Two-photon exchange: Experimental Overview

or

"How to turn an $O(\alpha_{EM})$ effect into a 200% error"

John Arrington
Argonne National Lab

Introduction

Rosenbluth measurements (LT): G_E, G_M

Polarization transfer (PT): G_E / G_M

Two-photon exchange corrections

Evidence for two-photon exchange

Uncertainties in the TPE, form factors

Future experiments

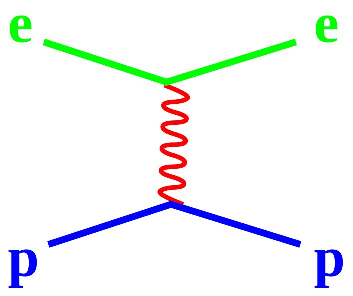
Size of TPE effects: e+/e- comparisons, PT/L-T comparisons

ε-dependence of TPE effects: Cross section and polarization transfer

Workshop on Nucleon Form Factors
Frascati, 12 October, 2005

Rosenbluth extractions of G_E and G_M

In the Born approximation:



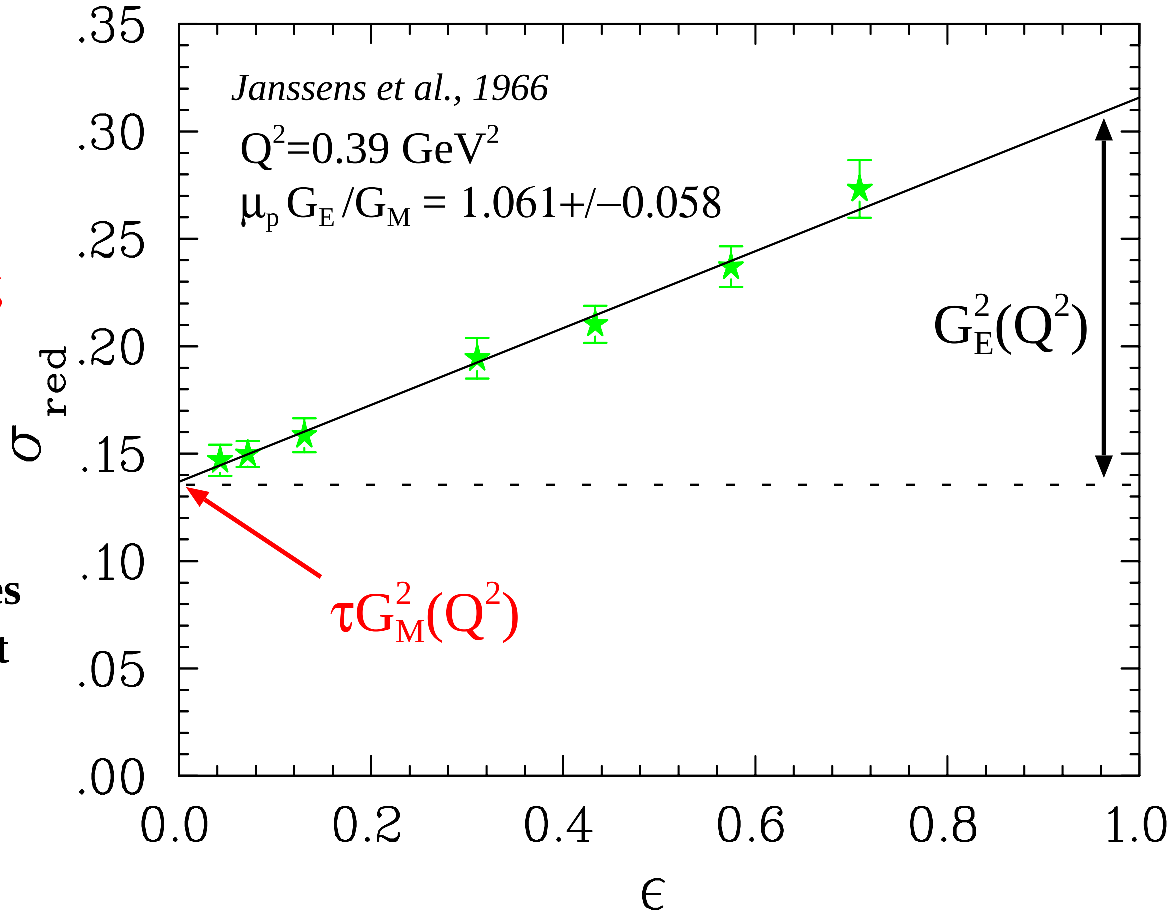
$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2)$$

$\tau = Q^2/(2M)^2$

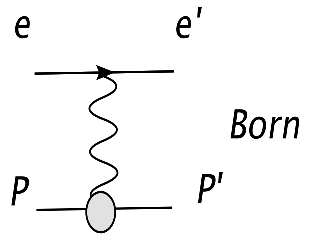
Initial Rosenbluth measurements consistent with form factor scaling

$G_M(Q^2) \cong \mu_p G_E(Q^2)$

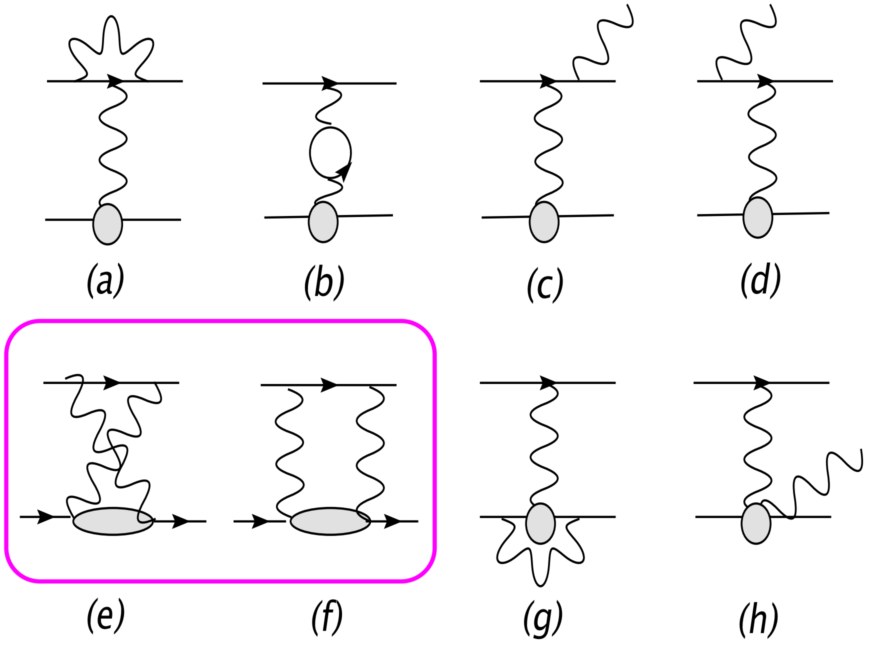
For large Q^2 values, τG_M^2 dominates and G_E^2 becomes difficult to extract



Radiative Corrections (1950s-1970s)



Rosenbluth formula: single-photon exchange (Born approximation)



Meisner, Mo and Tsai, others...

Prescriptions to correct for
higher-order elastic [(a), (b), and (g)]
and inelastic [(c), (d), and (h)] diagrams

Two-photon exchange [(e) and (f)]
treated in a limited way:

Soft photon approximation
Simplified photon propagator ($1/q^2$)
Neglects internal nucleon structure

Theoretical estimates generally indicated ~1% corrections

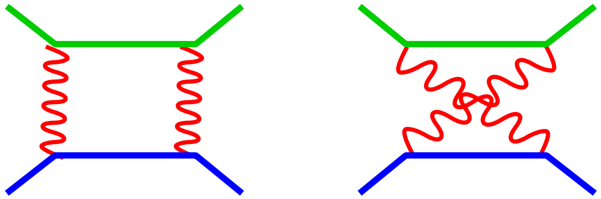
*R.R.Lewis, PR **102**, 537 (1956) ; S.D.Drell and M.Ruderman, PR **106**, 561 (1957) ; S.D.Drell and S.Fubini, PR **113**, 741 (1959) ; J.A.Campbell, PR **180**, 1541 (1969) ; G.K.Greenhut, PR **184**, 1860 (1969)*

Linearity of Rosenbluth plot taken as additional evidence of small corrections

Studies of two-photon effects ('50s and '60s)

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

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



e+/e–

<R> = 1.003+/–0.005

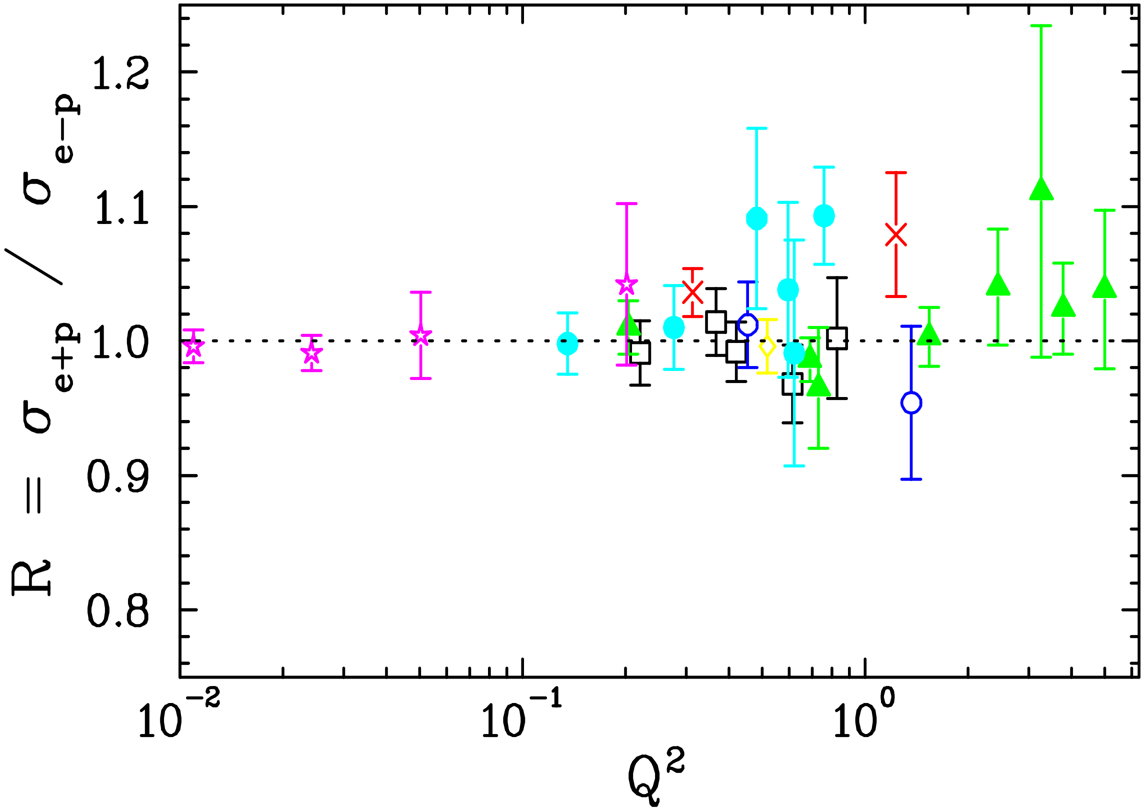
*J. Mar et al., PRL **21**, 482(1968)*
and refs therein

μ+/μ–

<R> = 0.993+/–0.006

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

($Q^2 < 1$ GeV^2)



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

However: Low luminosity of secondary e+/μ beams meant that precise limits were only available for low Q^2 and/or small scattering angles

G_E/G_M from Polarization Transfer

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

$P_L = M_p^{-1} \; (E+E') \sqrt{\tau(1+\tau)} \, G_M^2 \tan^2(\theta_e/2)$ — Polarization along ***q***

$P_T = 2\sqrt{\tau(1+\tau)} \; G_E G_M \tan(\theta_e/2)$ — Polarization perpendicular to ***q*** (in the scattering plane)

$P_N = 0$ — Polarization normal to scattering plane

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

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

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

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

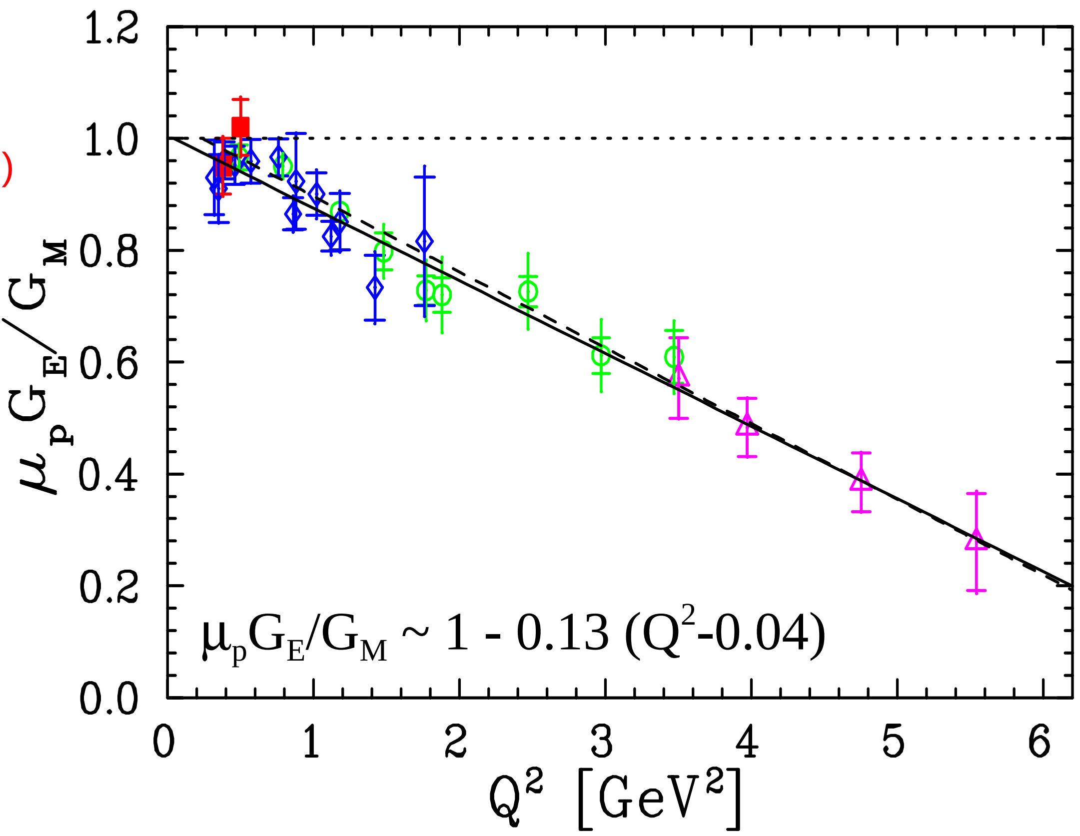
Also useful for neutron (where $G_E << G_M$, so L-T very difficult)

G_E/G_M from Polarization Transfer

MIT-Bates:
B. D. Milbrath, *et. al.*, PRL **82** (1999) 2221(E)

Jefferson Lab:
M. K. Jones, *et. al.*, PRL **84** (2000) 1398
O. Gayou, *et. al.*, PRC **64** (2001) 038202
O. Gayou, *et. al.*, PRL **88** (2002) 092301

Mainz:
Th. Pospischil, *et. al.*, EPJA **12**, (2001) 125
(low Q^2 - not shown in figure)



Surprising result: $\mu_p G_E \neq G_M$ **at large** Q^2

-Renewed interest in nucleon form factors, nucleon structure

-New examination of long-standing pQCD predictions

-Highlighted the role of relativity, angular momentum

-Generated interest outside of the field

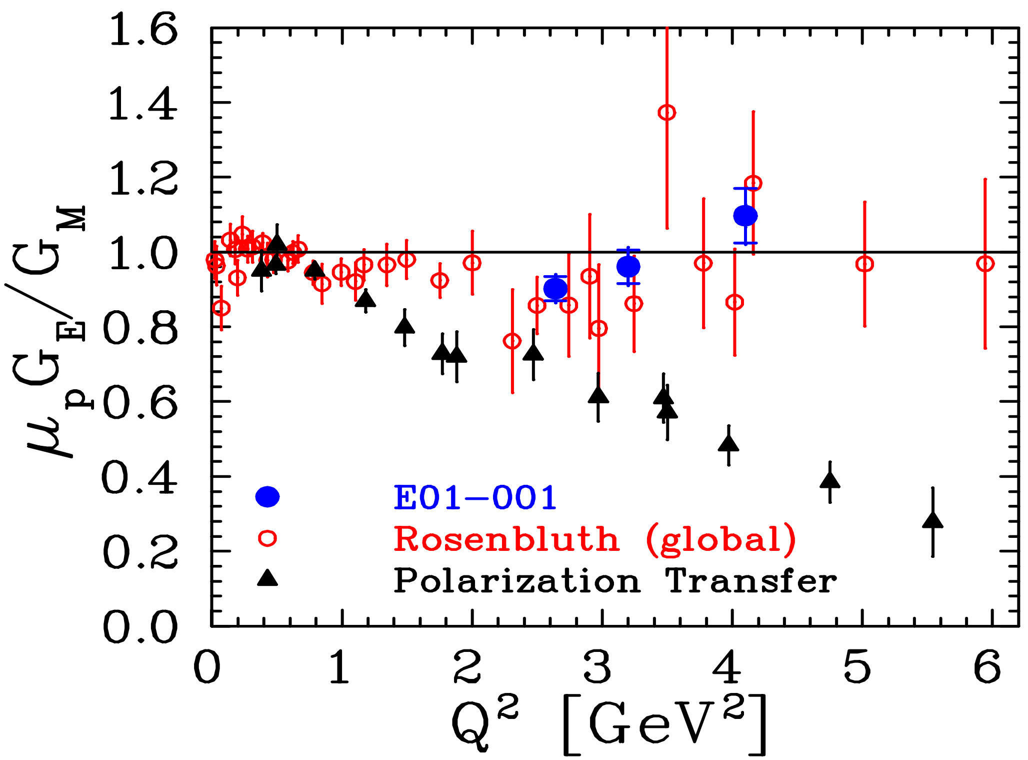
Articles in Science News, Physics Today, New York Times, USA Today, etc...

A small problem with the form factors...

G_E/G_M values differ by
<u>factor of three</u> at large Q^2

Question about the form factors:
as proton structure

Question about the form factors:
as parameterization of σ_{ep}
(input to other experiments)



Problem with Rosenbluth technique? cross section data?

Ruled out by reanalysis of old data, along with new Rosenbluth and "Super-Rosenbluth" extractions

JA, PRC 68, 034325 (2003)
M.E.Christy, et al., PRC 70, 015206 (2004)
I.A.Qattan, et al., PRL 94, 142301 (2005)

Problem with polarization transfer technique? data?

Appears to be OK: systematics have been studied and will be checked in future independent measurements

V. Punjabi, et al., PRC 71, 055202 (2005)
Polarization transfer: JLab E04-119, E04-108
Polarized target: JLab PR04-111

Two-photon exchange corrections

Two-photon exchange effects
can explain the discrepancy in G_E

Guichon and Vanderhaeghen,
***PRL 91**, 142303 (2003)*

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

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

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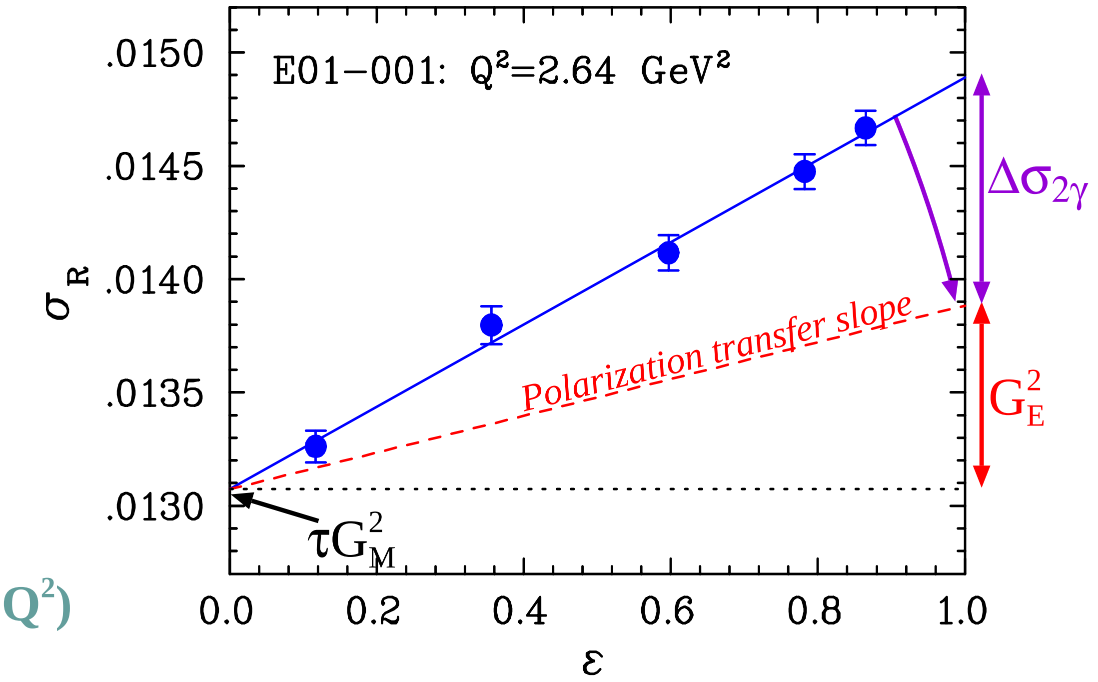

If this were the whole story, we would be done: L-T would give G_M, PT gives G_E

However, still need to be careful when choosing form factors as input in data analysis

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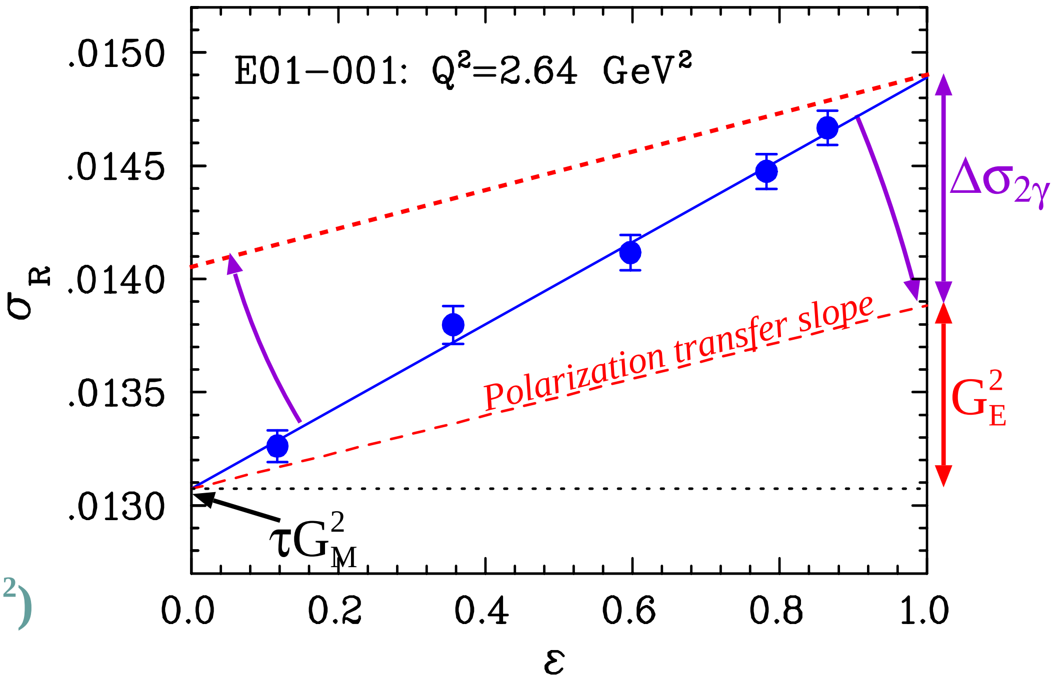

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There are still issues to be answered

What about the constraints (~1%) from positron-electron comparisons?

TPE effects on ***polarization transfer***?

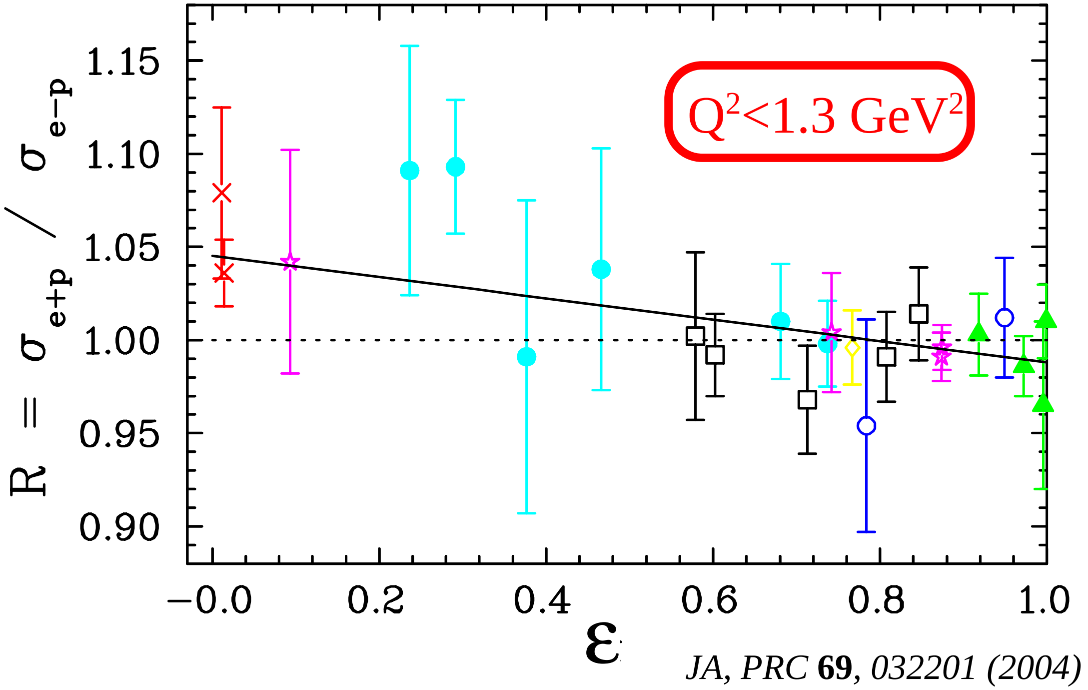
TPE effects on ***G_M***?

TPE effects on ***other measurements***?

Limits from positron-electron comparisons?

Data indicated very small effects: **$\langle R \rangle_{e+/e-}$ = 1.003+/–0.005**
$\langle R \rangle_{\mu+/\mu-}$ = 0.993+/–0.006

Problem: Data limited to low Q^2 or small θ (ε>0.7) because of low luminosities



JA, PRC **69**, *032201 (2004)*

For Q^2>1.3, positron data
only set limits for ε ≅ 1

Limited data at low ε shows
evidence of ε-dependent TPE

NOTE: TPE effects appear to be largest at low ε, so ***effect on G_M cannot be ignored***

Impact of the discrepancy on other measurements

Some cases need form factors to givecross section (including TPE)

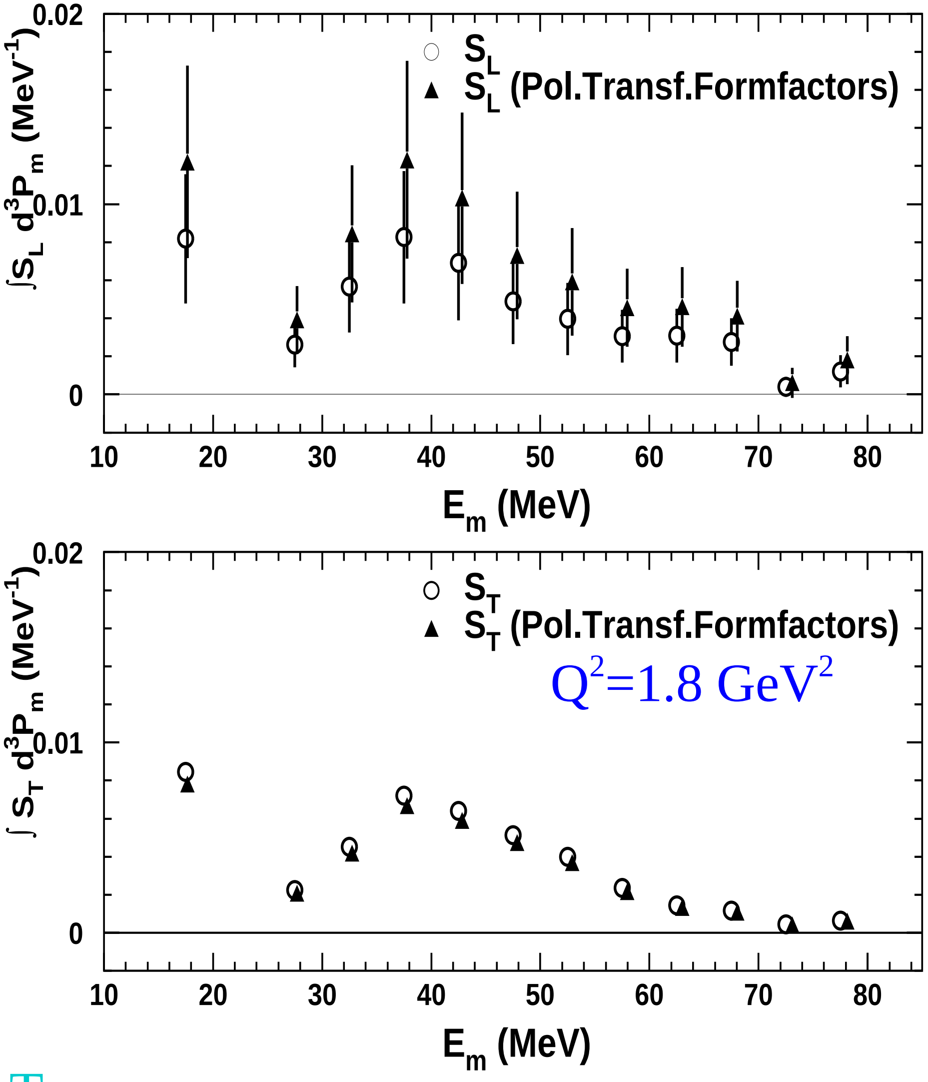
*Experiment normalizations

*Cross sections as input to analysis, e.g. A(e,e'p)

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

Rosenbluth form factors —> $S_L \cong S_T$

Polarization transfer form factors —> S_L ~ 60% larger than S_T



Not always clear if you need the true form factors, the elastic cross section, or something in between

*Extraction of weak/axial form factors: ν-N or PV e-N

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

*Calculations using the form factors (e.g. Bethe-Heitler)

A ***mixture*** of form factors (G_M from LT, G_E from PT) is never correct, and will almost always give the largest error

Recent (but slightly out of date) calculations

P. Blunden, W. Melnitchouk, and J. Tjon, PRL 91 142304 (2003)

-Improved calculation of box diagrams, (unexcited intermediate state only)

Chen, Afanasev, Brodsky, Carlson, Vanderhaeghen: PRL 93 122301 (2004)

-GPD based model, γ-q coupling

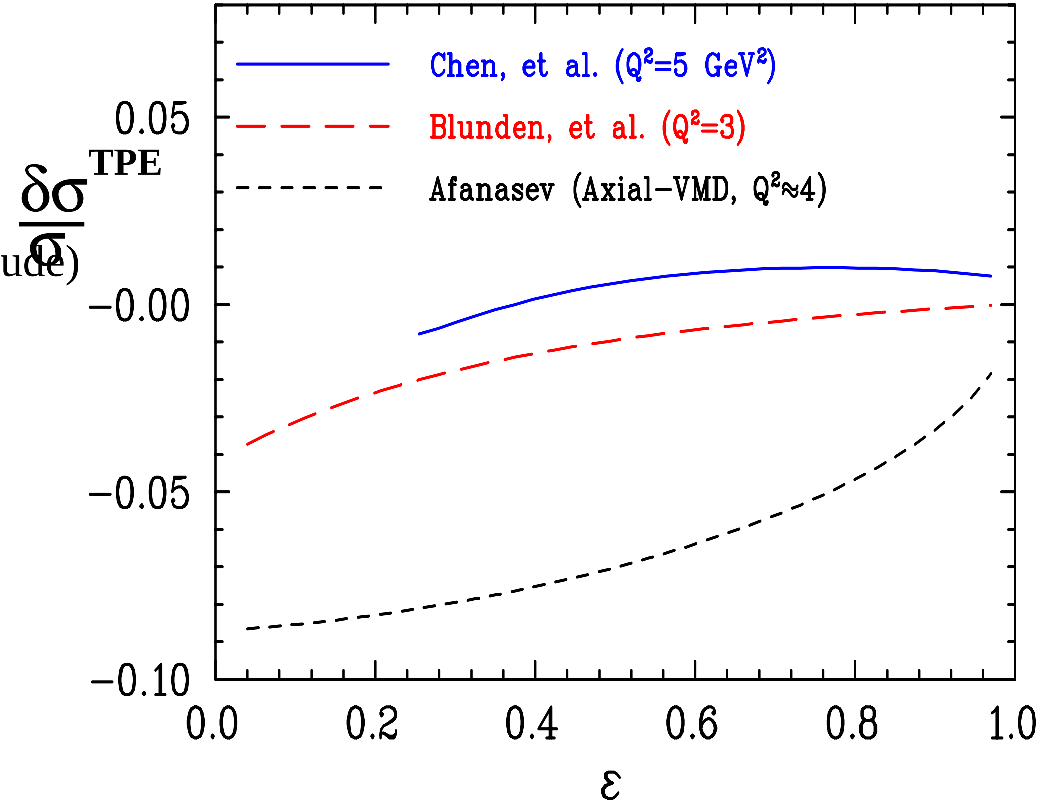
-Not valid at low Q^2 or ε values

A. Afanasev, private communication

-Axial-VMD model

-Provides ε-dependence (arbitrary magnitude)

-*Out of date, included for completeness*



My summary:

1) Calculations differ in magnitude and ε-dependence, but rapidly improving

2) **<u>All</u> show small effects at large ε**

<u>All</u> show decrease at low ε

<u>All</u> show weak Q^2-dependence

➡ Consistent with e+/e- ratios and observed form factor discrepancy

Other relevant works: P.A.M. Guichon and M. Vanderhaeghen, PRL 91, 142302 (2003)

-Generalized formalism for elastic scattering beyond Born approximation

M. Rekalo and E. Tomasi-Gustafsson, EPJ A22, (2004);
E. Tomasi-Gustafsson, F. Lacroix, C. Duterte, G.I. Gakh, EPJ A24 (2005)

-Model-independent properties, connection of time-like and space-like regimes

Two-photon corrections: Model-independent analysis

Three amplitudes: $\tilde{G}_E(\varepsilon,Q^2)$, $\tilde{G}_M(\varepsilon,Q^2)$, $Y_{2\gamma}(\varepsilon,Q^2)$

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

$$R_{poltrans} = (\tilde{G}_E/\tilde{G}_M) + (1-2\varepsilon/(1+\varepsilon)\tilde{G}_E/\tilde{G}_M)\, Y_{2\gamma}$$

$$R^2_{Rosen} = (\tilde{G}_E/\tilde{G}_M)^2 + 2\,(\tau+\tilde{G}_E/\tilde{G}_M)\, Y_{2\gamma}$$

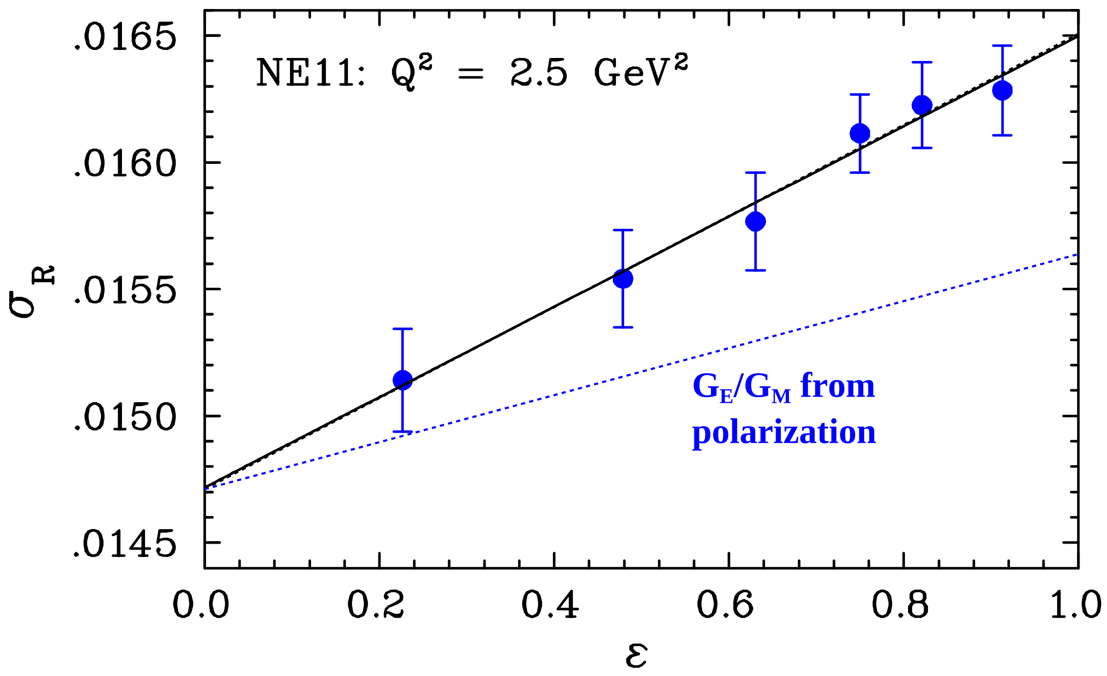
$$\frac{\Delta\sigma_R}{G_M^2} \sim 2\tau\frac{\Delta G_M}{G_M} + 2\varepsilon\frac{G_E^2}{G_M^2}\frac{\Delta G_E}{G_E} + 2\varepsilon(\tau + G_E/G_M)\, Y_{2\gamma}$$

$R = G_E/G_M$ as extracted in one-photon formalism ***assuming ε-independent ampltudes*** (convenient, but not necessary)

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

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

$$Y_{2\gamma}(\varepsilon,Q^2) = \underset{\substack{\uparrow\\ \textbf{Born}}}{0} + \underset{\substack{\uparrow\\ \textbf{TPE contribution}}}{Y_{2\gamma}(\varepsilon,Q^2)}$$



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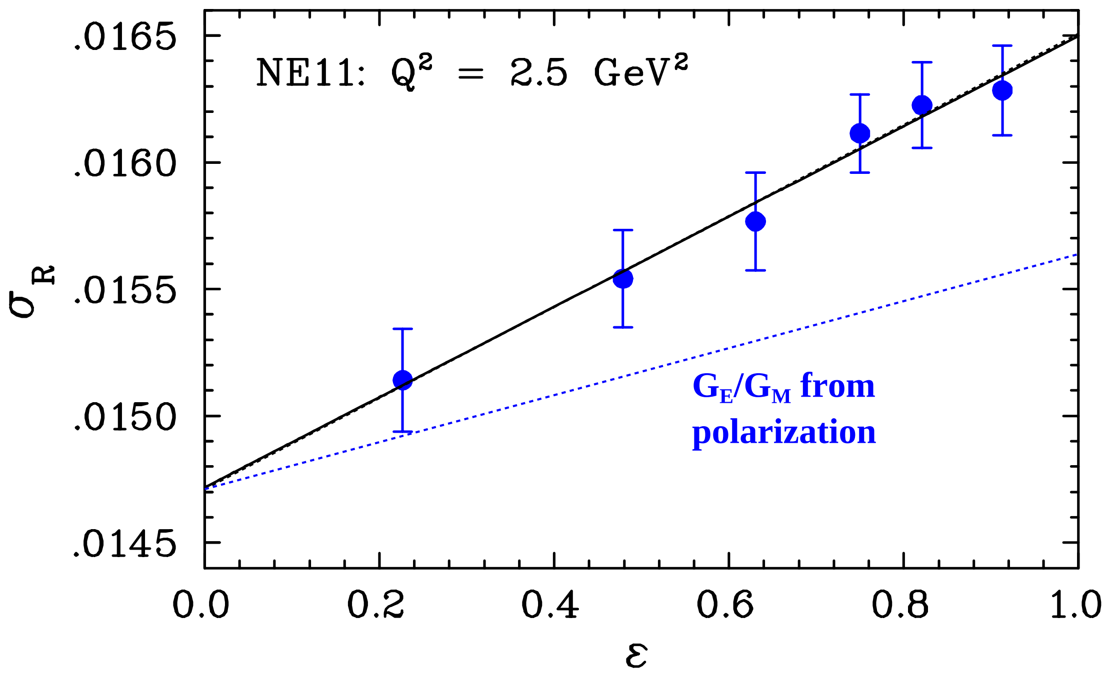
~ 0.05-0.10
small effect

Δ**G**$_E$ term is strongly suppressed



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~ 0.05-0.10
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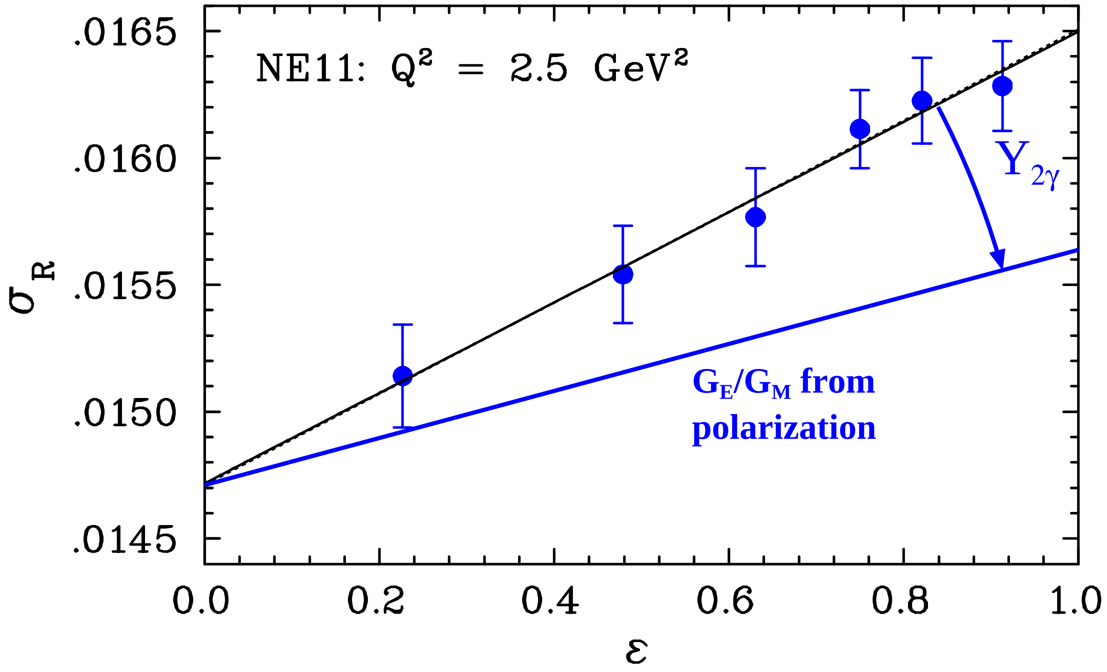
Δ**G**$_E$ term is strongly suppressed

Discrepancy must come from $\mathbf{Y}_{2\gamma}$



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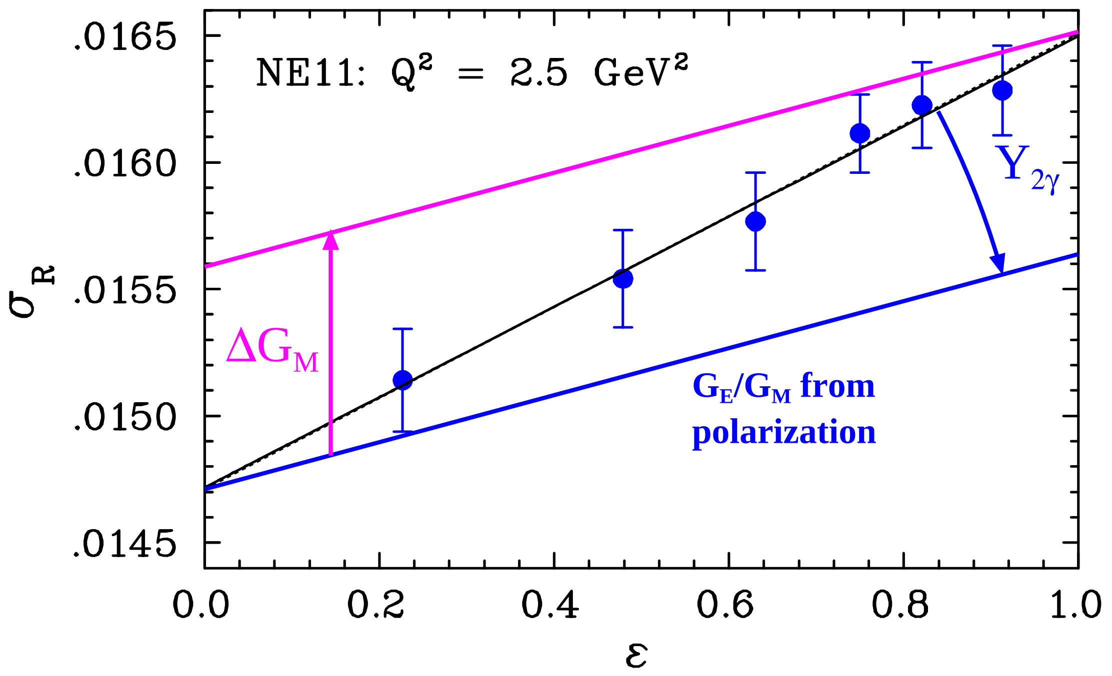
~ 0.05-0.10
small effect

Fixed by LT/PT
discrepancy

ΔG_E term is strongly suppressed

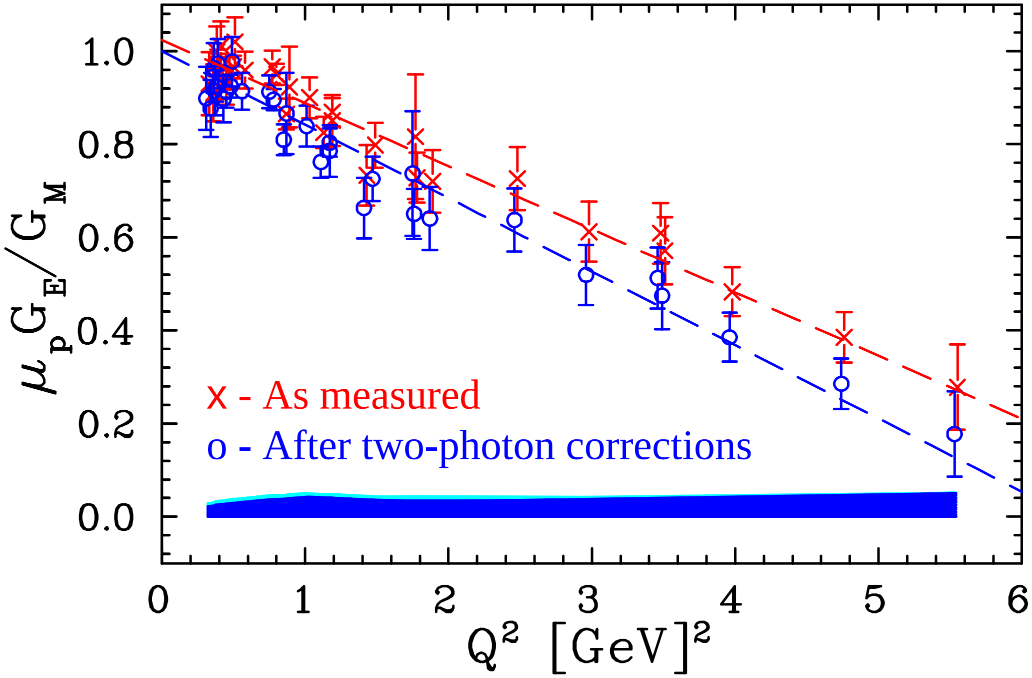
Discrepancy must come from $\mathbf{Y_{2\gamma}}$

e+/e– requires $\Delta\sigma_{2\gamma} \cong 0$ at $\varepsilon = 1$,
--> ***constrains*** $\mathbf{\Delta G_M/G_M}$



Assuming knowledge of the ε-dependence, we basically have two unknown amplitudes and two observables

Two-photon exchange corrections to G_E, G_M



Good news:

Discrepancy can be explained with small two-photon amplitudes (2-4%)

These amplitudes also explain the (very limited) low ε e+/e- data

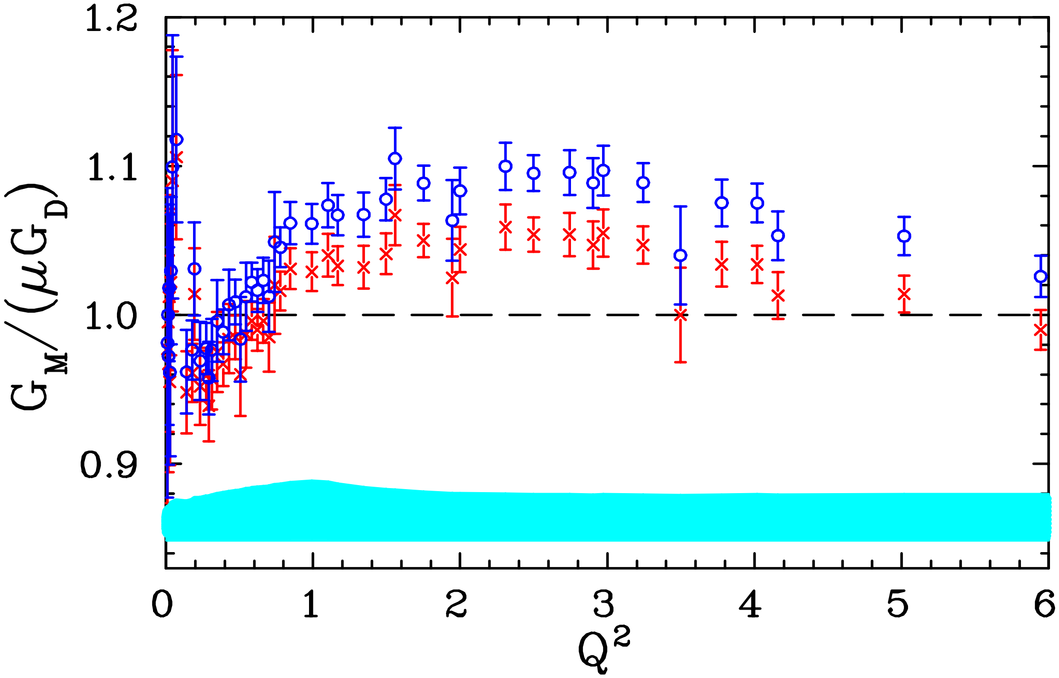
Bad news:

Large corrections

Up to 200% for G_E (Rosenbluth)

Up to 30% for G_E (polarization)

3-5% for G_M



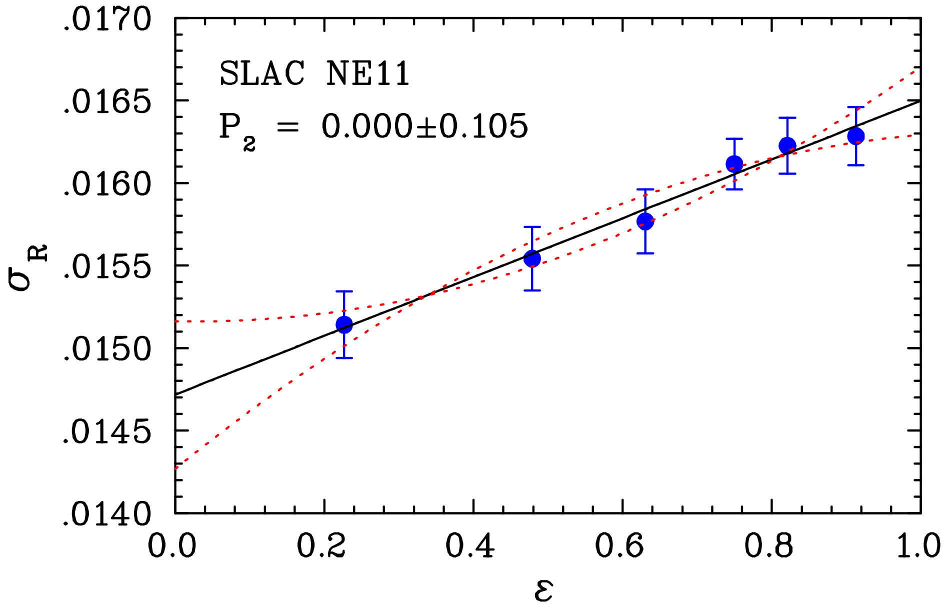
Large uncertainties, even neglecting uncertainty in ε dependence

$\delta G_M^{TPE} \cong 1.0\text{-}1.5\%$

$\delta G_E^{TPE} \cong 5\%$ (low Q^2) 15% (high Q^2)

As large or larger than the experimental uncertainties

Additional uncertainties from ε-dependence



Nonlinearity leads to uncertainty in extrapolation to ε=0, extraction of G_M

$\delta G_M^{TPE} = 3.0\%$ (best SLAC limit)

$\delta G_M^{TPE} = 1.1\%$ (best JLab limit)

Correction to polarization transfer (G_E) is ***extremely*** sensitive to ε-dependence

Even the <u>sign</u> depends on ε-dependence

<u>Emperical extractions:</u>

$Y_{2\gamma}$=A, ΔG_M=B

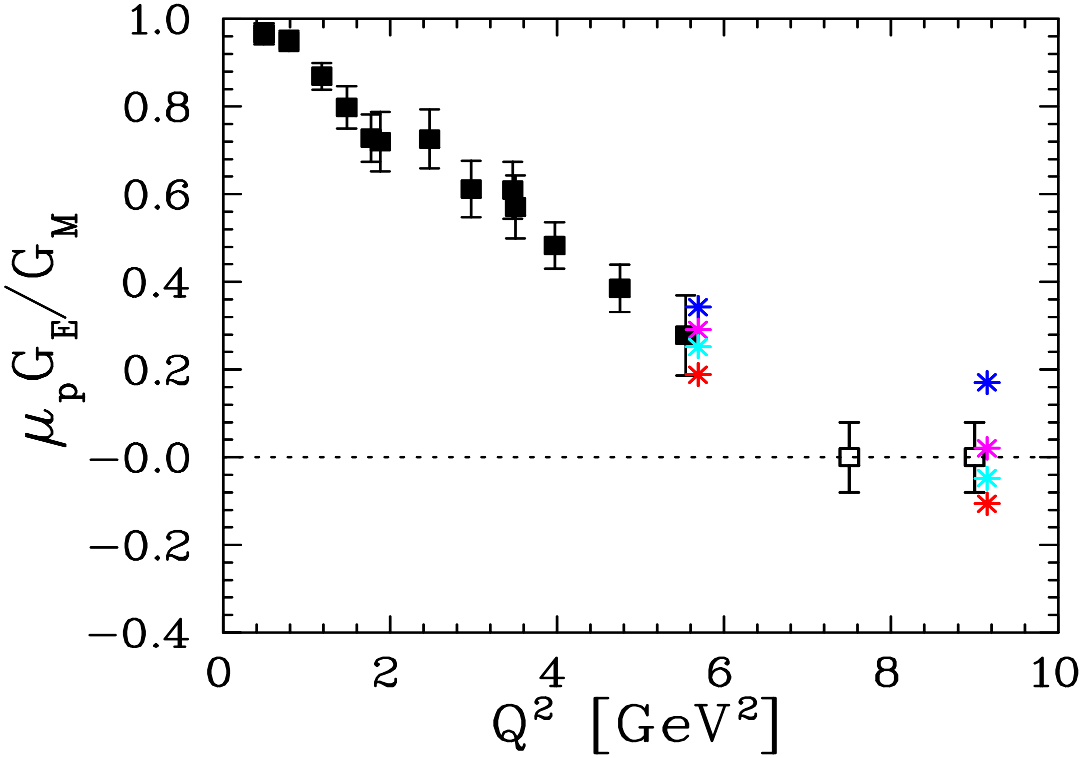
$Y_{2\gamma}$=A+B/ε, ΔG_M=0

(Both yield linear correction to σ_R)

<u>Calculations:</u>

Blunden, et al. (PRC-2005)

Chen, et al. (PRL-2004)



Present status

There appear to be significant corrections to both G_E (from PT) and G_M (from LT)

TPE is dominant source of uncertainty in both G_E and G_M

G_M: Main uncertainty from ***size*** of TPE effect on reduced cross section (~1-1.5%)
Additional uncertainty due to possible non-linearities at low ε (~1%)

⇨ e+/e- comparisons at small to moderate Q^2, large scattering angle
Better Rosenbluth data for precise LT - PT comparisons

G_E: Main uncertainty in ε-dependence of TPE amplitudes

⇨ Measure e-dependence of ***both*** cross section and Polarization transfer

Calculations of TPE effects improving very rapidly

Better data can help resolve differences between different approaches

Need best possible constraints for e-p scattering to provide reliable calculations for processes where we cannot make measurements

[Talks by Afanasev, Melnitchouk, Tomasi-Gustafsson]

Signatures of two-photon exchange terms: elastic e-p scattering

Real part of TPE amplitudes:

Positron-electron comparisons *(VEPP, JLab)*

- -Clean extraction of two-photon terms
- -Map out Q^2 and ε dependence of $\Delta\sigma^{TPE}$

Can test TPE explanation

Map out TPE for $Q^2 < 1\text{-}2$ GeV^2

Precise e-p elastic cross sections *(JLab)*

- -ε-dependence of cross section

Polarization transfer: P_l / P_t *(JLab)*

- -ε-dependence of polarization ratio

Map out TPE for $Q^2 > 1\text{-}2$ GeV^2

Imaginary part of TPE amplitudes:

Born-forbidden observables (e.g. normal polarization transfer P_N)

-No *direct* impact on form factors, but provide additional
independent constraints on TPE calculations

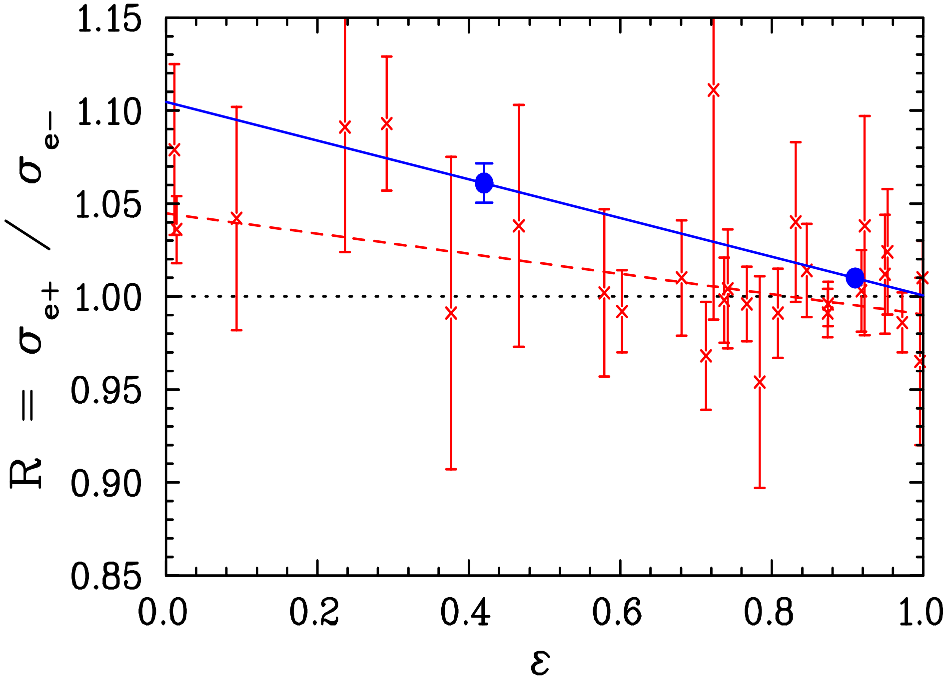
Already have data from SAMPLE, A4, G0. More to come... [Talk by F. Maas]

Approved experiment to measure A_y (target single spin asymmetry) from ^{3}He

New positron-electron experiment at VEPP-3 (2006)

"Two-photon exchange and elastic scattering of electrons/positrons on the proton"

JA, D. Nikolenko, spokespersons, nucl-ex/0408020



	$<Q^2>$	e+/e- slope
World's e+/e- data	**0.4 GeV^2**	**5.8 +/- 1.8%**
Novosibirsk e+/e-	**1.6 GeV^2**	**10.4 +/- 2.2%**

Projected slope based
on TPE amplitudes
from global extraction

Precise comparison of positron-proton and electron-proton scattering at moderate Q^2

- Confirm TPE as source of the discrepancy
- Provide best measurement on size of TPE effects at 1-2 GeV^2

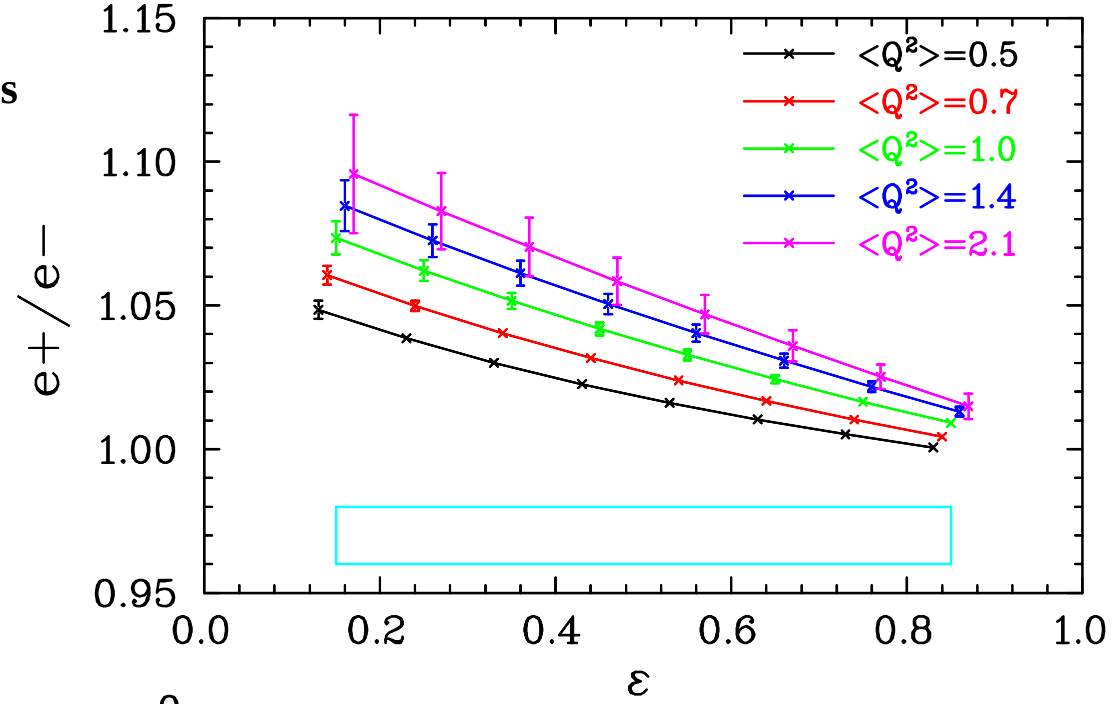
Would also like to have positron data over range in Q^2, and with complete ε coverage

E04-116 (Hall B): positron- and electron-proton scattering

1 μA beam on 5% radiator --> photons (electron beam send to tagger dump)

Photon beam through 2%converter --> electrons, positrons and photons

Chicane + photon blocker --> mixed beam of positrons and electrons

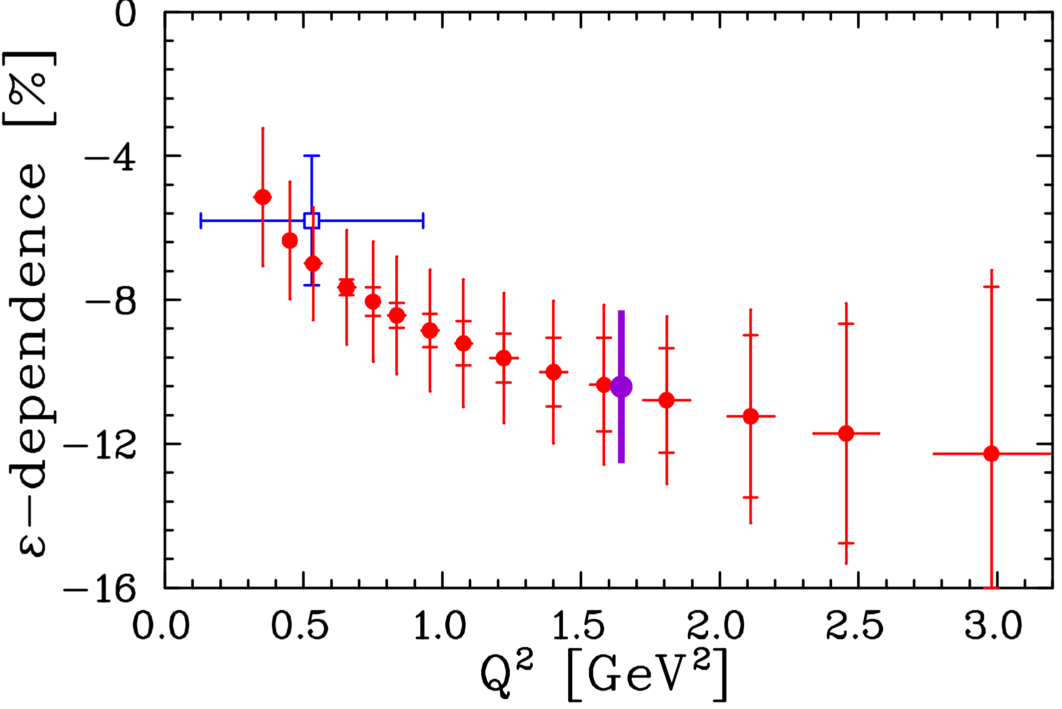


Detect scattered lepton and proton in CLAS - reconstruct initial lepton energy

Approved for five days (engineering run) by PAC26

W. Brooks, A. Afanasev, JA, K. Joo,
B. Raue, L. Weinstein, spokespersons

Main background from beam dump: Simulations and short tests runs performed to optimize shielding

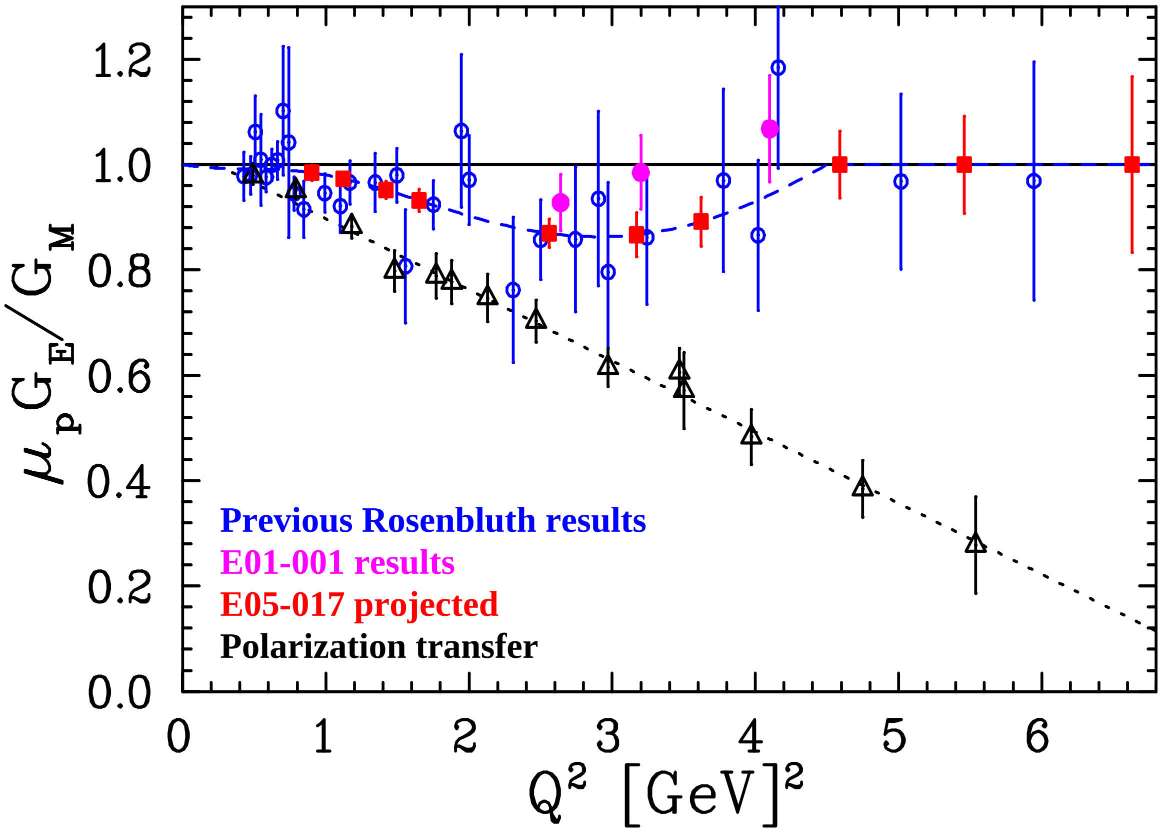


JLab E05-017 (Hall C): Improved Rosenbluth data

Proton detection can give factor of 2-3 improvement over world's L-T data on G_E / G_M

(as demonstrated by E01-001)

*I.A.Qattan, et al., PRL **94**, 142301 (2005)*



LT-PT comparisons provide $\Delta\sigma^{TPE}$ with 50-100% uncertainty

Reduce to 20-30% for Q^2>1-2

At lower Q^2, positron-electron comparisons will determine the size of $\Delta\sigma^{TPE}$

Reduce TPE uncertainties on G_M by factor of 2-3 for all Q^2, ***at or below the experimental uncertainties*** (if ε-dependence known)

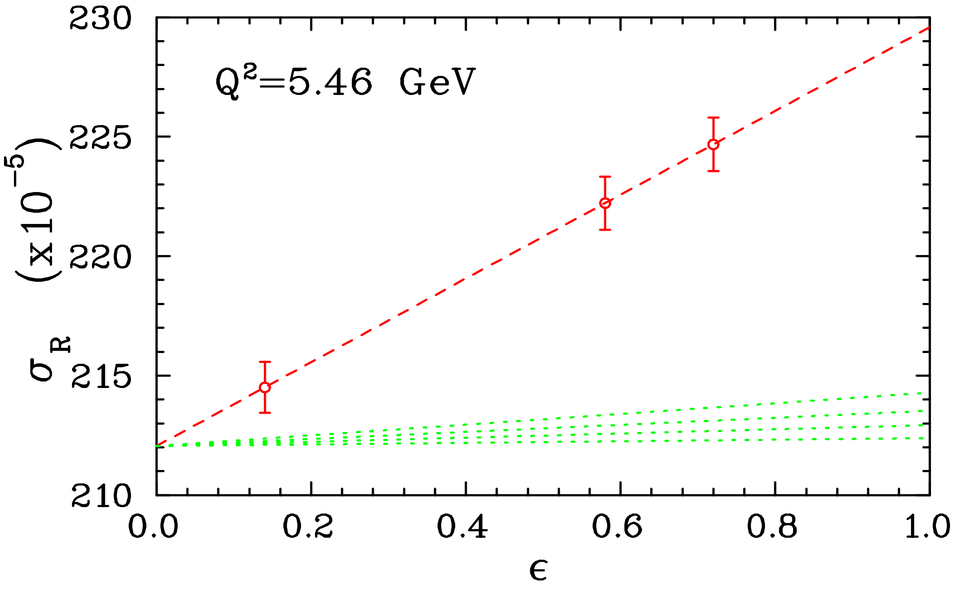
Final step: better knowledge of ε-dependence of amplitudes

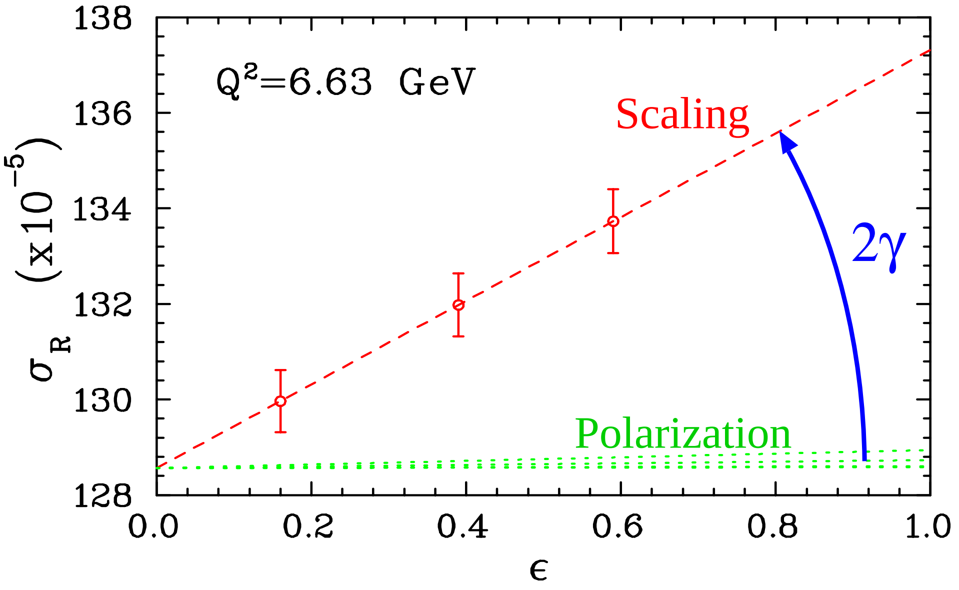
ε-dependence at lower (and higher) Q^2

At low-to-moderate Q^2, we can't separate effect of G_E from linear part of TPE
Rosenbluth data ***only constrains non-linearity*** in $\Delta\sigma^{TPE}$

At lower Q^2 values, e+/e- comparisons can yield a clean measure of the ε-dependence providing both ***linear and non-linear components***

At large Q^2 values, G_E —-> 0 and the ε-dependence is almost entirely from TPE





Extraction of TPE is almost as clean as in the e+/e- comparison

E05-017: ε dependence of $\Delta\sigma^{TPE}$

Can’t separate G_E from TPE terms, but can isolate (or limit) non-linear part

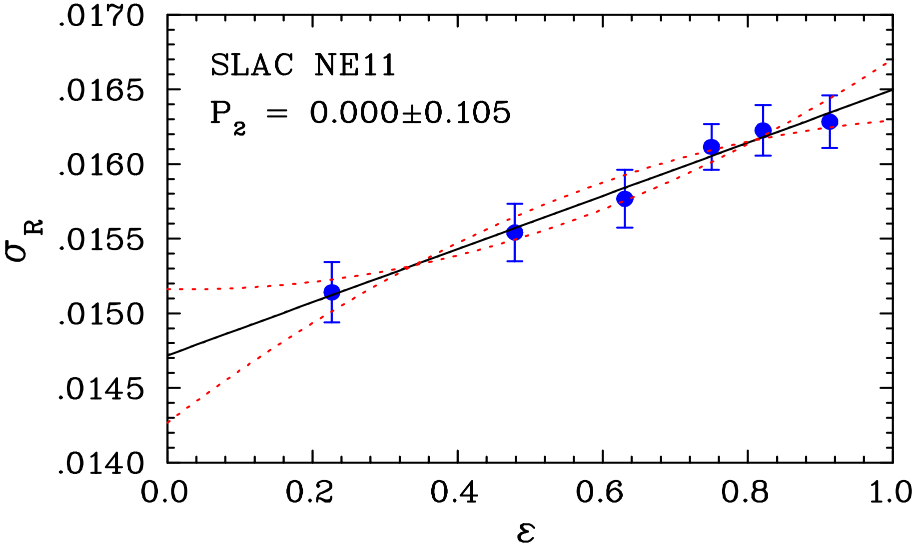
Fit to $\sigma_R = P_0\,(1 + P_1\varepsilon + P_2\varepsilon^2)$

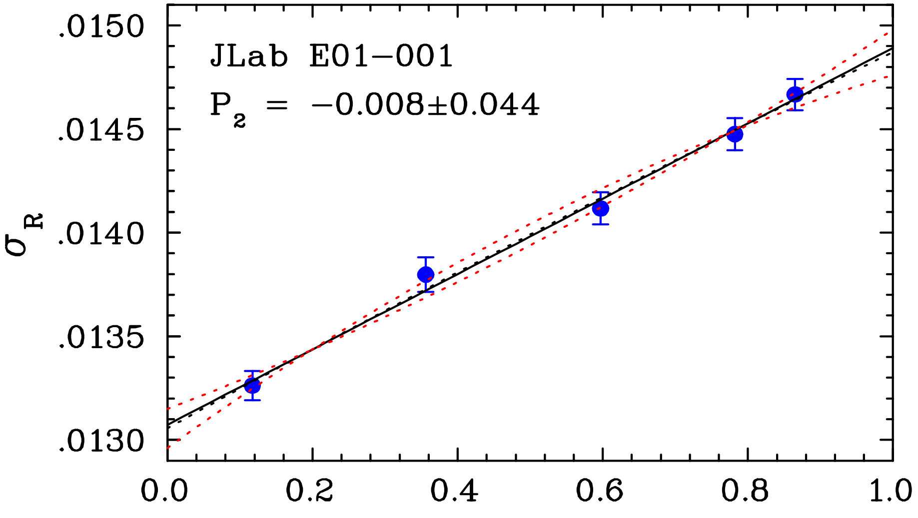
SLAC NE11 ⇨ P_2 = 0.000 +/– ***0.105***
(2.5 GeV^2) δσ (ε –> 0) = ***3.0%***

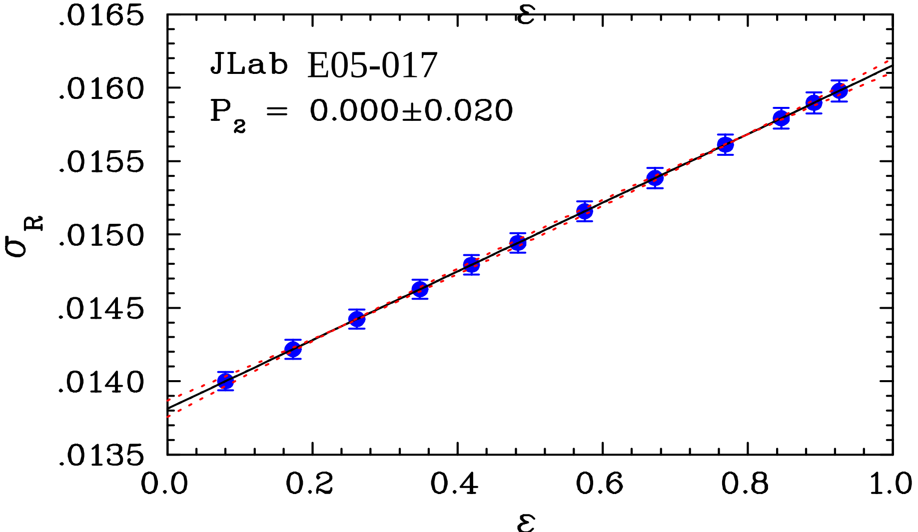
JLab E01-001 ⇨ P_2 = -0.008 +/– ***0.069***
(2.64 GeV^2) δσ (ε –> 0) = ***1.1%***

JLab E05-017 ⇨ P_2 = ??? +/– ***0.020***
(1.12, 2.56 GeV^2) δσ (ε –> 0) = ***0.4%***

Calculations predict non-linearity that would be ~5-7 sigma for this measurement







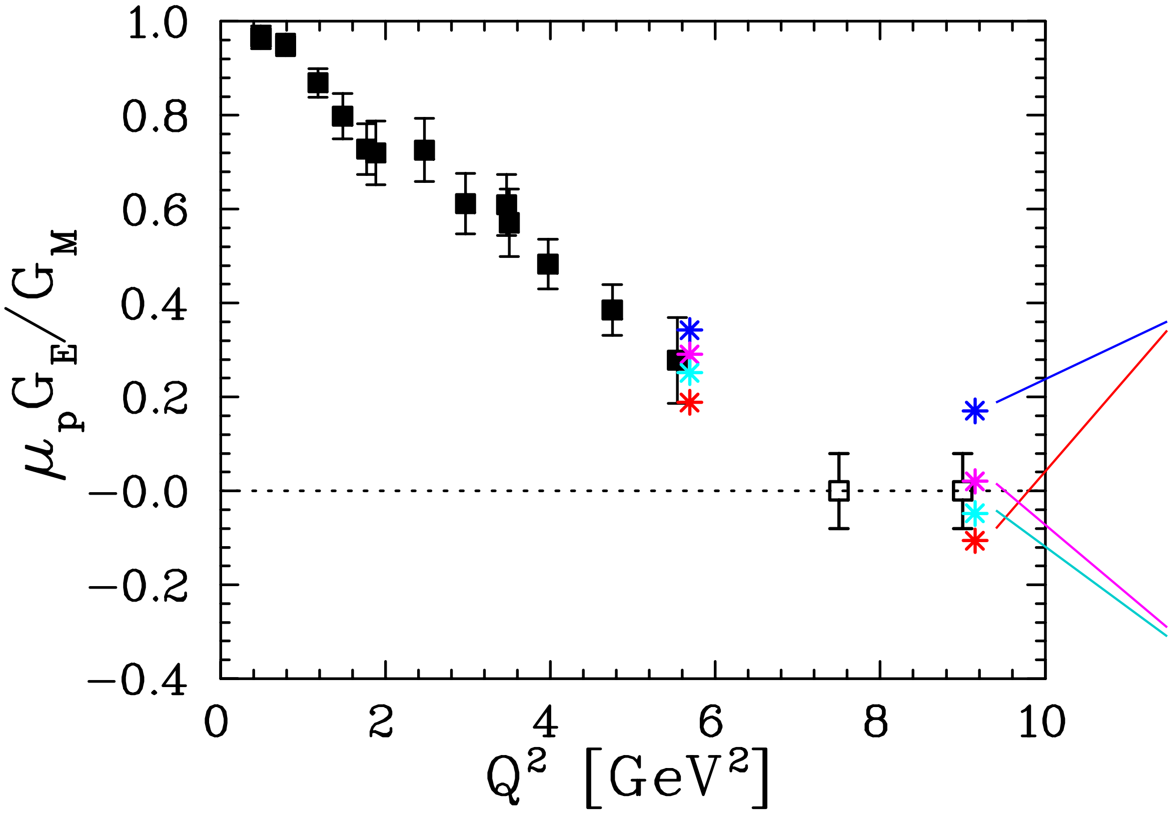
E04-019 (Hall C): ε dependence of polarization transfer

ε dependence of the cross section constrains ***one combination*** of TPE amplitudes:

ΔG_M, $Y_{2\gamma}$ both ε-independent yields linear effect on cross section

but $\Delta G_M=0$, $Y_{2\gamma} = A + B/\varepsilon$ also yields linear effect on cross section

These are ***indistinguishible*** in the cross section, but yield different corrections to polarization transfer



Emperical extraction with two different assumptions for ε dependence

Calcs of Chen, et al., and Blunden, et al. Both have nearly linear TPE corrections to the cross section

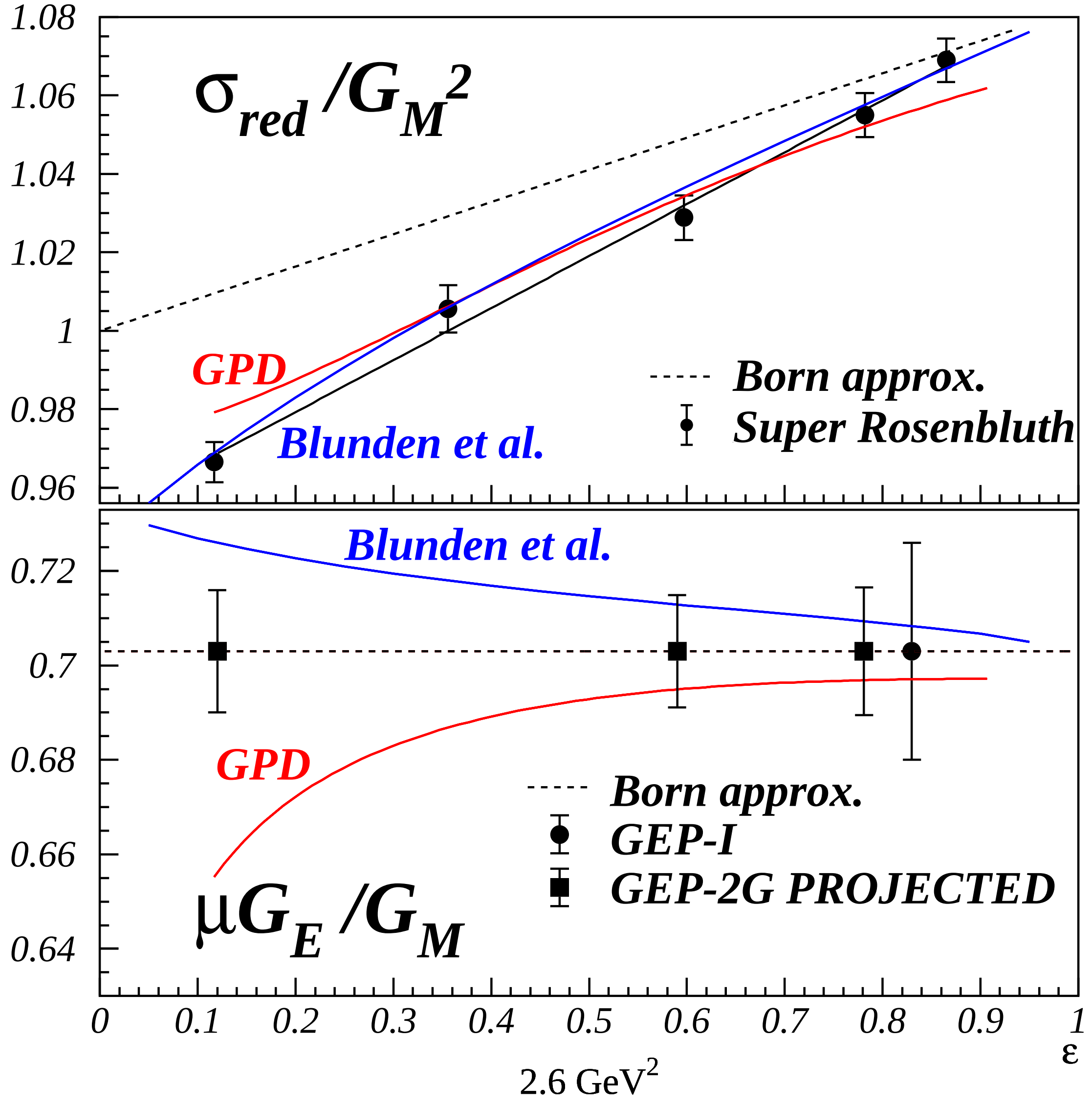
E04-019 (Hall C): ε dependence of polarization transfer

ε-independent TPE amplitudes yield linear effect on cross section, but $\Delta G_M=0$, $Y_{2\gamma} = A + B/\varepsilon$ also yields linear effect on cross section.

These are ***indistinguishible*** in the cross section, but yield different corrections to polarization transfer

E04-019: Measure ε dependence of ***polarization transfer*** result

Very different sensitivity to ε-dependence of $Y_{2\gamma}$, ΔG_M



Two-photon corrections: Future plans

Short term (direct connection to form factors):

Demonstrate that two-photon exchange is responsible

Experimental evidence is indirect (discrepancy) or weak (e+/e-)

More data to ***extract TPE corrections to G_E, G_M*** and to ***constrain calculations***

Better constraints on ε-dependence of the amplitudes

More precise positron-electron comparisons

More precise data for Rosenbluth-Polarization comparisons

Longer term (test models, study two-photon physics/GPDs):

Born-forbidden observables in p(e,e’p) - imaginary part of the TPE amplitudes

- Beam single-spin asymmetries (SAMPLE, A4, G0...)
- Normal polarization transfer, normal target spin asymmetries

Measurements to constrain TPE effects in other reactions

- Elastic form factors for neutron or light nuclei
- Other exclusive processes (e.g. N —> Δ form factors)
- Indirect impact due to uncertainty in form factors (e.g. extracting PV form factors)
- Experimentally, very little can be done without positron beams
  Need well tested, well constrained calculations

Positron beams?

A high-quality positron beam would allow test of TPE effects in other reactions

1999: Workshop on positron beams at Jefferson Lab

2004: Informal "micro-workshop" to discuss new options, new physics

- Much of the physics program could be done with 100-200nA beams, $5-10M
  - **Many TPE studies, Coulomb distortion, etc...**
- Certain options require more: 1-2 μA, $30M
  - **DVCS, Time-reversal invariance?**

Late 2005: Want to reexamine options for positron sources, start setting parameters

- Do we need electron/positron reversal in a day, a week, or a month?
- What current is good enough?
- What other measurments can we make?
  - **DICS** [see Bogdan’s talk]

Need to start thinking about what we can do and what we need to do it!

TPE corrections in other reactions (even at low Q^2)

Neutron form factors: G_E^n

Simple model: Two magnetic scatterings --> TPE is ~50% of e-p $[(\mu_n/\mu_p)^2]$

For $Q^2 \lesssim 1$ GeV^2, G_E^n is smaller than G_E^p by a factor of three or more, yielding a ***larger fractional correction to G_E^n***

➡ Important to know if e-p corrections are 1% or 10% ***(~10% in global analysis)***

Eventually, need a well tested model for e-p which can then be applied to e-n

Weak form factors: e.g. HAPPEX *K. Aniol, et al., PRC69:065501 (2004)*

Global analysis: $\Delta G_E^{2\gamma} = 7.5\%$ at Q^2=0.5 GeV^2

➡ ***1.2 ppm change in physics asymmetry*** (twice the assumed systematic)

Two-photon effects on G_M^p, G_E^n, G_M^n will yield ***additional corrections***

[NOTE: The HAPPEX example is probably a factor of two overestimate - needs to be redone]

Deuteron form factors: $B(Q^2)$

R. Suleiman, Ph.D. Thesis
K. McCormick, Ph.D. Thesis

E91-026: A and B extracted for $0.7<Q^2<1.3$, $\theta_{MAX} = 145^o$

Expect ***larger*** TPE for deuteron, but if we assume same $\Delta\sigma_{2\gamma}/\sigma$ as for proton:

➡ ***$\Delta B/B$ = 30% at Q^2 = 1.3*** ***Roughly <u>twice</u> the experimental uncertainties***

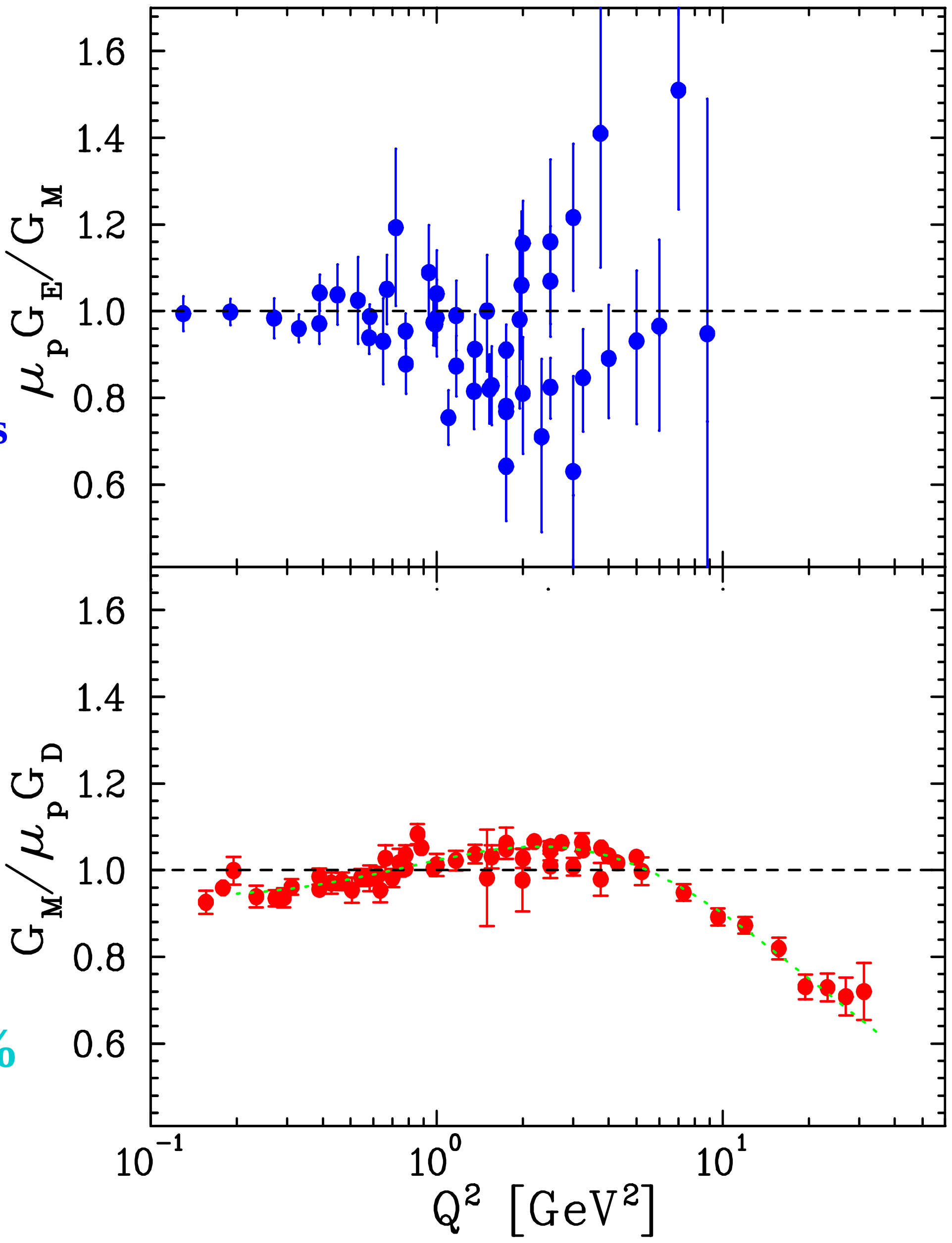
Different form factors (G_M, G_Q, and G_C) are combinations of A, B, and t_{20}

Probably even worse for ^{3}He - can't isolate G_E

There are many reactions where TPE might be important (>1-2σ), but often a rough understanding of TPE (30-50%) will be enough

Rosenbluth extractions of G_E and G_M (2000)

$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2)$$



G_E/G_M extracted to 10 GeV^2

Consistent with scaling: $G_E(Q^2) \sim G_M(Q^2)/\mu_p$

Identical charge, magnetization distributions

G_M up to 30 GeV^2 assuming scaling

G_M within 10% of G_D up to 10 GeV^2

Falls below dipole form at large Q^2

For Q^2>10 GeV^2, G_E contributes <5%

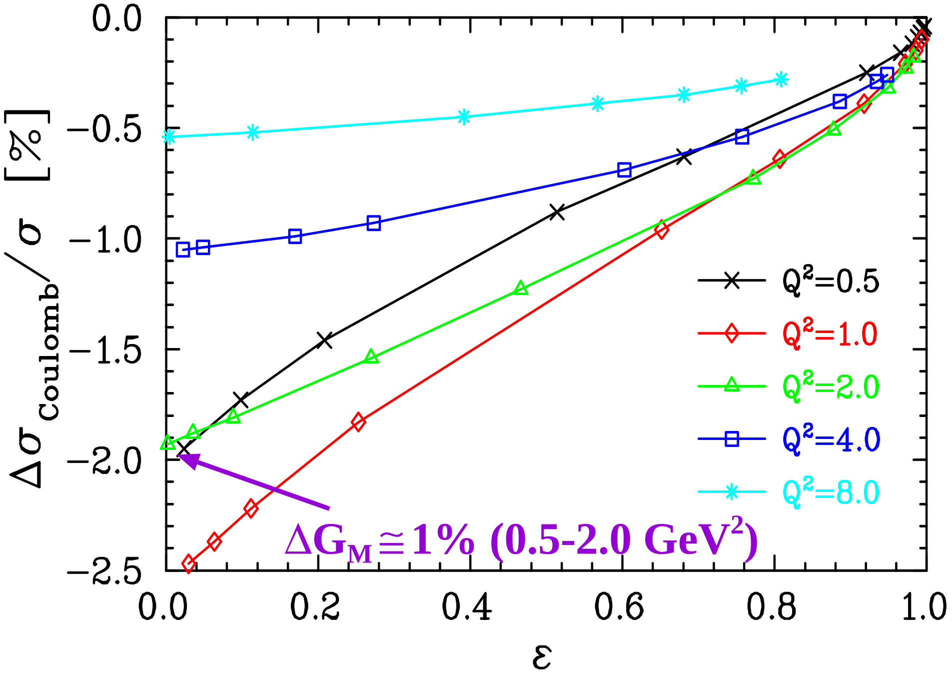
Coulomb distortion

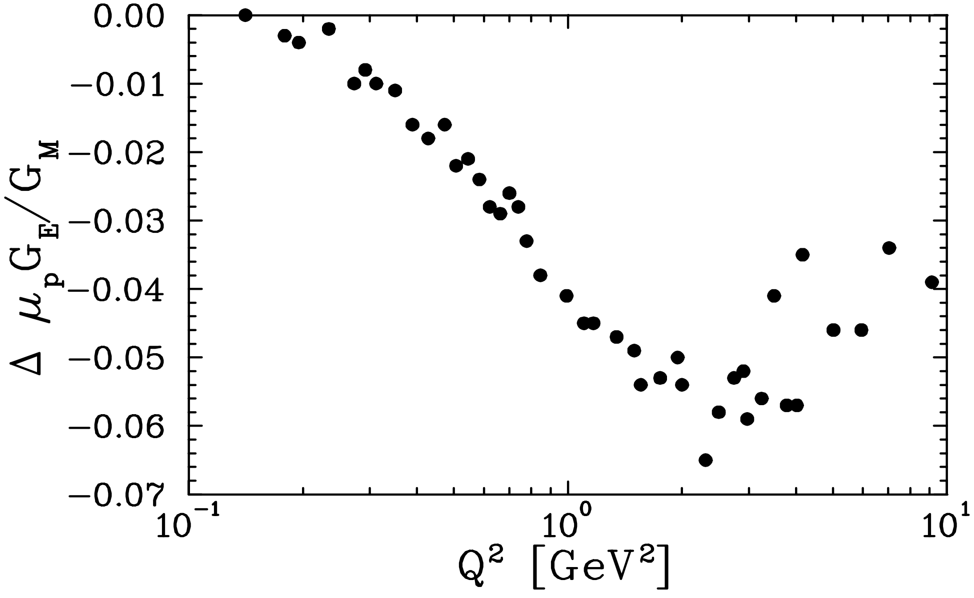
Other higher-order processes can also contribute - not just two-photon exchange

Soft multi-photon exchange (Coulomb distortion) also enters at order α

Effects are generally small, but do have a significant ε-dependence

JA and I. Sick, PRC ***70****, 028203(2004)*



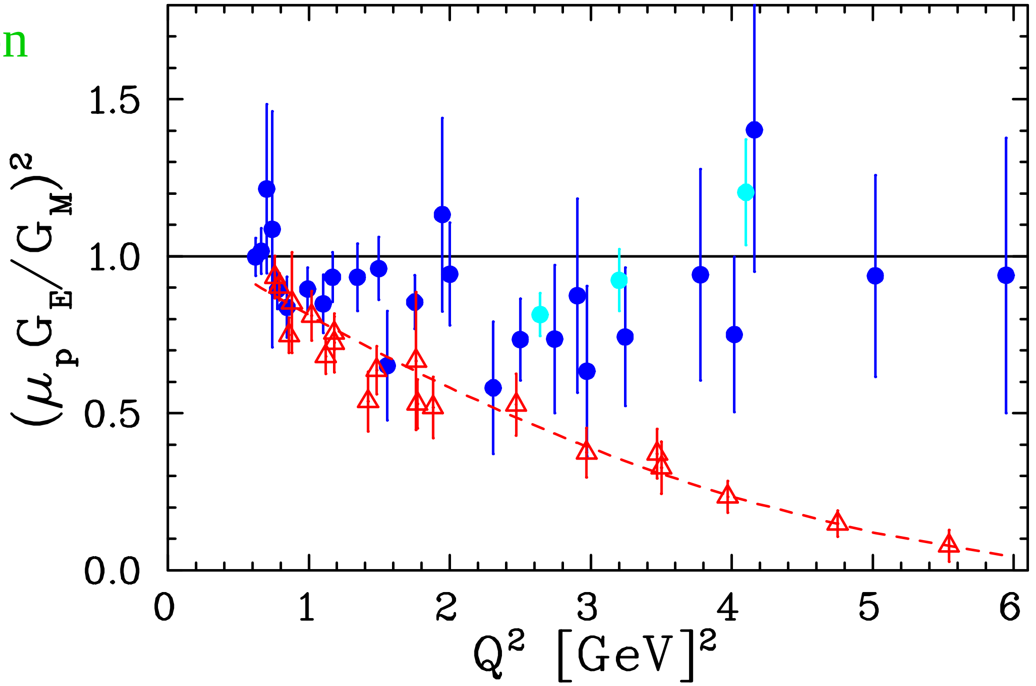


*Only explains a small part of the discrepancy above 3-4 GeV^2

*Can explain up to 30-40% of the discrepancy for $Q^2 \cong 1$ GeV^2)

*Explains much (most?) of the low-Q^2 positron/electron ratio

Emperical extraction of two-photon amplitudes



Uses full e$^-$p cross section and polarization data sets and constraint from e$^+$p data

Assumes ε-independent TPE amplitudes

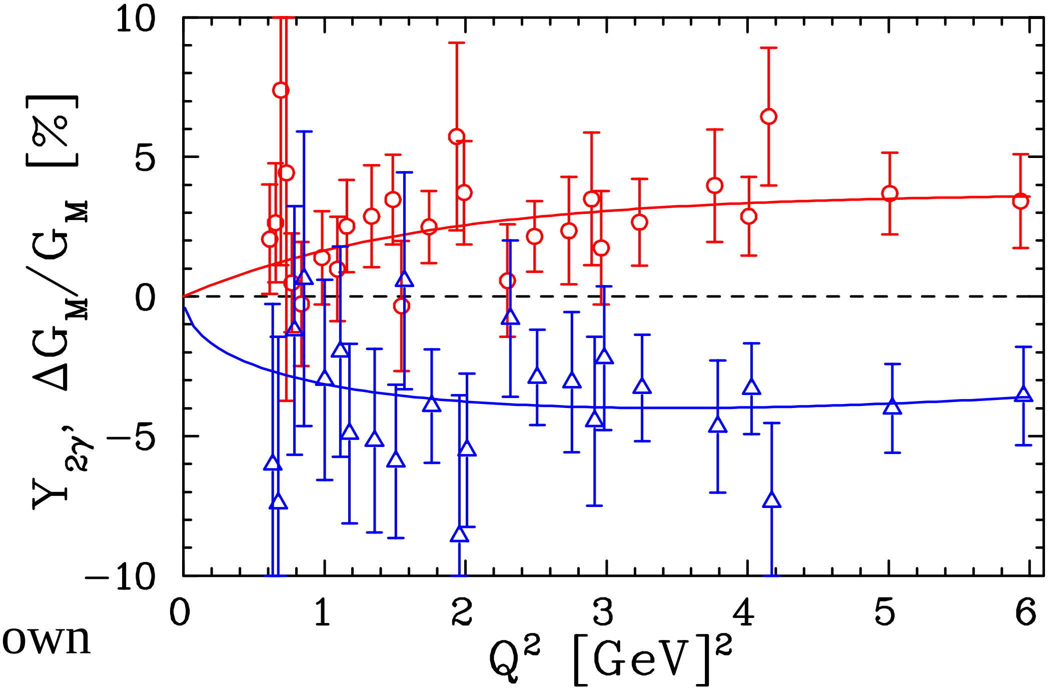
*JA, PRC **71**, 015202 (2005)*

$Y_{2\gamma}$ extracted from the difference between $R_{L\text{-}T}$ and R_{Pol}

Extract $Y_{2\gamma}$ with ~50-100% uncertainty

ΔG_M determined by e+/e- constraint: $\Delta\sigma \cong 0$ at large ε

$\mathbf{\Delta G_M/G_M} \cong -\varepsilon(1+\rho/\tau)\ \mathbf{Y_{2\gamma}}$ $\quad$ $\mathbf{(\rho=G_E/G_M)}$



➡ ***Significant corrections*** to G_E, G_M

TPE corrections ***dominate the uncertainty in the form factors***

Extraction limited by quality of present Rosenbluth extractions

Would be easy to resolve with better LT measurements **IF** ε-dependence were known

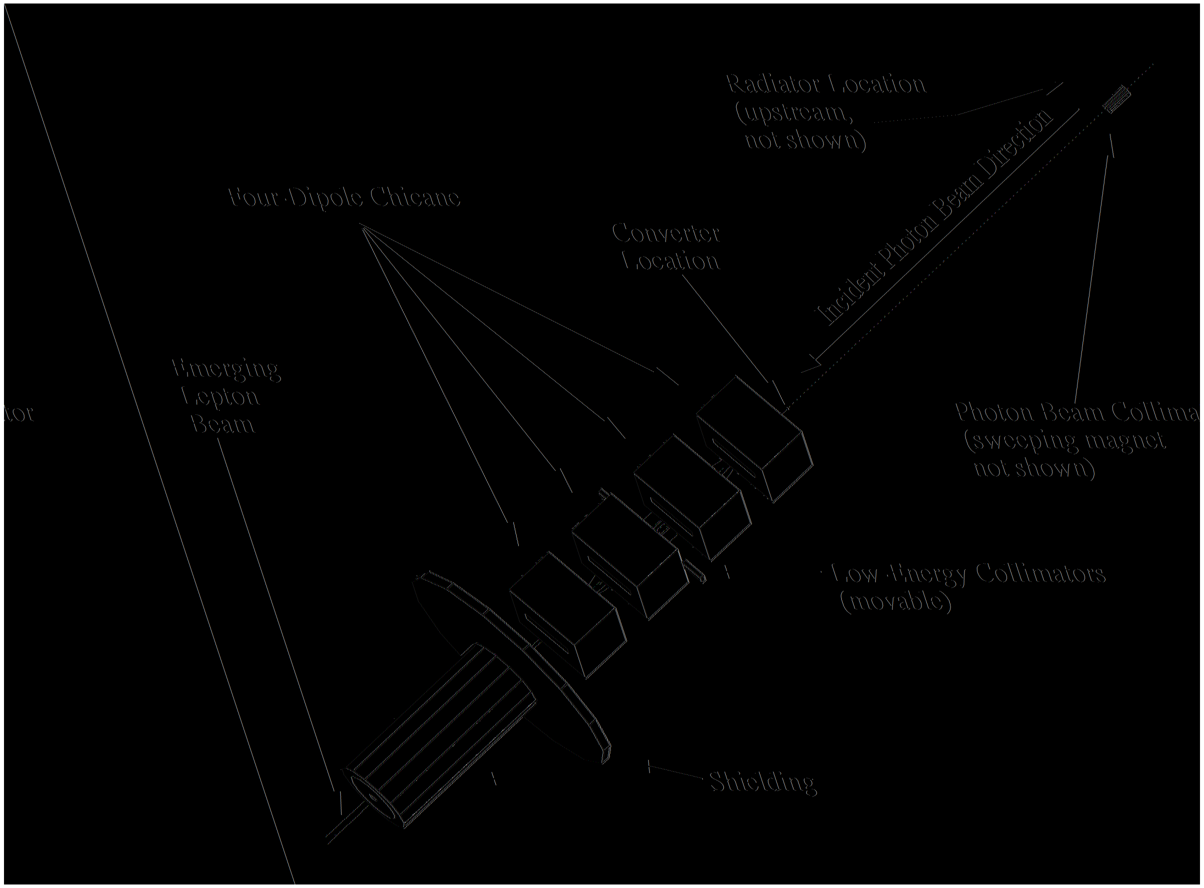
E04-116 (Hall B): positron- and electron-proton scattering

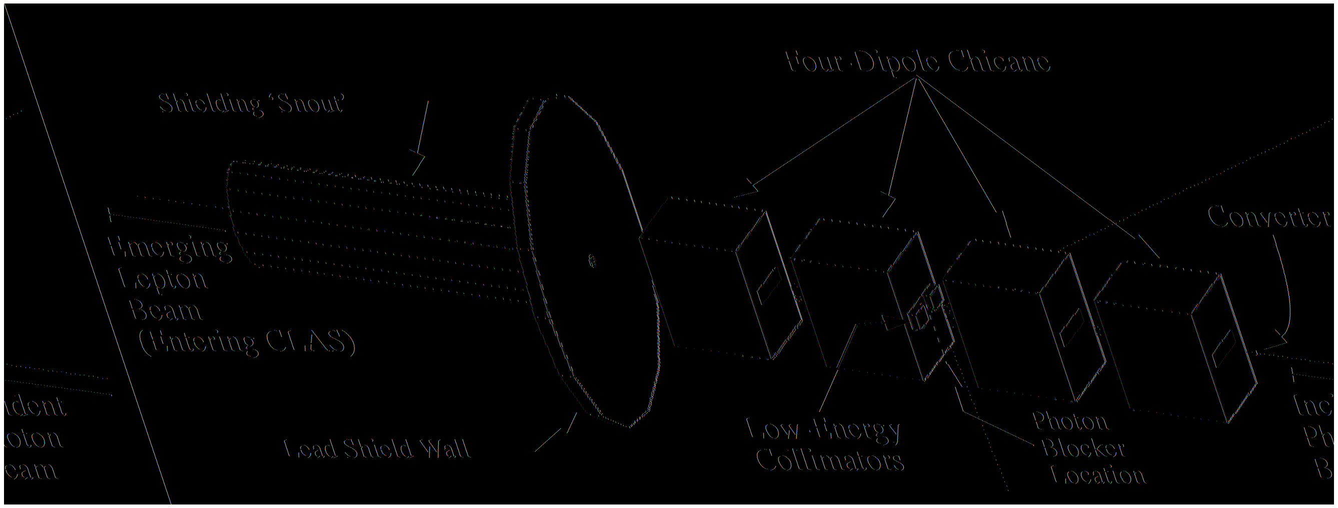
Use 5% radiator to generate photon beam, dump electron beam into tagger dump.

Put photon beam through 2% converter to generate positrons and electron

Steer positron(electron) beam above(below) photon blocker with a 4-dipole chicane system

Overlapping positron and electron beams incident on hydrogen target





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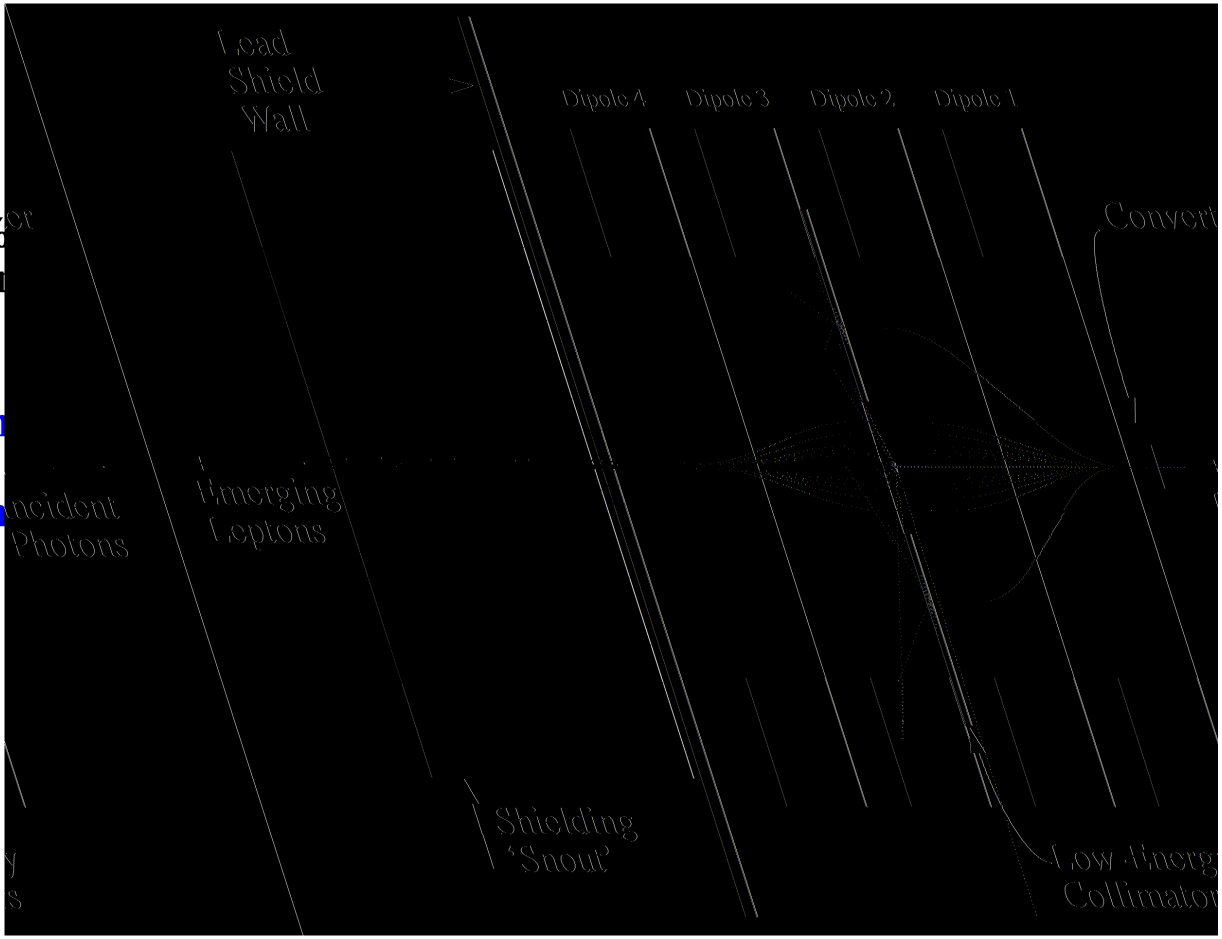
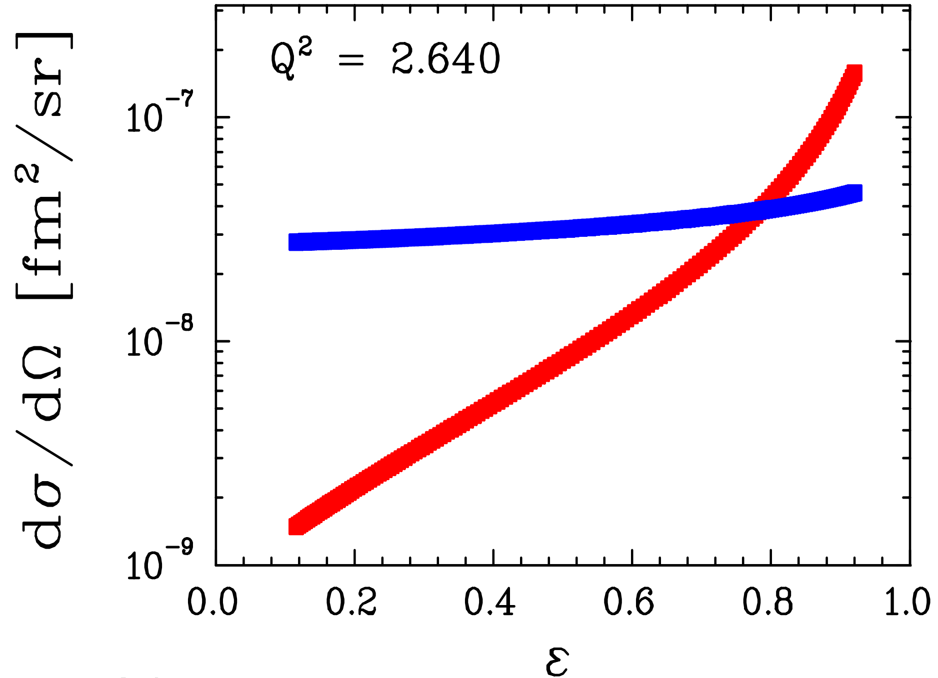


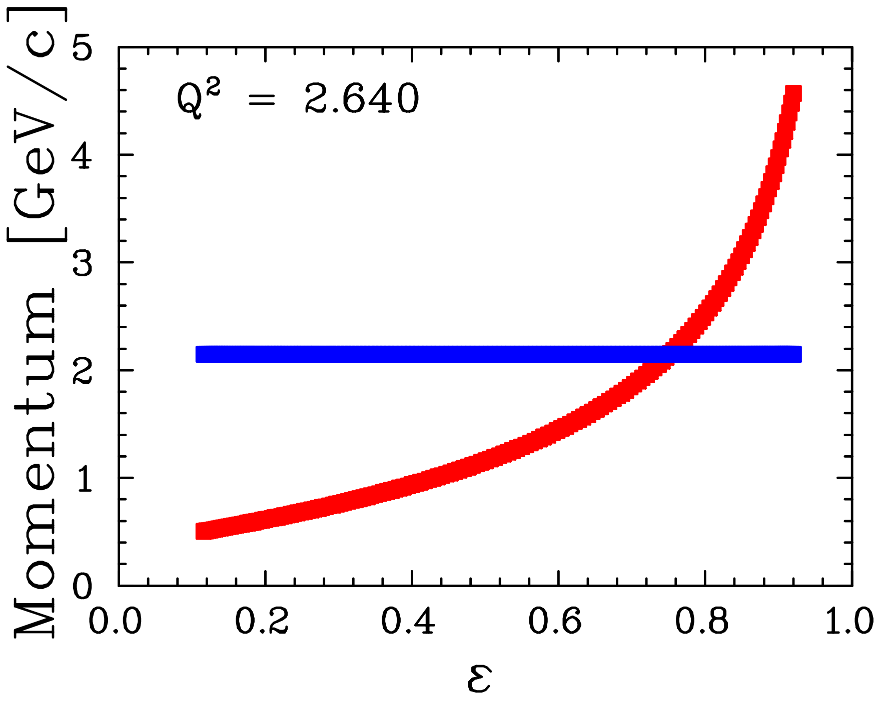
Advantages of Proton Detection

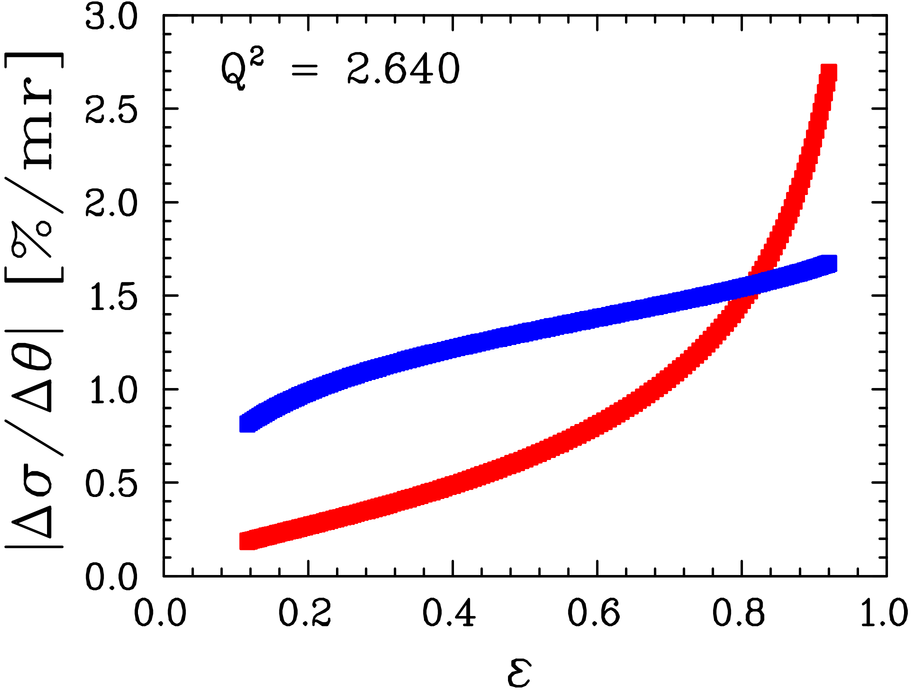
Electron detection: varying ε involves large changes in momentum, angle, cross section, etc...

For proton detection, these are much less sensitive to ε

- **-Smaller relative uncertainties**
- **-Better linearity tests**
- **-Better measurements of G_E/G_M**







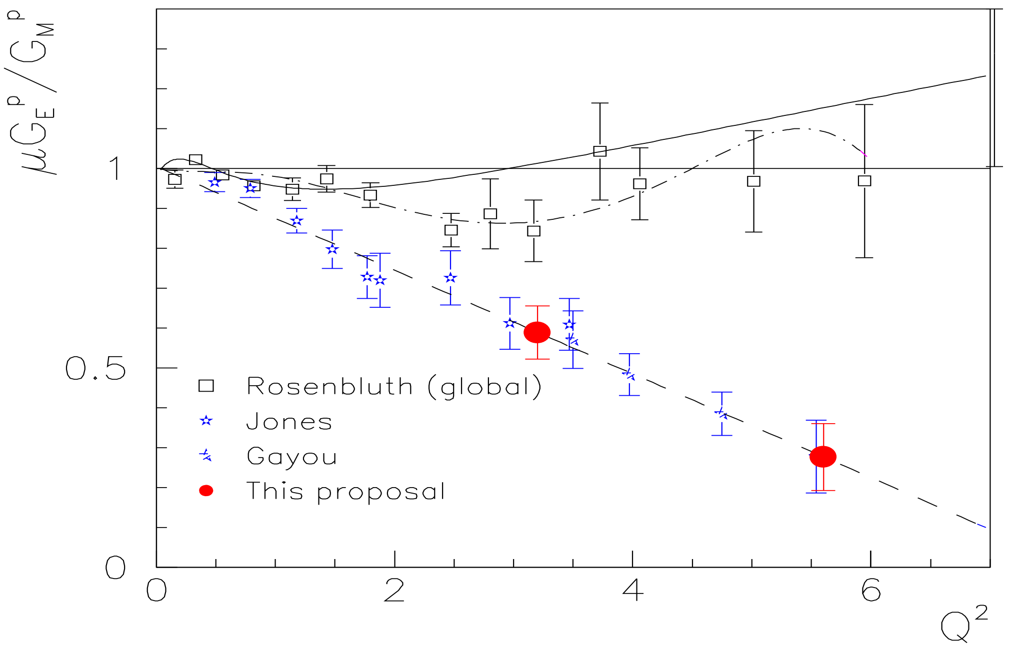
Checks on polarization transfer data

JLab E04-108 (Hall C):Extension to higher Q^2 (Perdrisat, Brash, Jones, Punjabi)

- -Extends data to $Q^2 \cong 9$ GeV^2
- -Different spectrometer and recoil polarimeter
- -Check on spin-transport and polarimeter systematics

JLab Proposal: G_E/G_M via polarized target asymmetry (Zheng, Calarco, Rondan)

- -Q^2 range and precision identical to existing polarization transfer data
- -Systematics are compleately different for this technique



Projected results vs. world's data

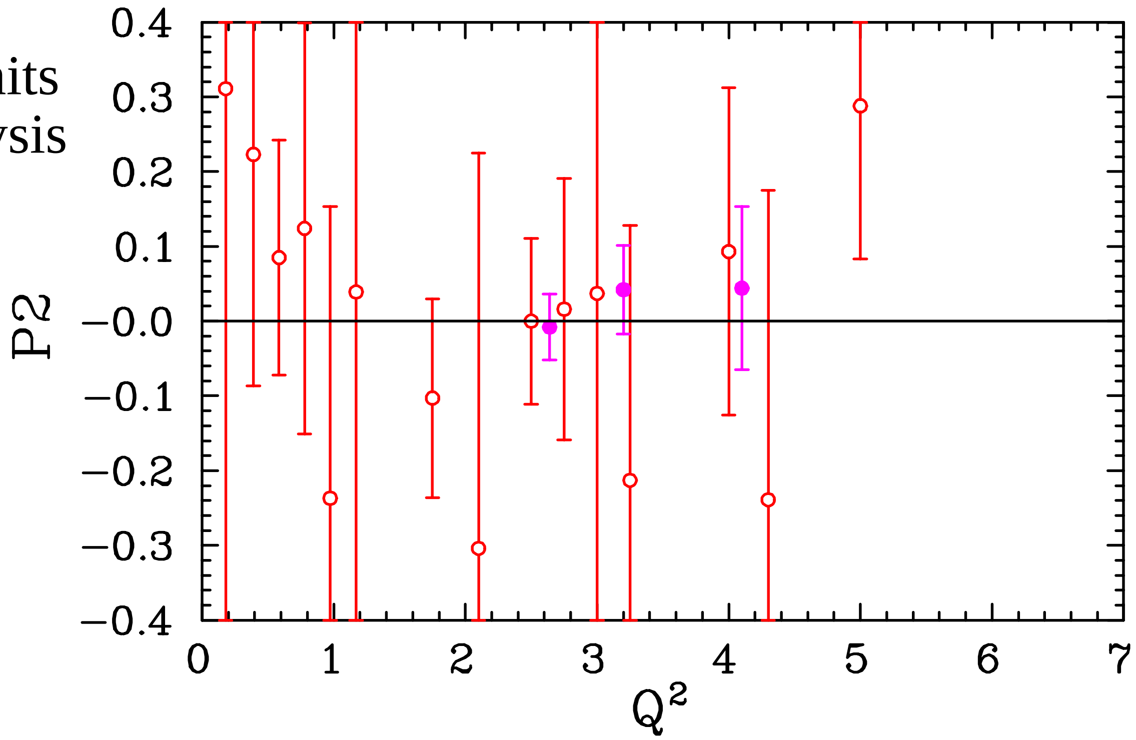
Normalization uncertainties
prevent meaningful linearity limits
from *global cross sections* analysis

Red points: All published L-T
separations for Q^2>0.4 with
$\delta P_2 < 0.8$ (i.e. full scale of plot)

Combined result:

$P_2 = 0.029$ +/– ***<u>0.055</u>***
Averaged over all Q^2 values
Almost no precise data for ε<0.2

Magenta: E01-001



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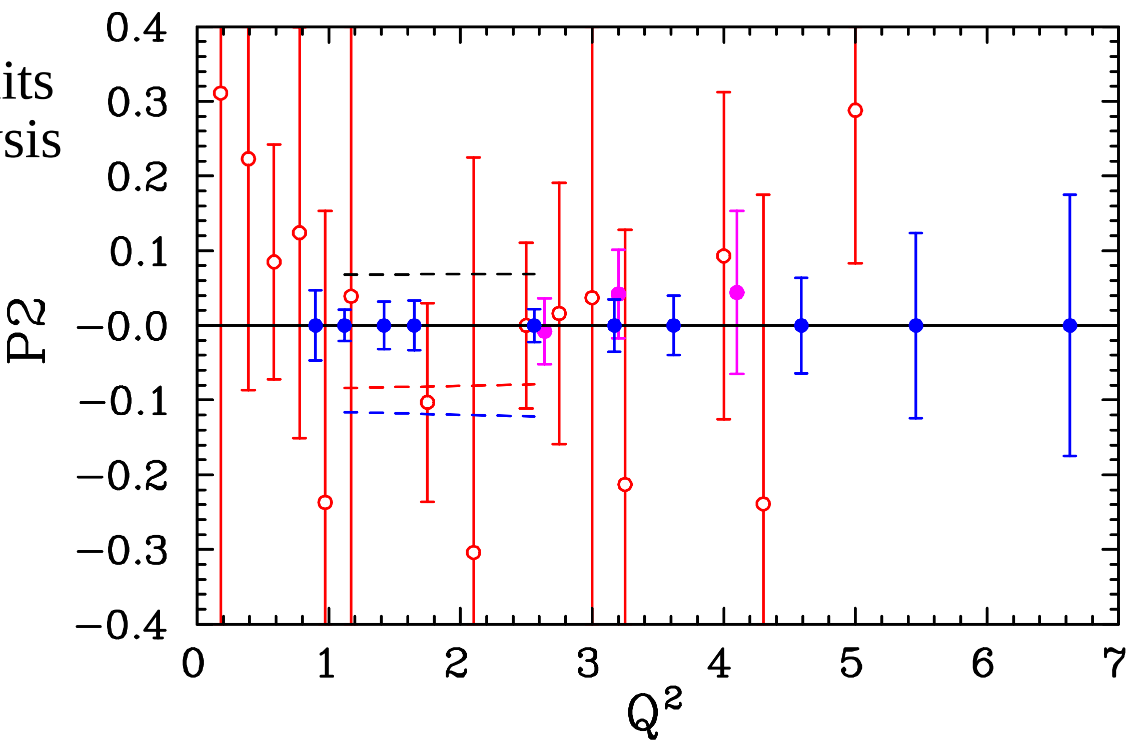


Blue points: E05-017

Every points below 4 GeV^2 has $\delta \boldsymbol{P_2}$ < ***0.055*** (seven of ten Q^2 values)

Combined result: $\delta \boldsymbol{P_2}$ = ***0.011***

Much more data at low ε values (down to ε=0.05, 0.08)

Important for extrapolation to ε=0, extraction of G_M

Two Q^2 values will have 12 ε points for detailed measurement of ε-dependence

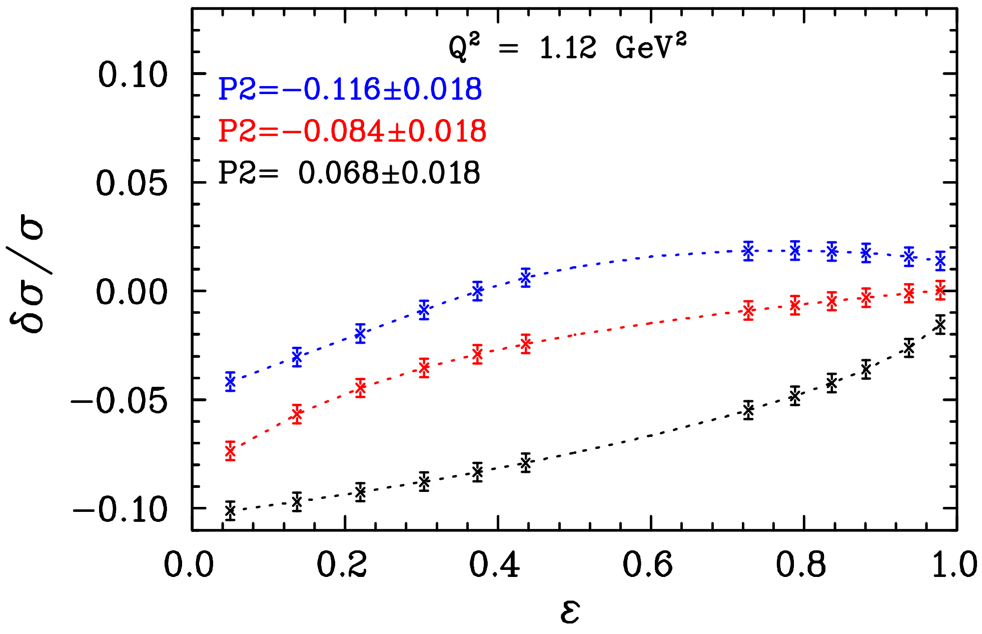
Projected results vs. calculations of two-photon effects

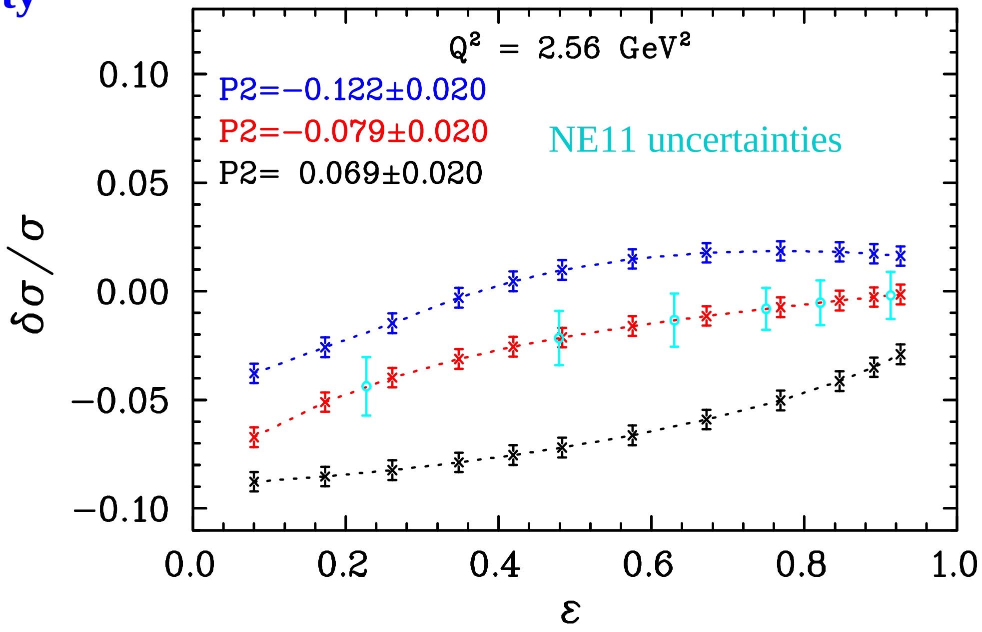
Projected results placed on calculations of Chen, *et al.*, Blunden, *et al.*, Afanasev (all scaled to yield 6% linear component)

E05-017 yields δ***P***$\boldsymbol{P_2} \cong \boldsymbol{0.02}$ at both Q^2

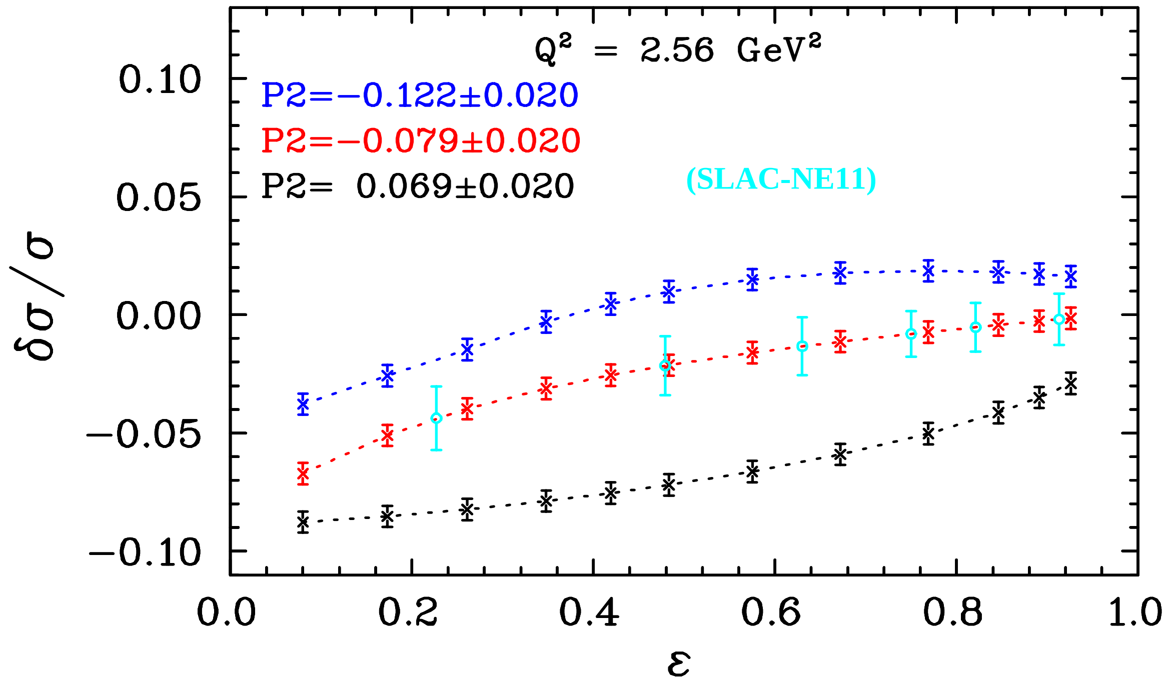
Models vary from ***–0.12 to +0.07***

- **Range of models is ~10x the projected sensitivity**
- **All three models yield 3-6 σ effect at each Q^2**
- **Detailed ε-dependence can further constrain models (non-linearity at high vs. low ε)**





Improved Rosenbluth measurements (PAC26)



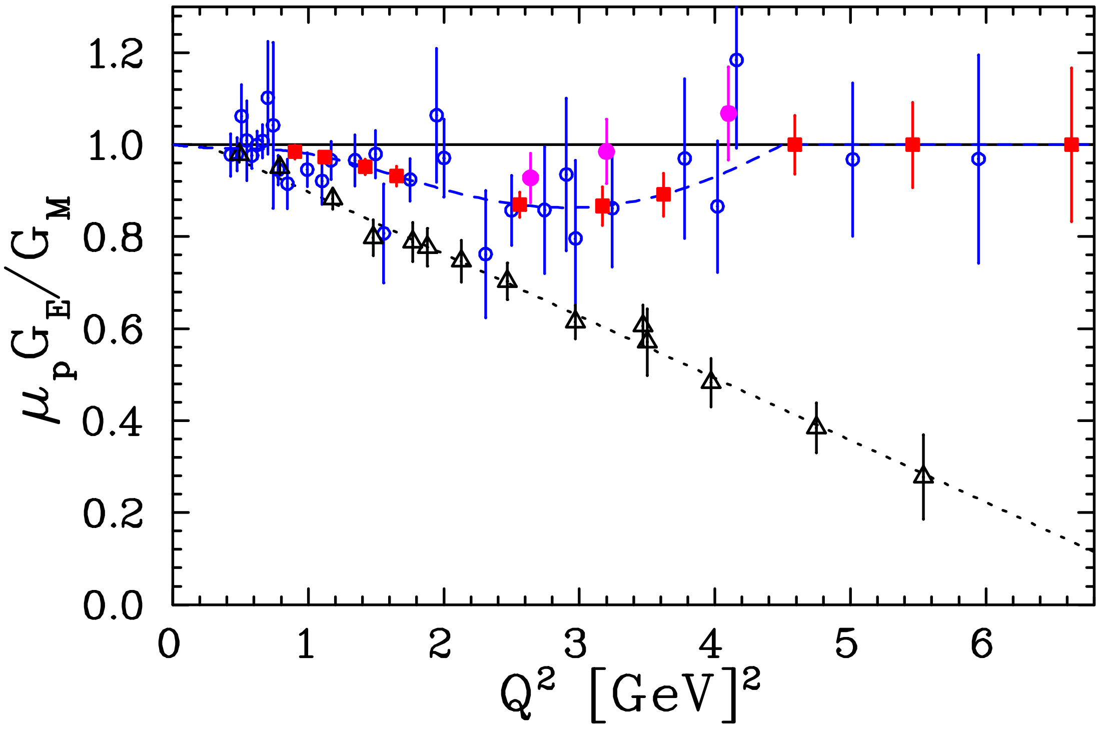
1) Improved linearity tests (precise ε-dependence)

Chen, et al., scaled to ~6%

Blunden, et al., scaled to ~6%

Afanasev, scaled to ~6%

P2 = curvature from quadratic fit



2) Improved extraction of form factor ratio

Previous data allows extraction of two-photon amplitudes with ~50-100% uncertainties

Proposed measurements yield ~20-35% uncertainties

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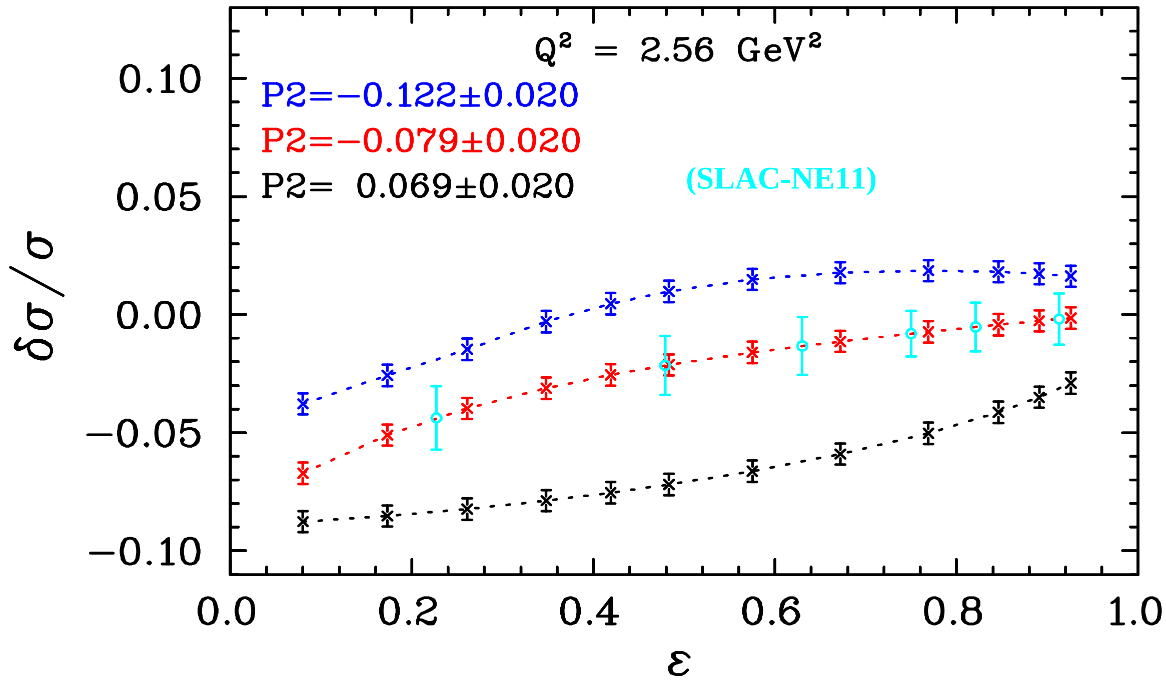

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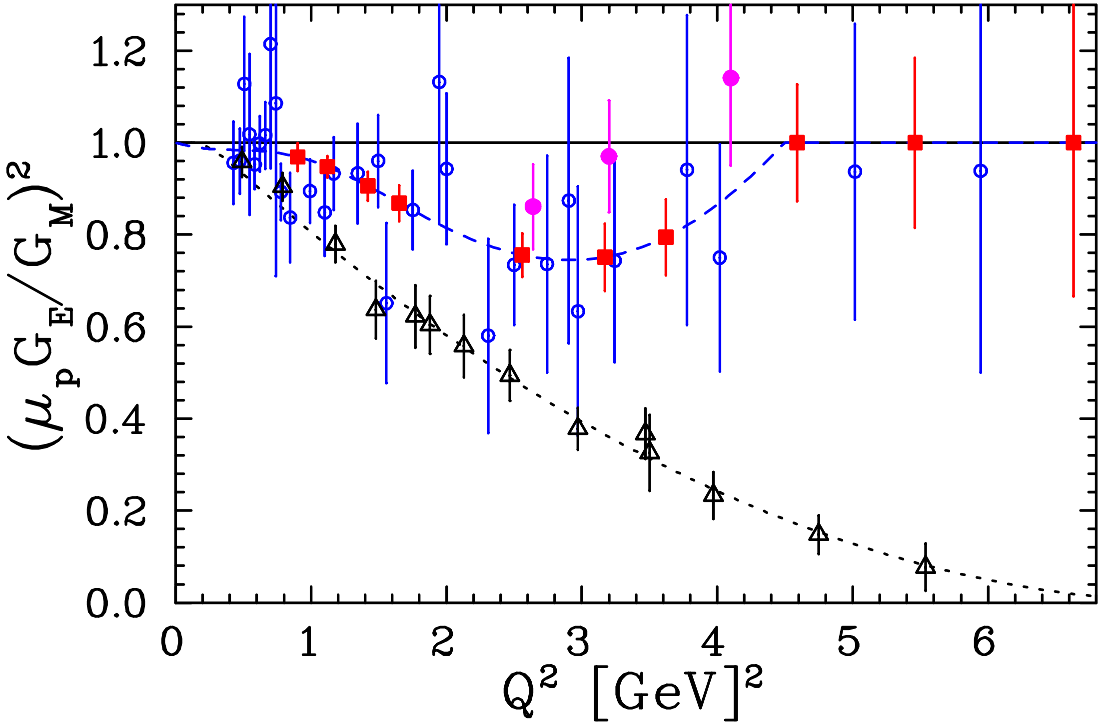

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Previous data allows extraction of two-photon amplitudes with ~50-100% uncertainties

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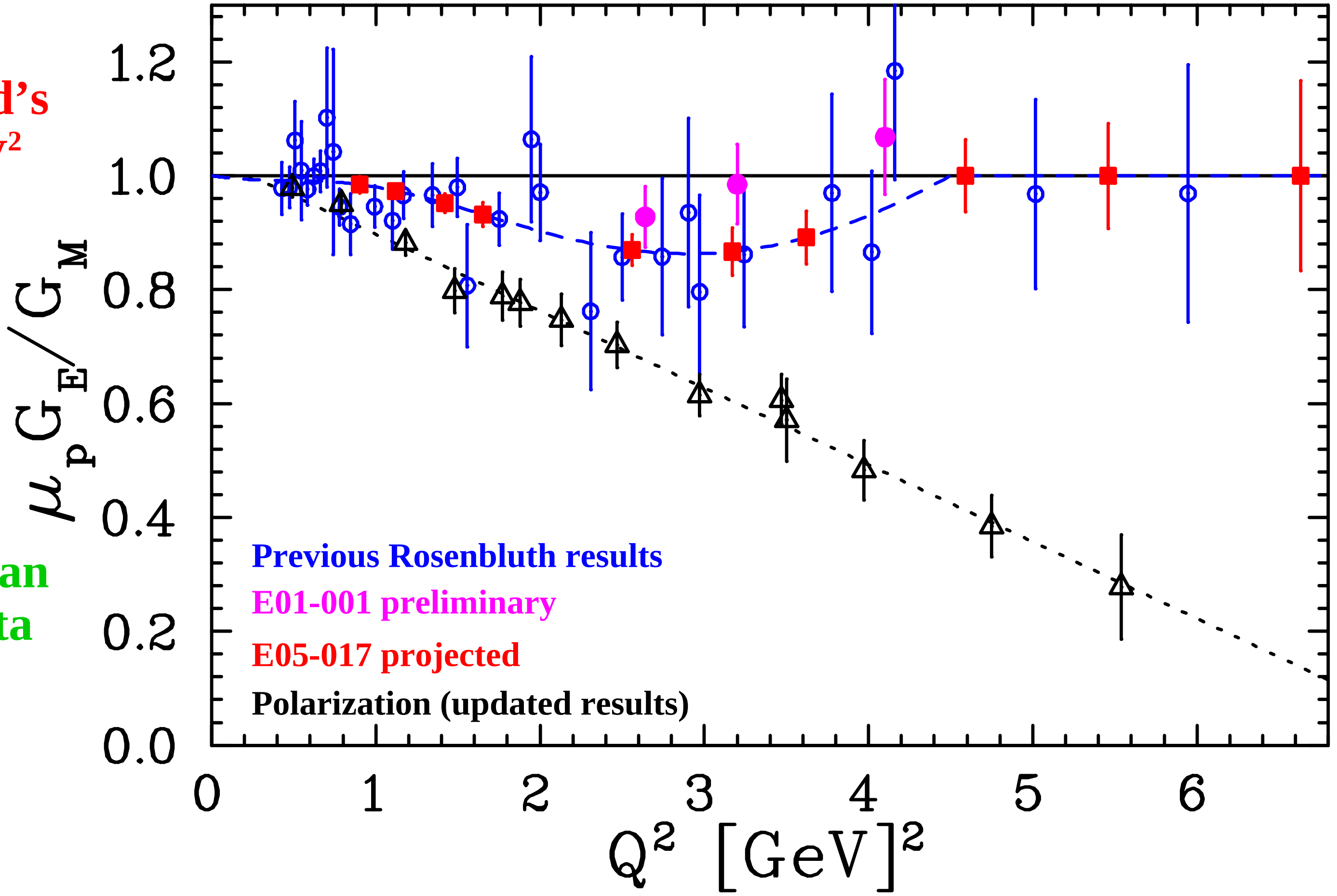
Improved Rosenbluth results for G_E/G_M

E05-017: Factor of 2-3 improvement over world's data for Q^2=0.9-6.6 GeV^2



Smaller uncertainties than polarization transfer data

Precise measurement of the discrepancy

Global analysis of Rosenbluth, polarization transfer, and positron data

⇨ ***Extract TPE amplitudes with good precision (20-30%) down to Q^2 = 1 GeV^2***
Currently, can extract TPE amplitudes to ~50-100%, down to Q^2 = 2 GeV^2

⇨ ***Apply two-photon corrections to extracted values of $G_M(Q^2)$** (Rosenbluth) **and $G_E(Q^2)$** (polarization transfer)*

Physics impact of "small" TPE corrections: other...

No data and little theoretical work on effects at lower Q^2, where the form factors must be known precisely:

- Analysis of A(e,e’p) measurements (especially L-T separations) *D. Dutta, et al., Phys. Rev. C68:064603(2003)*
- Extraction of parity violating form factors

Example: HAPPEX ($Q^2 \cong 0.5$ GeV^2) *K. Aniol, et al., PRC69:065501 (2004)*

- Extracted physics asymmetry = 15 ppm, 1 ppm stat. error, 0.6 ppm sys. error
- Uncertainty due to uncertainty in E-M form factors: 0.6 ppm

P. Guichon and M. Vanderhaeghen, PRL 91:142303 (2003)
J. Arrington, PRC71:015202 (2005)

Analyses following the approach of Guichon and Vanderhaeghen yield TPE corrections to G_E that are ***larger than the assumed uncertainties***:

- TPE change to G_E is 7.5% at Q^2=0.5 GeV^2
- Yields 1.2 ppm change in physics asymmetry (twice the assumed systematic)

There is a large uncertainty in this correction, which could easily be larger or smaller

The change in G_E yields 1.2 ppm, the other form factors will yield ***additional corrections***

Physics impact of "small" TPE corrections: neutron form factors

Simple model: TPE is roughly proportional to G_M^2

Assumes TPE mainly from two magnetic interactions:
J. Arrington and I. Sick, PRC 70:028203 (2004)
J. Tjon, priv. communication

Neutron ***magnetic*** form factor:

Cross section ~ G_M^2 (at large Q^2), Interference term ~ G_M^3

In the simple model, we expect the ***fractional*** TPE effects to be down by roughly $G_M^{\mathbf{n}}/G_M^{\mathbf{p}} \cong \mu_{\mathbf{n}}/\mu_{\mathbf{p}}$, or roughly 2/3 of the proton case (3-7% at large angle)

Most likely not an issue, since few G_M^n data are at large angle

Neutron ***electric*** form factor:

Simple model predicts e-n TPE will be half of the e-p correction [factor of $(\mu_n/\mu_p)^2$]

For $Q^2 < 1$ GeV^2, $G_E^{\mathbf{n}}$ is smaller than $G_E^{\mathbf{p}}$ by a factor of three or more, yielding a ***larger fractional correction to G_E^n***

First, we need to know if TPE corrections to e-p polarization transfer are 1% or 10%

Eventually, we need a well tested model for e-p which can then be applied to e-n

Physics impact of "small" TPE corrections: deuteron form factors

***Simple* model**: TPE is same as for proton (5-10% ε-dependence)

(General expectation is that TPE effects will be ***larger*** for e-d due to rapid cross section falloff)

$\sigma_R(e\text{-}d) \sim A(Q^2) + \tan^2(\theta/2)\, B(Q^2)$

In principle, measurements at $\theta=0^o$ and 180^o allow direct separation of A, B

In practice, $\theta_{MAX} < 180^o$ means TPE effects are enhanced in $B(Q^2)$

E91-026: A and B extracted for $0.7<Q^2<1.3$, $\theta_{MAX} = 145^o$

Assuming 6% ε-dependence (based on proton at similar Q^2)

R. Suleiman, Ph.D. Thesis
K. McCormick, Ph.D. Thesis

➡ $B(Q^2)$, extracted from L-T separation, has enhanced TPE correction

ΔB/B = 11% at Q^2 = 0.7
30% at Q^2 = 1.3

Roughly <u>twice</u> the experimental uncertainties

Different form factors (G_M, G_Q, and G_C) are combinations of A, B, and t_{20}, and certain combinations will be strongly effected by these TPE corrections, especially where there are large cancellations between the measured form factors (e.g. near minima)

TPE effects are probably even worse for ^{3}He:

Expect larger TPE corrections due to rapid falloff of form factors

Can never isolate G_E from G_M (same problem as for the proton)