Mapping out symmetry violation in nucleon structure

John Arrington
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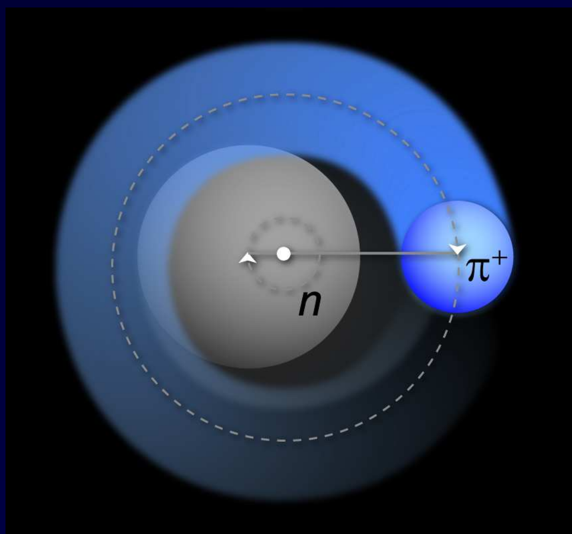
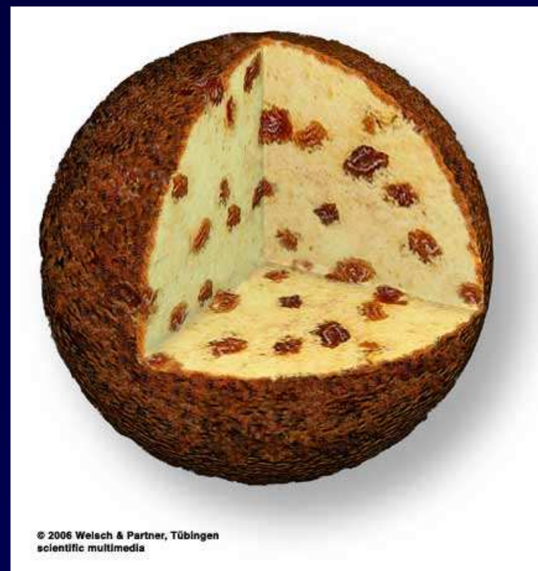
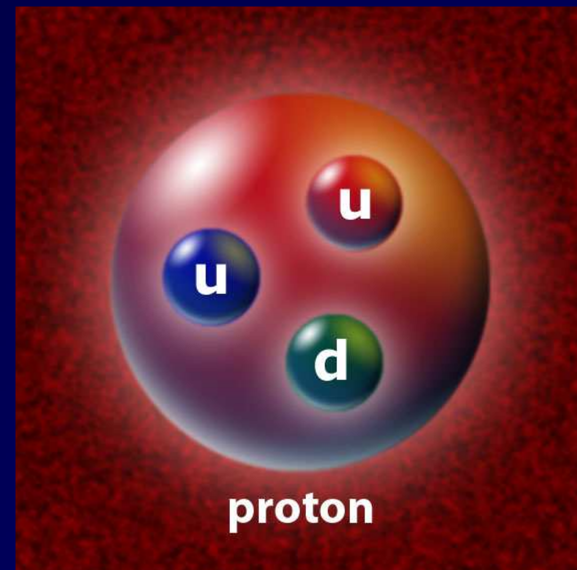
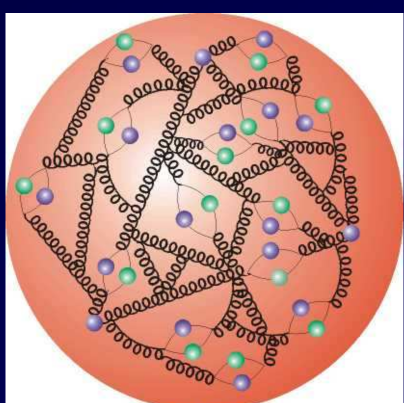
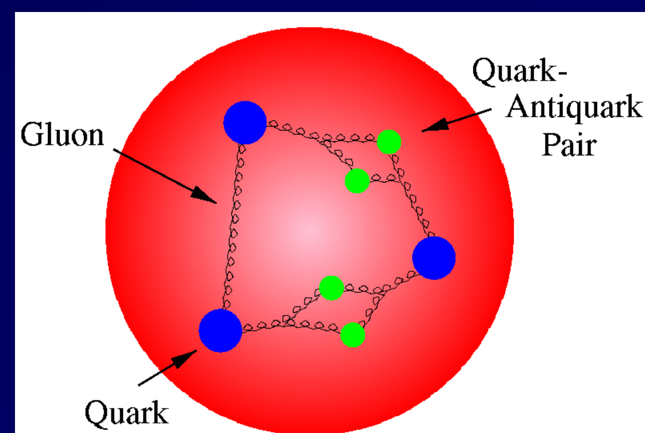








Ecole Joliot-Curie
Oct 1, 2010



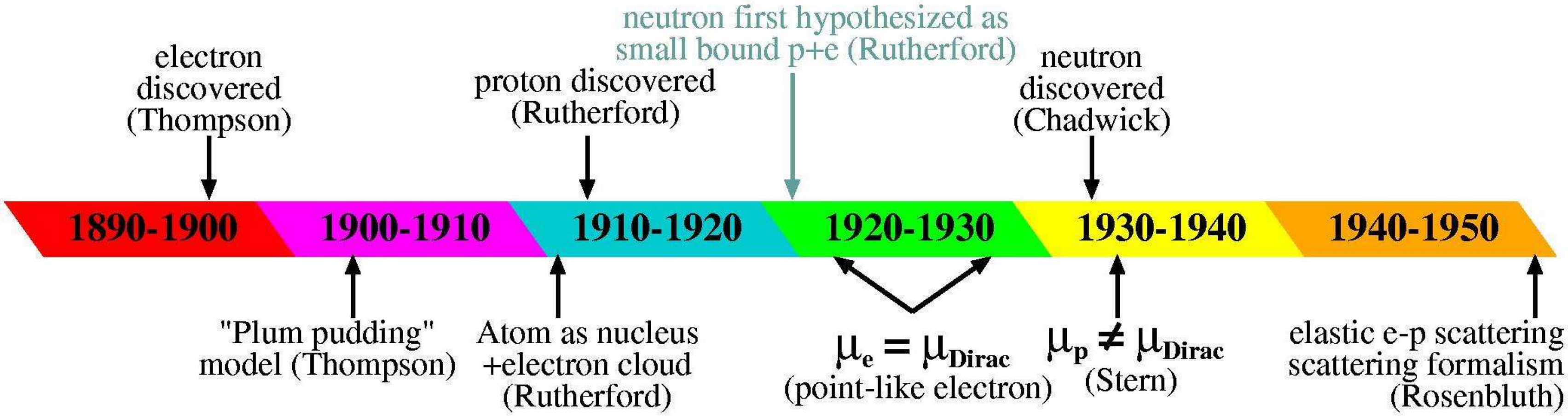
Where do we stand

- We do know what the constituents of hadrons are
- We do not know how many constituents there are
  - How much spin, Orbital angular momentum, etc… do they carry?
- We cannot calculate their interactions
- We cannot study their interactions directly
  - No phase shifts for q-q scattering
- Need to absorb all of the missing information into extremely simplified models OR measure observables that give us model-independent information

Key observables in probing proton sub-structure

- **Form factors: Elastic e-p scattering**
  - **Deviation from point-like scattering as function of momentum transfer (Q^2)**
  - **Encode spatial distributions of charge, magnetization**
  - **Equal to charge (magnetic moment)-weighted spatial distribution of quarks in non-relativistic limit**

Early History of the Proton



<1900: Gas discharge tubes used to study cathode rays (electrons) and canal rays (positive ions)

1902: W. Wein - "canal rays" identified as positive particles, measured e/m ratio

1913: Rutherford - Ionized Hydrogen as the simplest possible nucleus with unit charge
"proton" from "protos" (Greek "first") name adopted ~1920, used as early as 1908

1932: "Modern" picture of the atom (small nucleus of protons+neutrons, large electron cloud)
Protons, neutrons, and electrons all known:
- All have known charge, mass, spin
- Assumed to be fundamental, point-like particles

1933: $\mu_p \neq \mu_{Dirac}$ --> PROTON INTERNAL STRUCTURE (still considered fundamental)

1950: Rosenbluth - "High-Energy Electron Scattering of Electrons on Protons"
Formalism for e-p elastic scattering, discussion of q-dependence in terms of proton "size"

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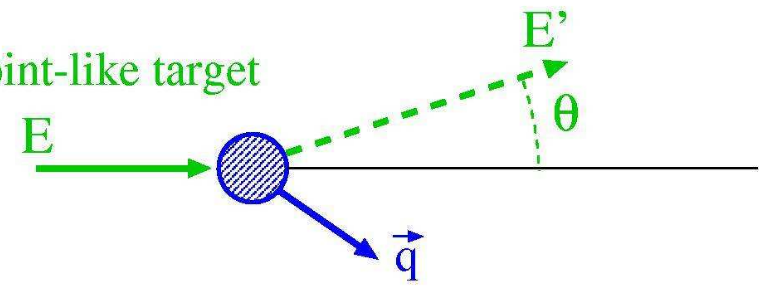
Electron Scattering and Form Factors



Form factor: Parametrizes deviation from point-like target

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{Point}} |F(\mathbf{q})|^2$$

$$F(q) = 1 - \frac{1}{6}|\mathbf{q}|^2\langle R^2\rangle + \ldots$$

1951: Lyman, Hanson, and Scott measured e-A scattering at the 22-MeV Betatron (UIUC), observed finite size of nuclei (Al to Au)

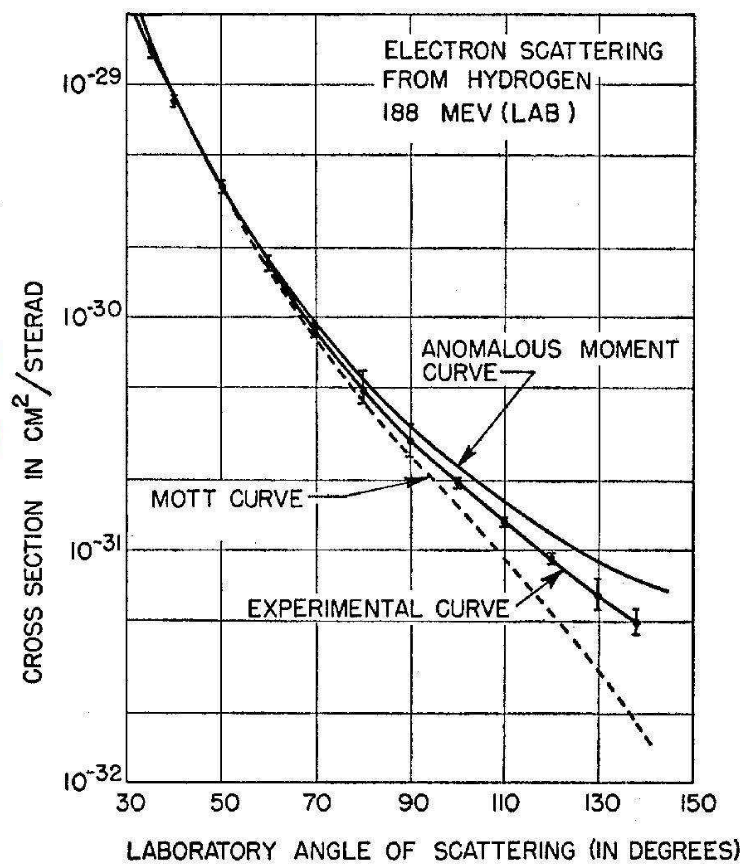
Au: R ≅ 10 fm, need q ~ 0.1 fm^{-1} to observe the effects of nuclear radius

1953: Hofstadter, Fechter, and McIntyre extract radii (Be to Au) at Stanford Mark-III linac. First measurement of e-p scattering (F(q)≅1)

Proton: R<1 fm, need q ~ 1 fm^{-1}

1955: Hofstadter and McAllister determine size of the proton using SLAC 240 MeV beam

➡ $R^{RMS}_{proton} \sim 0.74 +/- 0.24\, fm$



R.Hofstadter and R.W.McAllister, Phys. Rev. ***98****, 217 (1955)*

Electron Scattering and Form Factors

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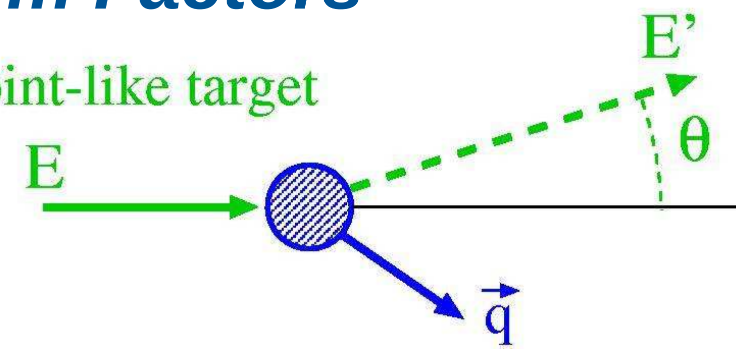
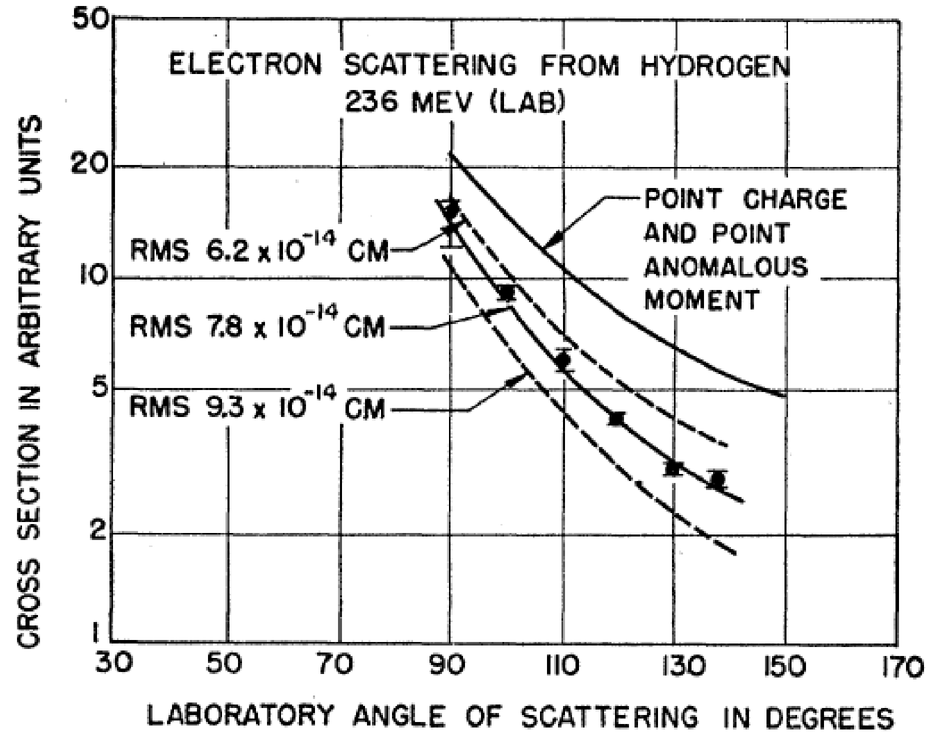


$Q^2 \sim \sin^2(\theta/2)$ for fixed beam energy << M_p



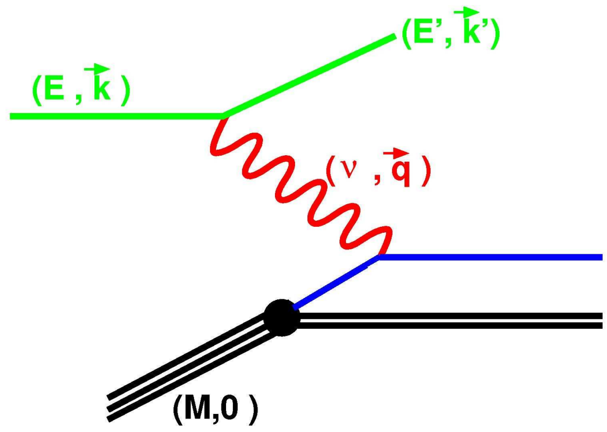
PHYSICAL REVIEW VOLUME 102, NUMBER 3 MAY 1, 1956

Elastic Scattering of 188-Mev Electrons from the Proton and the Alpha Particle*†‡§‖¶

R. W. McAllister and R. Hofstadter
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California

(Received January 25, 1956)

Proton Form Factors



$\nu = E - E'$

$\vec{q} = \vec{k} - \vec{k}'$

$Q^2 = q^2 - \nu^2$

$x_{Bj} = \dfrac{Q^2}{2M\nu}$

Full cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2(\theta/2)}{4\,E^2 \sin^4(\theta/2)} \frac{E'}{E} \left[\left(F_1^2 + \frac{\kappa^2 Q^2}{4M^2} F_2^2\right) - \frac{q^2}{2M}(F_1 + \kappa F_2)^2 \tan^2(\theta/2) \right]$$

$F_1(Q^2)$ and $F_2(Q^2)$ are the Dirac and Pauli form factors

κF_2 - anomalous magnetic moment

Sachs form factors:

$$G_E(Q^2) = F_1(Q^2) - \tau\kappa F_2(Q^2)$$
$$G_M(Q^2) = F_1(Q^2) + \kappa F_2(Q^2)$$

$G_E(Q^2{=}0) = q_p = 1$

$G_M(Q^2{=}0) = \mu_p = 2.79\,\mu_N$

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

At very low Q^2 values:

$G_E(Q^2) \sim 1 - \frac{1}{6} Q^2 \langle R^2 \rangle + \ldots$ yields *charge* radius

$G_E(Q^2)$ is the Fourier transform of the charge distribution in the Breit fram

Unpolarized Elastic e-N Scattering

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

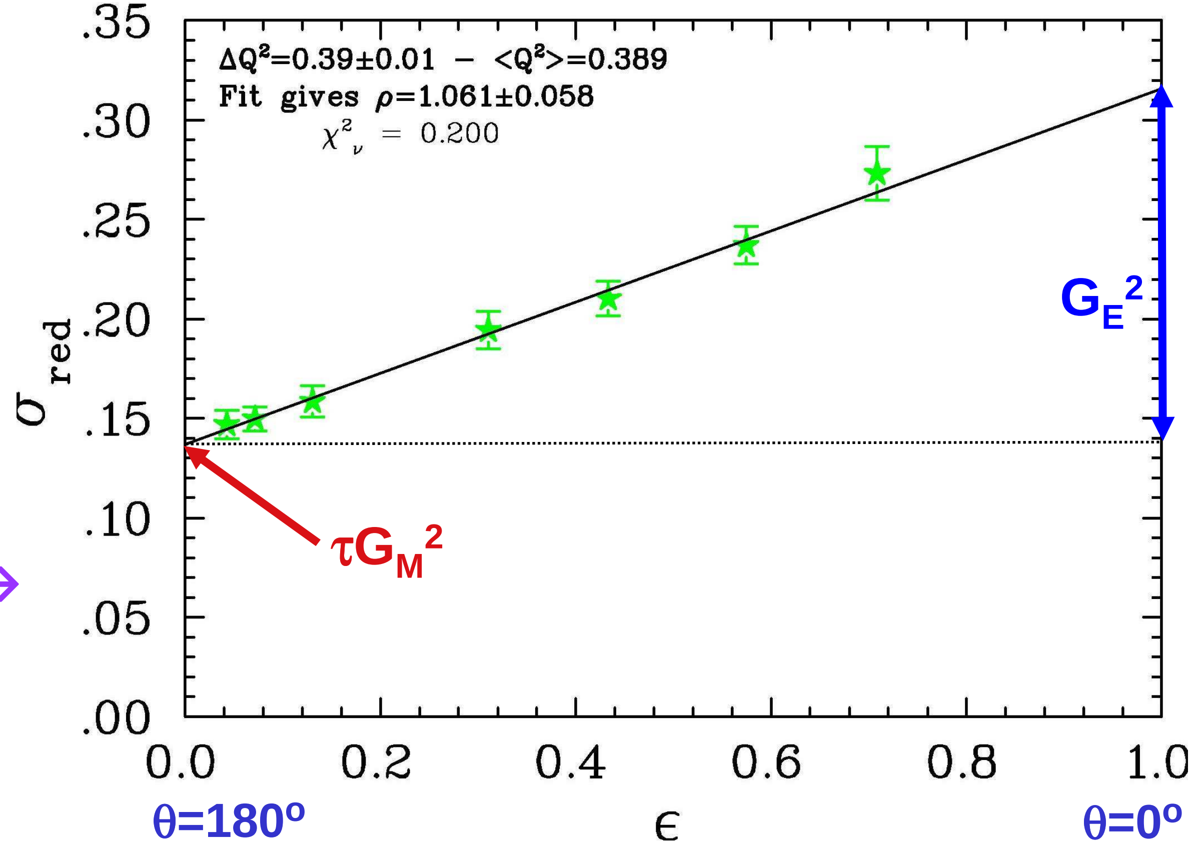
$\sigma_R = d\sigma/d\Omega\,[\varepsilon(1+\tau)/\sigma_{Mott}] = \tau G_M^2 + \varepsilon G_E^2$

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

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

Reduced sensitivity when one term dominates:

- **G_M if $\tau \ll 1$**
- **G_E if $\tau \gg 1$**
- **G_E if $G_E^2 \ll G_M^2$ (e.g. neutron)**



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

Simplest expectation, maximal symmetry

1. **Work in non-relativistic limit**
   - **Spatial density $\rho_{E,M}(r)$ = Fourier transform of $G_{E,M}(Q^2)$**
2. **Assume that up and down quarks have same spatial distributions**
   - **$\rho_u(r) = \rho_d(r) = \rho_0(r)$**
   - **$\rho_u(r)$ in proton = $\rho_u(r)$ in neutron**
   - **No contribution from other quarks (a different kind of "symmetry")**

Predictions:

$G_u(Q^2) = G_d(Q^2)$ for proton *(charge weighting removed)*

$G_{u,d}(Q^2)$ same in proton, neutron

$G_{E,M}^{proton}(Q^2) = 2 * (q_u,\mu_u) * G_u(Q^2) + 1 * (q_d,\mu_d)\, G_d(Q^2)$

$G_{E,M}^{neutron}(Q^2) = 1 * (q_u,\mu_u) * G_u(Q^2) + 2 * (q_d,\mu_d)\, G_d(Q^2)$

→ ***G_{Ep}, G_{Mp}, G_{En}, G_{Mn} all proportional to $G_0(Q^2)$***

→ ***Normalization at Q^2=0 is the charge, magnetic moment of nucleon***

→ ***$G_{En}(Q^2)$= 0, $\rho_E(r) = 0$***

Early Measurements of Nucleon Form Factors

- **Neutron electric form factor small**
  - **G_{En}=0 (neutron charge) at Q^2=0**
  - **Small but positive at low Q^2**
  - **Consistent with zero at higher Q^2**

- **Others well approximated by dipole form**

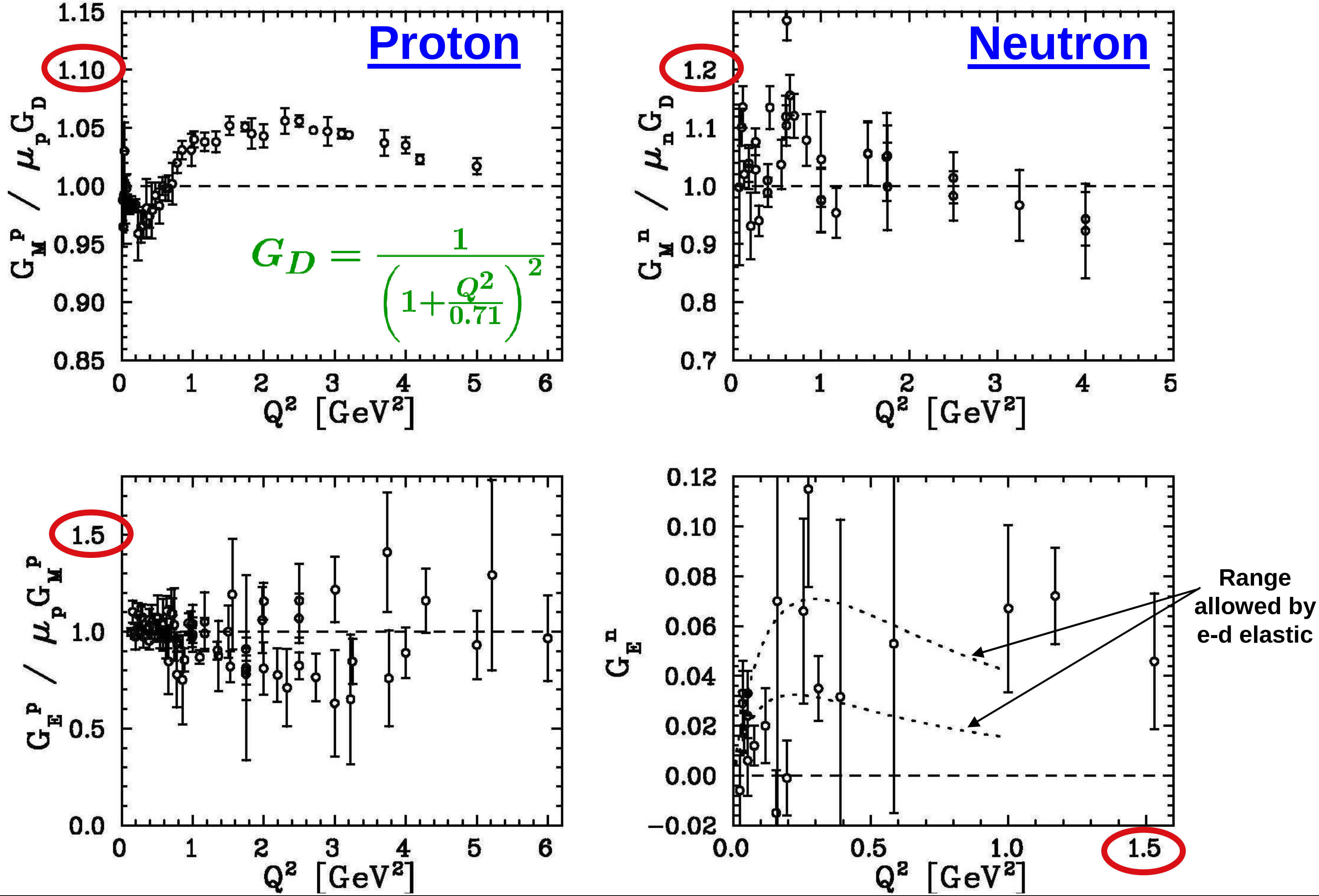
$$G_E^p \approx G_M^p/\mu_p \approx G_M^n/\mu_n \approx G_D$$

$$G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \quad \leftrightarrow \quad \rho_D(r) = \rho_0\, \mathrm{e}^{-\sqrt{0.71}r}$$

- **Only proton magnetic form factor well measured over large Q^2 range**

- **This is the level of most "textbook physics" discussions of the nucleon form factors**

Where Were We 10 (or 15 or 20) Years Ago?



Where Were We 10 (15, 20) Years Ago?

- **Charge, magnetization distributions**
  - **All "large" form factors have similar Q^2 dependence**
    - *Similar charge, magnetization distributions*
    - *Consistent with non-relativistic models where quarks carry charge and magnetization*
  - **Neutron has <u>positive core</u> and a <u>negative cloud</u>**
    - ***<u>Implies difference between up, down quark distributions</u>***
    - *Consistent with "pion cloud" picture:* $\mathbf{n \rightarrow p\, \pi^-}$

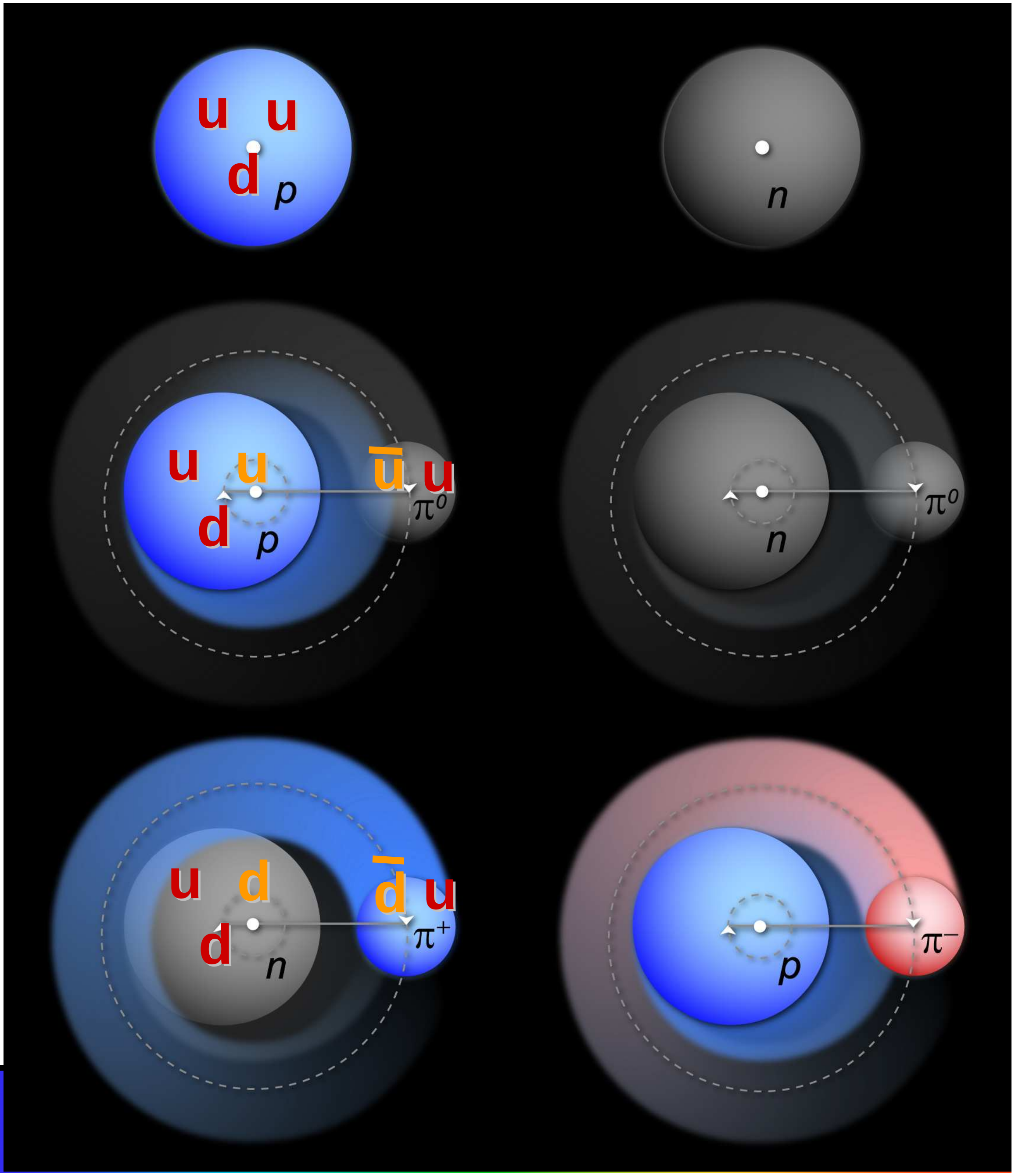
Pion Cloud Contributions

- Large distance behavior has important contributions from N → N + π fluctuations

- p → p π^+ : 'blur' p distribution
- p → n π^- : large-r tail

- Not a 'natural' component of most constituent quark models; often estimated in less detailed fashion

- n → p π^- : Positive core, negative "pion cloud"



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    - ***Implies difference between up, down quark distributions***
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- **Testing models of the nucleon structure**
  - **$G_{Mp}(Q^2)$ well measured over wide range**
    - *Provide constraints for model parameters*
  - **Others not measured as well; needed more complete set of measurements to differentiate between models**

Nucleon Electromagnetic Form Factors

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

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

90s: New Techniques, Better Tools

- Rosenbluth technique has severe limitations
  - Cross section ~ $\tau G_M^2 + \varepsilon G_E^2$ ($\tau = Q^2/4M^2$)
  - Insensitive to charge form factor at high Q^2, magnetic at low Q^2
  - Insensitive to neutron charge form factor
- Lack of free neutron target
  - No hope to measure neutron charge form factor
  - Large correction from subtracting proton in quasielastic ^{2}H(e,e')

- Improved techniques already known
  - Polarized targets or Recoil polarization measurements
  - Coincidence d(e,e'n) and ratio [d(e,e'p)/d(e,e'n)] to probe neutron

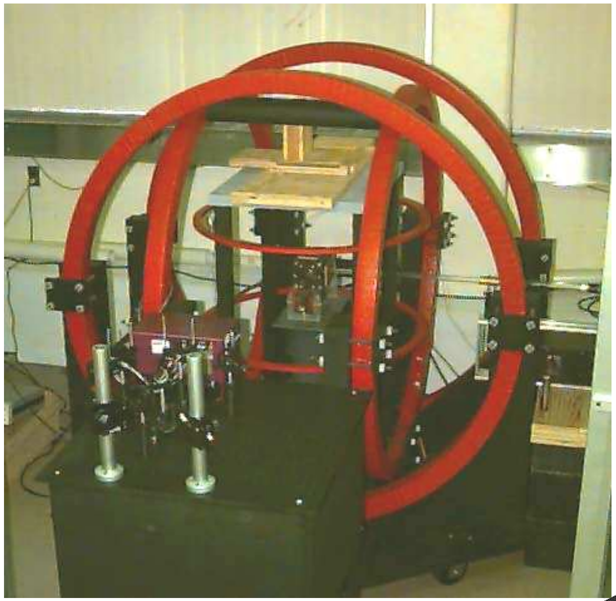
- 1990s brought the necessary experimental improvements…
  - Electron beams with high duty factor, luminosity, polarization
  - Improved polarized targets: hydrogen, deuterium, helium-3
  - High efficiency and/or large acceptance detectors

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

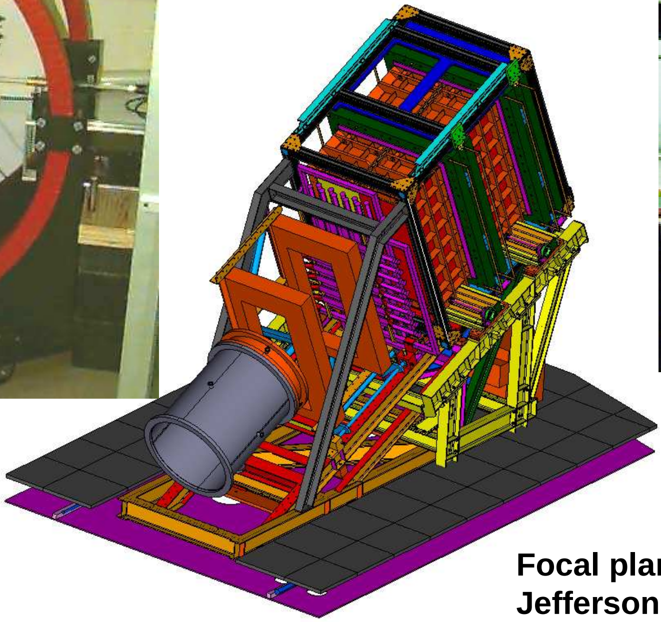
- **Mid '90s brought measurements using improved techniques**
  - **High luminosity, highly polarized electron beams**
  - **Polarized targets (^1H, ^2H, ^3He) or recoil polarimeters**
  - **Large, efficient neutron detectors for ^2H, $^3He(e,e'n)$**
  - **Improved nuclear correction models**

L/T: $\tau G_M^2 + \varepsilon G_E^2$

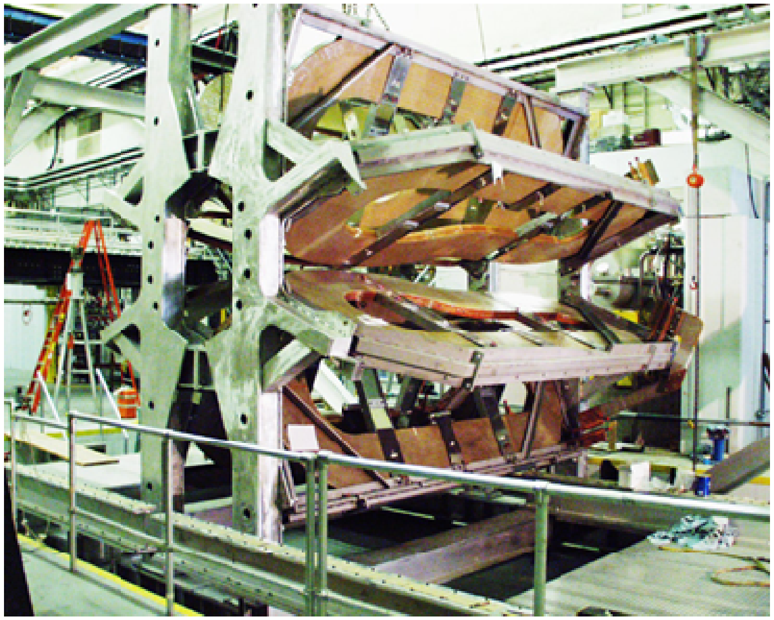
Pol: G_E/G_M



Polarized ^3He target



Focal plane polarimeter – Jefferson Lab



BLAST at MIT-Bates

Example: G_E / G_M from Recoil Polarization

Use polarized electron beam, unpolarized proton target, measure the polarization transferred to the struck proton

$$I_0 P_L = M_p^{-1} \, (E+E')\sqrt{\tau(1+\tau)}\, G_M^2 \tan^2(\theta_e/2)$$

Polarization along ***q***

$$I_0 P_T = 2\sqrt{\tau(1+\tau)}\, G_E G_M \tan(\theta_e/2)$$

Polarization perpendicular to ***q*** (in the scattering plane)

$$P_N = 0$$

Polarization normal to scattering plane

N. Dombey, Rev. Mod. Phys. 41, 236 (1969)

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

$$I_0 = [\tau G_M^2 + \varepsilon G_E^2]/\varepsilon$$

G_E/G_M goes like *ratio* of two components
--> insensitive to absolute polarization, analyzing power

Comparison of different electron polarizations
--> cancellation of false asymmetries

Also useful for neutron (where $G_E << G_M$, so L-T very difficult)

Physics impact of new techniques

- **FFs: Recent developments**
  - **Better separation of G_E, G_M[&]**
  - **Proton vs. Neutron → up vs. down[†]**
  - **Parity violation → strange quark contribution[&]**

- **GPDs (Generalized Parton Distributions)**
  - **Correlations between spin, momentum, spatial information**

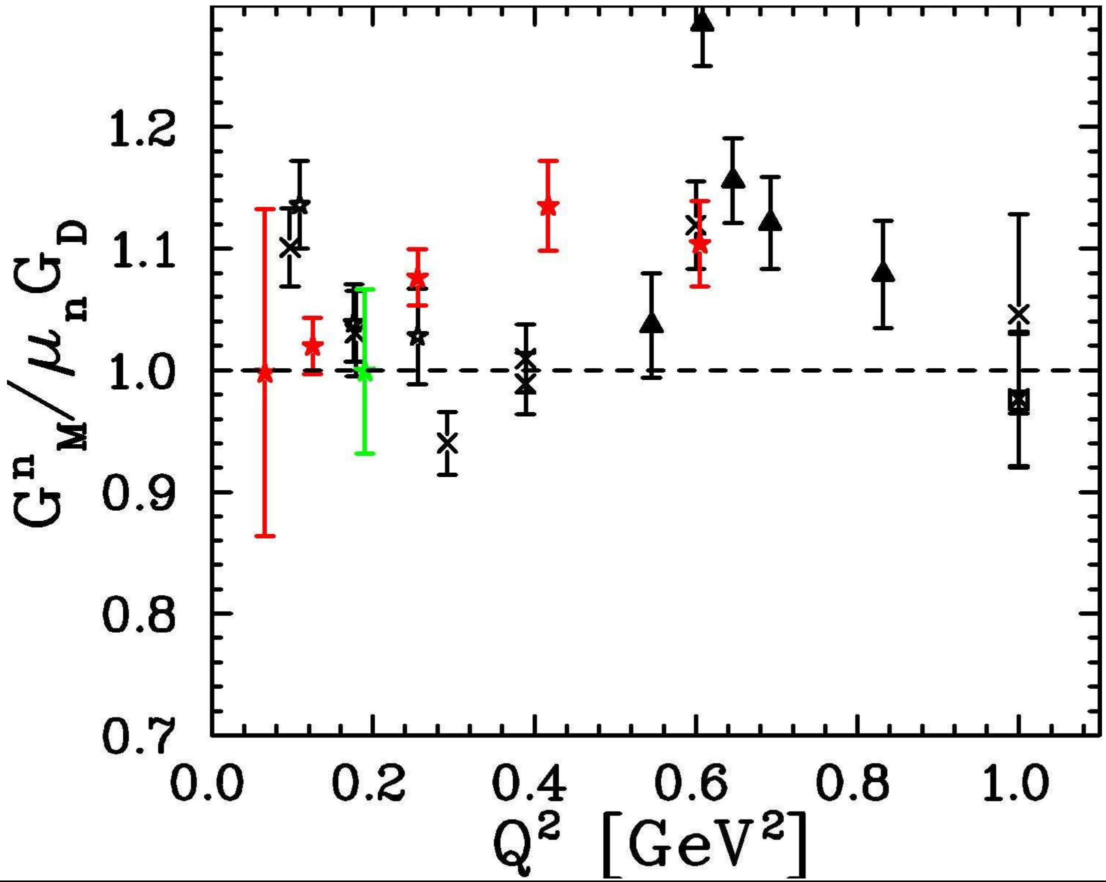
[†] Easy, except for lack of free neutron target

[&] Required significant technical development: polarized beams, polarized targets, polarimeters, etc…

Neutron Form Factors: Recent Advancements

- **Neutron form factor measurements**
  - 1997: Mainly d(e,e') - limited (e,e'n), (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



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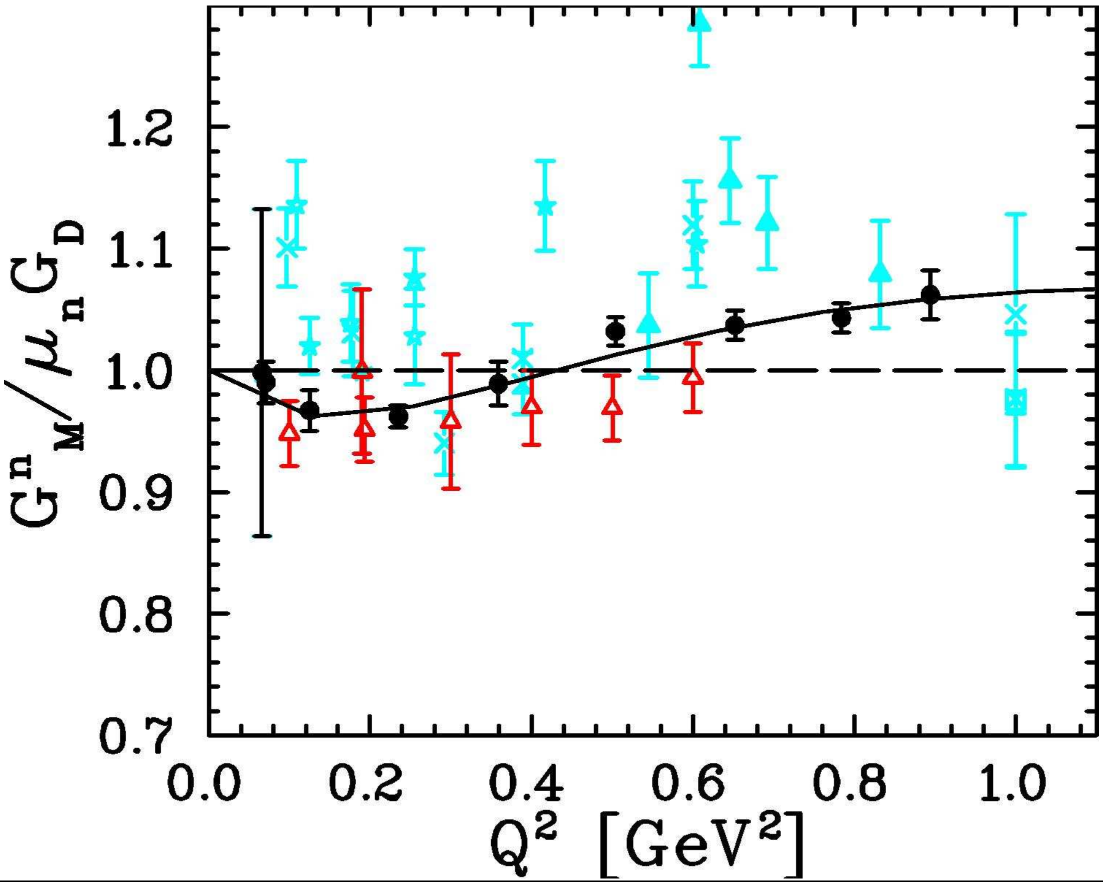

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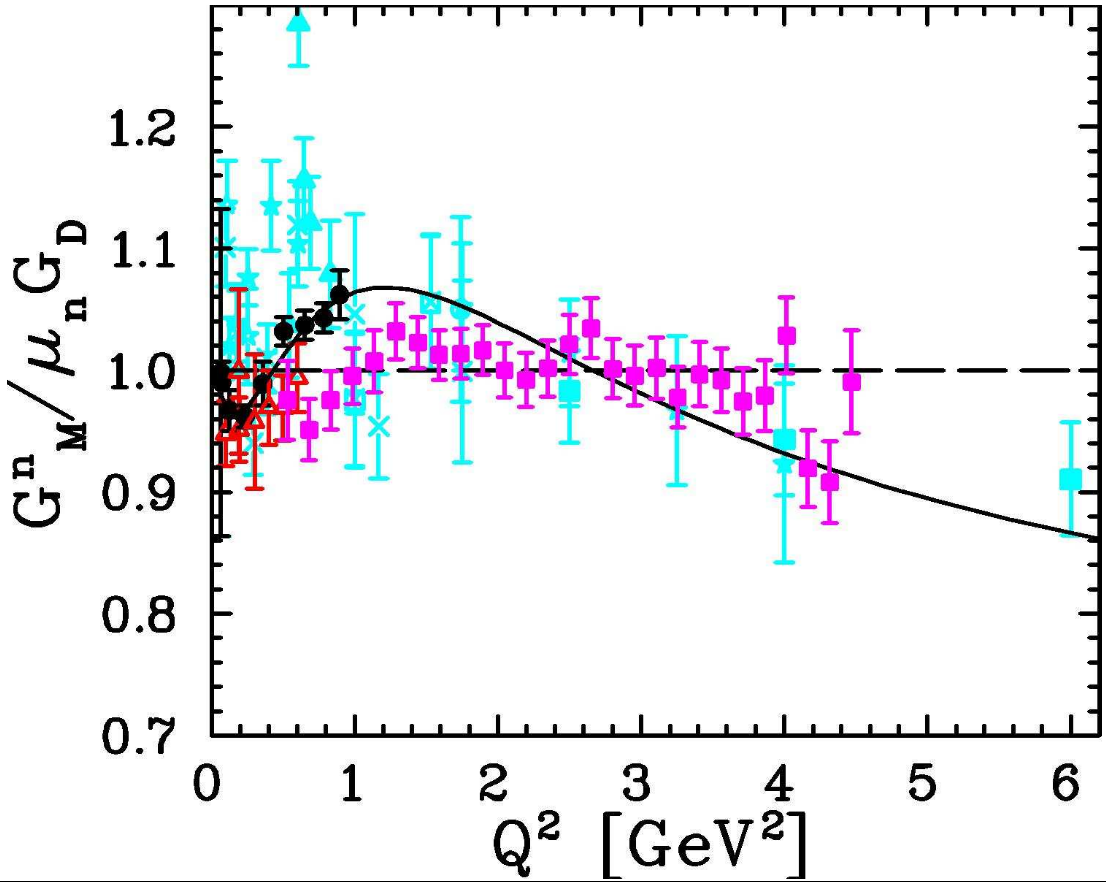
(+CLAS preliminary)



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  - Mostly from elastic e-d → very large model-dependence

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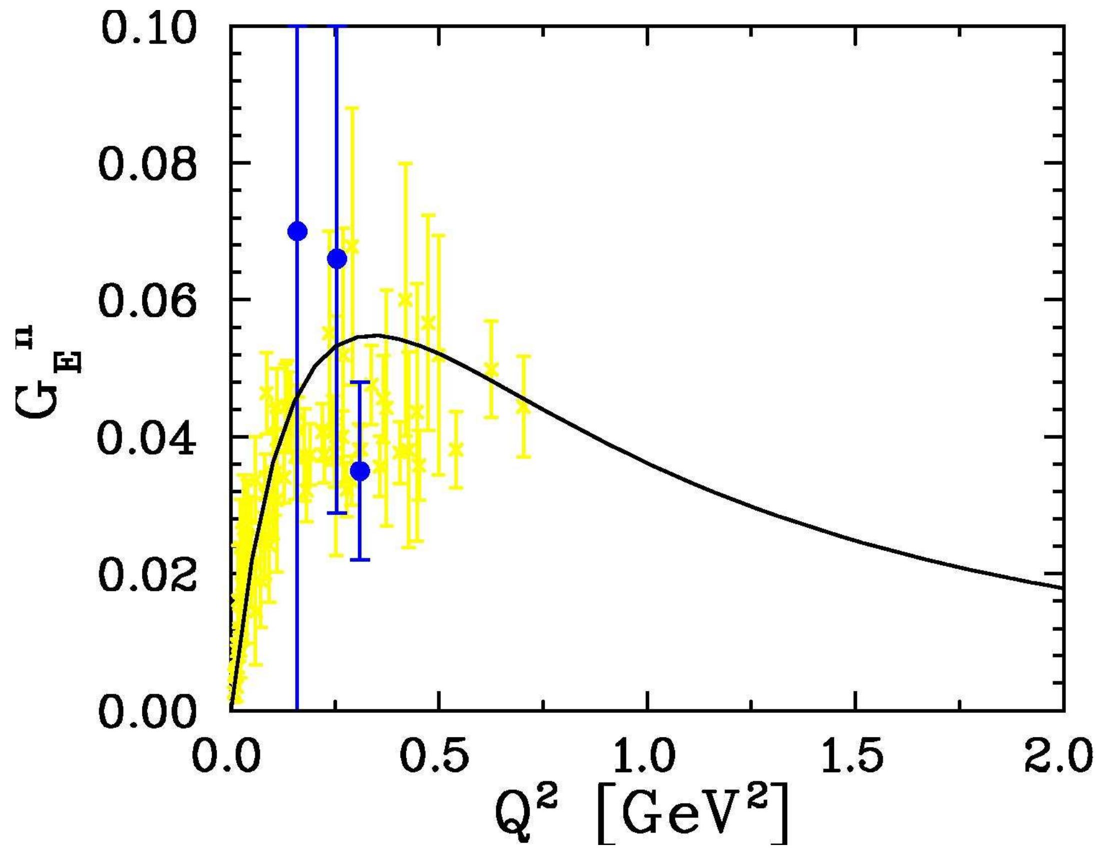

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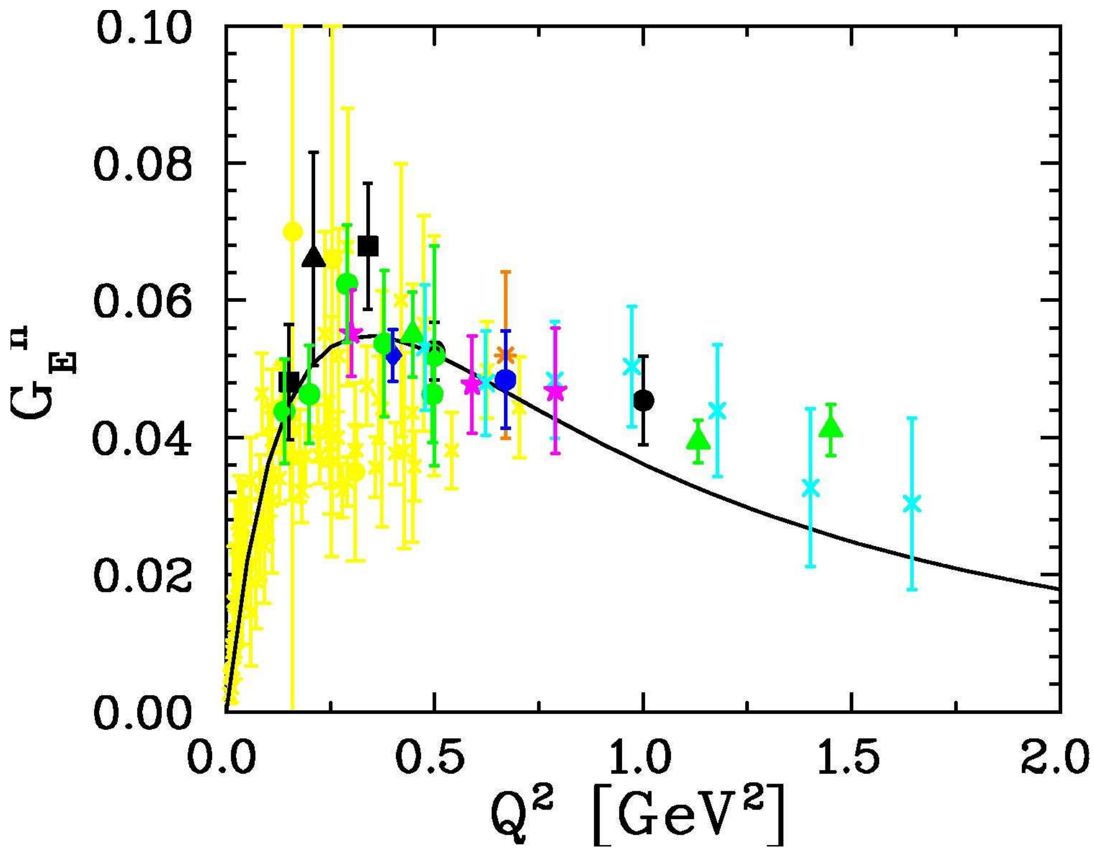

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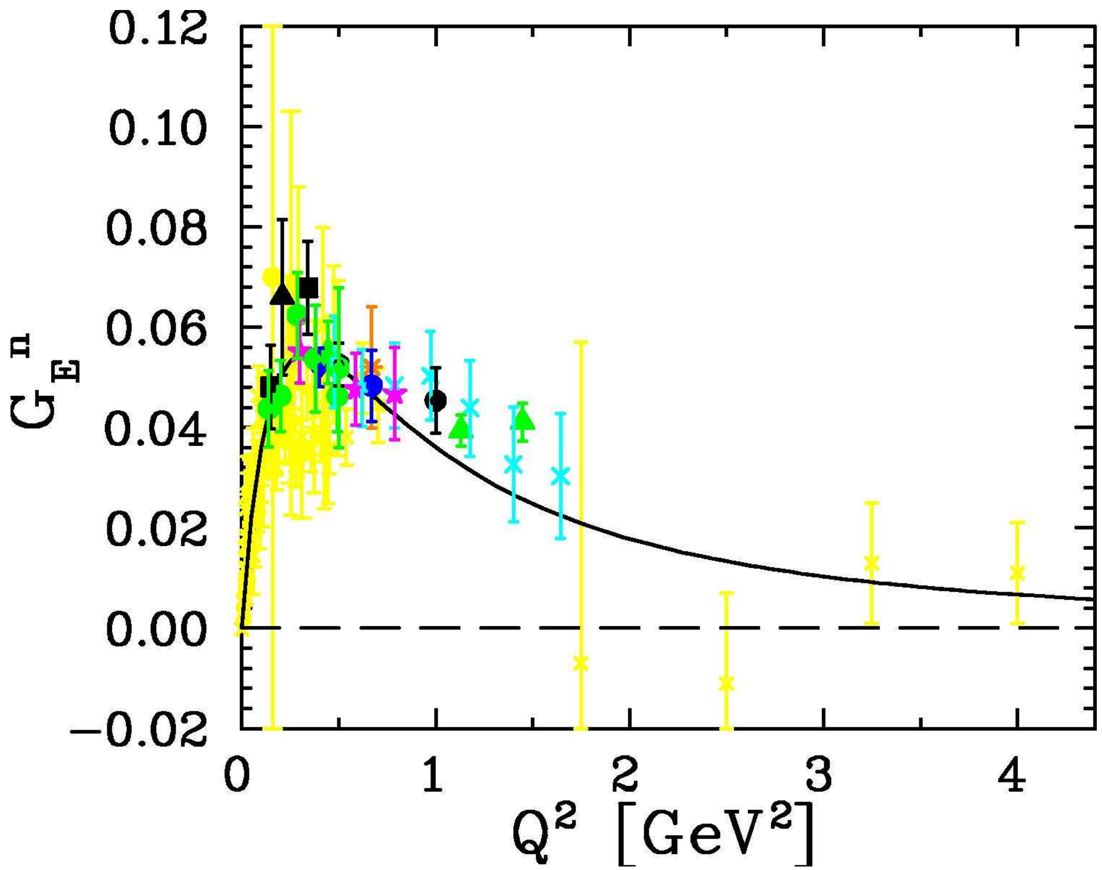

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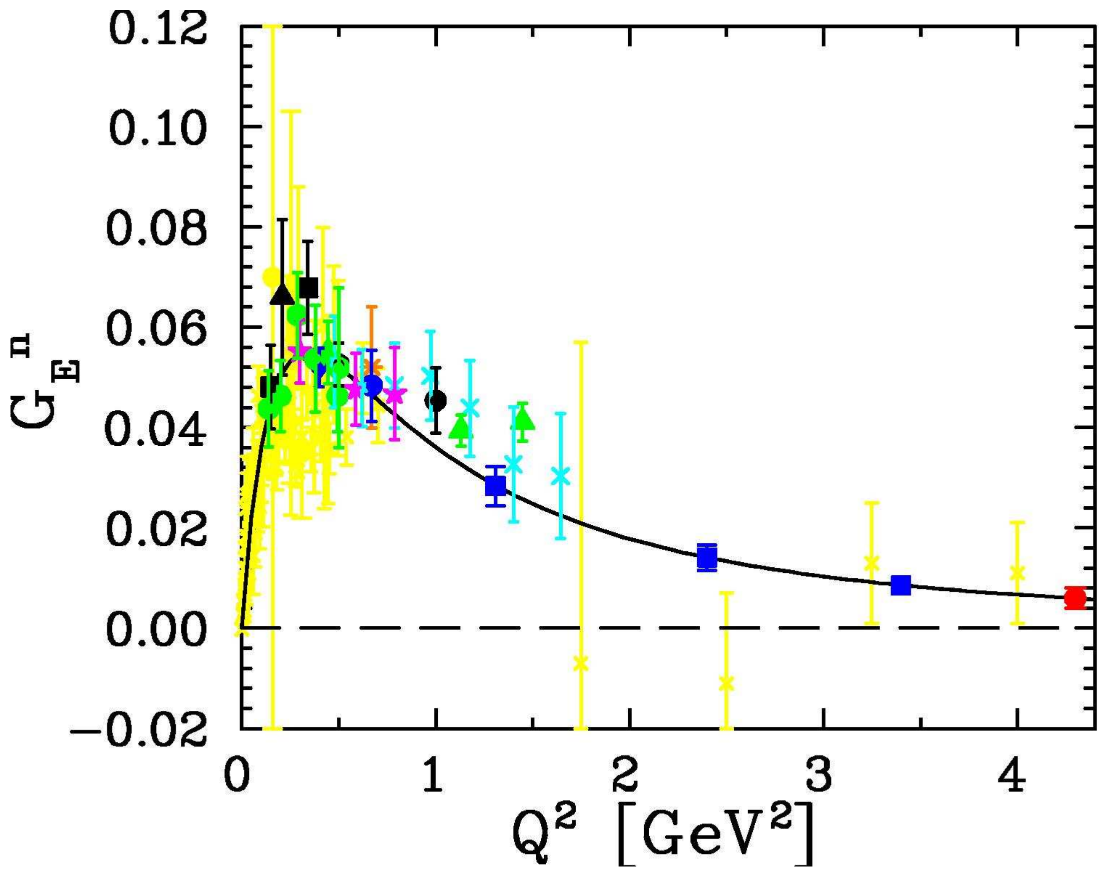
G_{En} as of 1997: elastic e-d and polarization measurements

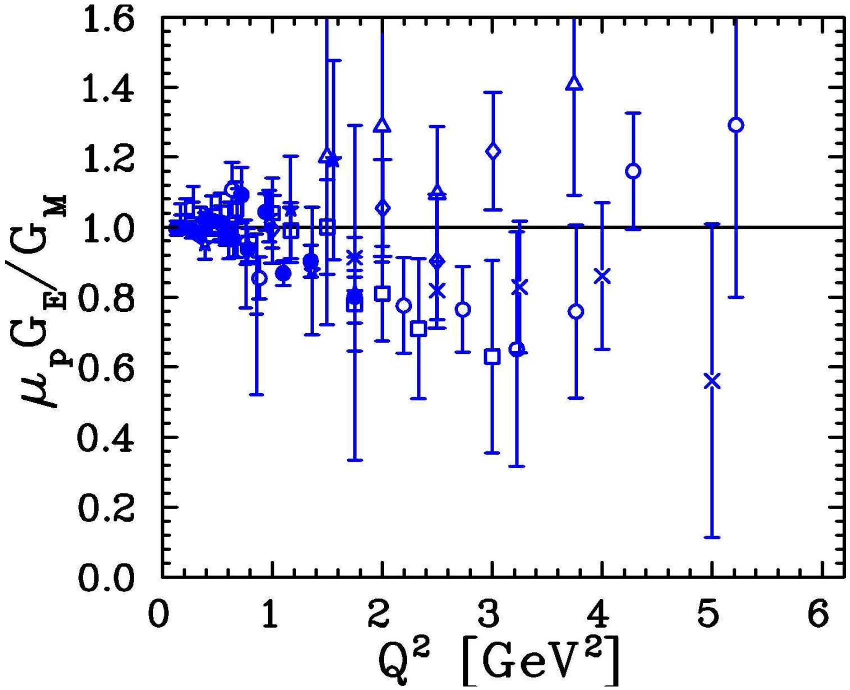
Since 1997: ^{2}H and ^{3}He polarized target and recoil polarization data, along with improved e-d analysis and projected future measurements

Note: If up, down quark have identical spatial distributions, then their charge cancels at all points in space, yielding $G_e^n = 0$ at all Q^2

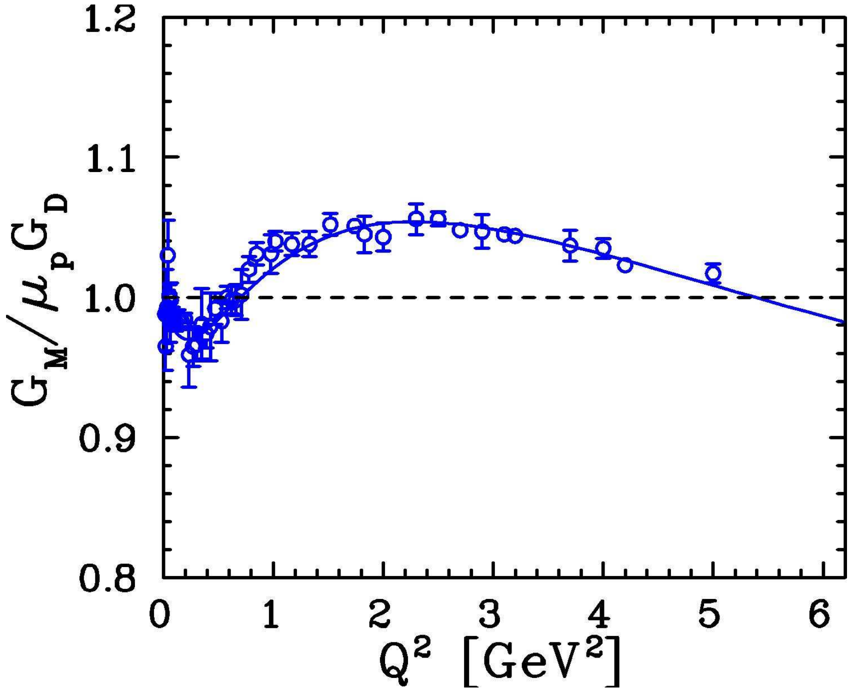


Proton Form Factors: Recent Advancements

- **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

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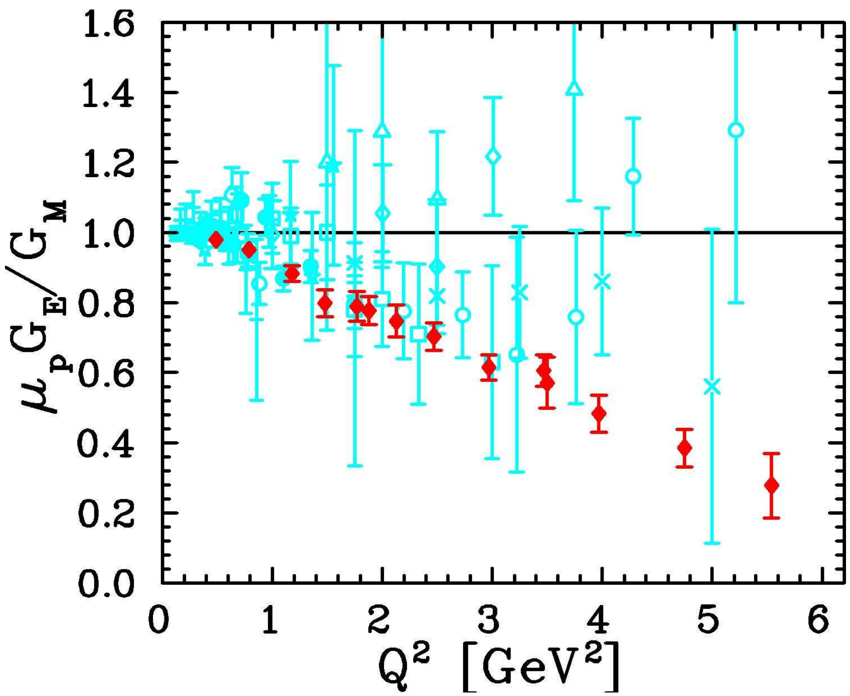
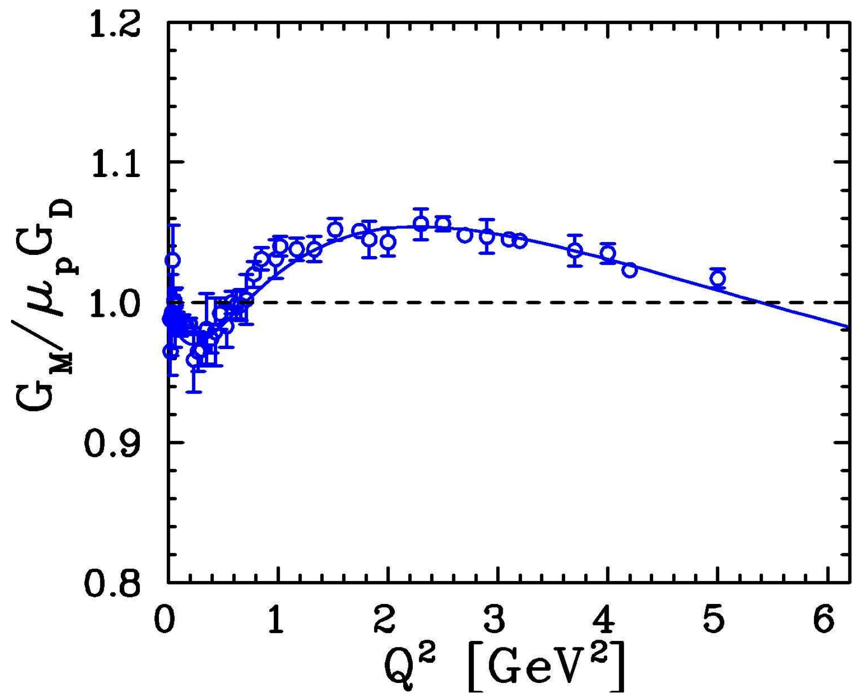


μ_pGEp/GMp from inclusive Rosenbluth measurements

New data: Recoil polarization



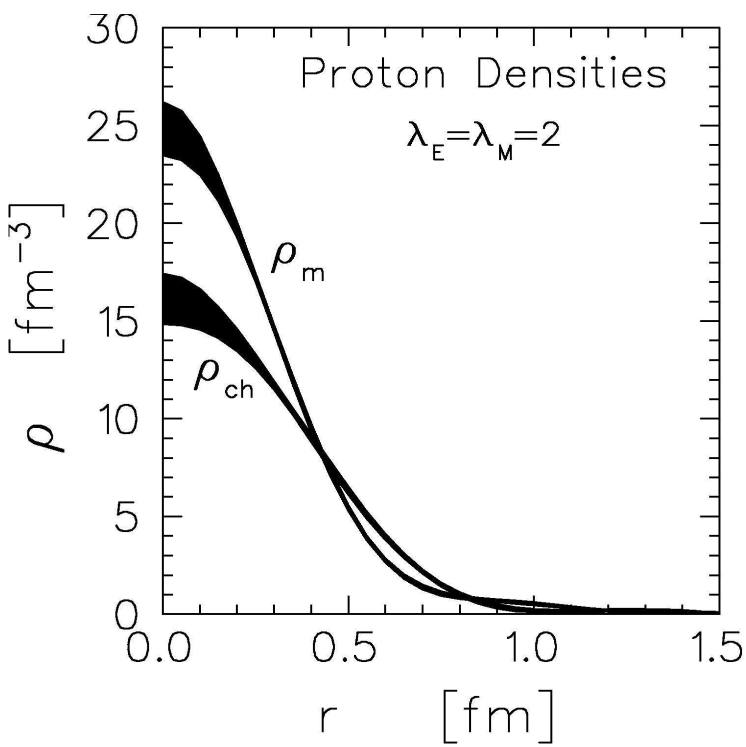
G_{Mp} from inclusive measurements – data extend to 30 GeV^2

Insight from New Measurements, new theoretical tools

- **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

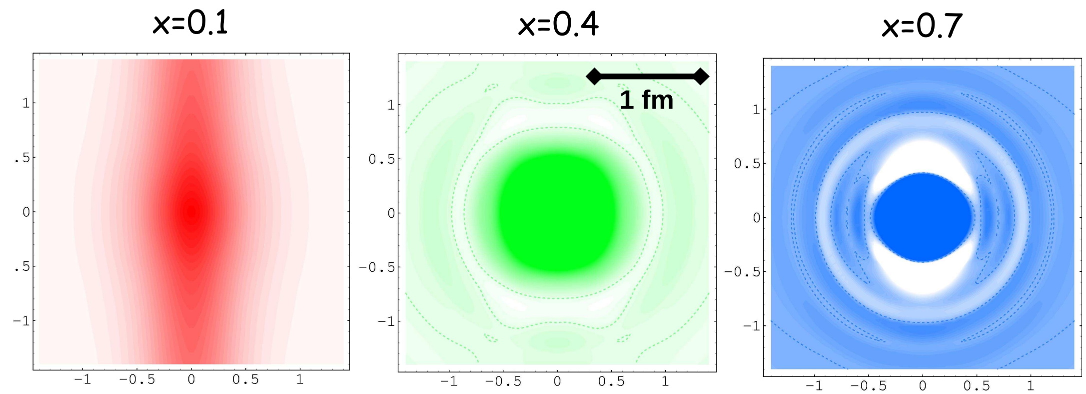
Model-dependent extraction of charge, magnetization distribution of proton:

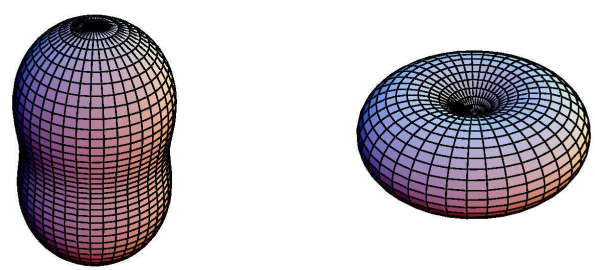
J. Kelly, Phys. Rev. C 66, 065203 (2002)



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

G.Miller, PRC 68:022201 (2003)





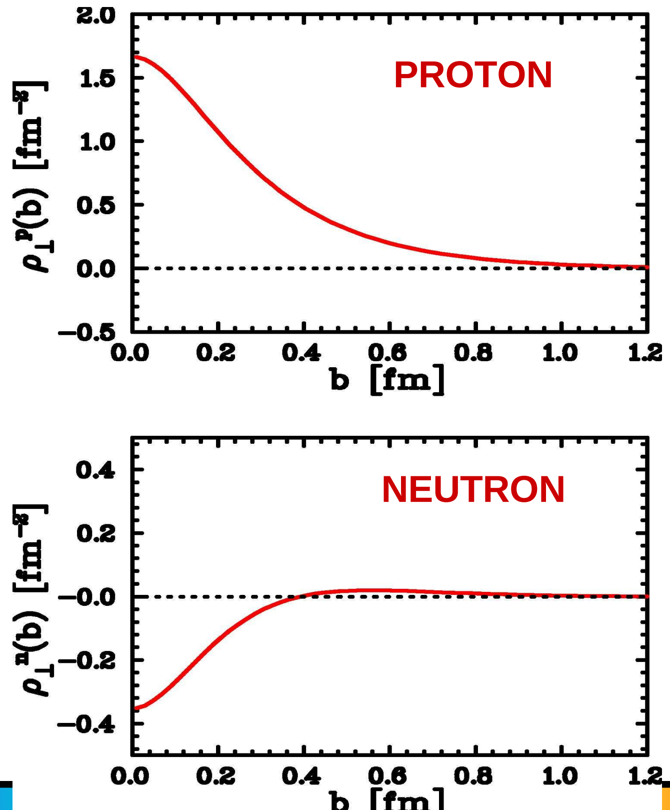
Above: quark spatial distributions (for proton with spin along y axis) for quarks of different momentum values.

Left: quark spatial distributions for quarks with spin parallel (left) and anti-parallel (right) to the proton spin.

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)



G. Miller, PRL 99, 112001 (2007); G. Miller and JA, PRC 78:032201,2008

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
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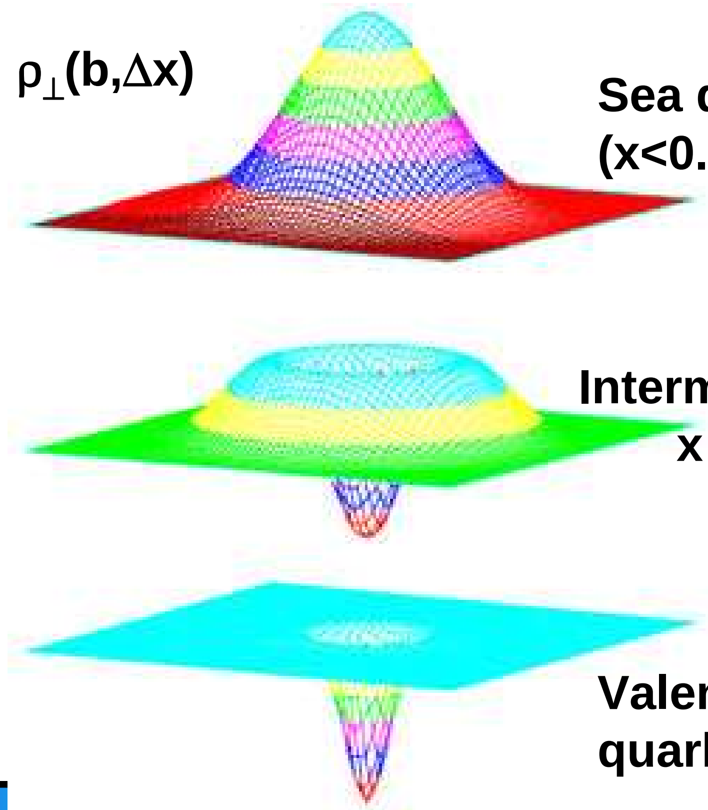


$\rho_\perp(b,\Delta x)$

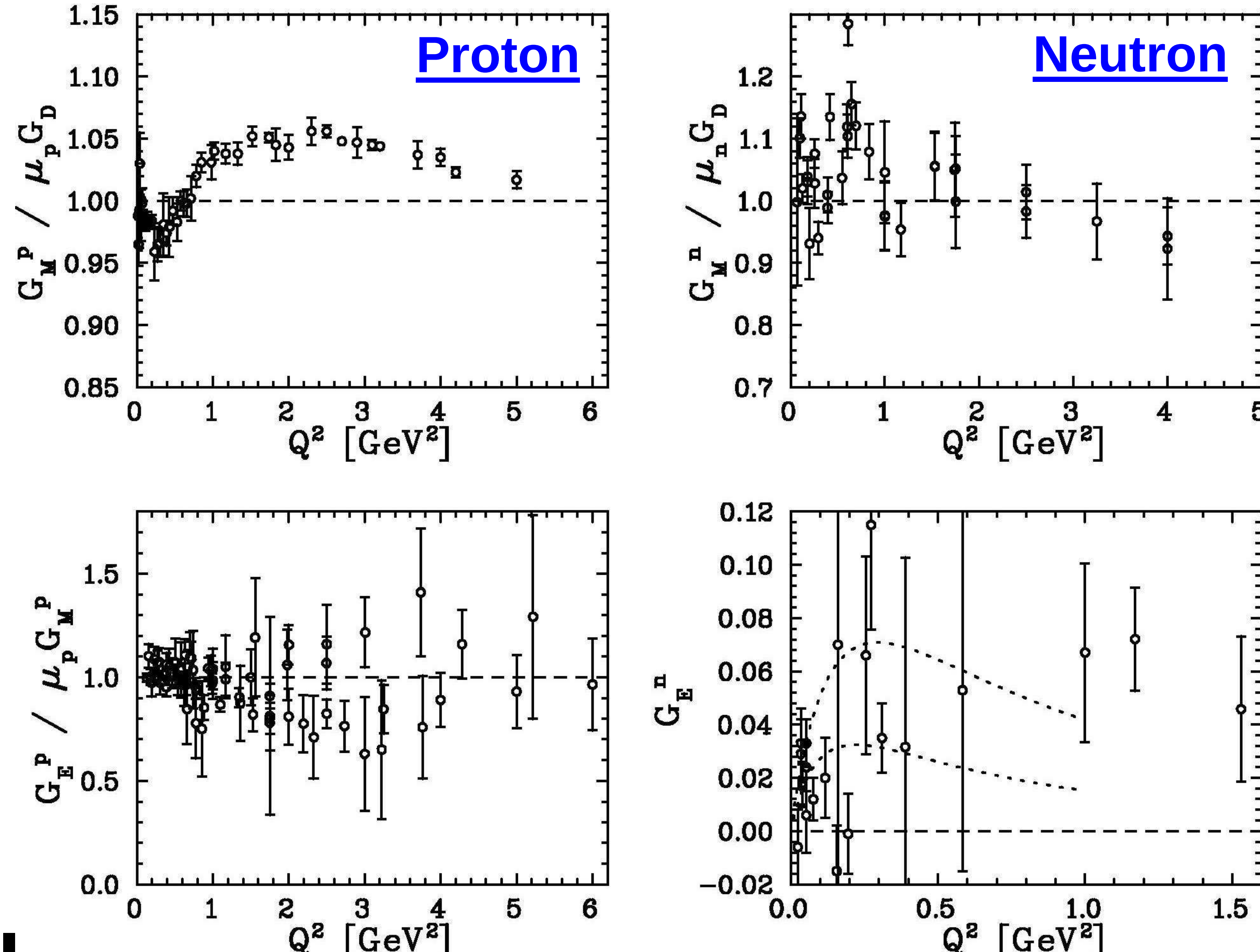
Sea quarks (x<0.1)

Intermediate x region

Valence quarks

G. Miller, PRL 99, 112001 (2007); G. Miller and JA, PRC 78:032201,2008

Nucleon Form Factors: Last Ten Years



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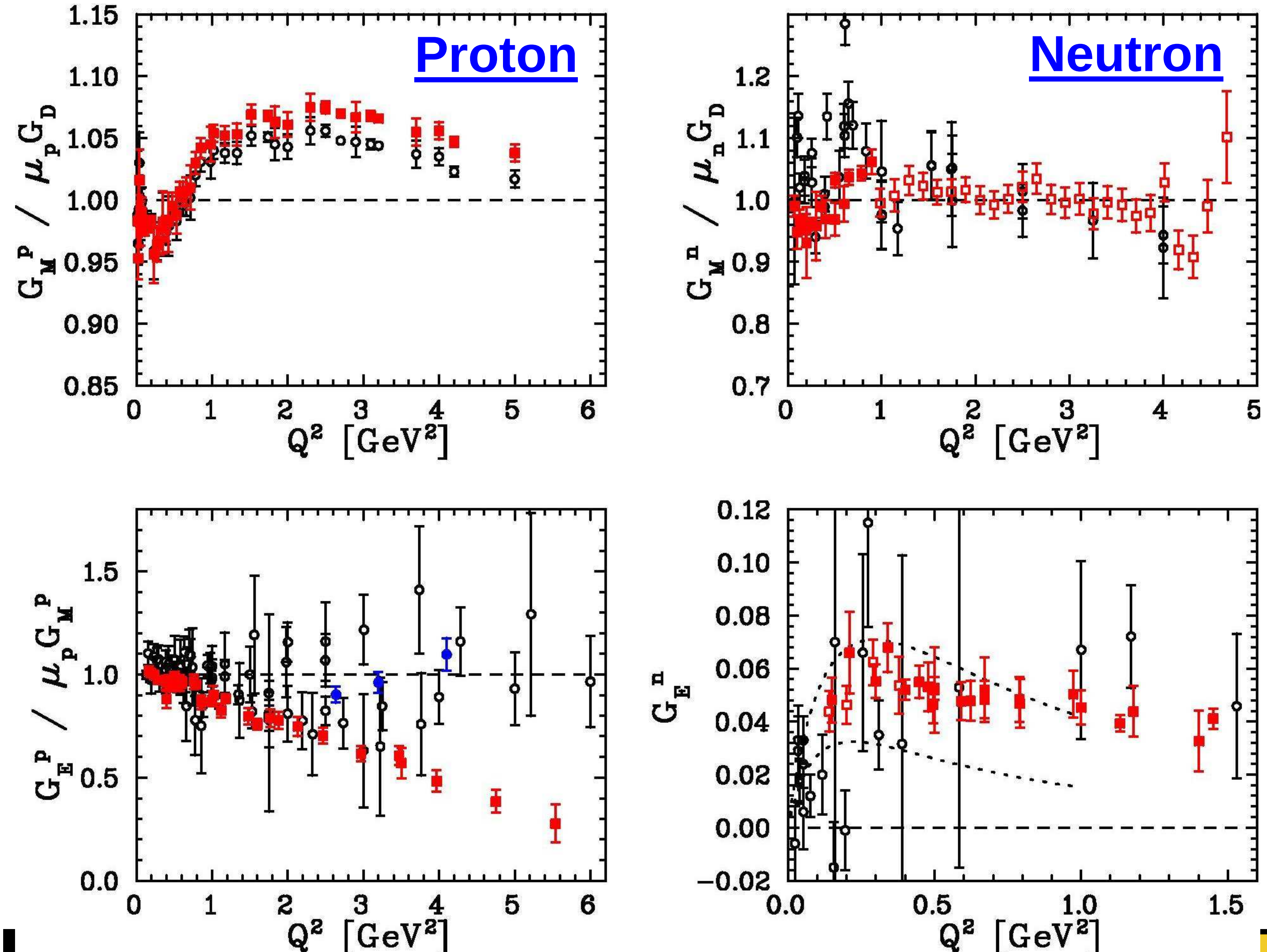
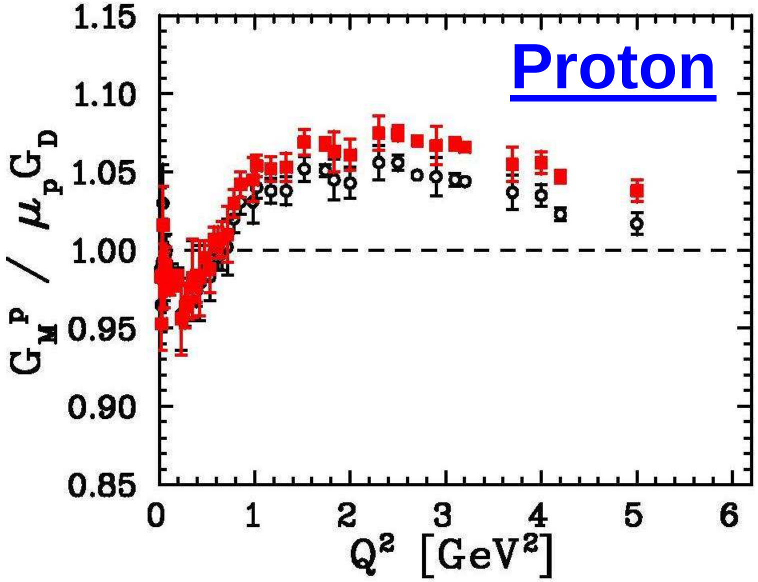
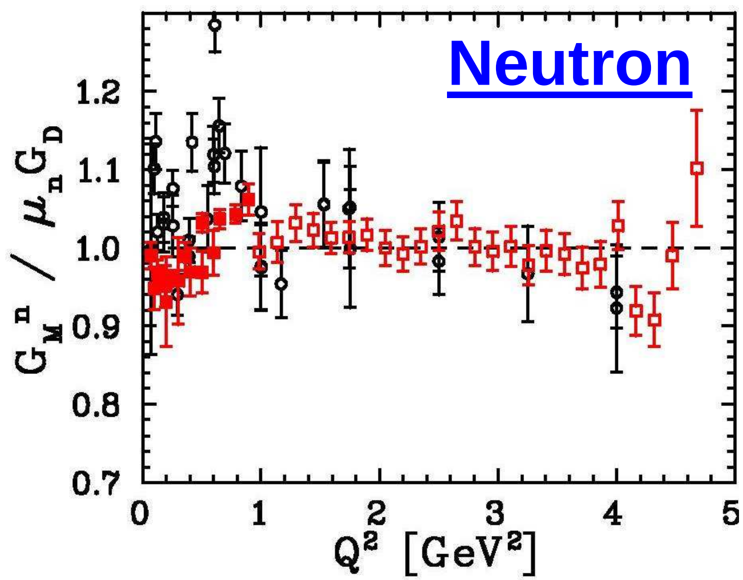


Discrepancy between cross section and polarizatoin for GEp believed to be due to two-photon exchange corrections; leads to shift in GMp (as shown) – see extra slides at end of talk

Nucleon Form Factors: Last Ten Years





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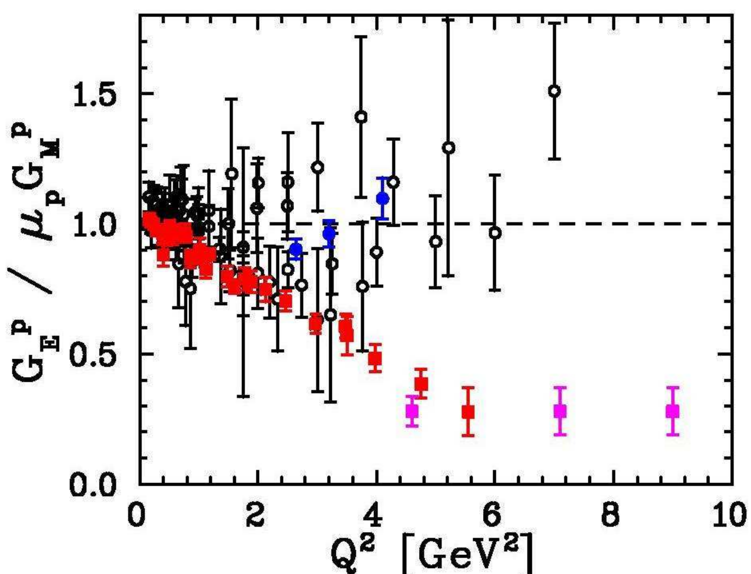
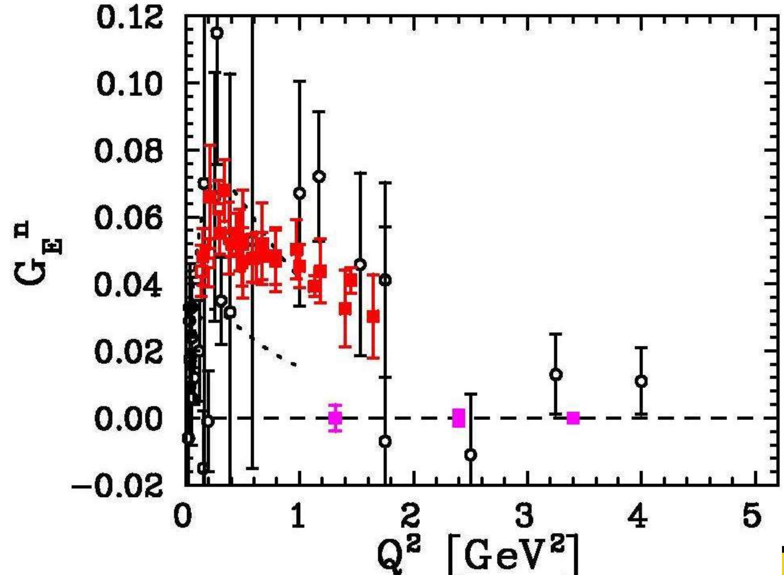
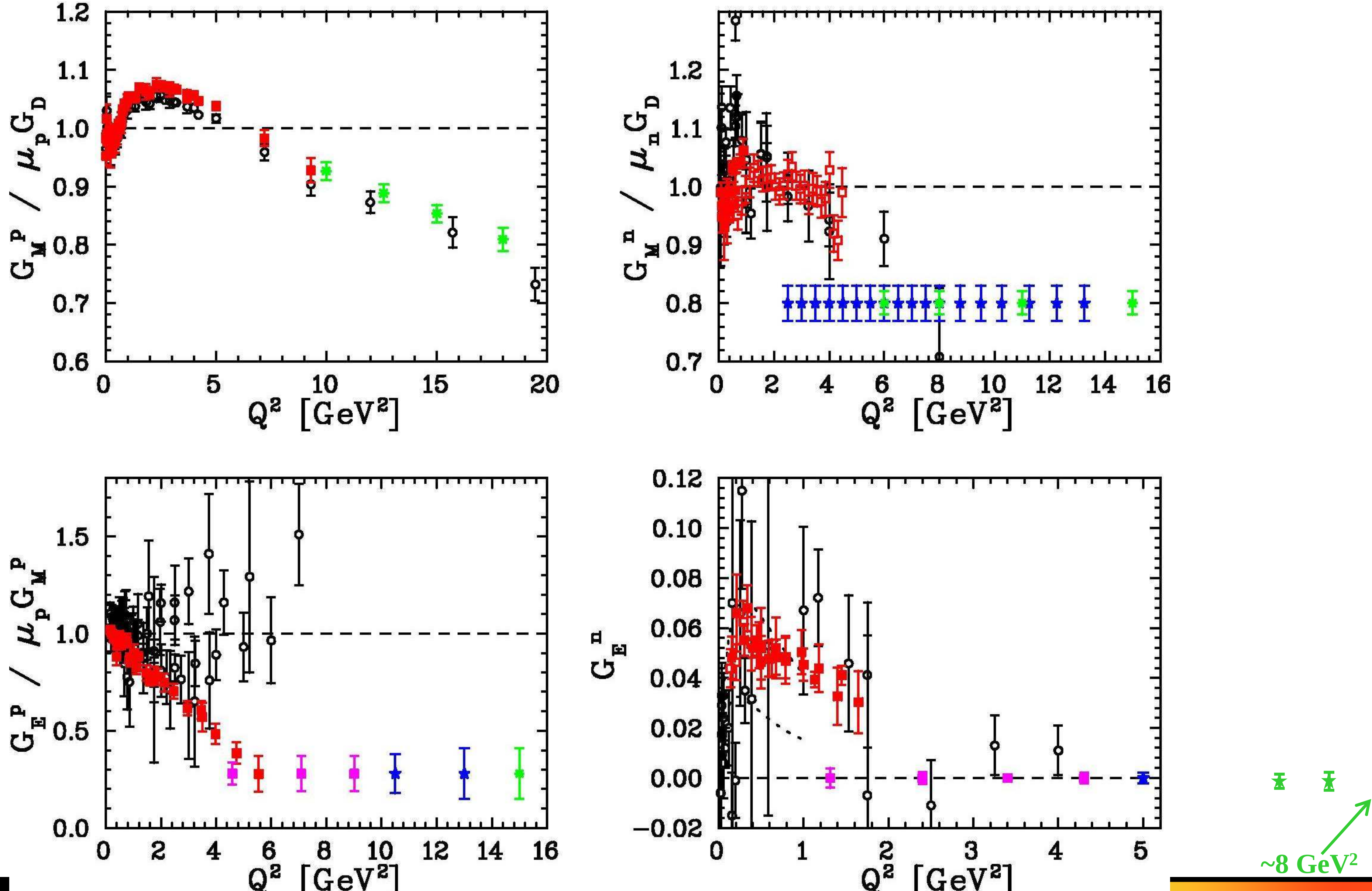




Magenta: Currently under analysis

Published: not yet updated here

Extensions with JLab 12 GeV Upgrade

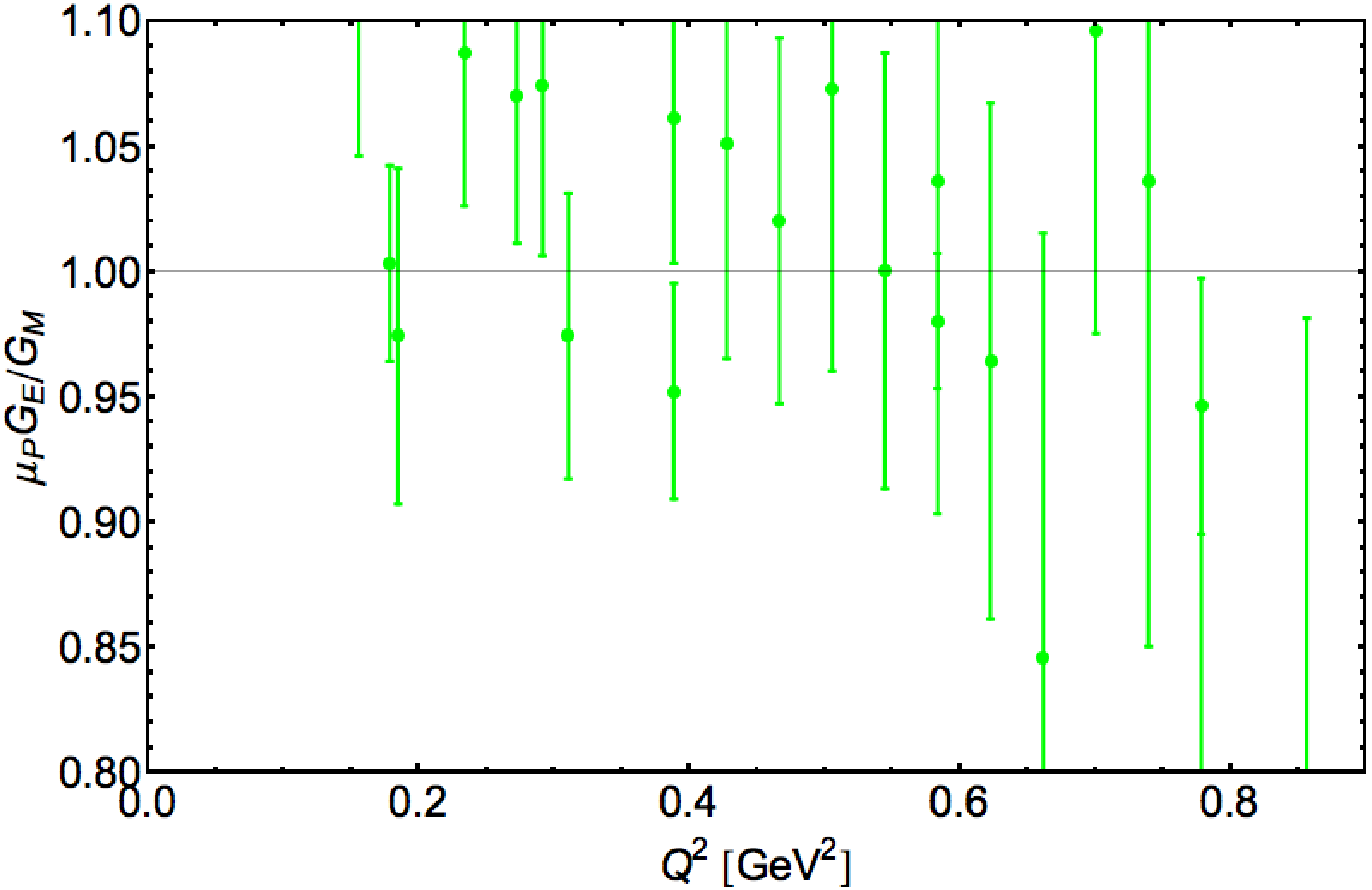


- **BLUE = CDR or PAC30 approved, GREEN = new ideas under development**

From Higher Energy to Higher Precision

- **Even at low Q^2, G_E/G_M for the proton not terribly well measured**
  - *Sensitive to electric, magnetic radii (and the difference)*
  - *Input to program of parity-violating measurements*
  - *Hadronic corrections to precision hyperfine splitting in hydrogen, muonic-hydrogen*

Rosenbluth Separations



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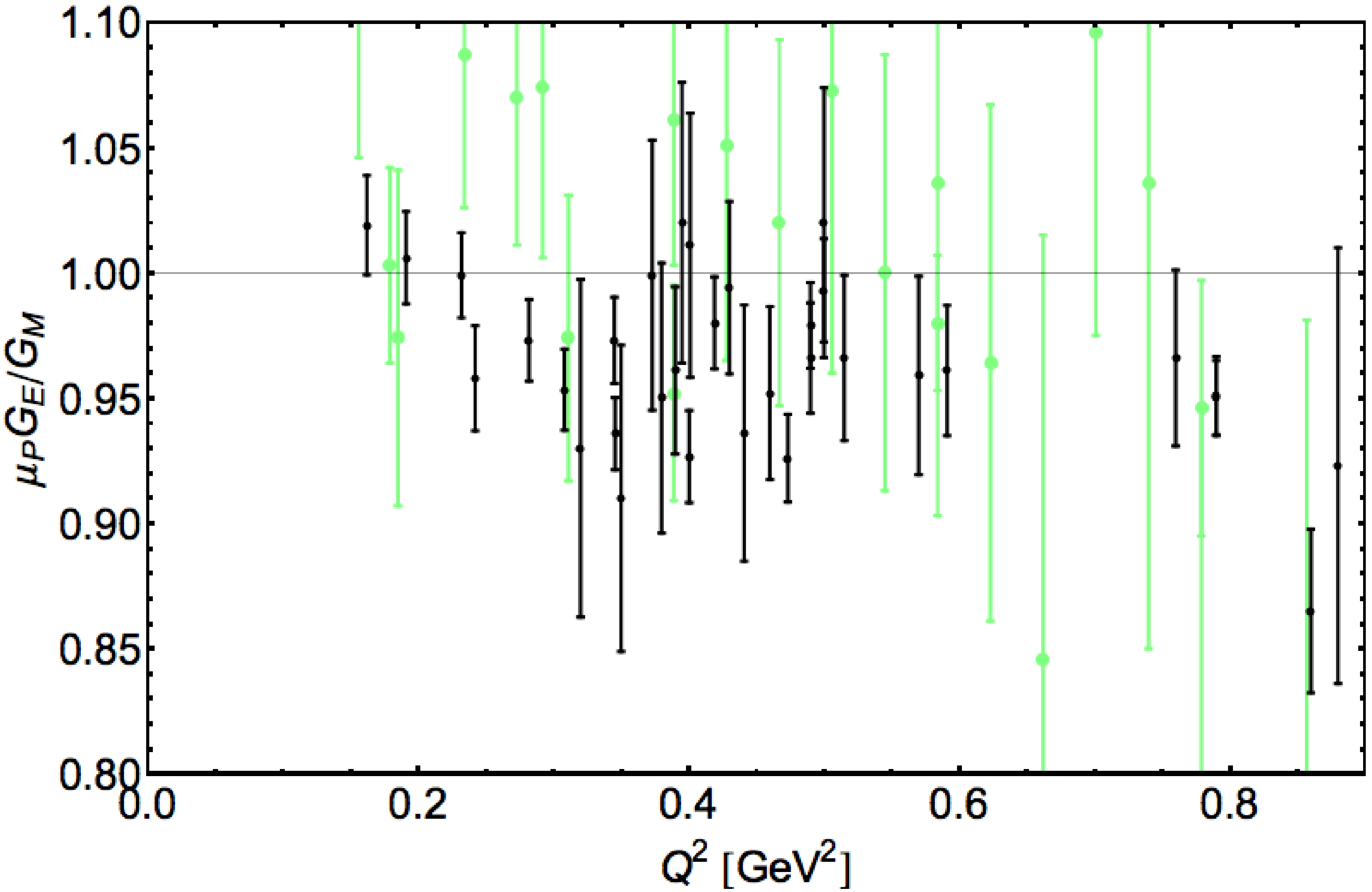
Rosenbluth Separations

Polarization (BLAST, Hall A)



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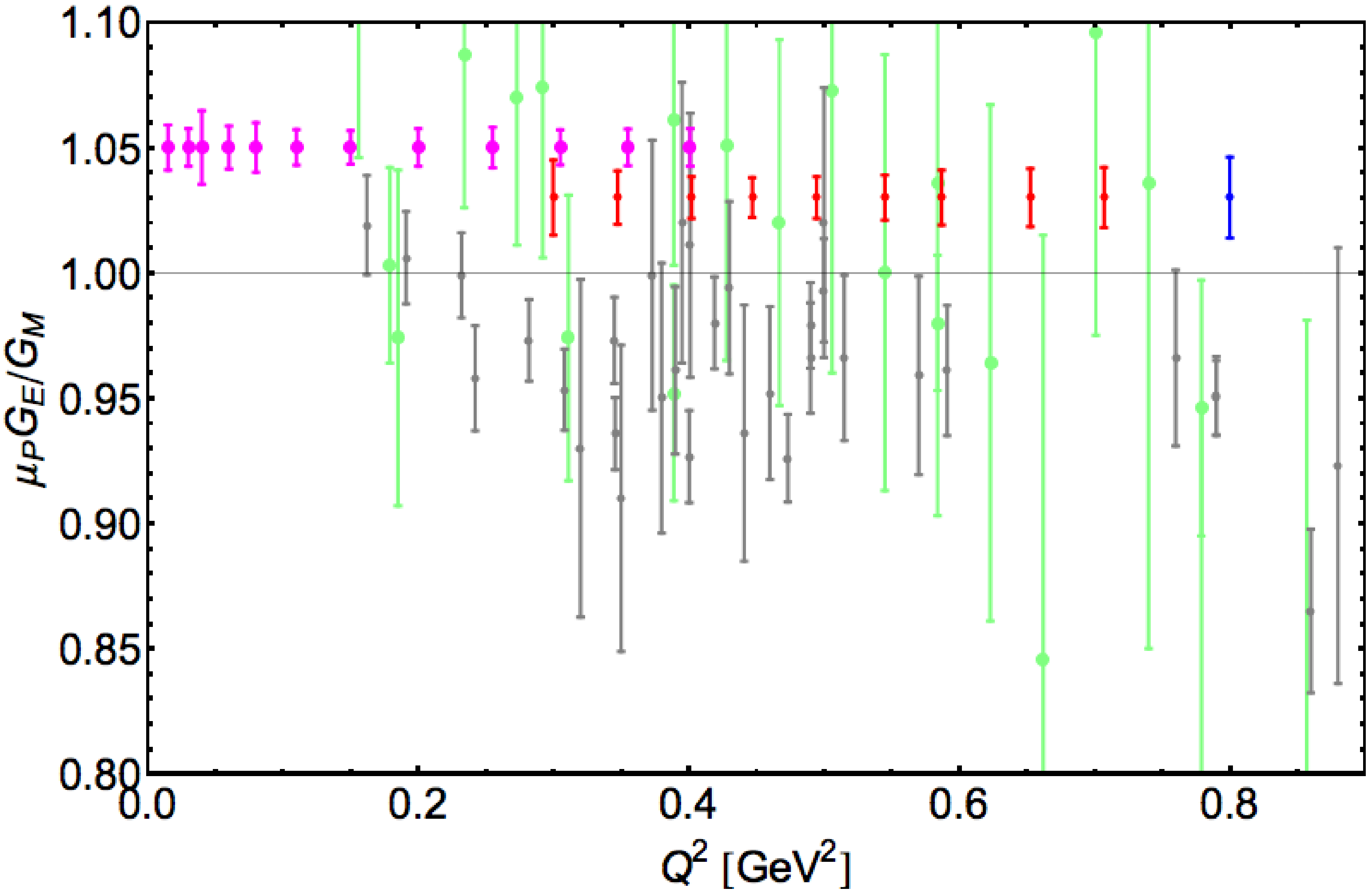
Rosenbluth Separations

Polarization (BLAST, Hall A)

PRELIMINARY/ PROPOSED: JLab E08-007



Comparisons to Lamb shift measurements

- **Finite size of the nucleus has an impact on electron energy levels**

- **Finite radius → level shifts**

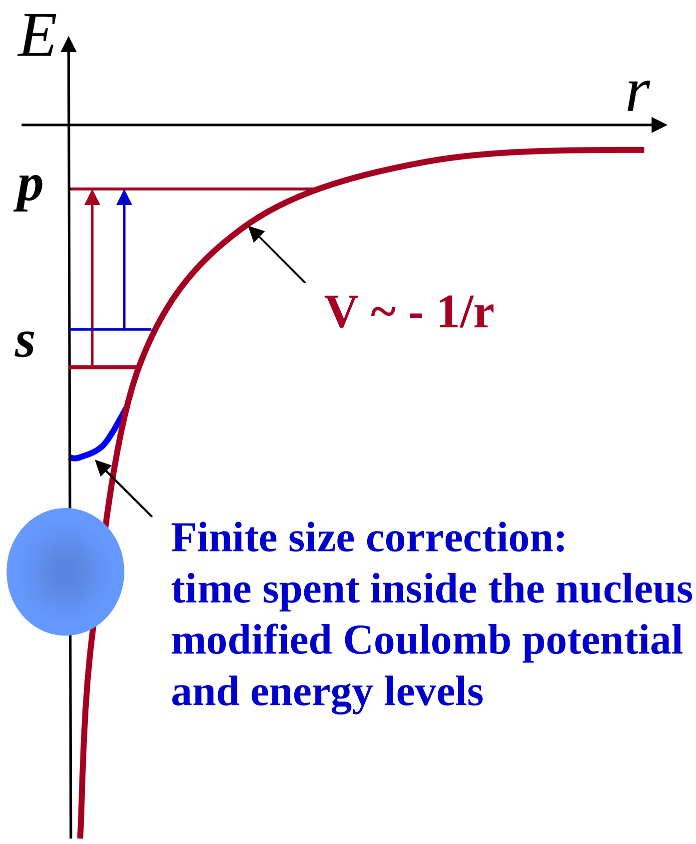
  Measurement of levels/transitions → measure nuclear size (charge radius)

  Field (volume) shift between two nuclei:

$$\delta\nu_{FS} = -\frac{2\pi}{3} Ze^2 \cdot \Delta\left|\Psi(0)\right|^2 \cdot \delta\left\langle r^2 \right\rangle^{AA'}$$

- Used to extract charge radius of ^{6,8}He

- Similar shifts used to extract proton radius



Comparisons of proton radius measurements

- Recently, an extremely precise result was obtained from muonic-hydrogen
  - Heavy muon spends much more time inside the proton
  - Much larger size-dependent correction → dramatically more sensitivity to proton radius [Pohl, et al., published in Nature]
  - $[\langle r_p^2 \rangle]^{1/2}$ = **0.897(18) fm** *(I. Sick, electron scattering global analysis – 1994)*
    0.877(07) fm *(CODATA(2006) – mainly hydrogen Lamb shift)*
    0.842(<1) fm (Pohl, et al. (2001) – muonic hydrogen Lamb shift)

- 5 sigma disagreement with between muonic hydrogen and atomic hydrogen (CODATA), which was in agreement with previous (less precise) extraction from electron scattering
  - Improved e-p scattering extraction will help examine the disagreement
    - *Mainz preliminary R_{RMS}=0.880(08) from new cross section measurements*
    - *Our global fit including new polarization data at low Q^2 (but not Mainz data) also favors CODATA value: final results available soon…*

Parity Violating Elastic e-p Scattering

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

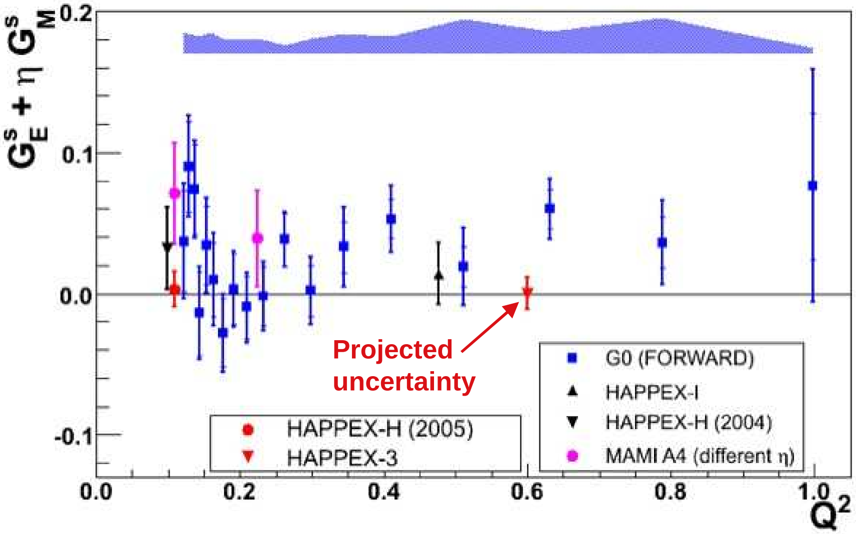
$$\begin{matrix} G_E^u & G_E^d & G_E^s \\ G_M^u & G_M^d & G_M^s \end{matrix} \rightleftarrows \begin{matrix} G_E^p & G_E^n & G_E^{p,Z} \\ G_M^p & G_M^n & G_M^{p,Z} \end{matrix}$$

Experiment	Q^2	A_{PV} [ppm]	Notes
SAMPLE	0.1*	6ppm	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*	-	

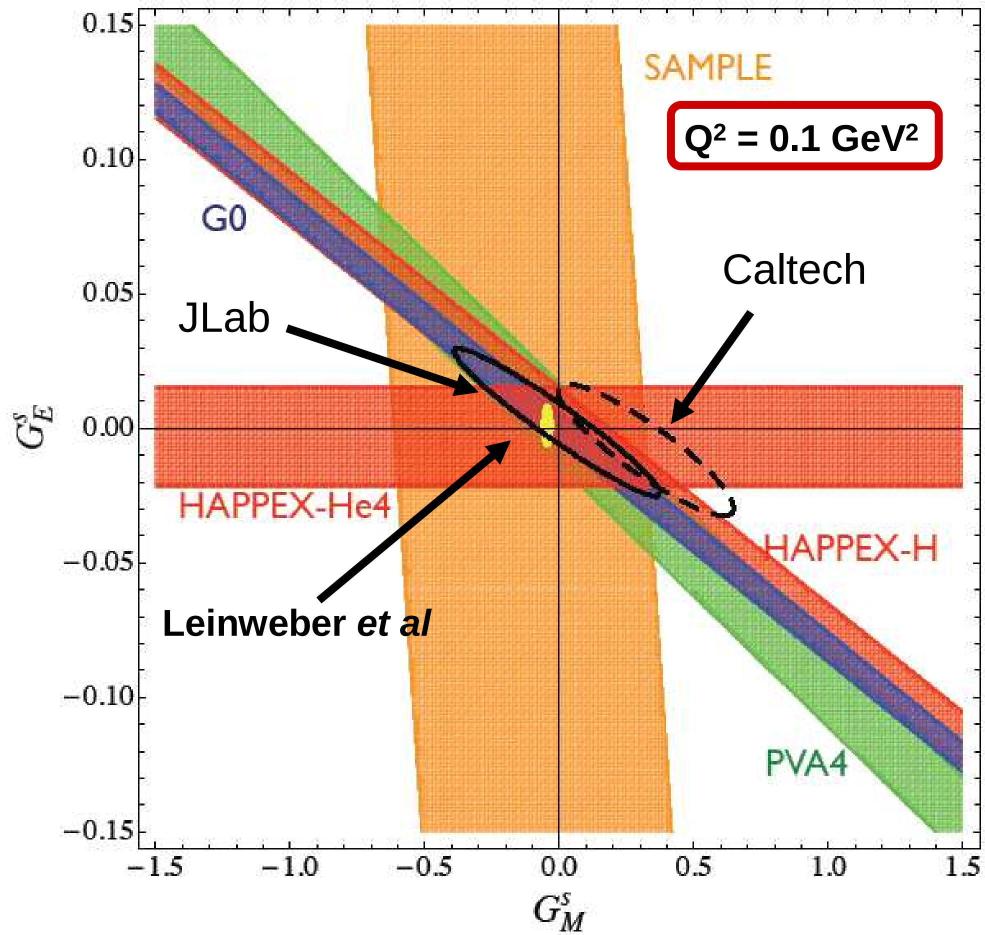
*** = backward angle**

Magneta for planned or ongoing measurements

Exploring the Strangeness Content of the Proton



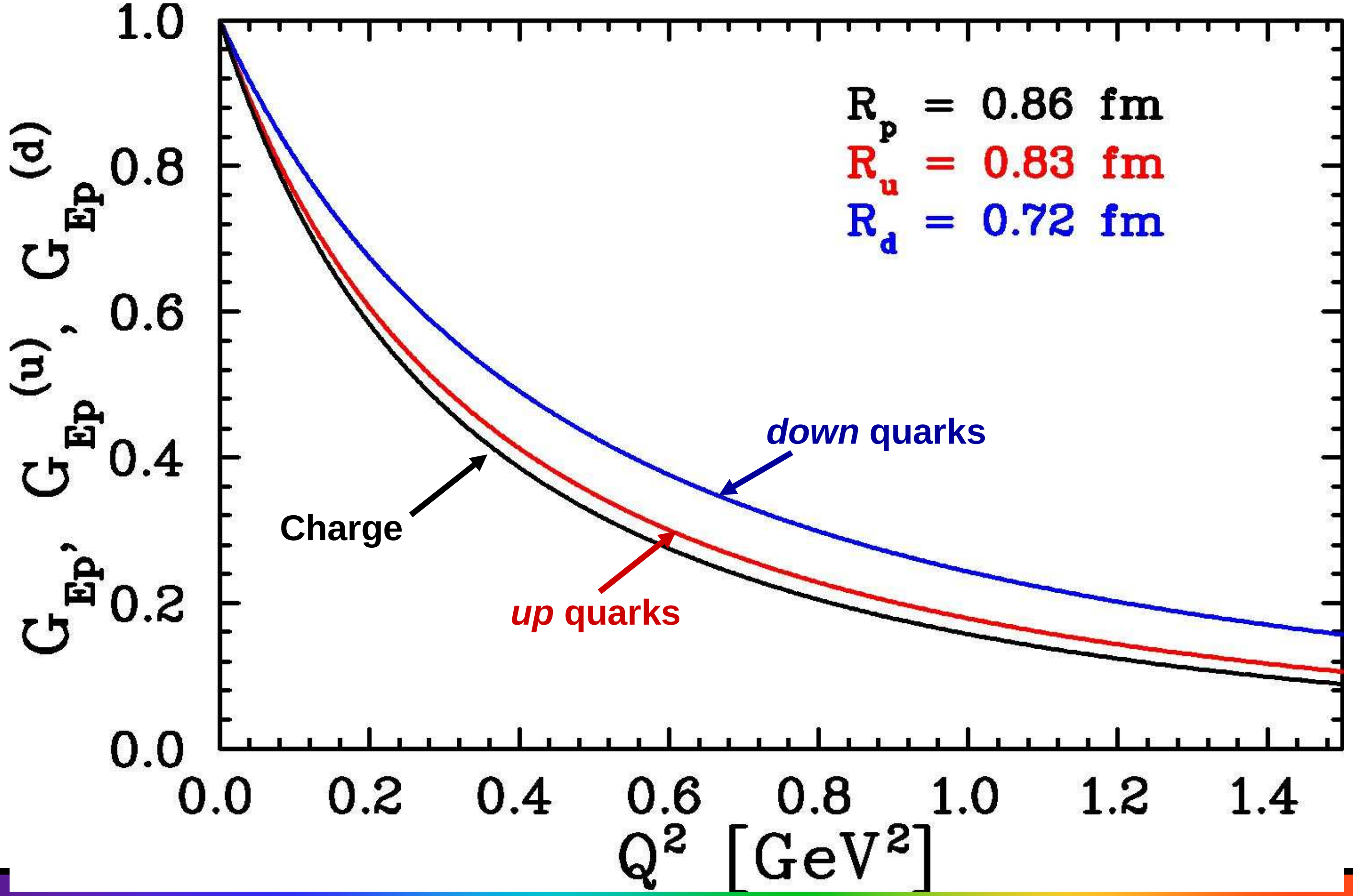
- ➢**Proton not all that strange**
- ➢**Separation possible at 0.1 GeV^2**
- ➢**New data coming at 0.23 and 0.6 GeV^2 (PVA4, G0, HAPPEx III)**



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

Constraining strangeness to look at up, down

- **Parity-violating elastic electron scattering**
  - A_{PV} depends on EM form factors, RC, and ***strangeness content***
  - Combine with EM FF to perform *full flavor decomposition* of form factors into $G_u(Q^2)$, $G_d(Q^2)$, $G_s(Q^2)$

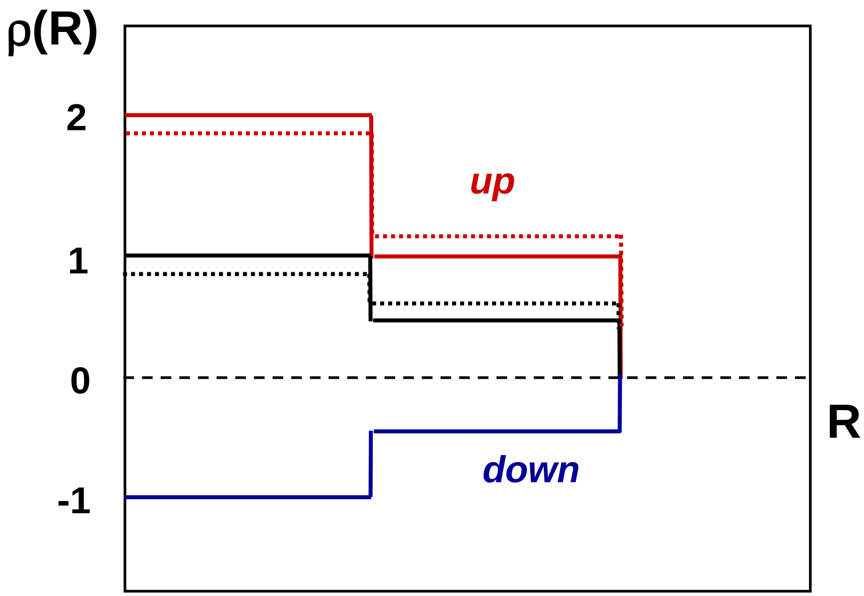


How does R_E end up below $R_{u,d}$?

- **Start with one *up* quark, one *down* quark (identical charge distributions)**
  - **Sum is ½ of up quark distribution**

- **Shift 10% of the *up* quark distribution to larger R**
  - **Sum has 10% of *up* quark strength shifted to large R**
  - **This shifts 20% of the sum charge on the total**

- **Yields larger increase in charge radius than in up quark radius**



Maximizing the impact of these measurements

- **Many conclusions about underlying physics are model-dependent**
  - **Consensus among models → stronger interpretation**
    - ***Orbital angular momentum behind G_E/G_M falloff at high Q^2***
  - **Differences (p-n, u-d) may be more sensitive to details of models, less sensitive to corrections**
  - **Data → GPD → interpretation/physics**
    - ***Longer but sometimes better path***
    - ***GPD part often left out of form factor talks (as form factors have their own clear and direct connection to underlying physics)***
    - ***Non-GPD physics conclusions sometimes left out of talks that focus on a single process (transition form factors, DVCS, …)***

Putting it all together

- **Nucleon Form Factors: time to update the textbooks**
  - ***Qualitatively new behavior for G_{Ep}***
  - ***Smaller but important corrections to G_{Mp}***
  - ***Dramatically improved data on G_{En}, G_{Mn}***

- **Impact of the data**
  - ***Test models of nucleon structure with precise, complete data set***
    - *Precise data at low Q^2, where pion cloud effects important*
    - *Soon have results for G_{En} at higher Q^2, dominated by quark core*
  - ***Better model-independent information***
    - *Difference in distributions of charge, magnetization*
    - *Transverse spatial distributions including short distance structure*
    - *Precise comparison of proton and neutron form factors, yielding information on up, down, and strange quark contributions*

- **Same techniques being used to extend other programs**

For more information…

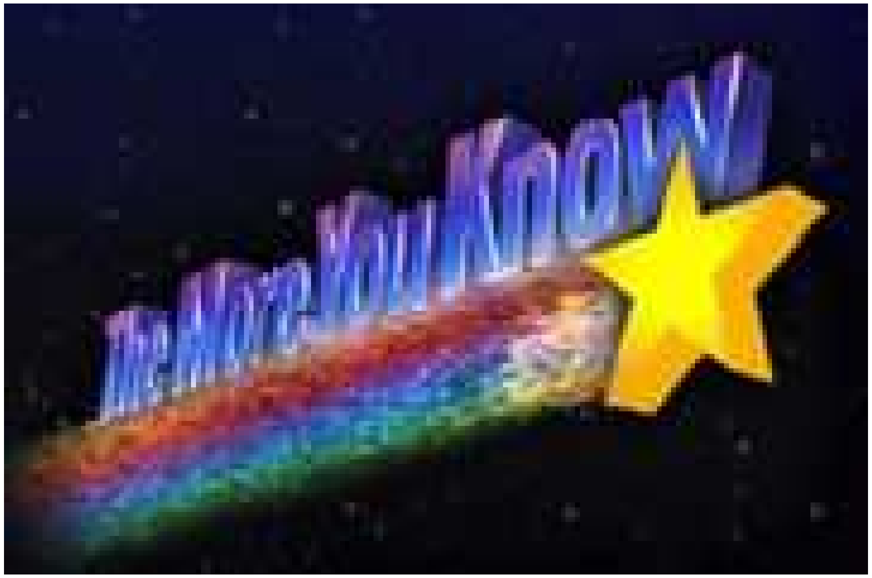
Nucleon form factors:

C.F.Perdrisat, V.Punjabi, and M.Vanderhaeghen, Prog. Part. Nucl. Phys 59, 694 (2007)

J.Arrington, C.D.Roberts, and J.M.Zanotti, J. Phys. G 34, S23 (2007)

C.E.Hyde-Write and K. de Jager, Ann. Rev. Nucl. Part. Sci. 54, 217 (2004)

H.Gao, Int. J. Mod. Phys. E12, 1 (2003)



Parity, GPDs, TPE, etc…:

E.J.Beise, M.L.Pitt, and D.T.Spayde, Prog. Part. Nucl. Phys. 54, 289 (2005)

D.H.Beck and R.D.McKeown, Ann. Rev. Nucl. Part. Sci. 51, 189 (2001)

D.H.Beck and B.R.Holstein, Int.J.Mod.Phys. E10, 1 (2000)

K.Kumar and P.Souder, Prog.Part.Nucl.Phys. 45, S333 (2000)

X.Ji, Ann. Rev. Nucl. Part. Sci. 54, 413 (2004)

M.Vanderhaeghen and C.E.Carlson, Ann. Rev. Nucl. Part. Sci. 57, 171 (2007)

"HADRONS IN THE NUCLEAR MEDIUM – QUARKS, NUCLEONS, OR A BIT OF BOTH?"

http://arxiv.org/abs/nucl-ex/0602007

Proceedings from HUGS summer school, discussing QCD in nuclei

Introduction #1

As we all know, matter in the universe is made from three fundamental particles; the proton, the neutron, and the electron. A collection of Z protons and N neutrons form bound states (nuclei) over a wide range of N and Z values…

……

Of course, some people in high energy physics or who study QCD worry about the quks and gl**ns, but they're missing the point. A practical description of matter in the universe requires a clear understanding of the interactions of protons and neutrons, and how they form the nuclei that provide the core of matter and the fuel of stars.**

Introduction #2

As we all know, matter in the universe is made from three fundamental families of particles: quarks, leptons, and bosons. The quarks exist only in bound states (hadrons) consisting of three quarks (baryons) or one quark and one anti-quark (mesons).

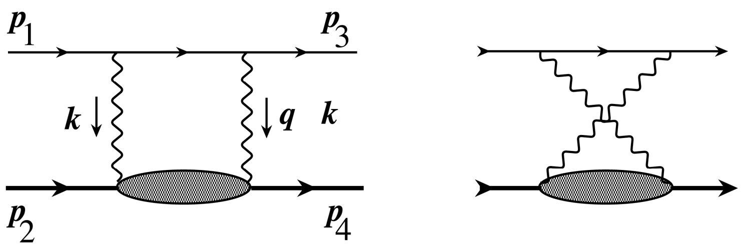
……

Of course, some people in nuclear physics or astrophysics worry about neutrons and protons as something other than bound states of QCD, but they're missing the point. Nucleons are just convenient degrees of freedom; QCD provides the true and fundamental description of matter in the universe.

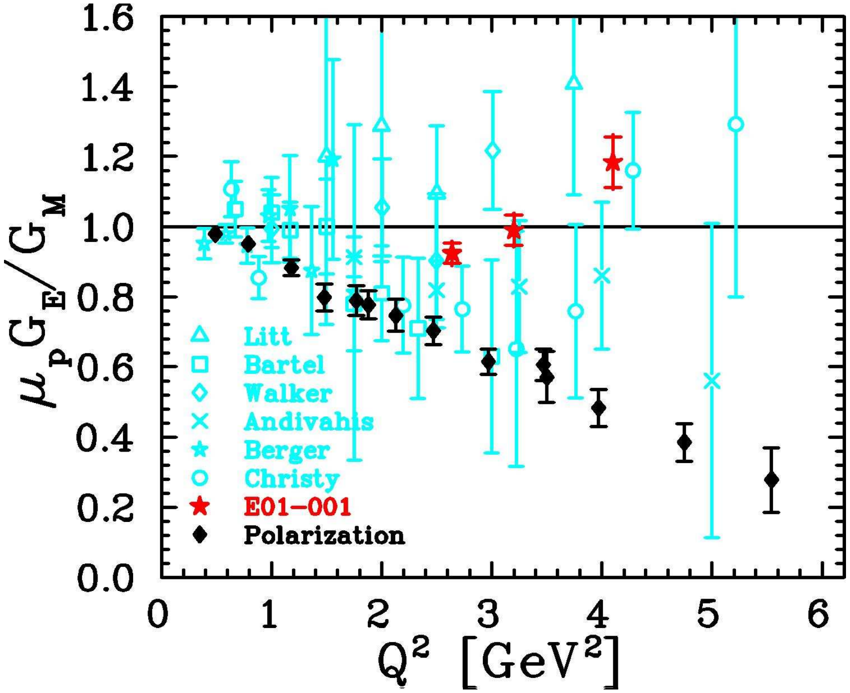
“Bonus material: Two-Photon Exchange”

New Techniques, Higher Precision: More Problems

- **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**



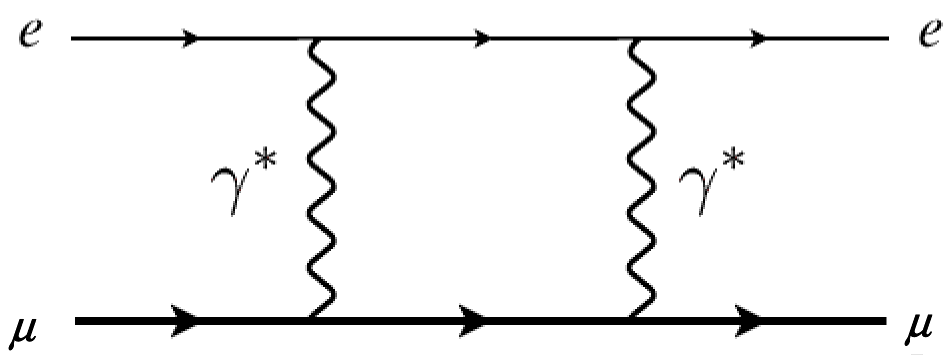
P.A.M.Guichon and M.Vanderhaeghen, PRL 91, 142303 (2003)



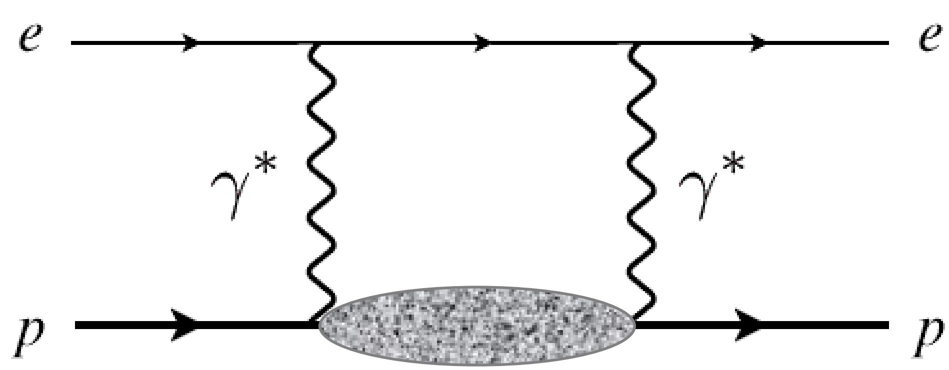
- **Have only limited direct evidence of effect on cross section**
  - Active experimental, theoretical program to fully understand TPE effects

*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)*

Radiative Corrections: ***QCD complications***



QED: straightforward to calculate



QED+QCD: depends on *proton internal structure*

Hadronic approach: proton plus sum of resonance contributions

Partonic approach: GPD to encode QCD structure of proton

Two-photon exchange corrections

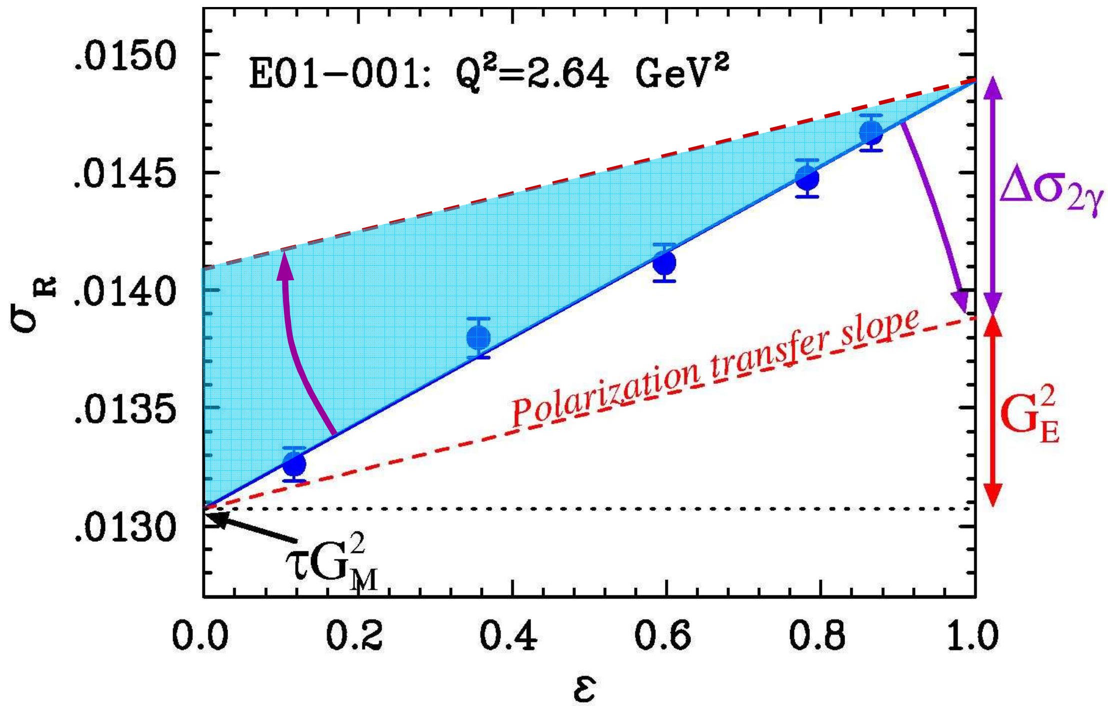
Clear discrepancy between LT, PT extractions

Two-photon exchange effects can explain discrepancy in G_E

Guichon and Vanderhaeghen, PRL 91, 142303 (2003)

Requires ~3-6% ε-dependence, weakly dependent on Q^2, roughly linear in ε

JA, PRC 69, 022201 (2004)



If this were the whole story, we would be done: LT would give G_M, PT gives G_E

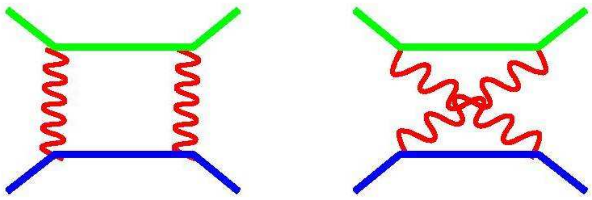
There are still issues to be addressed

- Are TPE corrections the ***only difference***?
- TPE effects on G_M?
- TPE effects on ***polarization transfer***?
- TPE effects on ***other measurements***?
- What about the constraints (~1%) from positron-electron comparisons?

Tests of Two-Photon Exchange ('50s and '60s)

Definitive test: Positron-proton scattering vs. electron-proton scattering

$$R \equiv \frac{\sigma_{e+}}{\sigma_{e-}} = \frac{(A_{1\gamma}+A_{2\gamma})^2}{(A_{1\gamma}-A_{2\gamma})^2} \approx 1 + 4\,\mathrm{Re}(A_{2\gamma}/A_{1\gamma})$$



<u>e+/e–</u>

$\langle R \rangle = 1.003 \pm 0.005$

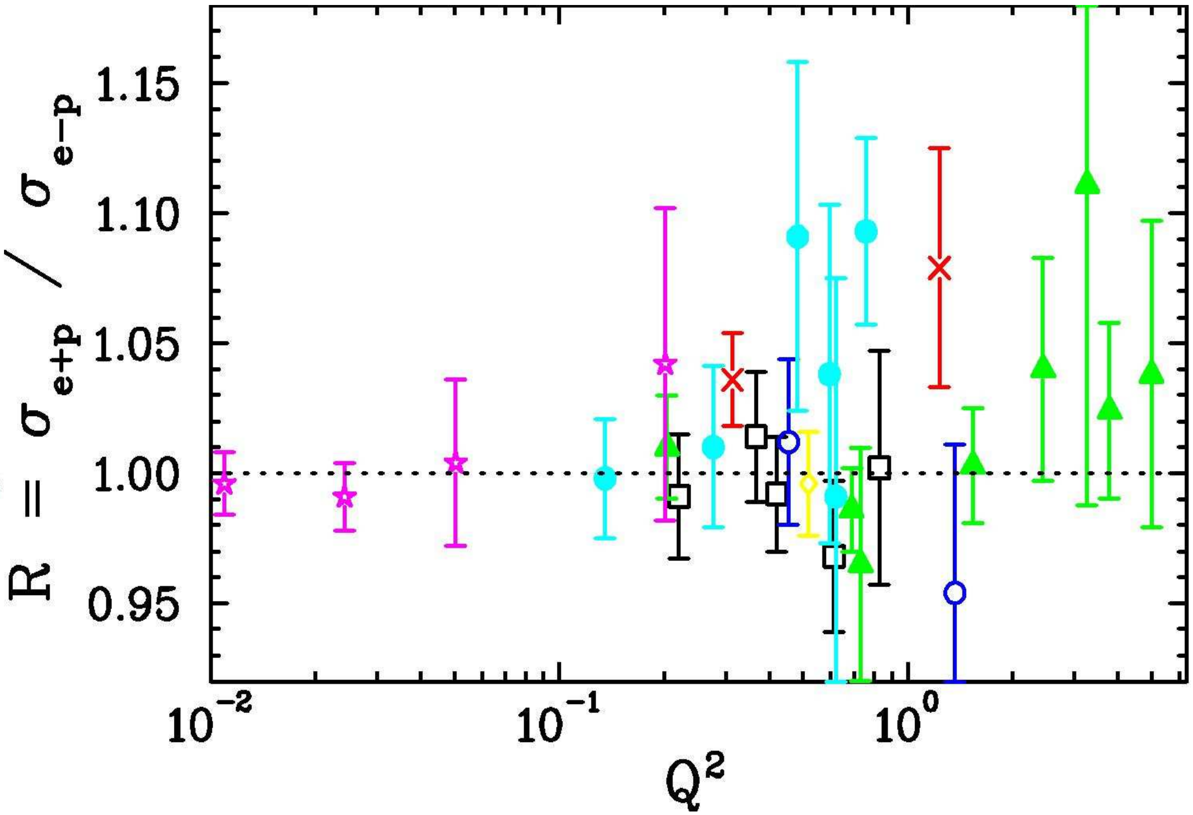
*J. Mar et al., PRL **21**, 482(1968) and refs therein*

<u>μ+/μ–</u>

$\langle R \rangle = 0.993 \pm 0.006$

*L. Camilleri et al., PRL **23**, 149 (1969)*

$(Q^2 < 1\ \mathrm{GeV}^2)$



One-photon approximation assumed to be good to ~1%

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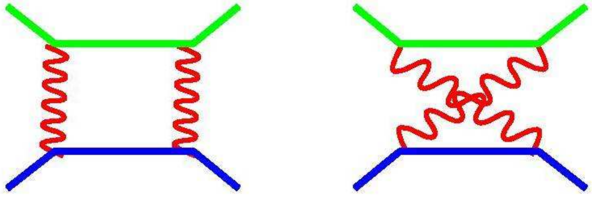
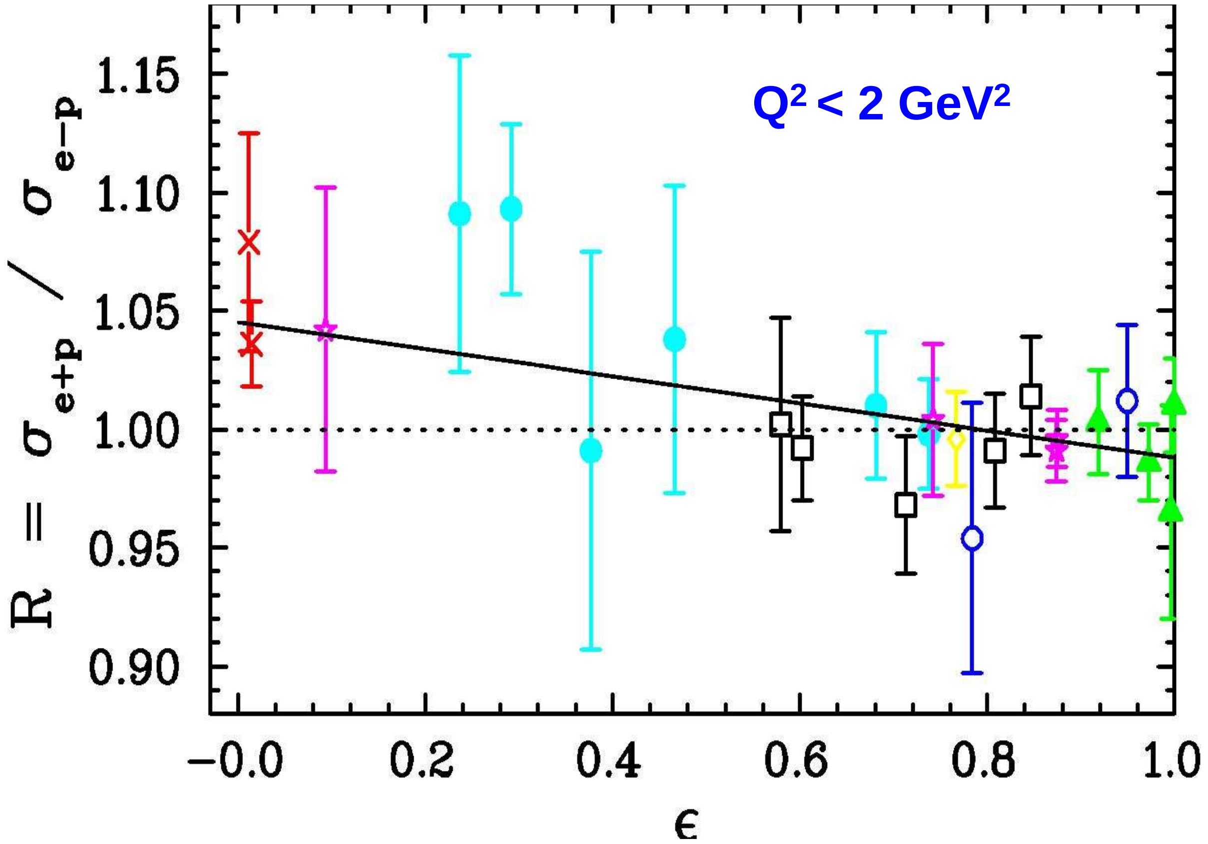


Secondary beams had low luminosity; data taken at high Q^2 OR large θ, never both.

If correction is at large θ (small ε), it would not have been clearly seen

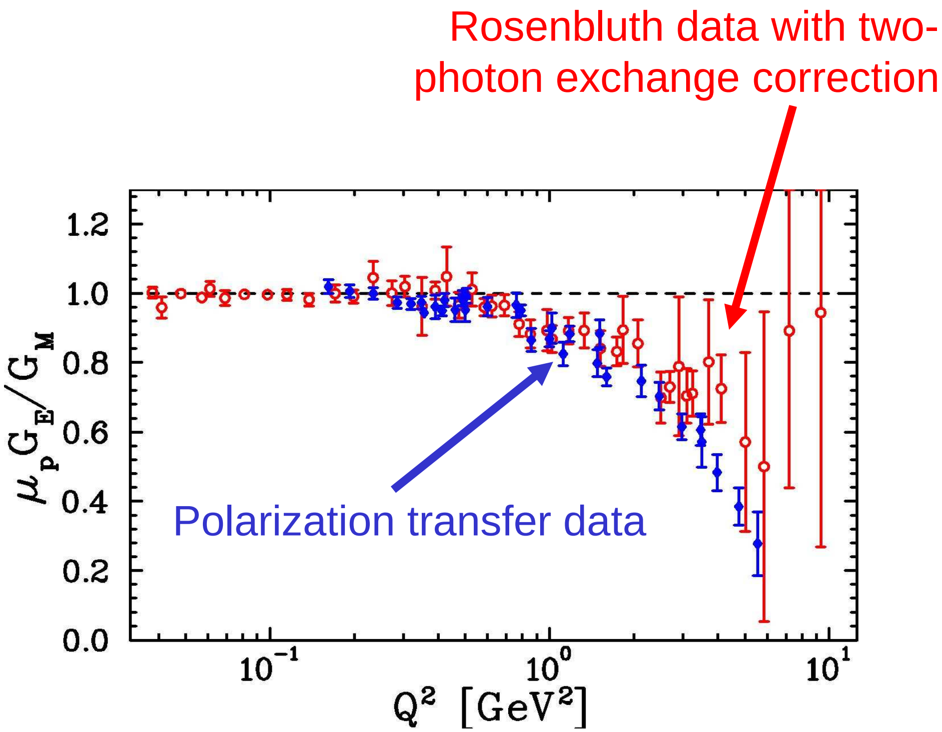
Suggests that TPE is significant even below Q^2=1 GeV^2



~~*One-photon approximation assumed to be good to ~1%*~~

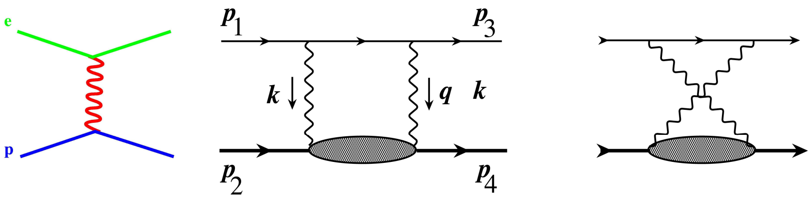
JA, PRC 69, 032201 (2004)

Two Photon Exchange



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

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



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

Three new e+/e- experiments:

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

Jefferson Lab CLAS e+/e- experiment

1. **Electron beam hits radiator foil, losing energy and proding photons**

   - Electrons removed by tagger magnet

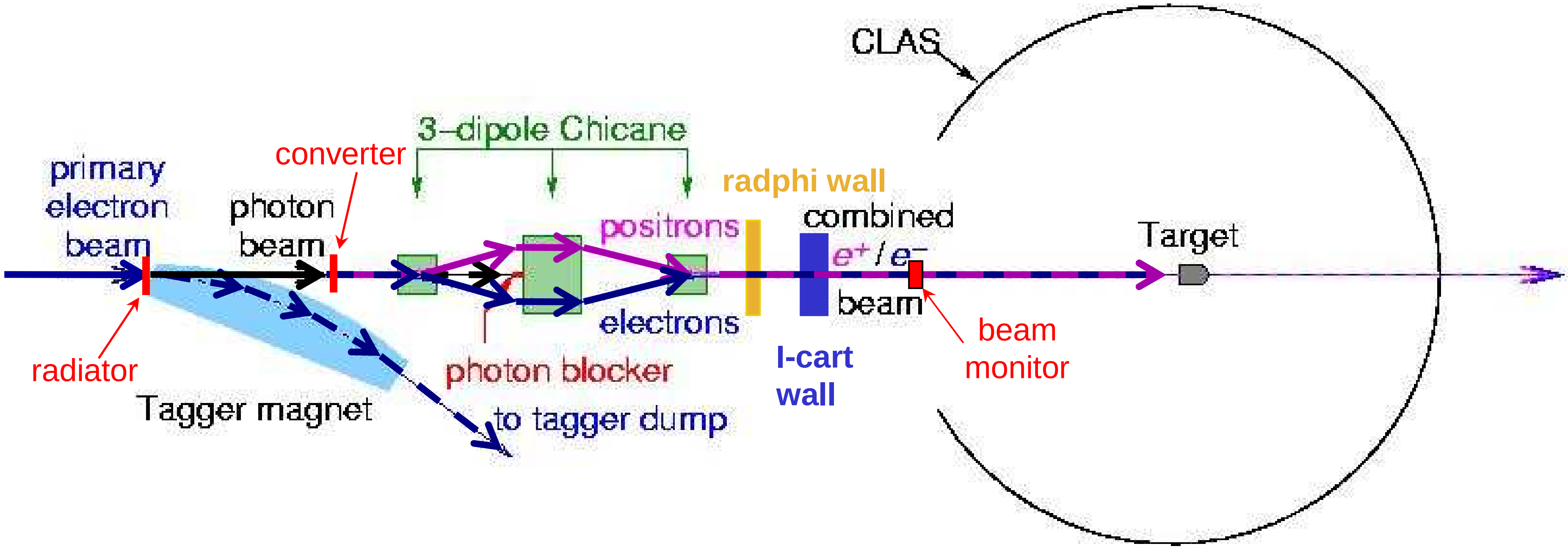
2. **Photon beam strikes converter foil; e+/e- pairs produce**

   - Photons stopped by photon blocker

3. **Magnetic chicane separates e+/e- beams**

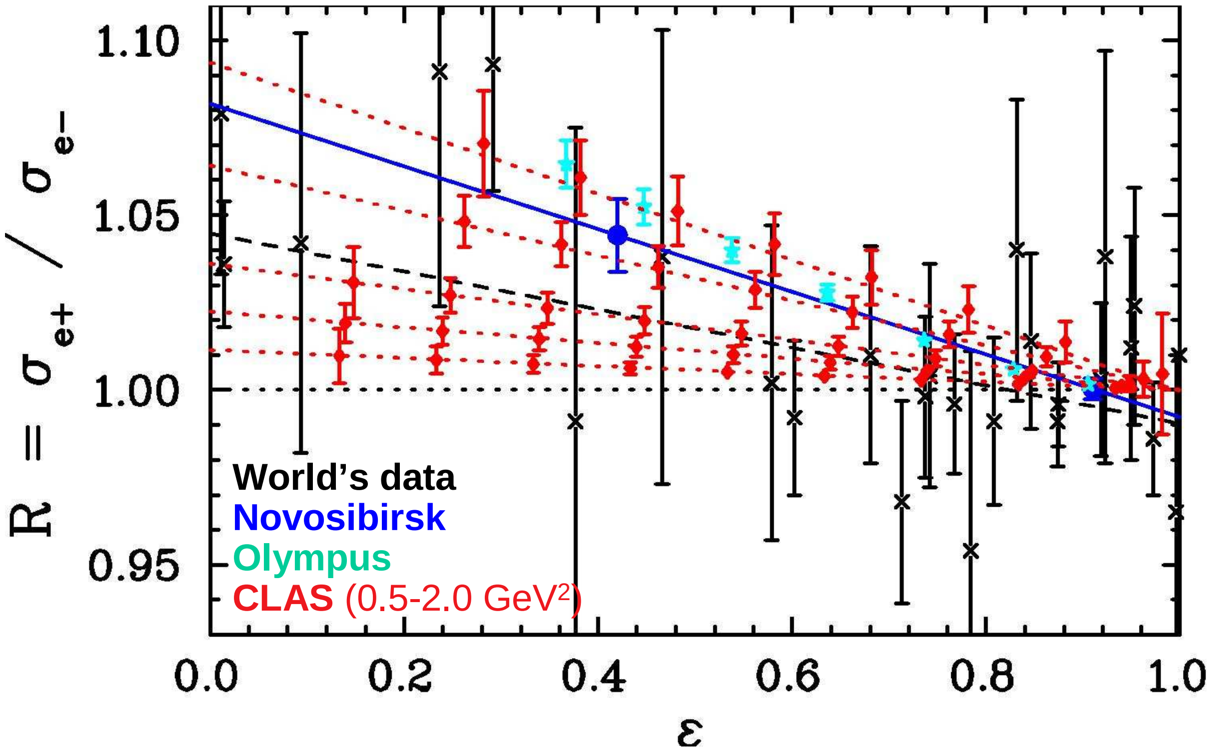
   - Remove low energy tail

   - Recombine e+/e-, send mixed charge, broad energy spectrum beam to CLAS target, detect lepton and proton to determine lepton sign, energy



Direct TPE Measurements

- Comparisons of **e⁺-p**, **e⁻-p** scattering [VEPP-III, DESY-Olympus, CLAS]



Previous e+/e- comparisons limited to low Q^2 or large ε, typically very low statistics

Three new e+/e- experiments planned:

- **BINP Novosibirsk** – 1st run completed
- **JLab Hall B** – E05-007
- **OLYMPUS** – Move BLAST detectors to DORIS ring at DESY (2011-2012)

World's data: Low ε excess yields 3-sigma evidence for TPE (<Q^2> ~ 0.5 GeV²)

Novosibirsk: One "real" point (ε~0.42, Q^2~1.5 GeV²), one high-ε, low-Q^2 "normalization" point

Olympus: Several ε points, max Q^2=2.2 GeV² (<Q^2> ~1.6 GeV²)

CLAS E05-007: **Map out ε-dependence** for ***several fixed Q^2 values*** (Q^2 ≈ 0.5, 0.7, 1.0, 1.4, 2.0 GeV²)

TPE Beyond the Elastic Cross Section

- **Precise experimental tests of TPE calculations possible for the proton**
  - Necessary to be certain of our knowledge of the form factors
  - Important for validating calculations used 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, Nuclear form factors***
  - ***Transition form factors***
  - ***Bethe-Heitler, Coulomb Distortion,…***

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)

S. Kondratyuk and P. Blunden, NPA778 (2006)

V. Pasculutsa, C. Carlson, M. Vanderhaeghen, PRL96, 012301 (2006)