Overview of proton, neutron, and pion form factor measurements

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Nucleon Electromagnetic Form Factors

- **Fundamental properties of the proton and neutron**
  - **Contain information on charge, magnetization distributions**
  - **Connect to distribution, dynamics of quarks in hadrons**

- **Experimental program reinvented over last decade**
  - **Considered by many to be well understood by end of 80s**
  - **New techniques → dramatic advances in coverage, precision**

- **Many implications of these new results**
  - **New information on basic hadron structure**
  - **Precise knowledge of FFs needed by other experiments**
    - *Strangeness contributions to nucleon form factors*
  - **Advances in other programs, relying on same techniques**
    - *Medium modification of nucleon structure*

Unpolarized Elastic e-N Scattering

- **Nearly all of the measurements used Rosenbluth separation**

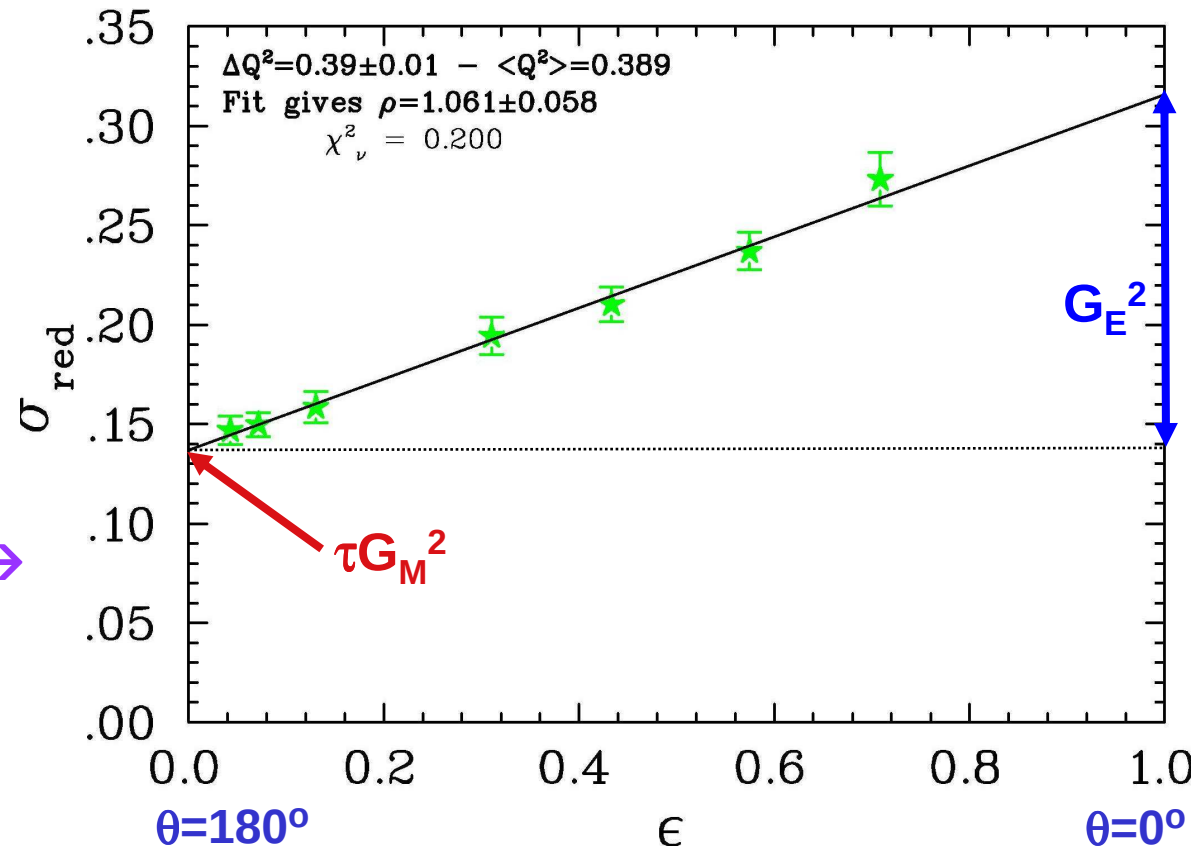
$$\sigma_R = d\sigma/d\Omega\,[\varepsilon(1+\tau)/\sigma_{Mott}] = \tau G_M^2 + \varepsilon G_E^2$$

$$\tau = Q^2/4M^2$$

$$\varepsilon = [\,1 + 2(1+\tau)\tan^2(\theta/2)\,]^{-1}$$

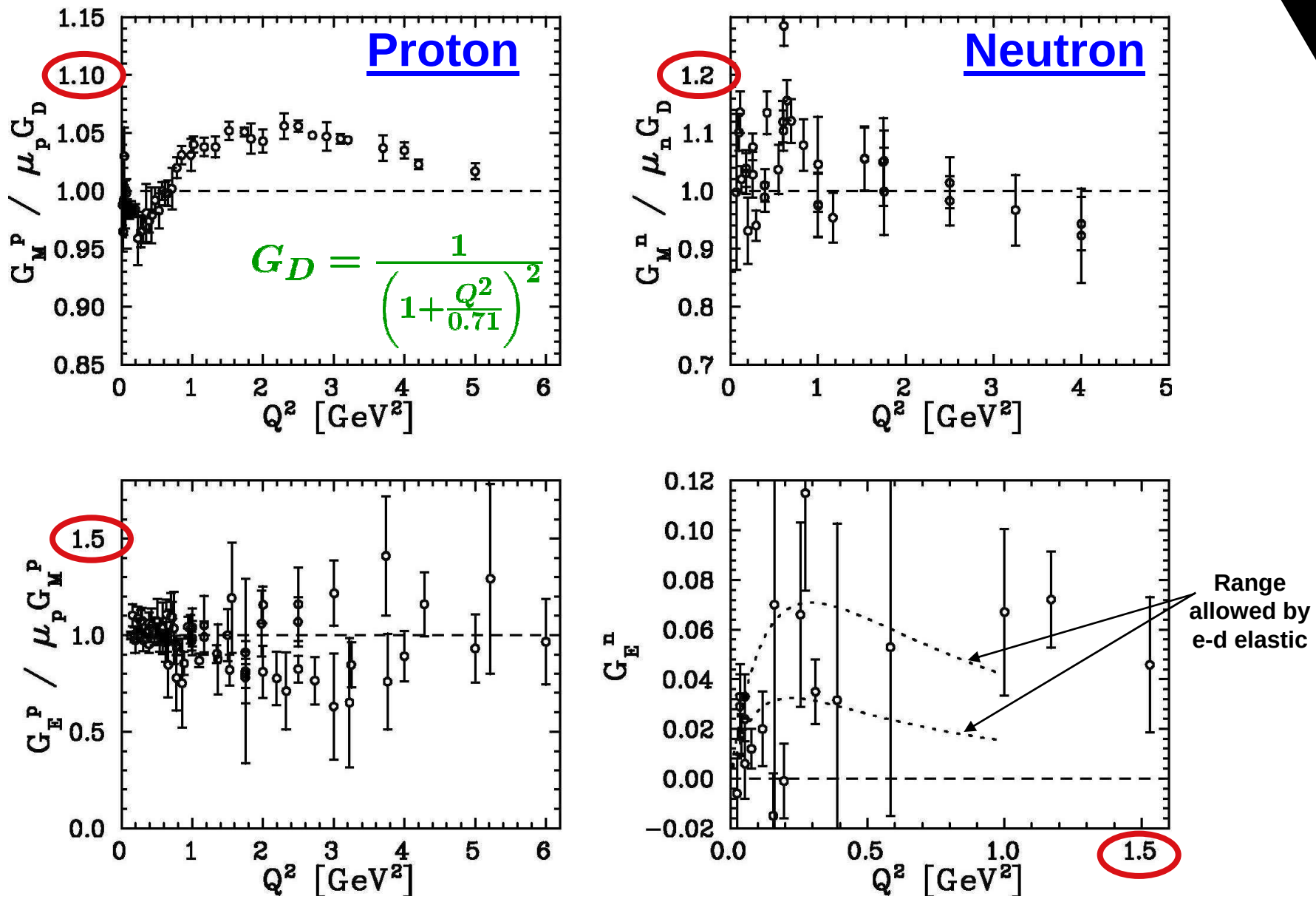
Reduced sensitivity when one term dominates:

- G_M if $\tau << 1$
- G_E if $\tau >> 1$
- G_E if $G_E^2 << G_M^2$ (e.g. neutron)



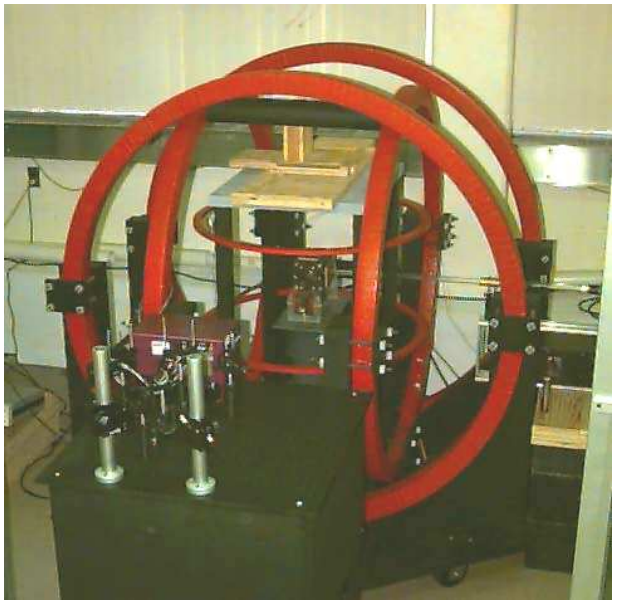
Lack of free neutron target →
corrections for nuclear effects (Fermi motion, FSI, MEC) and proton contributions

Where Were We Ten Years Ago?



New techniques: Polarization and A(e,e'N)

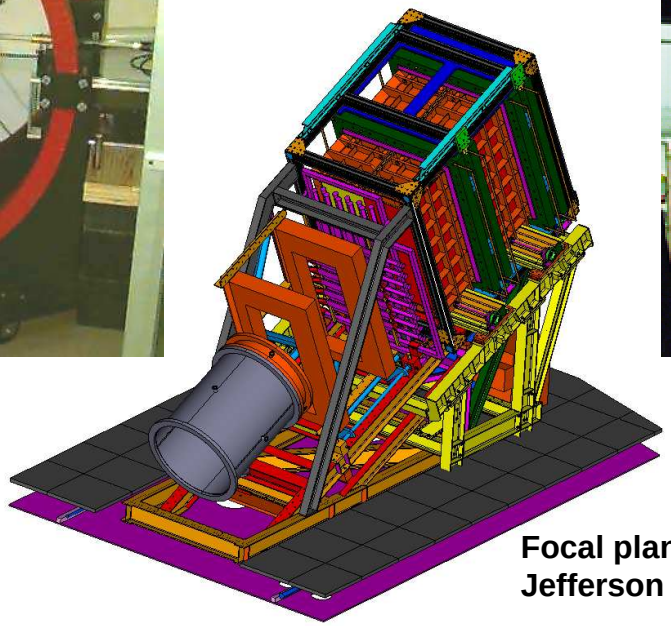
- **Mid '90s brought measurements using improved techniques**
  - **High luminosity, highly polarized electron beams**
  - **Polarized targets (^{1}H, ^{2}H, ^{3}He) or recoil polarimeters**
  - **Large, efficient neutron detectors for ^{2}H, ^{3}He(e,e'n)**
  - **Improved models for nuclear corrections**



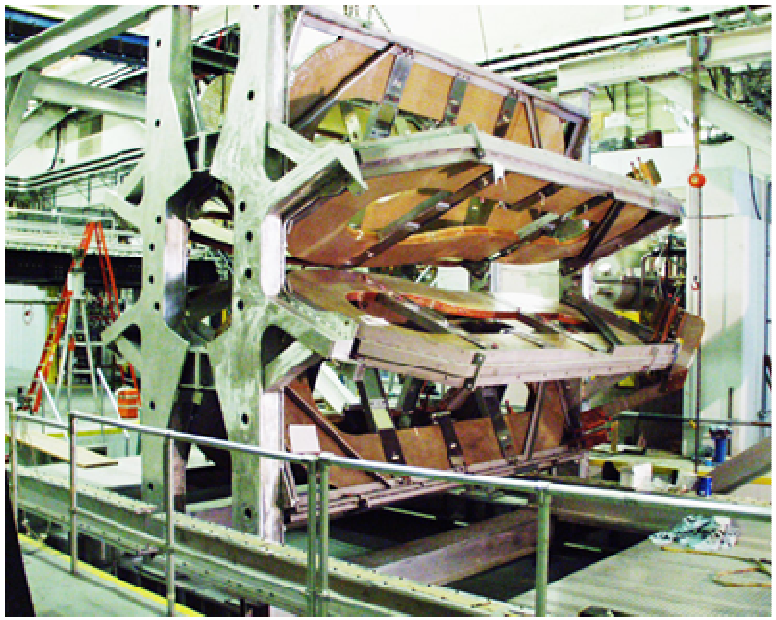
Polarized ^{3}He target

Unpol: $\tau G_M^2 + \varepsilon G_E^2$

Pol: G_E/G_M



Focal plane polarimeter – Jefferson Lab



BLAST at MIT-Bates

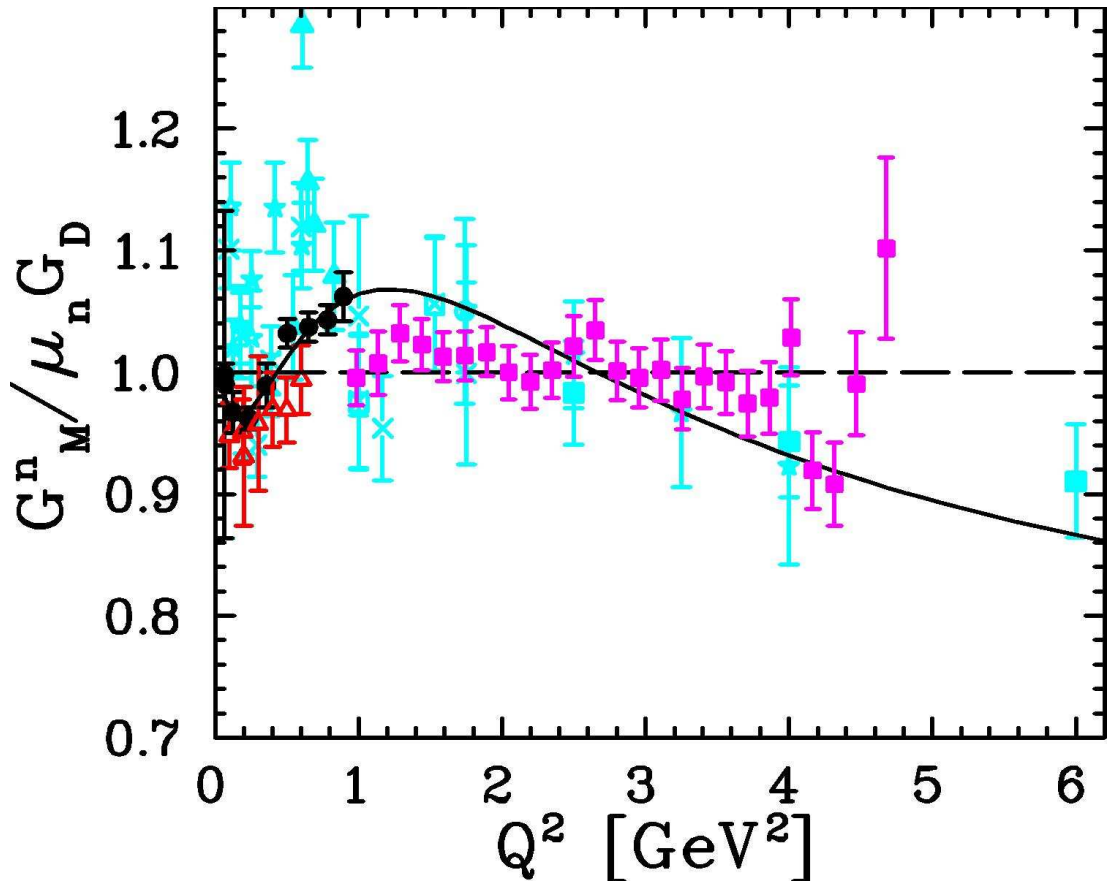
Neutron Magnetic Form Factor

- **Neutron form factor measurements**
  - 1997: Mainly ^{2}H(e,e'), few ^{2}H(e,e'n), ^{2}H(e,e'n/e,e'p), polarization data
  - Uncertainties and scatter made it difficult to evaluate models

G_{Mn} as of 1997: Inclusive, ratio, and polarization measurements

Since 1997: new polarization, ratio measurements

+CLAS (JLab Hall B) preliminary

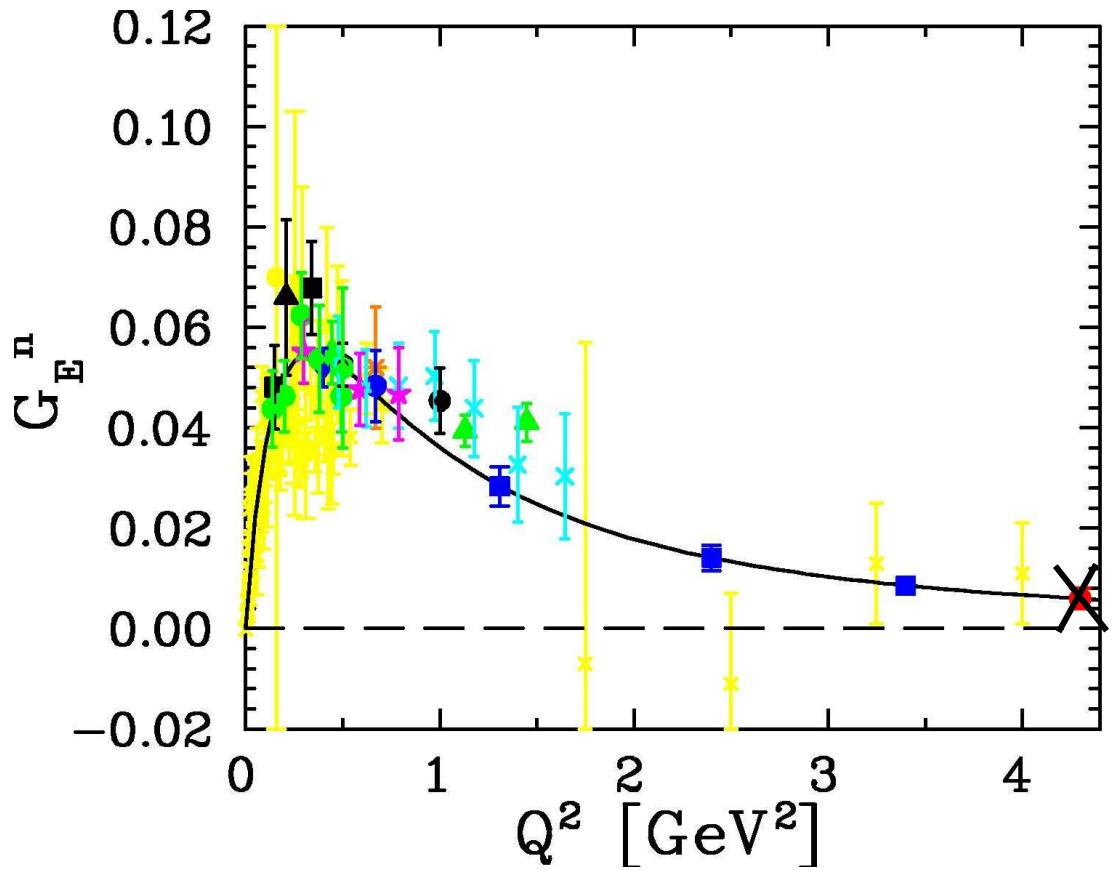


Neutron Electric Form Factor

- **Neutron form factor measurements as of ~1997**
  - G_{En} very poorly known
  - Mostly from elastic e-d → very large model-dependence

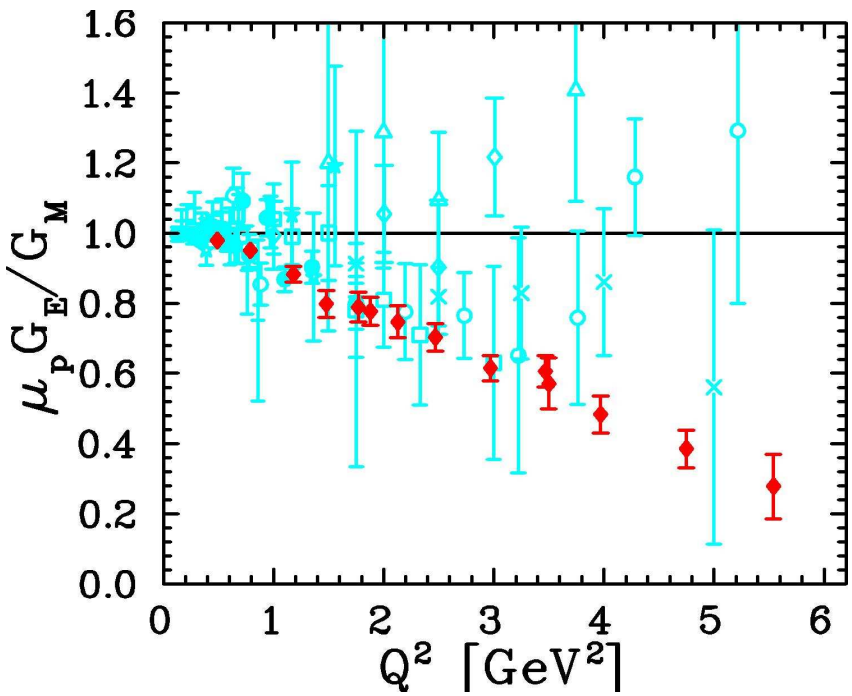
G_{En} as of 1997: elastic e-d and polarization measurements

Since 1997: ^{2}H and ^{3}He polarized target and recoil polarization data, along with improved e-d analysis and projected future measurements

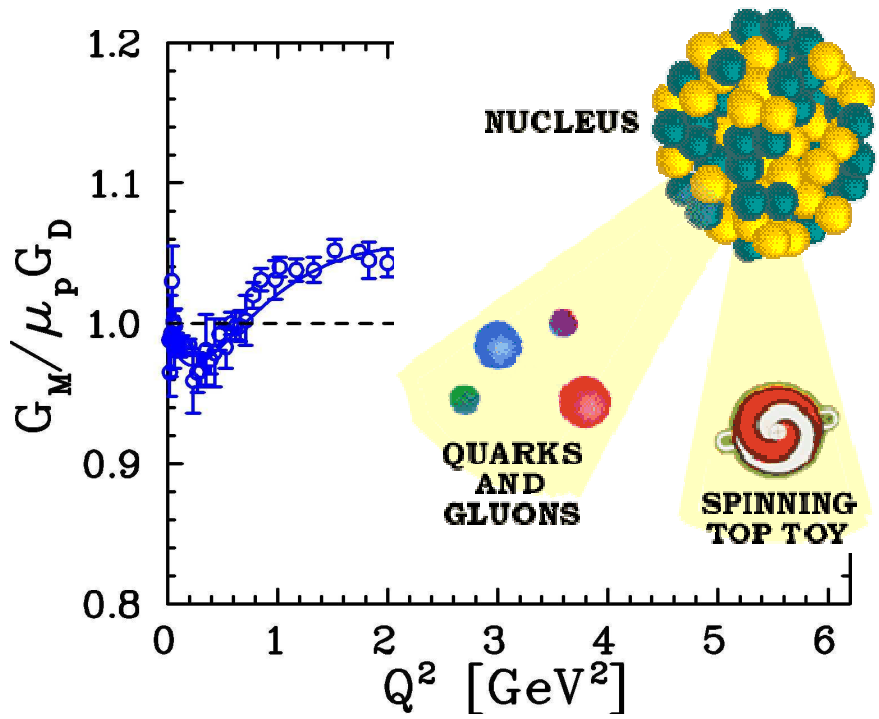


Proton Electric Form Factor

- **Proton form factor measurements from Rosenbluth separations**
  - G_{Mp} well measured to 10 GeV^2, data out to 30 GeV^2
  - G_{Ep} well known to 1-2 GeV^2, data to ~6 GeV^2



μ_pGEp/GMp from inclusive Rosenbluth measurements



G_{Mp} from inclusive measurements – data extend to 30 GeV^2

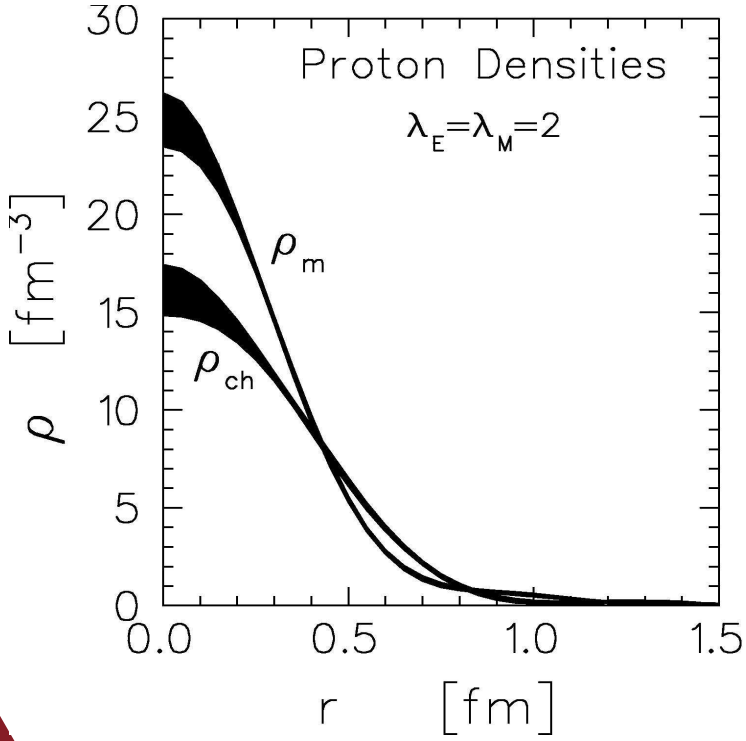
New data: Recoil polarization

Insight from New Measurements

- **New information on proton structure**
  - $G_E(Q^2) \neq G_M(Q^2)$ → different charge, magnetization distributions
  - Connection to GPDs: spin-space-momentum correlations

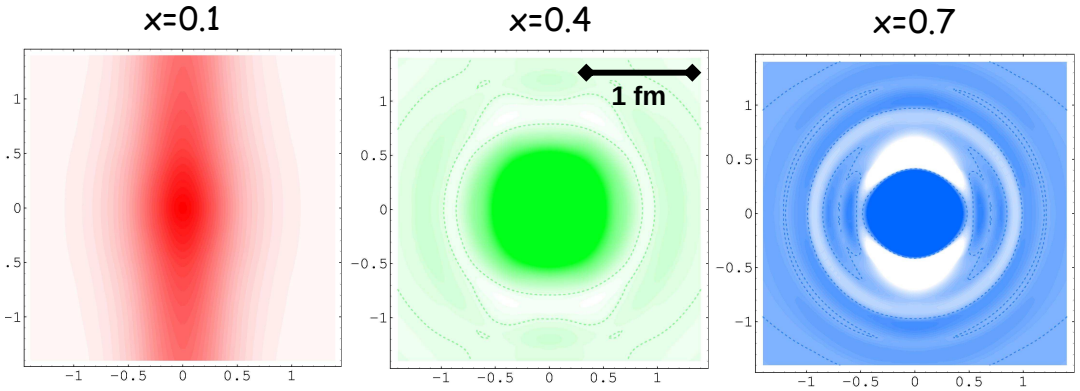
Model-dependent extraction of charge, magnetization distribution of proton:

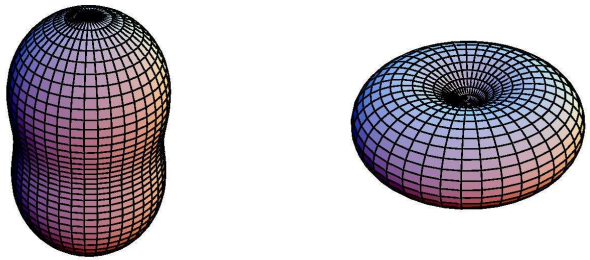
J. Kelly, Phys. Rev. C 66, 065203 (2002)



A.Belitsky, X.Ji, F.Yuan, PRD69:074014 (2004)

G.Miller, PRC 68:022201 (2003)

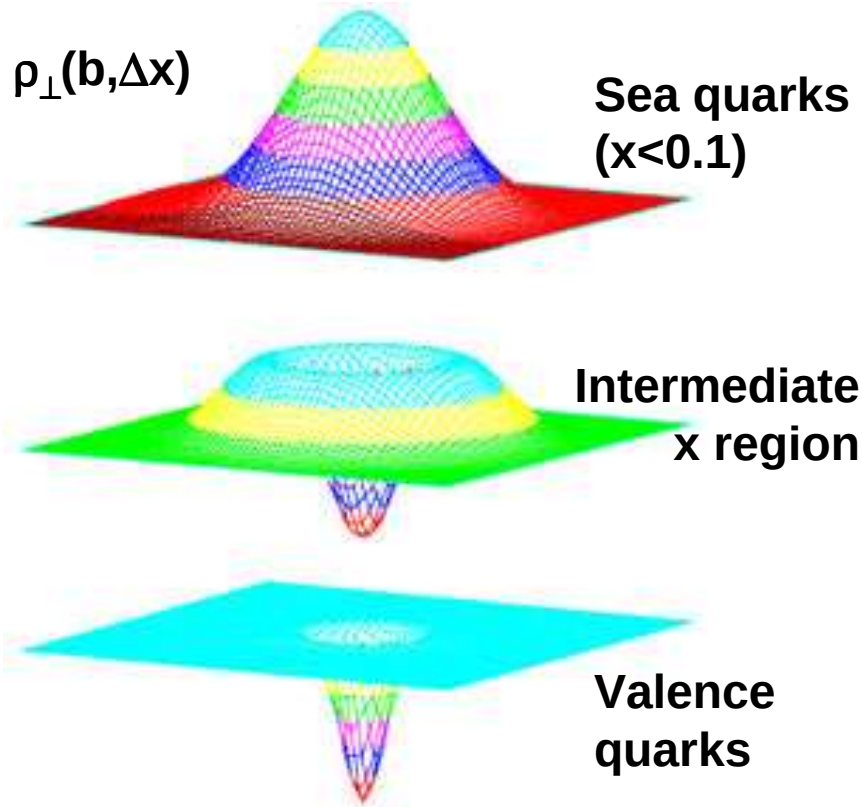




Transverse Spatial Distributions

- **Simple picture: Fourier transform of the spatial distribution**
  - Yields spatial distribution in Breit frame ($p_{init} = - p_{final}$ for proton)
  - **model dependent** corrections in extracting rest frame distributions

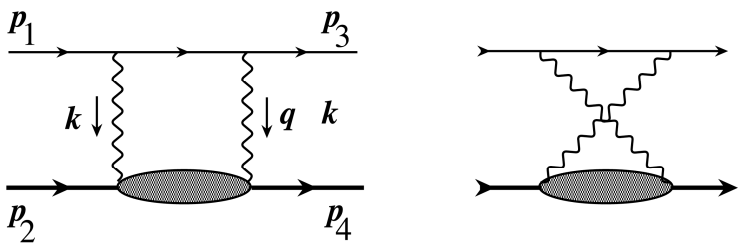
- **New model-independent relation found between form factors and transverse spatial distribution**
  - q(x,b) is quark distribution, b=transverse impact parameter, x=longitudinal quark momentum
  - $\rho_\perp(b) = \sum e_q \int dx\, q(x,b) =$ transverse density distribution in infinite momentum frame (IMF)

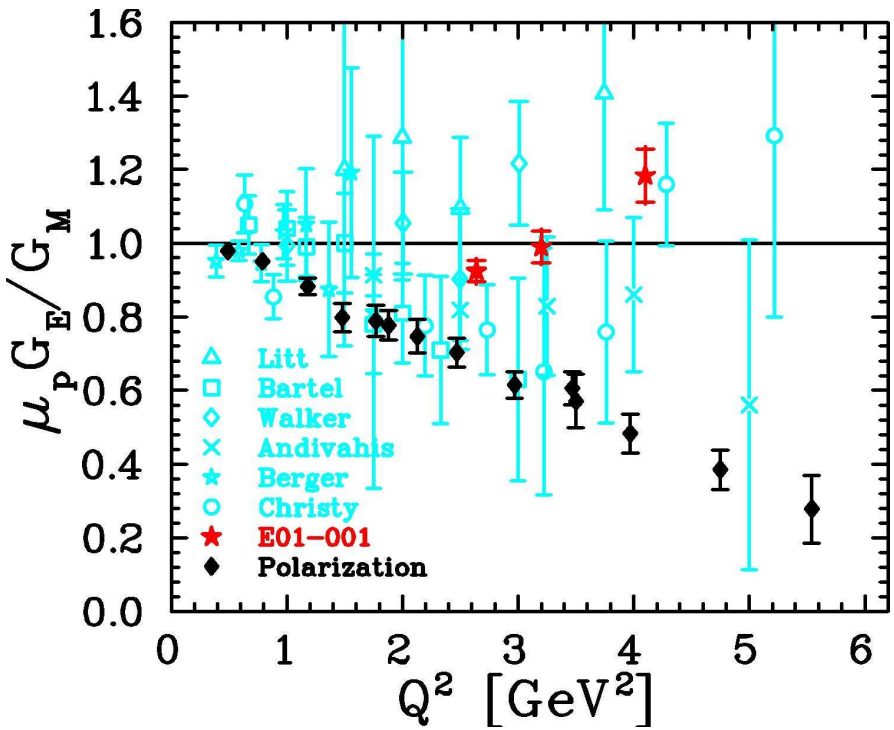


Two Photon Exchange

- **Proton form factor measurements**
  - Comparison of precise Rosenbluth and Polarization measurements of G_{Ep}/G_{Mp} show clear discrepancy at high Q^2
- **Two-photon exchange corrections believed to explain the discrepancy**

P.A.M.Guichon and M.Vanderhaeghen, PRL 91, 142303 (2003)





- **Have only limited direct evidence of effect on cross section**
  - Active experimental, theoretical program to fully understand TPE effects

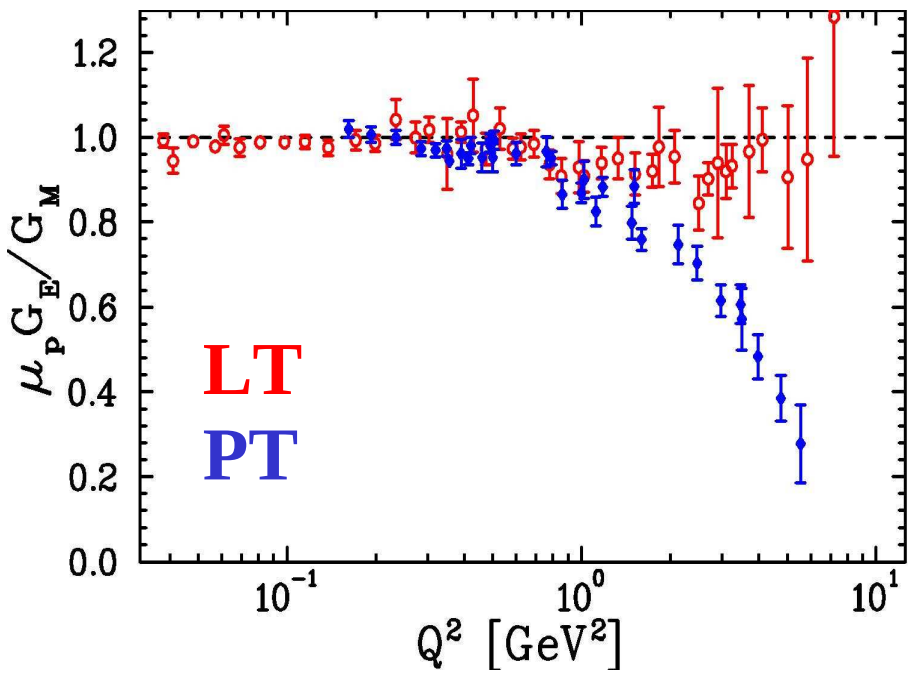
P. G. Blunden et al, PRC **72** (2005) 034612
A.V. Afanasev et al, PRD **72** (2005) 013008
JA, et al, PRC **76** (2007) 035205
J. Carlson, M. Vanderhaeghen,
Ann. Rev. Nucl. Part. Sci. **57** (2007) 171
etc…

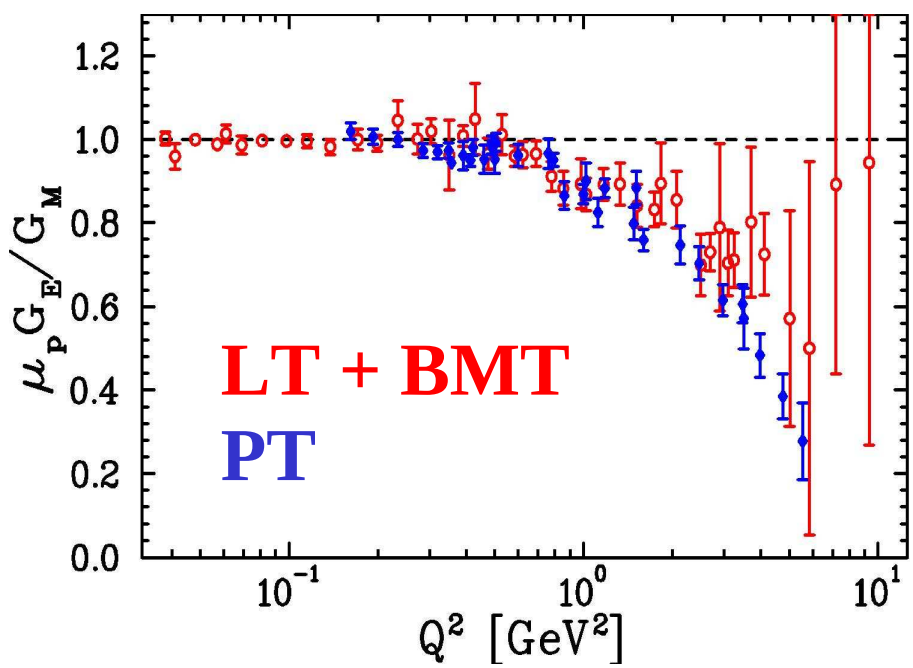
*M.K.Jones, et al., PRL **84**, 1398 (2000)*
*O.Gayou, et al., PRL **88**, 092301 (2003)*
*I.A.Qattan, et al., PRL **94**, 142301 (2005)*

Effect on Rosenbluth (L-T) Extractions

- **Calculation by Blunden, Melnitchouk, and Tjon resolves the discrepancy up to 2-3 GeV²**

P. Blunden, W. Melnitchouk, and J. Tjon, PRC 72, 034612 (2005)





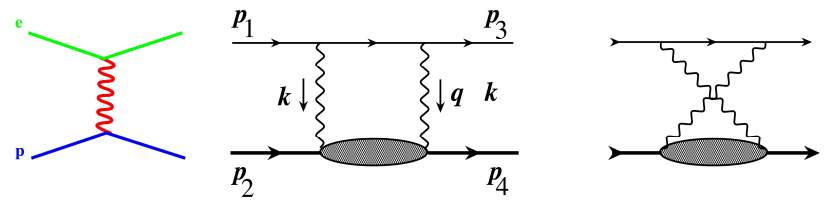
JA, W. Melnitchouk, and J. Tjon, PRC 76, 035205 (2007)

Two Photon Exchange

Golden mode: positron-proton vs. electron-proton elastic scattering

Existing data show evidence for TPE contributions that could explain the discrepancy

JA, PRC 69, 032201 (2004)

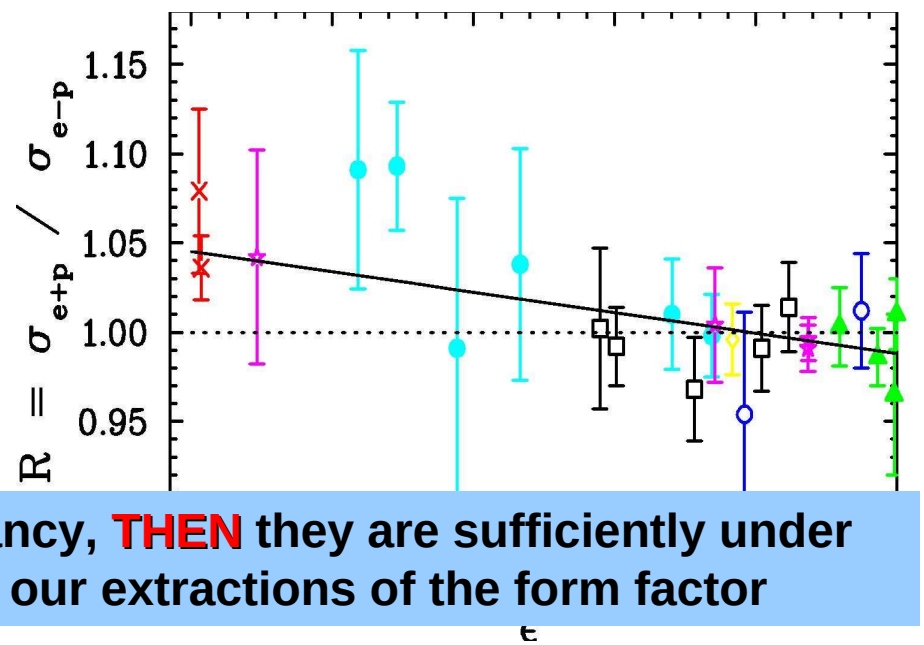


$$\frac{\sigma_{e+}}{\sigma_{e-}} = \frac{(A_{1\gamma}+A_{2\gamma})^2}{(A_{1\gamma}-A_{2\gamma})^2} \approx 1 + 4ReA_{2\gamma}A_{1\gamma}$$

Signal for non-zero TPE is only at 3σ level

Three new e+/e- experiments planned:

- **BINP Novosibirsk** – internal target
- **JLab Hall B** – LH2 target, CLAS (2012)
- **DESY (OLYMPUS)** - internal target



IF TPE <u>fully explains</u> the discrepancy, THEN they are sufficiently under control that they do not limit our extractions of the form factor

TPE Beyond the Elastic Cross Section

- **Two-photon exchange (TPE) corrections**
  - Calculations sufficient for proton form factors
    - *Additional uncertainty at high Q^2*
  - Precise experimental tests of TPE calculations possible for the proton
    - ***Validate calculations needed for other reactions***
  - Important direct and indirect consequences on other experiments
    - ***High-precision quasi-elastic expts.***
    - ***ν - N scattering measurements***
    - ***Proton charge radius, hyperfine splitting***
    - ***Strangeness from parity violation***
    - ***Neutron form factor measurements***

D.Dutta, et al., PRC 68, 064603 (2003)

JA, PRC 69, 022201(R) (2004)

H.Budd, A.Bodek, and JA hep-ex/0308005

P.Blunden and I.Sick, PRC 72, 057601 (2005)

S.Brodsky, et al., PRL 94, 022001 (2005)

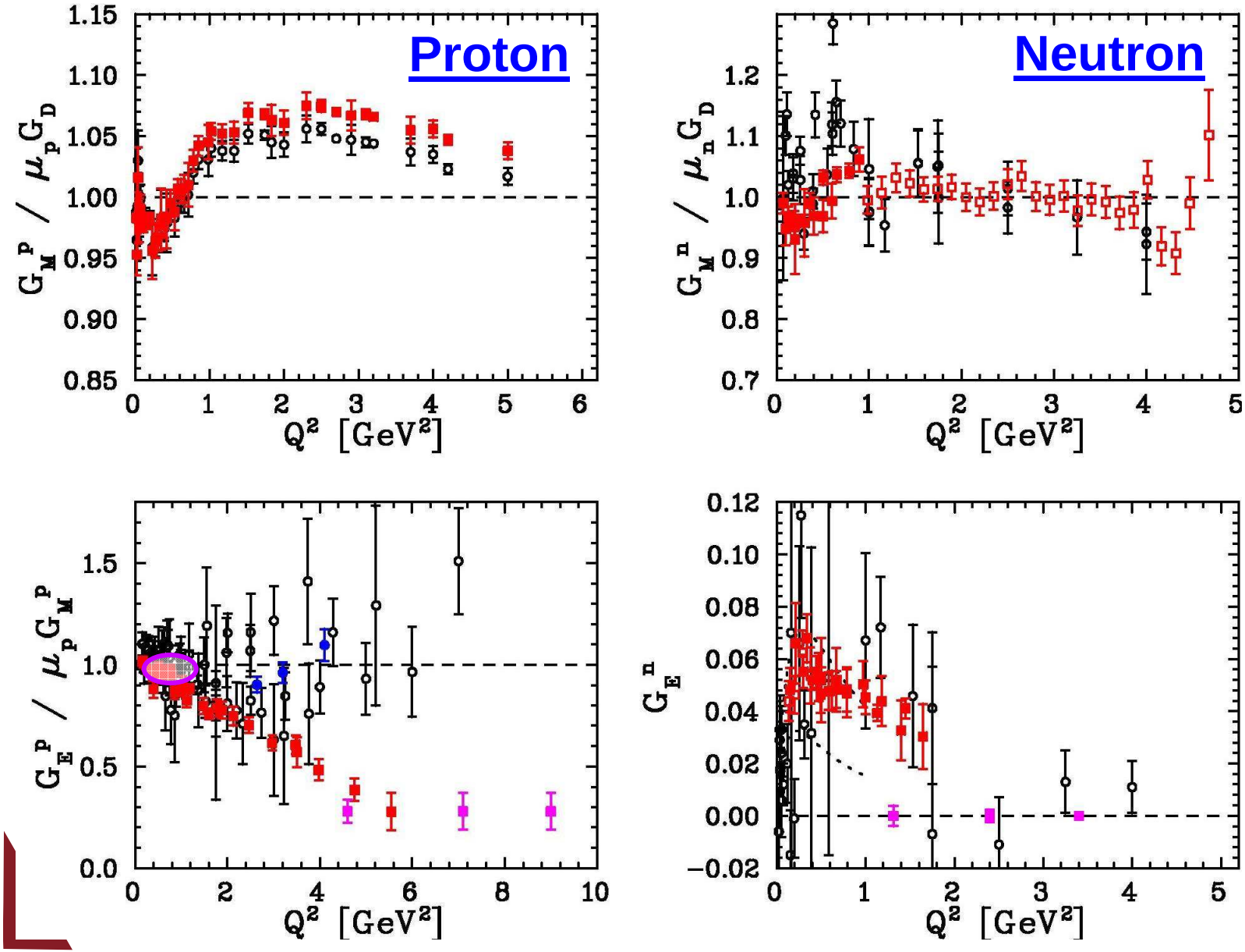
A.Afanasev and C.Carlson, PRL 94, 212301 (2005)

JA and I.Sick, nucl-th/0612079

P.Blunden, W.Melnitchouk, and J.Tjon, PRC72, 034612 (2005)

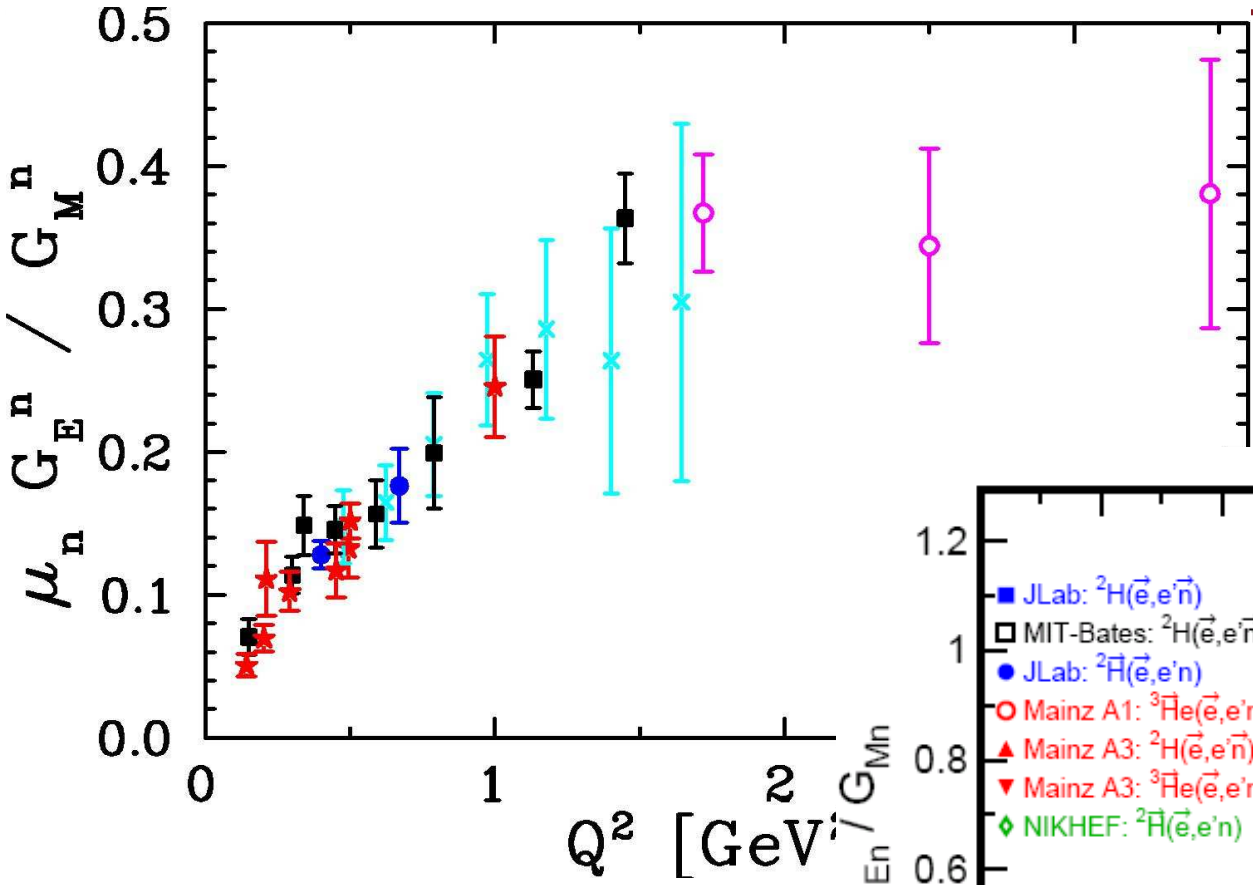
A.Afanasev, et al., PRD 72, 013008 (2005)

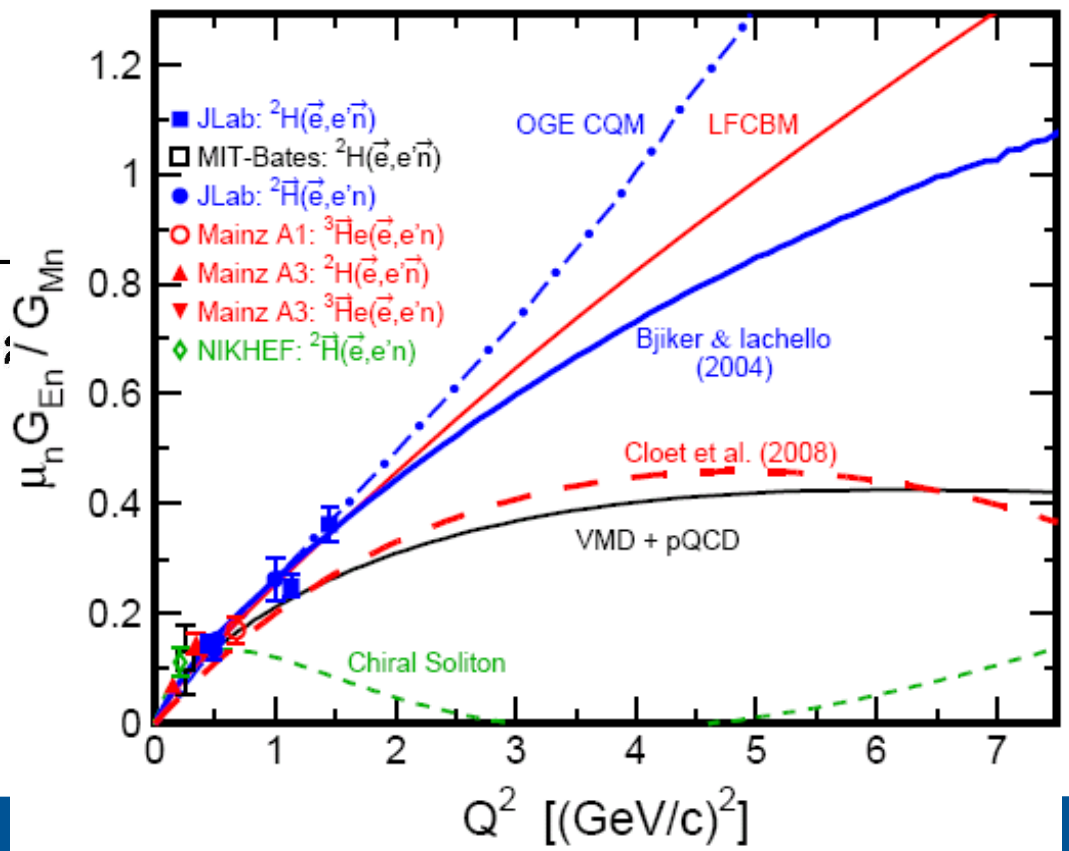
Nucleon Form Factors: Last Ten Years



Magenta:
Currently under analysis

PRELIMINARY RESULTS - GEn



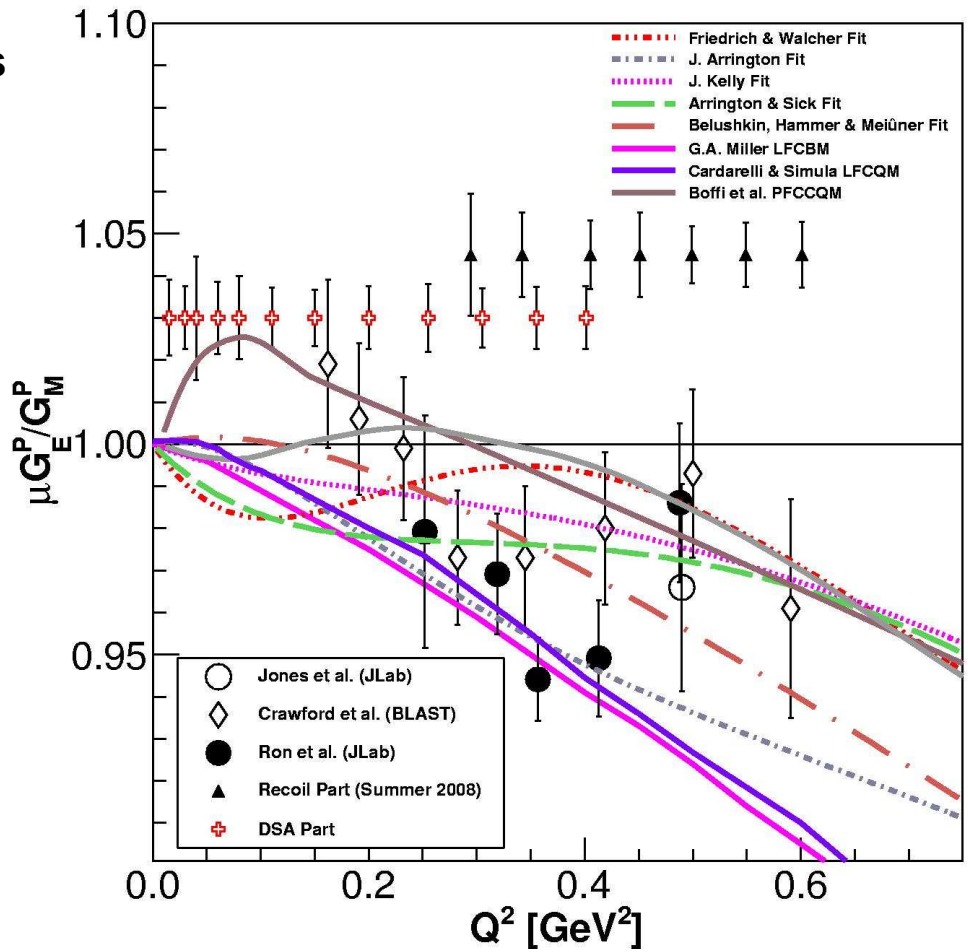


From Higher Energy to Higher Precision

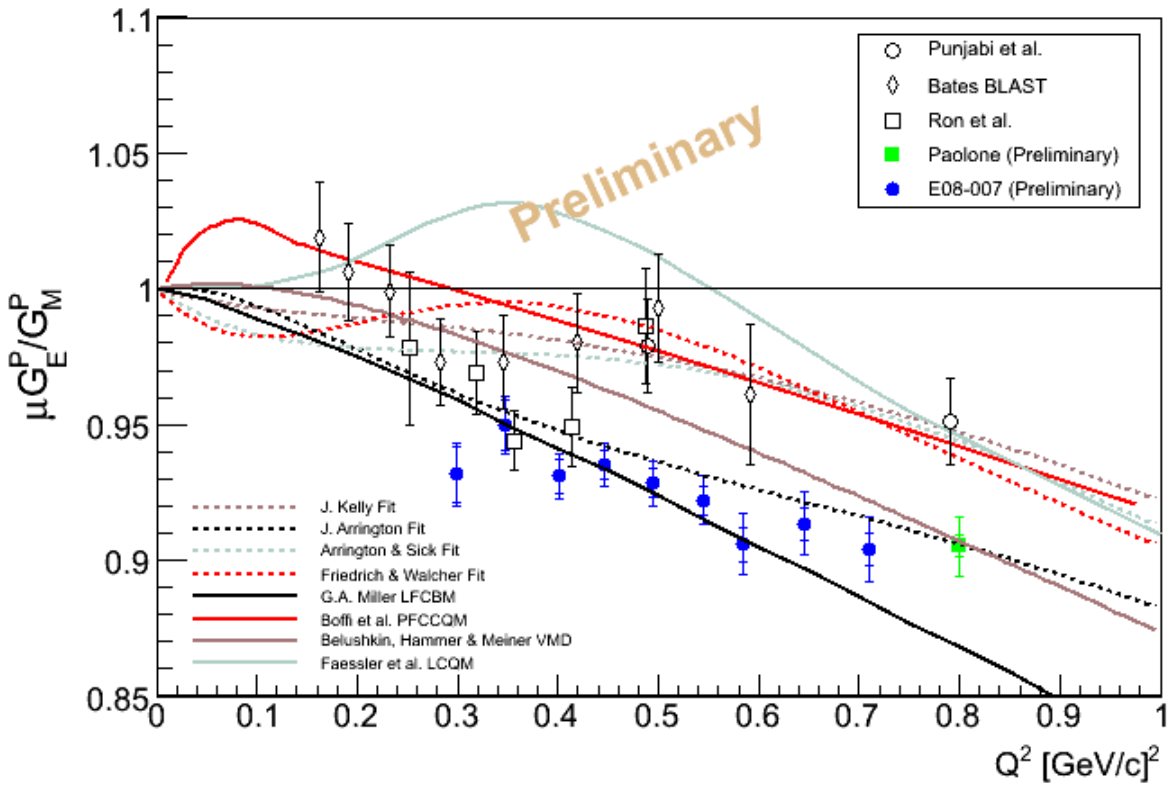
At low Q^2, very high precision measurements possible

Map out in detail the "pion cloud" region

- **G_{En} shows a "bump" at low Q^2, taken as $n \rightarrow p\,\pi^-$ contribution**
- **Proton G_E/G_M ratio shows hint of structure in same region**
  - *New data will map out low Q^2 with 3-5 time smaller uncertainty*
- **Low Q^2 data give other information**
  - *Difference in electric, magnetic radius*
  - *Hadronic corrections to precision hyperfine splitting in hydrogen, muonic-hydrogen*
  - *Important input to program of parity-violating measurements*



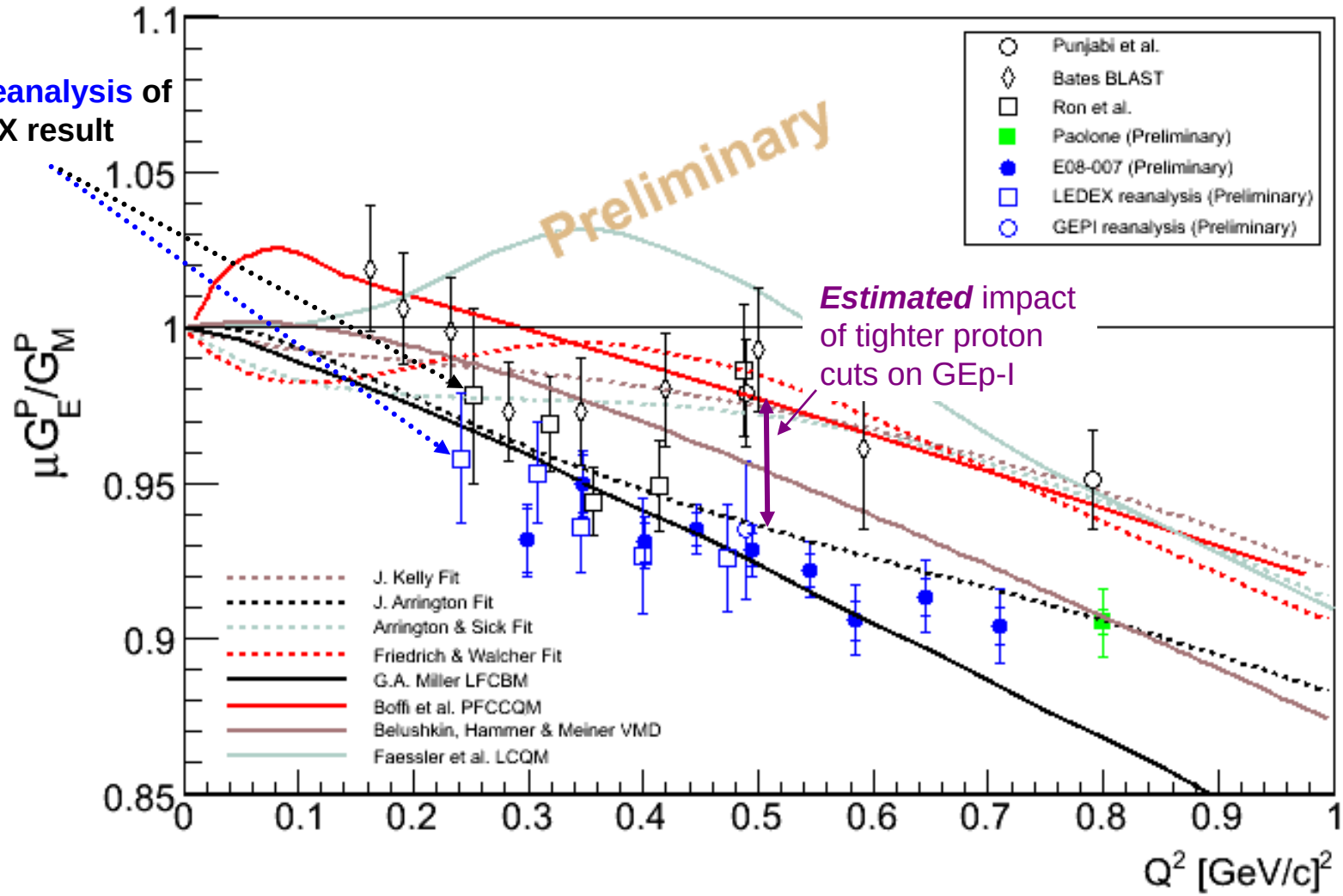
Preliminary results



- 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.

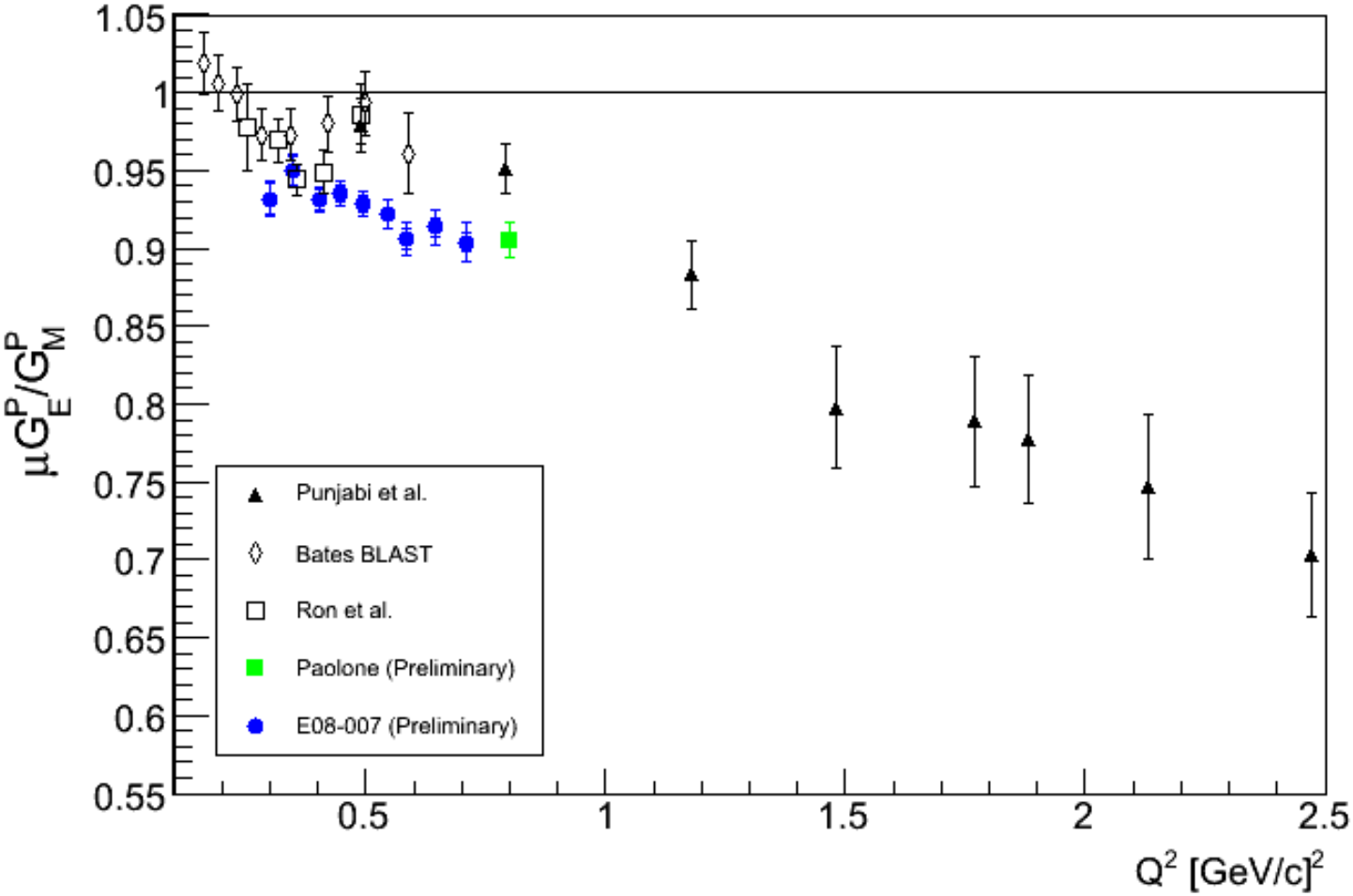
- Disagreement with:
  - **GEp-I** (Punjabi *et al.*): reanalysis with tighter elastic cuts leads to agreement at 0.5 GeV^2, 0.8 GeV^2 to be investigated.
  - **LEDEX** (Ron *et al.*): preliminary reanalysis lowers into agreement.
  - **BLAST** (Crawford *et al.*): origin of difference to be investigated.

Full reanalysis of LEDEX result



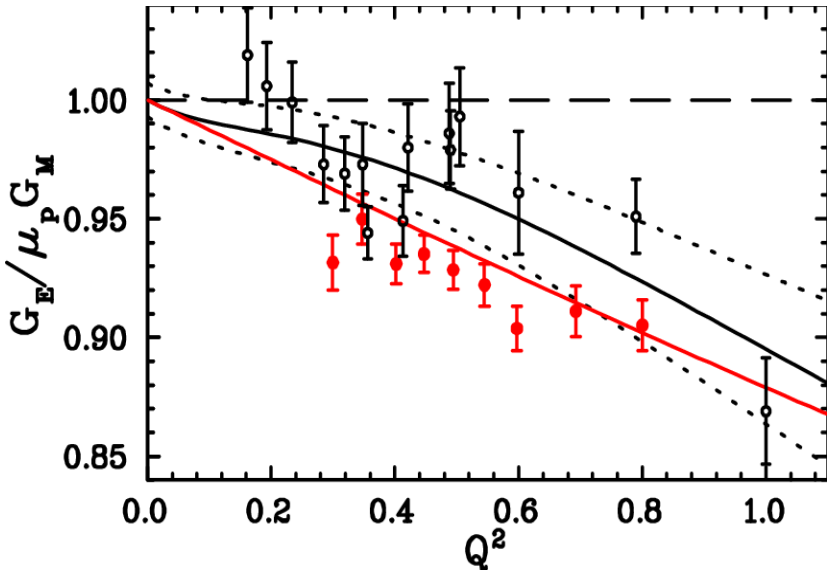
Estimated impact of tighter proton cuts on GEp-I

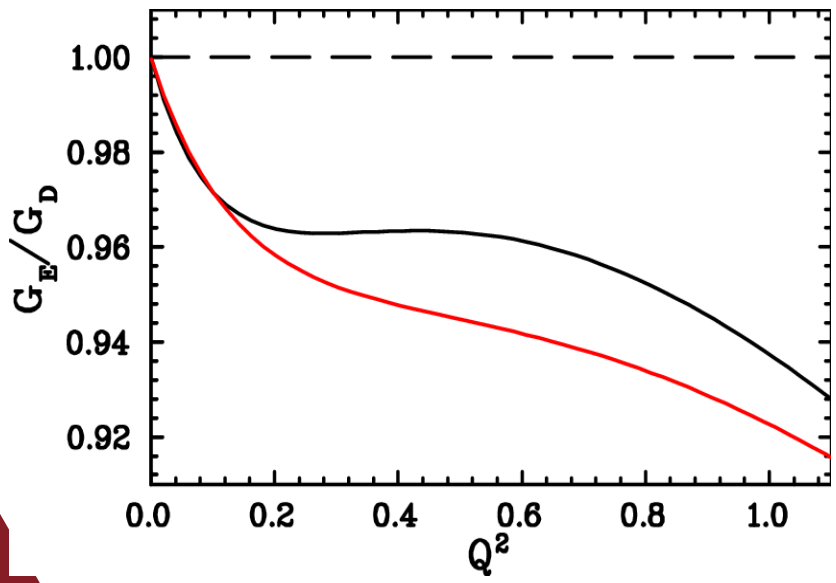
Comparison to higher Q^2 data

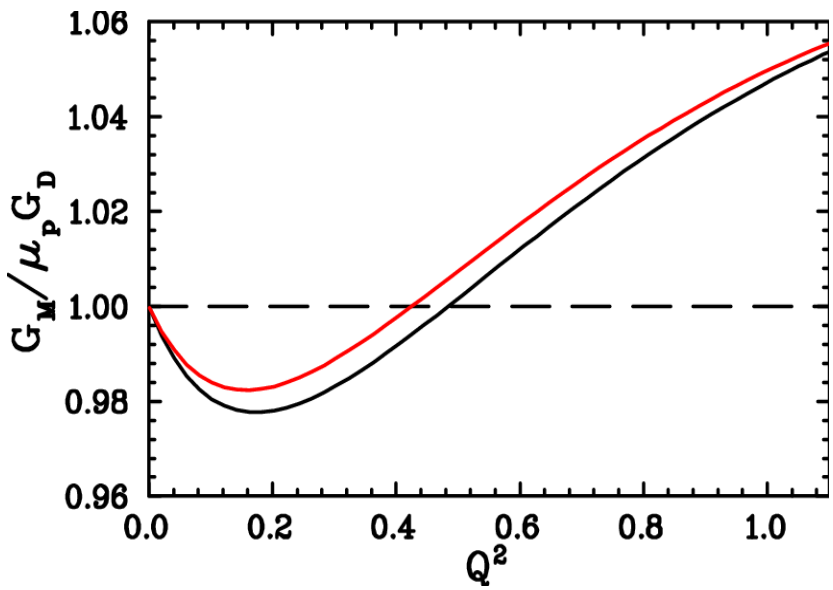


Impacts and Future Outlook I

- Global fits of individual form factors
- 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% lower, G_M ~ 0.5% higher



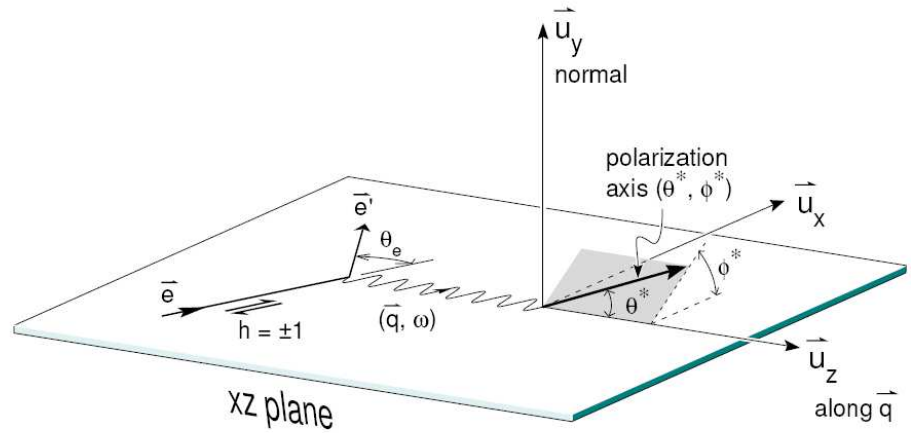




Impacts and Future Outlook III

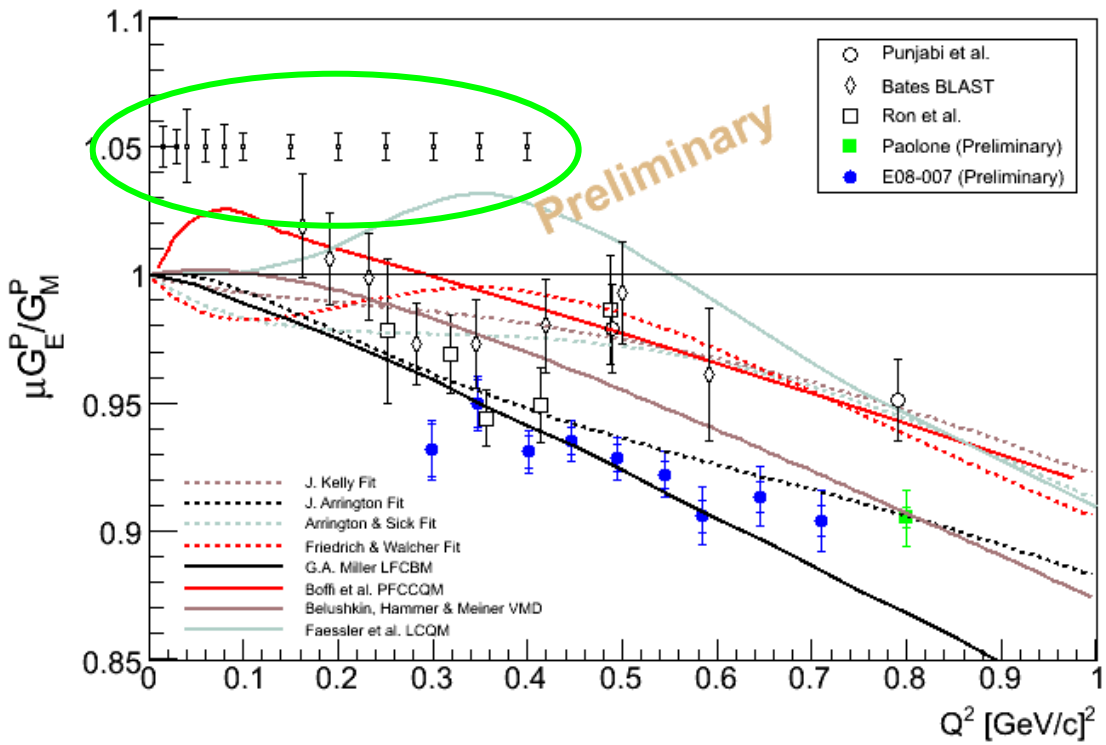
- Second half of the experiment (DSA) is scheduled in early 2012

$$A_{phys} = \frac{v_z \cos\theta' G_M^2 + v_x \sin\theta' \cos\varphi' G_E G_M}{\left(\varepsilon G_{Ep}^2 + \tau G_{Mp}^2\right)/\left[\varepsilon(1+\tau)\right]}$$



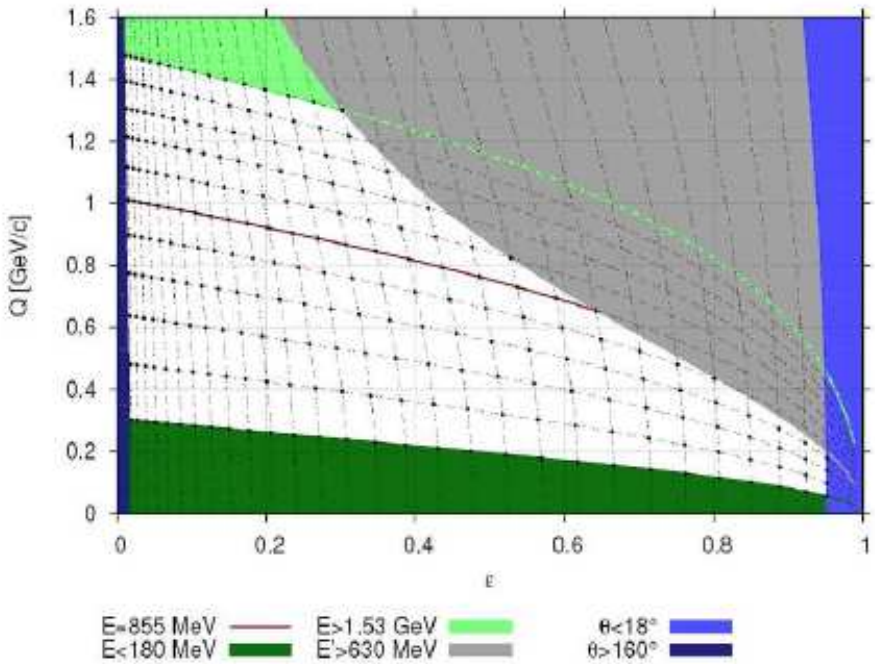
- Opportunity to see the FFR behavior at even lower Q^2 region.
- Compare electric and magnetic radii
- Challenges: Solid polarized proton target & effect of target field to septum magnets.

- Stay tuned …



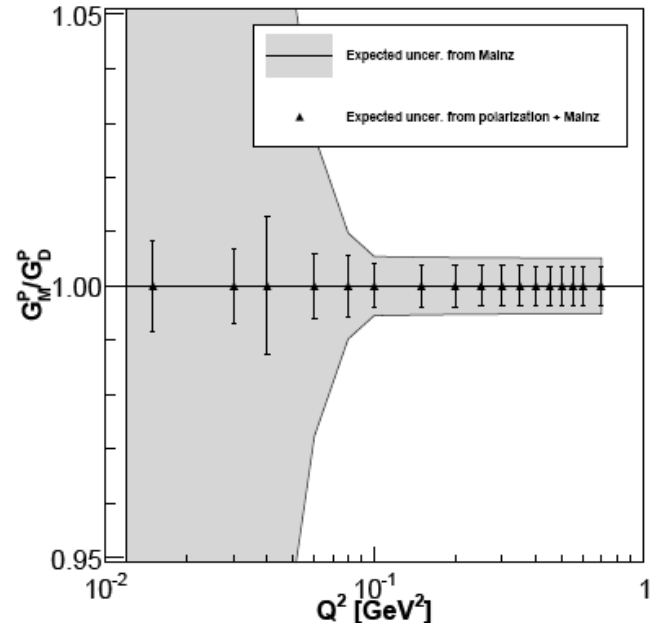
New Mainz, JLab (Hall C) Rosenbluth separations

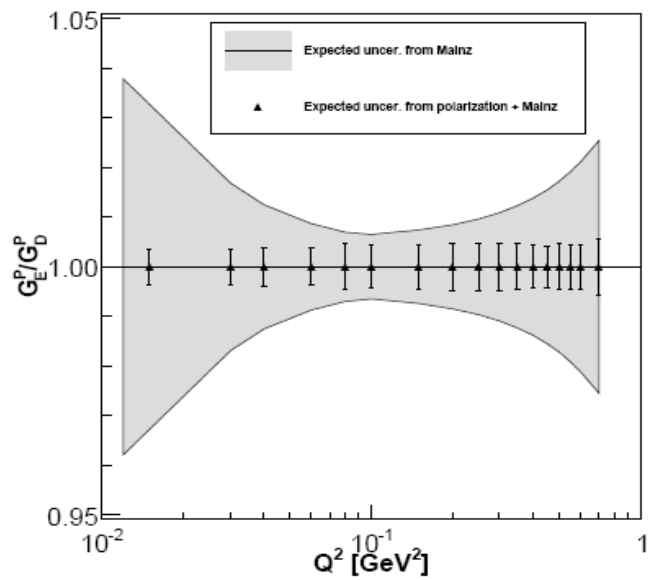
Mainz: High precision cross sections for 0.1 to ~1.5 GeV²



JLab Hall C: Very high relative precision cross sections for 0.4-5 GeV²

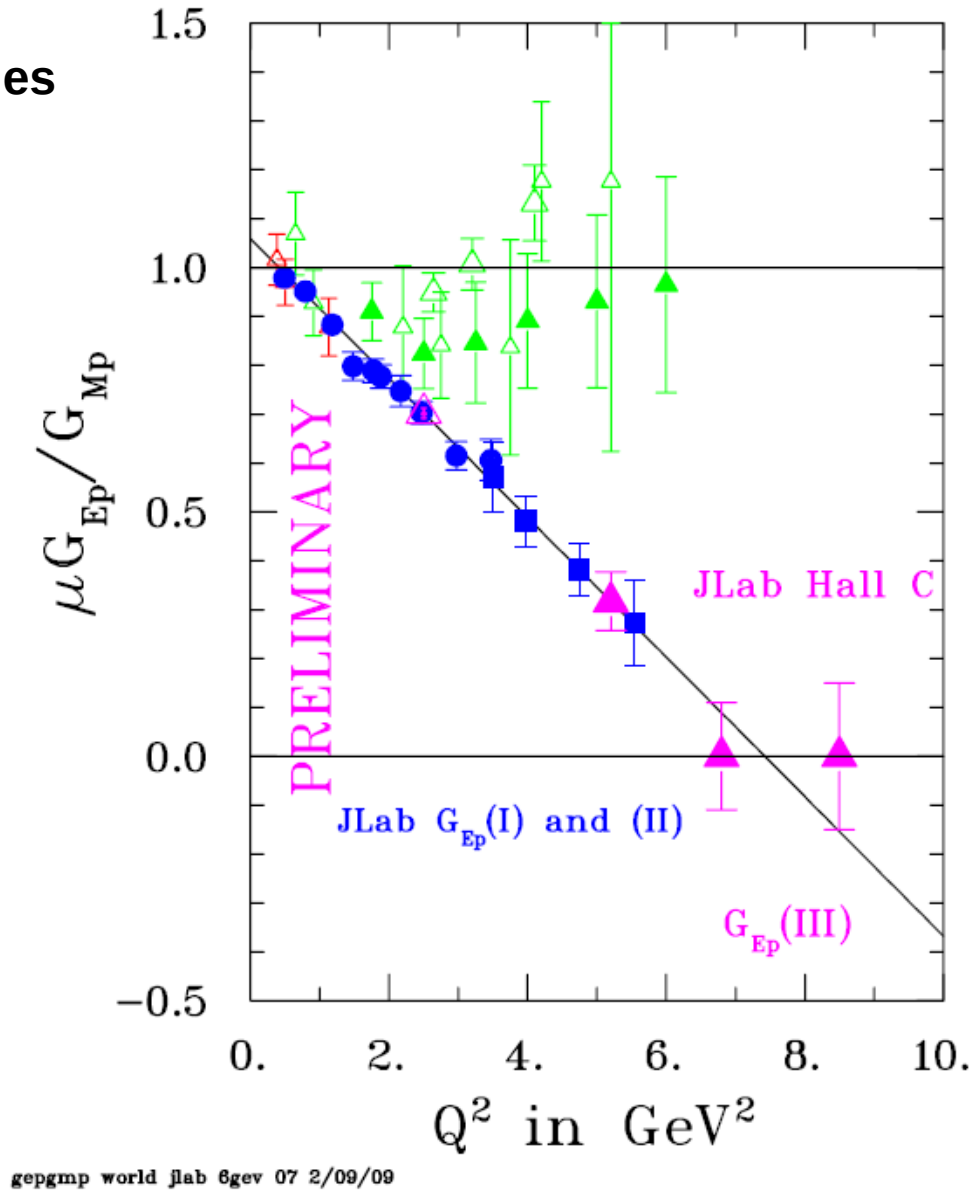
Relative precision → G_E/G_M ratio, TPE-induced non-linearities



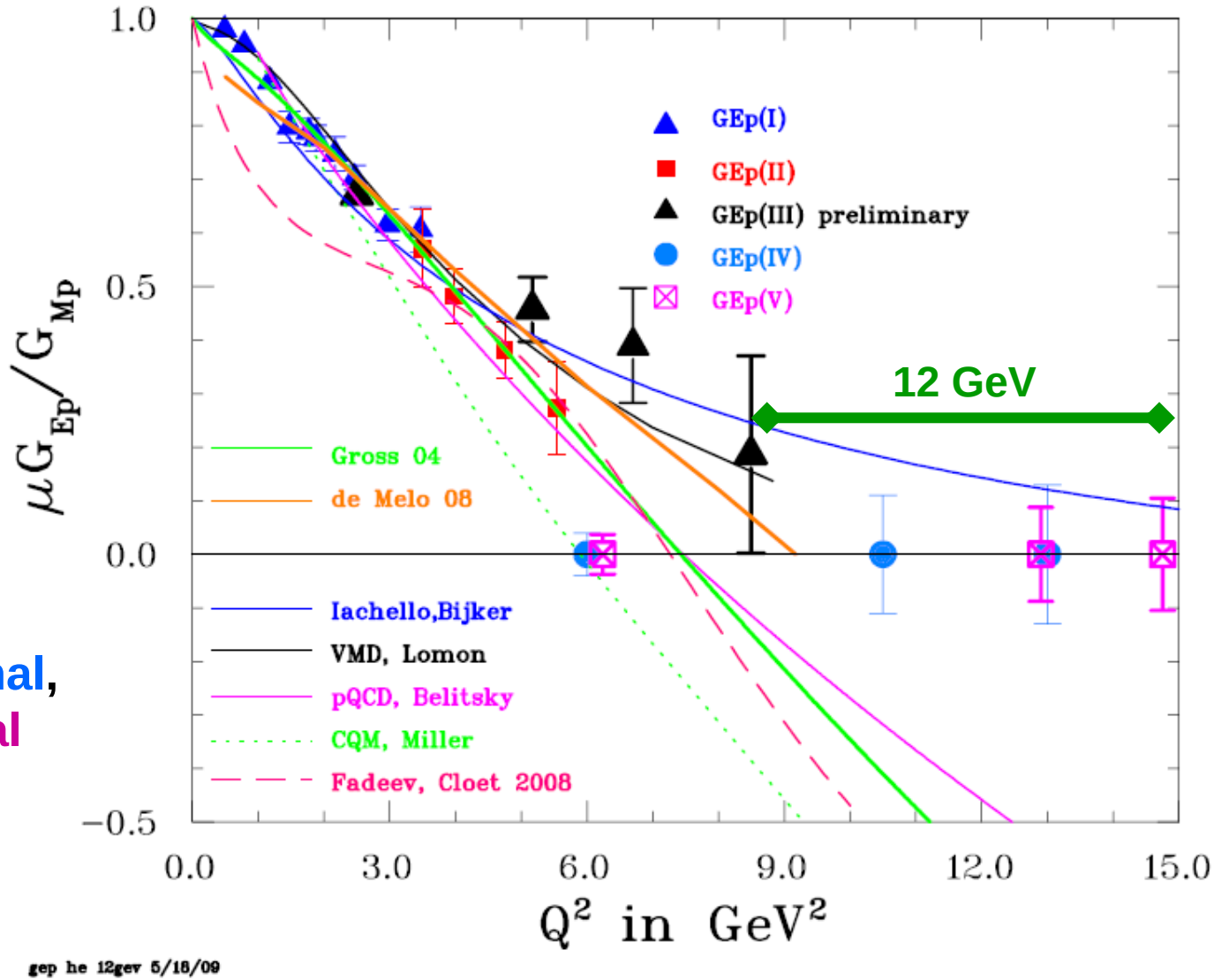


GEp(III) – High Q^2

Magenta – projected uncertainties



GEp – Projections for 12 GeV upgrade

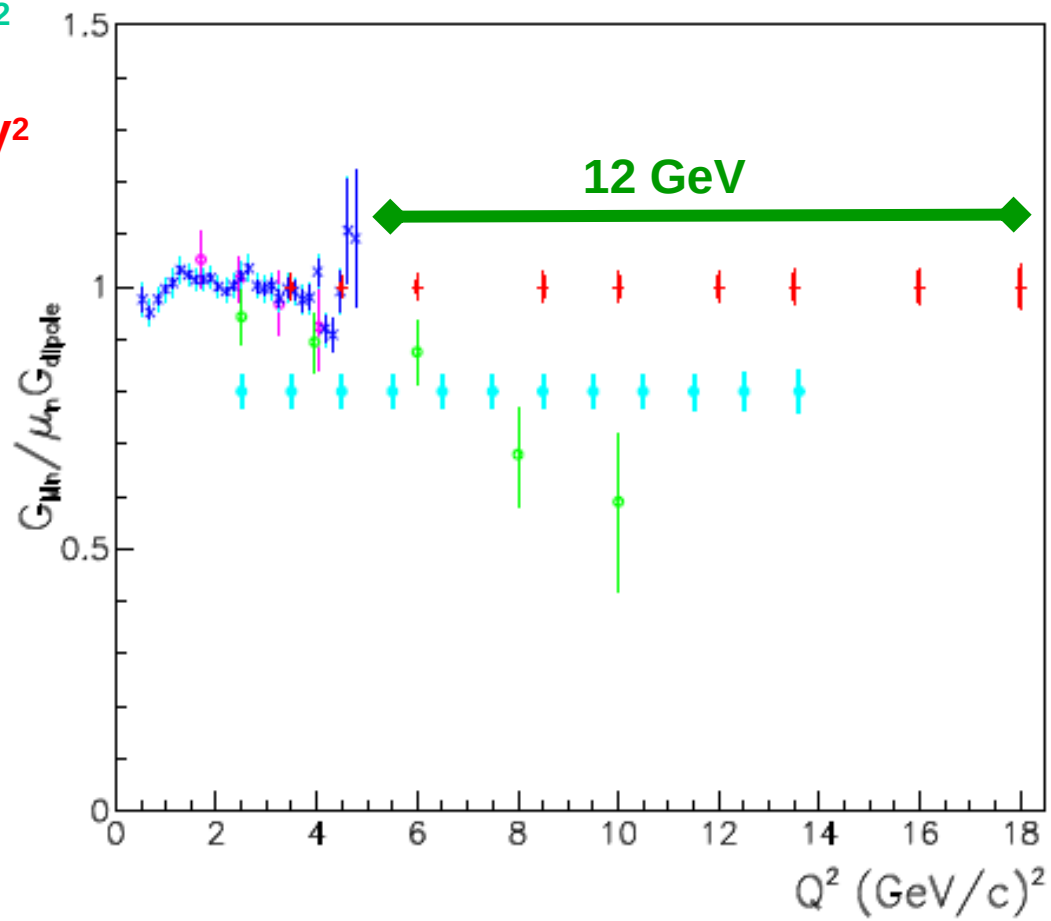


Two proposals;
more conventional,
less conventional

GMn – Projections for 12 GeV

CLAS12 extension – 3-14 GeV^2

Hall A proposal – up to 18 GeV^2

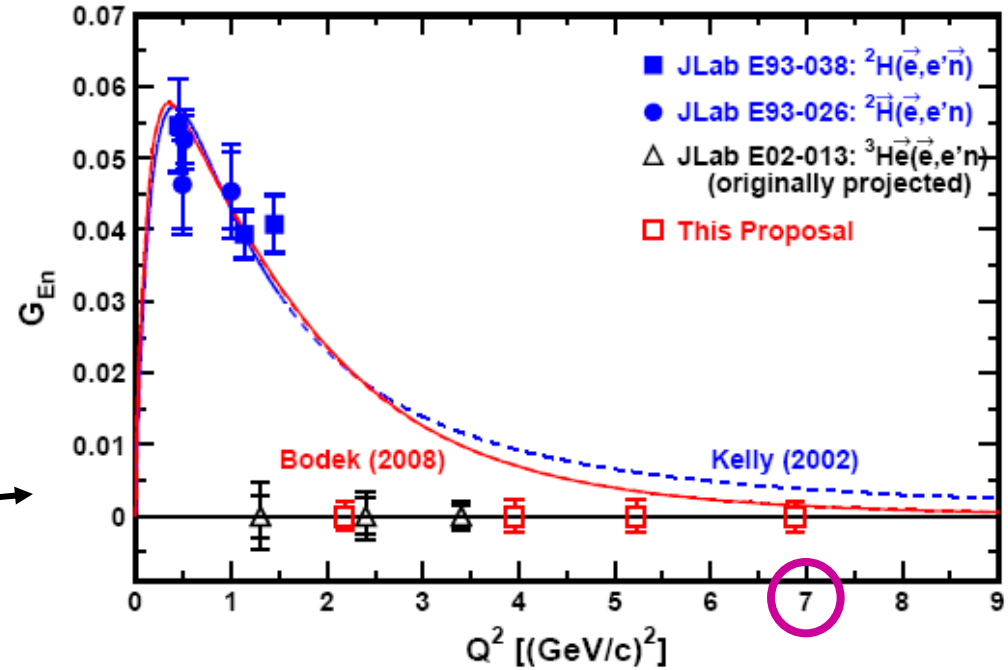


Two proposals;
more conventional,
less conventional

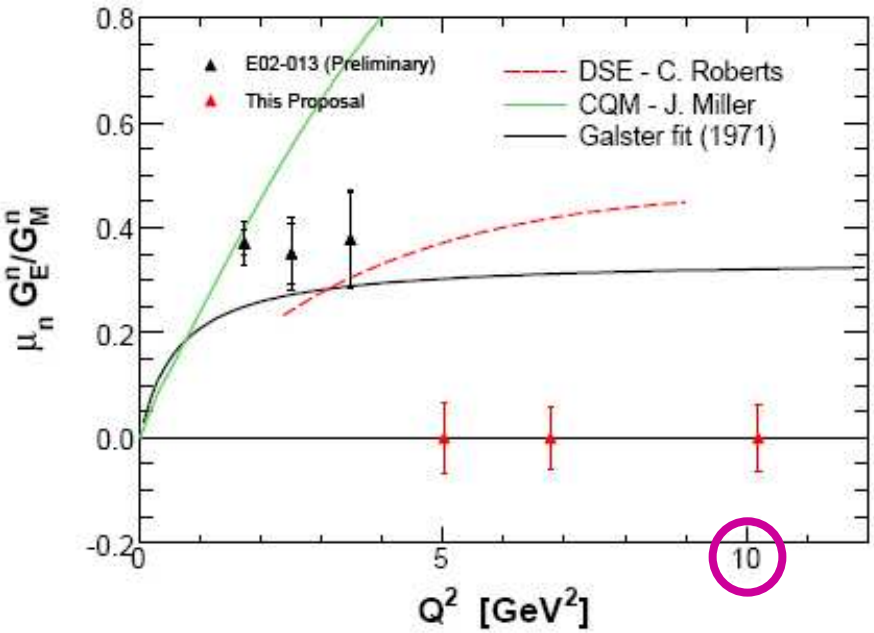
GEn – Projections for 12 GeV

Two proposals – both conventional

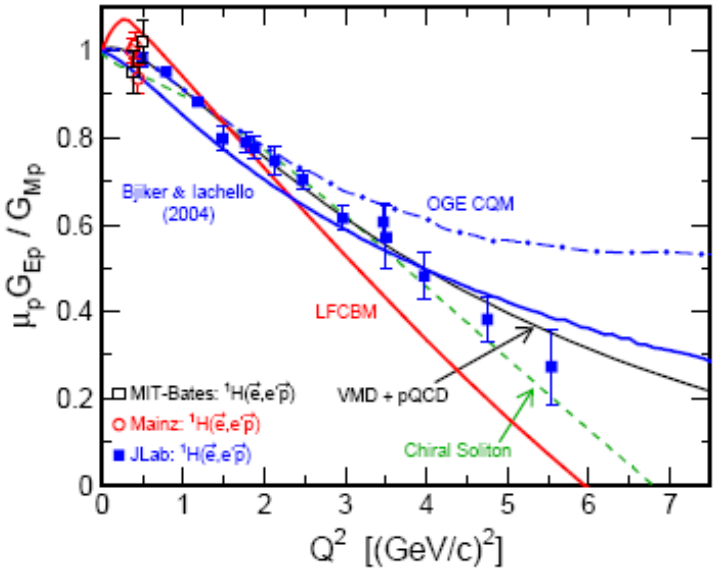
Existing capabilities

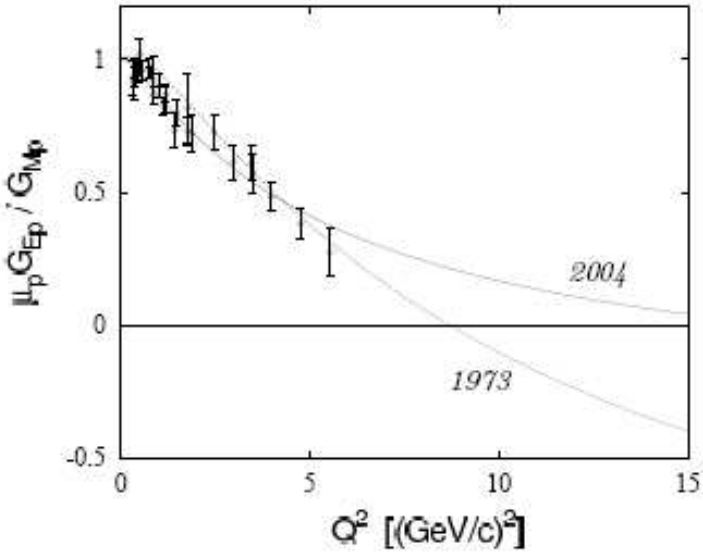


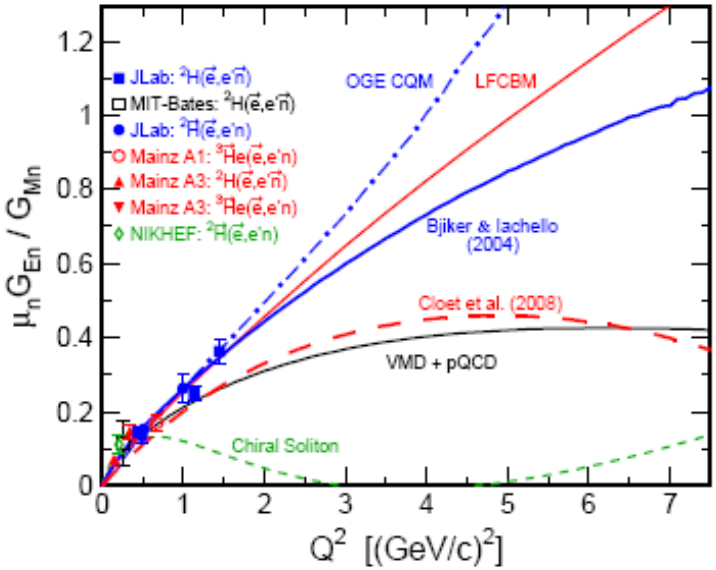
New target advances

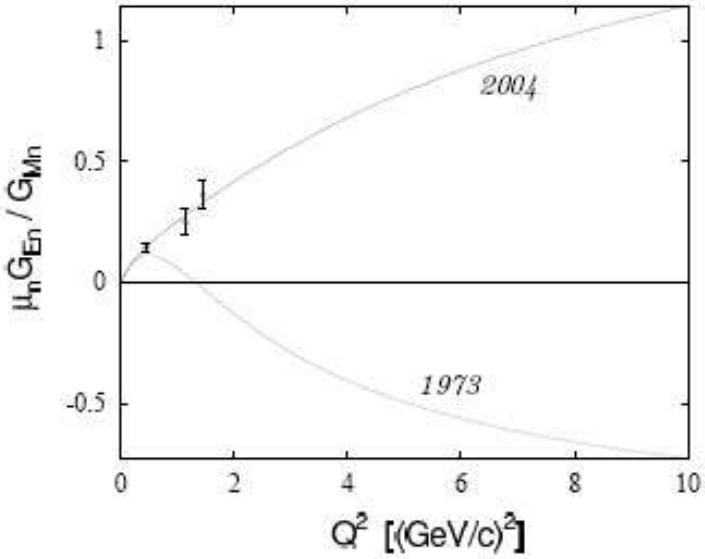


GEn: Wide (and blurry) range of predictions





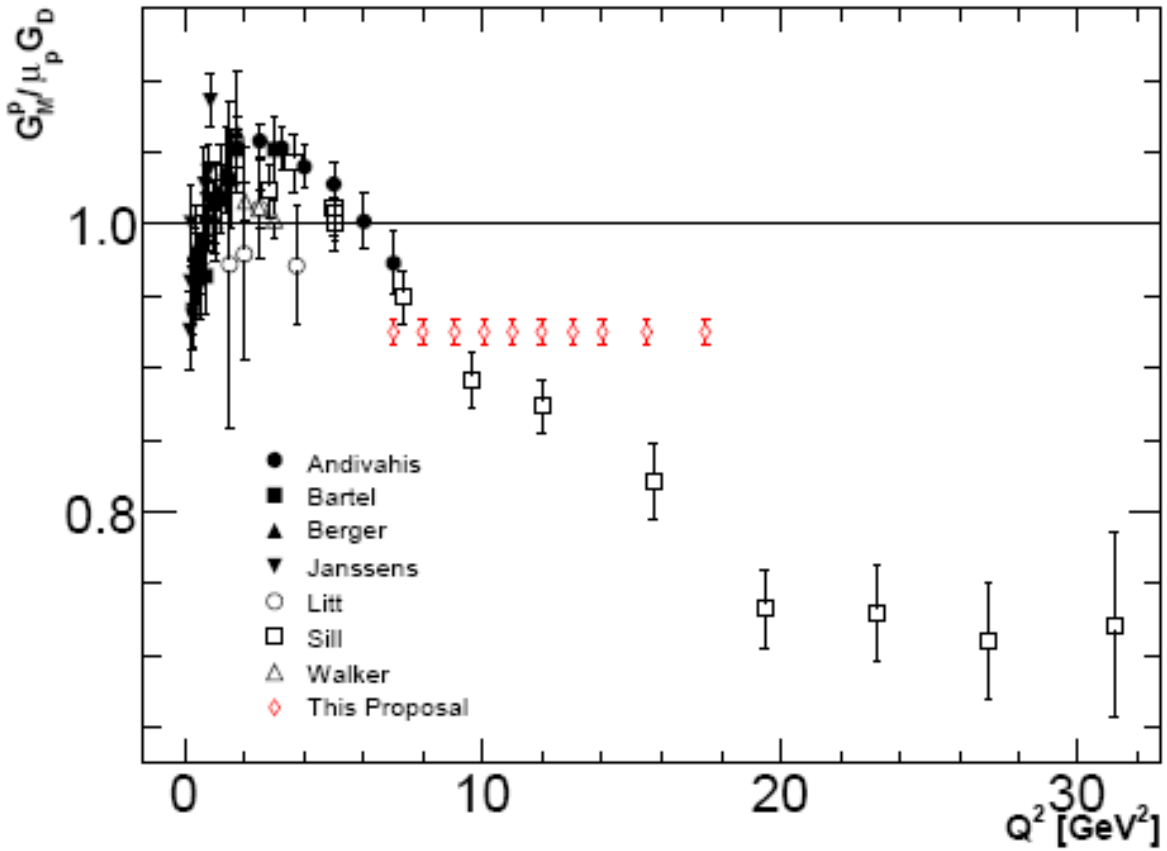




GMp – Projections for 12 GeV

- **Improved precision but limited Q^2 range**

- **Precise cross sections at JLab-12 kinematics**
  - *Reduce TPE corrections in interpolating from existing high Q^2 data*



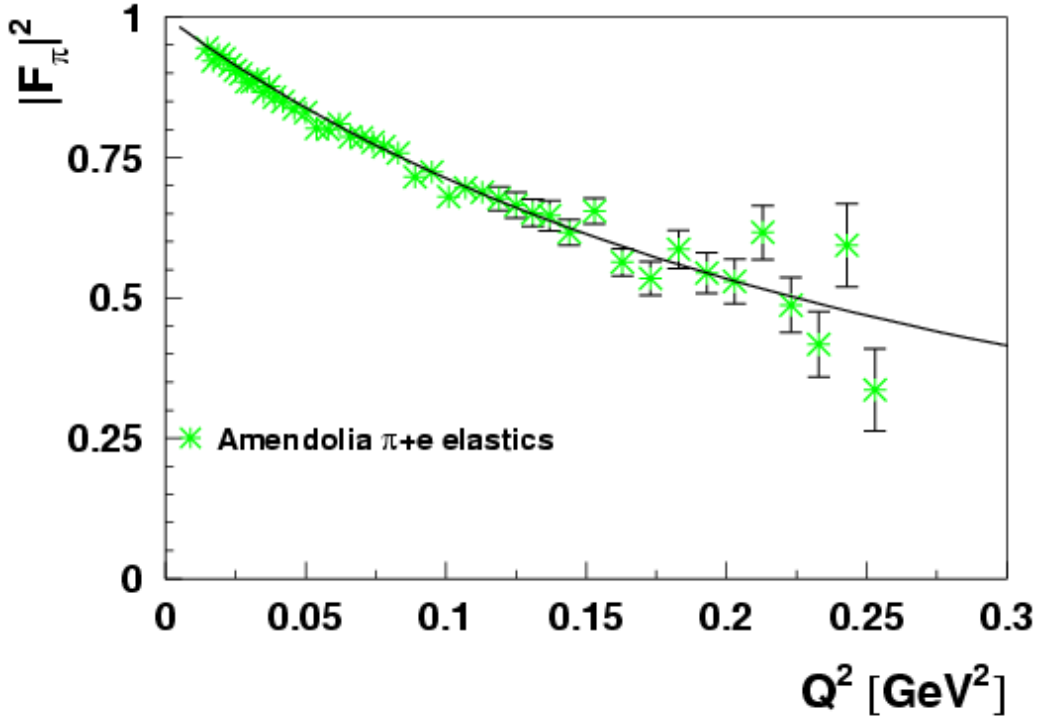
Pion form factor

Measurement of π^+ Form Factor – Low Q^2

- At low Q^2, F_π can be measured ***directly*** via high energy elastic π^- scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure F_π up to $Q^2 = 0.25$ GeV^2

    [Amendolia et al, NPB277, 168 (1986)]
  - These data used to extract the pion "charge radius"

    $r_\pi = 0.657 \pm 0.012$ fm

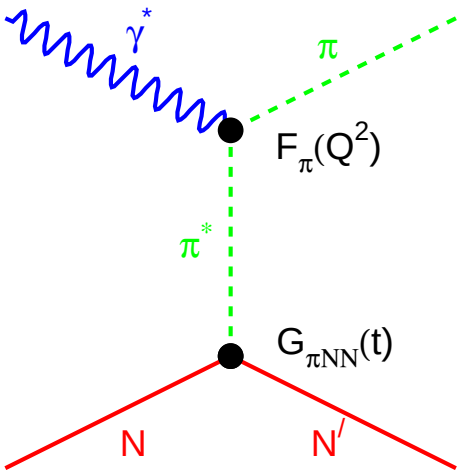


Measurement of π^+ Form Factor – Larger Q^2

- At larger Q^2, F_π must be measured **indirectly** using the "pion cloud" of the proton via $p(e,e'\pi^+)n$
  - At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
  - In Born term model, F_π^2 appears as,

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2,t)$$

- Drawbacks of the this technique
  - Isolating σ_L experimentally challenging
  - Theoretical uncertainty in form factor extraction



F_π *Program at Jefferson Lab*

• Two dedicated F_π experiments have been carried out at JLab

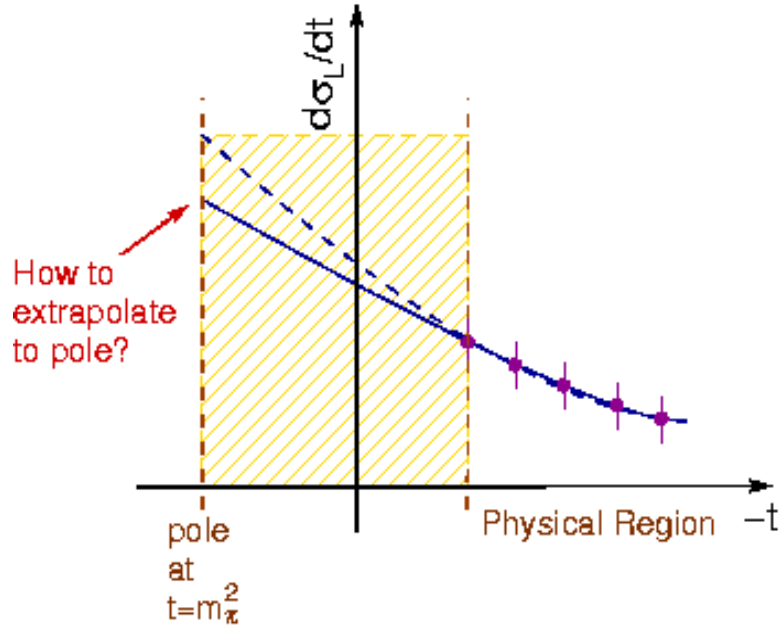
F_π-1: Q^2=*0.6-1.6* GeV^2
F_π-2: Q^2=*1.6, 2.45* GeV^2

Expt	Q^2 (GeV^2)	W (GeV)	$\lvert t_{min}\rvert$ (Gev^2)	E_e (GeV)
F_π-1	0.6-1.6	1.95	0.03-0.150	2.45-4.05
F_π-2	1.6,2.45	2.22	0.093,0.189	3.78-5.25

- Second experiment took advantage of higher beam energy to access larger *W*, smaller *-t*
- Full deconvolution of *L/T/TT/LT* terms in cross section
- Ancillary measurement of π/π^+ (separated) ratios to test reaction mechanism
- Both experiments ran in experimental Hall C: F_π-1 in 1997 and F_π-2 in 2003

Extraction of π^+ Form Factor in p(e,e'π^+)n

- π^+ electroproduction can only access *t<0* (away from pole)
- Early experiments used "Chew-Low" technique
  - Measured *–t* dependence
  - Extrapolated to physical pole
- This method is unreliable – different fit forms consistent with data yet yield very different FF



- Need reliable cross section model
- Fit model to σ_L in physical region
  - → vary F_π to match data to model
  - → *t-pole* "extrapolation" is implicit

Model for F_π Extraction

After σ_L is determined, a model is required to extract $F_\pi(Q^2)$

→ Model incorporates π^+ production mechanism

JLab F_π measurements use the Vanderhaeghen-Guidal-Laget (VGL) Regge model *[Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)]*

Additional calculations would be nice to check model dependence and there is some recent activity on that front:

→*Obukhovsky, Fedorov, Faessler, Gutsche, and Lyubovitskij* *[PLB 634, 220 (2006), PRC 76, 025213 (2007)]*

→*Kaskulov, Gallmeister, and Mosel,* *[arXiv:0804.1834 (hep-ph)]*

→ *T. Mart,* *[arXiv:0805.1800 (hep-ph)]*

Although we extract the form factor in the context of a particular model, the separated cross sections will always be available to any future, alternate models that come along

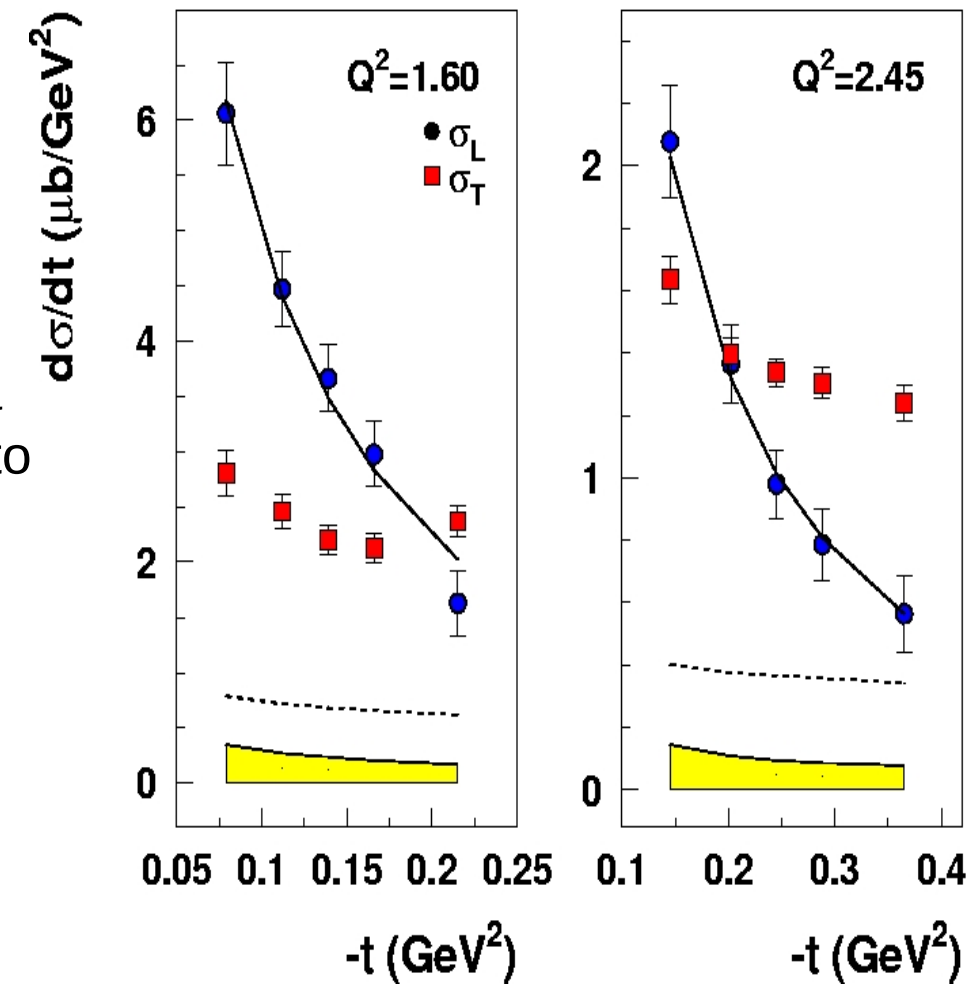
F_π *Extraction from JLab data*

VGL Regge Model

- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$ replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Model parameters fixed from pion photoproduction.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

$$F_\pi(Q^2) = \frac{1}{1 + Q^2/\Lambda_\pi^2}$$

Horn et al, PRL97, 192001,2006



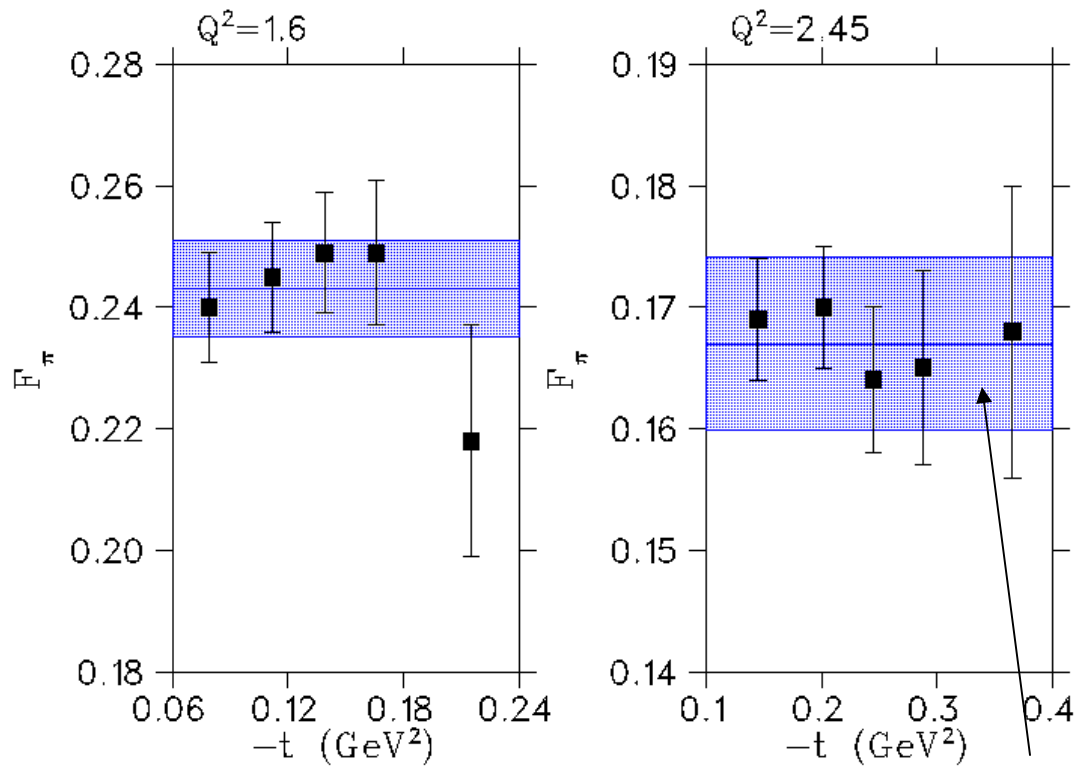
Λ_π^2=0.513, 0.491 GeV², Λ_ρ^2=1.7 GeV²

Model Check of F_π *Extraction*

Test VGL model by extracting form factor for each –*t* bin

→If calculation appropriately models reaction mechanism, should get same result independent of –*t*

→F_π*-2* results almost totally insensitive to –t bin used



Published F_π error band based on fit to all *t*-bins.

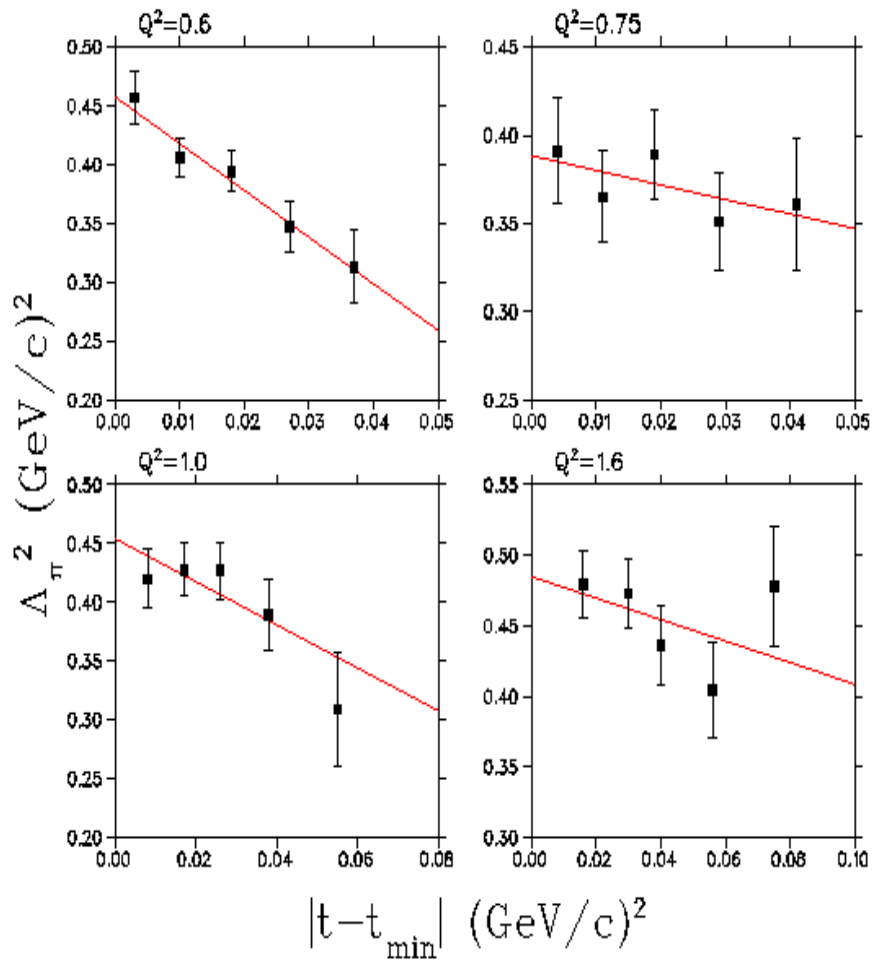
Form Factor Extraction from F_π-1 Data

First experiment: results **are** sensitive to value of t

1. Fit Λ_π^2 in each $-t$ bin
2. Extrapolate to $-t = -t_{min}$
   →NOT $-t=m_\pi^2$

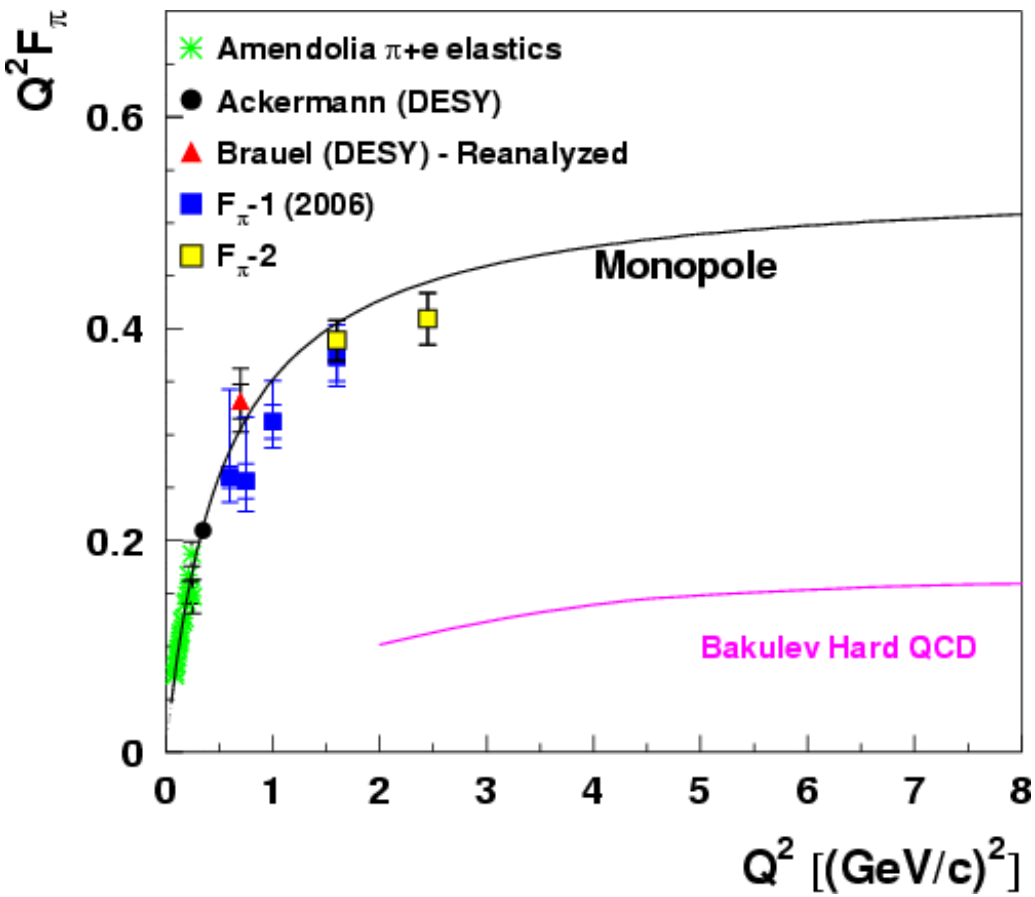
Assumes backgrounds are minimized at t_{min}

Model uncertainty evaluated assuming particular forms for the background



$F_{\pi^+}(Q^2)$ *in 2008*

Only true L-T separated data shown



Asymmetric "model-dependence" error bars from varying form of assumed background

- Very important for low Q^2 points

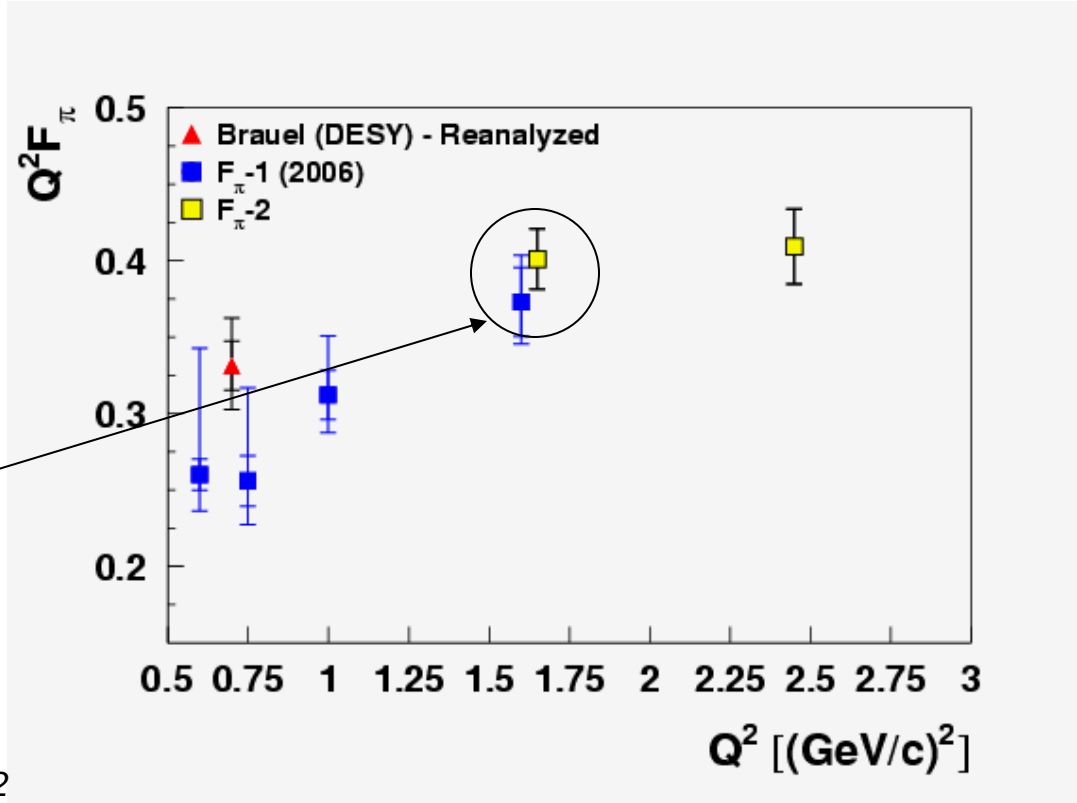
Form Factor Extraction at different $-t_{min}$

Is the model used to extract the form factor sensitive to the distance from the pion pole?

→Test by extracting FF at different distances from –t pole

→Ex: F_π-2, $-t_{min}=0.093$ GeV^2

F_π-1, $-t_{min}=0.15$ GeV^2



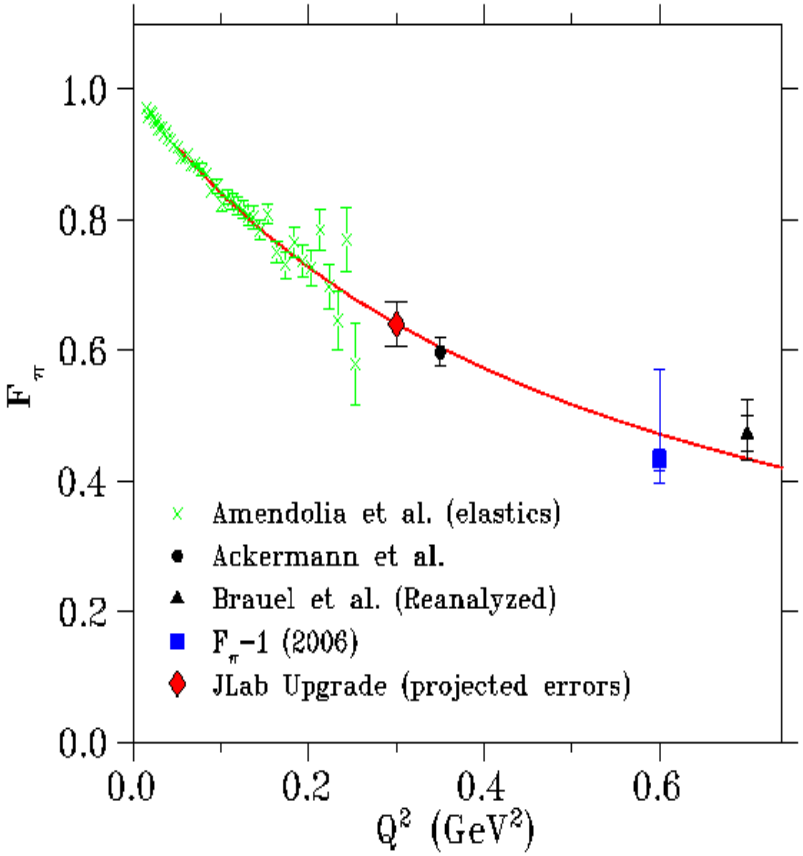
Additional data at JLab at 12 GeV will provide further tests:

$Q^2=1.6$ GeV^2, $-t_{min}=0.029$ GeV^2

$Q^2=2.45$ GeV^2, $-t_{min}=0.048$ GeV^2

Comparison of π+e *to* H(e,e'π^+)

- More direct test: scattering from pion cloud vs. real e-π scattering
- This can be tested making *p(e,e'π^+)* measurements at same kinematics as π+*e* elastics
- Looks good so far
  - *Electroproduction data at Q^2 = 0.35 GeV^2 consistent with extrapolation of SPS elastic data*



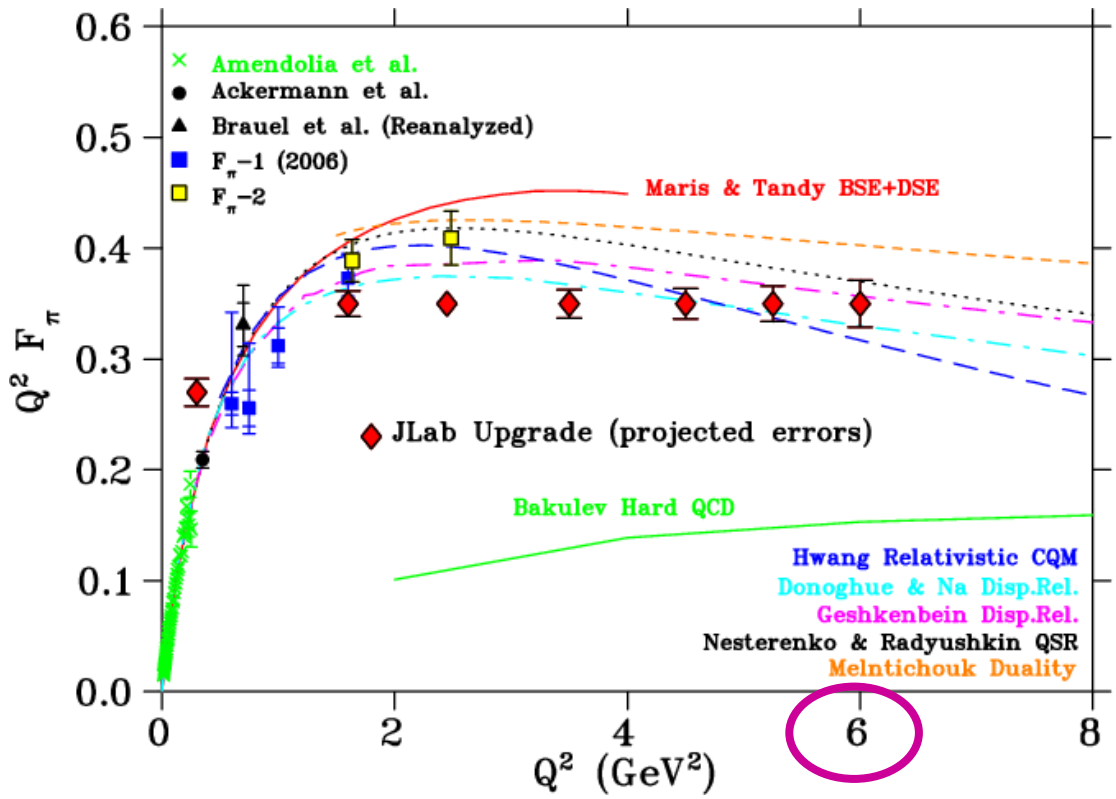
An improved test will be carried out after the JLAB 12 GeV upgrade

→ **smaller *Q^2 (=0.30* GeV^2)**

→ ***-t* closer to pole (=*0.005* GeV^2)**

$F_{\pi^+}(Q^2)$ *after JLAB 12 GeV Upgrade*

- **JLab @ 12 GeV will allow measurement up to 6 GeV^2**
- **Additional point at *Q^2=1.6, 2.5* GeV^2 will be closer to pole: provide another test of *-t_{min}* dependence**
- ***Q^2=0.3* GeV^2 point will be best direct test of agreement with elastic *π+e* data**
- ***Q^2=6* limit due to self-imposed limitation on *–t_{min}*, based on 20-year old calculation at lower Q^2**
  - ***9 GeV^2 possible with somewhat larger t_{min}***
  - ***4 GeV^2 data already exist***
  - ***Requires calculations for higher Q^2***



Parity Violating Elastic e-p Scattering

- **Nucleon charge, mag. distributions determined by quark distributions**

$$G_E^u \quad G_E^d \quad G_E^s \longrightarrow G_E^p \quad G_E^n$$

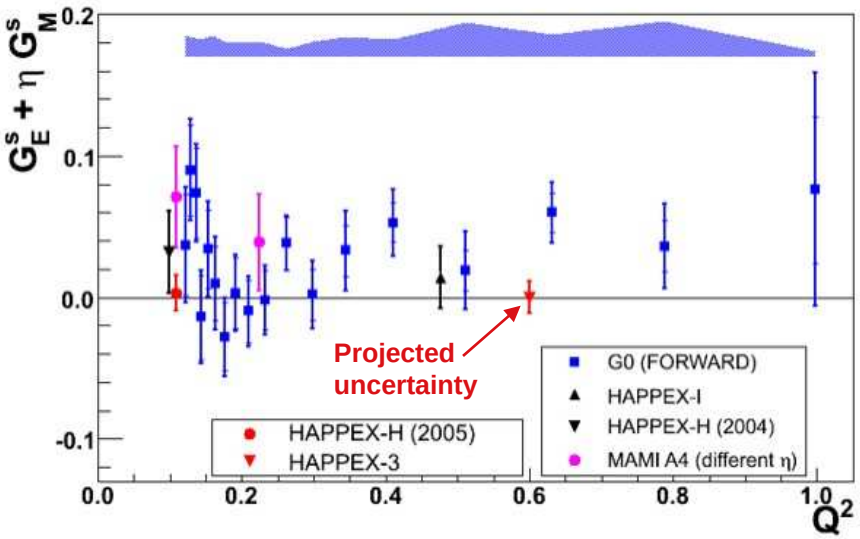
$$G_M^u \quad G_M^d \quad G_M^s \longleftarrow G_M^p \quad G_M^n$$

Experiment	Q^2	A_{PV} [ppm]	Notes
SAMPLE	0.1*	6 ppm	1997
	0.1*	7	deuterium
	0.04*	2	deuterium
HAPPEX	0.5	15	
	0.1	2	
	0.1	6	^{4}He
	0.5	-	
G0	0.1-1	1-10	
	0.4*	-	
	0.7*	-	
PVA4	0.1	1	
	0.2	5	
	0.2*	-	

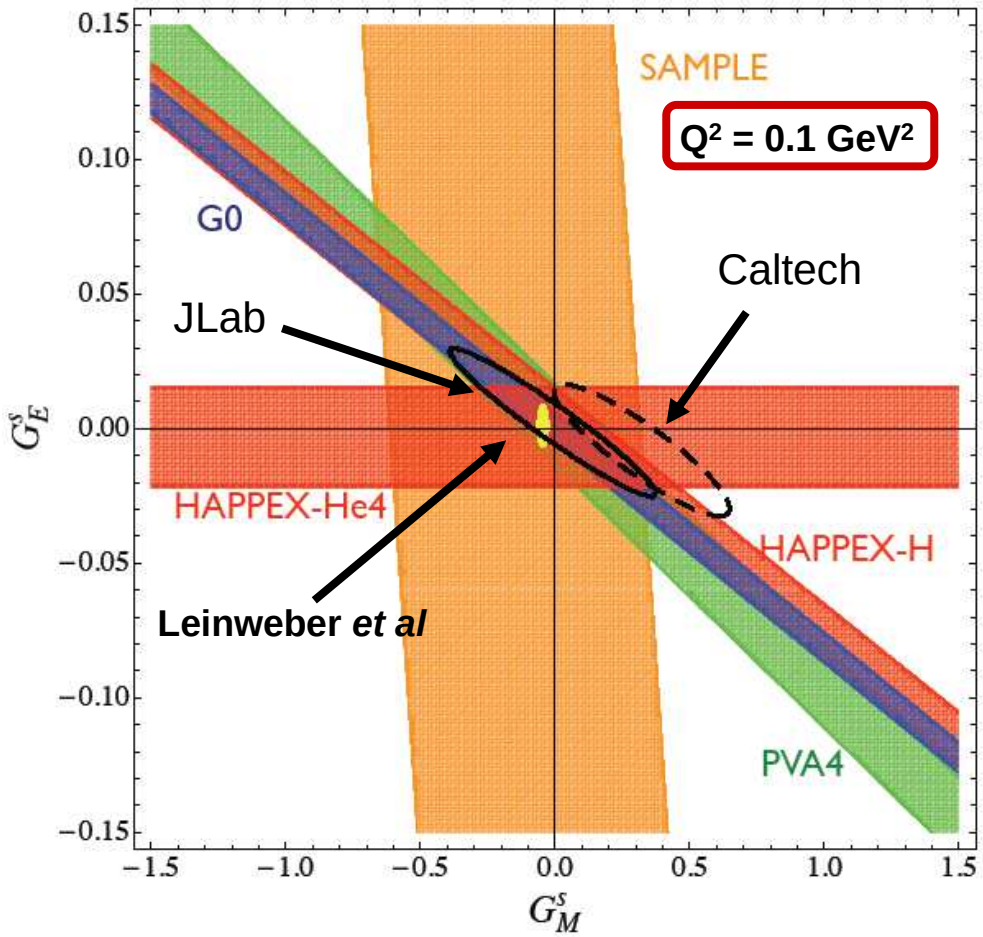
*** = backward angle**

Magneta for planned or ongoing measurements

Exploring the Strangeness Content of the Proton



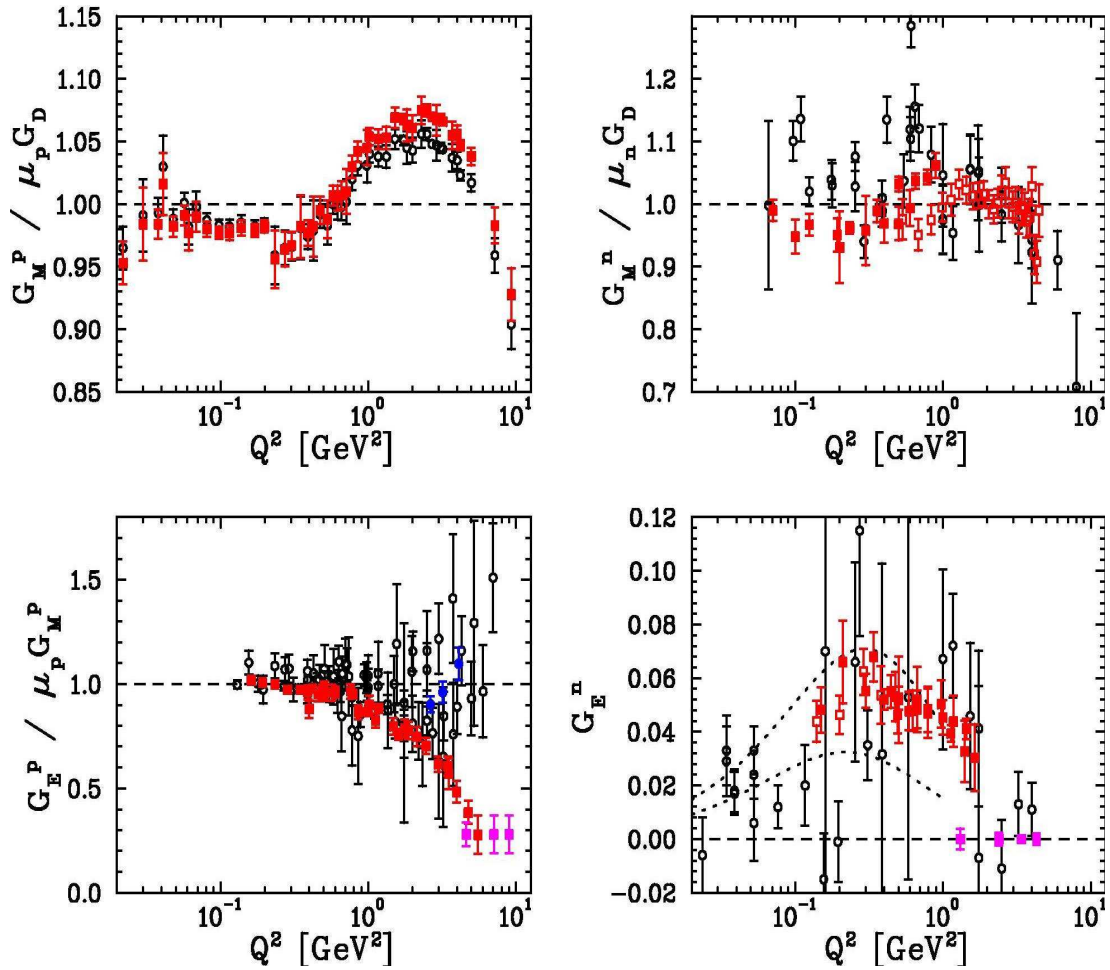
- **Proton not all that strange**
- **Separation possible at 0.1 GeV^2**
- **New data coming at 0.23 and 0.6 GeV^2 (PVA4, G0, HAPPEx III)**



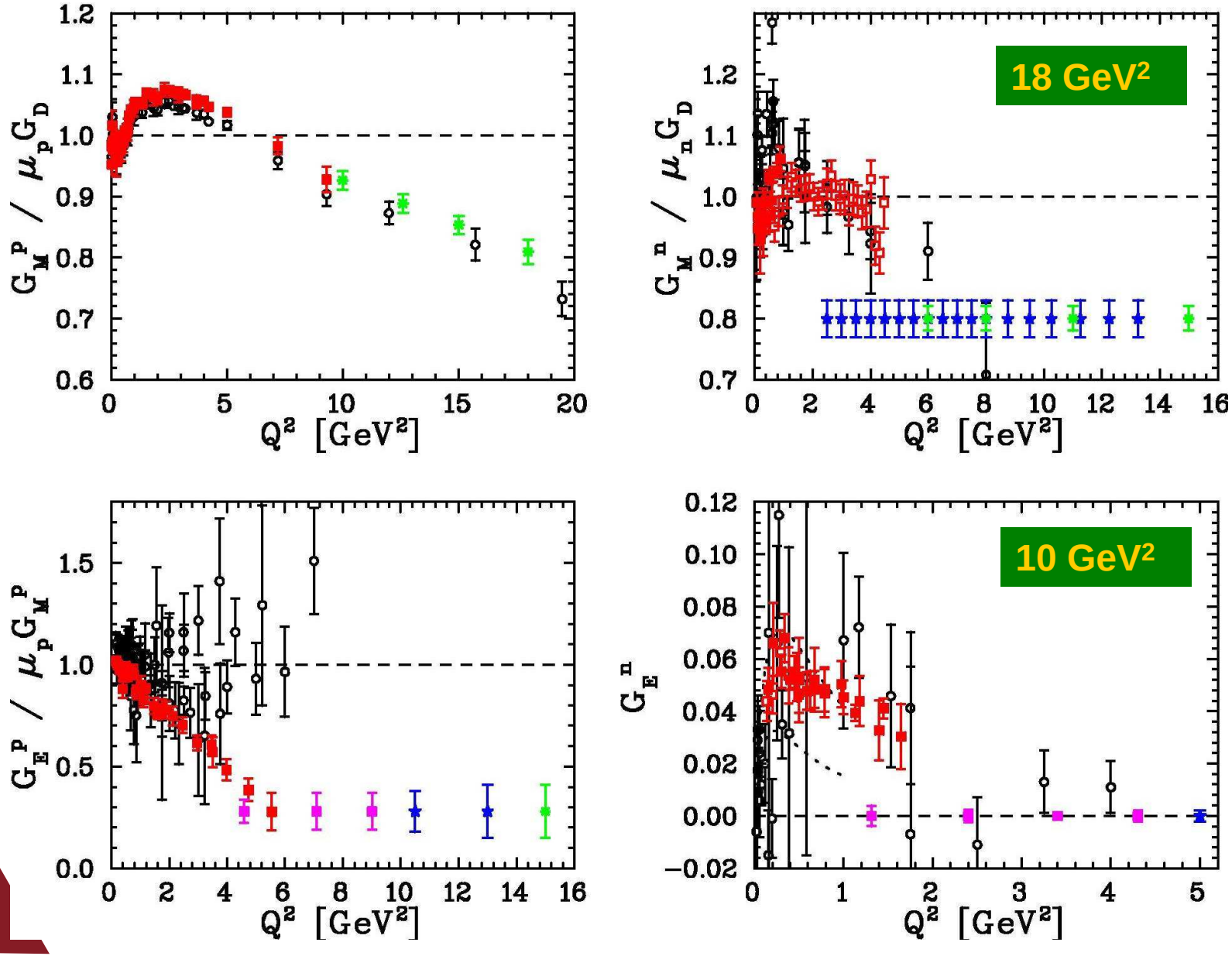
Courtesy of R. McKeown, R. Young, J. Liu

Insight from New Measurements

- **Can test models with data on both proton and neutron form factors**
  - Previously, precise data and large Q^2 range only for G_{Mp}, lower precision and limited Q^2 range for G_{Ep}, G_{Mn}, little data for G_{En}
- **Data for all FFs at low Q^2**
  - G_{Ep}, G_{Mn}, G_{En} known to greater precision – discrepancies resolved
- **Soon, FFs known to 4-5 GeV^2**
  - G_{Ep} changed dramatically, G_{Mp} also modified
  - Complete data set in "quark core" and "pion cloud" region
- 12 GeV era: Nucleon form factors to ~10 GeV^2, pion to 6+



Extensions with JLab 12 GeV Upgrade



~8 GeV^2

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

Fin…