Nucleon Electromagnetic Form Factors: Recent Results

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[Gep-2γ (5C Wed 3pm)]

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[π^0 prod. (2E Mon 4:30pm)]

Edward Brash

The Science Problem

Quantum Chromodynamics (QCD) in the confinement regime:

How does it work?

- What do we know?

QCD works in the perturbative (weak) regime

Many experimental tests led to this conclusion, example:

- Proton is not point-like; Elastic electron scattering (Nobel Prize: Hofstadter, 1961).
- Quarks and gluons/Partons are the constituents; Deep Inelastic electron Scattering (Nobel prize: Friedman, Kendall and Taylor, 1990).

Theory celebrated recently

Asymptotic freedom (Nobel prize: Gross, Politzer and Wilczek, 2004),

but

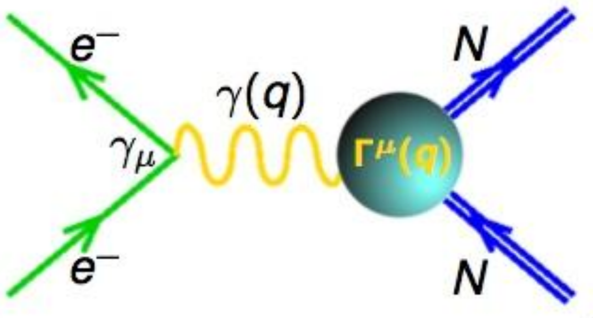
Quantitative QCD description of the nucleon's properties
(i.e. understanding of the confinement regime) remains a puzzle!

Elastic EM Nucleon Form Factors

- Fundamental to our understanding of hadronic structure
  - At low Q^2 (larger distance), they shed information on the pion cloud
  - At intermediate/large Q^2 (shorter distance), they contain information on the quark and gluon structure of the nucleon
- At JLab energies, we gain knowledge about the non-perturbative structure of the nucleon
- Together with other observables (in DIS, SIDIS, DVCS, RCS, etc.), we develop a greater understanding of the nucleon's rich internal structure, or

"The Adventures of an Incurable Optimist"

Elastic Form Factors



(Born Term)

Nucleon current operator (Dirac & Pauli)

$$\Gamma^\mu(q) = \gamma^\mu F_1(q^2) + \frac{i}{2M_N}\sigma^{\mu\nu} q_\nu F_2(q^2)$$

$F_1(Q^2)$: non spin-flip Dirac form factor

$F_2(Q^2)$: spin-flip Pauli form factor

$$F_1^p(0) = 1, \quad F_1^n(0) = 0$$
$$F_2^p(0) = \kappa_p, \quad F_2^n(0) = \kappa_n$$

Electric form factor: $G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$

Magnetic form factor: $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$

where $\tau = \frac{Q^2}{4M_p^2}$

- Details of nucleon substructure are in the Q^2 evolution of $F_1(Q^2)$ and $F_2(Q^2)$.

Proton Form Factor Data (pre-1998)

- Found to follow the dipole approximation (exponential charge/mag. distribution)

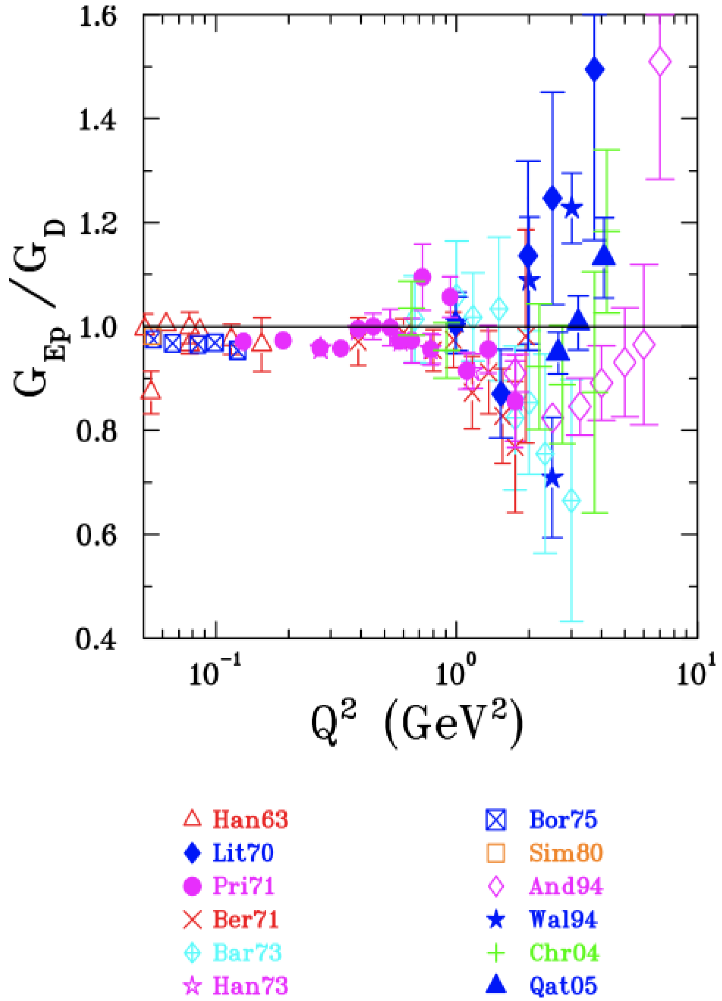
$$G_{E_p} \sim \frac{G_{M_p}}{\mu_p} \sim G_d = \frac{1}{\left(1 + \frac{Q^2}{0.71}\right)^2}$$

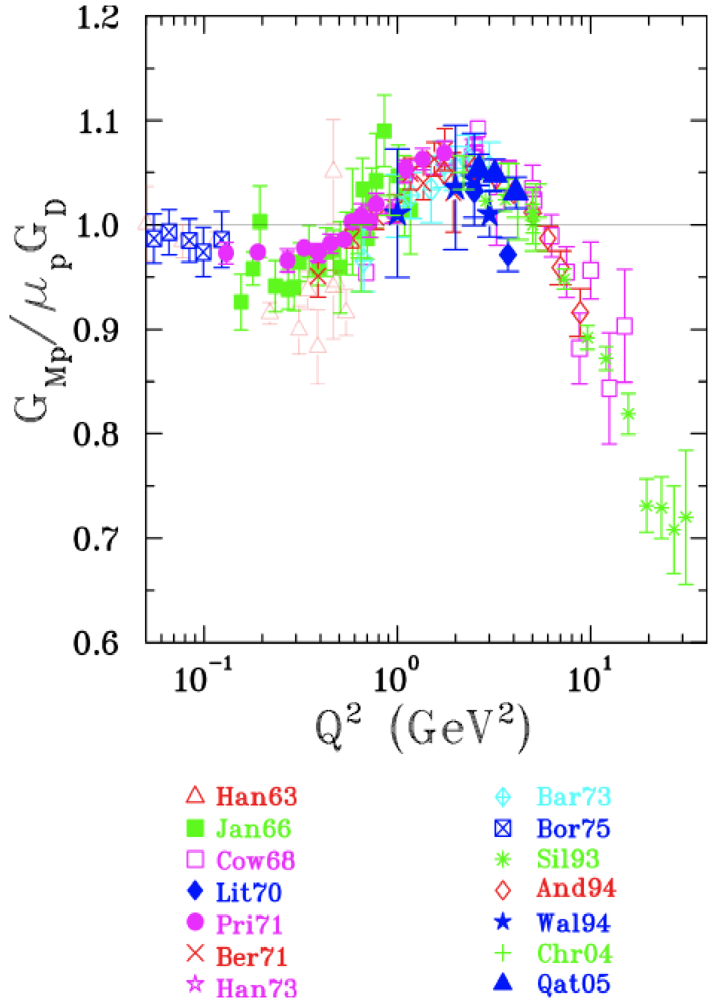
- G_{M_p} well measured with Rosenbluth separation, but not G_{E_p}

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{Mott}} \left[G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2)\right] \frac{1}{1+\tau}$$

with $\frac{1}{\epsilon} = 1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)$

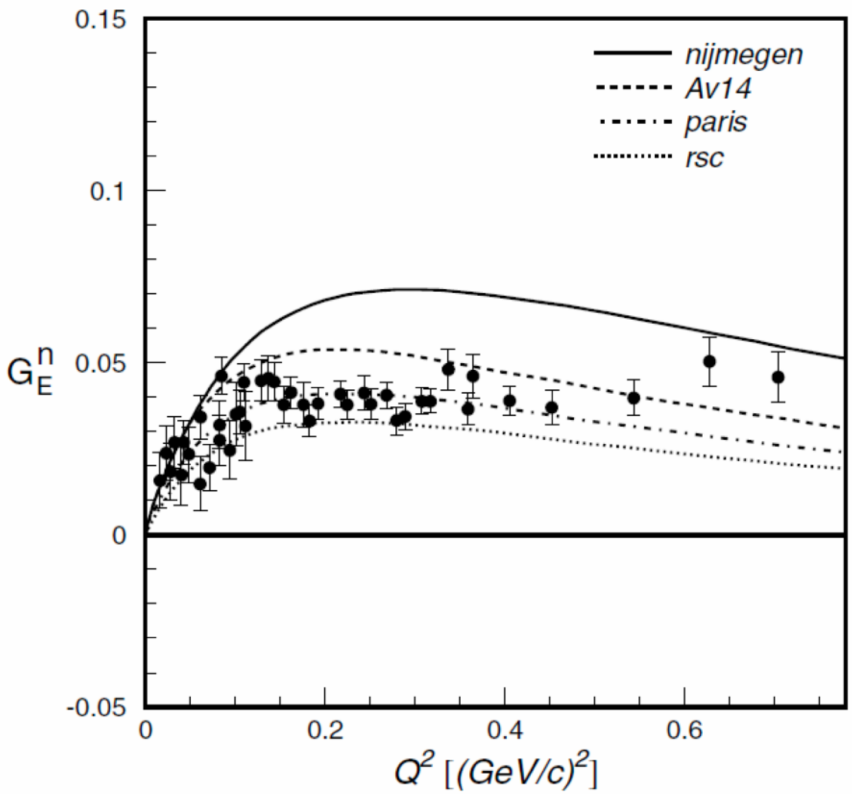
Summary of Rosenbluth Data

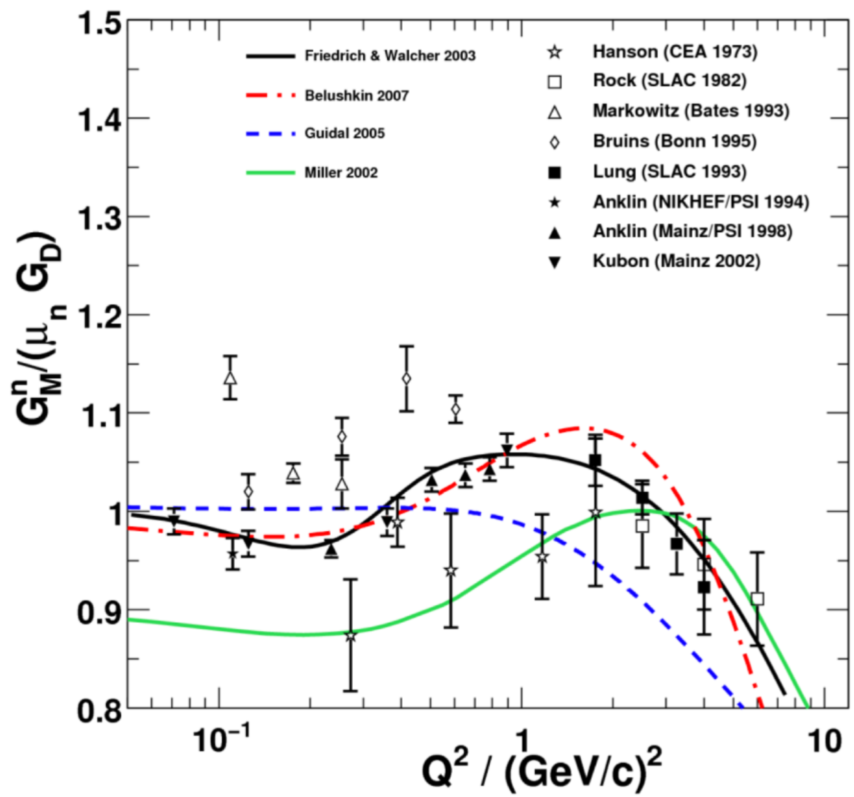




Neutron Form Factors

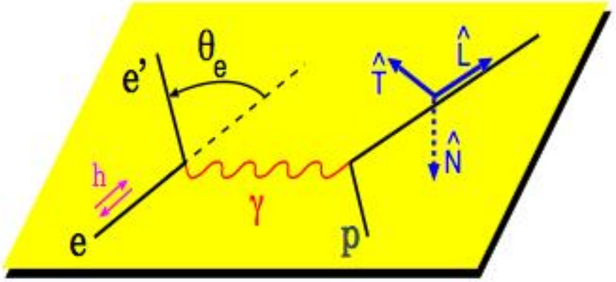
From elastic and quasi elastic electron-deuteron scattering cross sections





Recoil Polarization Method

• Elastic $\vec{e}p \to e\vec{p}$ (A. I. Akhiezer and M. P. Rekalo, Sov. J. Part. Nuc. **3**, (1974) 277; and Arnold, Carlson and Gross, Phys. Rev. **C23** (1981) 363):



$$P_n = 0$$

$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_{Ep}G_{Mp}\tan\frac{\theta_e}{2}$$

$$I_0 P_\ell = \frac{1}{M_p}(E_e + E_{e'})\sqrt{\tau(1+\tau)}G_{Mp}^2\tan^2\frac{\theta_e}{2}$$

$$I_0 = G_{Ep}^2 + \tau G_{Mp}^2\left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]$$

Relative Measurement:

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e + E_{e'})}{2M_p}\tan\left(\frac{\theta_e}{2}\right)$$

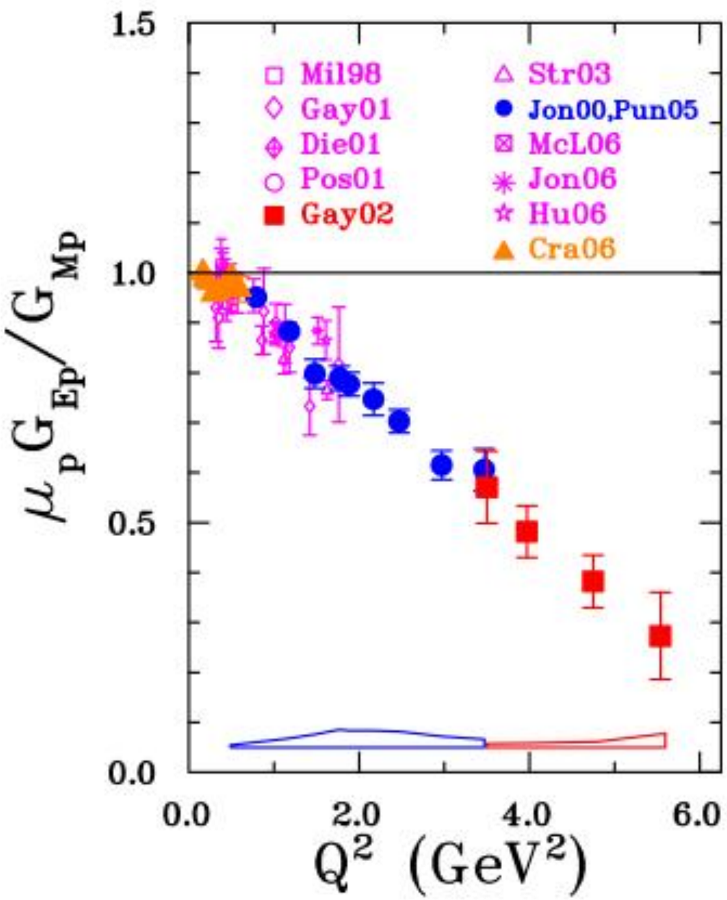
Gep-I and Gep-II at JLab

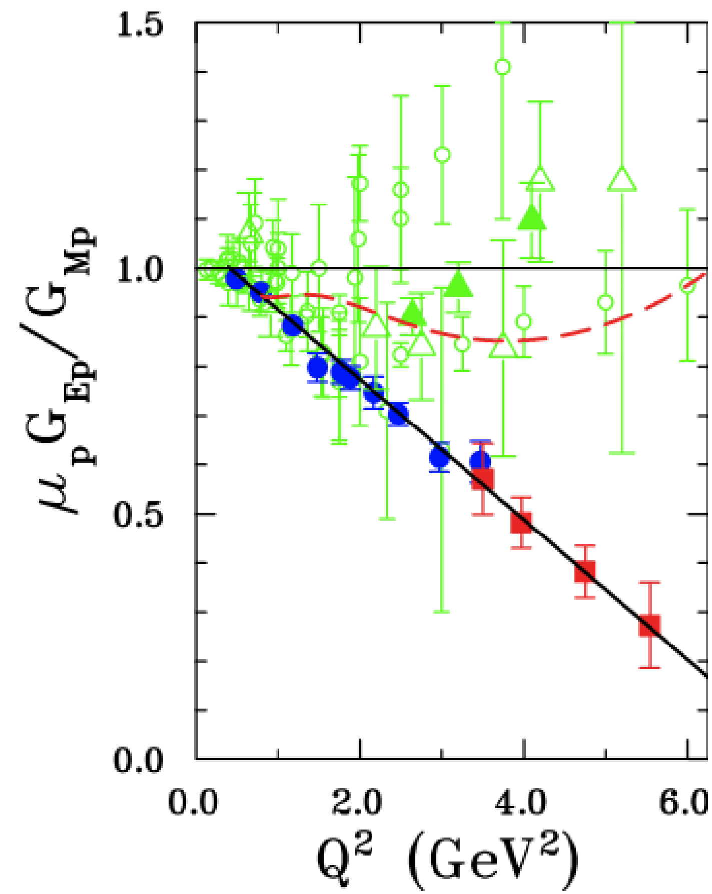
Famous Papers

M.K. Jones et al., Phys.Rev.Lett., 84 (2000) 1398 (G_{Ep}-I)

O. Gayou et al., Phys.Rev.Lett., 88 (2002) 092301. (G_{Ep}-II)

(932 total citations, 2 Ph.D.'s, 3 Masters, ~8 UG theses, several tenure track faculty and staff appointments)





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Theoretical Progress

- VMD-based models
  - Describe all four nucleon FF's well
  - Favour ratio reaching a constant value at intermediate Q^2
- rCQM
  - Show the importance of relativistic dymamics
- pQCD-inspired models
  - Predict logarithmic scaling behaviour of F_2/F_1 at intermediate Q^2 (Belitsky and Ji) -> related to quark OAM
- GPD-inspired models
  - Show a connection with OAM of the quarks in the nucleon
  - FF's provide important constraints on GPD's
  - Behaviour of G_{Ep}/G_{Mp} at intermediate Q^2 related to u/d ratio at small distances (Miller)
- Lattice QCD Models
  - Good progress already, and will get much better in the future

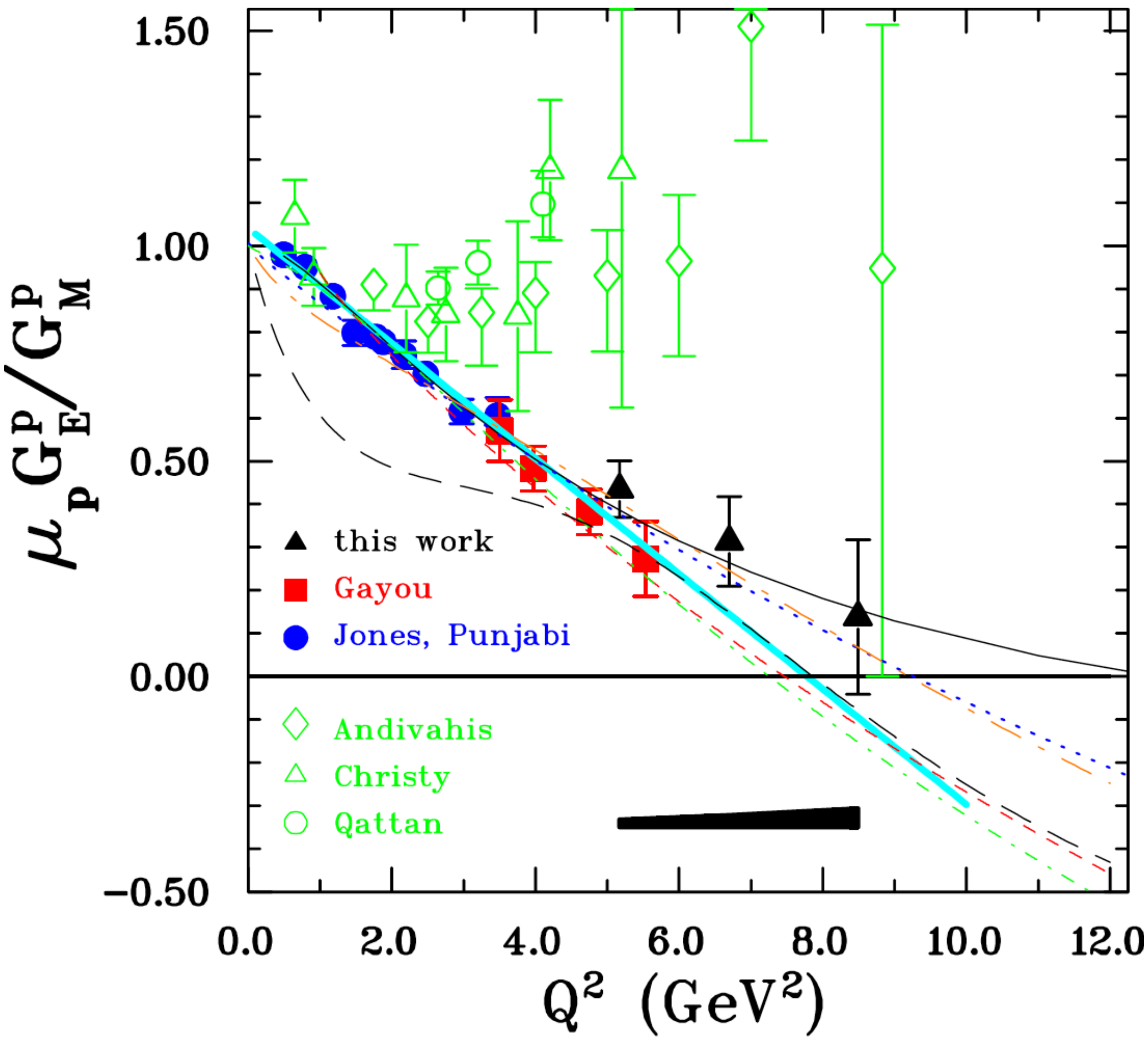
Open Questions

- How does the form factor ratio behave at large momentum transfers?
  - Severe test of theoretical models
    - What sort of scaling behaviour do we see, if any?
    - What is the asymptotic trend of the ratio?

G_{Ep}-III in Hall C

- What is the source of the discrepancy between the polarization transfer results and the Rosenbluth results?

G_{Ep}-2γ in Hall C



Theory curves:

Lomon 2002, 2006 (VMD)

Belitsky 2003 (pQCD scaling)

Guidal 2005 (GPD)

Gross 2006, 2008 (covariant spectator model)

de Melo 2009 (Bethe-Salpeter Amplitude)

Cloet 2009 (Dyson-Schwinger/Faddeev/quark-diquark)

Systematic Uncertainties

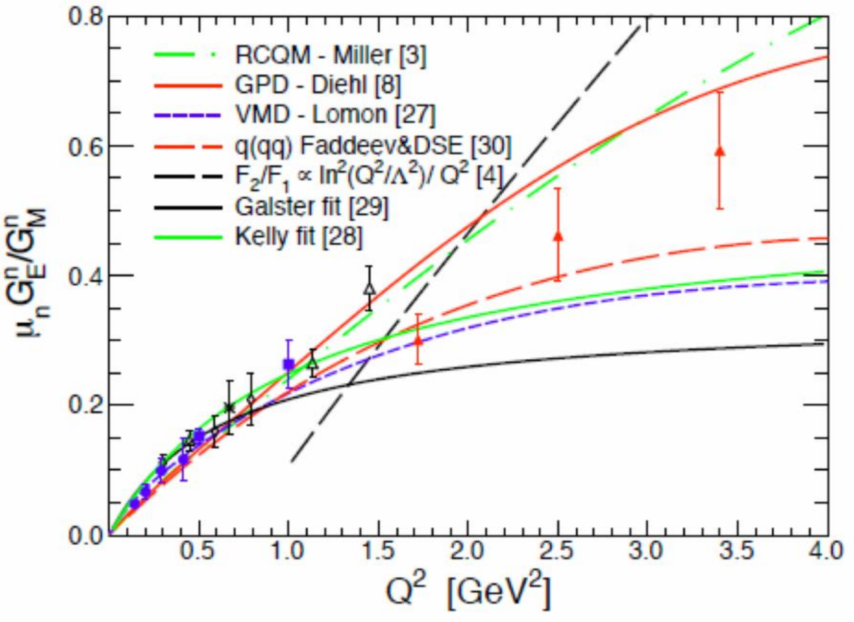
Q^2, GeV^2	5.2	6.7	8.5
ϕ_{bend} (±.5 mrad)	.0162	.0202	.0378
θ_{bend} (±2 mrad)	.0009	.0006	.0002
δ (±0.3%)	.0029	.0027	.0024
φ_{fpp} (±.14 mrad/sin(ϑ_{fpp}))	.0003	.0057	.0178
E_{beam} (±.05%)	.00027	.00009	.00025
False asym.	.0069	.0057	.0018
Background	.0015	.0013	.0130
Rad. Corr. (% of R)	0.05% ($\Delta R \approx$ -.0002)	0.12% ($\Delta R \approx$ -.0004)	0.13% ($\Delta R \approx$ -.0002)
Total ΔR_{syst}	.018	.022	.043

- Non-dispersive precession uncertainty dominates the systematic uncertainty in R
- **A_y, h cancel**, no uncertainty for R
- Standard radiative corrections (not applied) **negligible** compared to other uncertainties

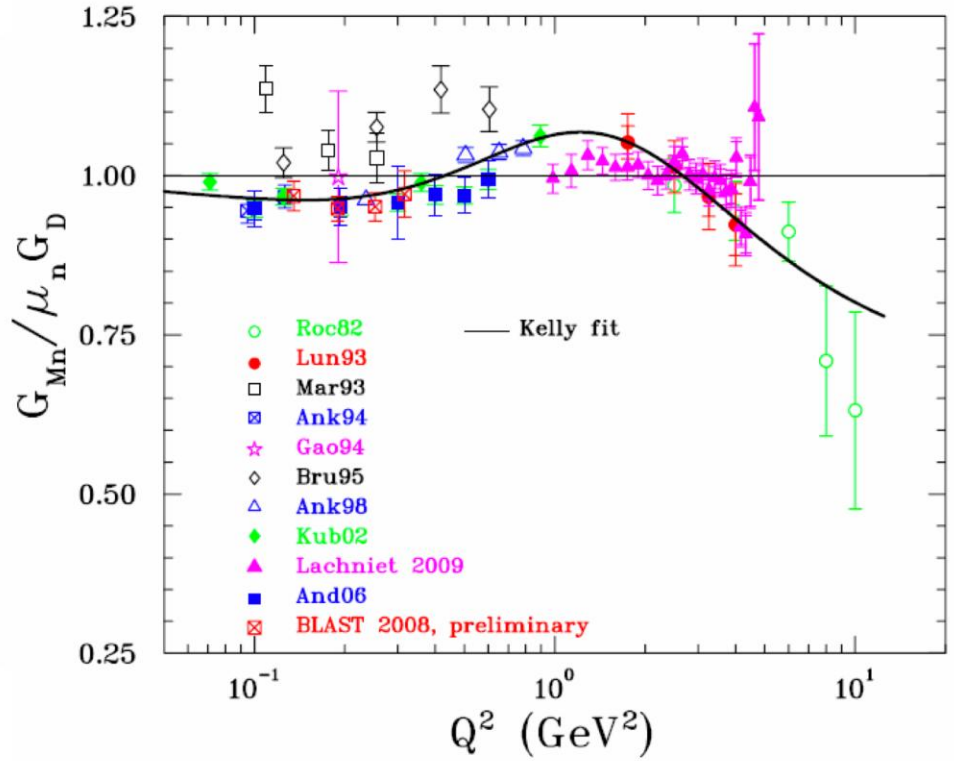
Neutron Form Factors

From recent experiments at JLab

▲ preliminary



All polarization data



Polarization and cross section data

Dispersion Theory/VMD

VMD (dispersion relation) earliest model for nucleon e.m. Form Factors

Virtual photon couples to nucleon through exchange of a vector meson

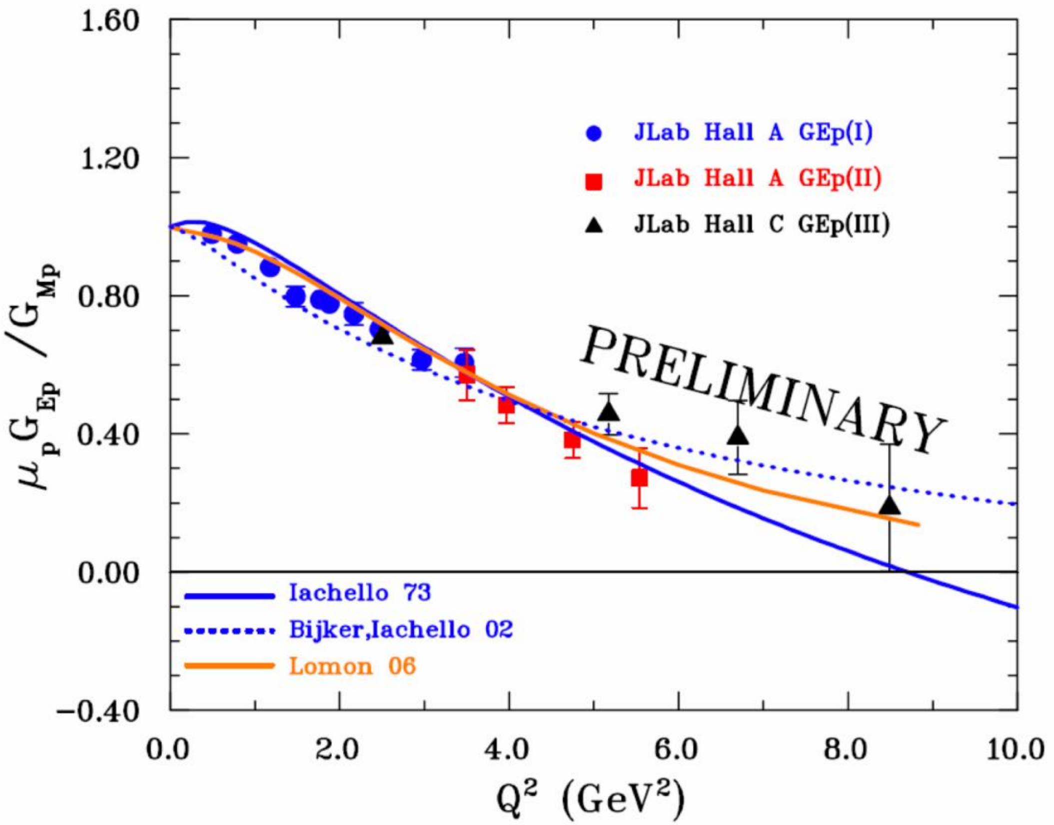
Iachello's in 1973, first to predict zero crossing of GEp: VMD+small structure.

Early work of Höhler (DR) (76): ρ(770), ω(782), Φ(1020) and effective ρ'(1250)

Gary and Krumpelman (85) asympt. pQCD

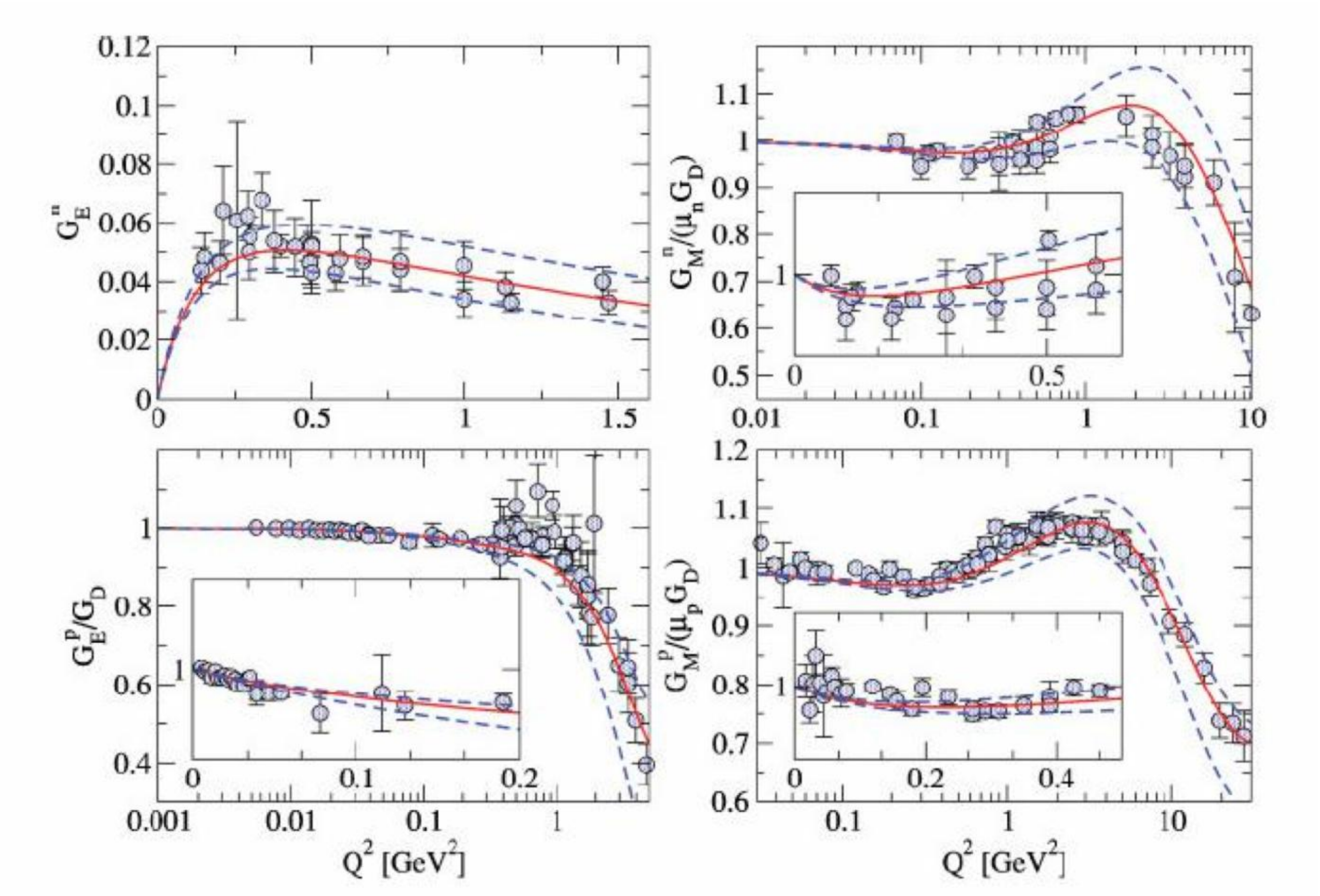
Mergell, Meissner and Drechsel (96) (DR)
Lomon (01,02) used two more VMs, 11 parameters. Lomon (06) revised fit better for GEn.

Bijker and Iachello (02); now fits G_{En} data



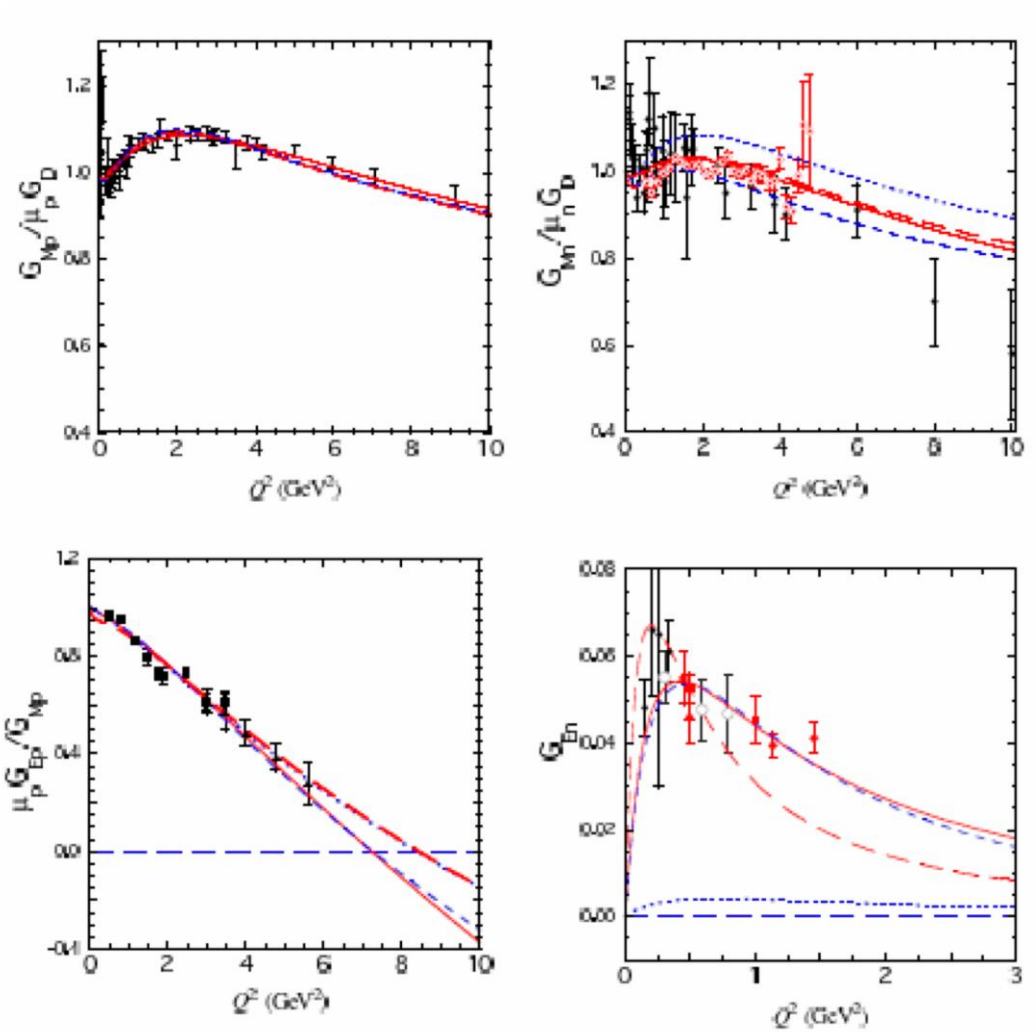
Continue VMD

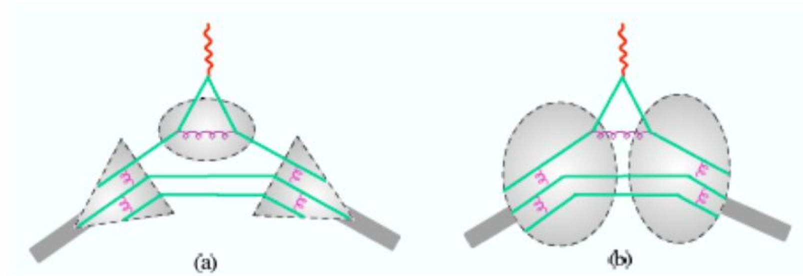
Belushkin et al. (06) with several more mesons, 2π and KK' continua. 15 parameter fit



Constituent Quark Models (III)

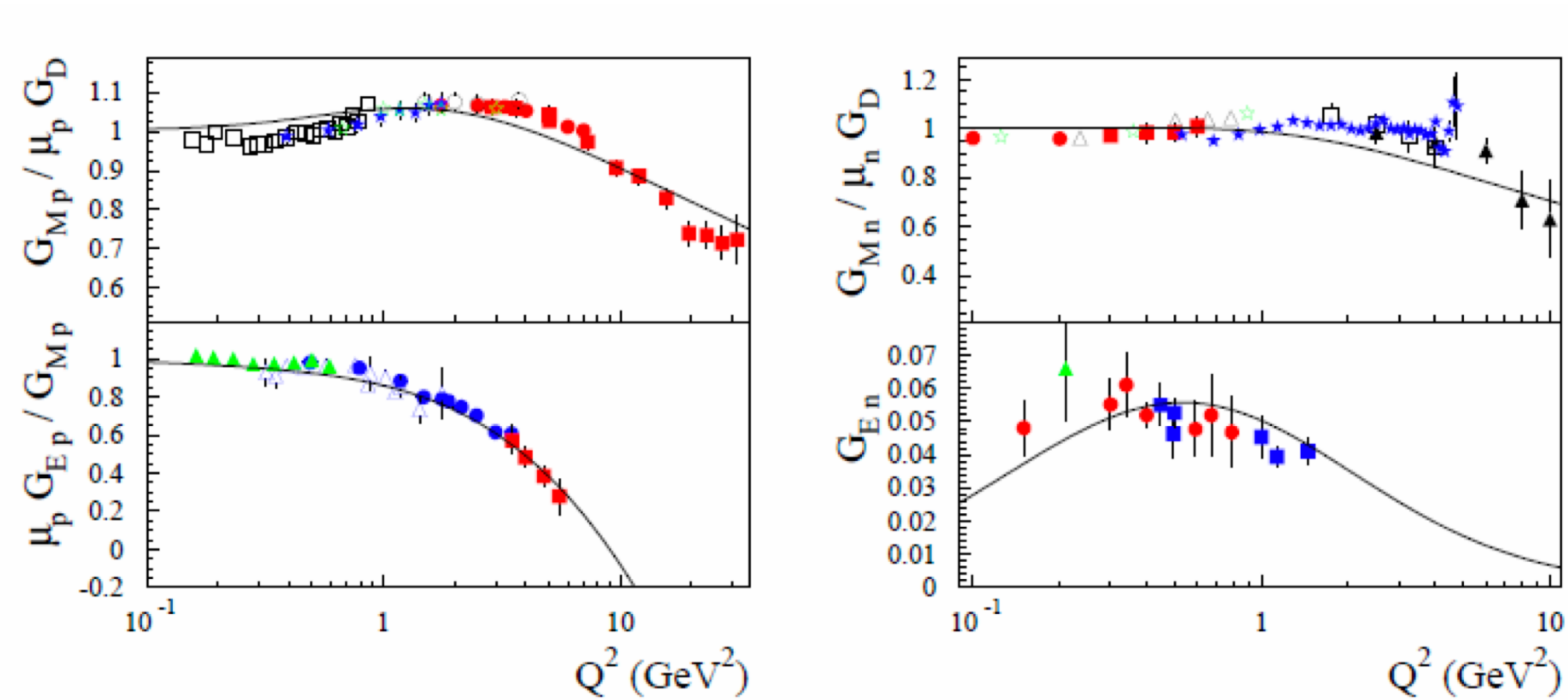
Franz Gross et al., Phys. Rev. C 77, 015202 (2008)





Covariant spectator theory modeling nucleon as a system of three valence Constituent Quarks with their own form factors

GPD predictions of Electromagnetic FF



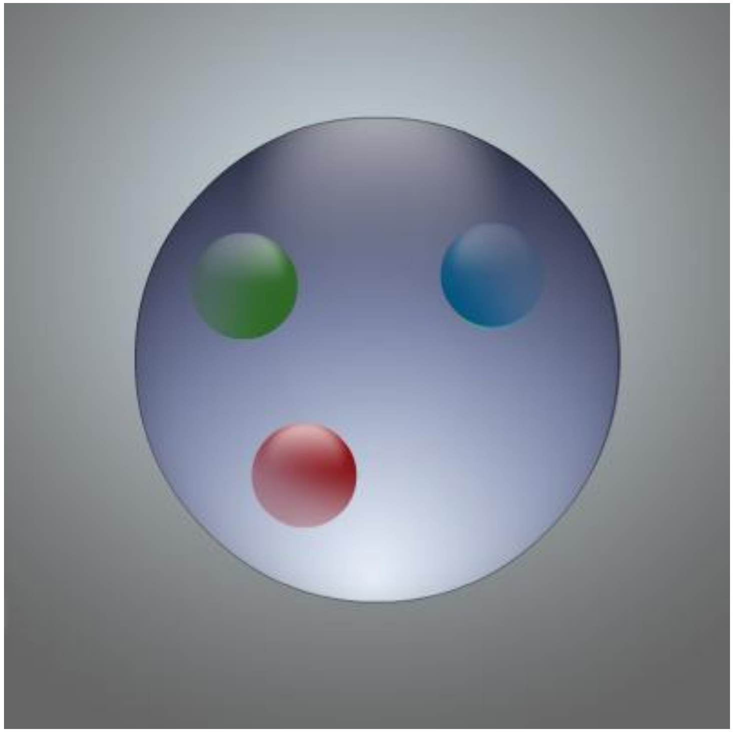
The first moments of GPDs are related to the elastic FF (Ji, 97)

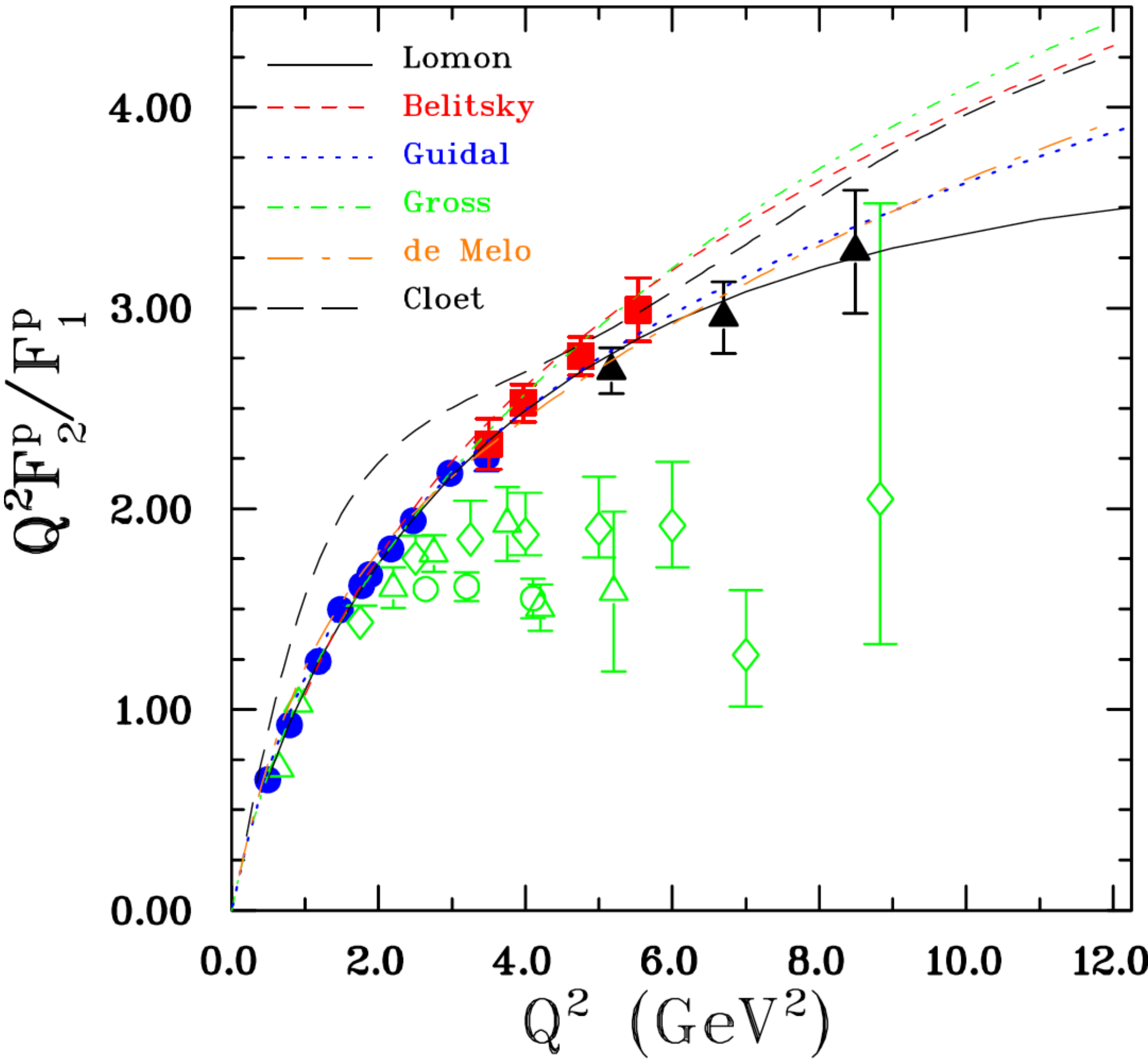
$$\int_{-1}^{+1} dx\, H^q(x, \xi, Q^2) = F_1^q(Q^2), \qquad \int_{-1}^{+1} dx\, E^q(x, \xi, Q^2) = F_2^q(Q^2),$$

Modified Regge Parametrization for H and E (Guidal et al., (2005)

$$H^q(x, 0, Q^2) = q_v(x) x^{\alpha'(1-x)Q^2}, \qquad E^q(x, 0, Q^2) = \frac{\kappa^q}{N^q}(1-x)^{\eta^q} q_v(x) x^{\alpha'(1-x)Q^2}$$

Proton: F2 /F1 and pQCD

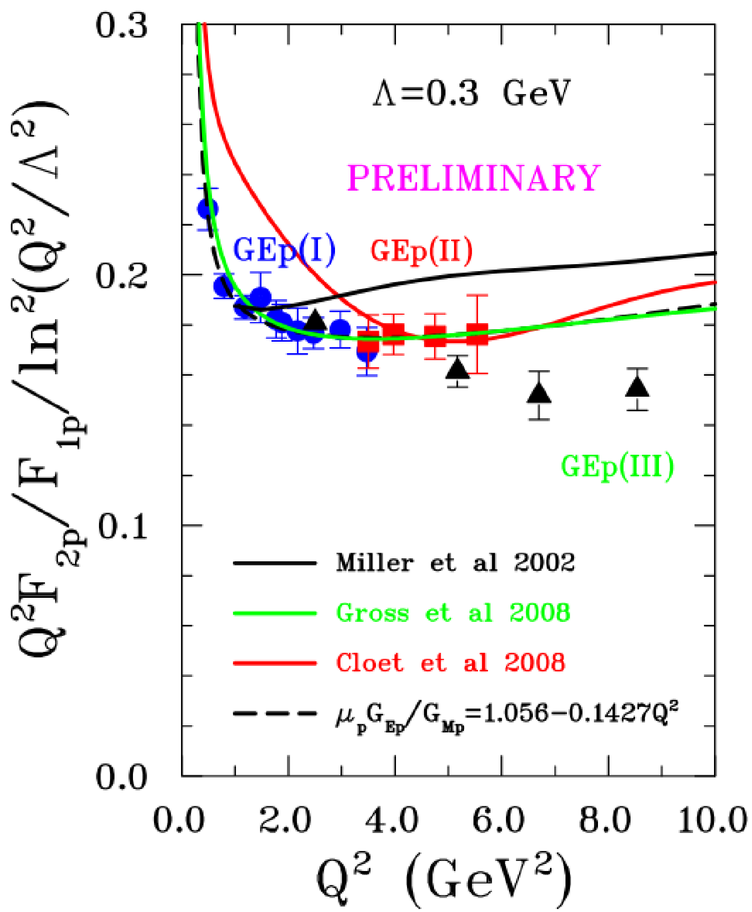




Brodsky & Farrar (75):

→ Q^2F_2/F_1 → constant

Proton: F2 /F1 and pQCD



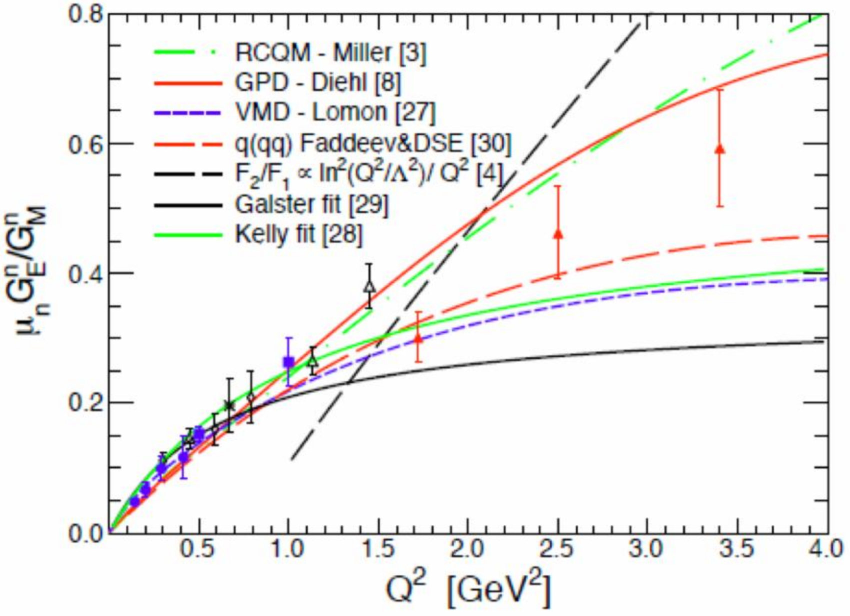
Belitsky, Ji and Yuan (03):

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

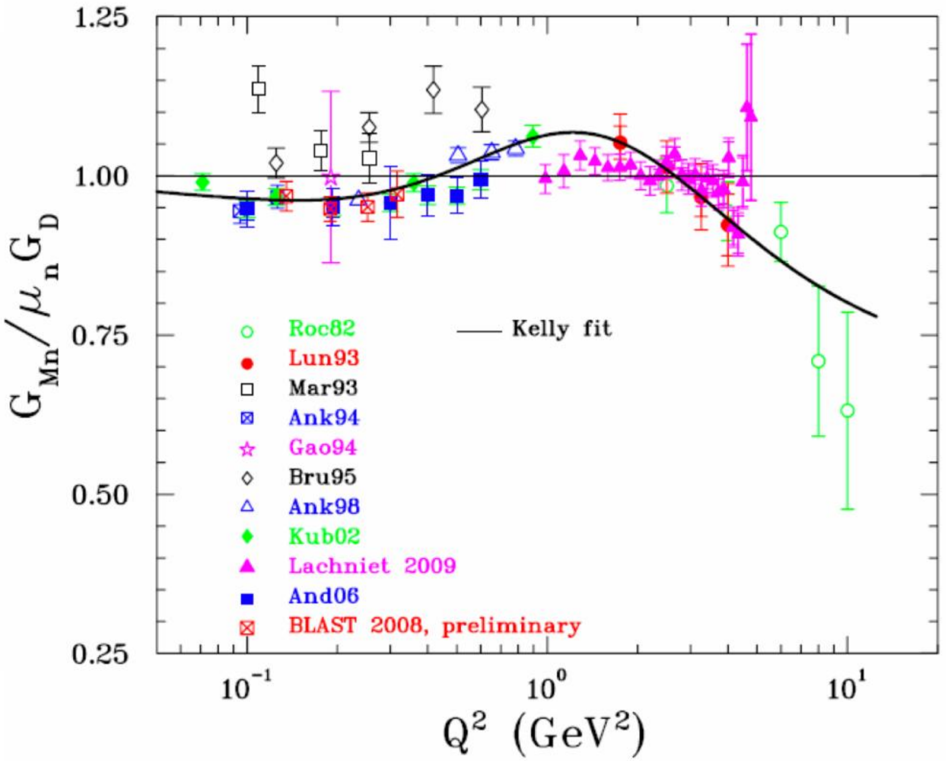
Neutron Form Factors

From recent experiments at JLab

▲ preliminary

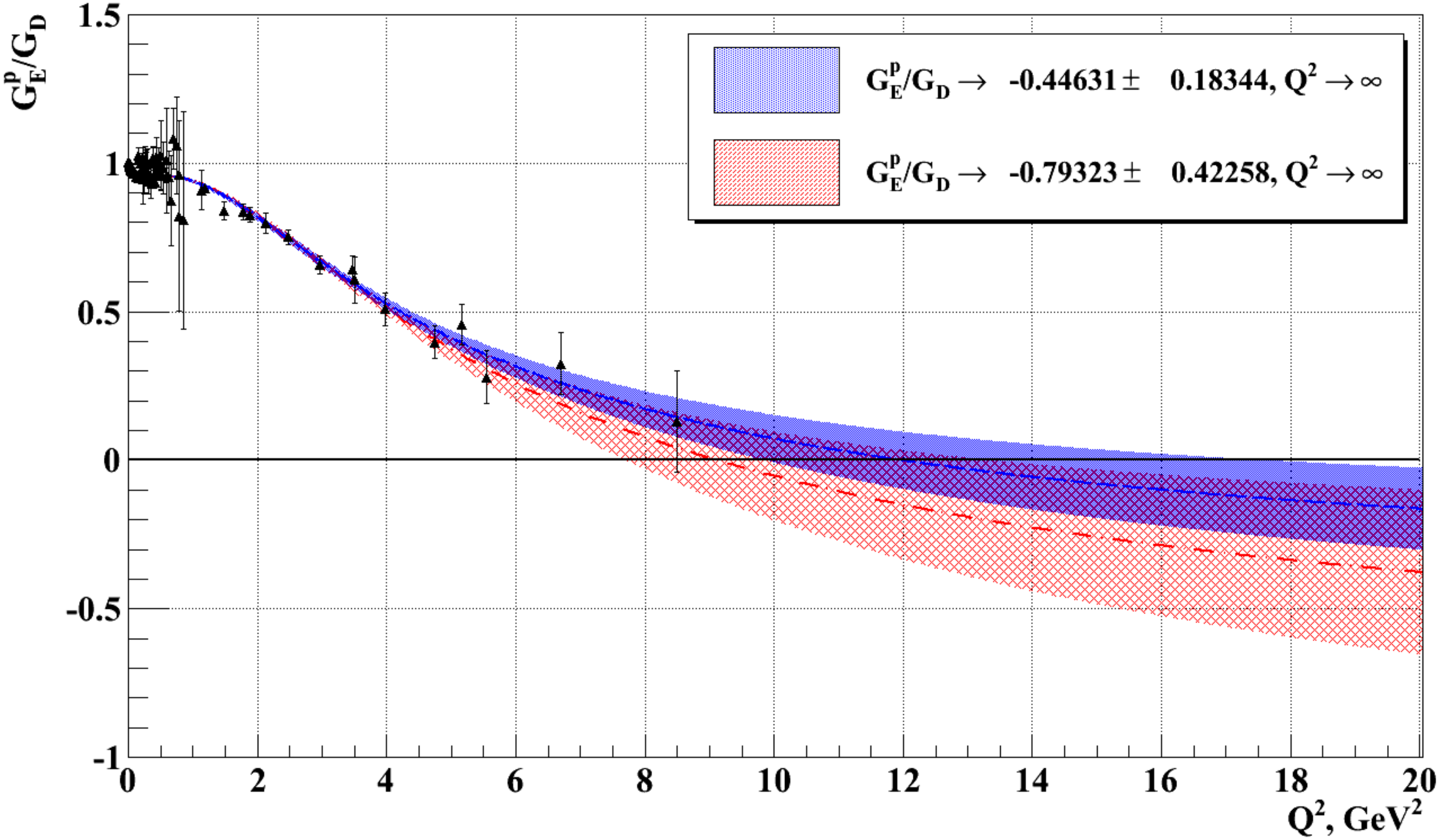


All polarization data



Polarization and cross section data

Effect of New Data on Asymptotic Value of Gep/GMp



- Parameterization of all four nucleon form factors à la Kelly
- Reduction in the uncertainty in the asymptotic value of the ratio

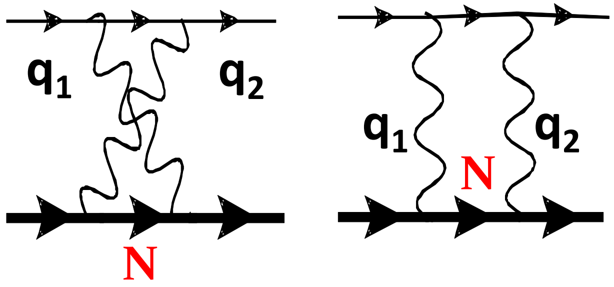
Beyond the Born-Approximation

Parity, Wigner time reversal invariance and lepton helicity conservation give the following hadronic vertex function:

(P.A.M Guichon, M. Vanderhaeghen, Phys. Rev. Lett. 91, 142303 (2003))

$$\Gamma^{\mu}(p,p') = \tilde{G}_M \gamma^{\mu} - \tilde{F}_2 \frac{P^{\mu}}{M} + \tilde{F}_3 \frac{\gamma . K P^{\mu}}{M^2}$$

Beyond the Born Approximation a third complex amplitude arises.



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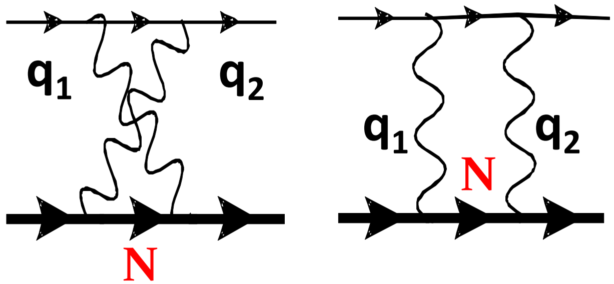
Born Approx.	Beyond Born Approx.
$G_M(Q^2), F_2(Q^2)$	$\tilde{G}_M(Q^2,\varepsilon), \tilde{F}_2(Q^2,\varepsilon)$
$\tilde{F}_3(Q^2,\varepsilon) = 0$	$\tilde{F}_3(Q^2,\varepsilon)$
real	complex



The kinematical parameter ε is: $\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$ with $\tau = \frac{Q^2}{4M^2}$

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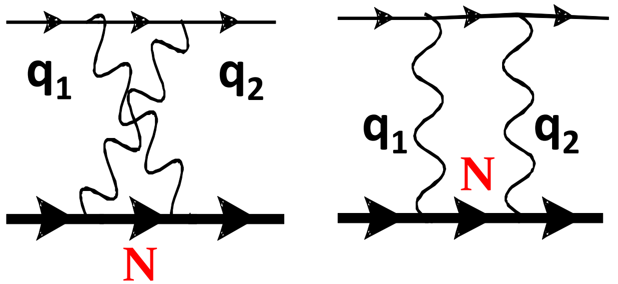


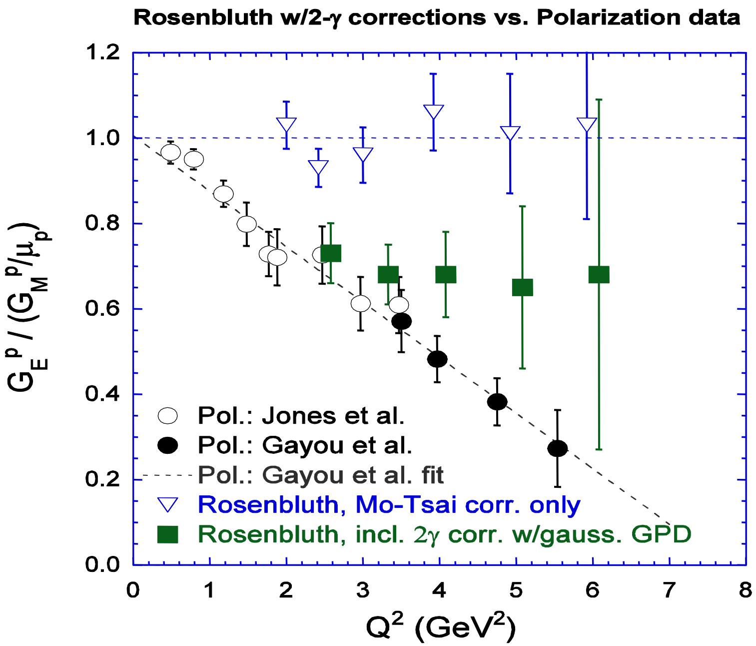
$$\tilde{G}_M(Q^2,\varepsilon) = G_M(Q^2) + \delta\tilde{G}_M(Q^2,\varepsilon)$$
$$\tilde{G}_E(Q^2,\varepsilon) = G_E(Q^2) + \delta\tilde{G}_E(Q^2,\varepsilon)$$

The kinematical parameter ε is: $\varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$ with $\tau = \frac{Q^2}{4M^2}$

Discrepancy between Rosenbluth and Recoil Polarization

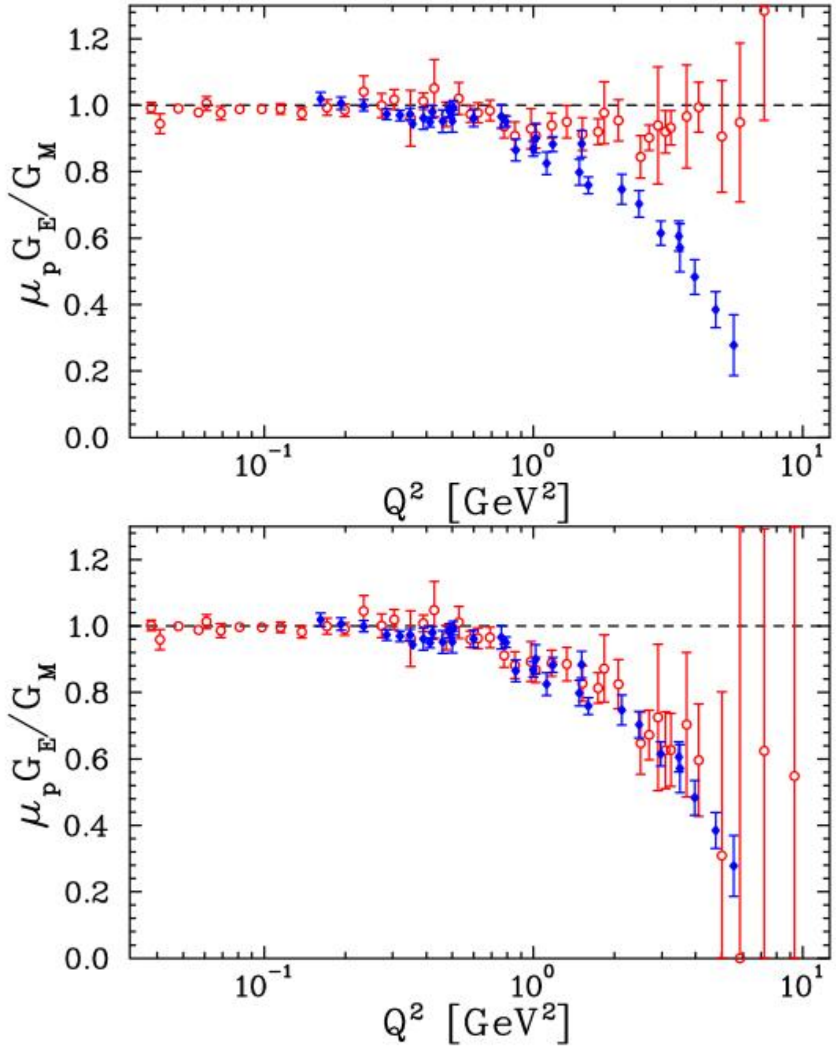
Two photon exchange process -> significant contribution at higher Q^2

leads το ε–dependence of observable

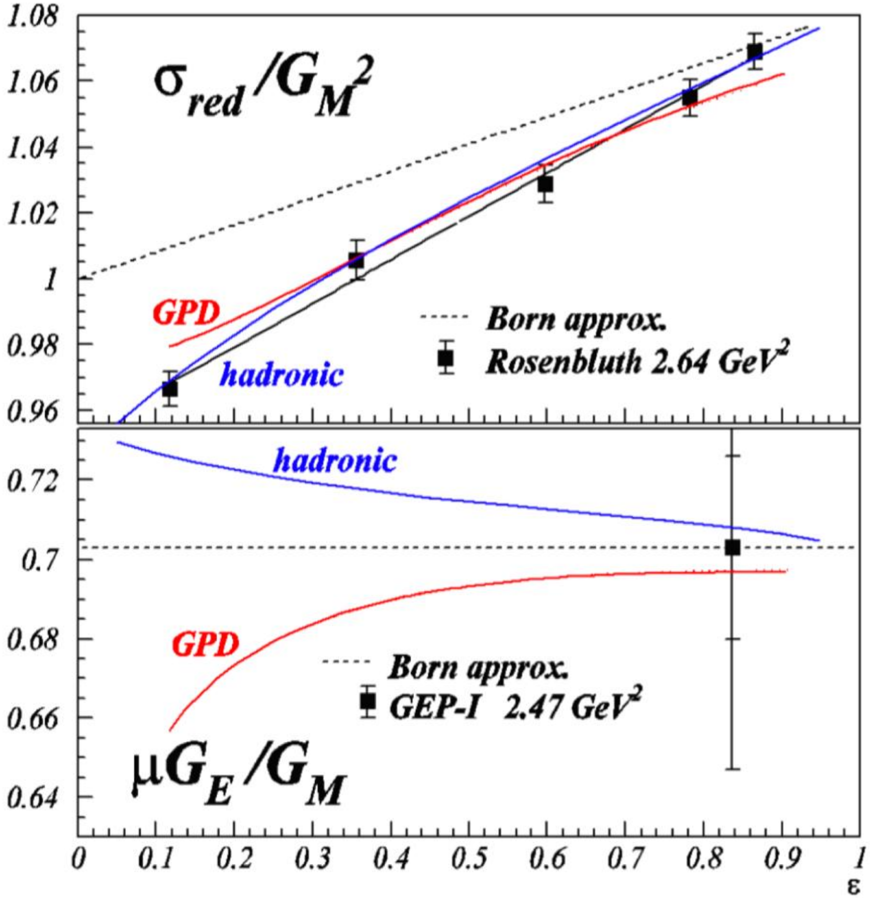


Afanasev, Guidal et al.

Arrington, Melnitchouk, Tjon



Theoretical Estimates



Hadronic (elastic) : dominated by correction to $G_{M.}$

P.Blunden et al., Phys.Rev.C72: 034612 (2005)

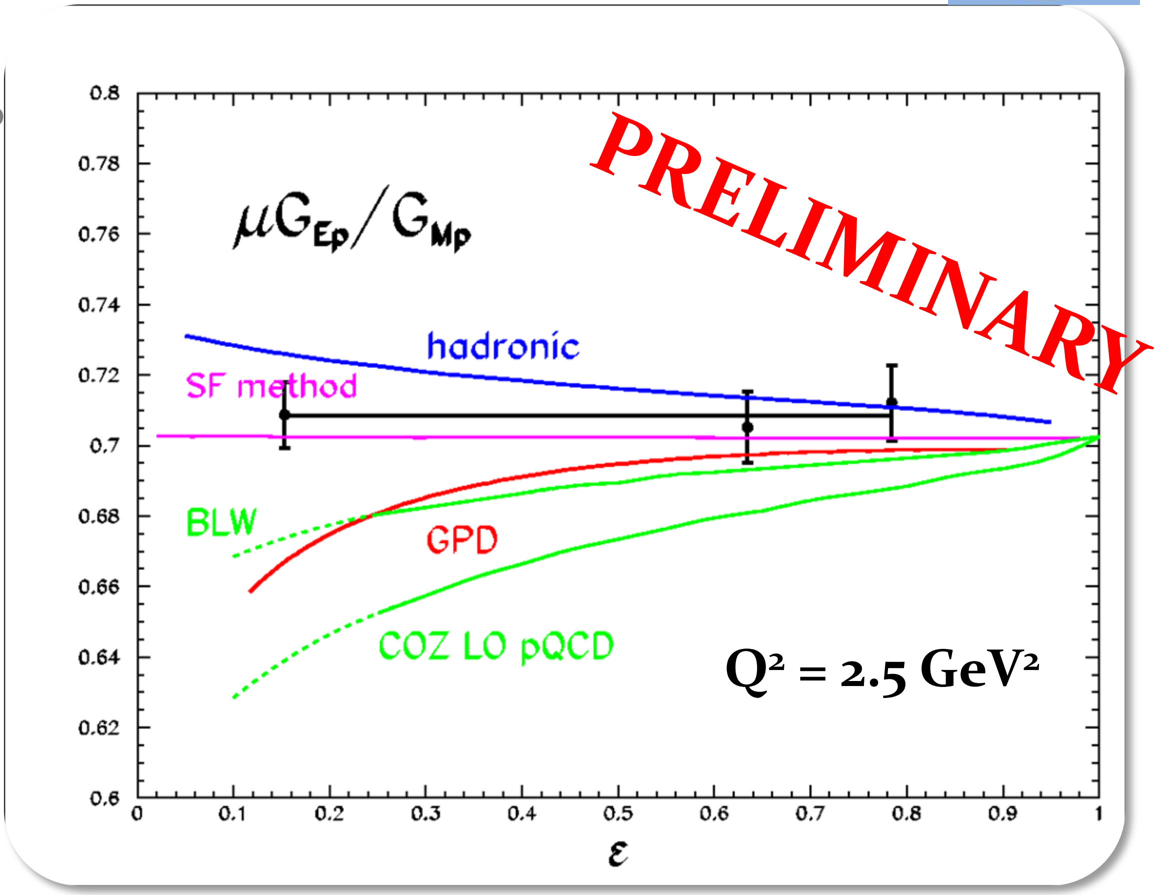
GPD (includes inelastic) : dominated by two-gamma correction and correction to $G_{E.}$

A.Afanasev et al., Phys.Rev.D72:013008 (2005)

Both theories describe Rosenbluth data but have opposite prediction for $G_{Ep}/G_{Mp.}$

Form Factor Ratio (II)

- No evidence of an epsilon dependence at a 0.01 level for a ratio of 0.7 in the polarization data at $Q^2 = 2.5\ GeV^2$.
- Models predict a bigger correction (opposite sign) at small ε, not seen in the data.
- Theoretical predictions are with respect to the Born approximation. (calculated from the fit to the polarization data)
- Validate the recoil polarization transfer technique to extract the proton form factor ratio
- Radiative corrections calculated with MASCARAD ~0.01-0.02% (*Afanasev et.al, Phys. Rev. D 64, 113009 (2001)*)



*P.Blunden et al., Phys.Rev.C**72**: 034612 (2005)*

*A.Afanasev et al., Phys.Rev.D**72**:013008 (2005)*

*N. Kivel and M. Vanderhaeghen Phys.Rev.Lett.**103**:092004 (2009)*

*Bystritskiy, Kuraev and Tomasi-Gustafsson, Phys.Rev.C**75**: 015207 (2007)*

Future FF measurements at JLab

The 12 GeV upgrade has officially started; beams of 11 GeV in Halls A, B and C; beam of 12 GeV into new Hall D, dedicated to search for exotic hadronic states. Complete shut down expected in 2011. First experiment in 2014!

Hall B upgrades to CLAS12, Hall C gets new 12 GeV/c high resolution spectrometer (SHMS).

After the 12 GeV upgrade

Approved experiment E12-07-109 in Hall A: G_{Ep}/G_{Mp} to 15 GeV^2 with new large acceptance Super Bigbite Spectrometer (SBS), to be built with single dipole and GEM trackers.

Conditionally approved experiment E12-09-001 in Hall C: G_{Ep}/G_{Mp} to 13 GeV^2, with SHMS, will be resubmitted at next JLab PAC

Approved experiment E12-09 in Hall A: G_{En} to 10 GeV^2, with SBS

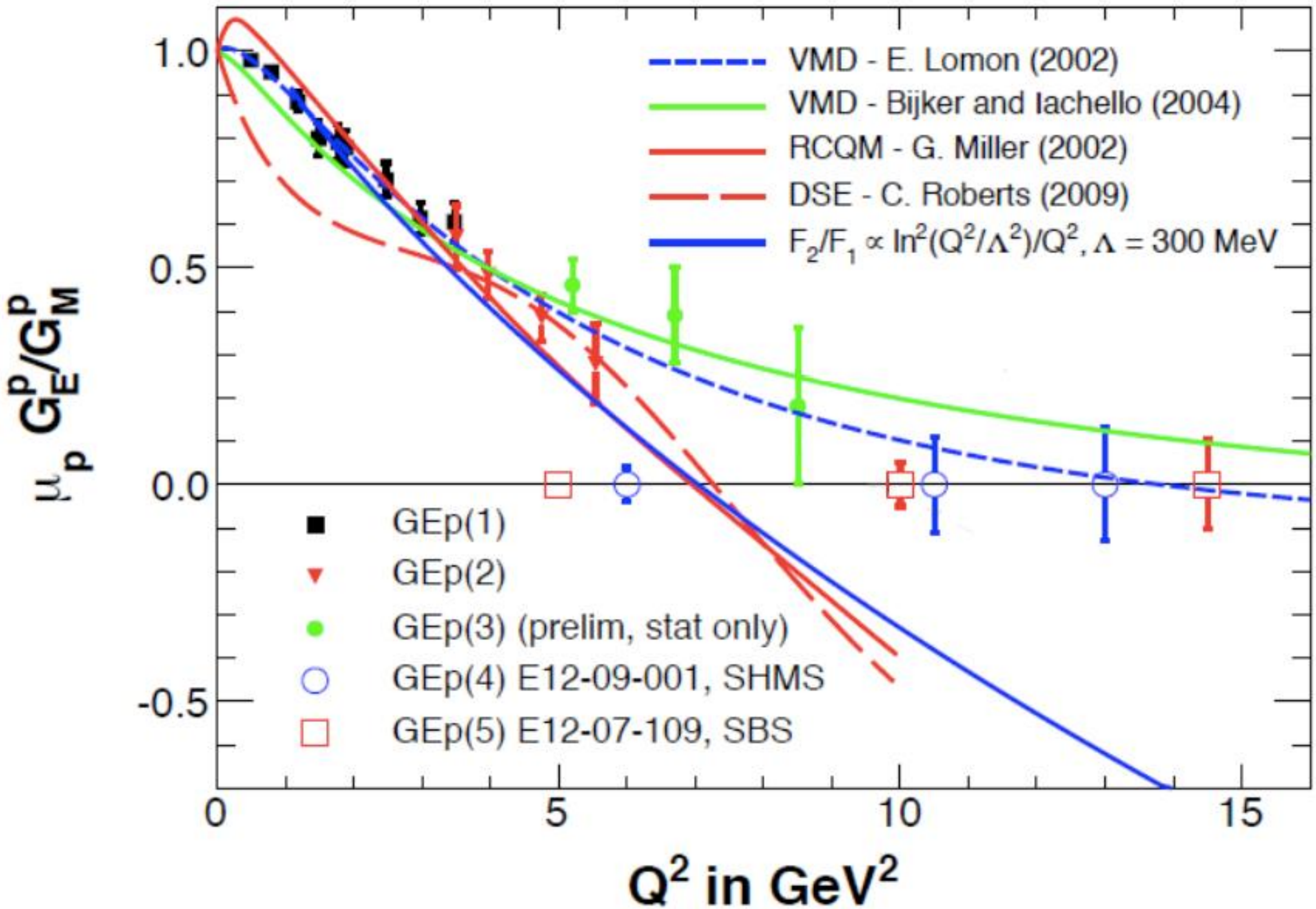
Approved Experiment PR12-09-006 in Hall C: G_{EN} to 7 GeV^2 with SHMS and NPOL

Approved Experiment PR12-07-104 in Hall B: G_{Mn} to 14 GeV^2 with CLAS12

Approved Experiment PR12-09-019 in Hall A : G_{Mn} to 13.5 GeV^2

Approved Experiment E12-07-108 in Hall A: G_{Mp} to 17.5 GeV^2

High Q^2 Measurements with 11 GeV Beam at JLab

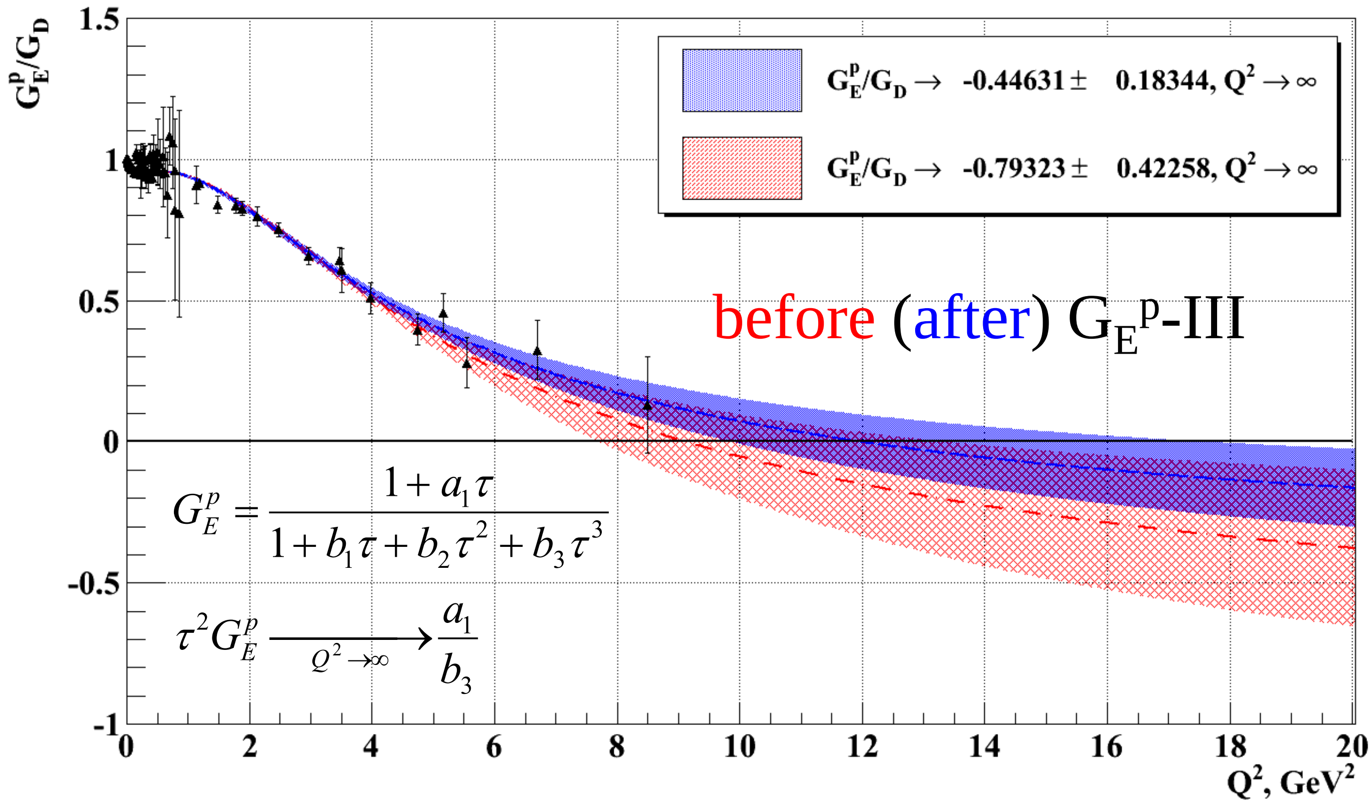


Summary

- Measurements of the electromagnetic form factors of the proton and neutron at JLab have led to a fundamental change in our picture of the internal structure of the proton
  - Valence (u and d) quark distributions
  - Relativistic dynamics
  - Current data described well by VMD-based phenomenological models
- These results, together with further results following the 12GeV upgrade, will provide answers to a number of open questions crucial to our understanding of fundamental nucleon properties, and the nature of QCD in the confinement regime
  - Severe test of theoretical models
  - "Scaling" behaviour of Gep/Gmp
    - Higher Twist / Quark OAM
  - Understanding higher-order processes

Backup Slides

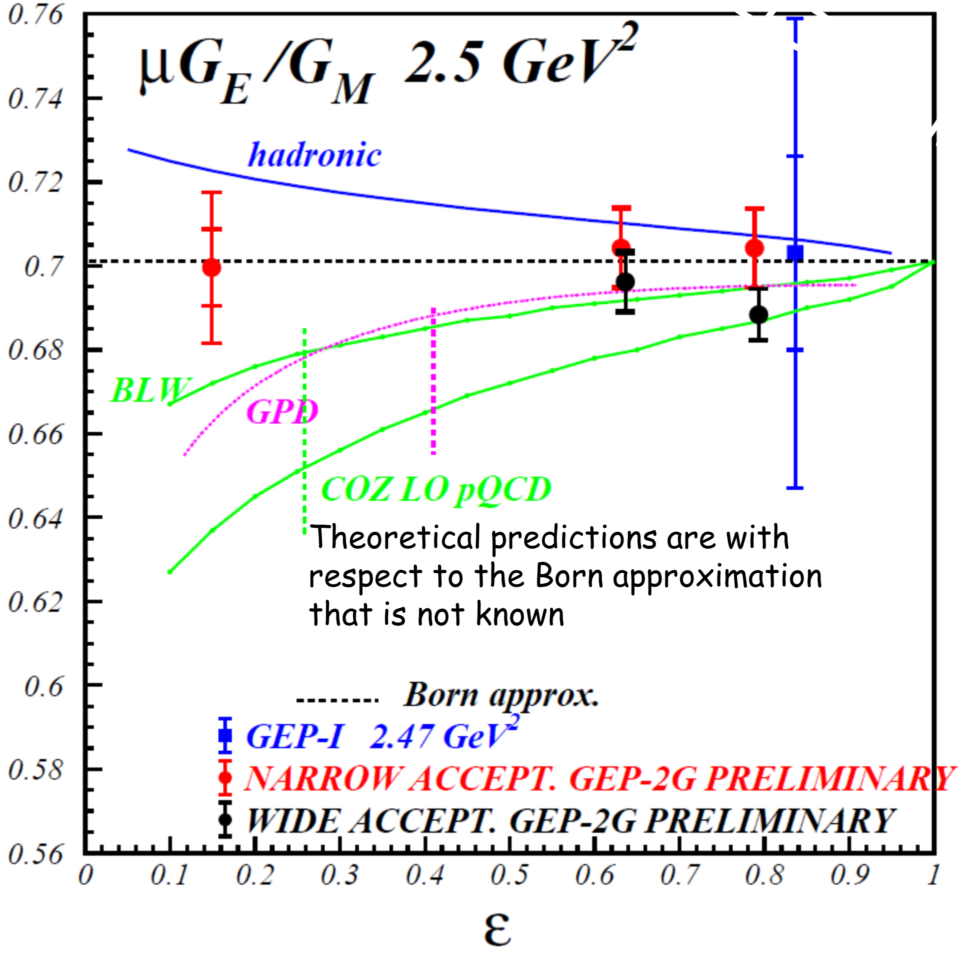
Statistical Impact of GEp-III

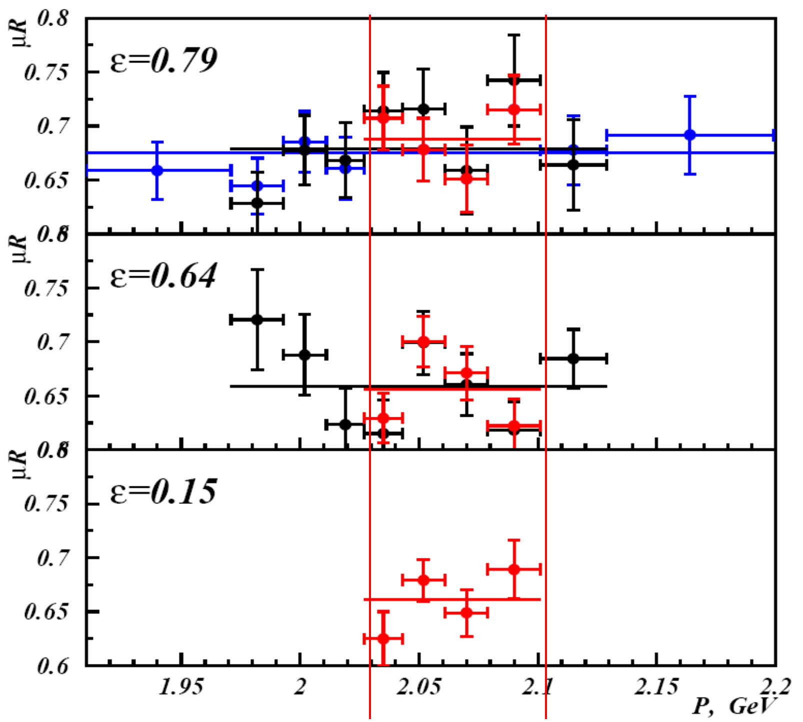


- Global fit of G_E^p and G_M^p using Kelly parametrization: PRC 70, 068202 (2004)

- Including GEp-III data pushes zero crossing from ~9 to ~12 GeV^2, reduces uncertainty in asymptotic G_E^p/G_D by a factor of more than 2.

GEp-2γ preliminary results: form factor ratio

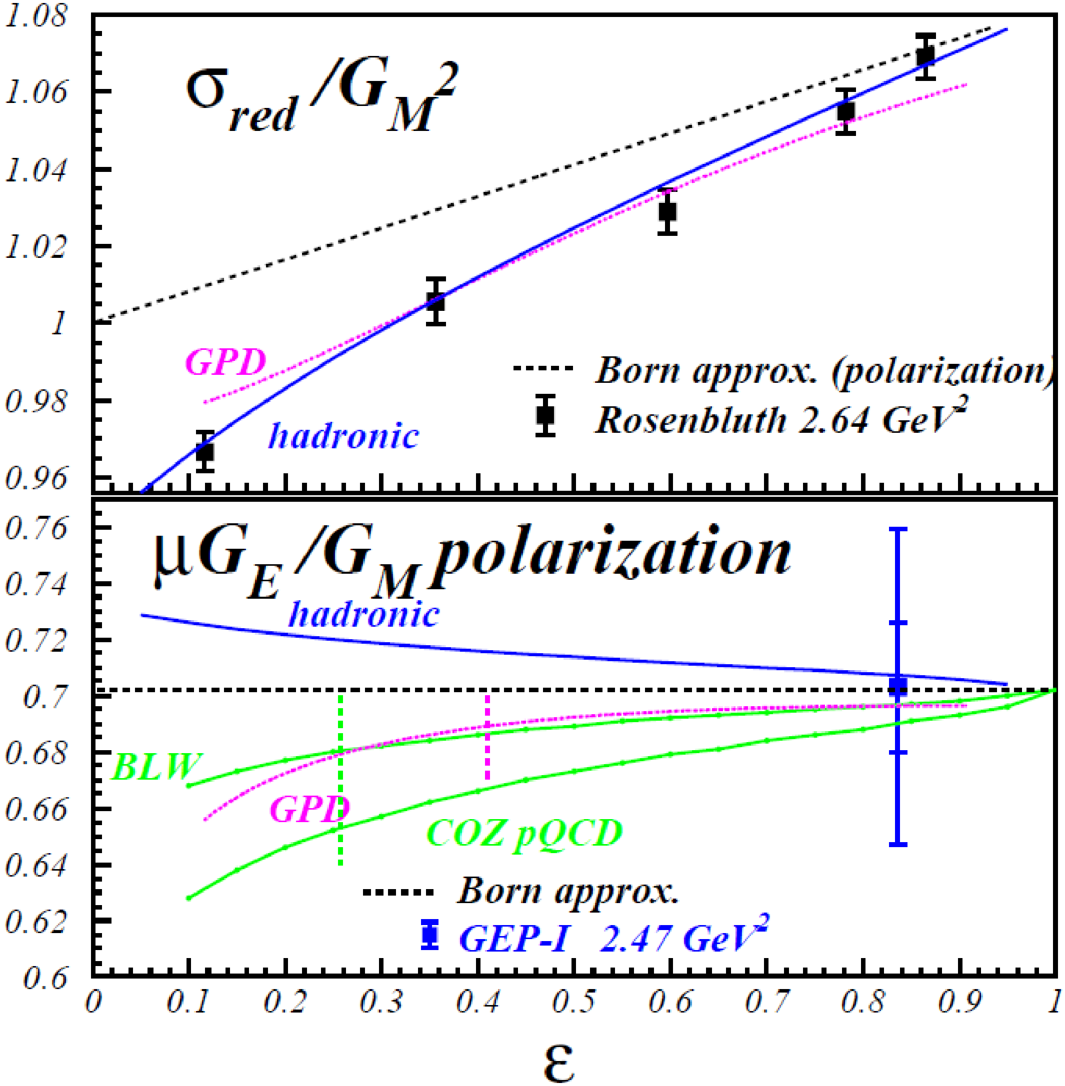




Narrow acc. matching all kinematics

NO RADIATIVE CORRECTIONS APPLIED,
Less than 1% (Afanasev et.al, Phys.Rev. D64 (2001) 113009)

Two-Photon Exchange: theoretical predictions



Hadronic calculations

- **P.Blunden et al., Phys.Rev.C72: 034612 (2005)** elastic (at the figure)
- **S.Kondratyuk et al., Phys.Rev.Lett. 95: 172503 (2005)** including Delta reduces the effect
- **S.Kondratyuk et al., nucl-th/0701003 (2007)** including 1/2 and 3/2 resonances – no effect

GPD

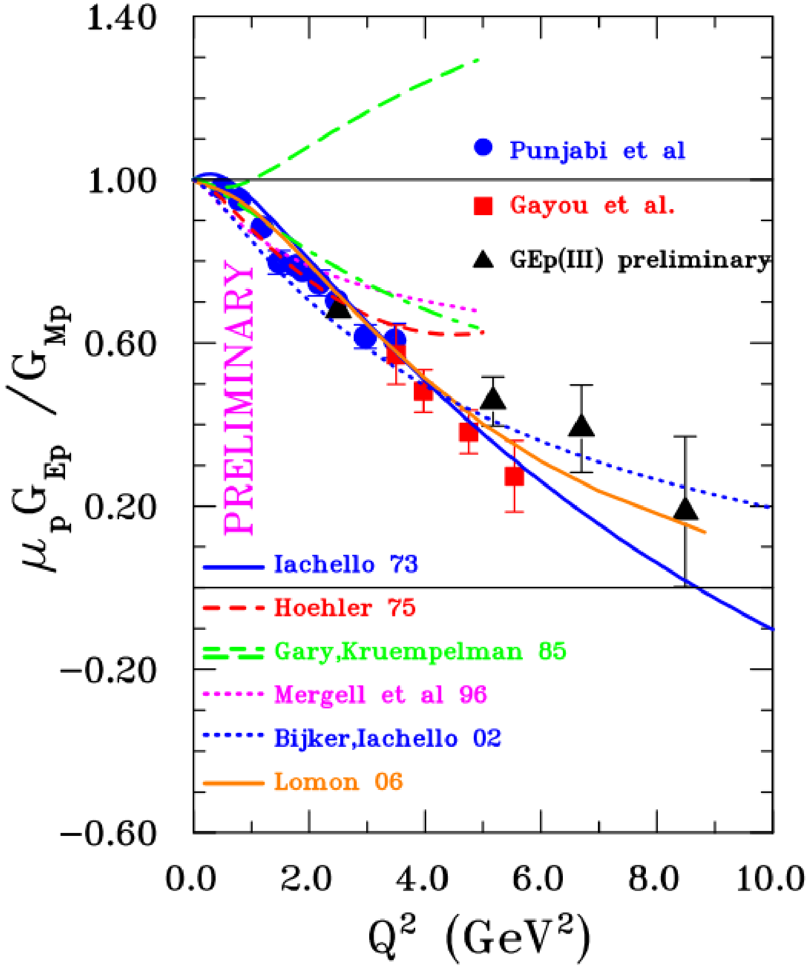
A.Afanasev et al., Phys.Rev.D72:013008 (2005) – GPD models: Gauss (figure), smaller effect with Regge, or non-zero quark mass
Valid at high ε region (vertical line at figure)

LO pQCD

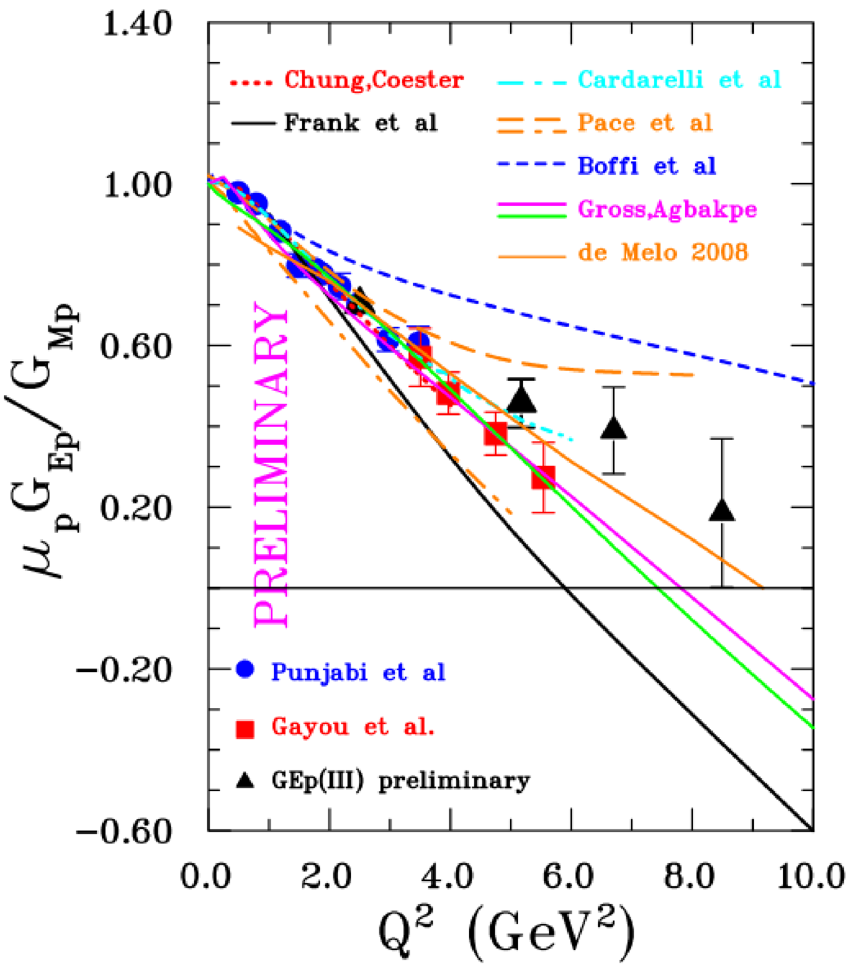
N. Kivel and M. Vanderhaeghen arXiv:0905.0282 [hep-ph] LO pQCD using two different distribution amplitude models: BLW (good agreement with lattice QCD!) and COZ
Valid in high ε region (vertical line at figure)

Two theories describe Rosenbluth data but have opposite predictions for $\mu G_E/G_M$

VMD and CQM



1.40
1.00
0.60
0.20
−0.20
−0.60
$\mu_p G_{Ep} / G_{Mp}$
0.0
2.0
4.0
6.0
8.0
10.0
Q^2 (GeV^2)
Punjabi et al
Gayou et al.
GEp(III) preliminary
PRELIMINARY
Iachello 73
Hoehler 75
Gary,Kruempelman 85
Mergell et al 96
Bijker,Iachello 02
Lomon 06



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Cardarelli et al
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Boffi et al
Gross,Agbakpe
de Melo 2008
PRELIMINARY
Punjabi et al
Gayou et al.
GEp(III) preliminary

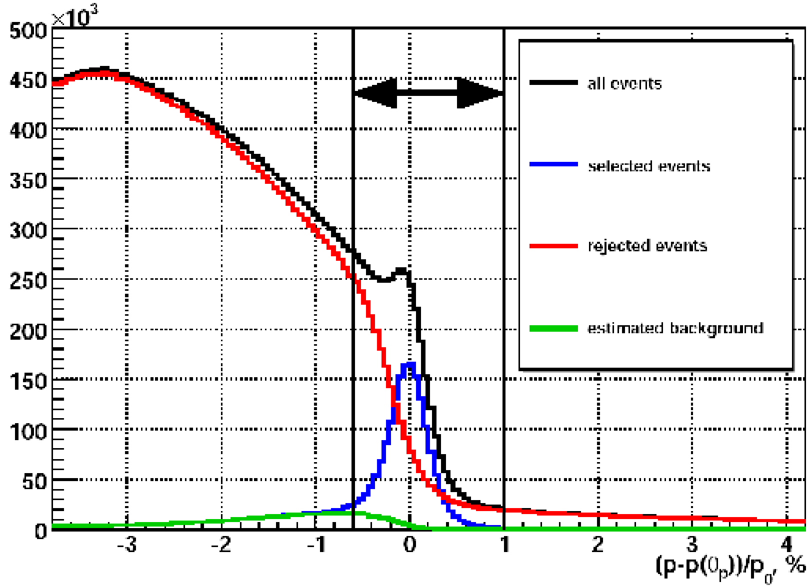
Gep-III in Hall C at JLab

- Continuation of successful Hall A expt's to higher momentum transfer - Q^2=5.2, 6.8, 8.5 GeV^2

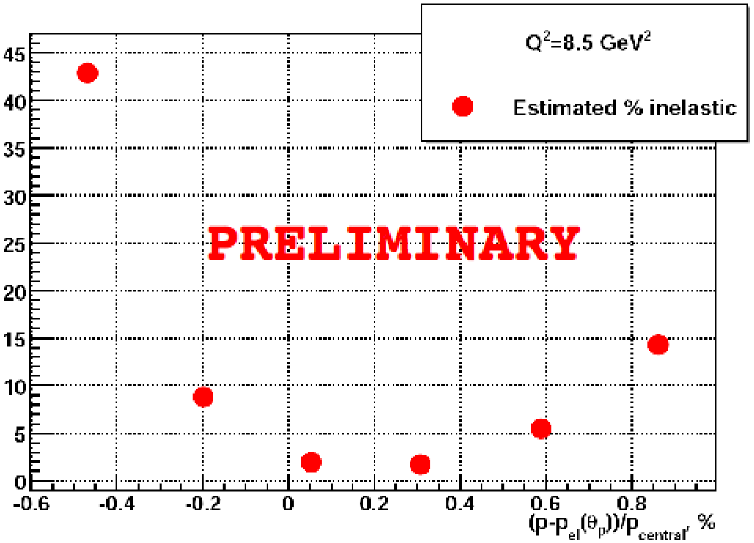
- Required new EM Calorimeter (BigCal), new scattering chamber, new FPP in the HMS spectrometer

- Also required new HMS trigger electronics, coincidence trigger, and new HMS trigger scintillator

Elastic Event Selection

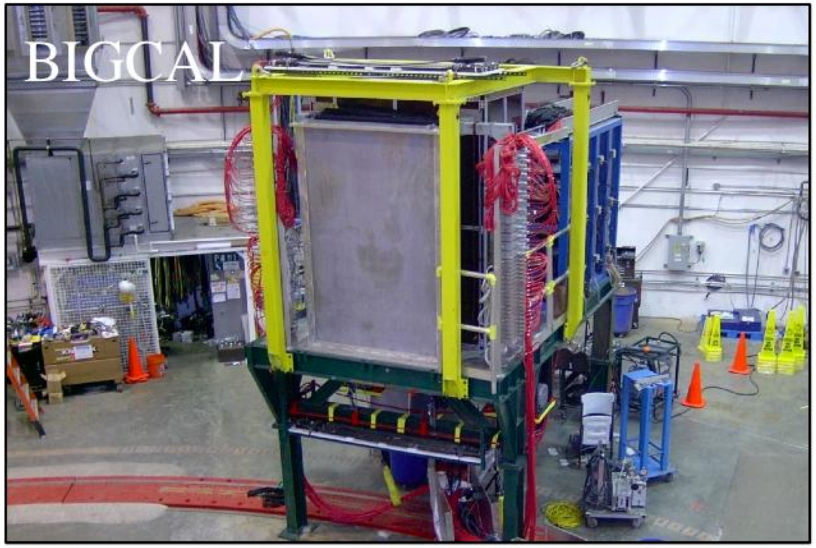


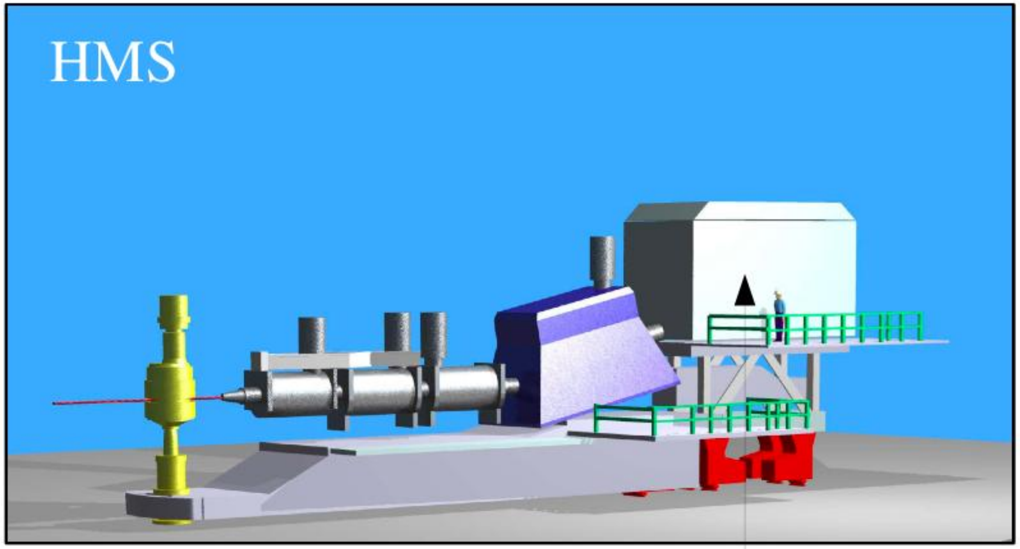
Missing momentum selected by BigCal cut



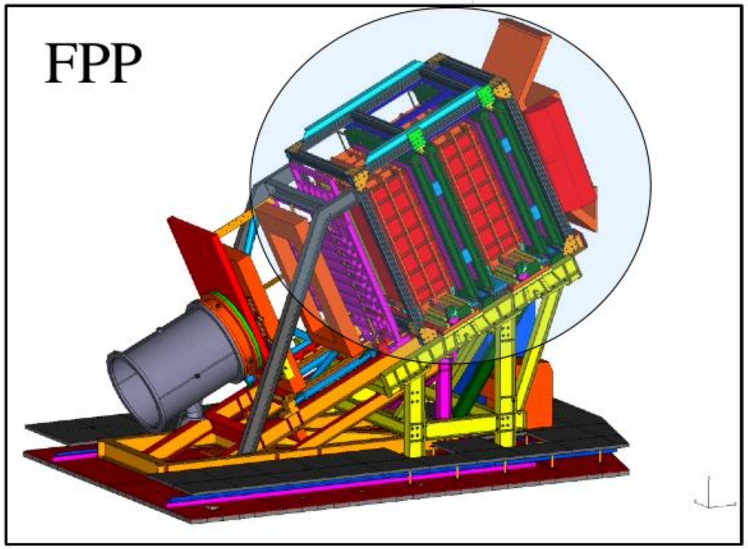
Estimated Background vs. missing momentum

Gep-III and Gep-2γ



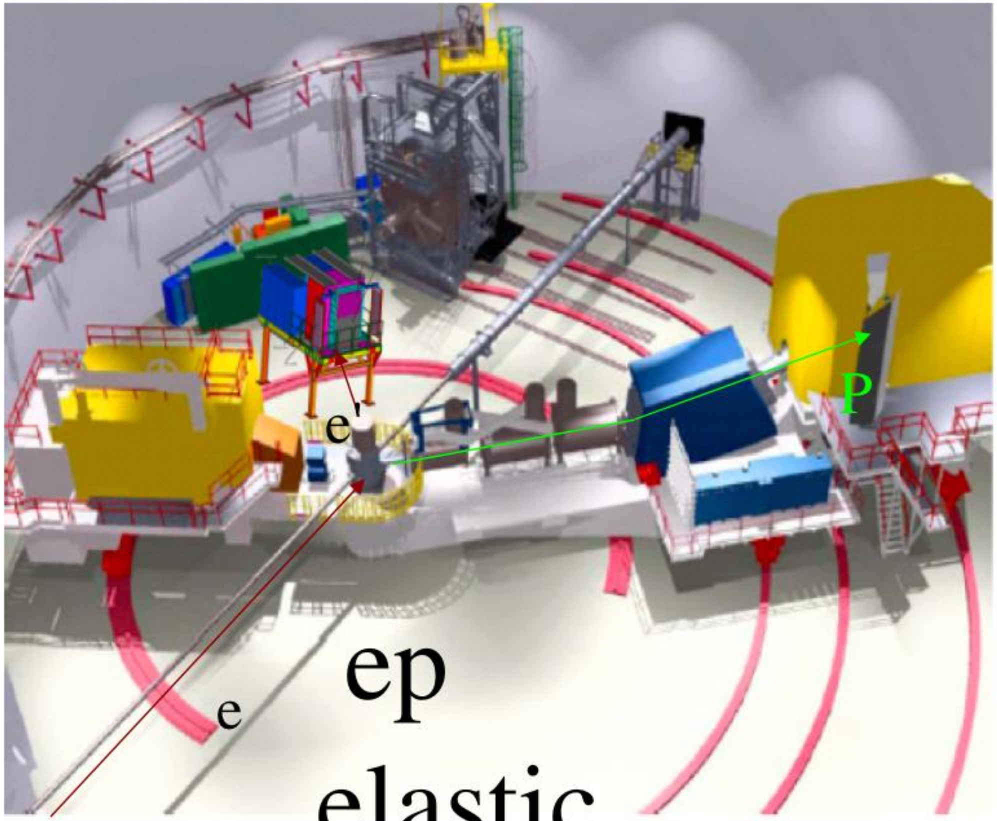


New experiments carried out from Oct. 2007-Jun. 2008 in Hall C at JLab—New detectors BigCal and FPP



Christopher Newport University
Jefferson Lab Exploring the Nature of Matter
NSU Norfolk State University

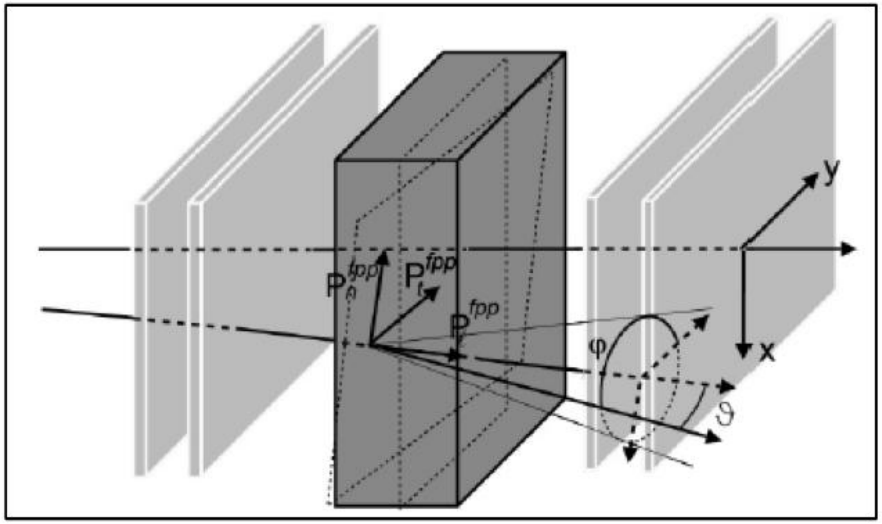
Experimental Layout



Q^2, GeV^2	ϵ	E_{beam}, GeV	θ_e, °	BC distance, m	Ω_e, msr
2.5	0.154	1.873	105.2	4.93	111.2
2.5	0.633	2.847	44.9	12.00	18.8
2.5	0.789	3.680	30.8	11.03	22.2
5.2	0.377	4.053	60.3	6.05	73.9
6.8	0.507	5.714	44.4	6.00	75.1
8.5	0.236	5.714	69.0	4.30	146.2

- At such high Q^2, need to detect electron in coincidence for clean elastic event sample
- Solid-angle acceptance of proton arm is fixed at ~7 msr
- Reaction kinematics are such that electron solid angle ≠ proton solid angle.
- BigCal has good angular resolution and "telescoping" ability for acceptance matching.
- Matching inexact—location in hall is constrained by obstacles

Polarimetry Principles



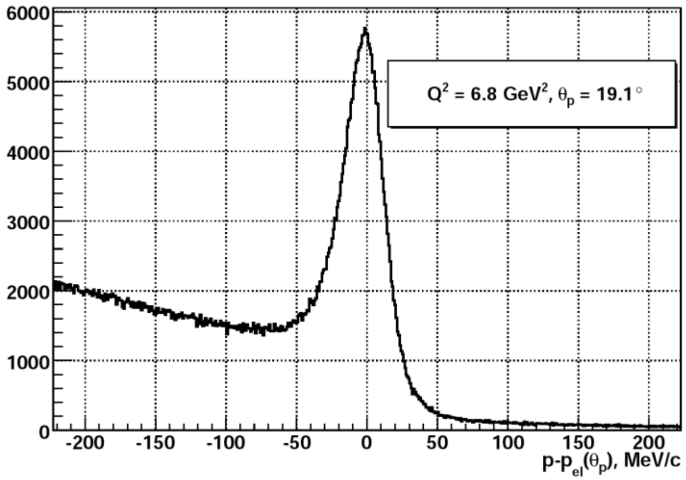
Secondary scattering in CH_2 analyzer measures polarization at the focal plane

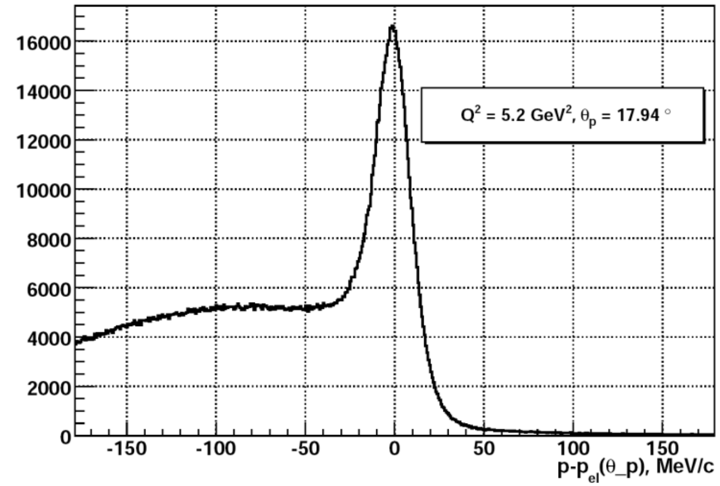
- Helicity difference distribution cancels instrumental asymmetry
- Ratio cancels beam polarization and analyzing power
- Likelihood analysis determines polarization at target

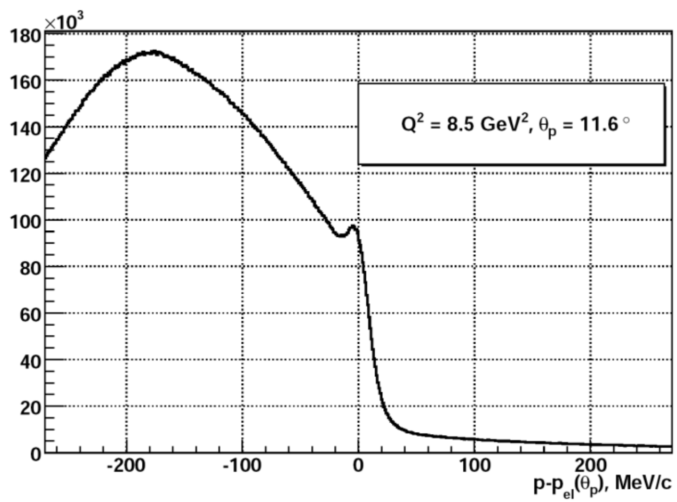
$$N_p^{\pm}(\vartheta,\varphi) = N_p^{\pm}\left[1 + (\pm h A_y(\vartheta) P_t^{fpp} + a_{inst.})\sin\varphi + (\pm h A_y(\vartheta) P_n^{fpp} + b_{inst.})\cos\varphi\right]$$

$$L(P_t, P_\ell) = \prod_{i=1}^{N_p}\{1 \pm A_y(\vartheta_i)\,(S_{tt,i} h P_t + S_{t\ell,i} h P_\ell)\sin\varphi_i \mp A_y(\vartheta_i)\,(S_{nt,i} h P_t + S_{n\ell,i} h P_\ell)\cos\varphi_i\},$$

Elastic Event Selection







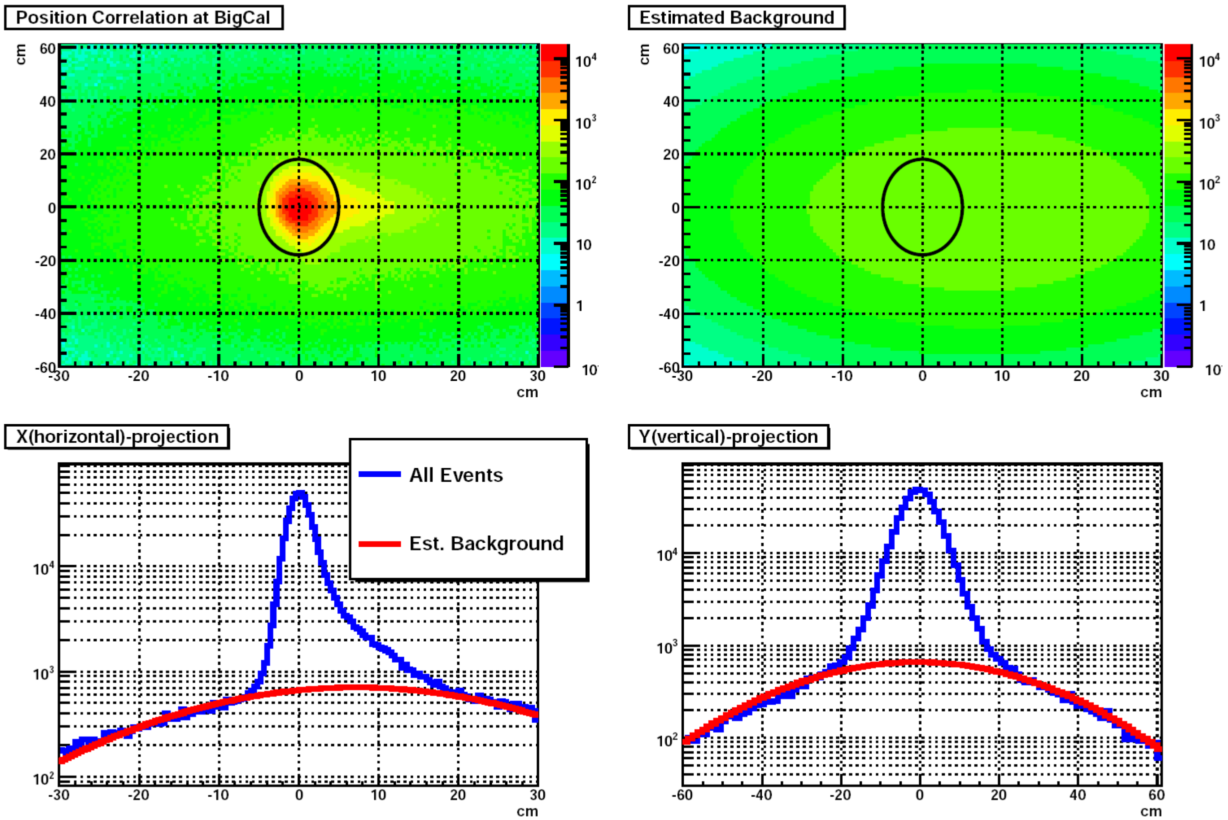
$$p(\theta_p) \quad = \quad \frac{2M_pE_{beam}(M_p + E_{beam})\cos\theta_p}{M_p^2 + 2M_pE_{beam} + E_{beam}^2\sin^2\theta_p}$$

- Looking only at the proton, we know:
  - Elastic peak is located at p-p(θ)=0
  - Clearly visible at 5.2 and 6.8 GeV^2
  - Barely visible at 8.5 GeV^2
  - Need to look for the electron!

Elastic Event Selection

-compare "xy" position in BigCal and prediction from proton seen in HMS

- fit to "background" extrapolated into central ellipse

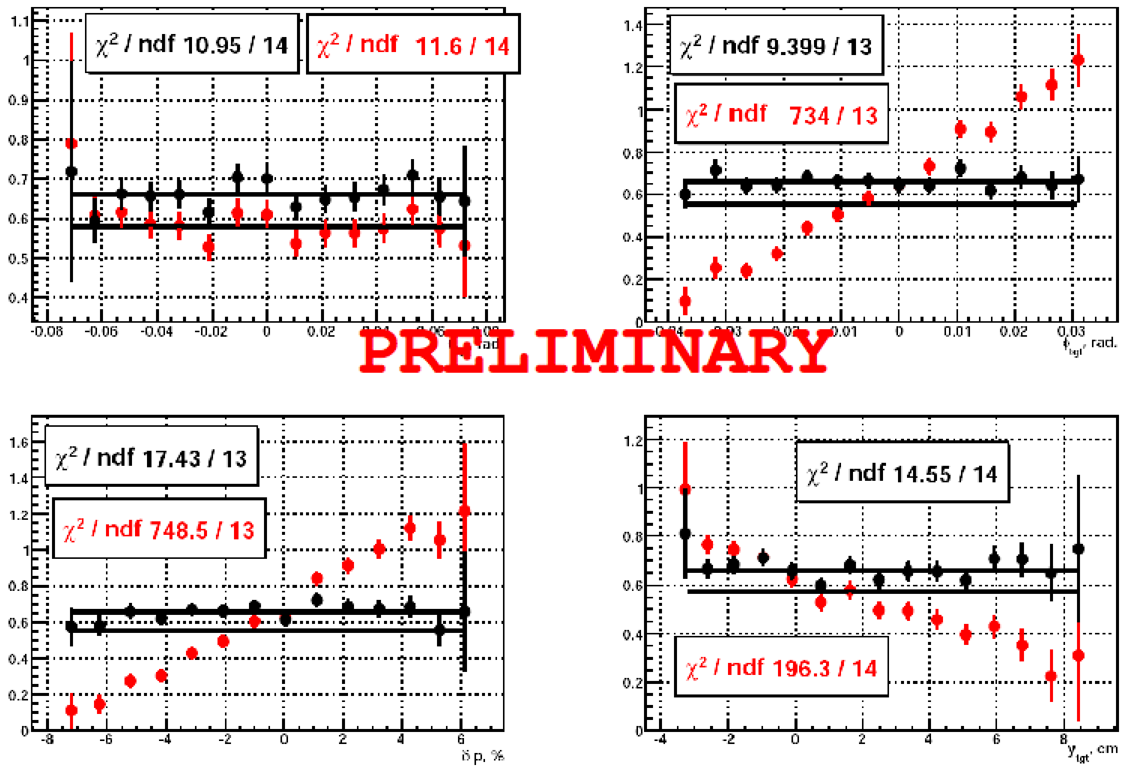


Background ~6%

Quality of COSY Calculation

Primary benchmark for spin precession calculation:

The F.F. ratio should be independent of reconstructed target variables



F.F. ratio vs. target variables, Q^2=2.5 GeV^2, ε=0.79

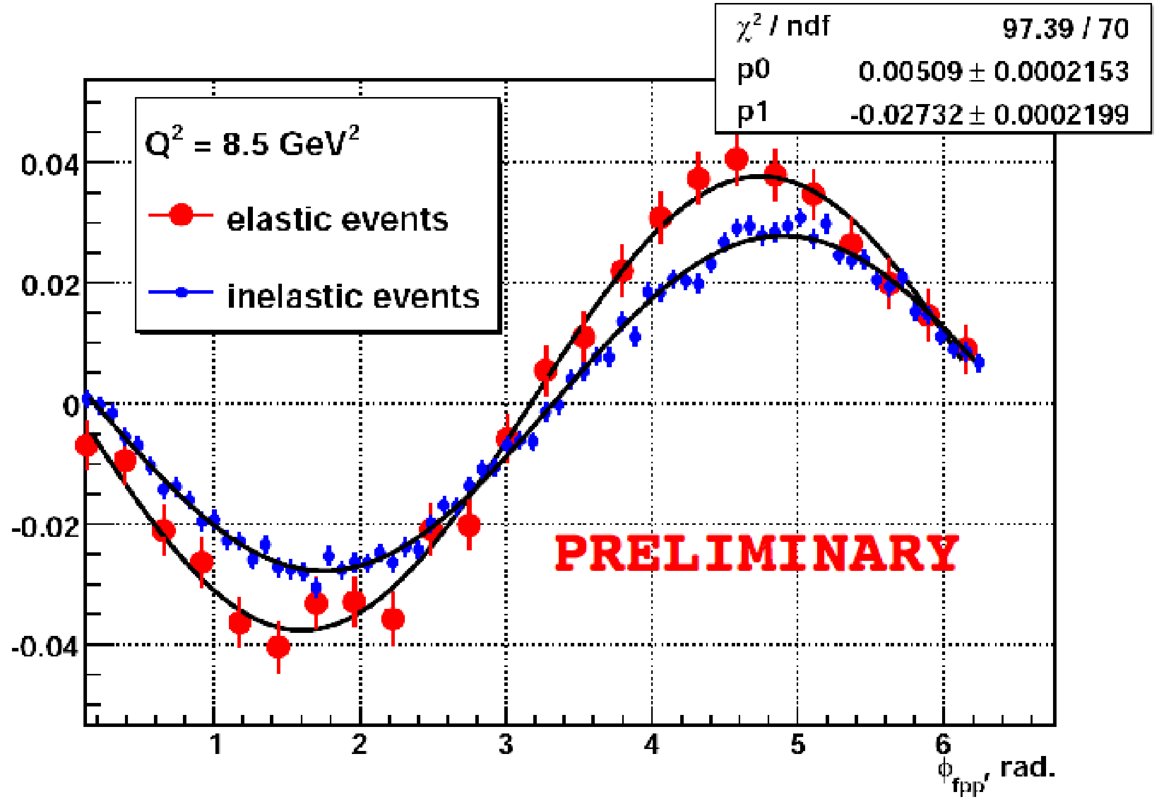
Red=Ideal dipole approximation, Black=COSY

Polarization of Background

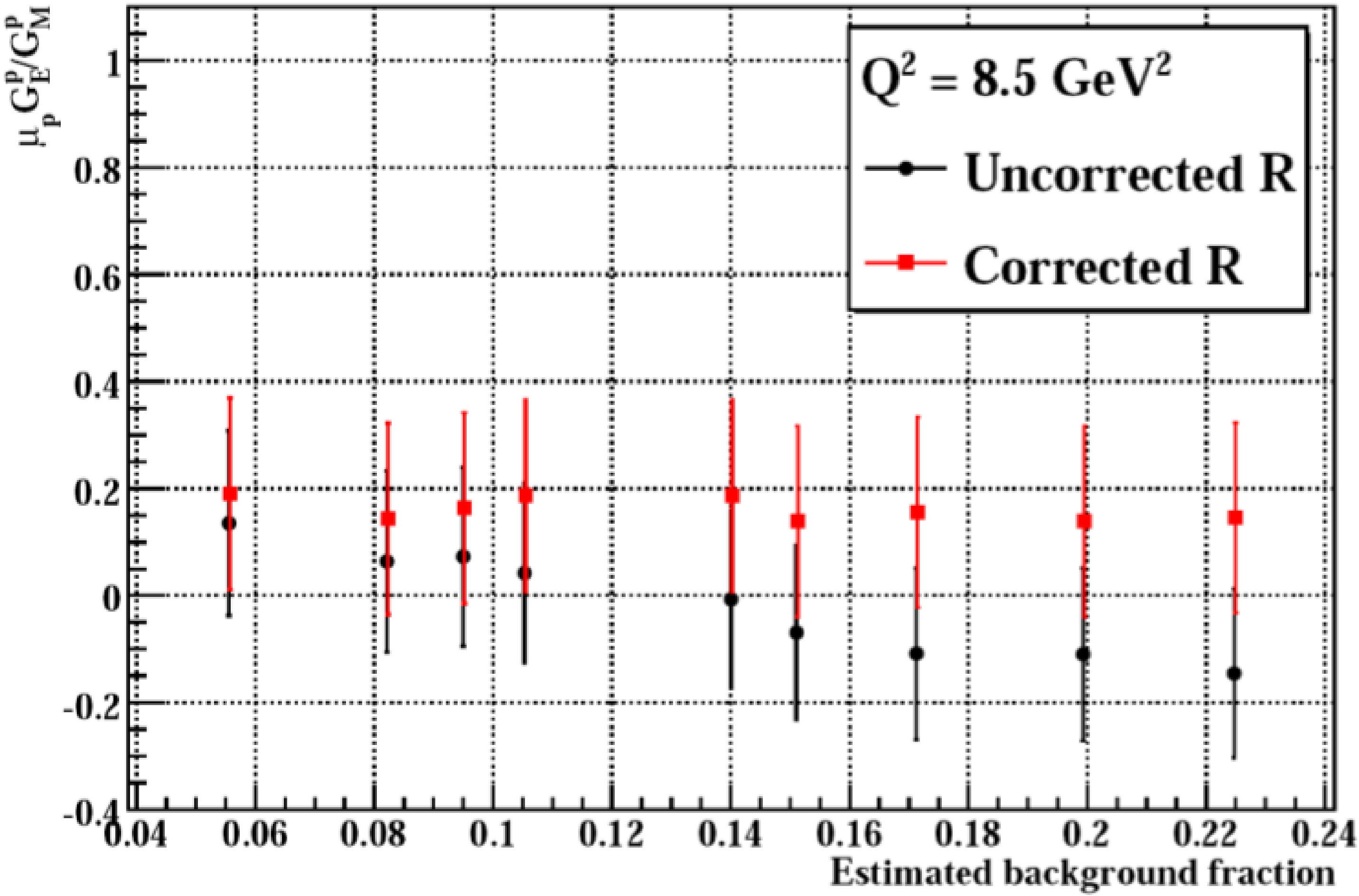
-inelastic asymmetry is of a different size and phase shift than elastic

- corresponds to a large NEGATIVE F.F. ratio

- represents a significant correction at Q^2=8.5 GeV^2, but the uncertainty in the correction is much smaller

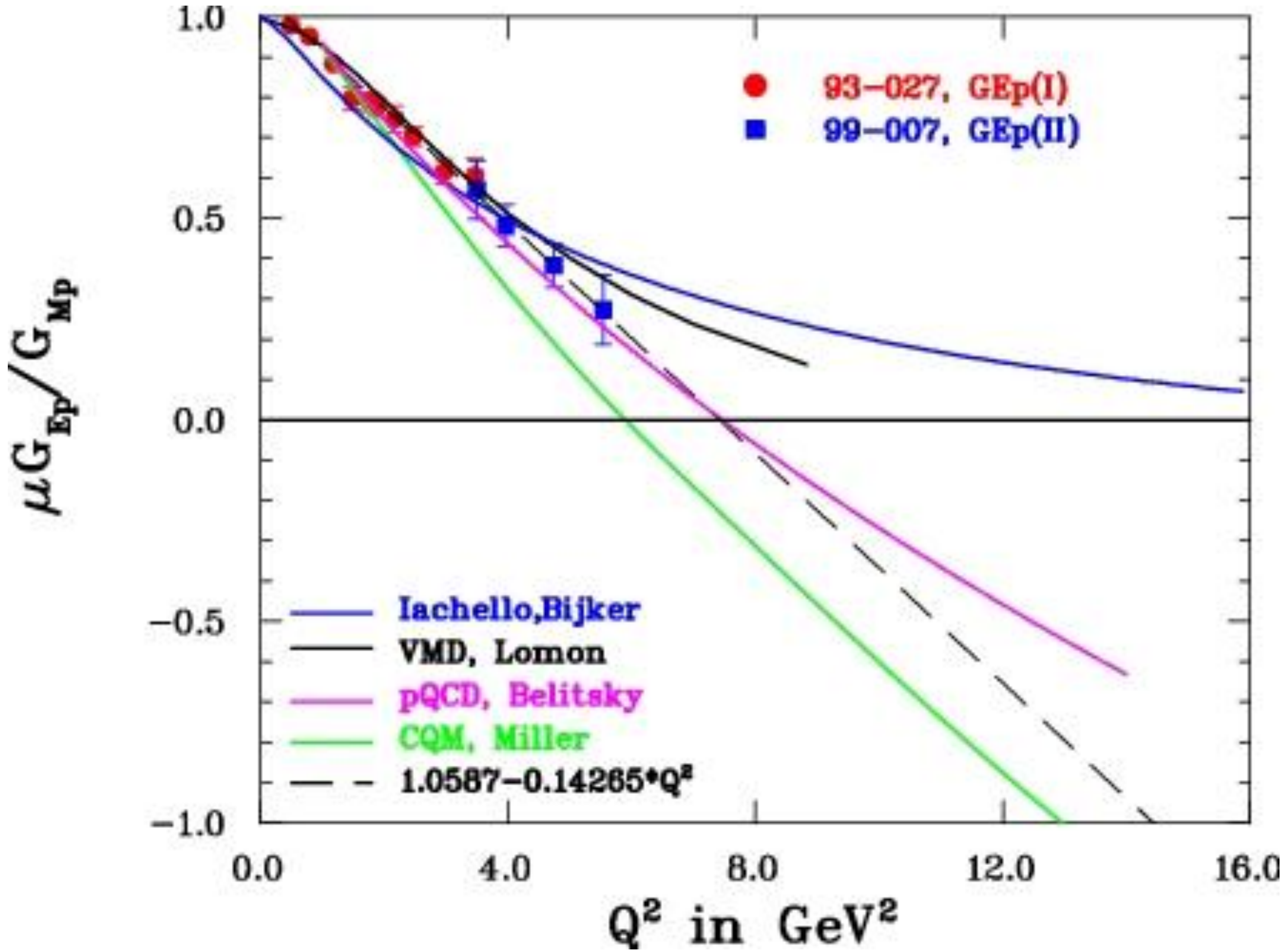


Comparison of elastic and inelastic asymmetries at 8.5 GeV^2



- If the background correction is handled properly, then the background-corrected form factor ratio does not depend on the width of the cuts; i.e., the amount of background accepted by the cuts
- The background increases rapidly as the cuts are opened up at Q^2=8.5 GeV^2, and the “raw” F. F. ratio drops accordingly due to the large difference between signal and background polarizations
- The corrected form factor ratio is, however, invariant with respect to the cuts.

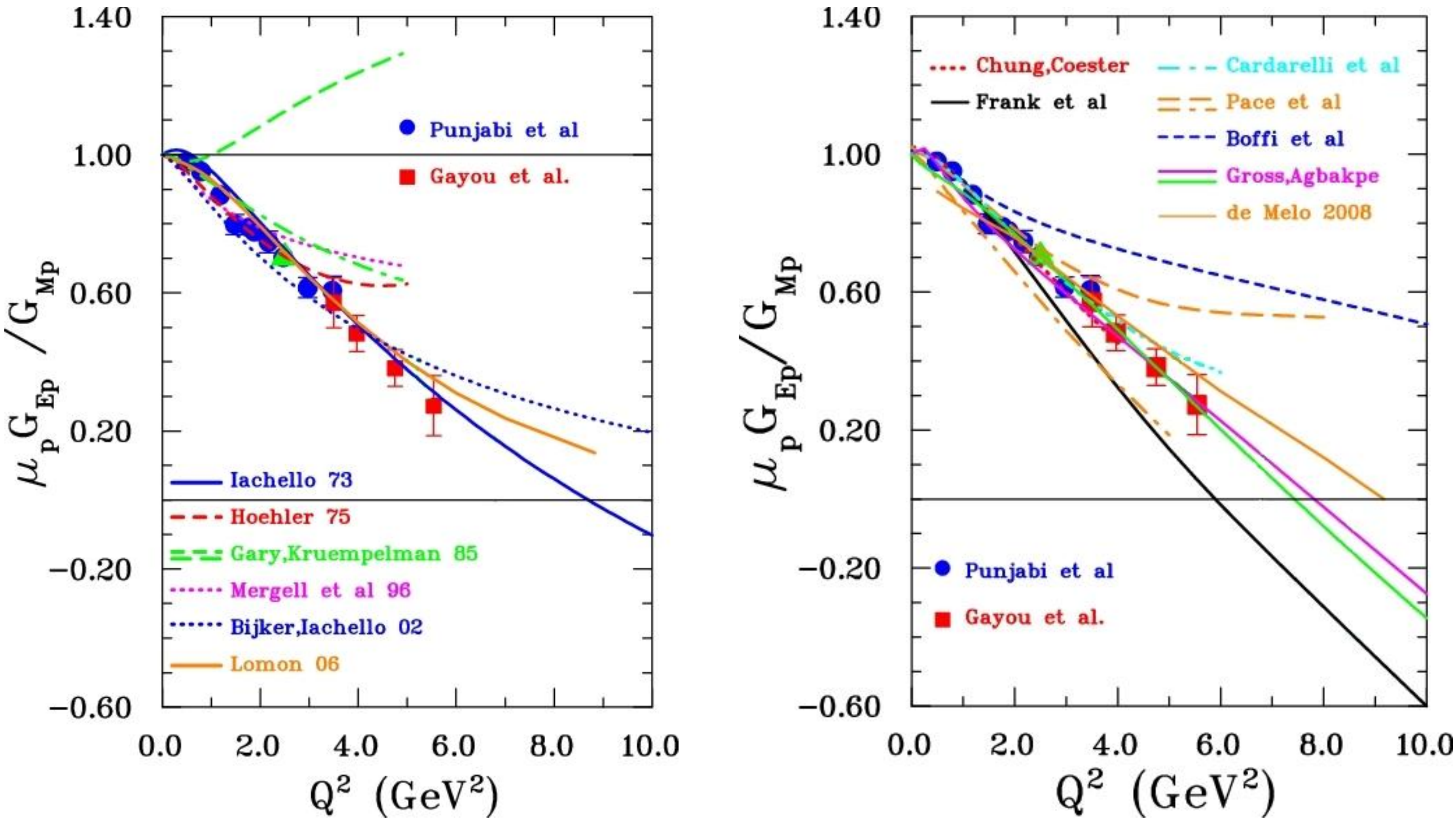
Recoil Polarization Measurements



Measuring Elastic Form Factors at High Q^2 - Technical Details

- Electron solid angle >> proton solid angle - need large acceptance electron detector with good angular resolution
  - Lead-glass Cerenkov detector array
- To isolate (rare!) elastic scattering events, need a magnetic spectrometer to detect proton (good momentum and scattering angle resolution)
- To measure outgoing proton polarization, need a Focal Plane Polarimeter

VMD and CQM



1.40
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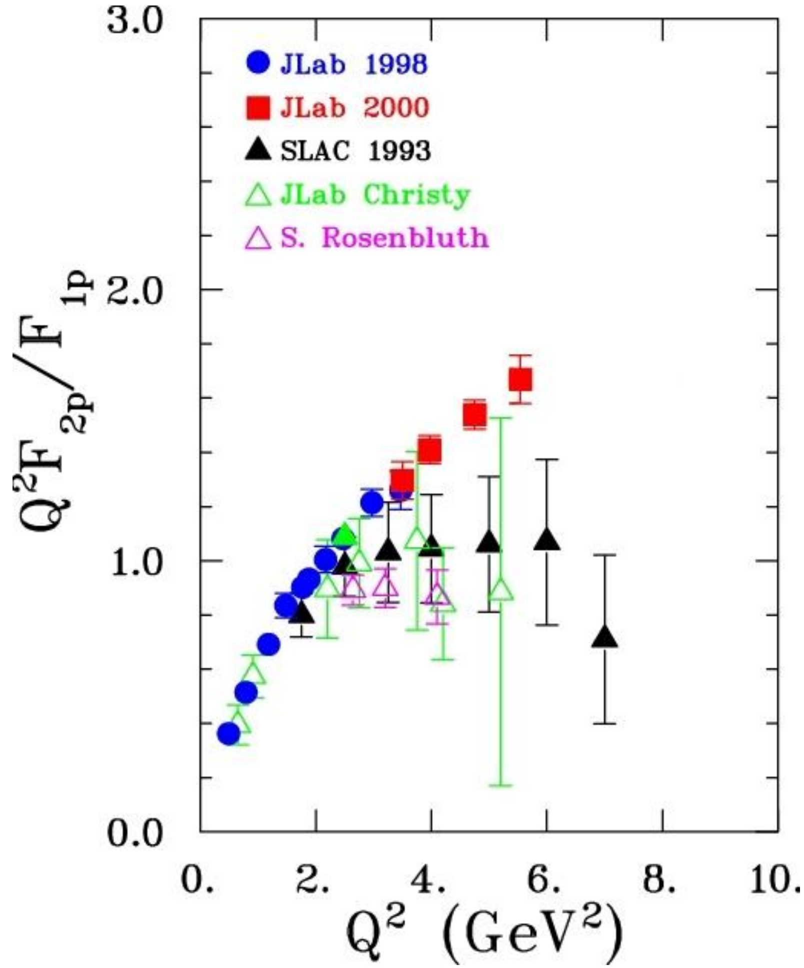
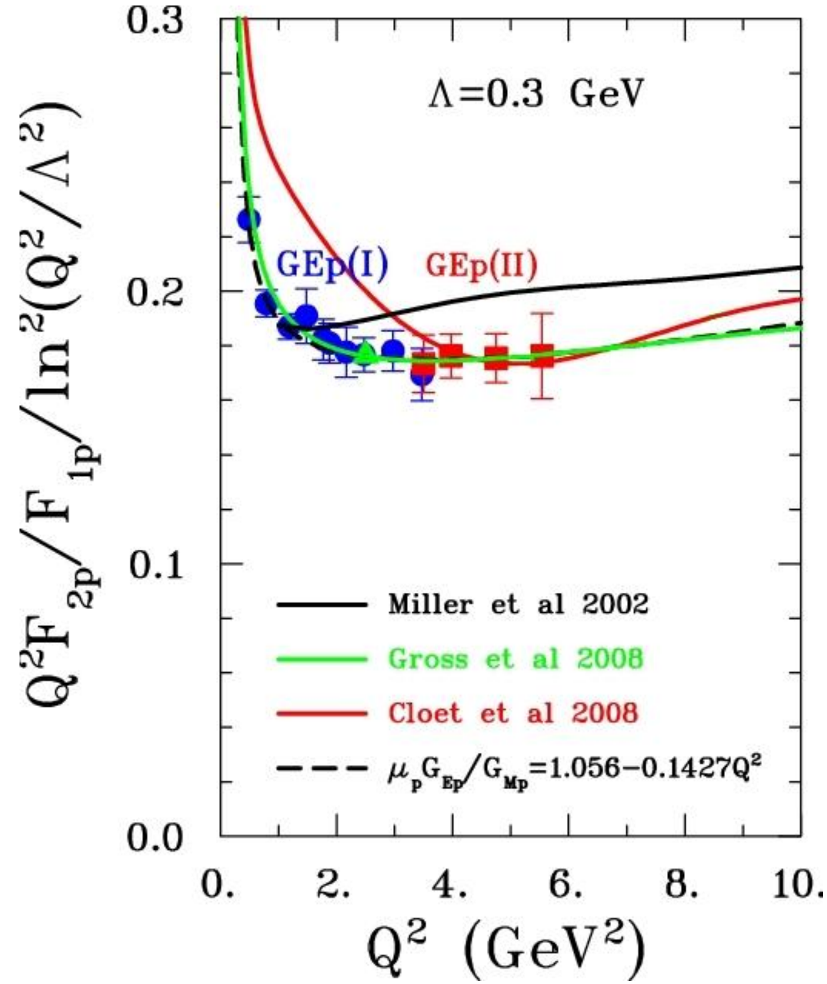
8.0
10.0
$\mu_p G_{Ep}/G_{Mp}$
Q^2 (GeV^2)
Punjabi et al
Gayou et al.
Iachello 73
Hoehler 75
Gary,Kruempelman 85
Mergell et al 96
Bijker,Iachello 02
Lomon 06
Chung,Coester
Frank et al
Cardarelli et al
Pace et al
Boffi et al
Gross,Agbakpe
de Melo 2008

Proton: F2 /F1 and pQCD





Brodsky and Farrar (75):
$Q^2F_2/F_1 \rightarrow$ constant

Belitsky, Ji and Yuan (03):
$Q^2F_2/F_1 \rightarrow \ln^2(Q^2/\Lambda^2)$

Vector Meson Dominance
(Many-parameter Model + QCD-based constraints)

VMD earliest model for nucleon e.m. Form Factors

Virtual photon couples to nucleon through exchange of a vector meson

Iachello's in 1973, first to predict 0 crossing of G_{Ep}: VMD+small structure.

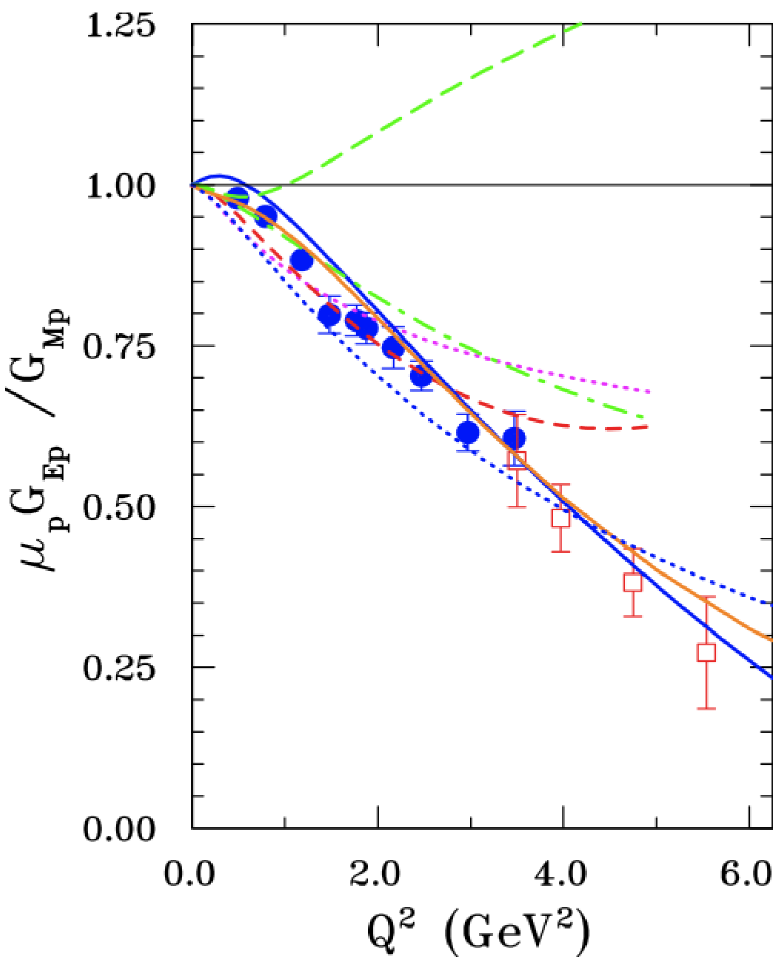
Early work of Höhler (76): ρ(770), ω(782), Φ(1020) and effective ρ'(1250)

Gary and Krumpelman (85) pQCD

Mergell, Meissner and Drechsel (96)

Lomon (01,02) used ρ(770), ω(782), Φ(1020) and ρ'(1450), ω'(1419), 11 parameters.
Lomon (06) revised fit better for G_{En}.

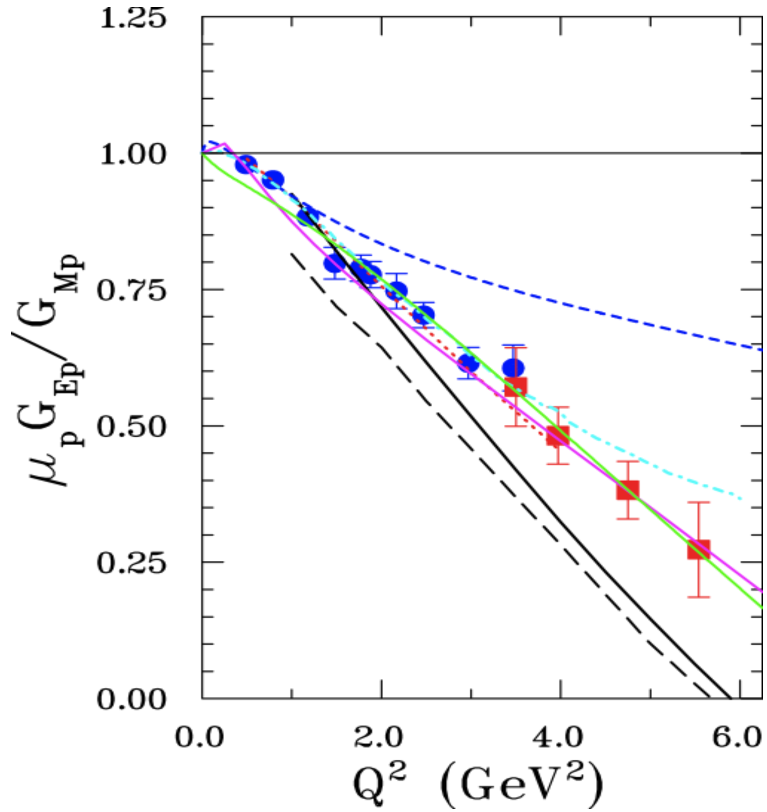
Bijker and Iachello (02)



Constituent Quark Models (Understanding the Dynamics)

Initially proposed by Isgur & Karl (78)
Early non-relativistic CQM

Relativistic CQM: 3 forms of dynamics: instant, point like and light-front



Point-like: Chung & Coester (91) ·········
Cardarelli et al (00) ———

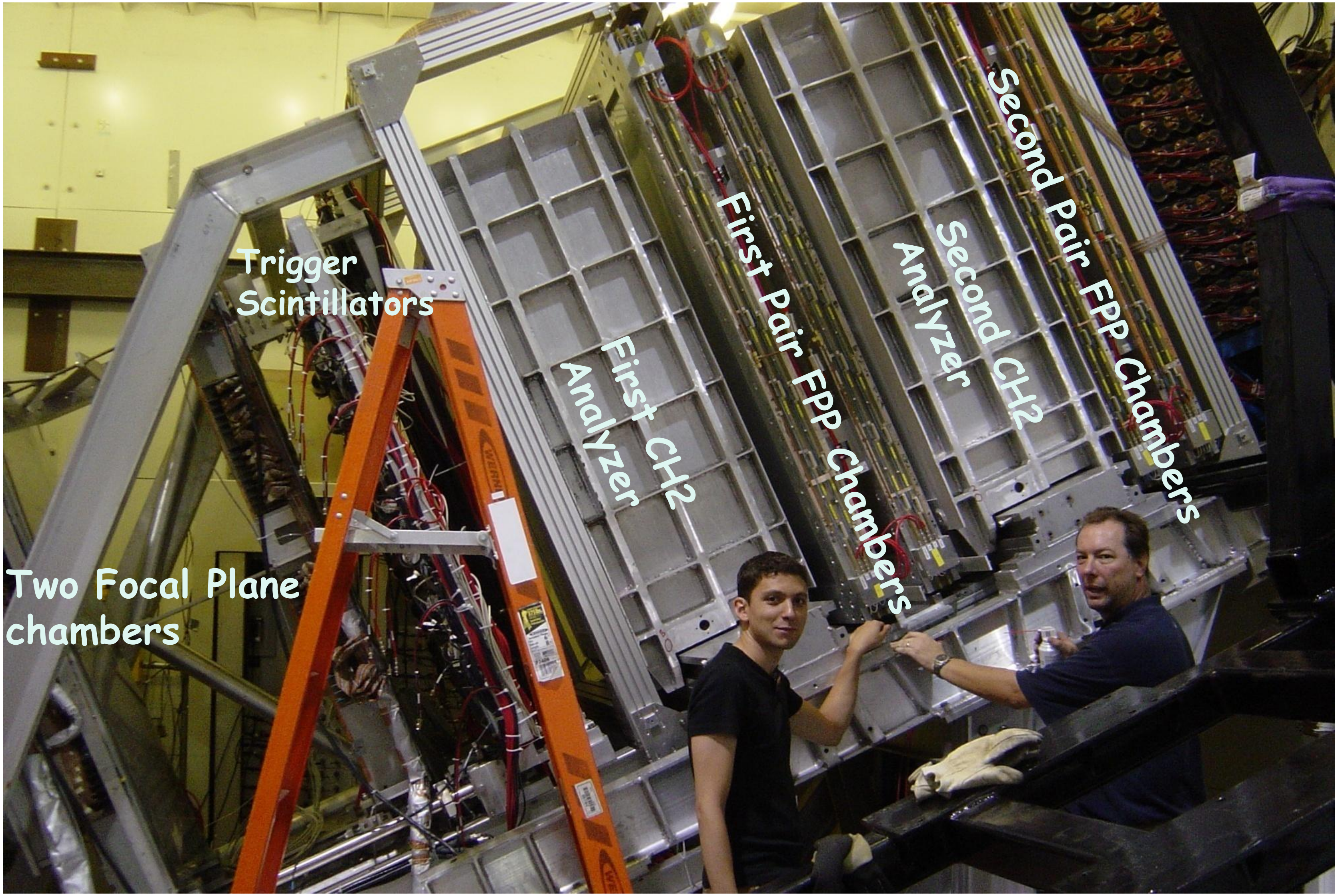
Front form:
Frank, Jennings, Miller (96) - - - - -
G.A. Miller, Frank (02) ———

Goldstone boson: Boffi et al (01) – · –

Cov. spectator: Gross, Agbakpe (04) – – –
Gross, Ramalho, Pena (06) ———

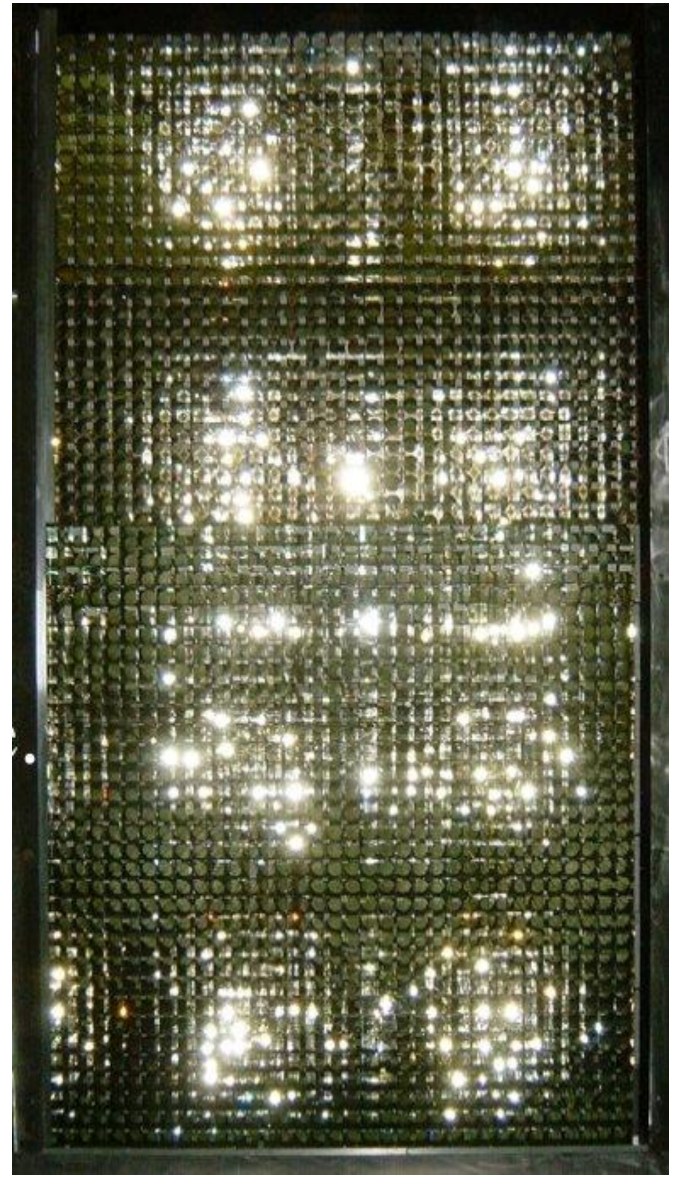
Conclusion: Relativistic CQ are relevant degrees of freedom

Double Focal Plane Polarimeter

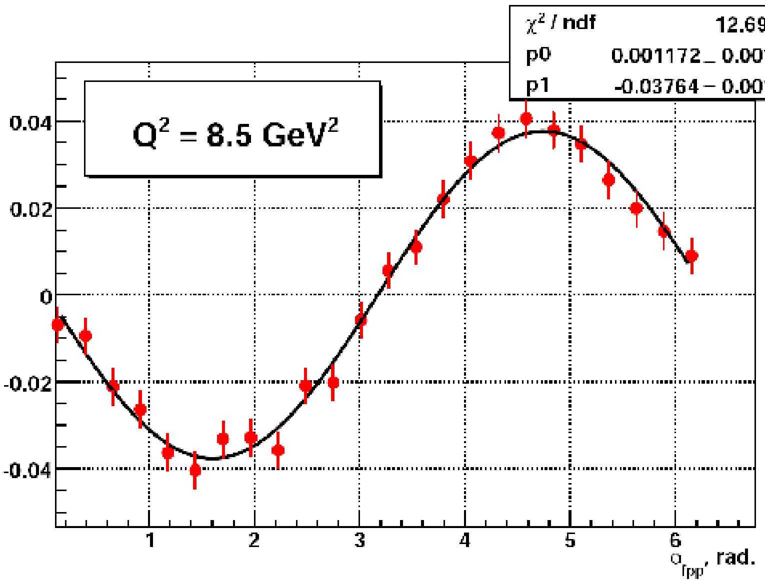


BigCal in Hall C

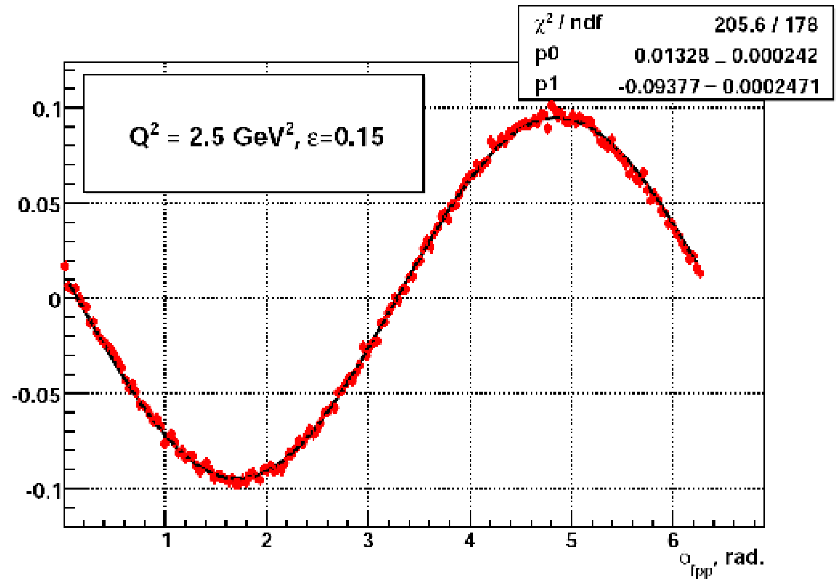
BigCal glass



Focal Plane Asymmetries



8.5 GeV^2



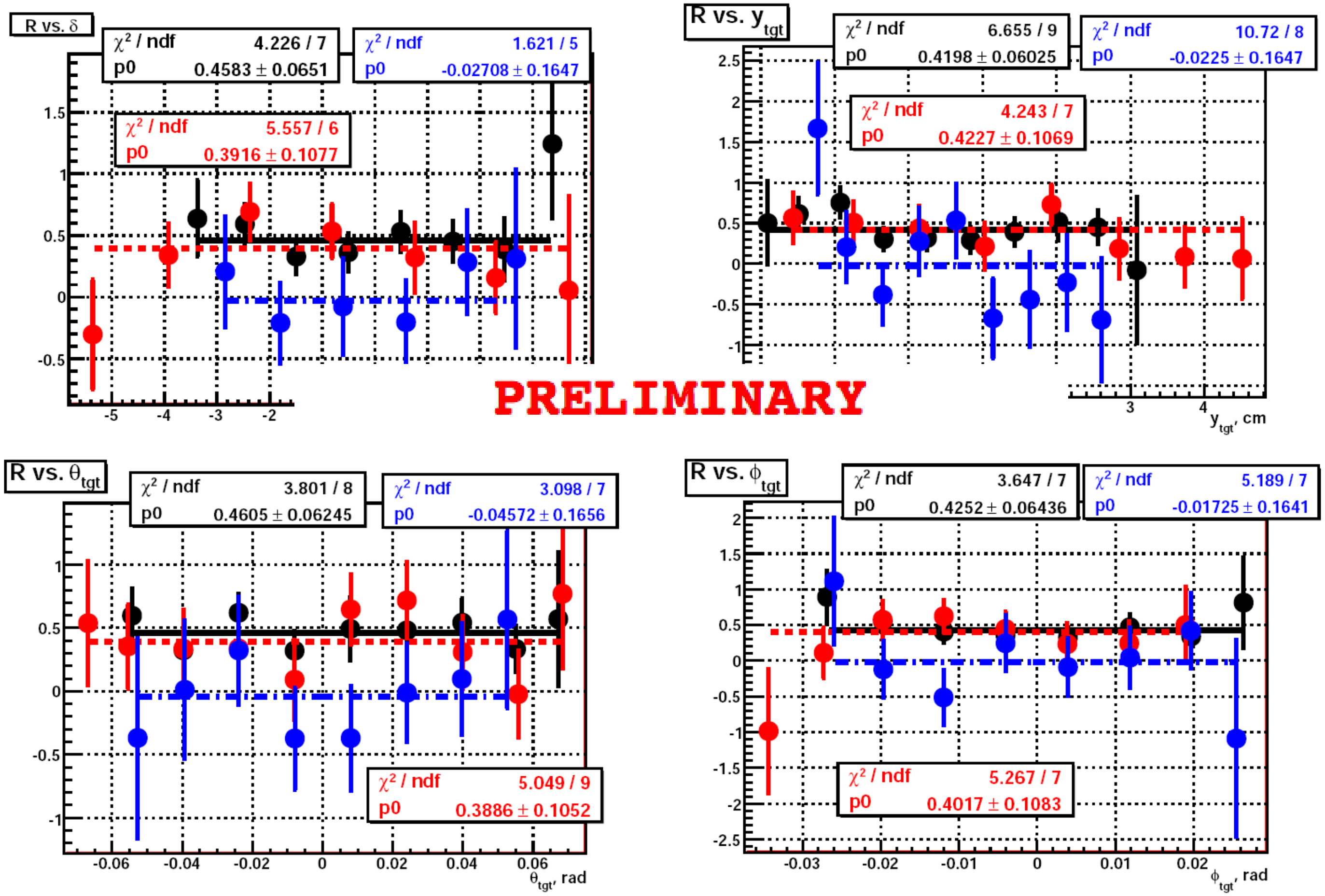
2.5 GeV^2, lowest ε

$$f(\theta,\phi) \propto \sin(\phi+\delta)$$

$$\tan\delta = -\frac{P_t^{fpp}}{P_n^{fpp}}$$

- Focal plane azimuthal asymmetry can be written as a sine curve with a phase shift which is related to the ratio of polarization components at the f.p.
- What is measured by the FPP is the proton polarization after undergoing precession in the HMS magnets

Quality of COSY Calculation



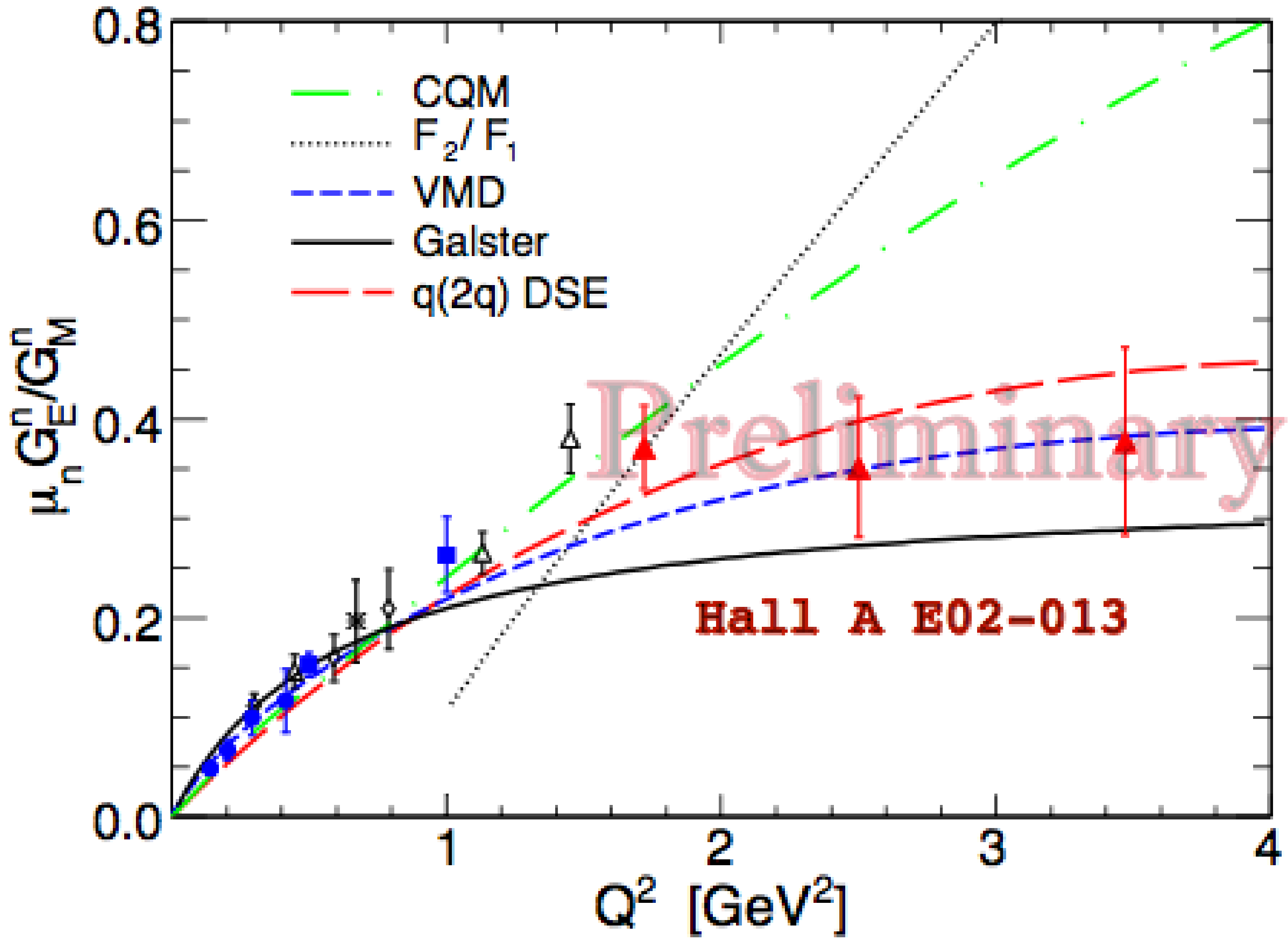
$Q^2 = 5.2\ GeV^2$

$Q^2 = 6.8\ GeV^2$

$Q^2 = 8.5\ GeV^2$

To within statistics, the F.F. ratio is independent of reconstructed target variables for all three high Q^2 data points

Recent JLab Results for G_E^n



(Figure courtesy of B. Wotjekhowski)

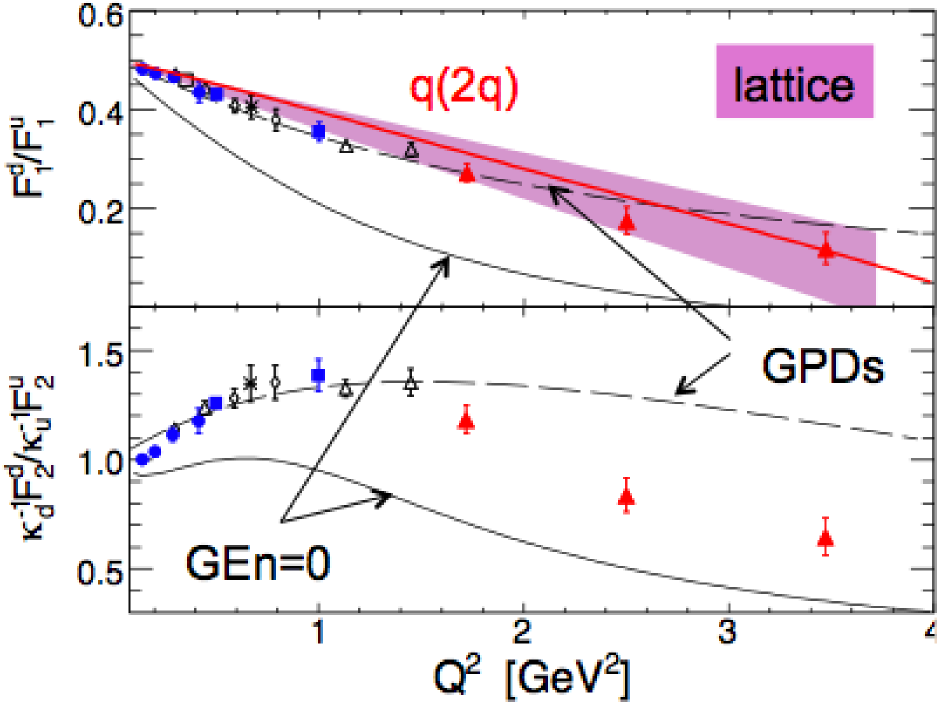
F1(2)d/F1(2)u with proton and neutron FFs

$$F_1 = \frac{G_E + G_M}{1 +}$$

$$F_2 = -\frac{G_E - G_M}{1 +}$$

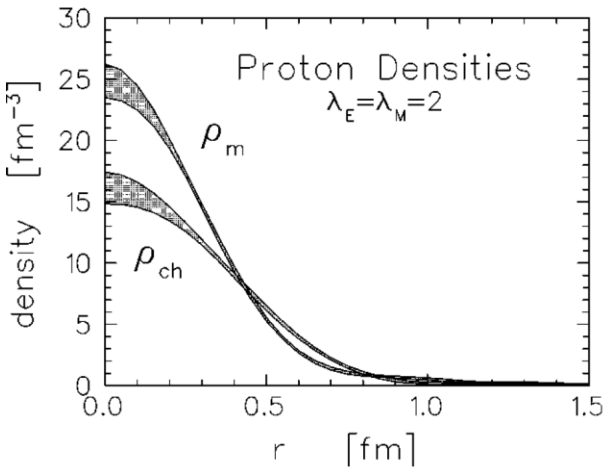
$$F_1^u = 2 F_{1p} + F_{1n}$$

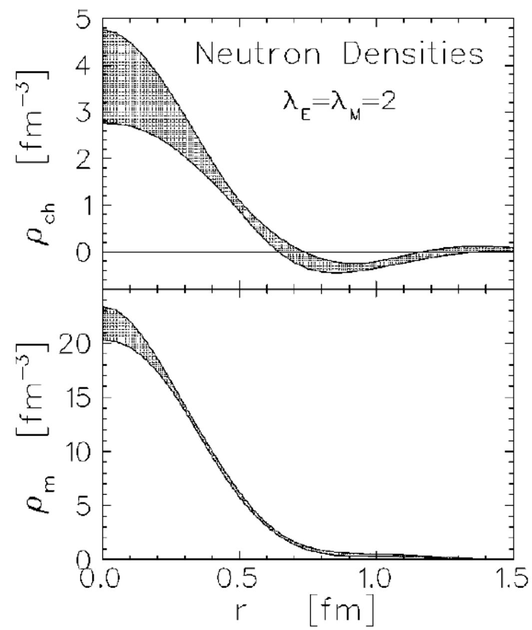
$$F_1^d = 2 F_{1n} + F_{1p}$$



Lattice calculation => very good agreement with the trend, need accuracy
q(2q) DSE => too good, may be a signature of dominant degrees of freedom
Our data allow to constrain E^d and E^u GPDs much better than was possible

Charge and Magnetization Densities





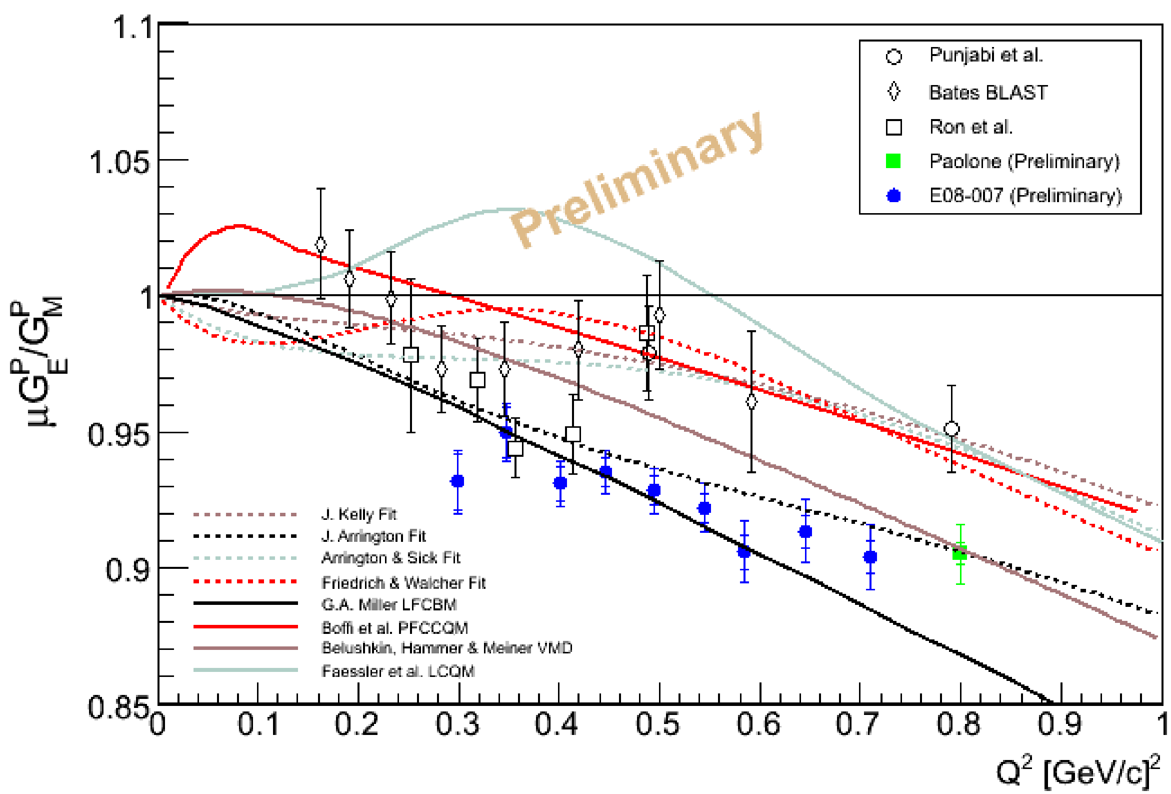
-Interpretation of FF's in terms of charge/mag. densities complicated by relativistic effects - Kelly (2002) attempts to address this.

-Proton charge distribution "broader" than mag. Distribution.

-Neutron has a positive core, with negative exterior (pion cloud?).

-G. Miller calculation indicates different u/d quark distributions

E08007 preliminary results

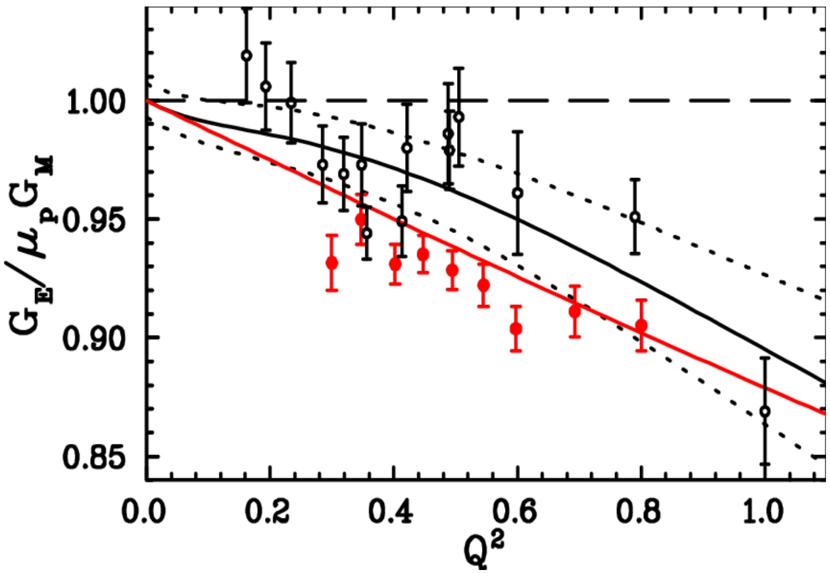


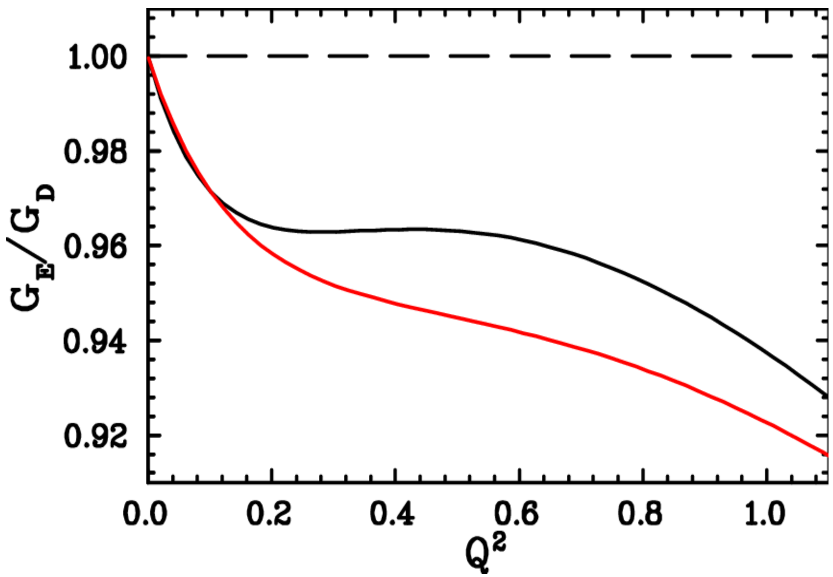
- Smooth slow falling off. A few percent below typical expectations.
- No obvious indication of "Structure".
- Agreement with independent analysis of Paolone at 0.8 GeV^2.
- No obvious trend to rise quickly to unity at the lowest Q^2 point.
- None of the existing models & fits can well describe the new data.

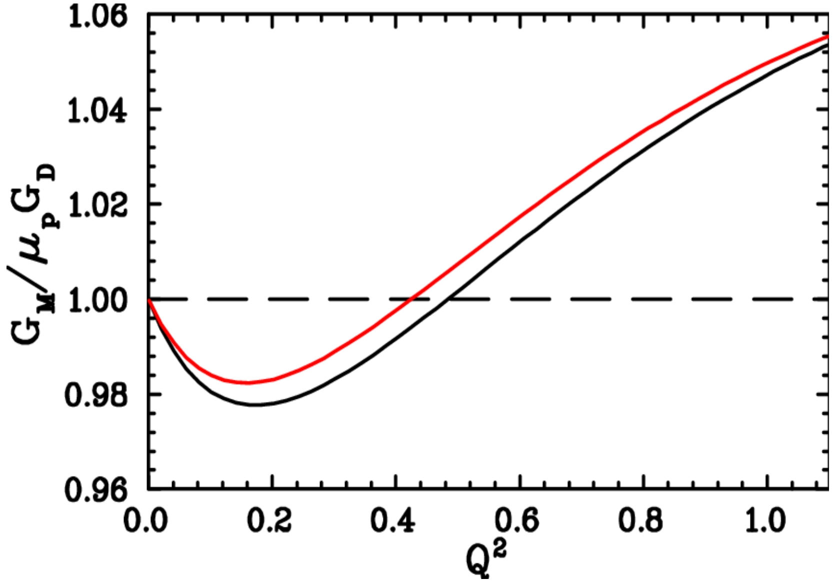
- Disagreement with
  - GEp-I : reanalysis with tighter elastic cuts leads to agreement at 0.5 GeV^2, 0.8 GeV^2 to be investigated.
  - LEDEX : preliminary reanalysis lowers into agreement.
  - Internal consistency is expected within Jlab data.
  - BLAST: origin of difference needs to be investigated.

Impacts and Future Outlook I

• Global fits of individual form factors by John Arrington.
• Old fit (black) : include all previous data (AMT).
• New fit (red) : add new data and remove lowest point of GEp-I, and highest point of LEDEX.
• Preliminary fits suggest lower G_E (~2%).







Impacts and Future Outlook II

- Proton Zemach radius:

$$\Delta_Z = -2\alpha Z \frac{m_e m_p}{m_e + m_p} r_Z$$

$$r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[\frac{G_E(Q^2)\,G_M(Q^2)}{1+\kappa_p} - 1\right]$$

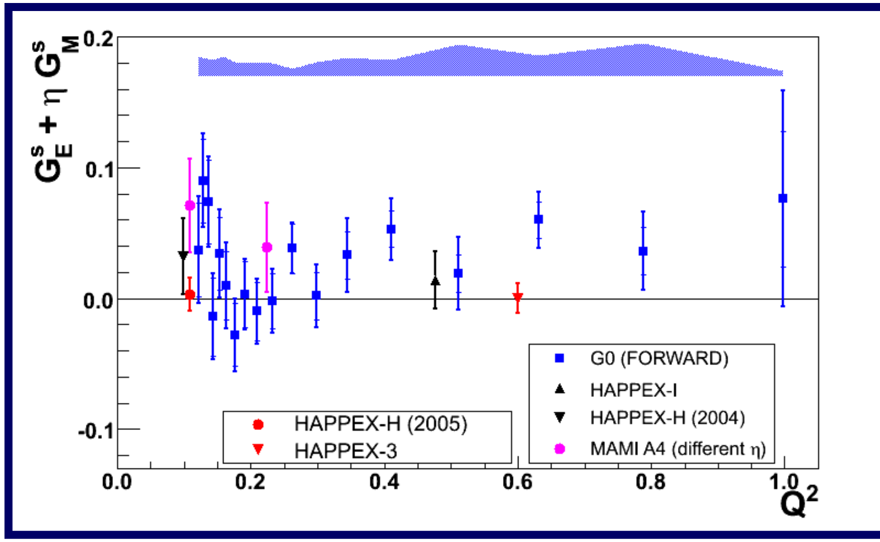
  - FFs at Low Q^2 (<0.3 GeV^2) accounts for ~40% of r_Z. It would shift in the right direction with smaller G_E .

Quantity	value (ppm)	uncertainty (ppm)
$(E_{\rm hfs}(e^- p)/E_F^p) - 1$	1 103.48	0.01
$\Delta_{\rm QED}$	1 136.19	0.00
$\Delta^p_{\mu\rm vp} + \Delta^p_{\rm hvp} + \Delta^p_{\rm weak}$	0.14	
Δ_Z (using [31])	−41.43	0.44
Δ^p_R (using [31])	5.85	0.07
$\Delta_{\rm pol}$ (this work, using [31])	1.88	0.64
Total	1102.63	0.78
Deficit	0.85	0.78

Carlson, Nazaryan, and Griffioen, arXiv:0805.2603v1

- Strange form factor through PV:

  - G0 expect to report backward angle measurements for Q^2 = 0.2 – 0.6 GeV^2 soon.
  - HAPPEX-III expect to run late 2009.
  - Improved FF could shift HAPPEX-III by ~1σ.



Gep-IV in Hall C at JLab

- One of two approved experiments to extend the measurement of G_{Ep}/G_{Mp} to the largest value of Q^2 possible after the 12 GeV upgrade.
- Gep-IV uses base equipme□nt together with existing dectectors in Hall C

  - Hall C SHMS, equipped with the existing Hall C FPP, for proton detection

  –The existing BigCal detector for electron detector - perfect match to the SHMS