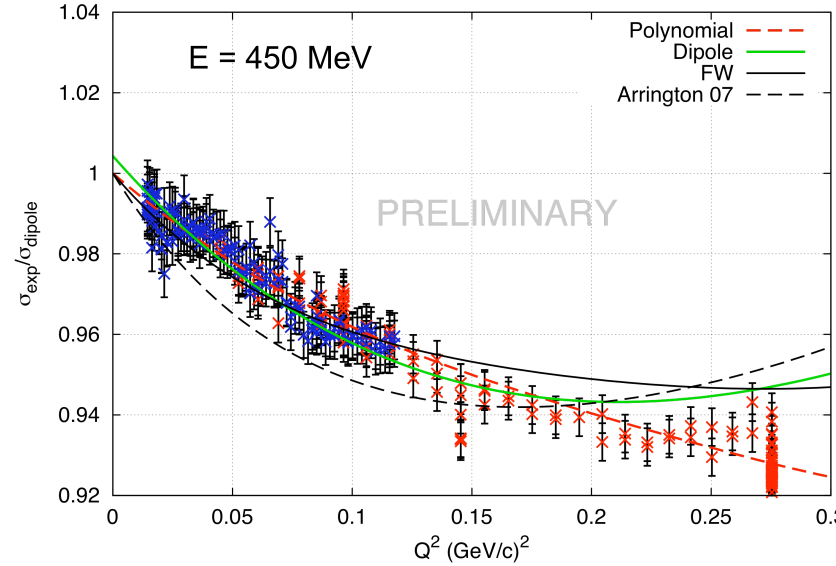
New Proton Measurements at Low Q^2

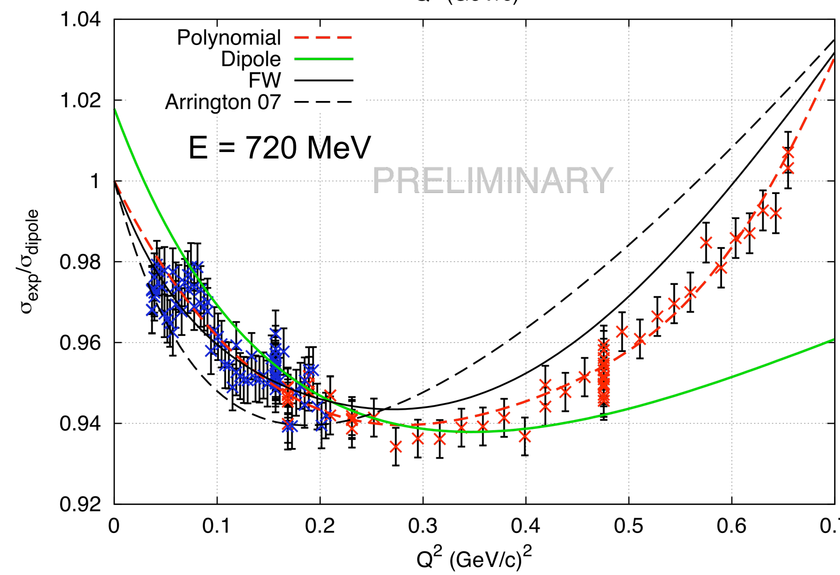




Rosenbluth separation at low Q^2
Precise charge and magnetic radii

MAMI A1 (Three-Spectrometer Facility)



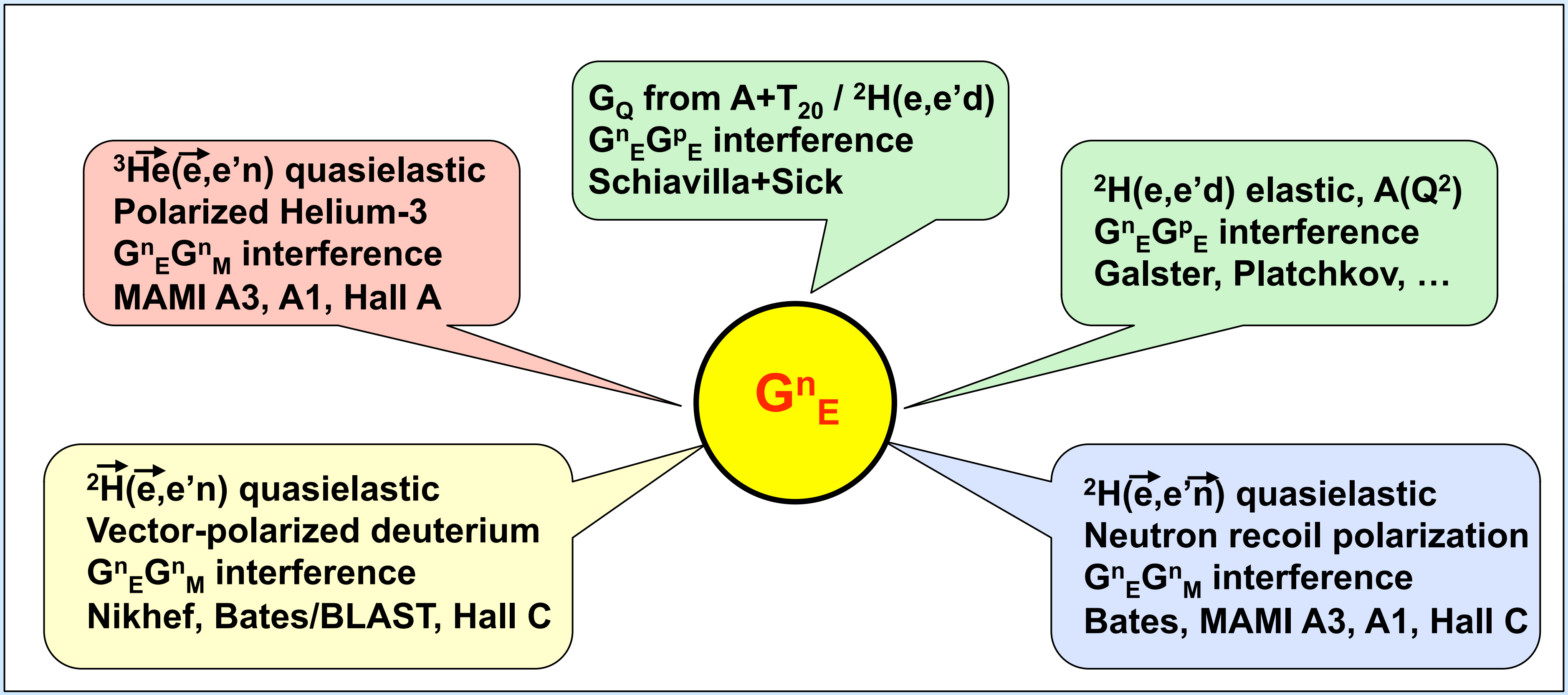


Neutron

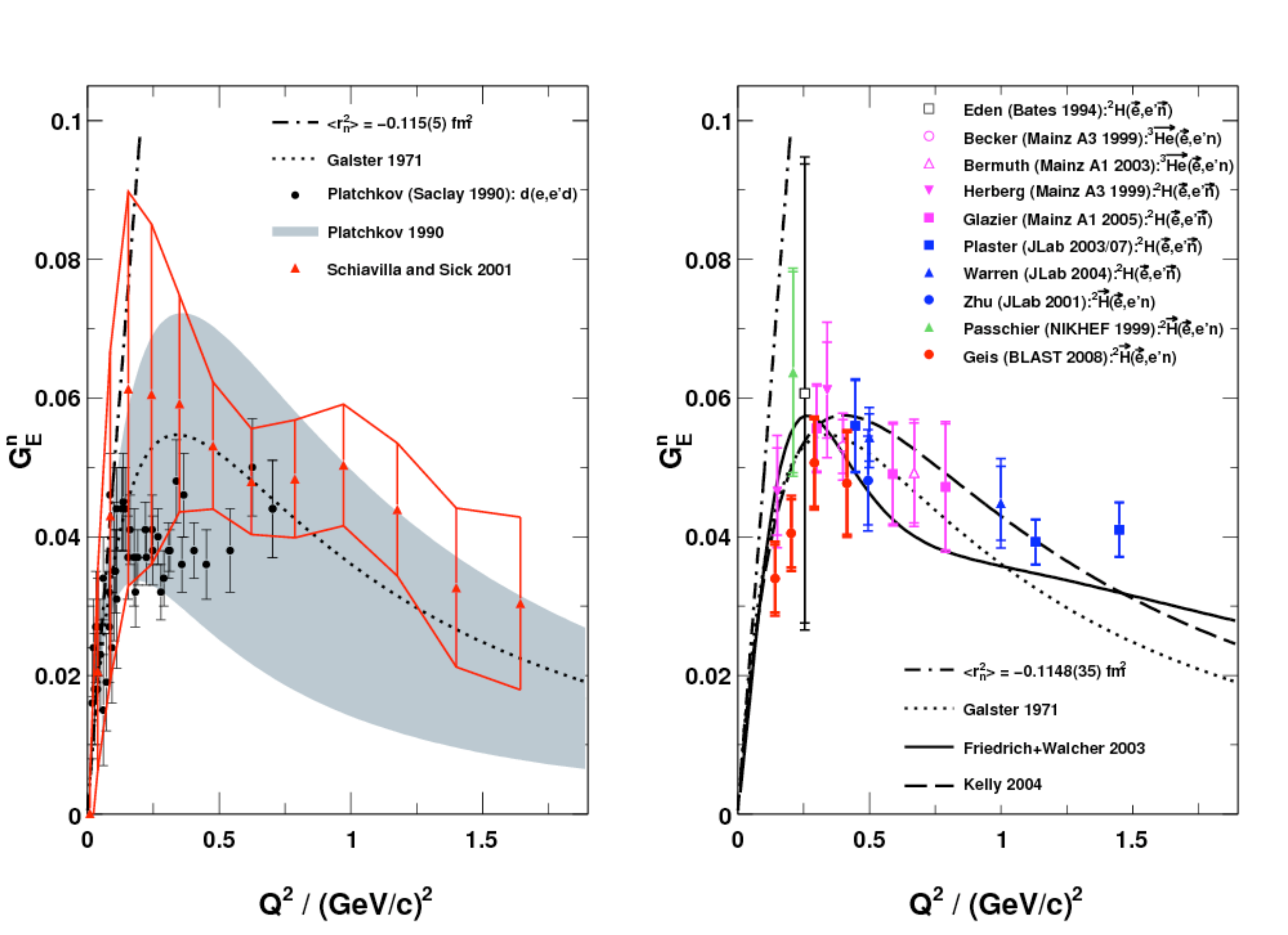
G^n_E in Absence of Free Neutron Target

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

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)

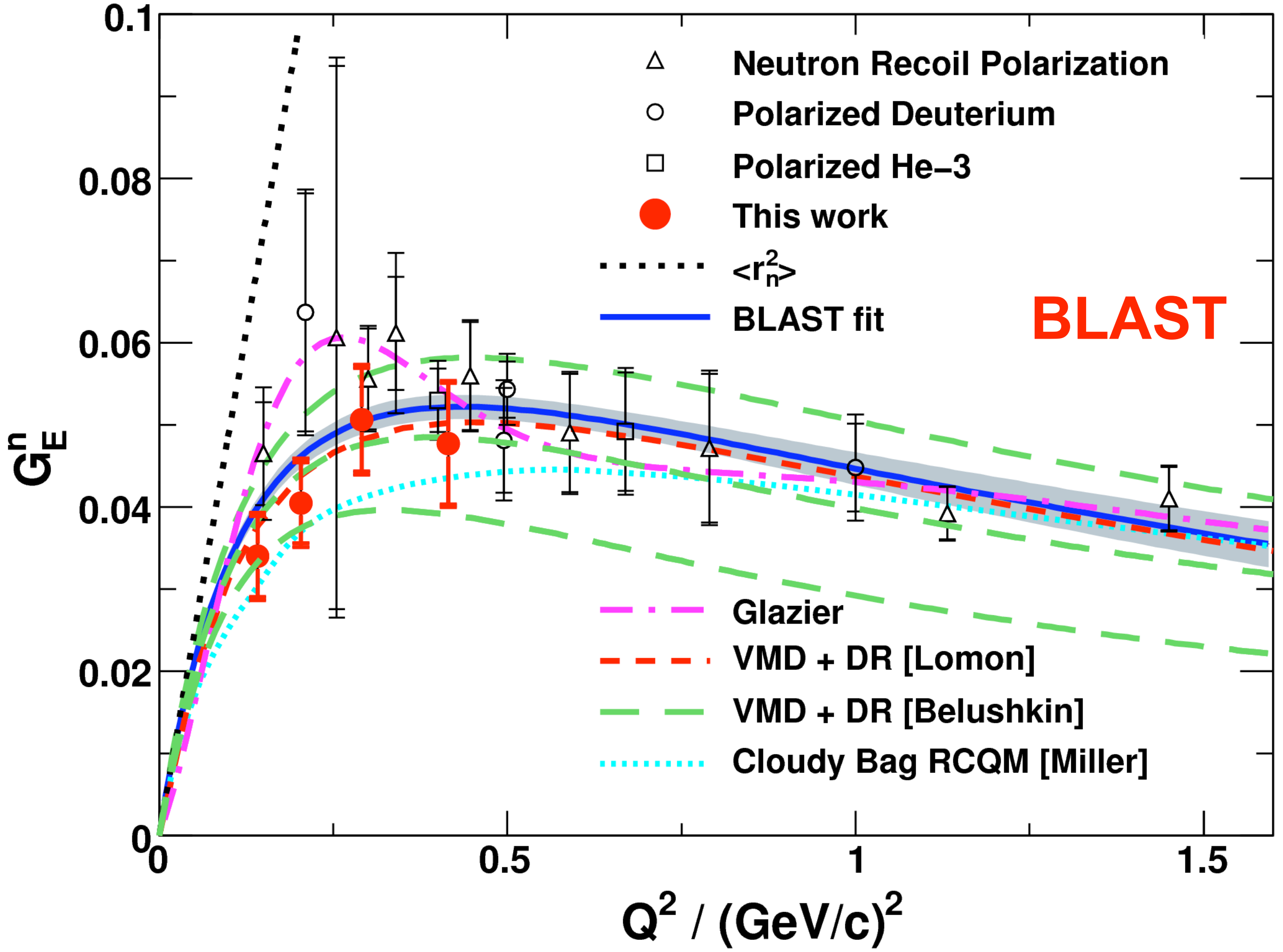


Neutron Electric Form Factor G^n_E



Neutron Electric Form Factor G^n_E*

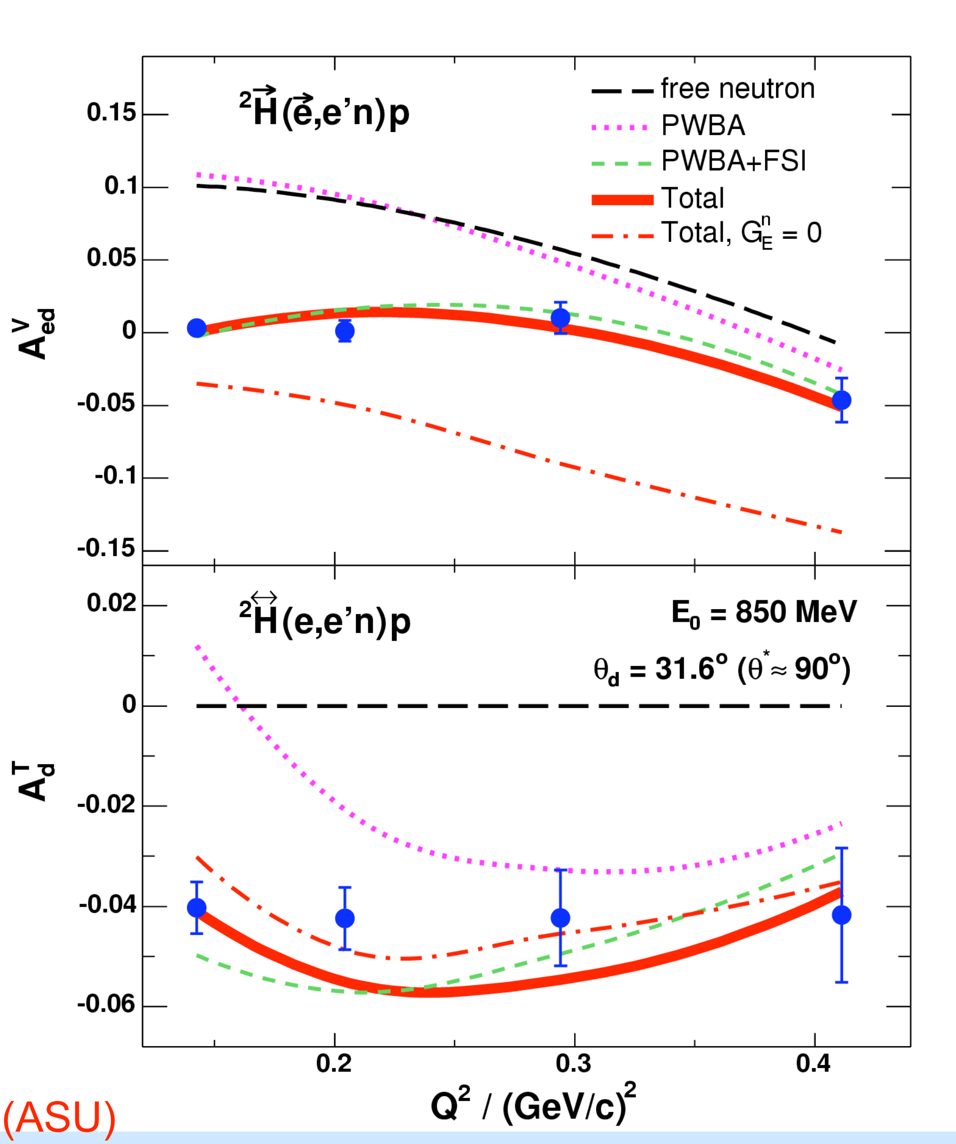
E. Geis et al., PRL101 (2008) 042501



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

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**



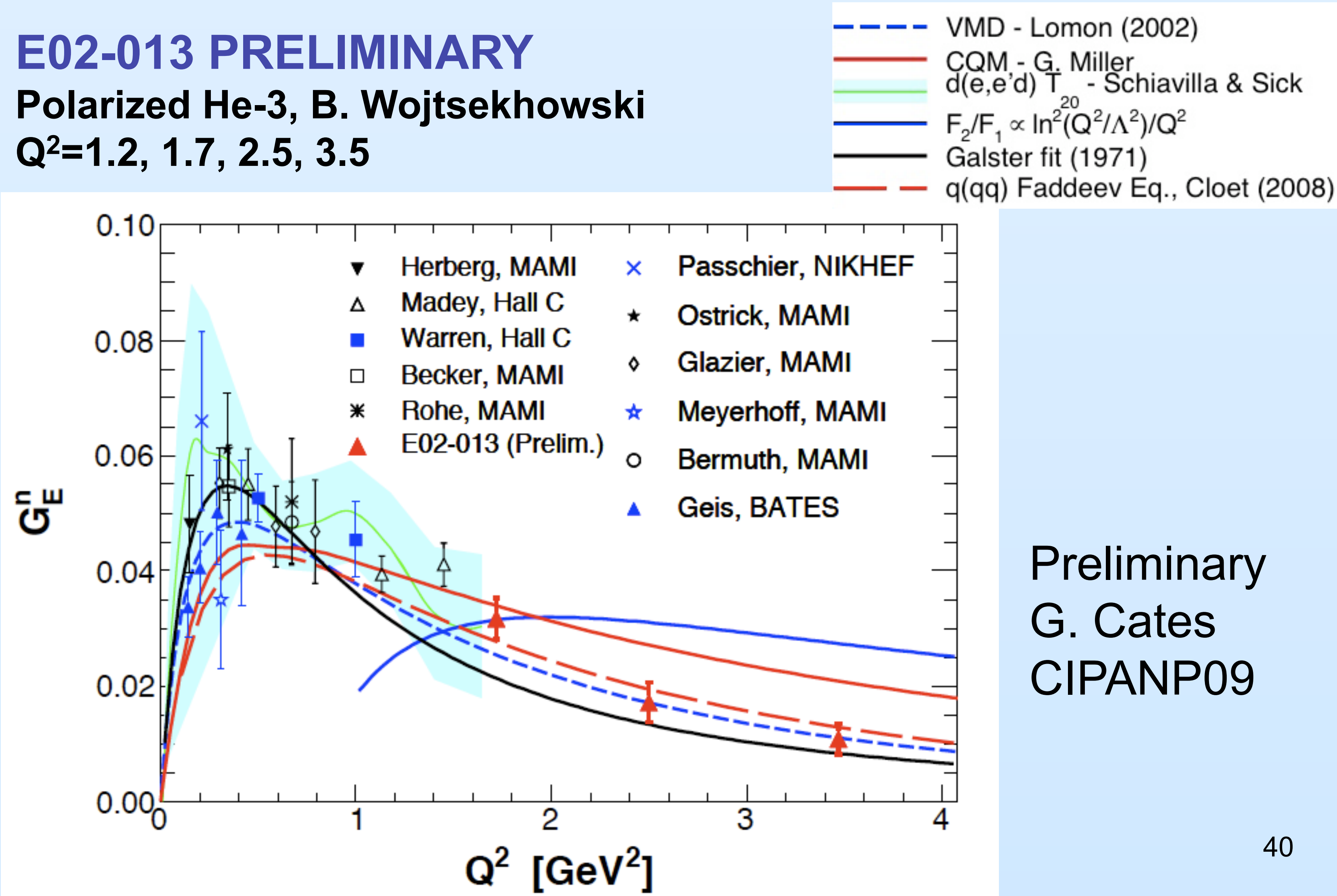
*Ph.D. work of V. Ziskin (MIT) and E. Geis (ASU)

New Measurements of G^n_E

E02-013 PRELIMINARY

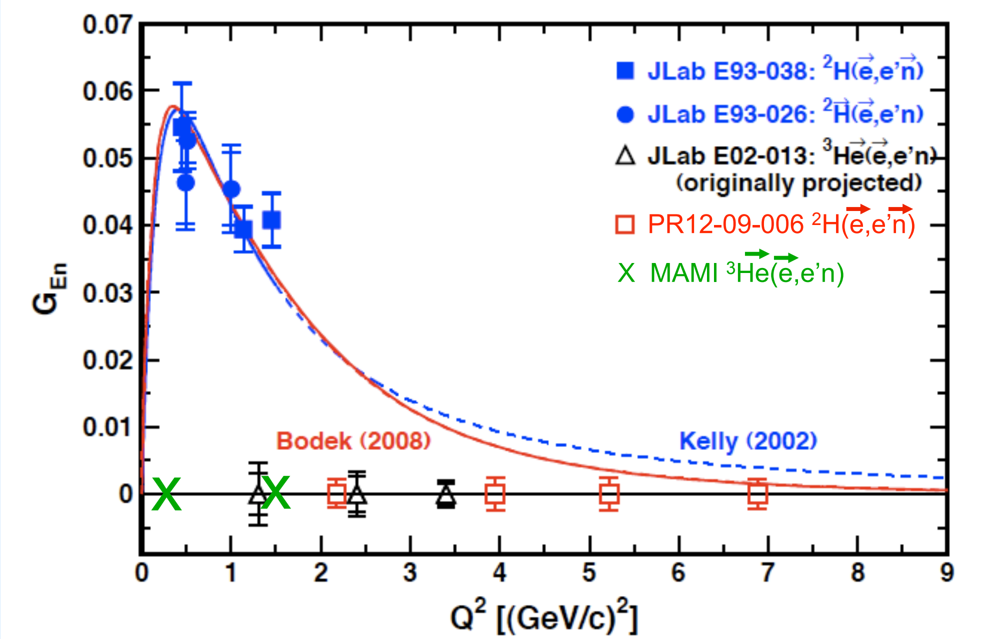
Polarized He-3, B. Wojtsekhowski

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**

Superseding PR04-110

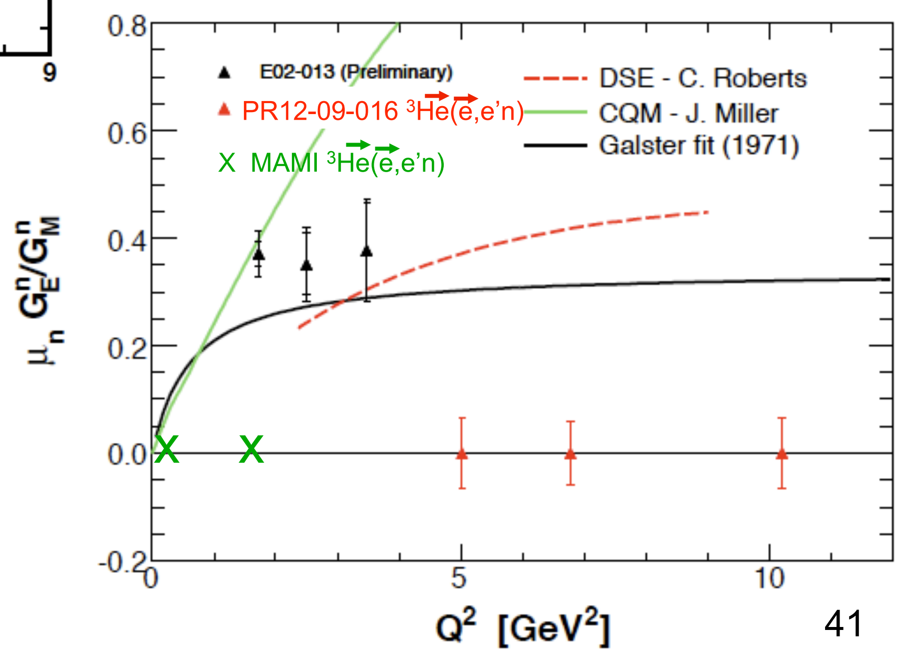
PAC34 (2009): PR12-09-016

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

$^3\overrightarrow{He}(\vec{e},e')$ 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

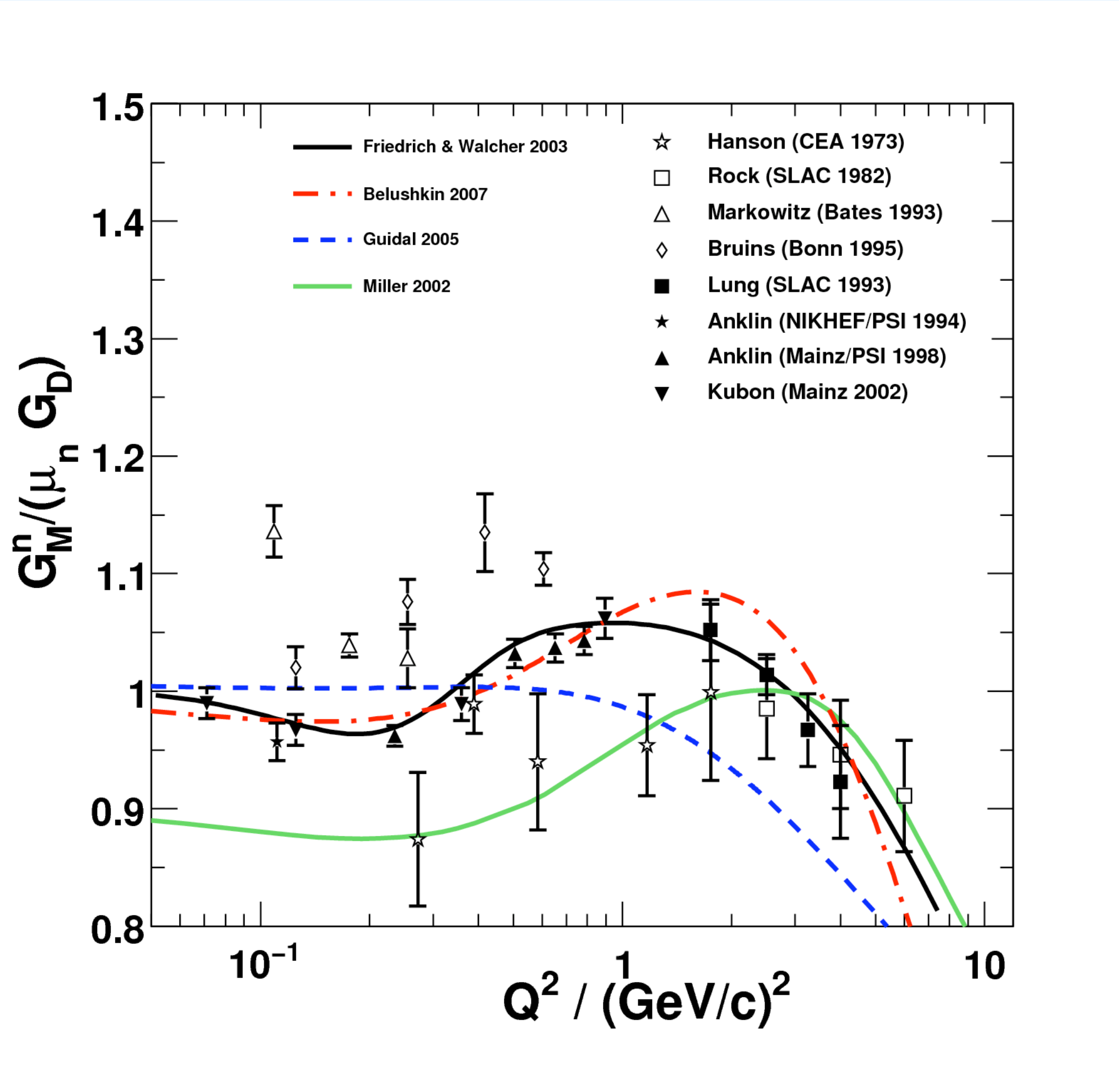
G^n_M

$^2\overrightarrow{H}(\vec{e},e')$ 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

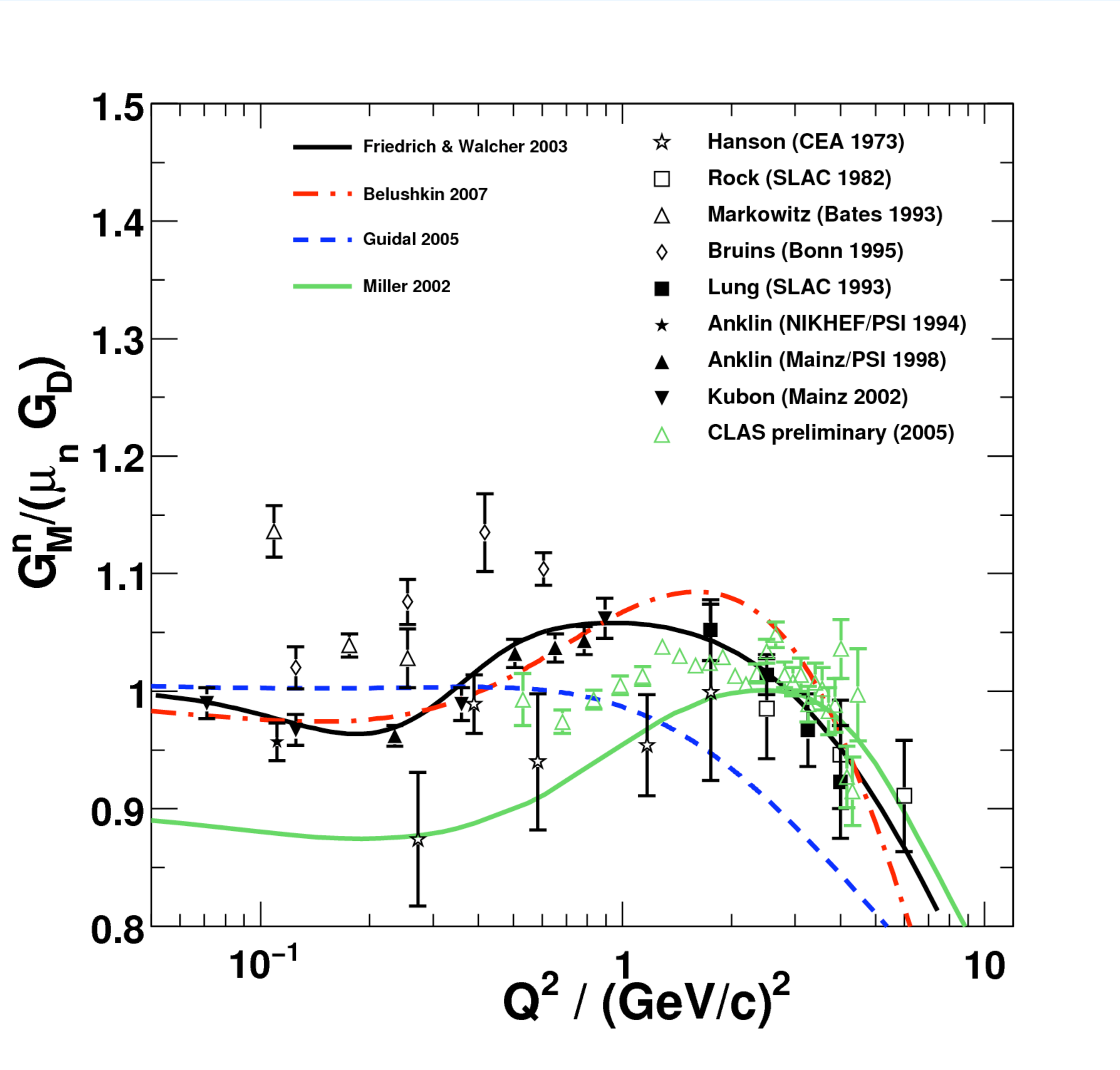


Pre-polarization era

- G^n_M world data from unpolarized experiments
- Cross section ratio

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

Neutron Magnetic Form Factor G^n_M



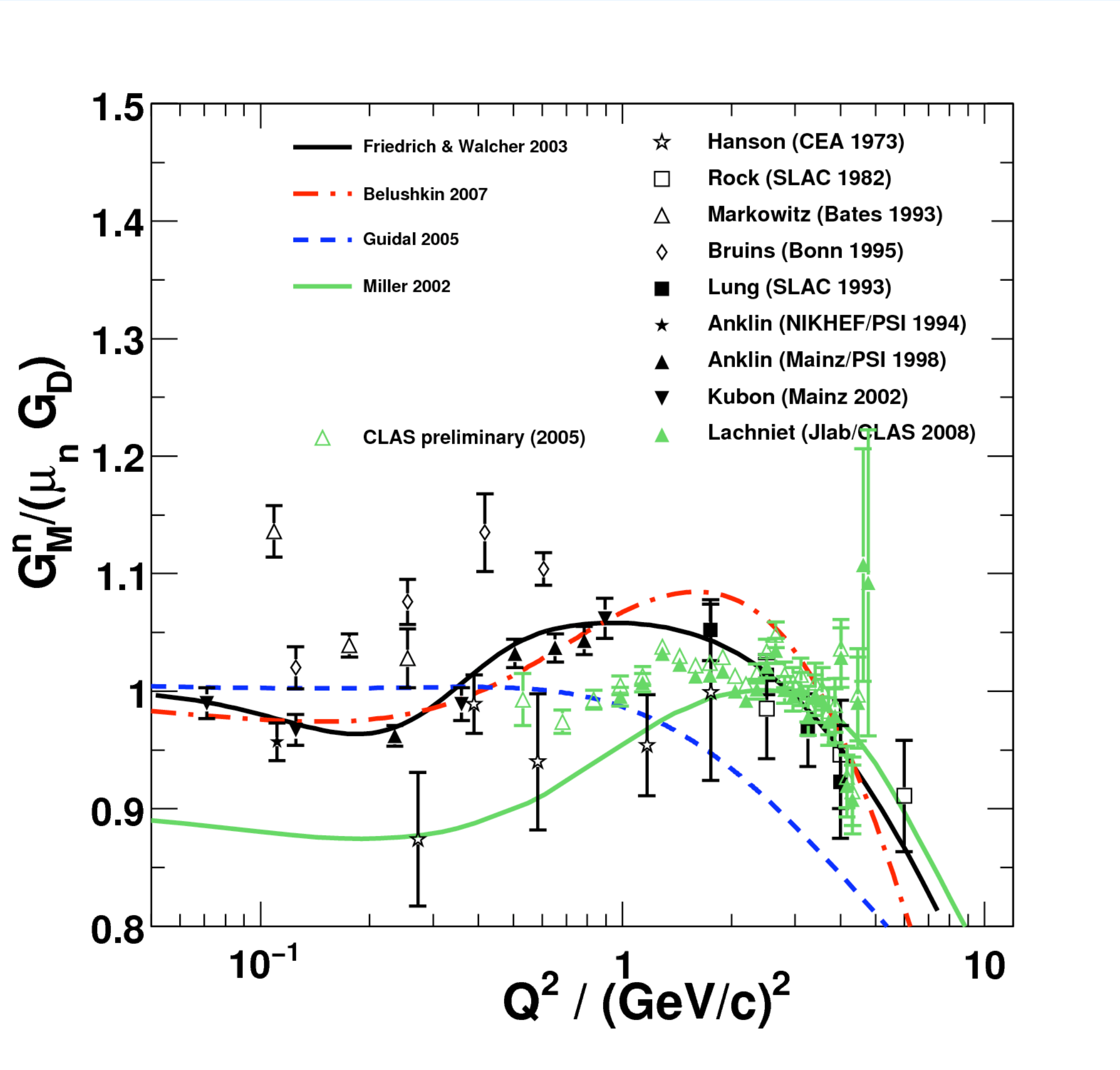
Pre-polarization era

- G^n_M world data from unpolarized experiments
- Cross section ratio

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

  + CLAS preliminary

Neutron Magnetic Form Factor G^n_M



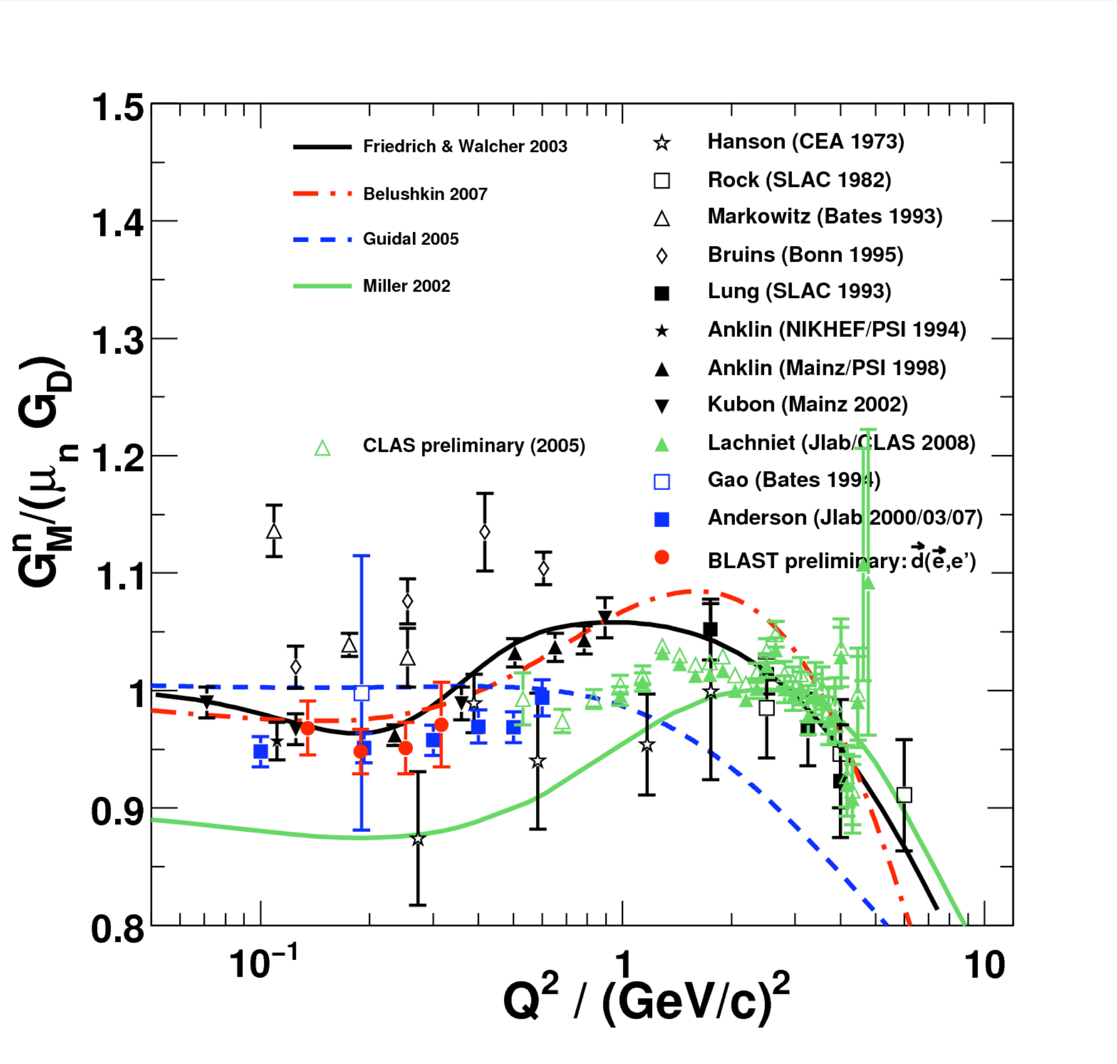
Pre-polarization era

- G^n_M world data from unpolarized experiments
- Cross section ratio

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

+ CLAS preliminary (final)

Neutron Magnetic Form Factor G^n_M



Pre-polarization era

- G^n_M world data from unpolarized experiments
- Cross section ratio

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

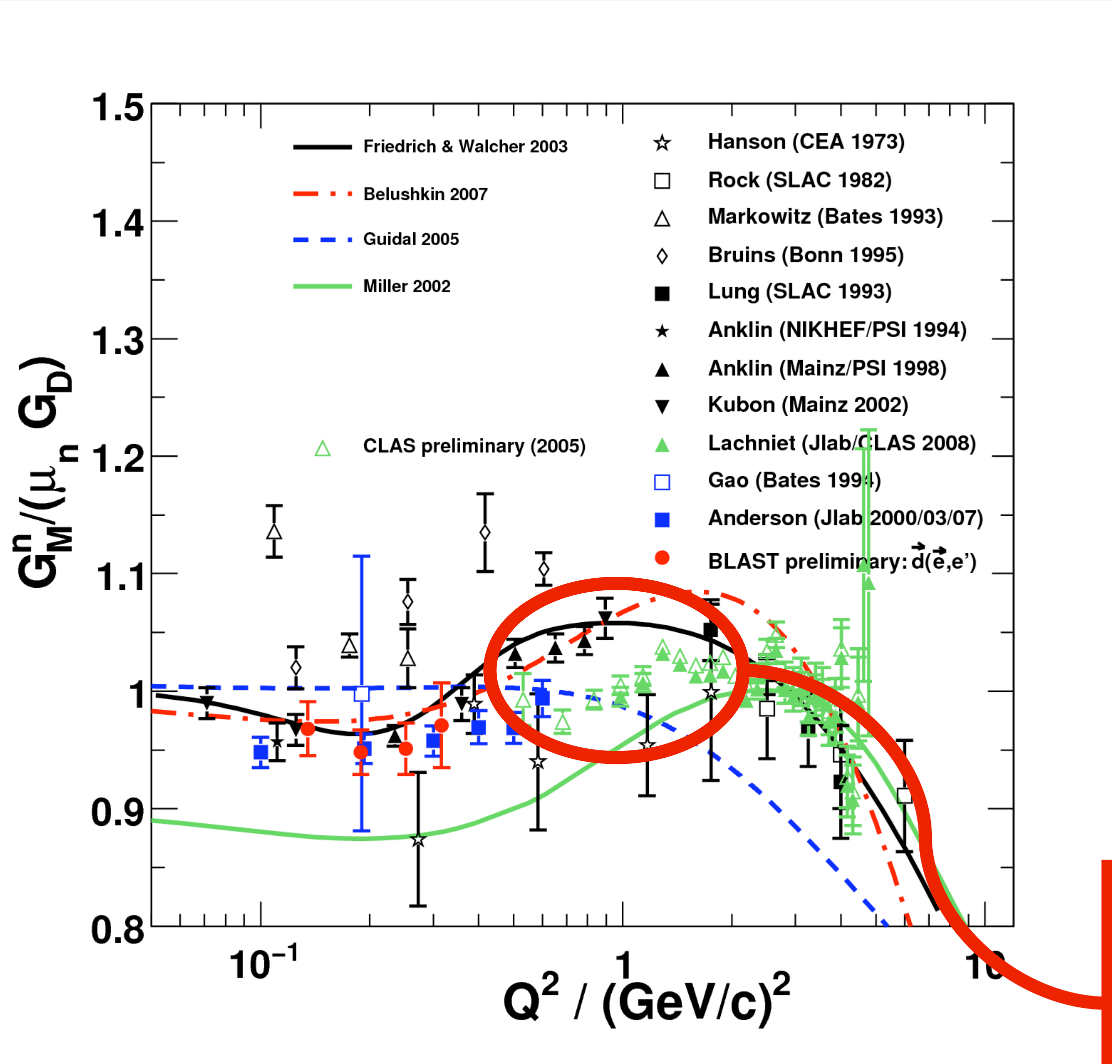
  + CLAS preliminary (final)

Polarization era

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

  + BLAST preliminary

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 (final)

Polarization era

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

  + BLAST preliminary

- **No pol. data >0.6 (GeV/c)^2**
- **Discrep./jump of several σ at Q^2 ~ 0.6-1.0 (GeV/c)^2**
- **IncAs/LOI-09-003 case deemed "uncompelling" by PAC34**

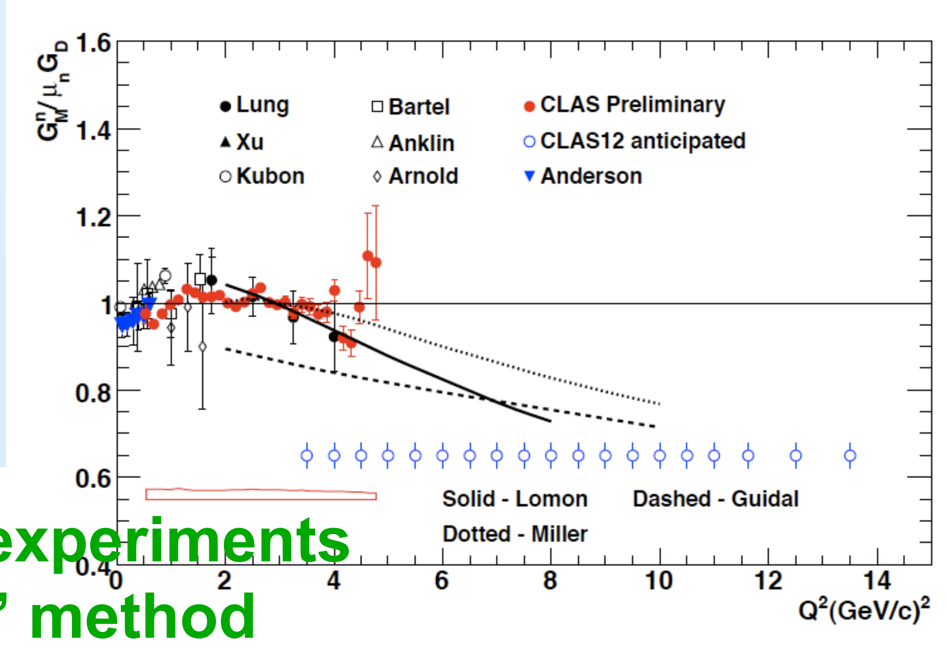
Future Measurements of G^n_M

PAC32 (2007): PR12-07-104

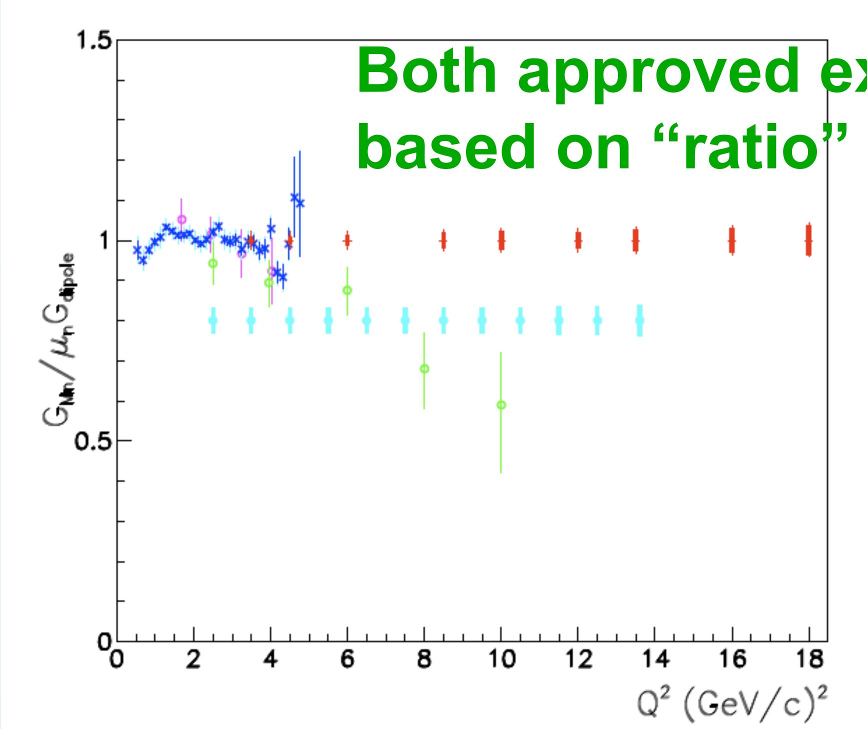
G.P. Gilfoyle, W.K. Brooks, M.F. Vineyard, J.D. Lachniet, L.B. Weinstein et al.

Hall B /CLAS12

Up to **Q^2 = 14 (GeV/c)^2**



Both approved experiments based on "ratio" method



PAC34 (2009): PR12-09-019

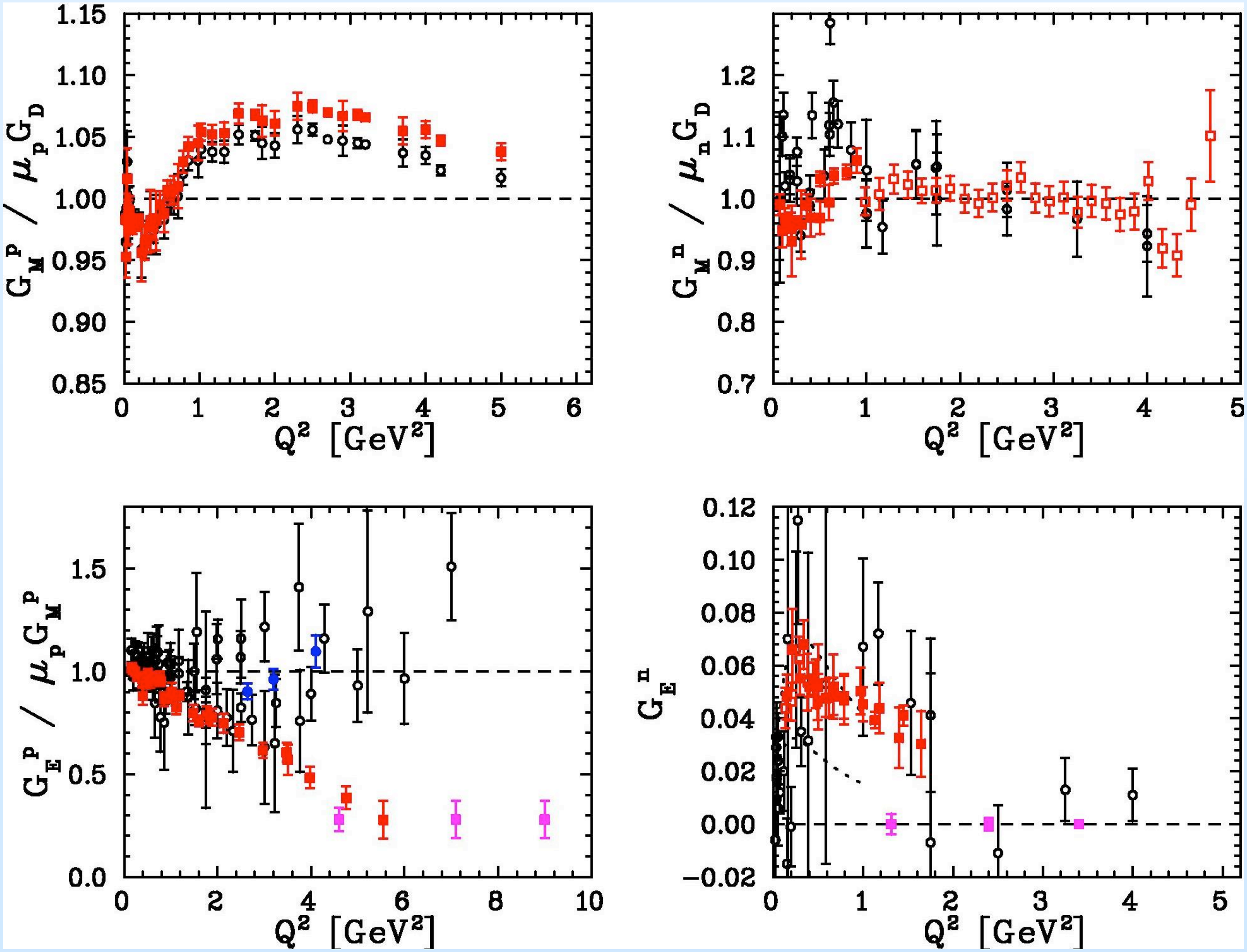
B. Wojtsekhowski, R. Gilman, B. Quinn et al.

Hall A /BigFamily

Proposed up to Q^2 = 18 (GeV/c)^2

Approved up to **Q^2 = 12 (GeV/c)^2**

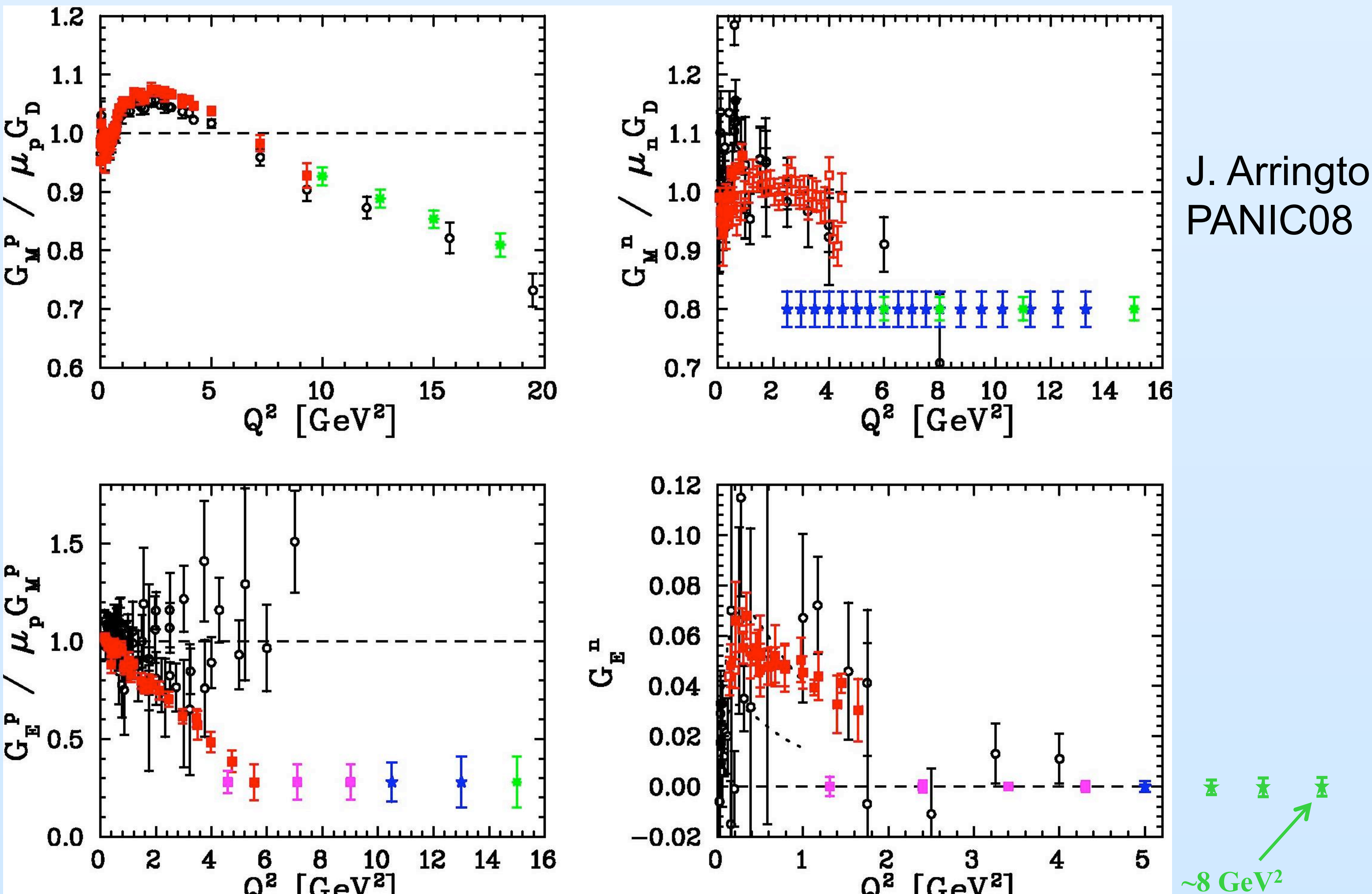
Nucleon Form Factors: Last Ten Years



J. Arrington
PANIC08

Magenta: underway or approved

Extensions with Jlab 12 GeV Upgrade



J. Arrington
PANIC08

- BLUE = CDR or PAC30 approved, GREEN = new ideas under development

Summary

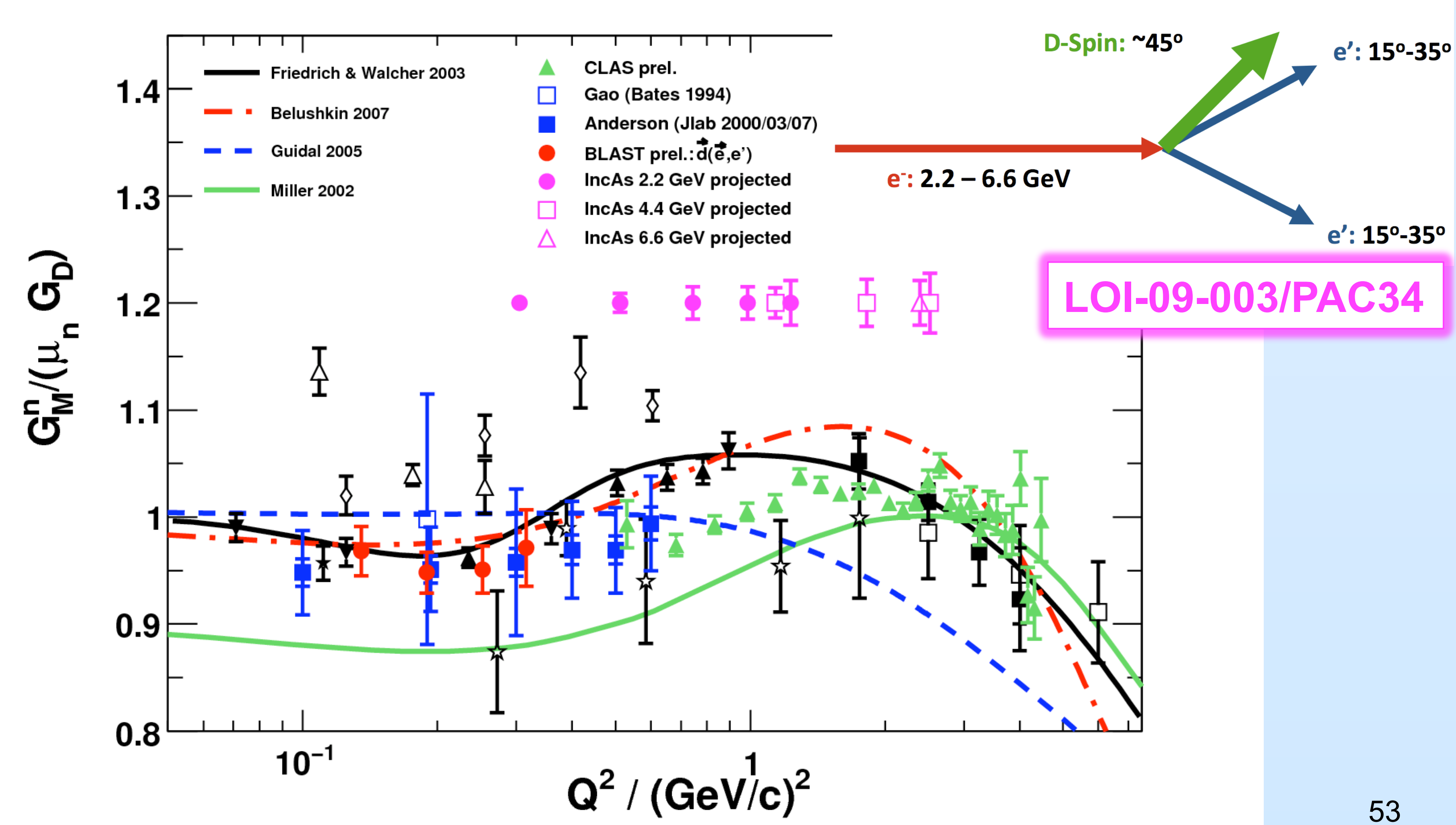
- **Nucleon electromagnetic elastic form factors**
- **Tremendous progress during last decade**
- **High precision, low systematic uncertainties through polarization experiments**
- **Worldwide activity at its peak**

- **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**
  - **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**

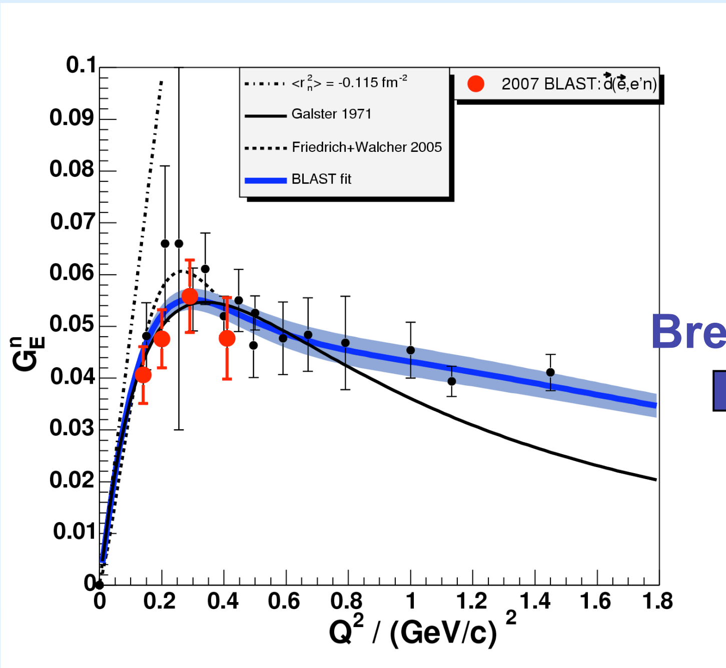
Backup slides

IncAs: A precision G^n_M measurement

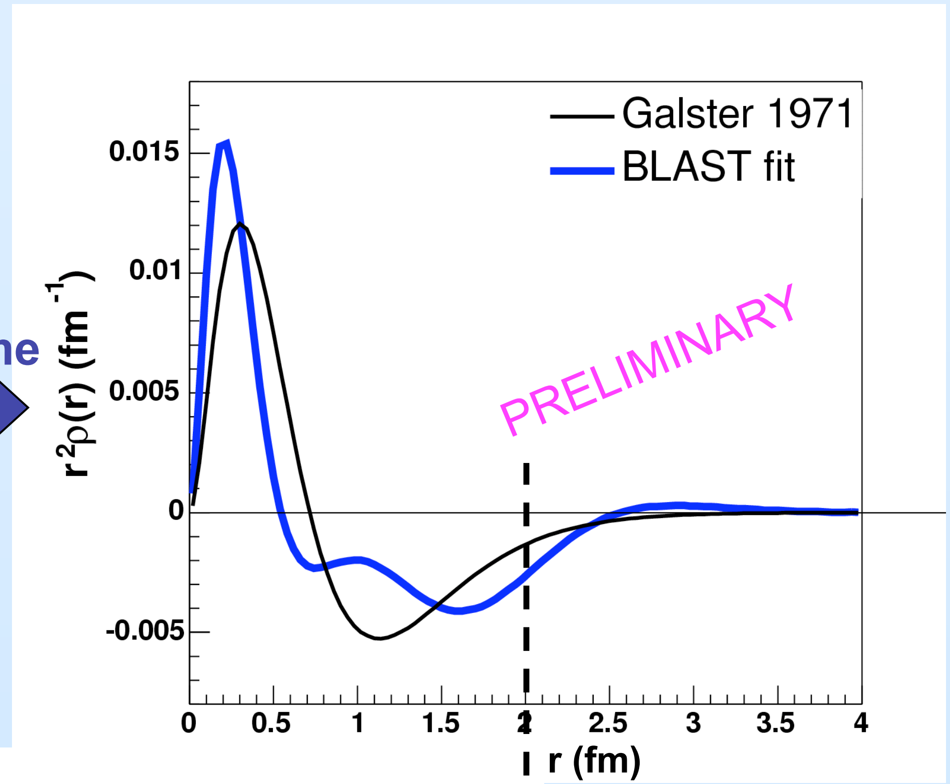


Neutron Electric Form Factor G^n_E

Charge form factor ↔ Charge distribution

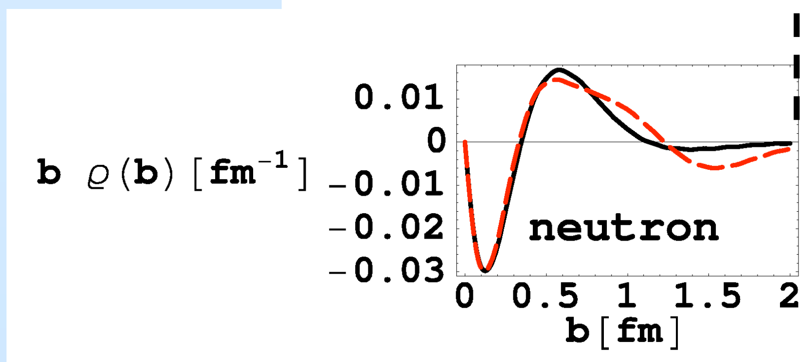


Breit frame



Forbidden interpretation as rest charge distribution

Transverse size from GPD



G. Miller, nucl-th/0705.2409