Review on Nucleon Electromagnetic Form Factors

ECT* Workshop on Hard Meson and Photon Production
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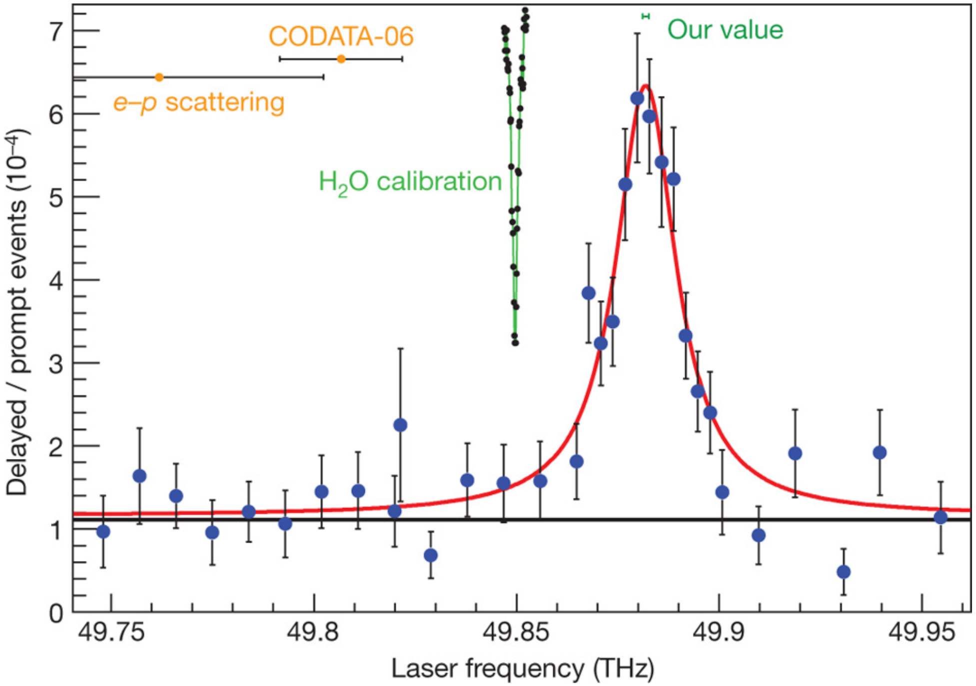
Outline

- Introduction
- Recent progress on nucleon electromagnetic form factors (experiments)
- Upcoming program
- Summary and outlook

``Experimental Status on Nucleon Electromagnetic Form Factors and the Proton Charge Radius'', ECT* Workshop on Structure of the Nucleon, Sep 2 - 11, 2002.

Disclaimer: I will not cover F.F. in the timelike region in this talk

Electromagnetic form factor of nucleons



- ***Electromagnetic form factors from electron scattering (Hofstadter, Nobel Prize 1961)***
- **Nucleon electromagnetic form factors are related to the charge and magnetization distribution inside the nucleon**
- **In the limit of Q^2 goes to zero, the slope of the electric form factor determines the charge radius of the nucleon**

proton charge radius R. Pohl et al., Nature 466, 213 (2010)

Discovery of New Physics or something else?

Proton charge radius from electron scattering and Lamb shift measurements

2005: Re-analysis electron-proton scattering $\mathbf{r_p = 0.897(18)}$ **fm**

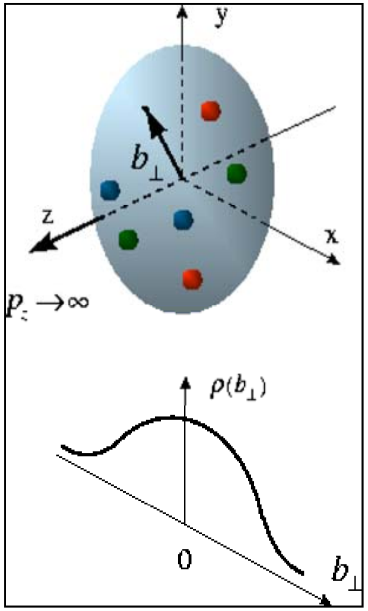
2008: Hydrogen spectroscopy (CODATA) $\mathbf{r_p = 0.8768(69)}$ **fm**

2010: The new value is $\mathbf{r_p = 0.84184(67)}$ **fm**

Generalized Parton Distributions (GPDs)

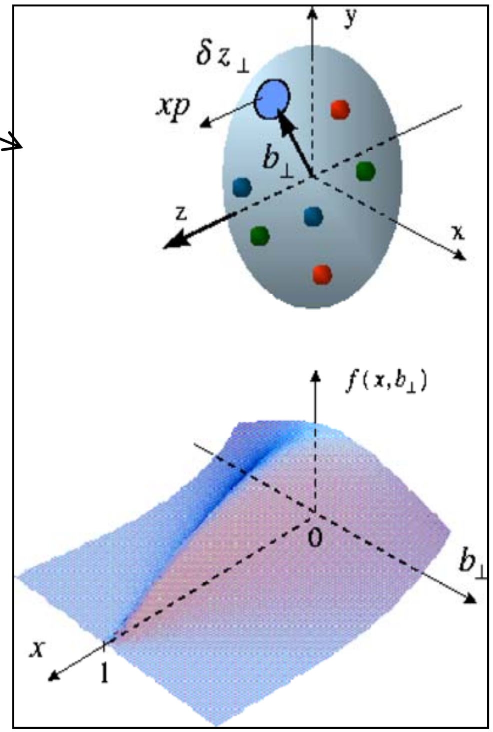
D. Mueller, X. Ji, A. Radyushkin, A. Belitsky,

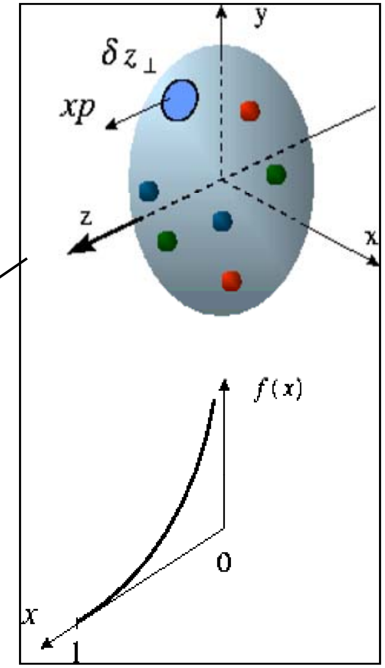
GPDs connect the charge and parton distribution



The size and structure of proton.
transverse

Nobel prize 1961- R. Hofstadter





Internal constituents of the nucleon
longitudinal

Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Extend longitudinal quark momentum & helicity distributions
to transverse momentum distributions - TMDs

Link to DIS and Elastic Form Factors

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) \right] = F_1(t) \text{ Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t) \right] = F_2(t) \text{ Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \widetilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \widetilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x)$$

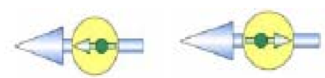
$$\widetilde{H}^q(x,0,0) = \Delta q(x)$$

$$H^q, E^q, \widetilde{H}^q, \widetilde{E}^q(x,\xi,t)$$

$$J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

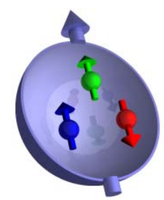
Nucleon Spin Structure

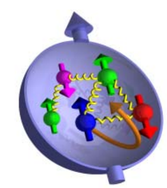
- Understand Nucleon Spin in terms of quarks and gluons (QCD).
  - **Nucleon spin is ½ at all energies, how to divide non trivial (recent development by Chen *et al.*, Wakamatsu)**



Nucleon's spin
Ji's Sum Rule
(example)

$$\frac{1}{2} = \underbrace{\frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q}_{J_q} + J_g$$



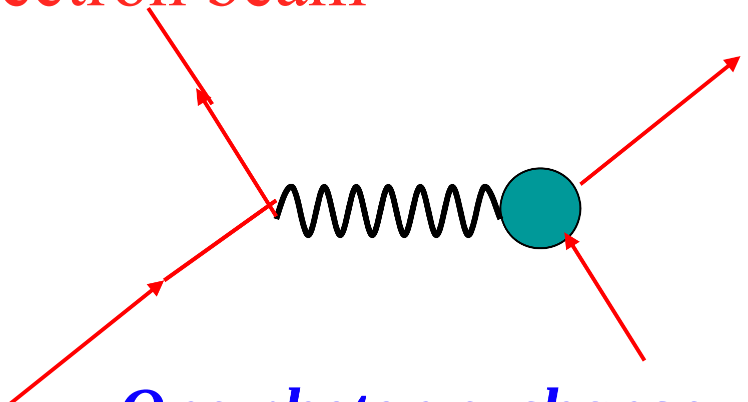


~30% from quark spin by EMC
1/3 confirmed by more precise data
Gluon intrinsic spin contribution not large

  - Small contribution from quarks and gluons' intrinsic spin
  - Orbital angular momentum of quarks and gluons is important
    - **Understanding of spin-orbit correlations.**

Proton Electromagnetic Form Factors

- Unpolarized electron-proton elastic scattering
  - Rosenbluth separation, G_E^p , G_M^p
- Double polarized electron-proton elastic scattering $\dfrac{G_E^p}{G_M^p}$
  - Longitudinally polarized electron beam
    - ***Recoil proton polarization***
    - Polarized proton target



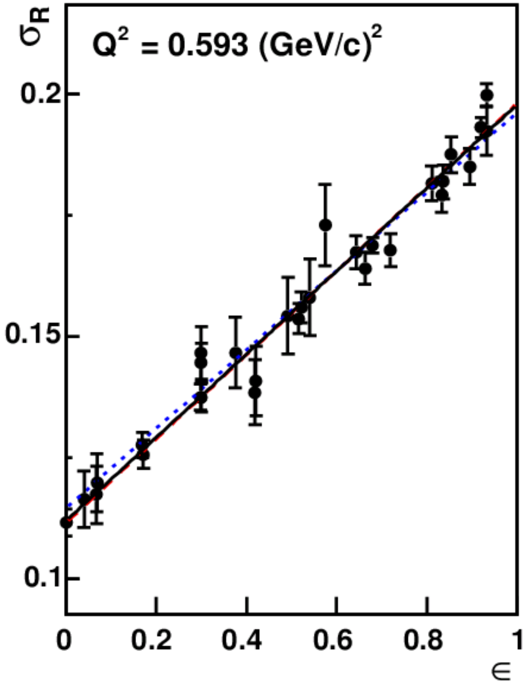
One-photon exchange

Rosenbluth Separation

- Elastic e-p cross section

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}}\frac{E'}{E}\left(\frac{G_E^{p\,2} + \tau G_M^{p\,2}}{1+\tau} + 2\tau G_M^{p\,2}\tan^2\frac{\theta}{2}\right)$$

$$= \sigma_M f_{rec}^{-1}\left(A + B\tan^2\frac{\theta}{2}\right)$$



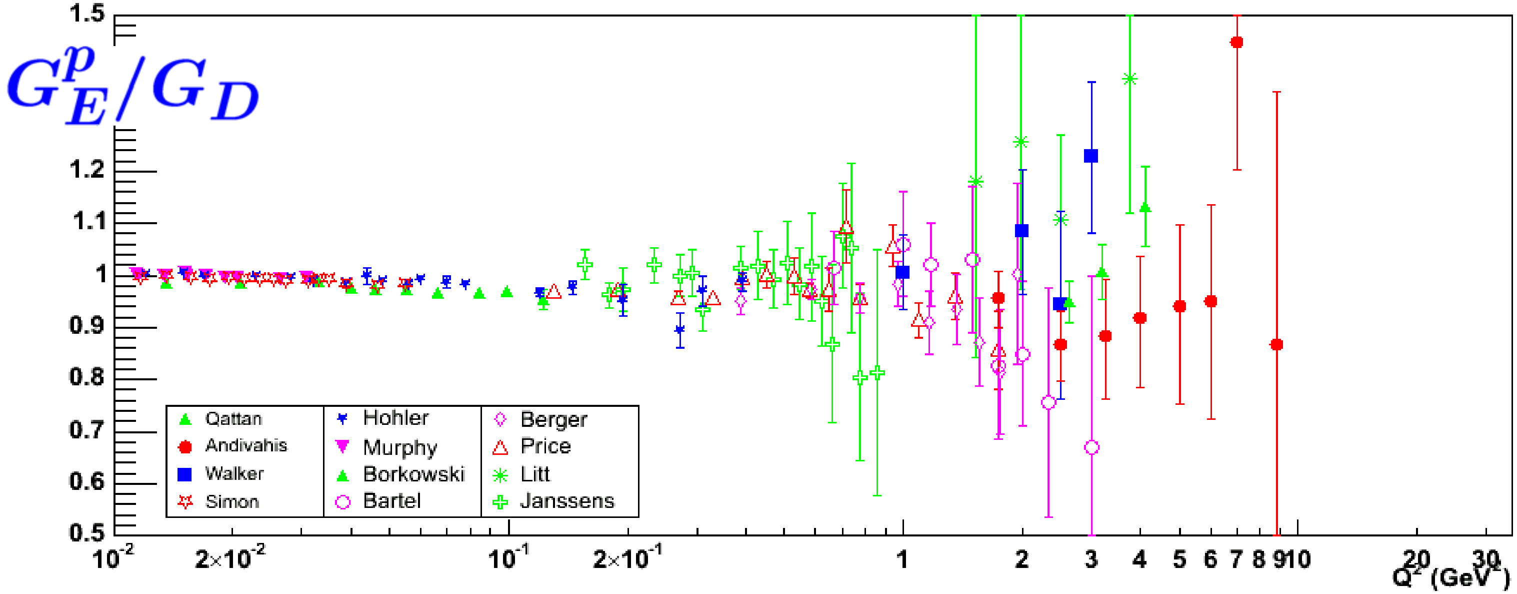
- At fixed Q^2, fit $d\sigma/d\Omega$ vs. $\tan^2(\theta/2)$
  - Measurement of absolute cross section
  - ***Dominated by either G_E or G_M***
    - **Low Q^2 by G_E**
    - **High Q^2 by G_M**

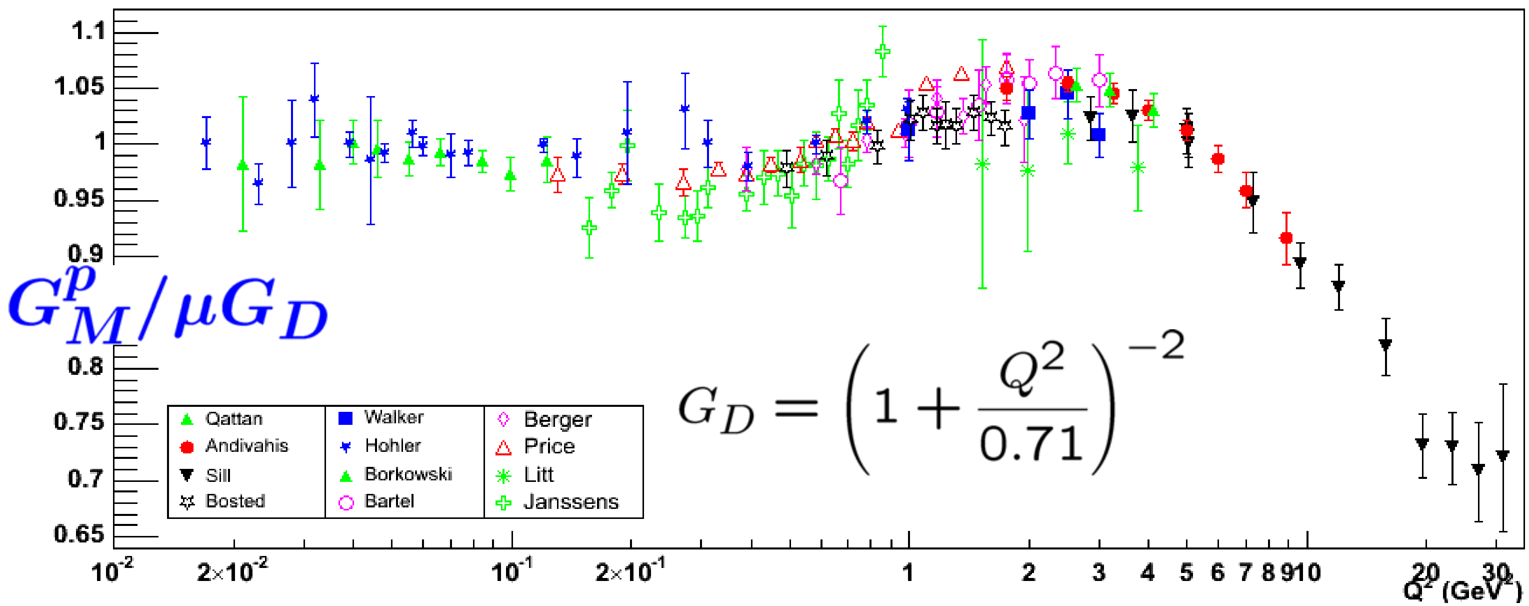
$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

$$\tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1}$$

World Unpolarized Data



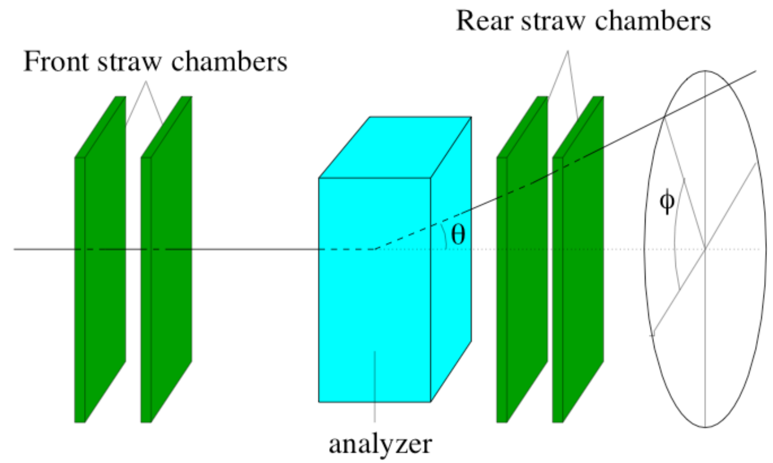


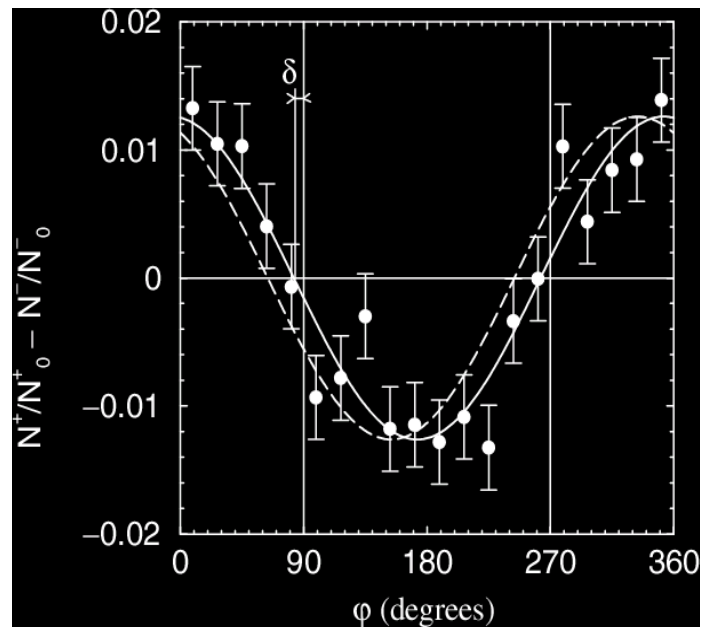
Polarization Transfer

- Recoil proton polarization

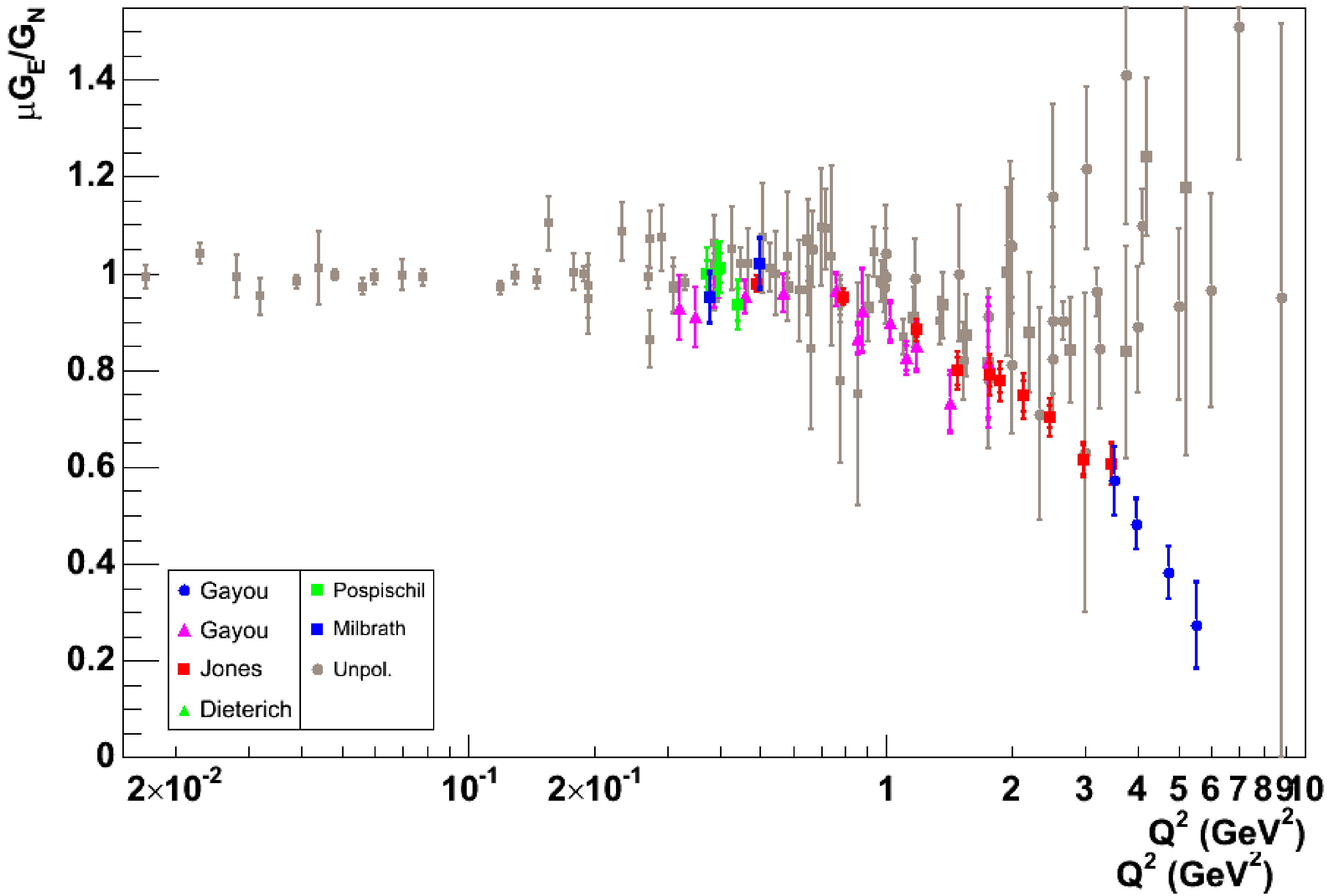
$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan\frac{\theta}{2}$$

- Focal Plane Polarimeter
  - recoil proton scatters off secondary ^{12}C target
  - P_t, P_l measured from φ distribution
  - P_b, and analyzing power cancel out in ratio

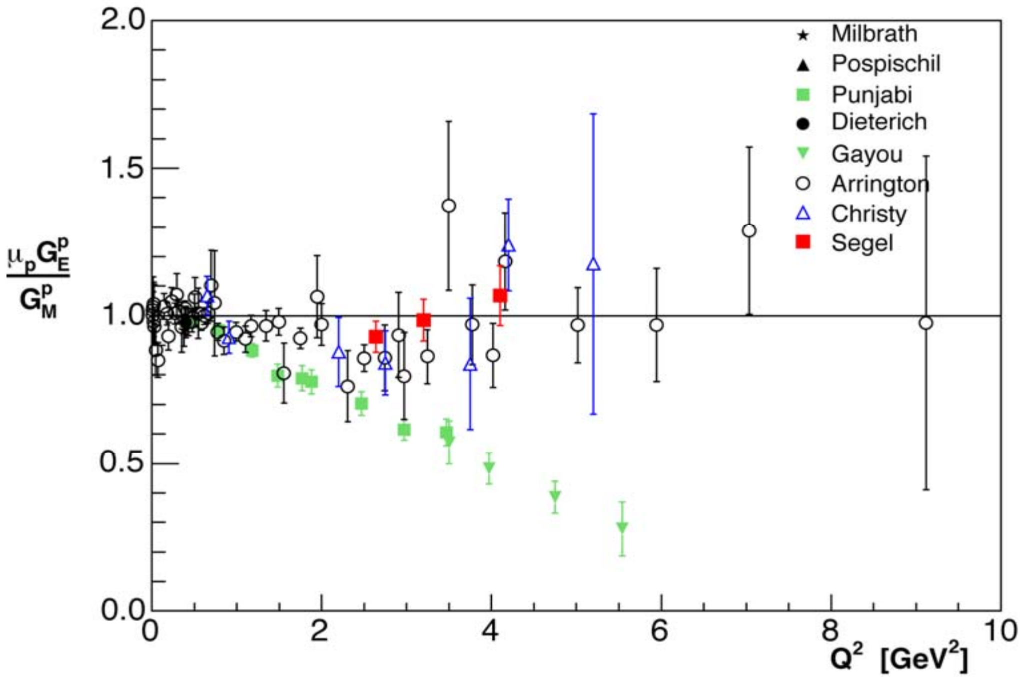


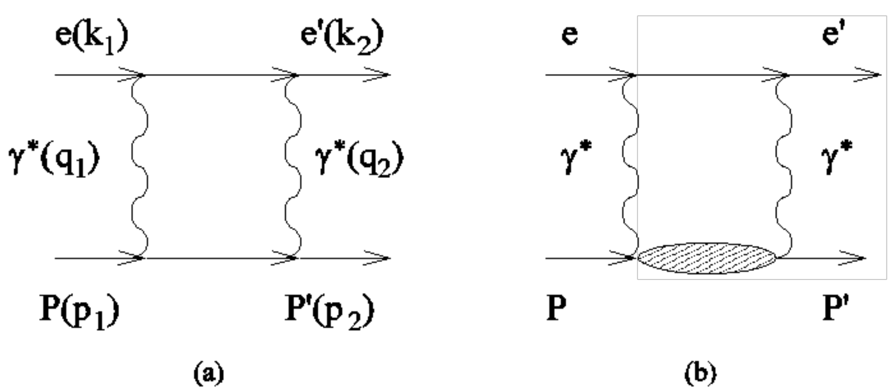


$\mu G_E/G_M$ — World Data



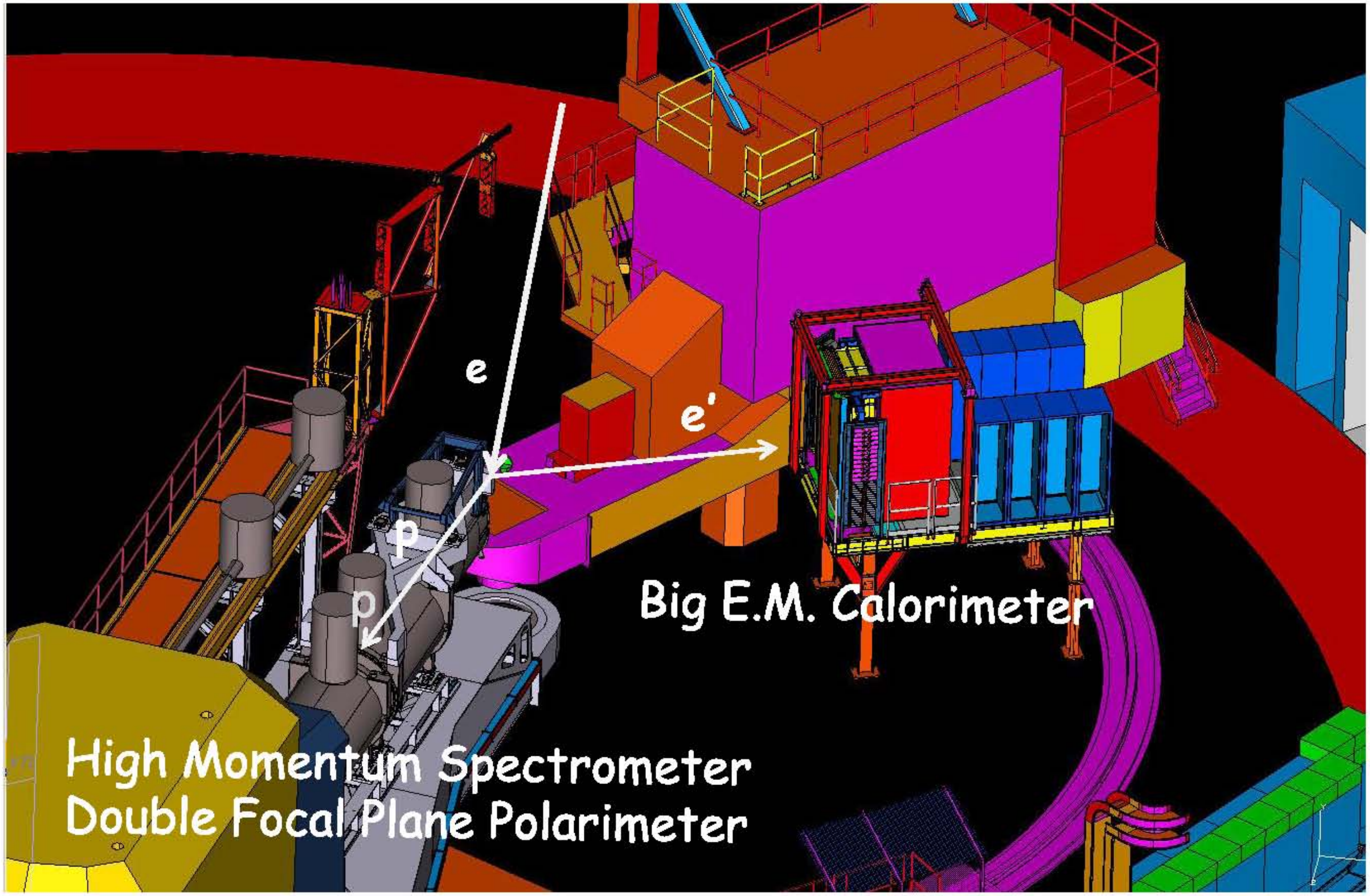
Difference persists between two techniques: one-photon exchange picture not complete





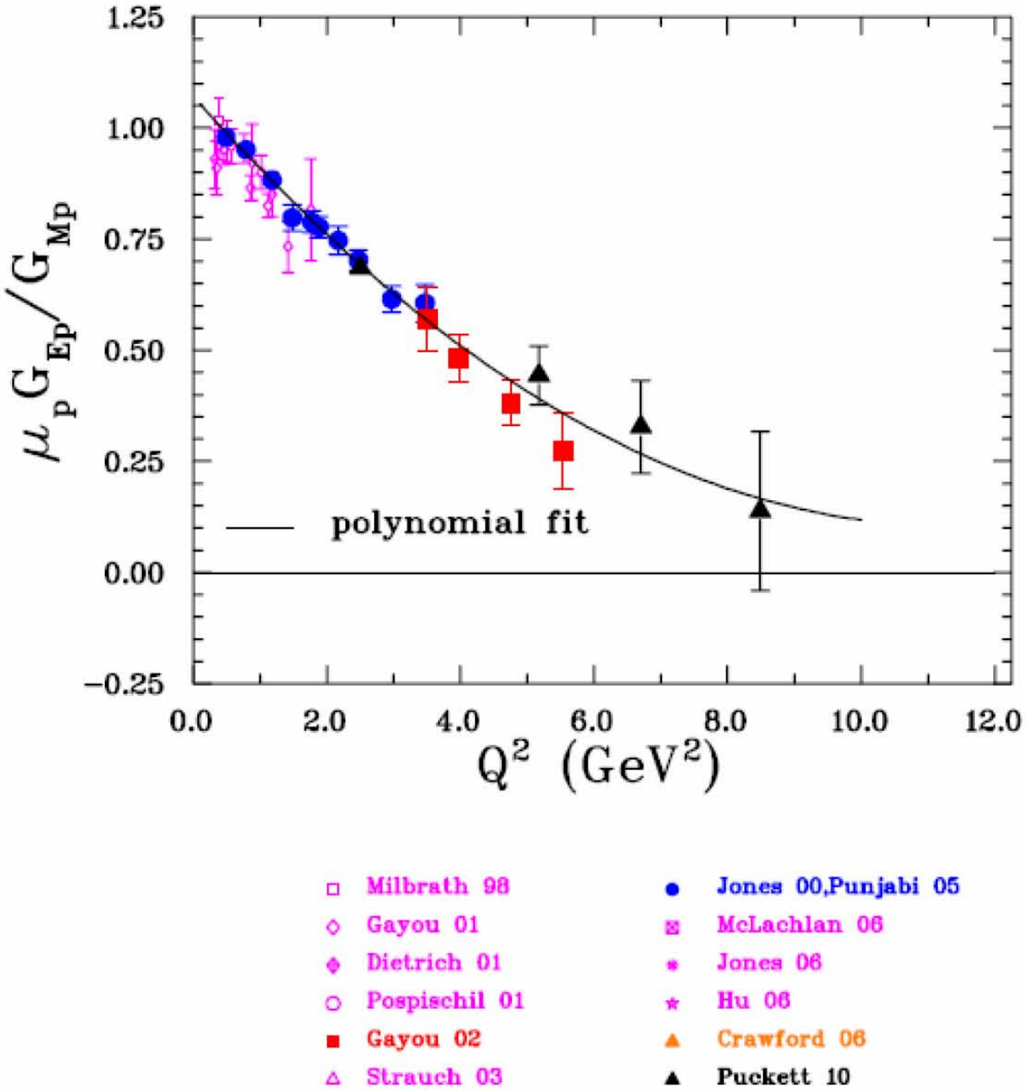
- *JLab Rosenbluth separation data (Christy et al.) and Super Rosenbluth separation data (Arrington and Segel et al.) confirm earlier data and the global analysis*
- *no evidence for experimental errors for either of the experimental techniques*
- *Two-photon exchange (TPE) amplitudes can explain a significant part of the discrepancy*
- *Intensive theoretical and experimental effort on addressing the TPE effect*

GEp(III) Setup



1.87- 5.71 GeV beam
80-100 μA beam current
80-85% polarization
20cm LH_2 target

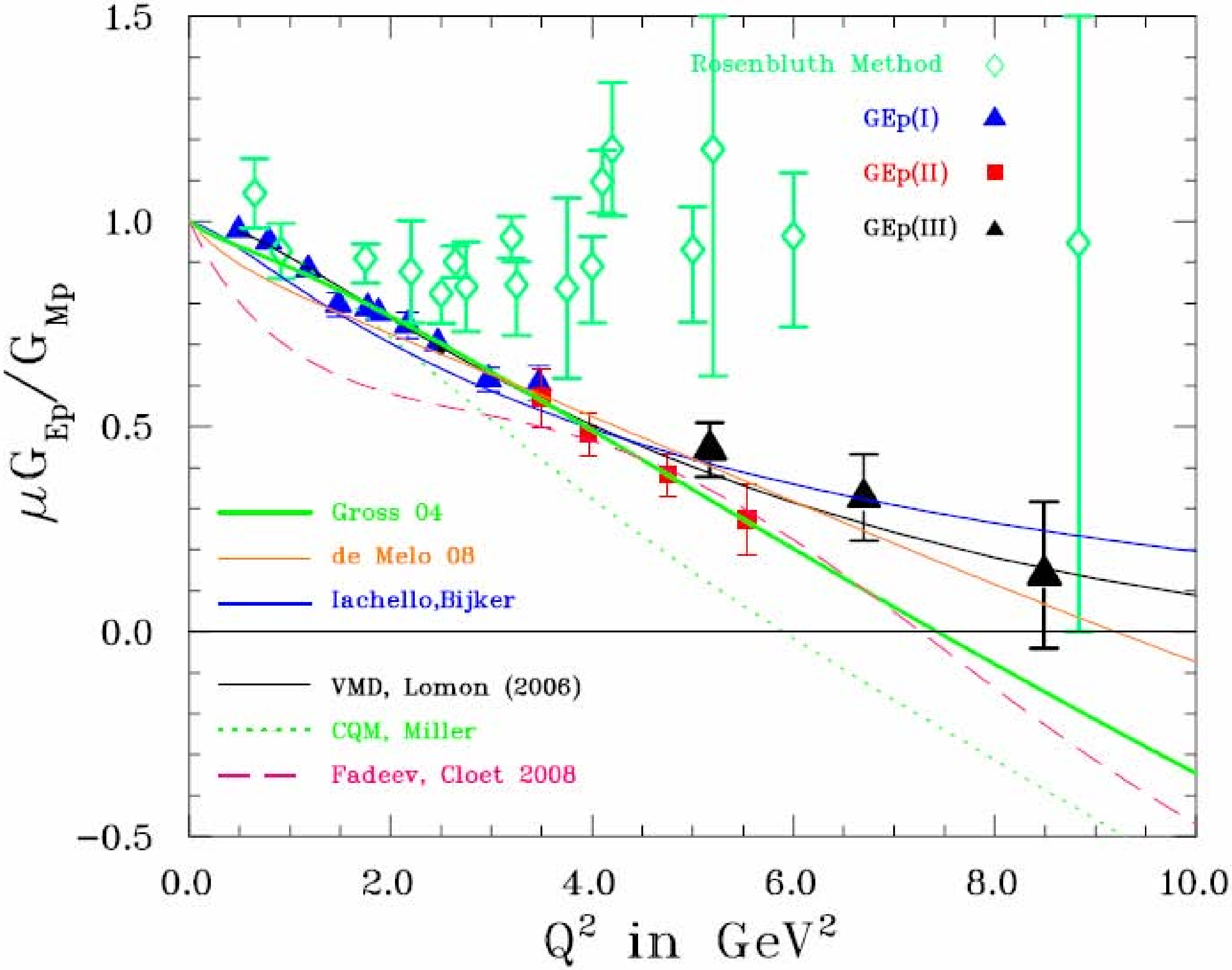
All data for the ratio G_{Ep}/G_{Mp} from Double Polarization



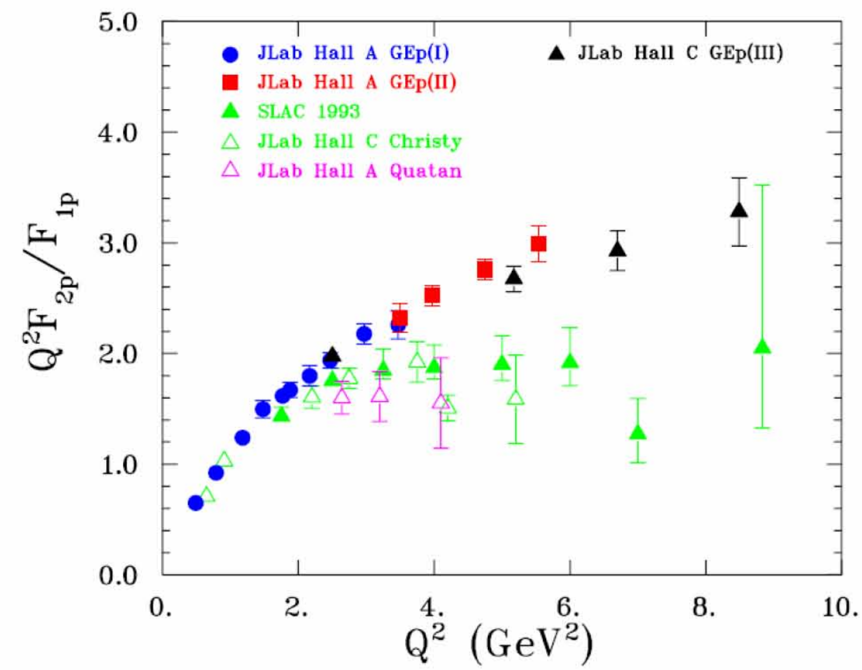
Theoretical Progress

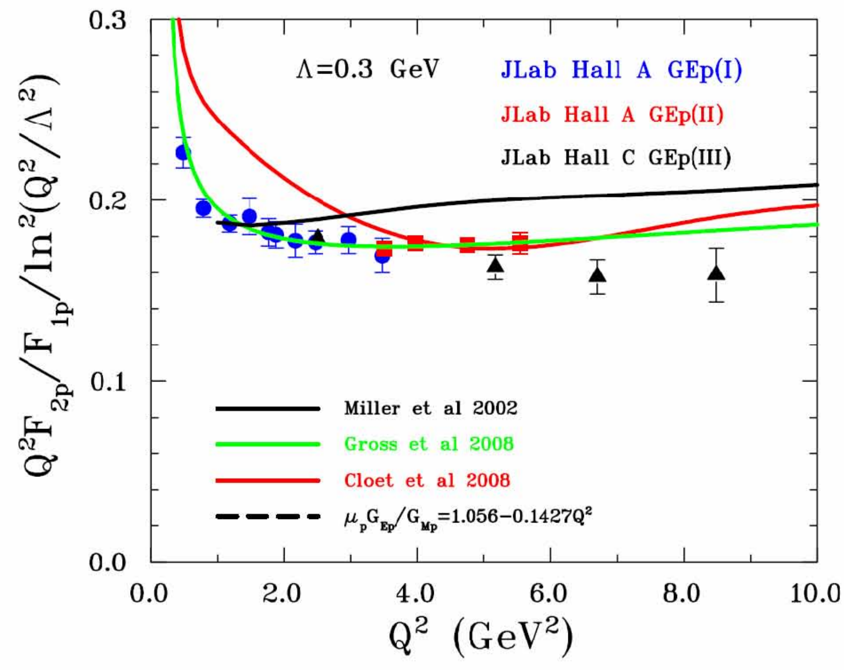
- VMD-based models
  - Describe all four nucleon FF's well
  - Tend to favor ratio reaching a constant value at intermediate Q^2
- rCQM
  - Show the importance of relativistic dynamics
- pQCD-inspired models
  - Predict logarithmic scaling behavior of F_2/F_1 at intermediate Q^2 (Belitsky and Ji) ->related to quark Orbital angular momentum (OAM)
- GPD-inspired models
  - Show a connection with OAM of the quarks in the nucleon
  - FF's provide important constraints on GPD's
- Dyson-Schwinger Equations
  - Dressed quarks are fundamental degrees of freedom, diquark correlations, Solution of Poincare-covariant Faddeev equations based on rainbow-ladder truncation of DSEs of QCD. photon-nucleon vertex depends on a single parameter: diquark charge radius.
- Lattice QCD Models
  - Good progress already, and will get much better in the future

Theoretical predictions



Proton: F_2/F_1 and pQCD





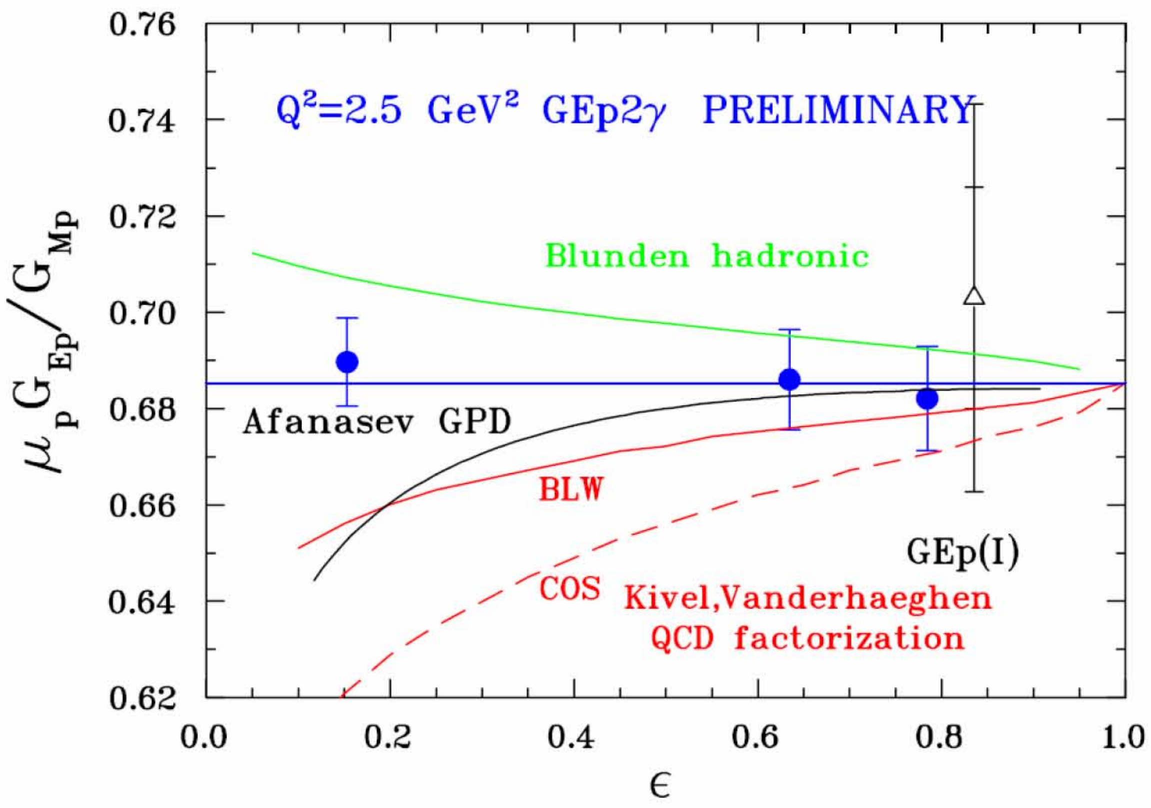
Brodsky and Farrar (75):

Q^2F_2/F_1 constant

Belitsky, Ji and Yuan (03):

$Q^2F_2/F_1 \rightarrow \ln^2(Q^2/\Lambda^2)$

Results of $G_{Ep}(2\gamma)$ Experiment from JLab



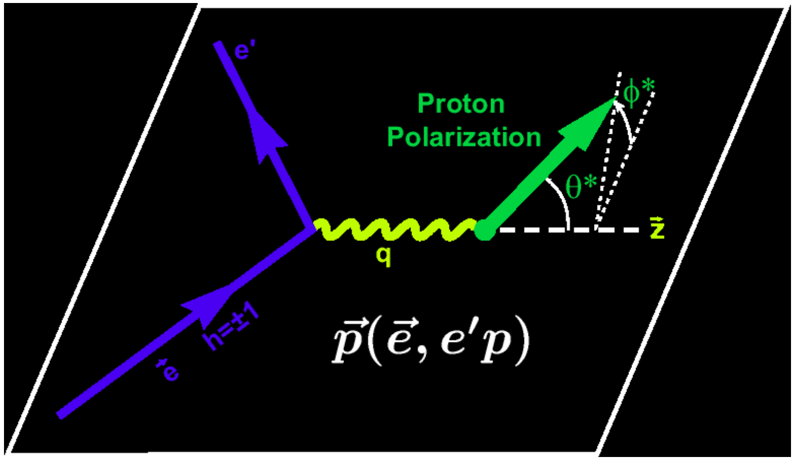
The predictions are normalized to converge at the fitted value of ε = 1.

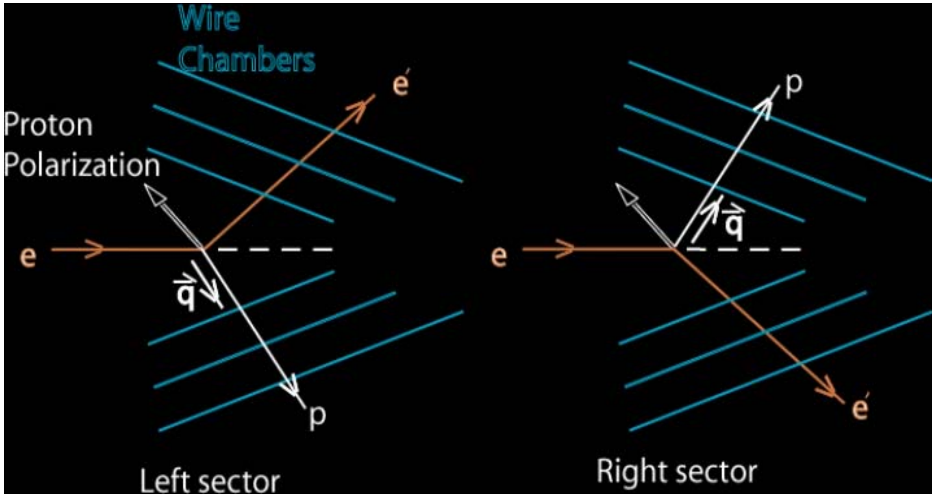
radiative corrections applied, they are negligible
(Afanasev et.al, Phys.Rev. D64 (2001) 113009)

Asymmetry Super-ratio Method

- Polarized beam-target asymmetry

$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$

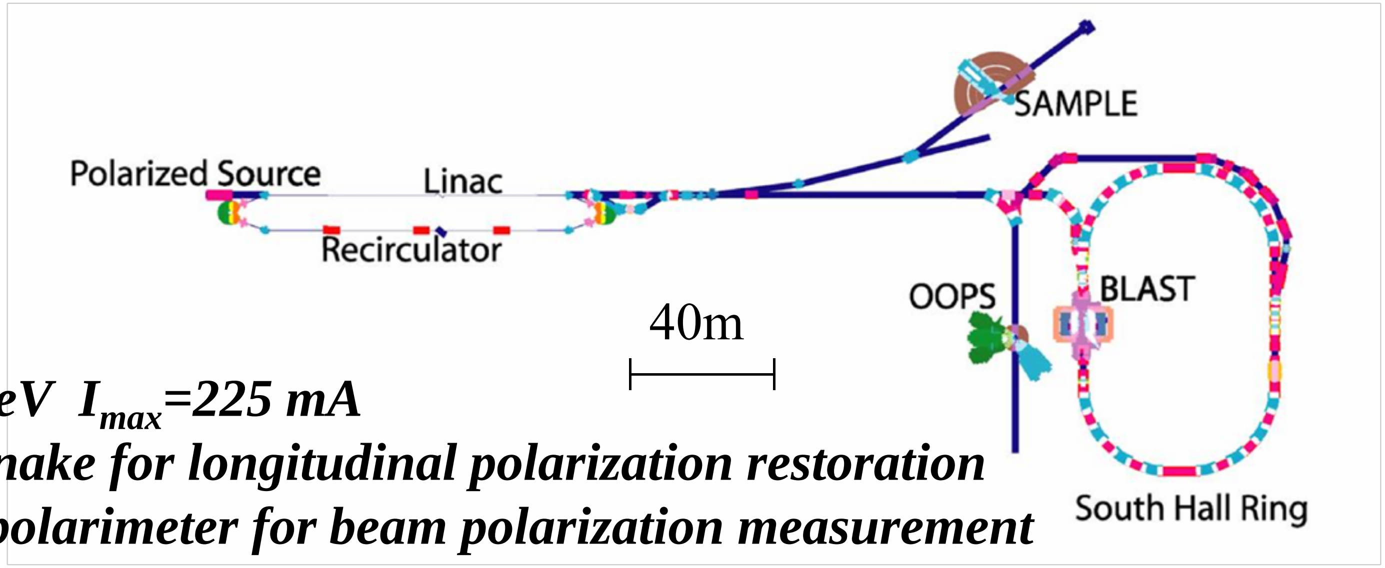




- Super-ratio

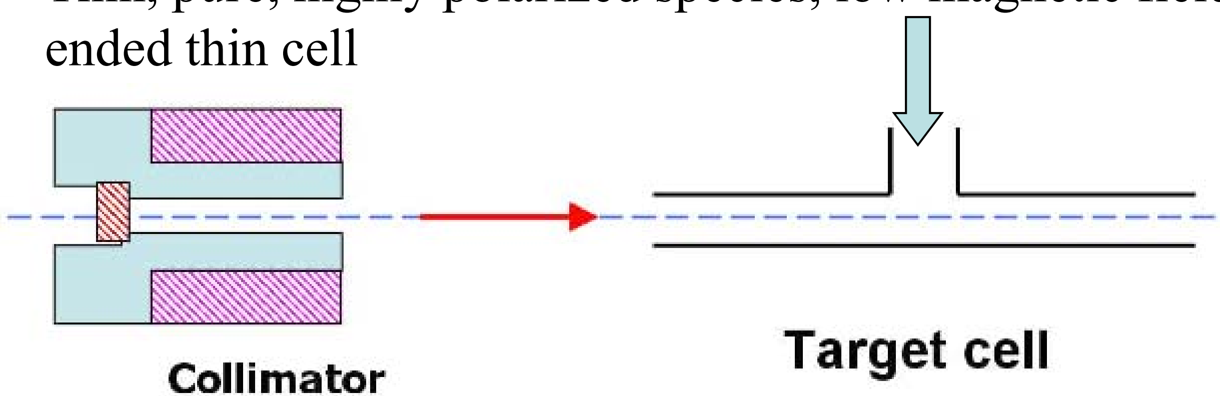
$$R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p / G_M^p}{a_2 - b_2 \cdot G_E^p / G_M^p}$$

The BLAST Experiment

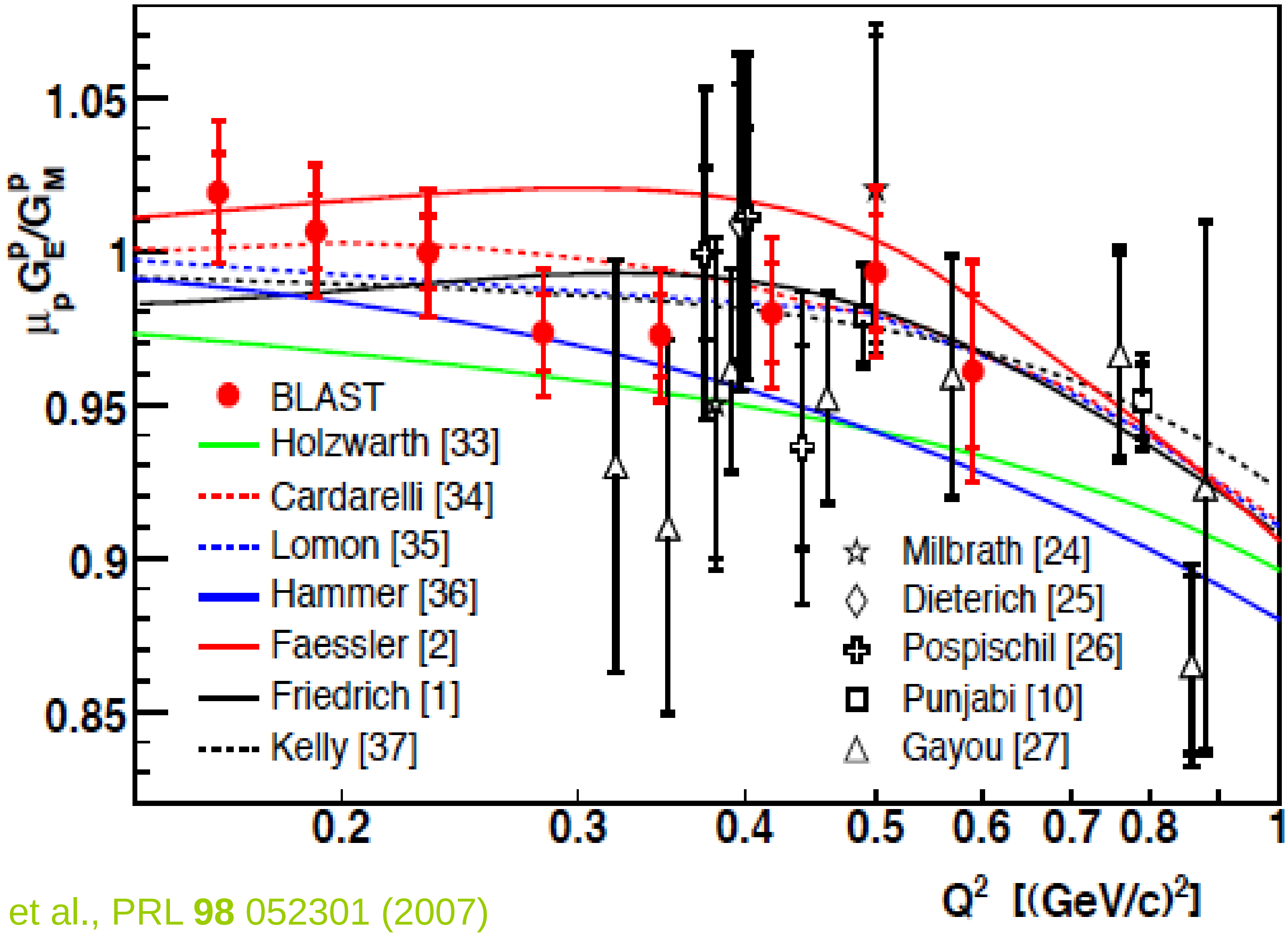


E_0=850 MeV I_{max}=225 mA
Siberian snake for longitudinal polarization restoration
Compton polarimeter for beam polarization measurement

- ***BLAST: internal target physics program***
  - ***Nucleon electromagnetic structure*** ***This talk***
  - Spin structure of few nucleon system,…….
  - Thin, pure, highly polarized species, low magnetic field, open-ended thin cell

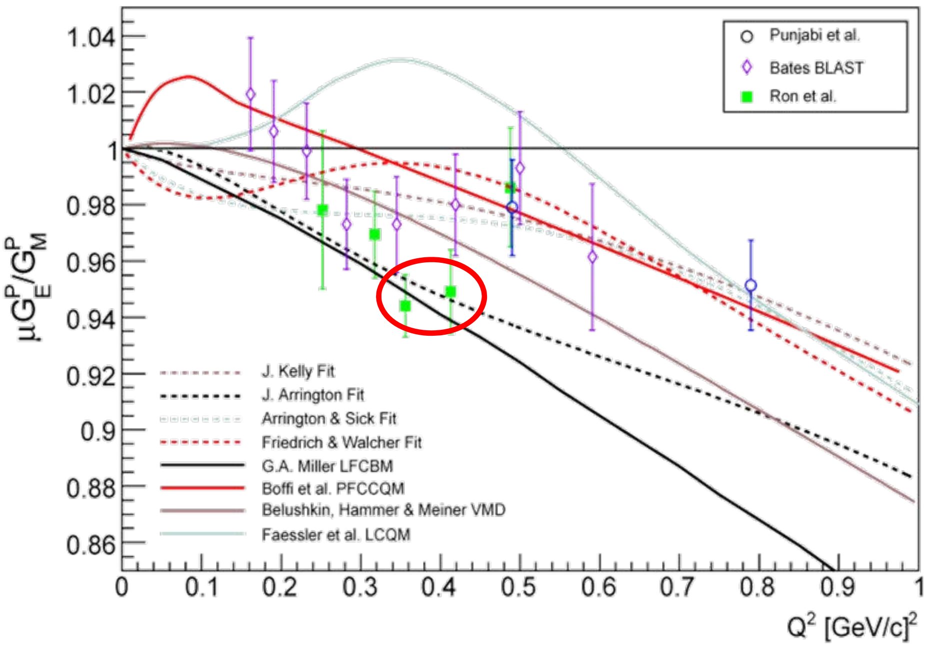


Results – G_E^p / G_M^p



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

Proton FFs at Low Q^2

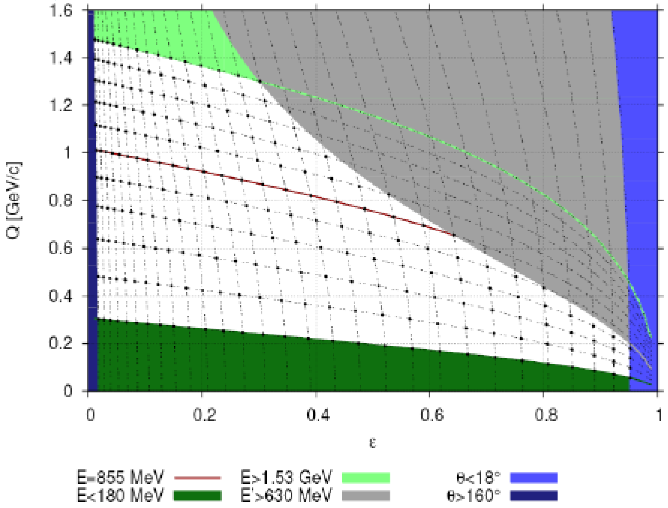


- Bates **BLAST** result consistent with 1.

Crawford et al., *Phys. Rev. Lett* 98 052301 (2007)

- Substantial deviation from unity is observed in **LEDEX** (Ron et al.).
- Both data inconsistent with F&W fit.
- New dedicated experiment **E08-007**.

- Complementary to the high precision XS measurement at **Mainz (Q^2~ 0.1 – 2 GeV^2)**.



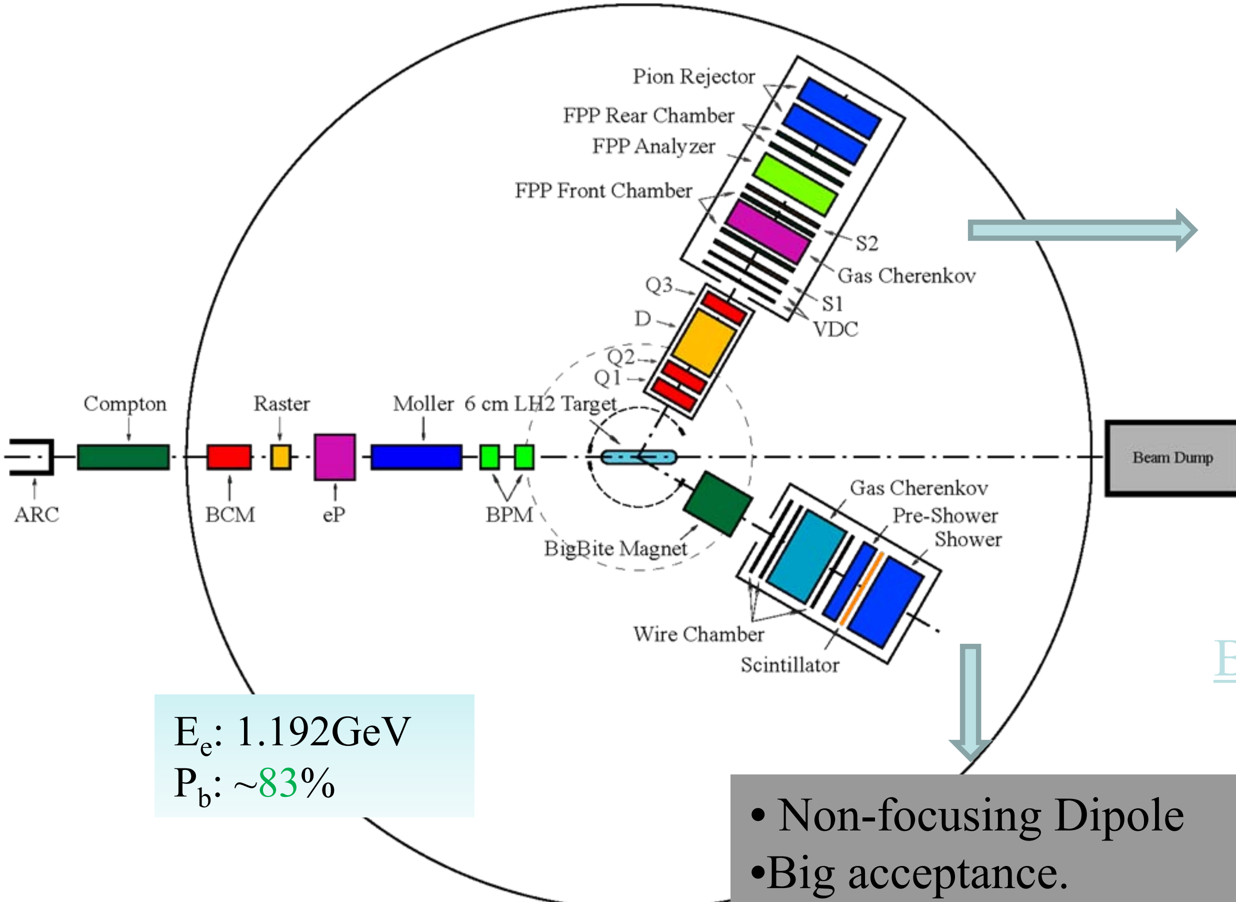
- strange form factors through PV

$A^{PV} + G_{E,M}^{p,n\gamma} + G_A^{pZ}$ (calculated) --> $G_{E,M}^{s}$

- proton Zemach radius and hydrogen hyperfine splitting

$$\Delta_Z = -2\alpha Z \frac{m_e m_p}{m_e + m_p} r_Z, \quad r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[\frac{\mu_N}{\mu_p} G_E(Q^2) G_M(Q^2) - 1\right]$$

Experimental Setup



LHRS

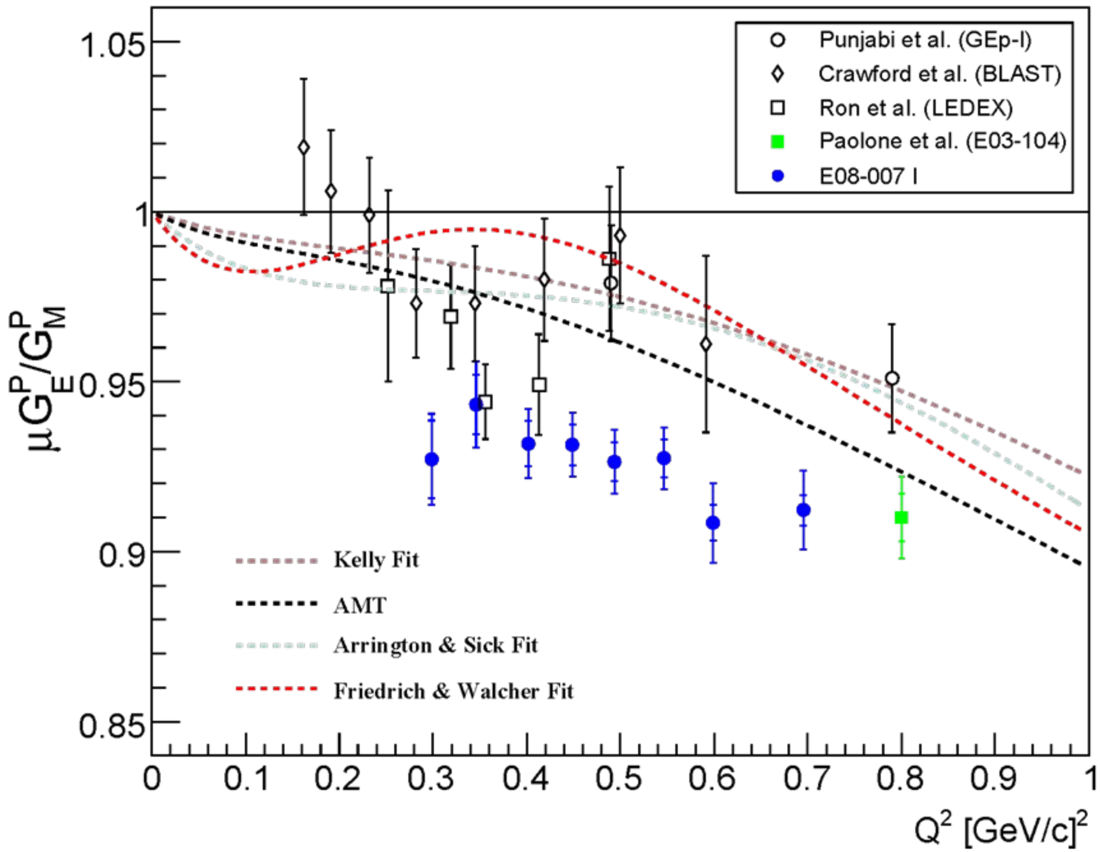
- $\Delta p/p0$: $\pm$ 4.5% ,
- out-of-plane: $\pm$ 60 mrad
- in-plane: $\pm$ 30 mrad
- $\Delta\Omega$: 6.7msr
- QQDQ
- Dipole bending angle 45^o
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

E_e: 1.192GeV
P_b: ~83%

BigBite

- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - $\Delta\Omega$: 96msr
- PS + Scint. + SH

E08-007 Results

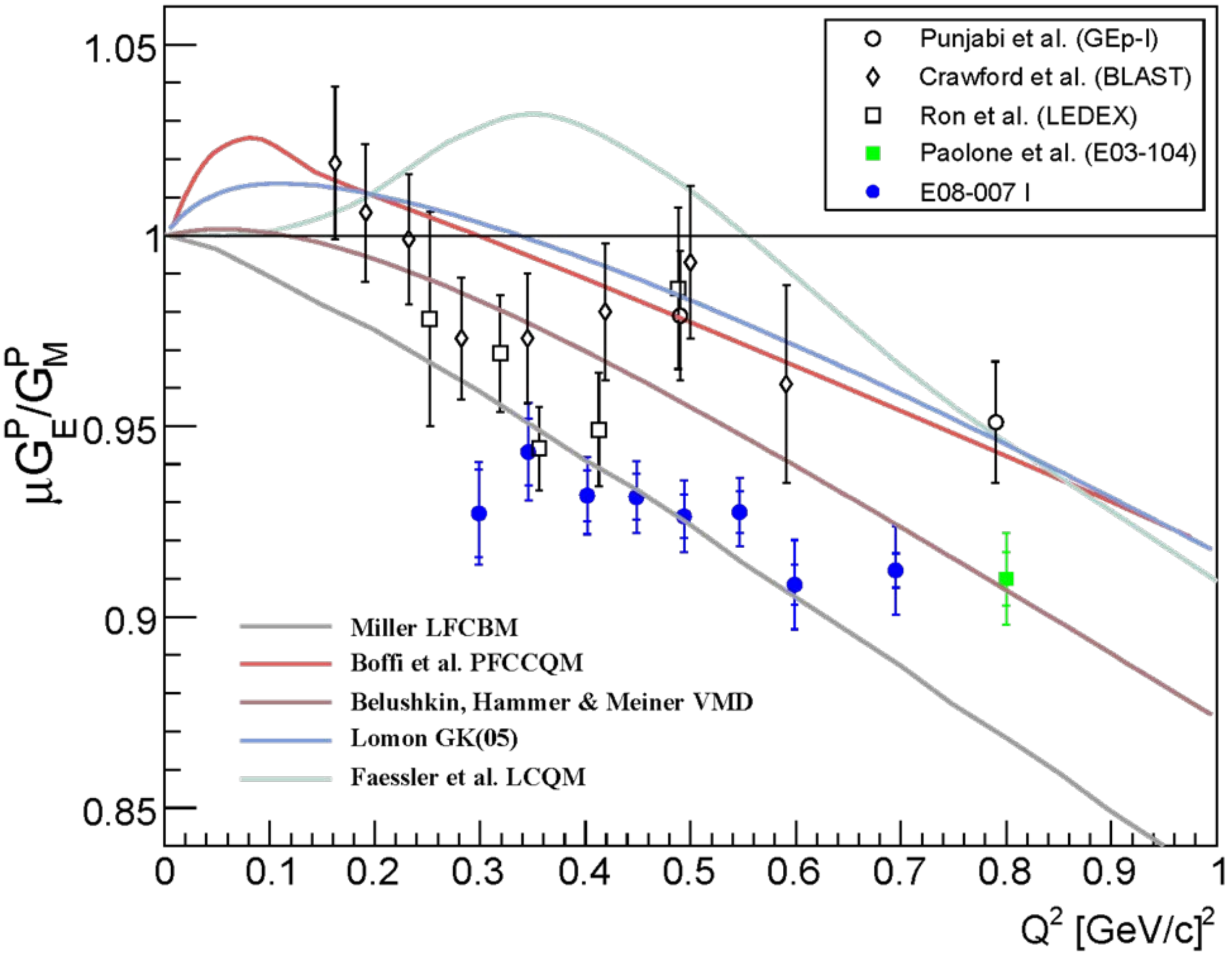


- Agreement with independent analysis of Paolone *et al.* at 0.8 GeV^2.
- Slow decrease with Q^2. A few percent below typical expectations.
- No obvious indication of "Structure", inconsistent with F&W fit.
- No obvious trend to rise quickly to unity at the lowest Q^2 point.

LEDEX : preliminary reanalysis lowers into agreement.
GEp-I reanalysis at 0.5 GeV^2 is underway, 0.8 GeV^2 to be investigated.
BLAST: origin of difference needs to be investigated.

Zhan et al, to be submitted

Comparison with Models



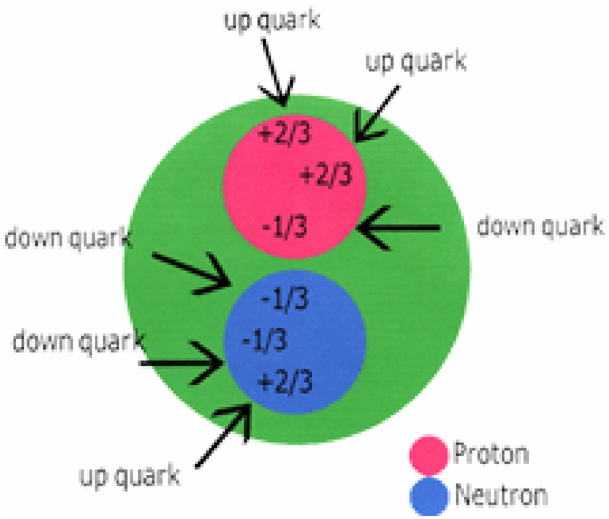
New Mainz data, new JLab experiment

$$Q^2 \to 0$$

Crucial for proton charge radius

Recent surprising results from PSI muonic hydrogen atom Lamb shift measurement of proton charge radius

No Stable Free Neutron Target



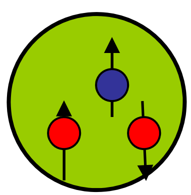
$$d(e,e')d \qquad d(e,e'n)$$

$$\vec{d}(\vec{e},e'n) \qquad d(\vec{e},e'\vec{n})$$

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

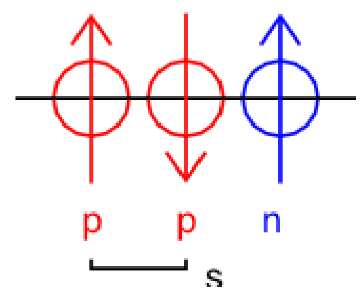
Polarized ^{3}He

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



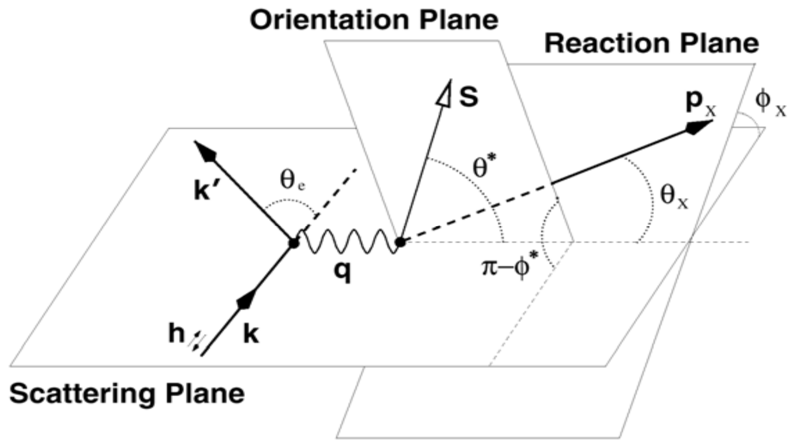
About 88%

- Unpolarized e-d elastic and quasielastic scattering
- Spin-dependent quasielastic scattering from deuteron
- Spin-dependent quasielastic scattering from ^{3}He



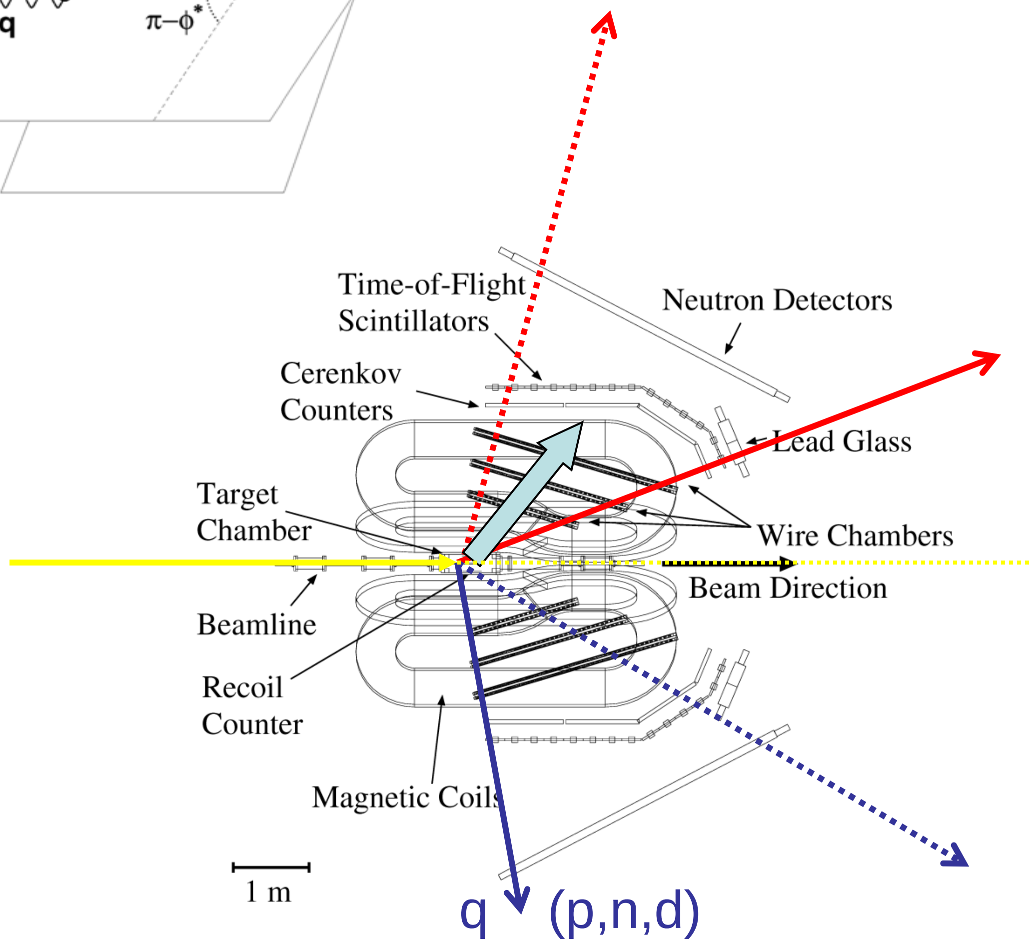
Spin-dependent quasifree Electron Scattering from vector polarized deuteron

$$\vec{d}(\vec{e},e'n)$$



$$\frac{d\sigma^h}{de'd\Omega_e d\Omega_N} = \Sigma + \mathbf{h}\Delta$$

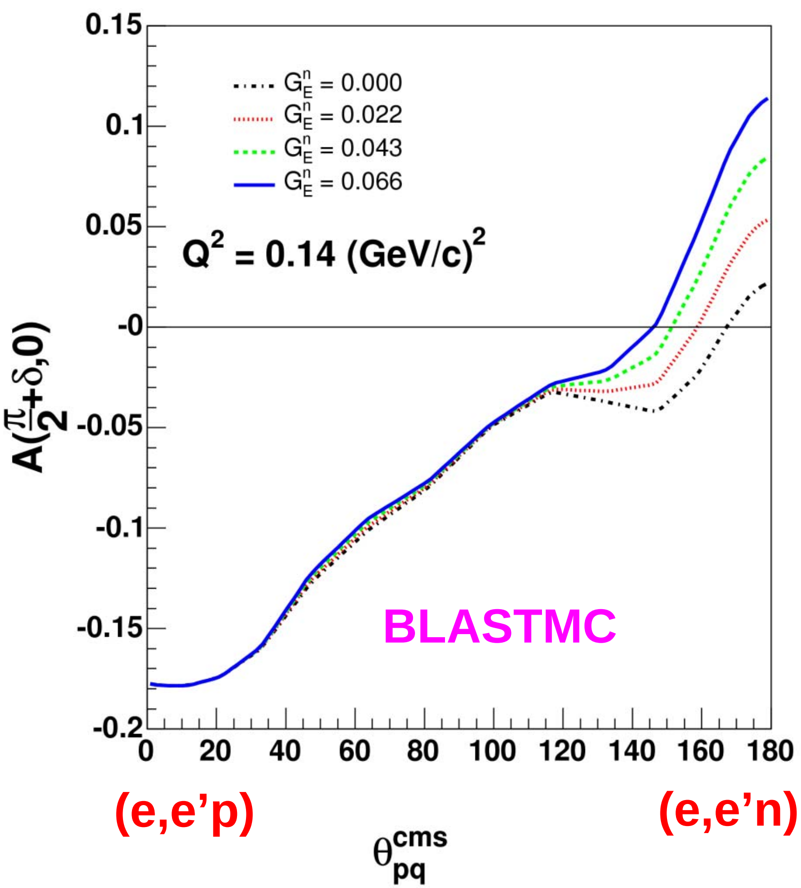
$$A_{x,y,z} = p_e \cdot p_T \frac{\Delta}{\Sigma}$$



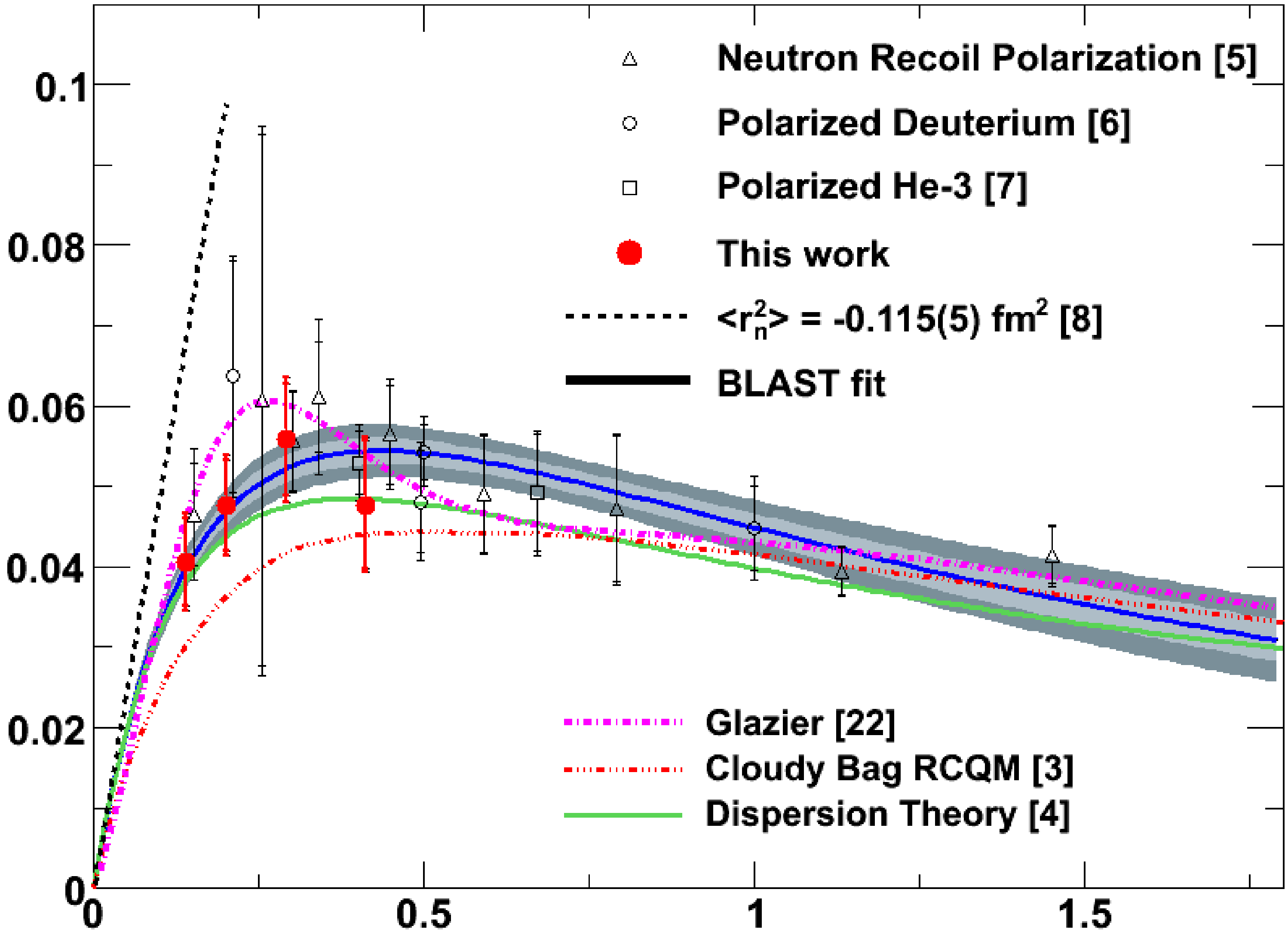
Extraction of G_E^n

$$A_{ed}^{V} = \frac{a\,G_M^{n\,2}\cos\theta^* + b\,G_E^n G_M^n \sin\theta^*\cos\phi^*}{c\,G_E^{n\,2} + G_M^{n\,2}} \approx a\cos\theta^* + b\,\frac{G_E^n}{G_M^n}\sin\theta^*\cos\phi^*$$

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

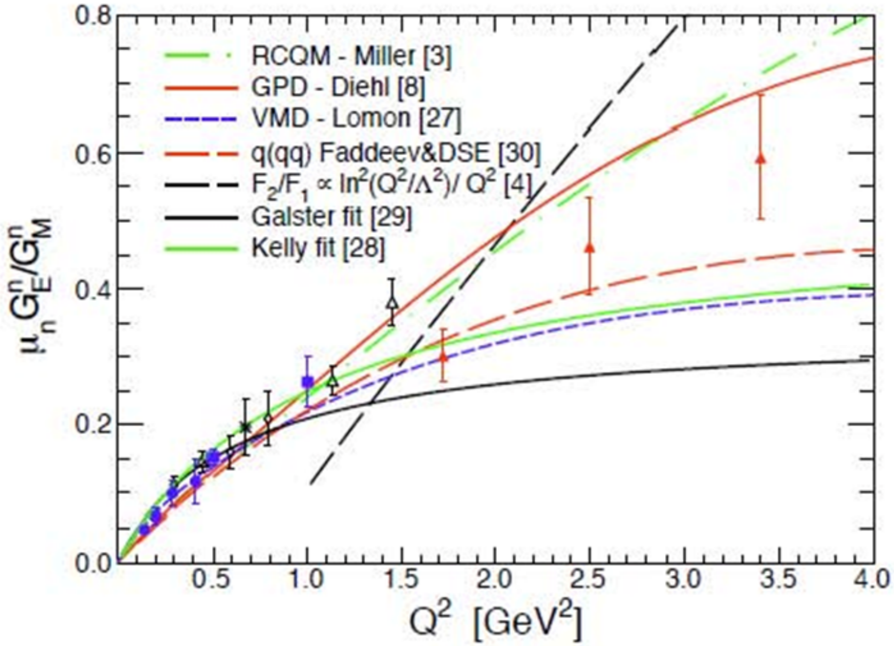


The BLAST results on neutron electric form factors



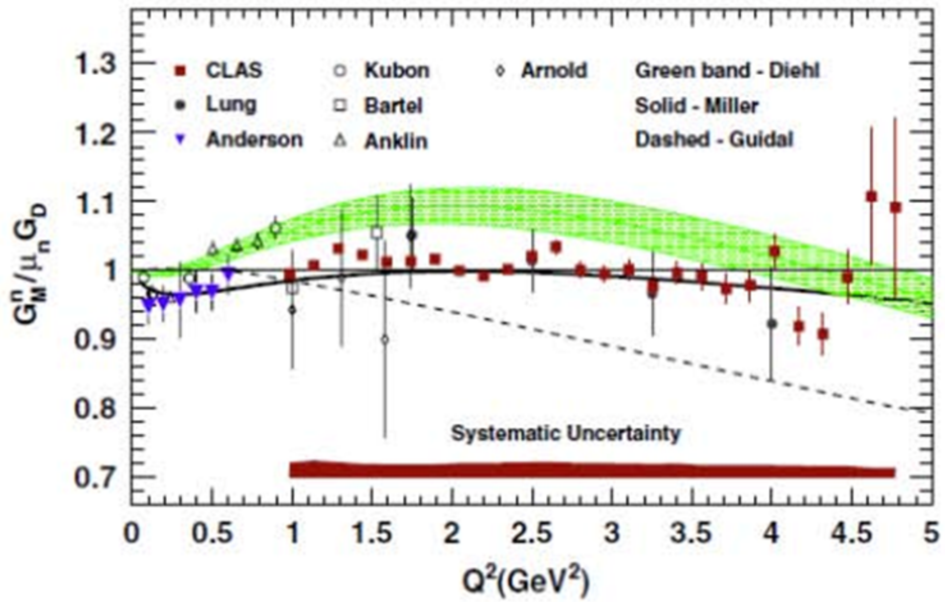
Geis et al., Phys. Rev. Lett. 101, 042501 (2008)

Neutron form factor data compared to theoretical estimates



Preliminary, Riordan *et al.*

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

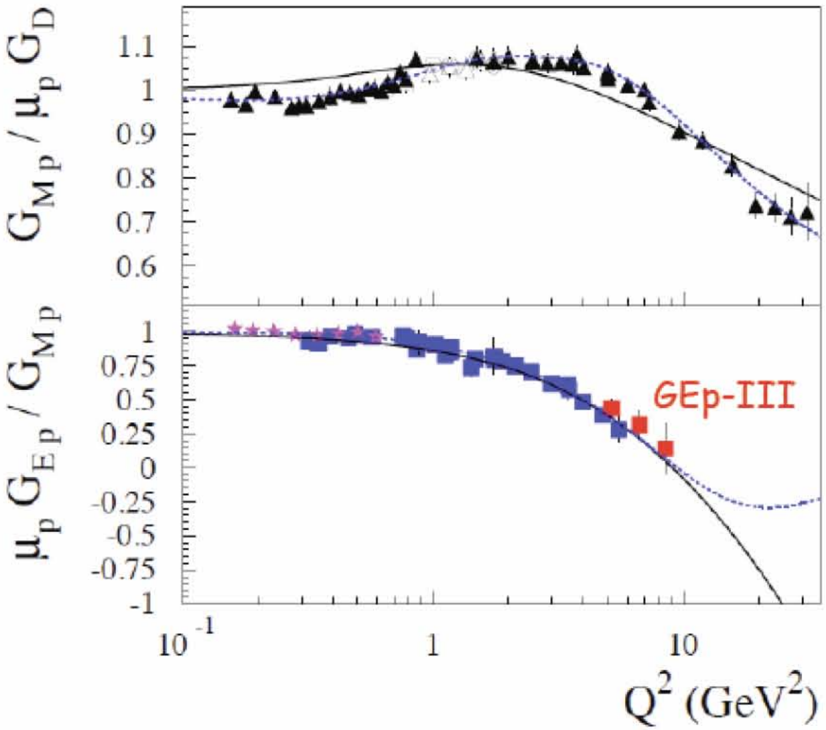


Lachniet *et al.*, Phys. Rev. Lett. 102 192001 (2009).

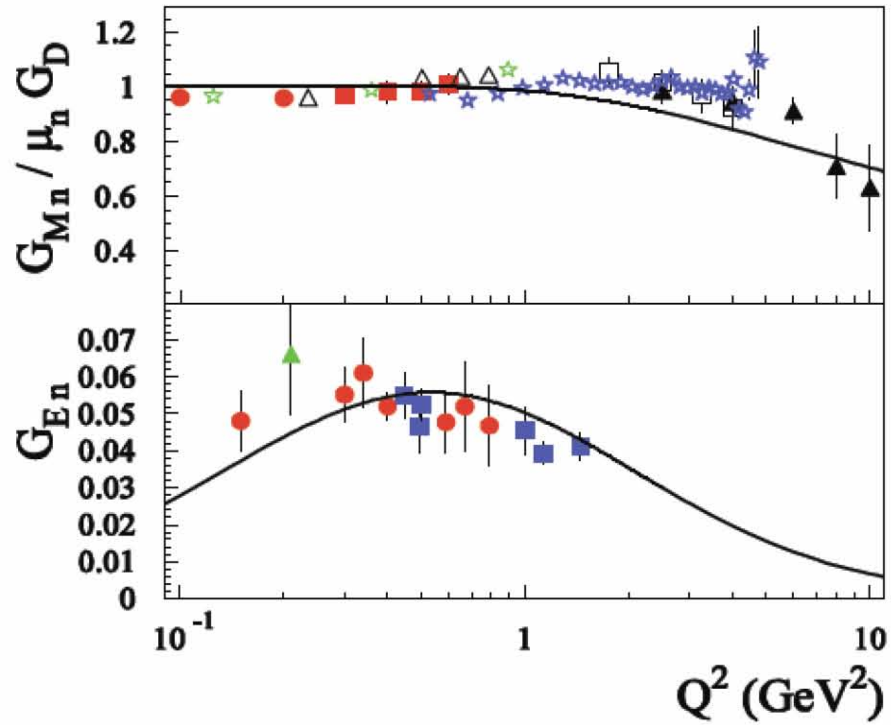
$$\frac{d\,(e, e'n)}{d\,(e, e'p)}$$

GPD parametrization of Nucleon FF

PROTON



NEUTRON



Guidal *et al.*, (2005)

3-parameter fit

modified Regge GPD parameterization:

1 : Regge slope -> proton Dirac (Pauli) radius

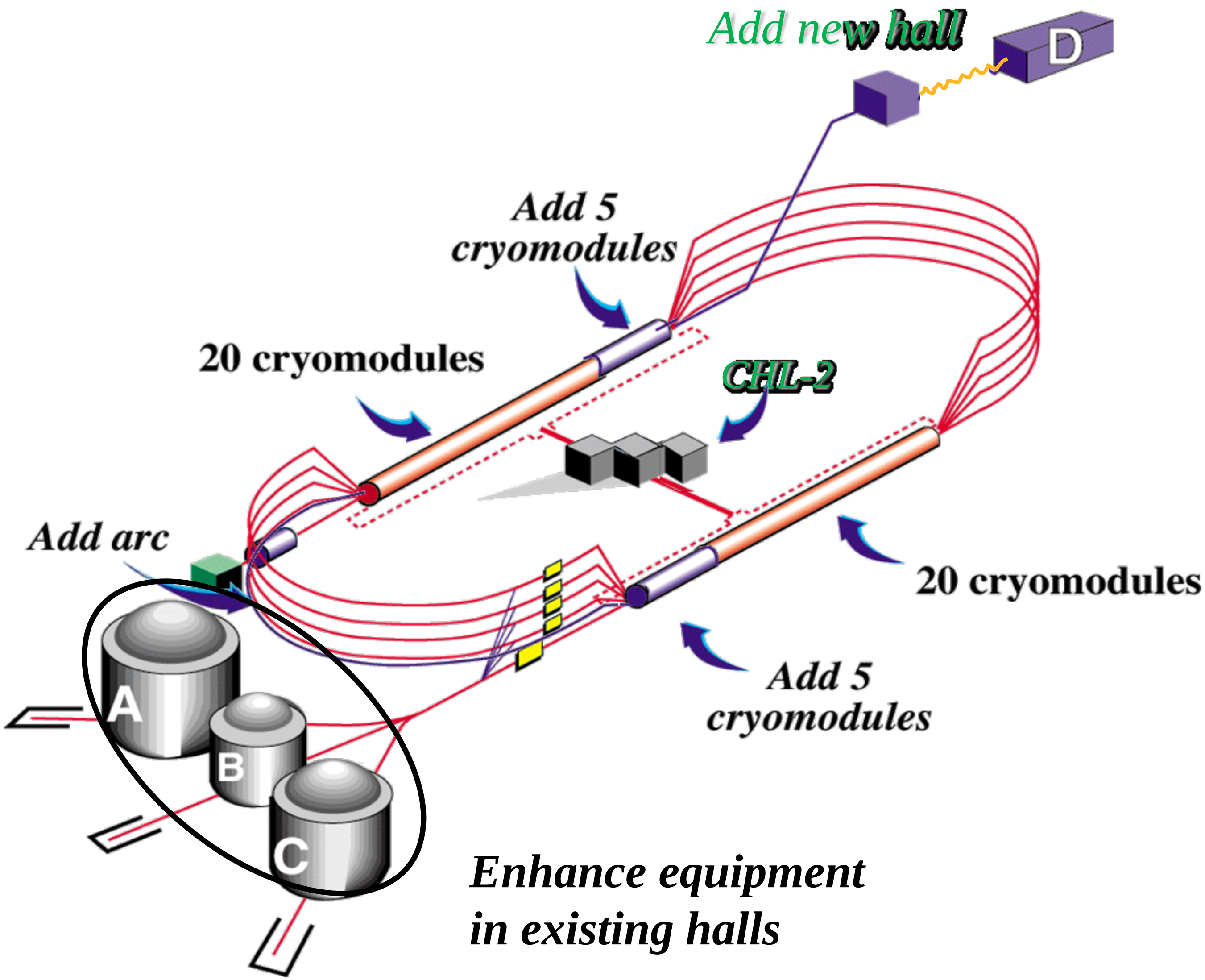
2, 3 : large x behavior of GPD E^u, E^d -> large Q^2 behavior of F_{2p}, F_{2n}

• Form factors constrain GPDs through sum rules: 0th moments of vector (H) and tensor(E) GPDs equal e.m. form factors

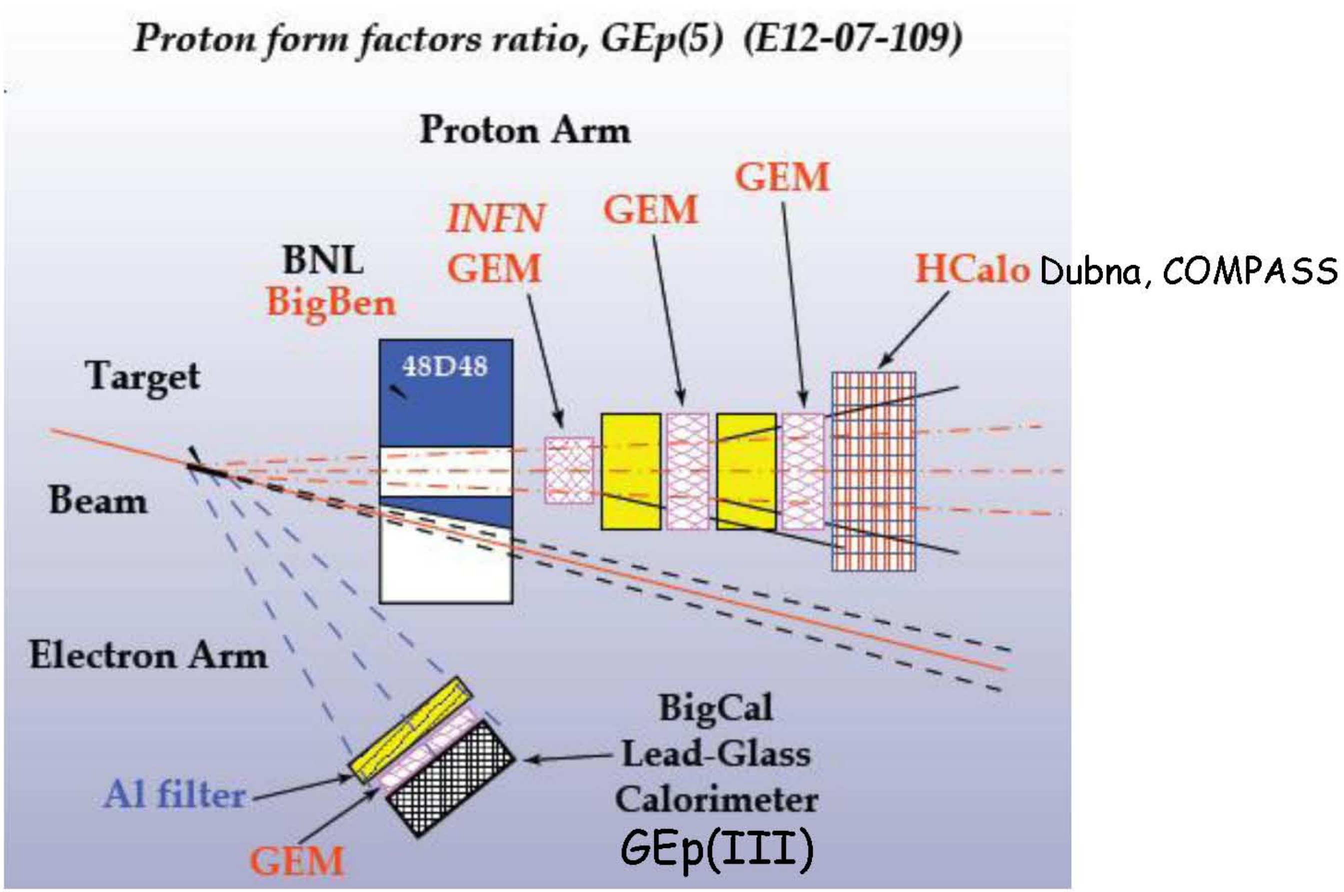
$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

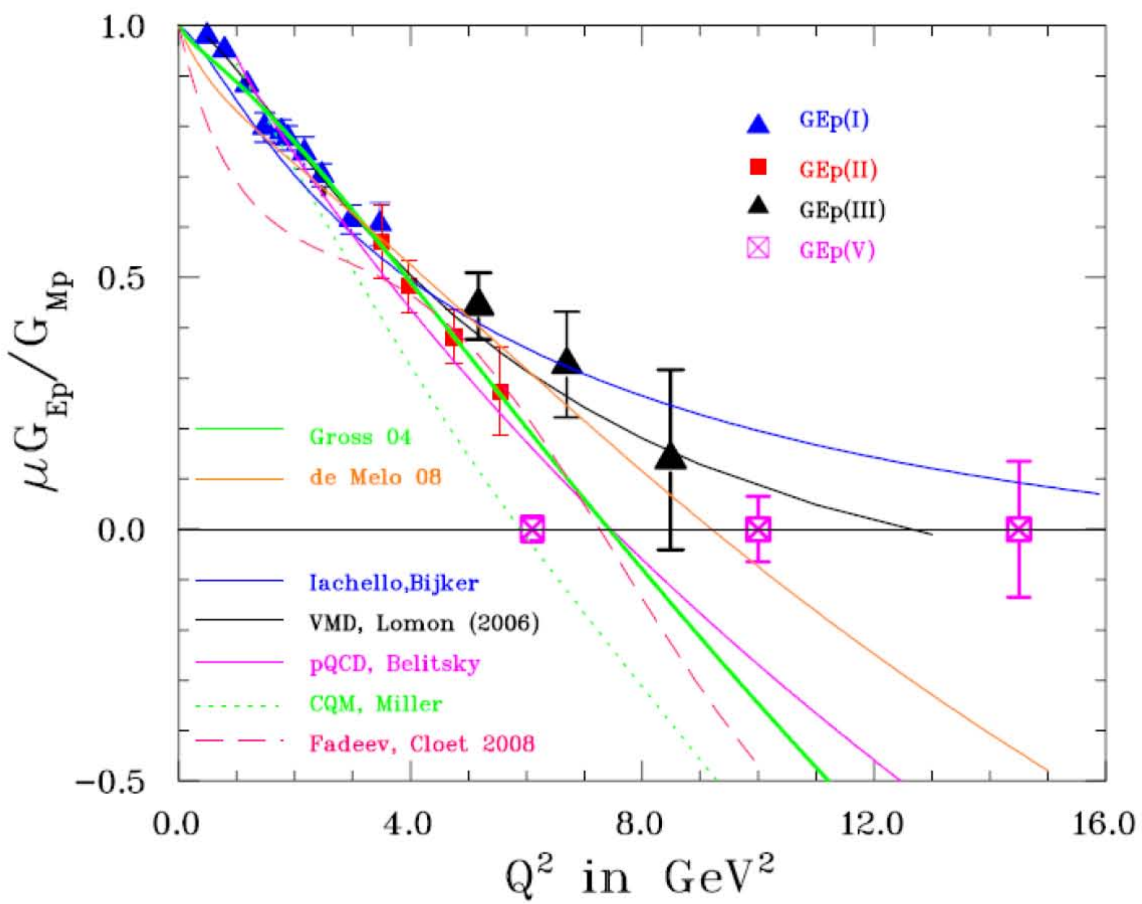
JLab Upgrade to 12 GeV



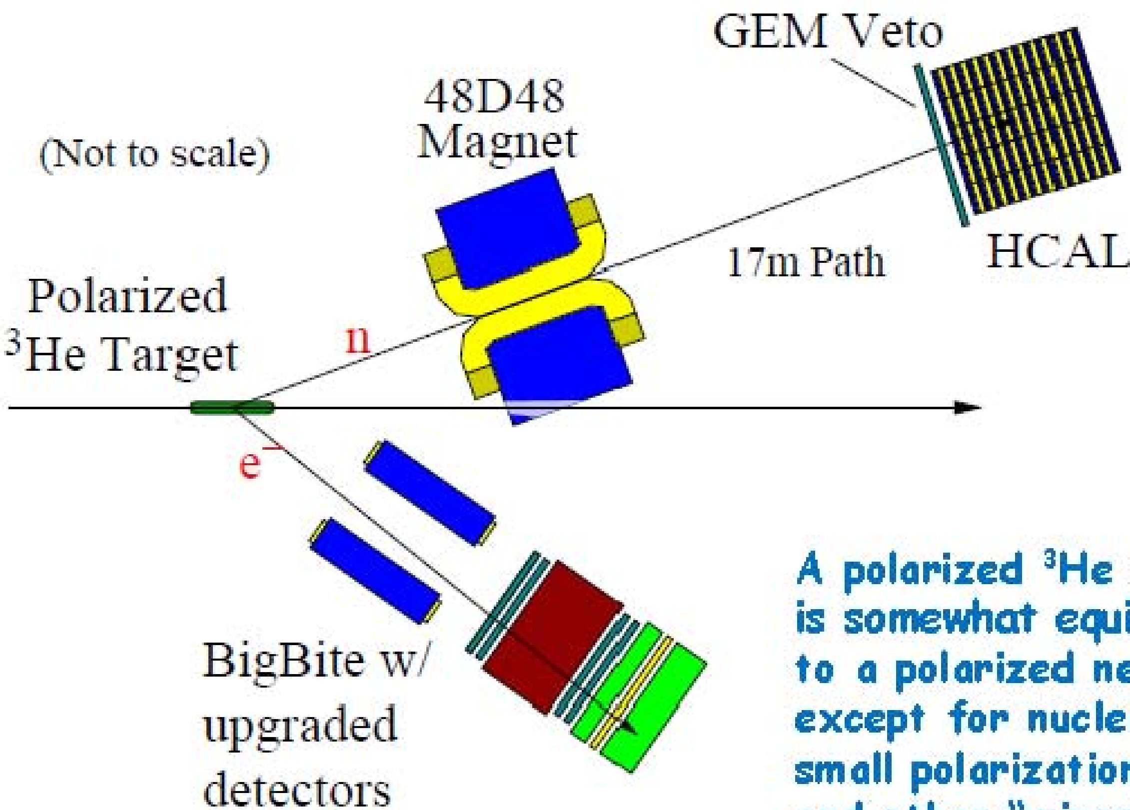
The solution: the SBS in Hall A, Gep(V)



Anticipated statistical uncertainties from original GEp(5) proposal with 60 days of beam. Actual time may be shorter, currently not defined; statistical uncert. larger!

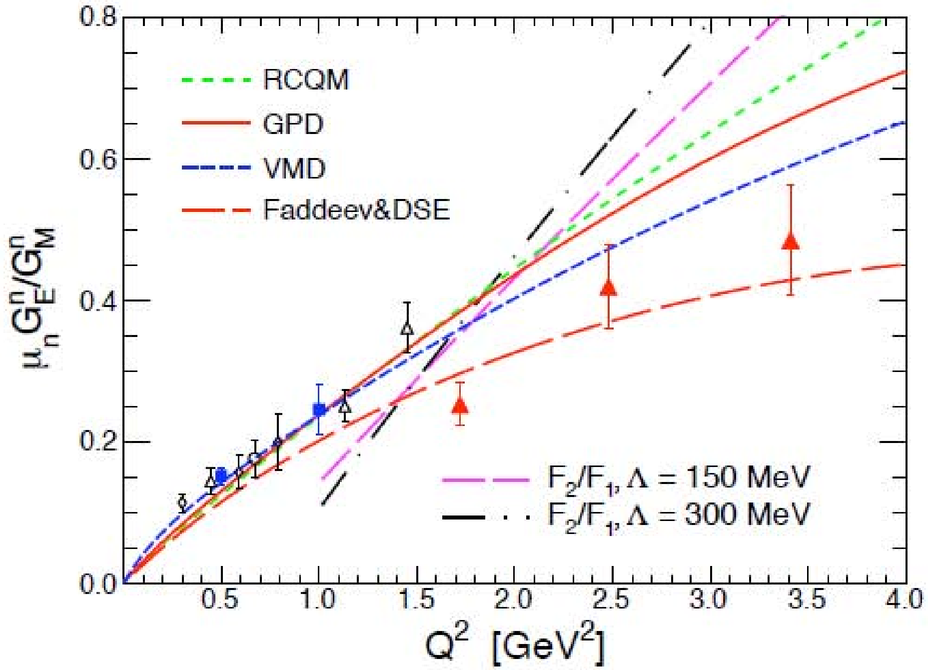


Setup for G_{En}/G_{Mn}, approved for Q^2=5, 6.8 and 10.2 GeV^2

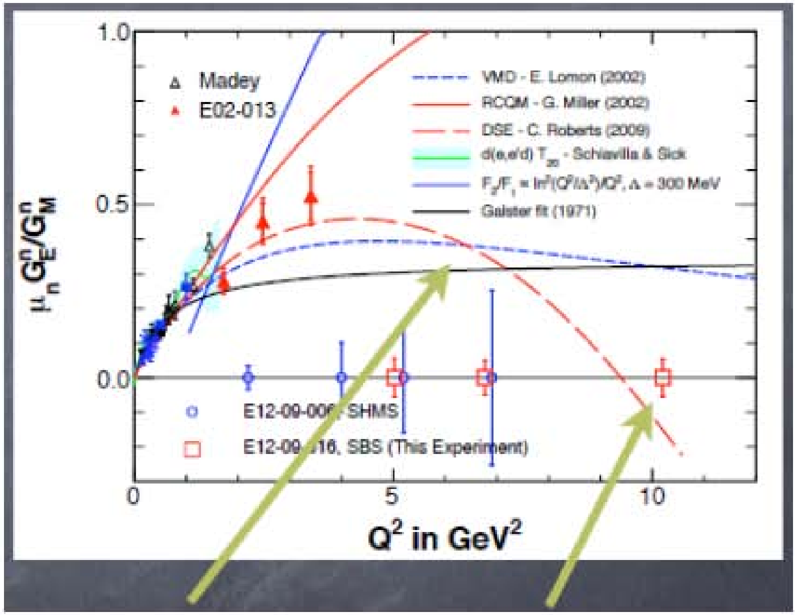


A polarized ^{3}He target
is somewhat equivalent
to a polarized neutron target,
except for nuclear corrections,
small polarization of protons
and other "minor" problems.

Current and projected situation for the neutron electric form factor



Red filled triangles: GEn(I) data to be published.



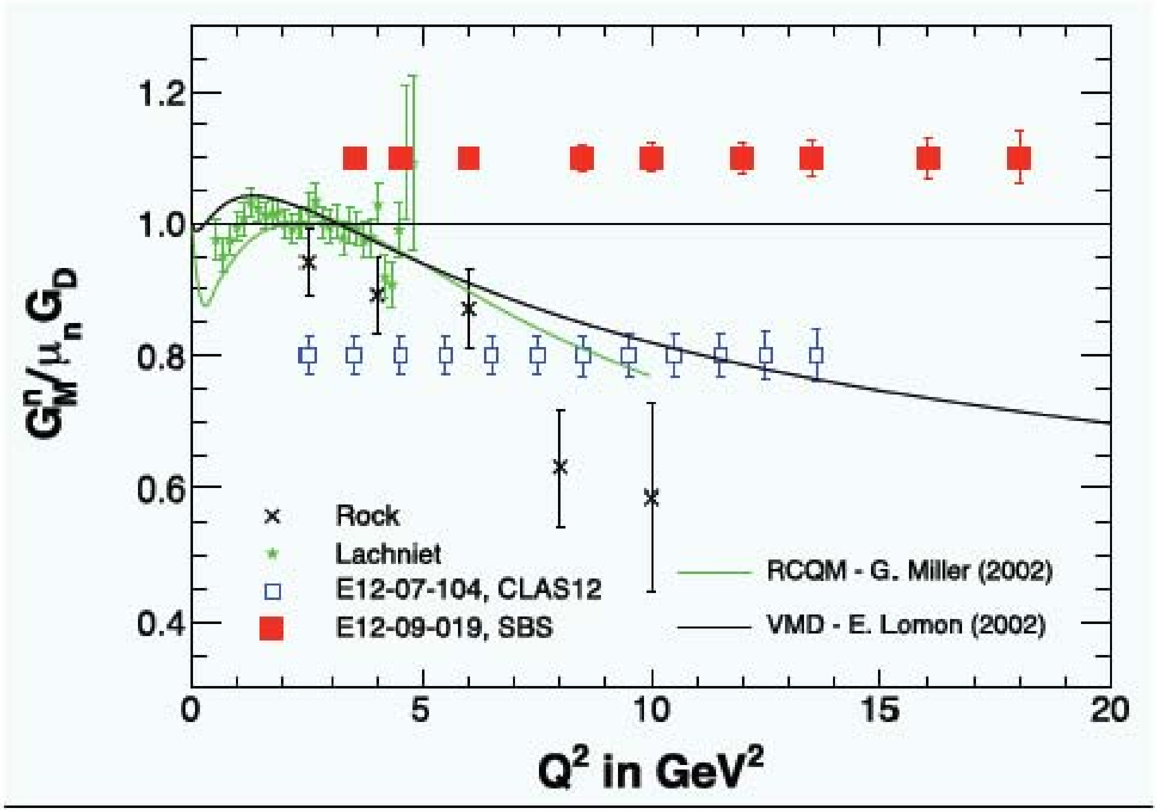
Arrows illustrating the point that one needs to go to 10 GeV^2 to distinguish between various models.

Fadeev, Dyson-Schwinger, Cloet

The two approved GMn experiments

In Hall A with the SBS, in Hall C with CLAS12

G_{Mn} by the ratio of the quasi elastic d(e,e'n) to d(e,e'p)the cross sections method, and to Q^2 values of 18 GeV^2.



Summary and outlook

- New data on nucleon electromagnetic form factors using novel experimental technique
- Surprise on proton charge radius from muonic hydrogen atom Lamb shift measurement, new precision measurement from electron scattering is **a MUST**
- New form factor data improve constraints of theoretical models and test lattice QCD results in the near future
- New data at higher Q^2 will become available from 12-GeV upgrade at JLab
- Better theoretical understanding of the nucleon electromagnetic structure from QCD is important

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