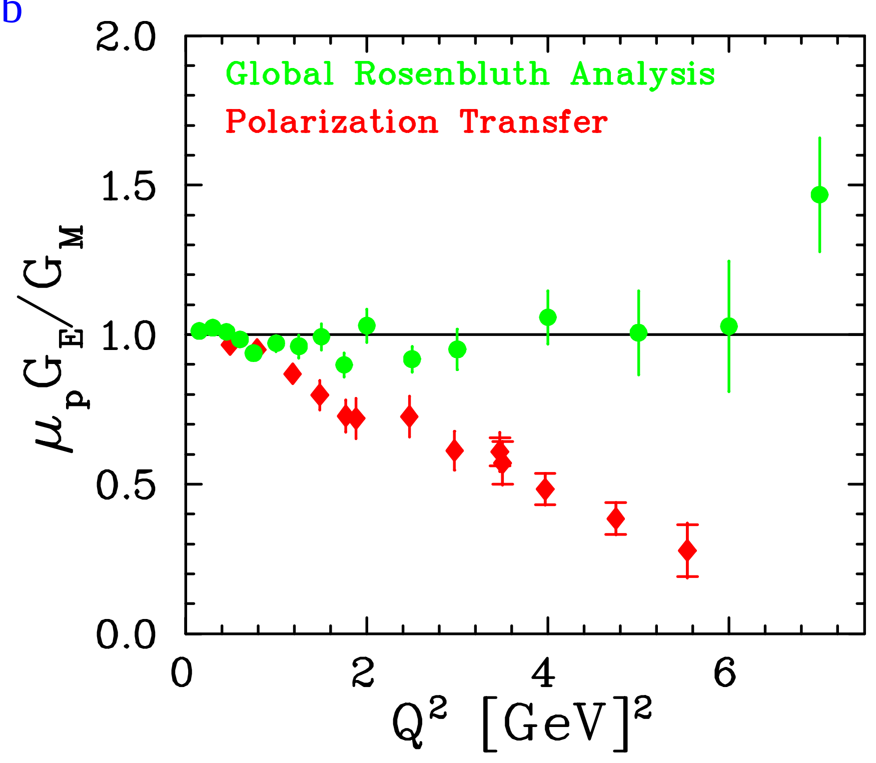
Two-photon exchange: Experimental Overview

or

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

John Arrington
Argonne National Lab



Introduction

Rosenbluth measurements: G_E, G_M

Polarization transfer: G_E / G_M

E01-001 "SuperRosenbluth": G_E / G_M

Two-photon exchange corrections

Evidence for two-photon exchange

Uncertainties in the TPE, form factors

Future experiments

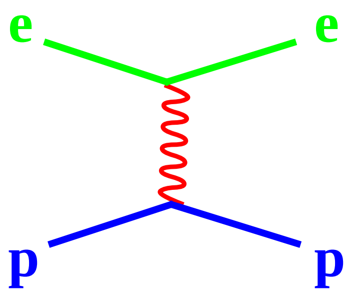
Size of TPE effects: e+/e- comparisons, PT/LT comparisons

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

Workshop on Precision ElectroWeak Interactions
Williamsburg, VA, August 15-17, 2005

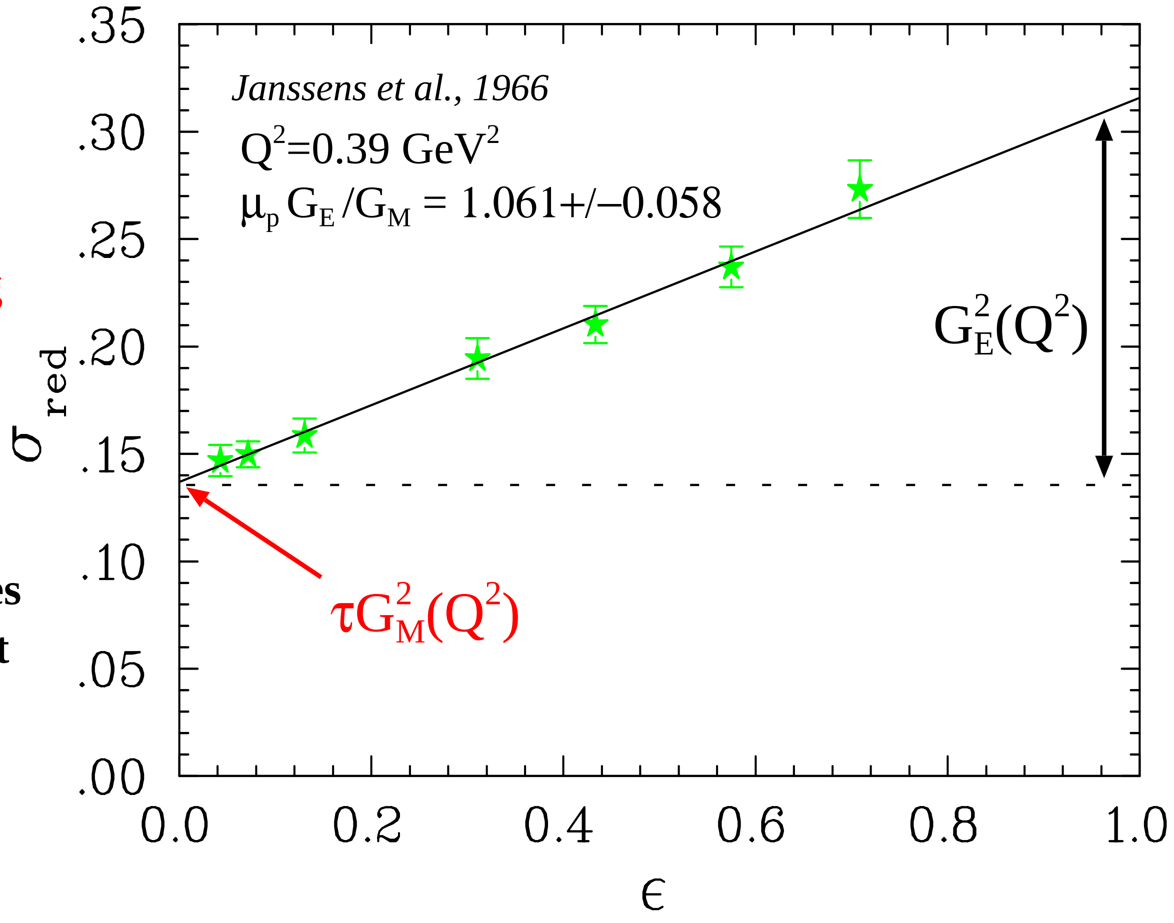
Rosenbluth extractions of G_E and G_M

In the Born approximation:



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

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

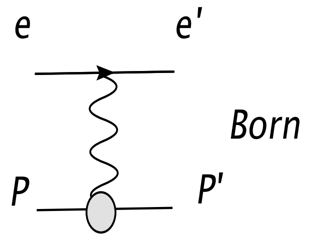


Initial Rosenbluth measurements consistent with form factor scaling

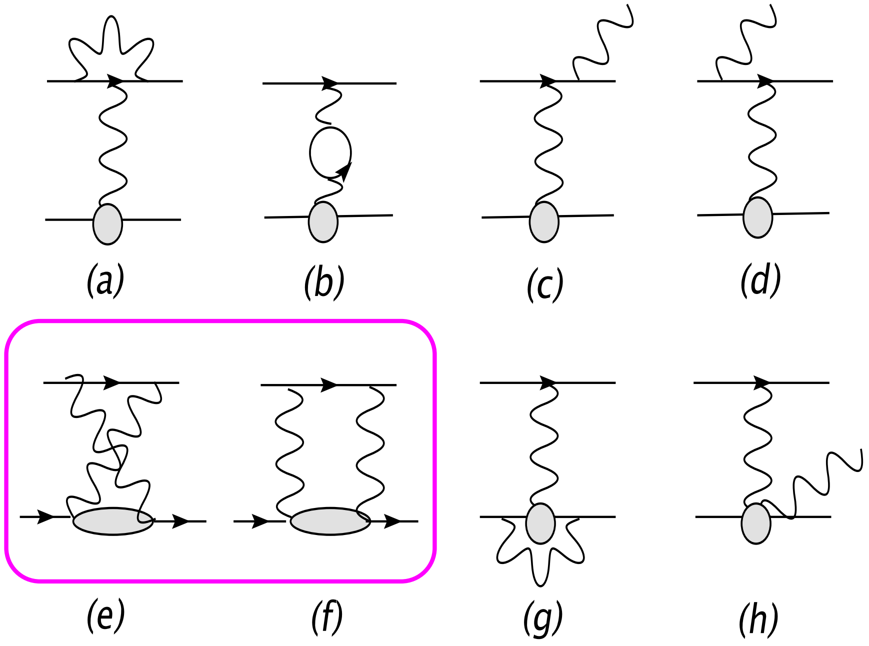
$G_M(Q^2) \cong \mu_p G_E(Q^2)$

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

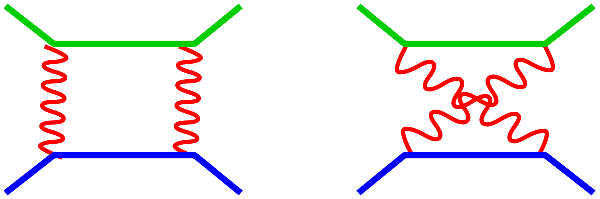
*R.R.Lewis, PR **102**, 537 (1956) ; S.D.Drell and M.Ruderman, PR **106**, 561 (1957) ; S.D.Drell and S.Fubini, PR **113**, 741 (1959) ; J.A.Campbell, PR **180**, 1541 (1969) ; G.K.Greenhut, PR **184**, 1860 (1969)*

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*

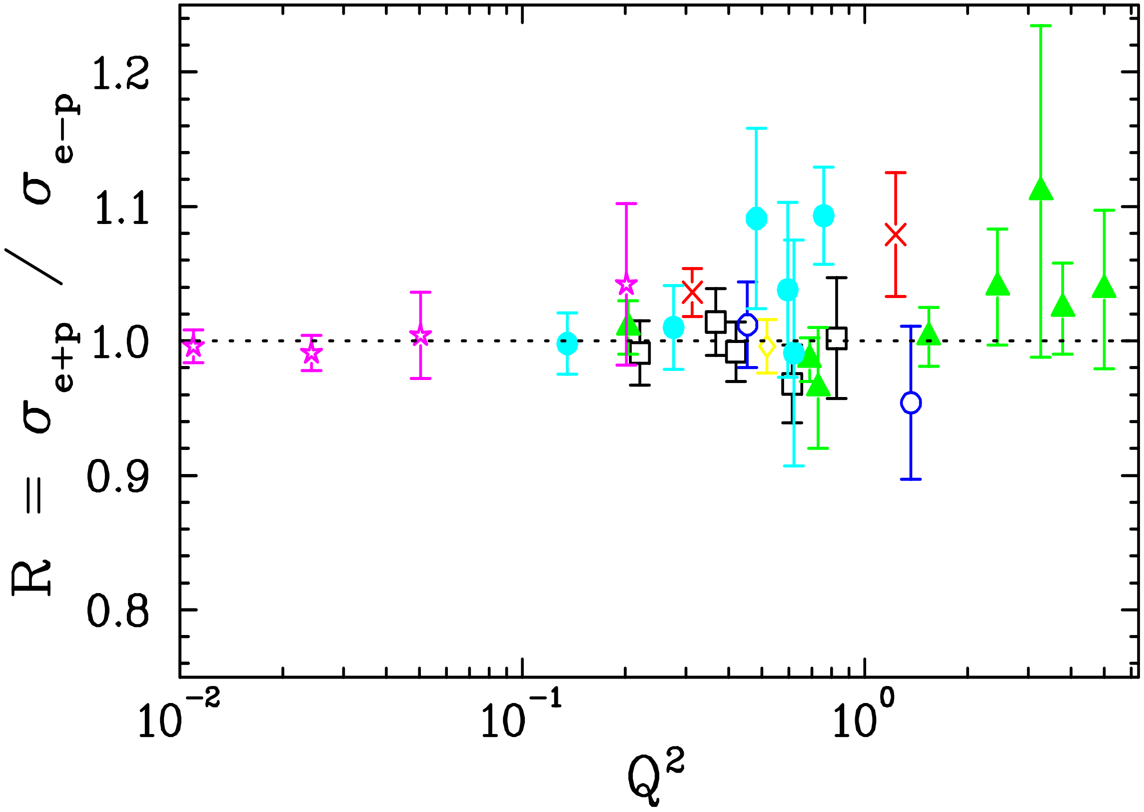
μ+/μ–

<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

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

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

$\mathbf{P_N = 0}$ 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

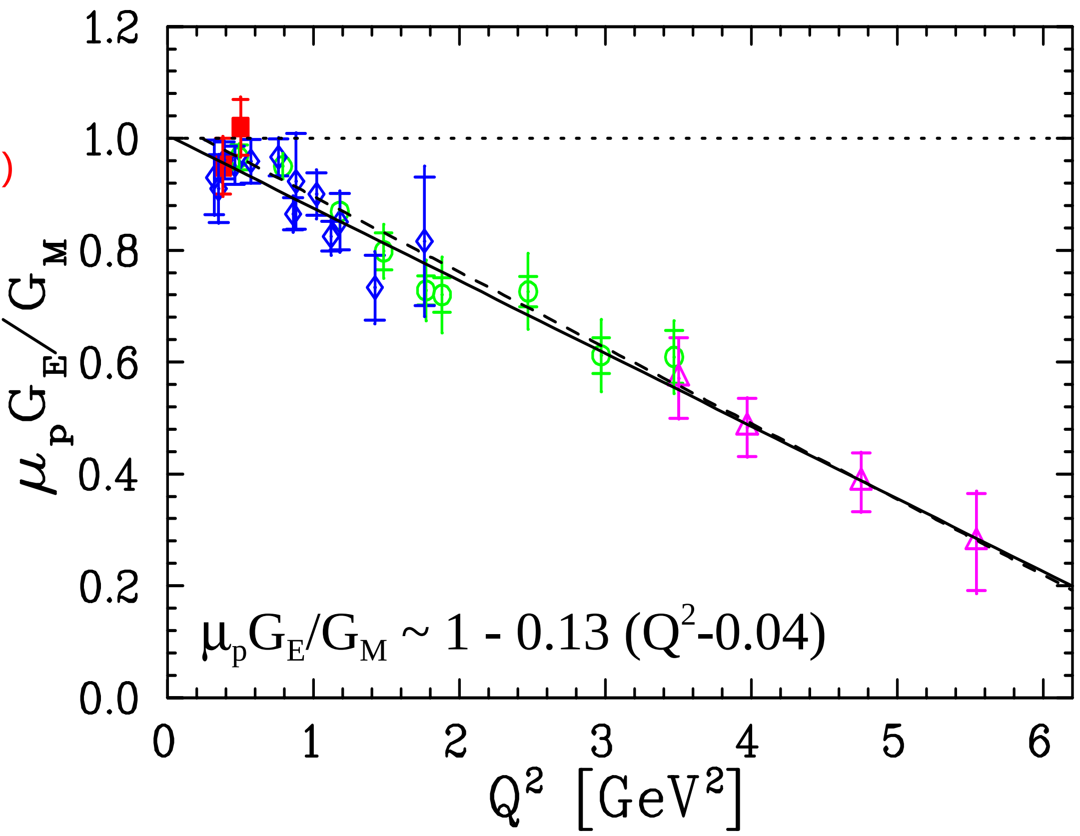
Also useful for neutron (where $G_E << G_M$, so L-T very difficult)

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

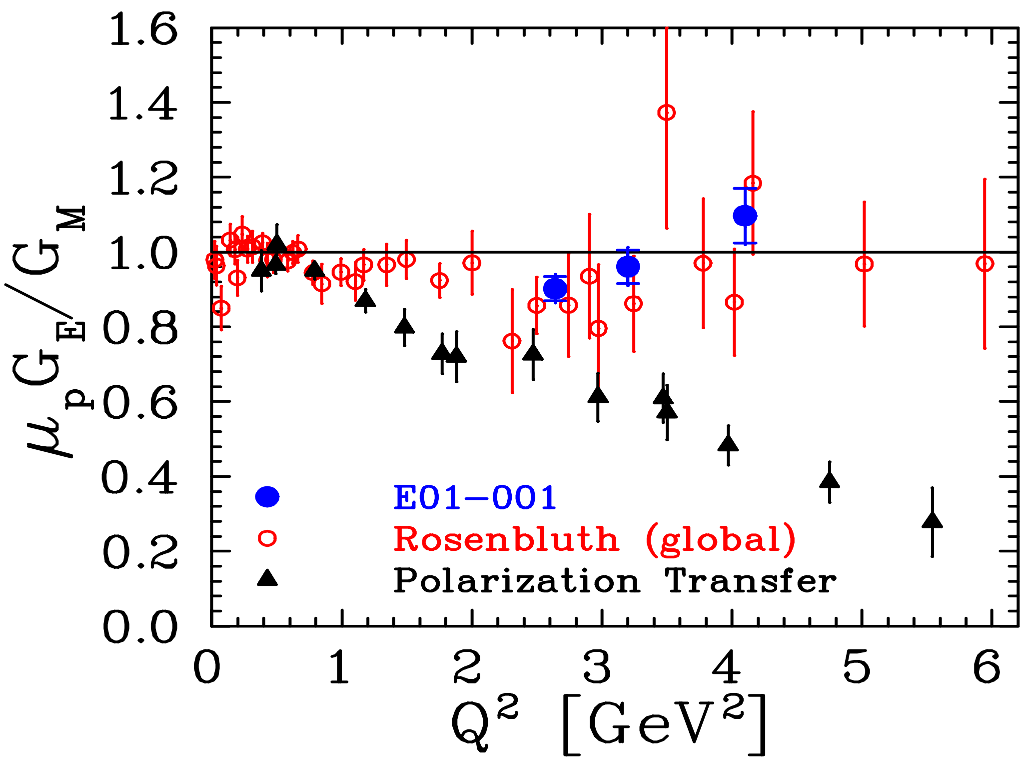
Articles in Science News, Physics Today, New York Times, USA Today, etc...

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., nucl-ex/0501018 (2005)
Polarization transfer: JLab E04-119, E04-108
Polarized target: JLab PR04-111

Two-photon exchange corrections

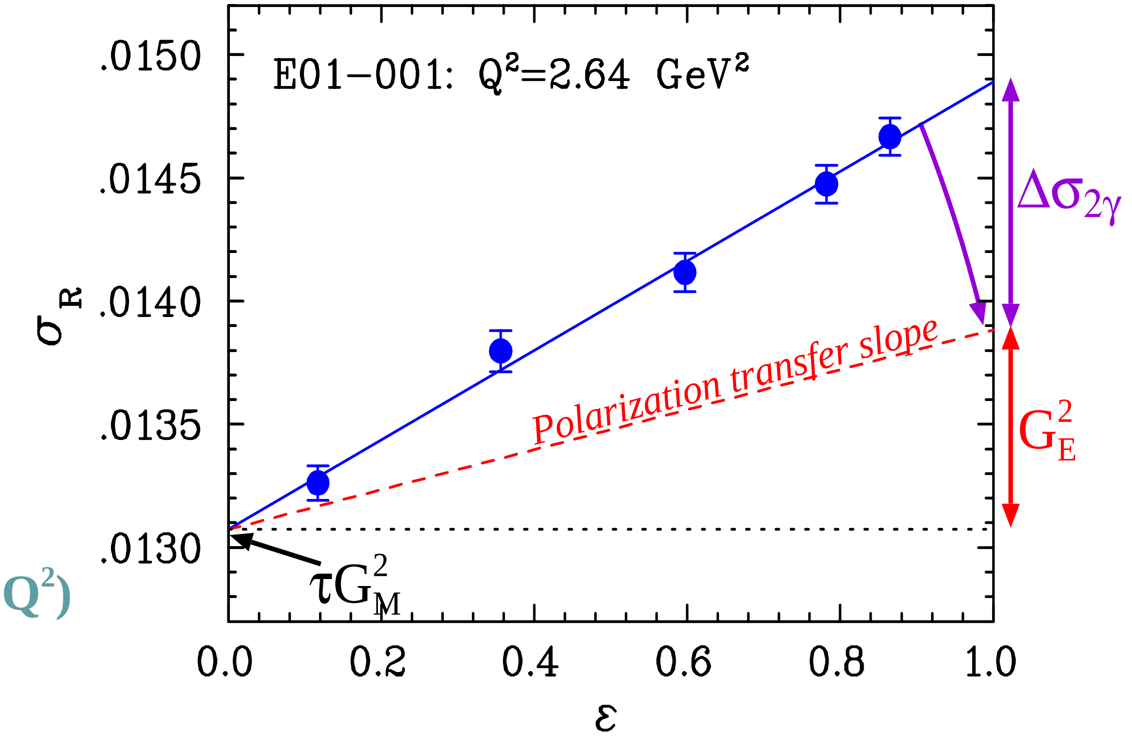
Two-photon exchange effects can explain the discrepancy in G_E

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)

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



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

There are still issues to be answered

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

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

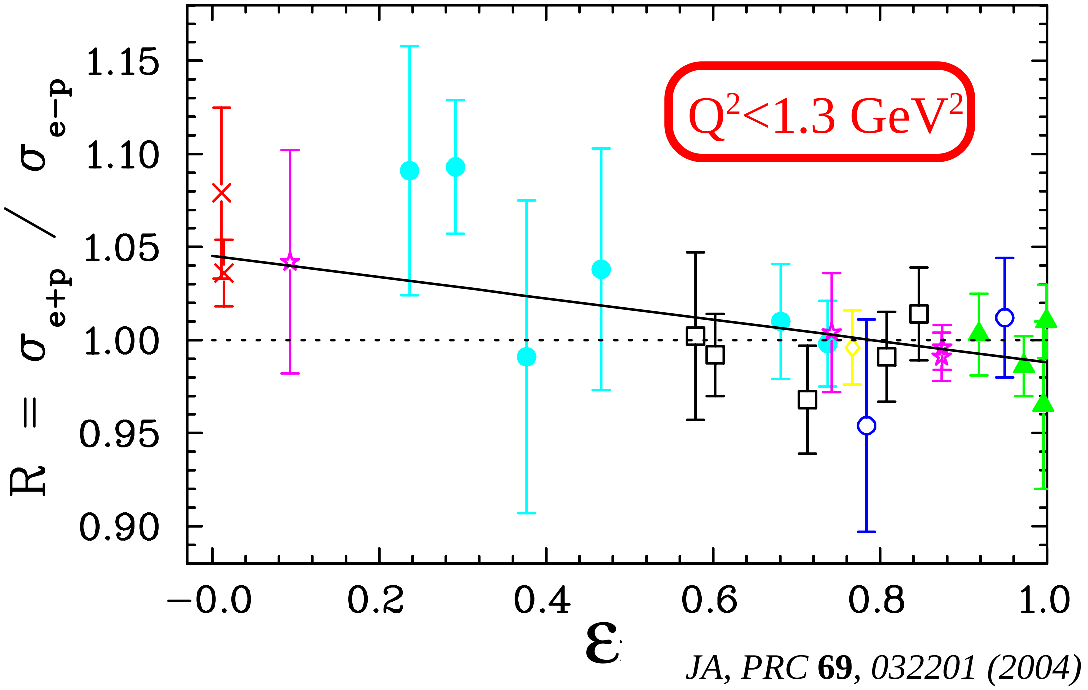
TPE effects on ***G_M***?

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***

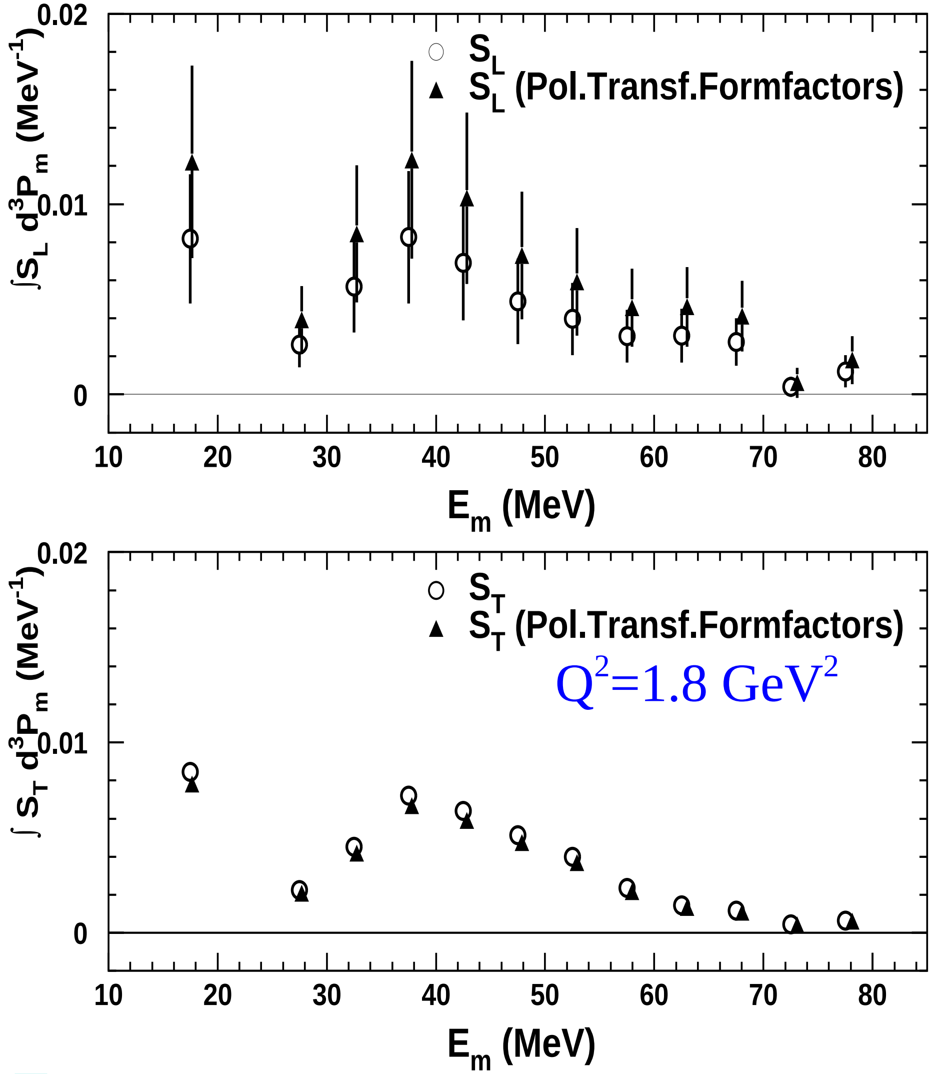
Impact of the discrepancy

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)

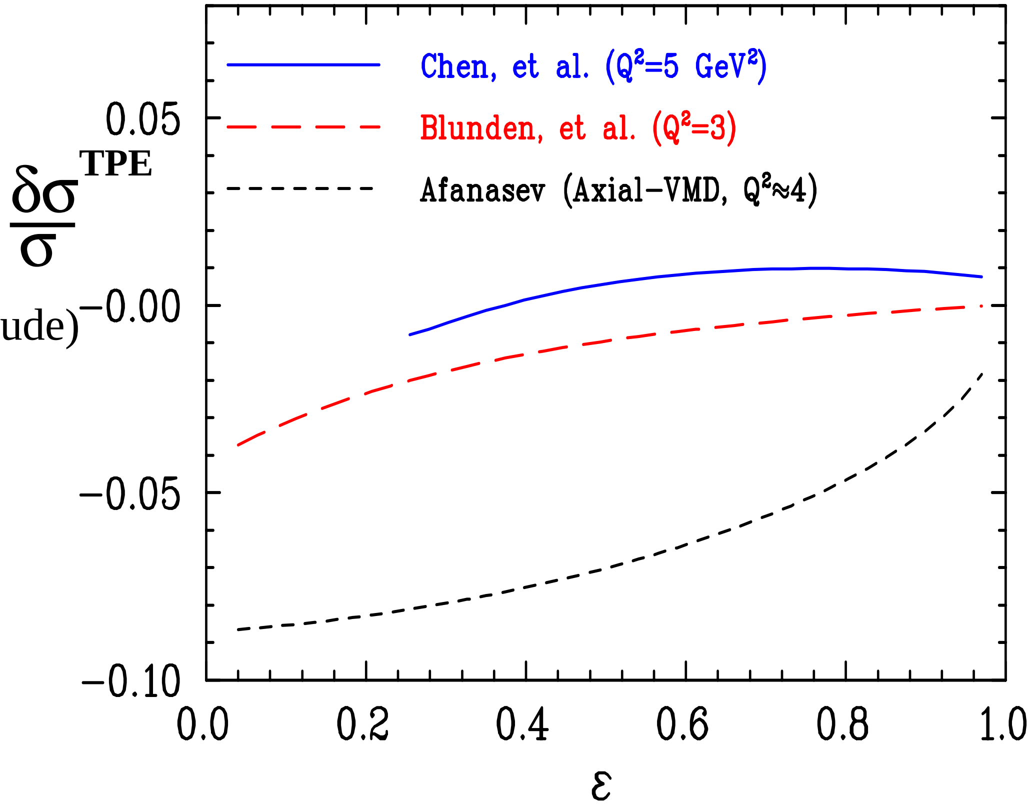
A ***mixture*** of form factors (G_M from LT, G_E from PT) is never correct, and will almost always give the largest error

Old (2004)
~~Modern~~ 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, photons interact with two different quarks
-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

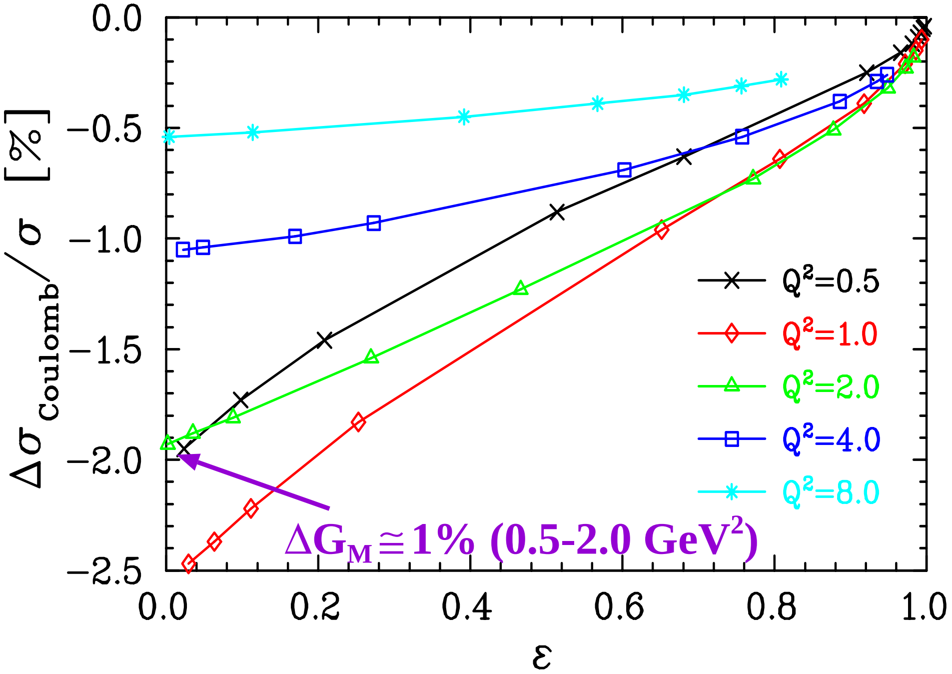
Coulomb distortion

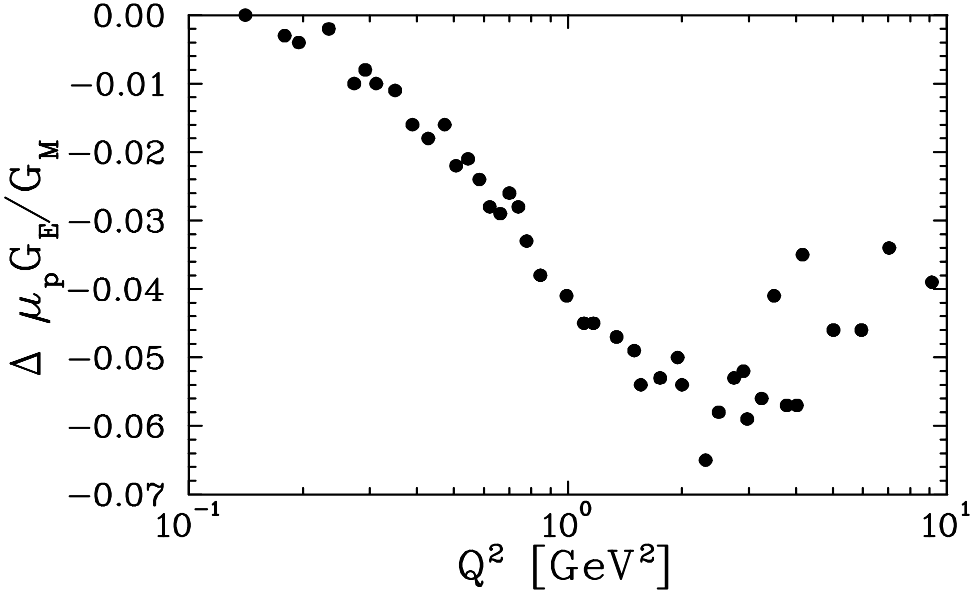
Other higher-order processes can also contribute - not just two-photon exchange

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

Two-photon corrections: Model-independent analysis

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

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

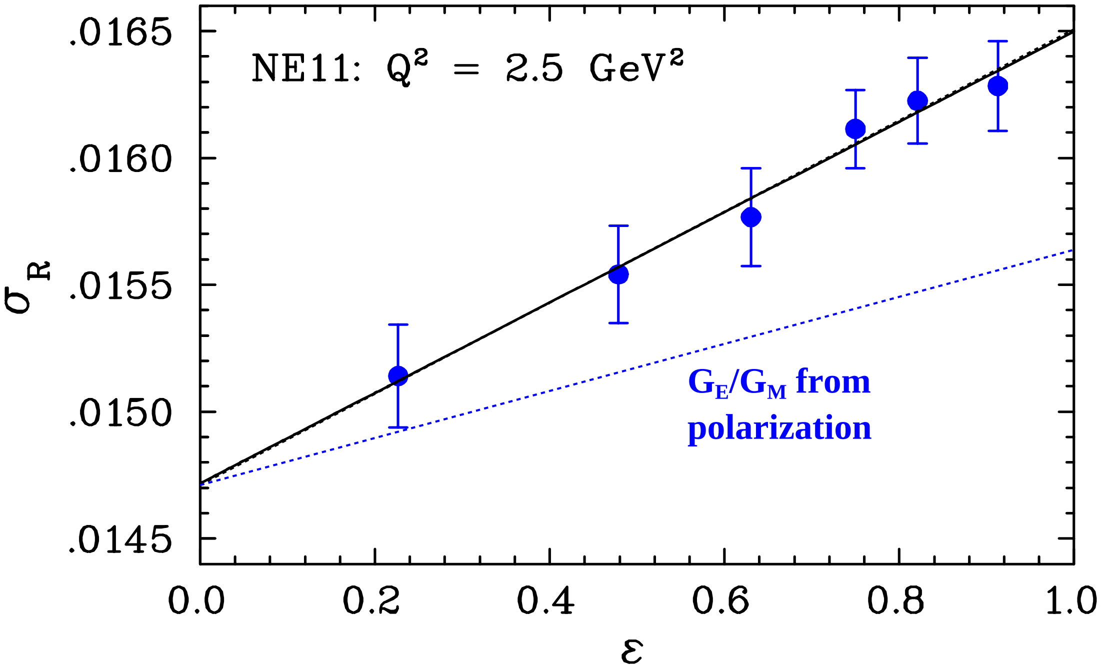
$$R_{poltrans} = (\widetilde{G}_E/\widetilde{G}_M) + (1-2\varepsilon/(1+\varepsilon)\widetilde{G}_E/\widetilde{G}_M)\, Y_{2\gamma}$$

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

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

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

$$\begin{aligned}
\widetilde{G}_E(\varepsilon,Q^2) &= G_E(Q^2) + \Delta G_E(\varepsilon,Q^2)\\
\widetilde{G}_M(\varepsilon,Q^2) &= G_M(Q^2) + \Delta G_M(\varepsilon,Q^2)\\
Y_{2\gamma}(\varepsilon,Q^2) &= \underset{\underset{\textbf{Born}}{\uparrow}}{0} + \underset{\underset{\textbf{TPE contribution}}{\uparrow}}{Y_{2\gamma}(\varepsilon,Q^2)}
\end{aligned}$$



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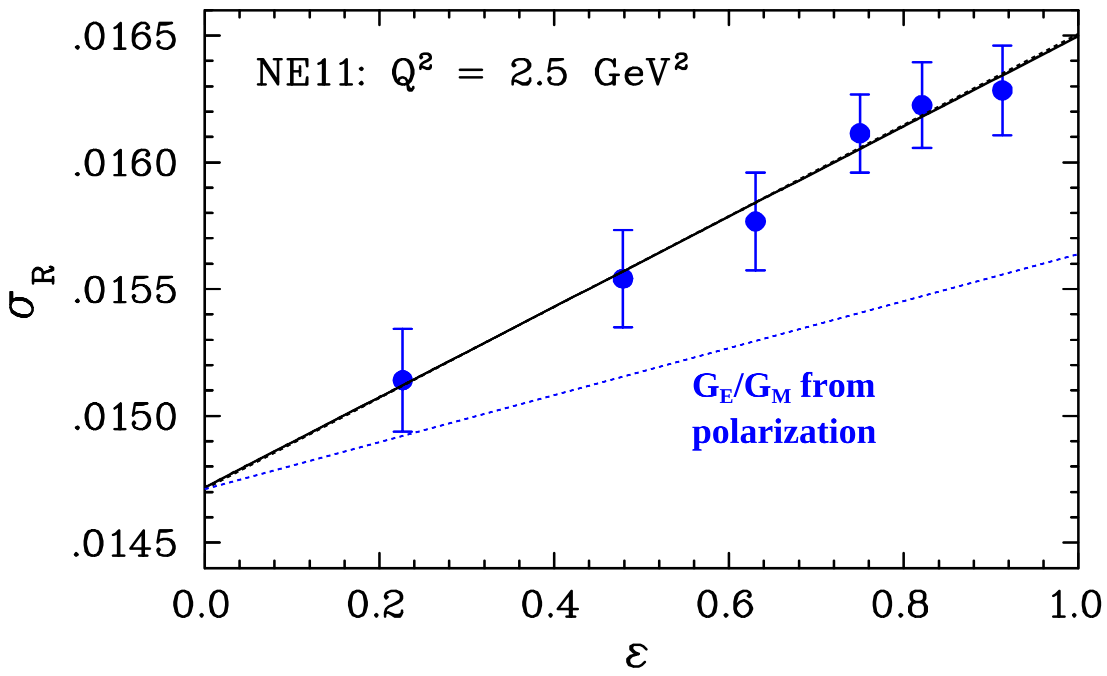
~ 0.05-0.10
small effect

ΔG_E term is strongly suppressed



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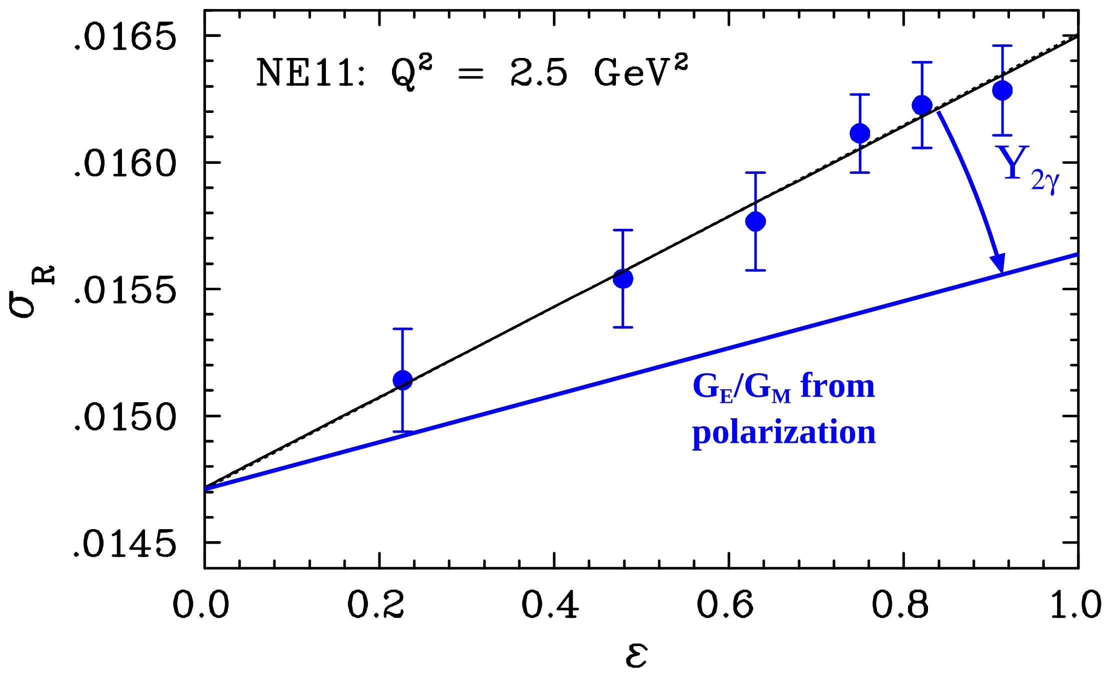
Δ**G_E** term is strongly suppressed

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



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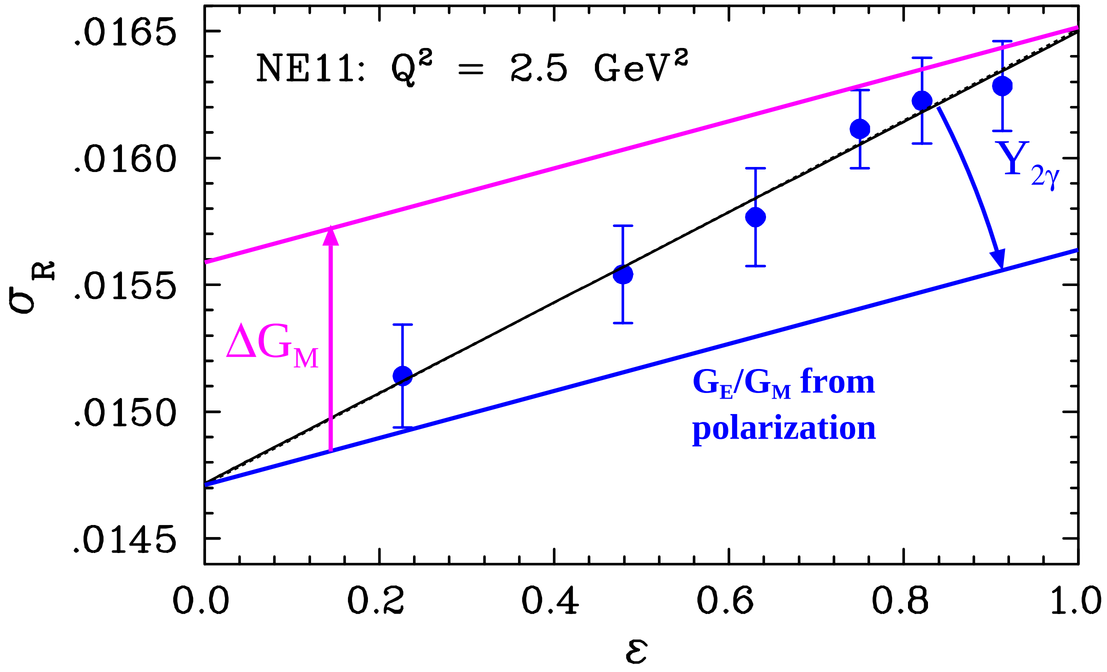
~ 0.05-0.10
small effect

Fixed by LT/PT
discrepancy

Δ**G**$_E$ 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*** $\Delta G_M/G_M$



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

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

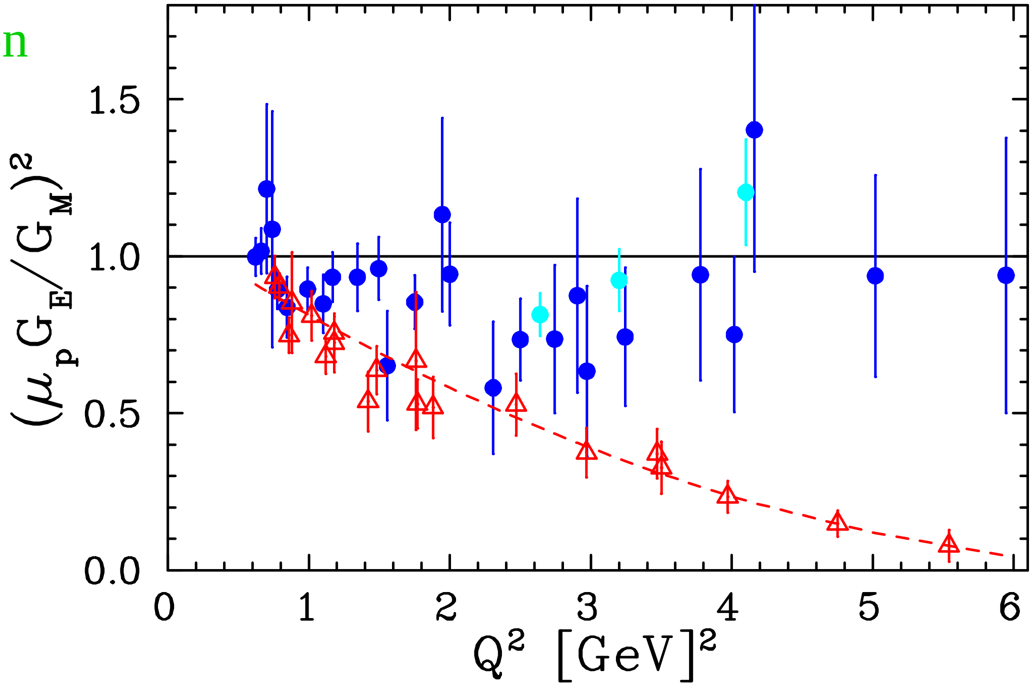
$\mathbf{\Delta G_M/G_M} \cong -\varepsilon(1+\rho/\tau)\ \mathbf{Y_{2\gamma}}$ $\quad (\rho = G_E/G_M)$

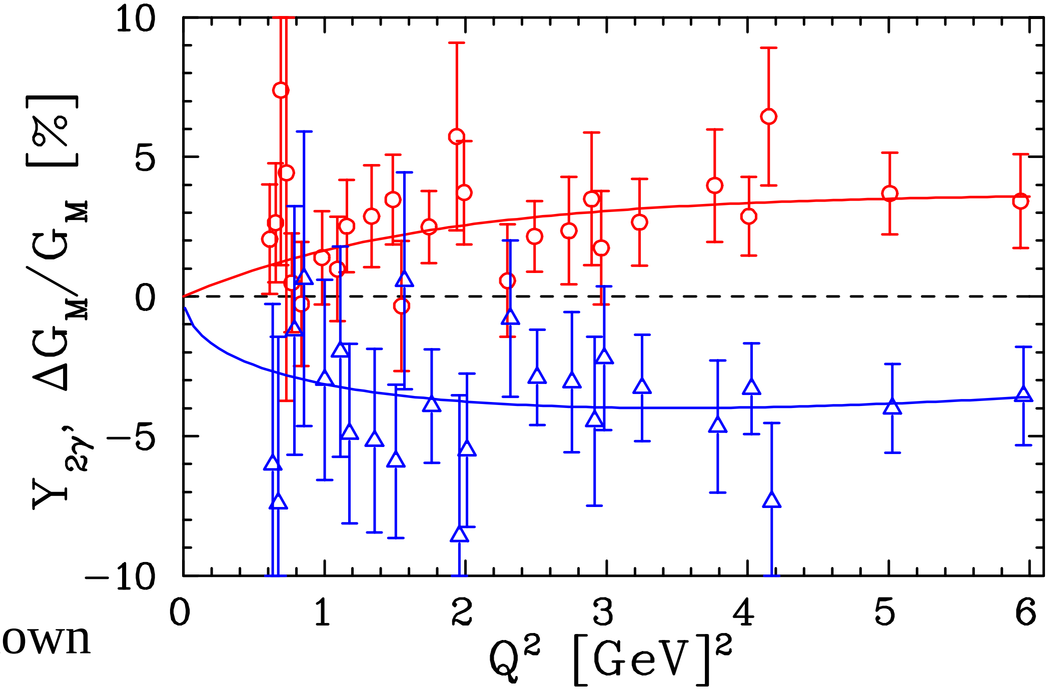
Significant corrections to G_E, G_M

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



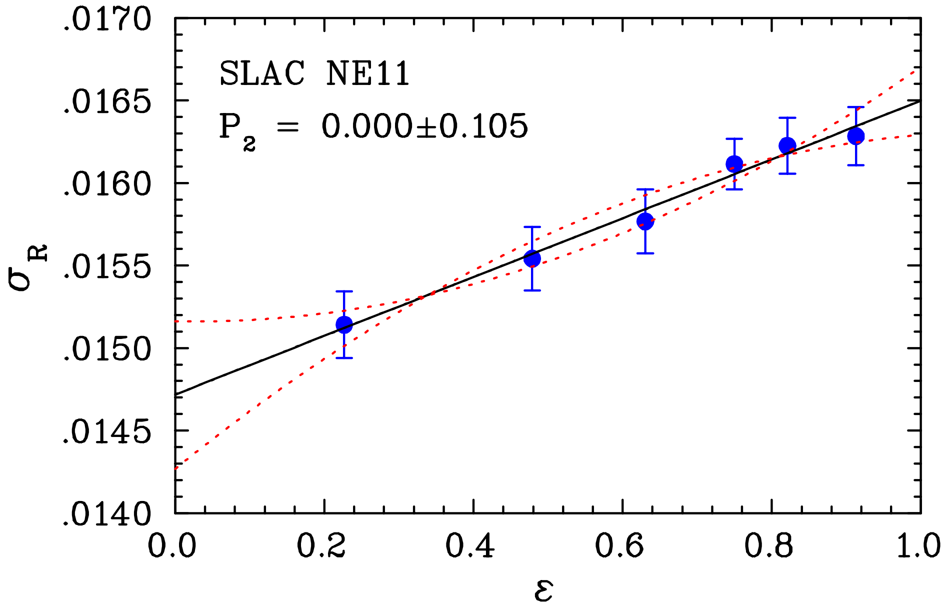


Additional uncertainties from ε-dependence

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 E01-001 limit)



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

Even the sign depends on ε-dependence

Emperical extractions:

$Y_{2\gamma}$=A, ΔG_M=B

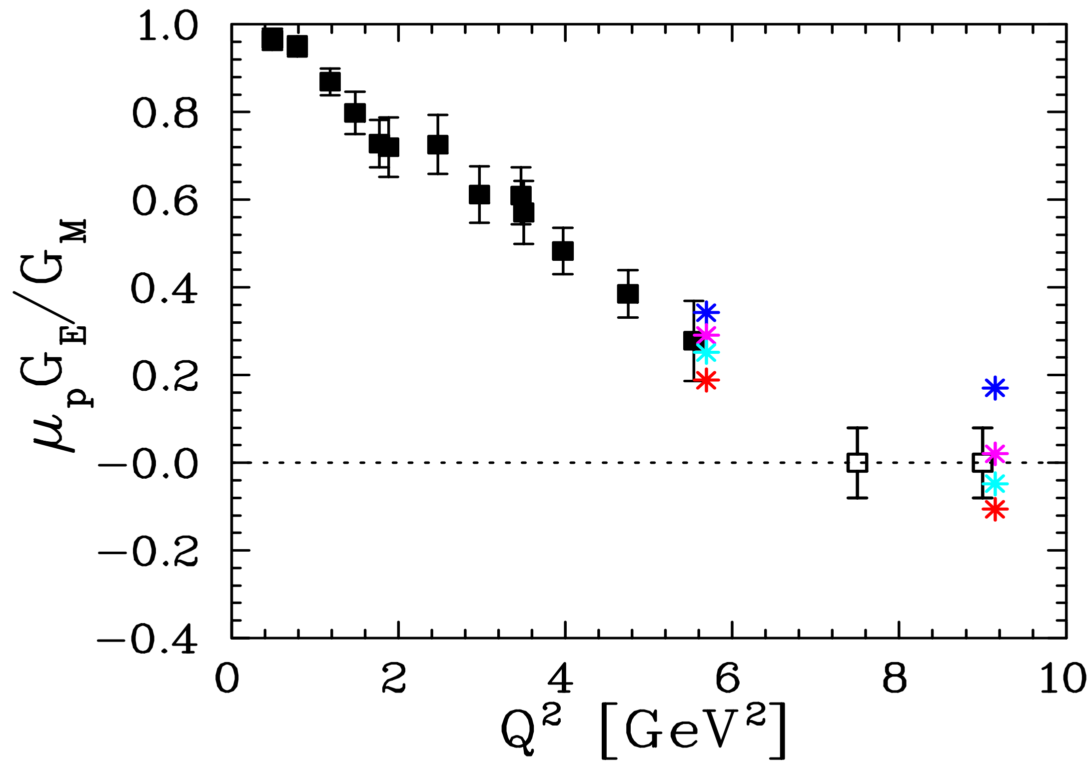
$Y_{2\gamma}$=A+B/ε, ΔG_M=0

(Both yield linear correction to σ_R)

Calculations:

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 [Talks by Blunden, Chen, Afanasev, Pascalutsa]

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

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

Real part of TPE amplitudes:

Positron-electron comparisons *(VEPP, JLab)*

[Talk by L. Weinstein]

-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...

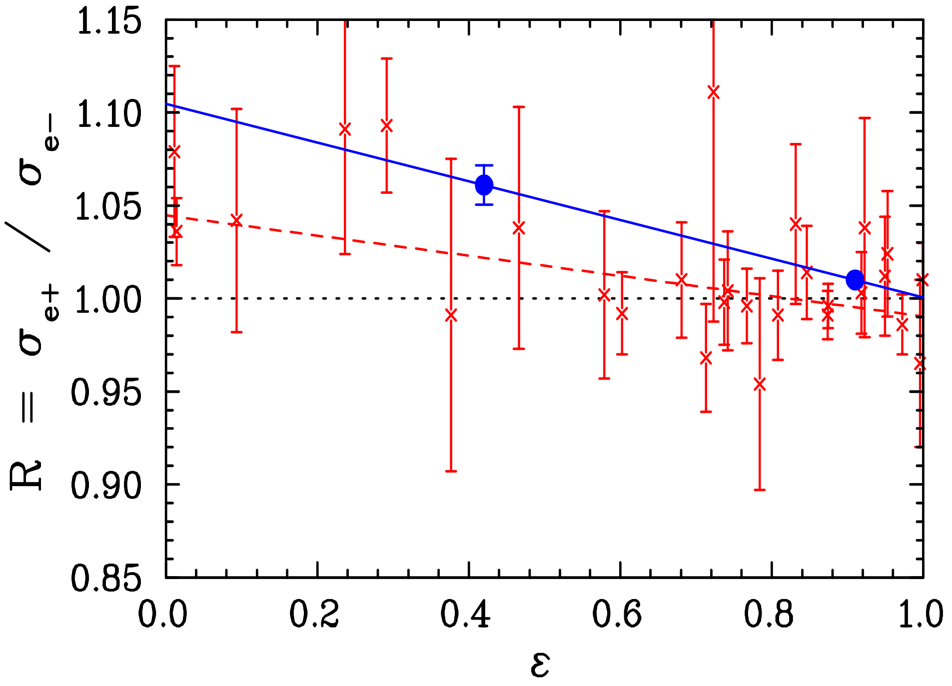
Approved experiment to measure A_y (target single spin asymmetry) from ^{3}He

[Talk by X.Jiang]

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



	$\langle Q^2 \rangle$	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%**

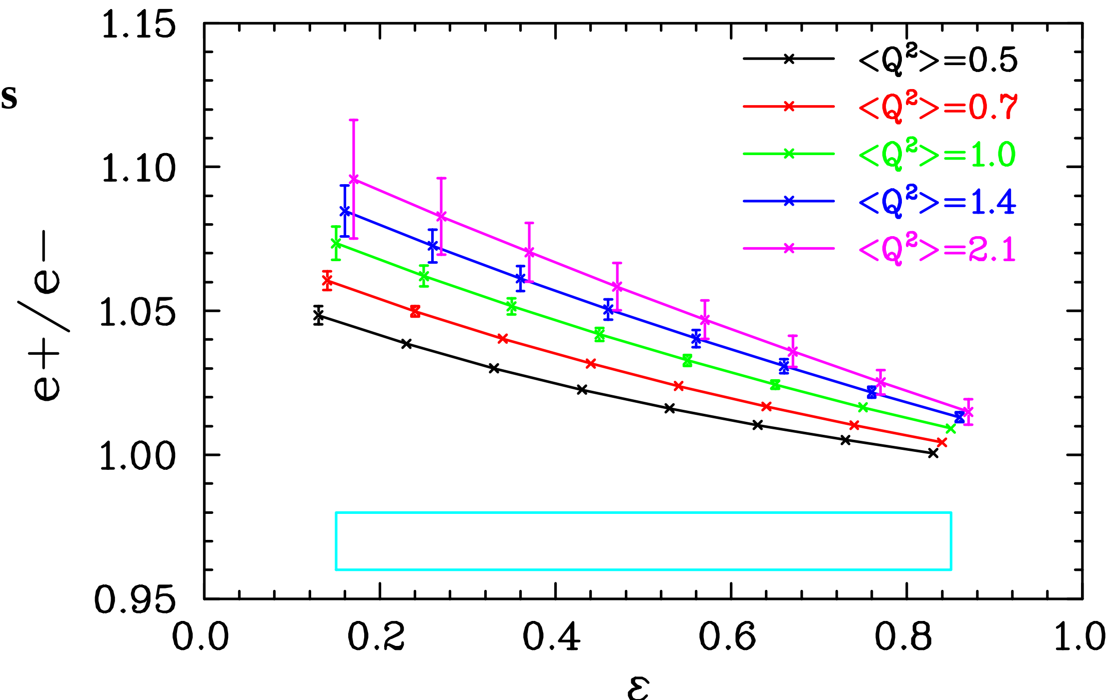
Projected slope based
on TPE amplitudes
from global extraction

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

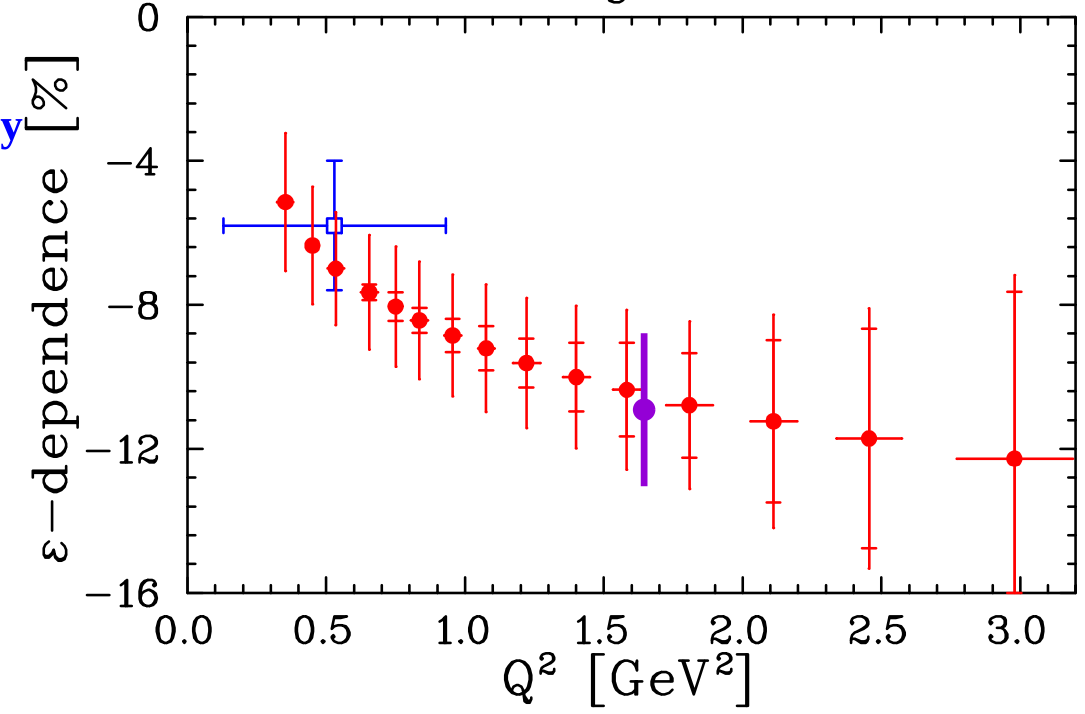
E04-116 (Hall B): positron- and electron-proton scattering



<u>1 μA beam</u> on <u>5% radiator</u> --> 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

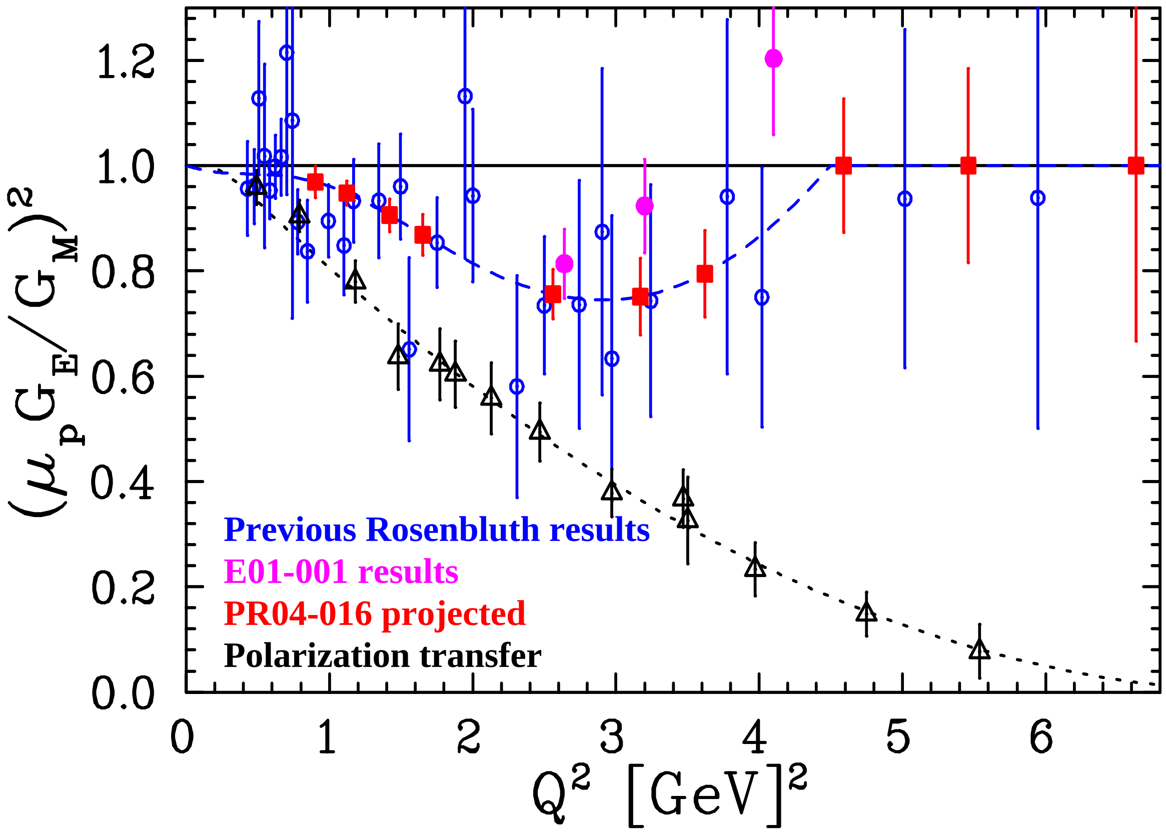
(as demonstrated by E01-001)

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

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

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

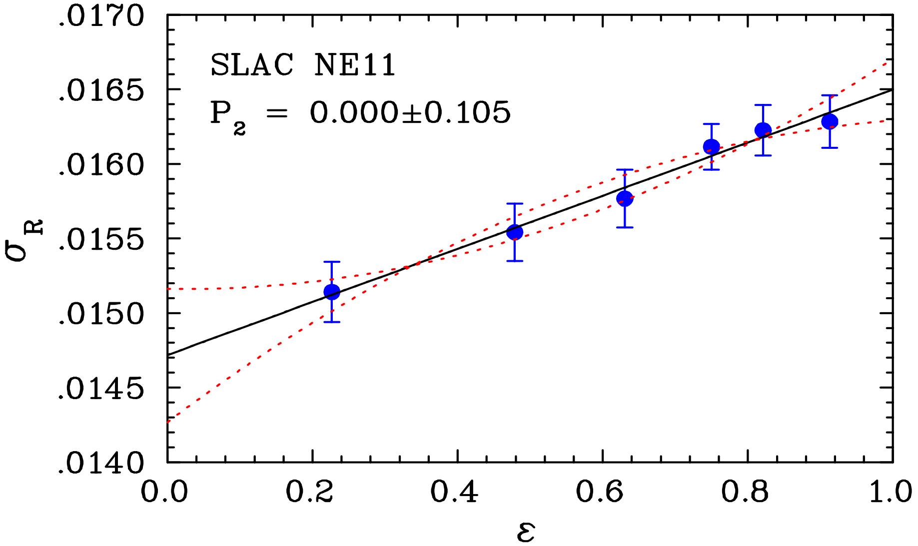
Fit to $\sigma_R = P_0 (1 + P_1\varepsilon + P_2\varepsilon^2)$

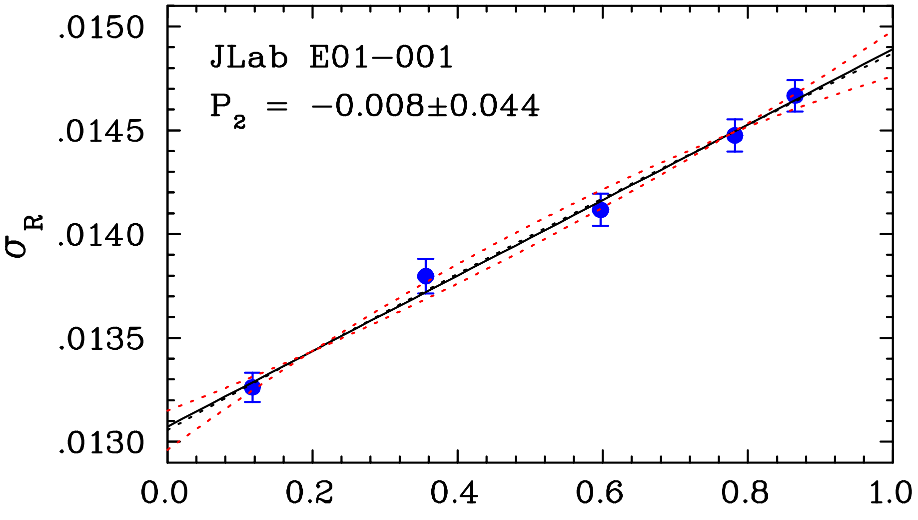
SLAC NE11 ⇨ P_2 = 0.000 +/– ***0.105***
(2.5 GeV^2)
$\delta\sigma$ (ε –> 0) = ***3.0%***

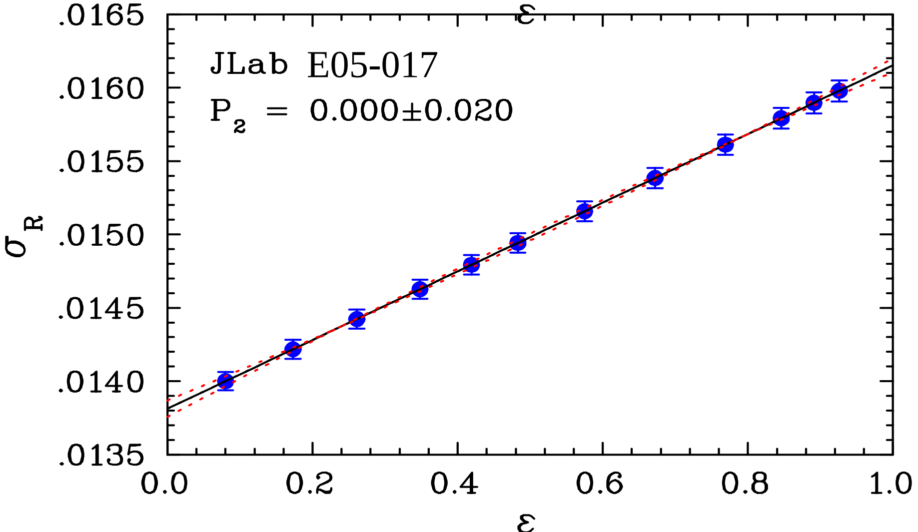
JLab E01-001 ⇨ P_2 = -0.008 +/– ***0.069***
(2.64 GeV^2)
$\delta\sigma$ (ε –> 0) = ***1.1%***

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

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





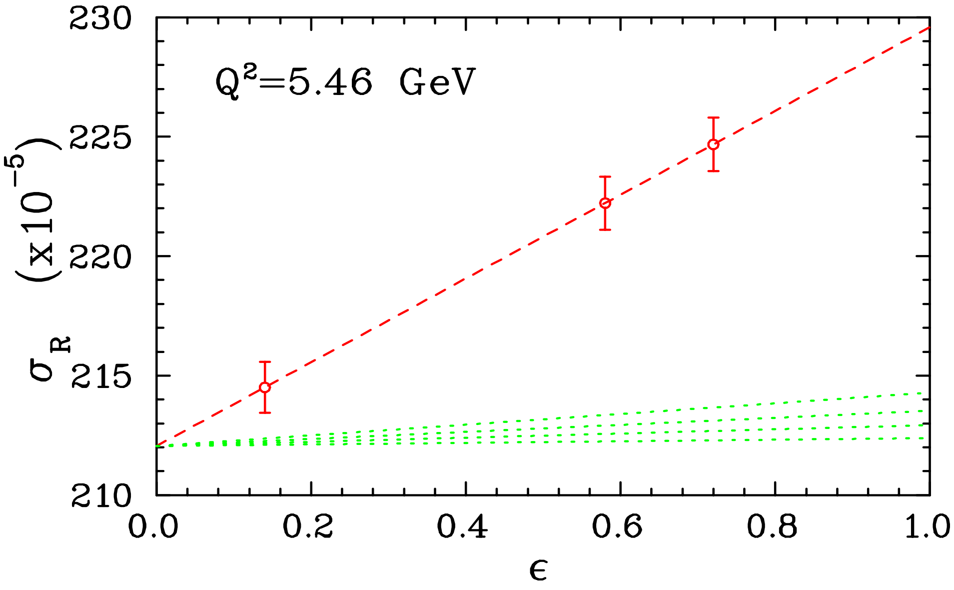


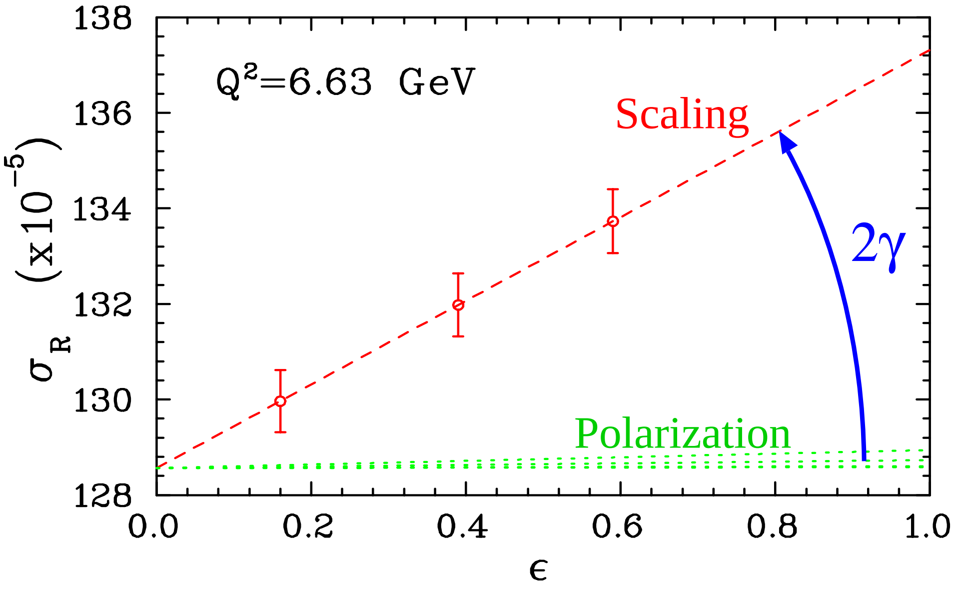
ε-dependence at lower (and higher) Q^2

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

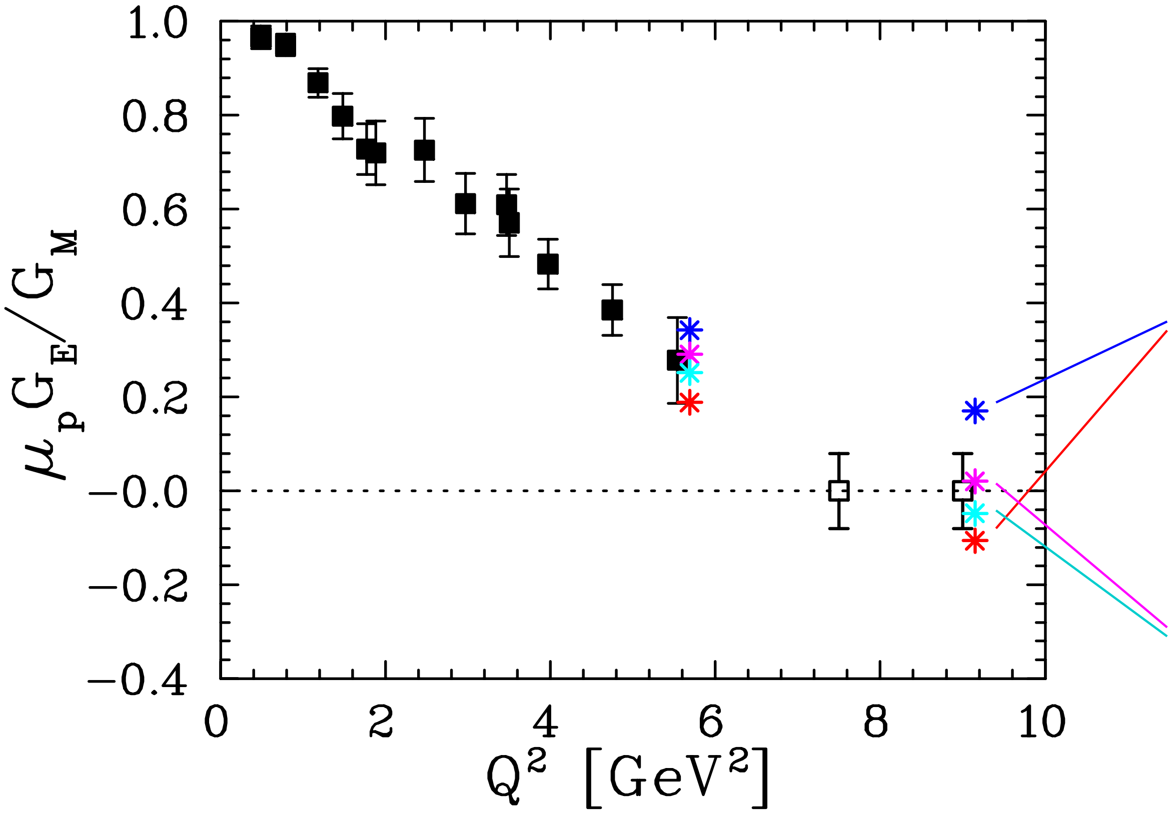
E04-019 (Hall C): ε dependence of polarization transfer

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

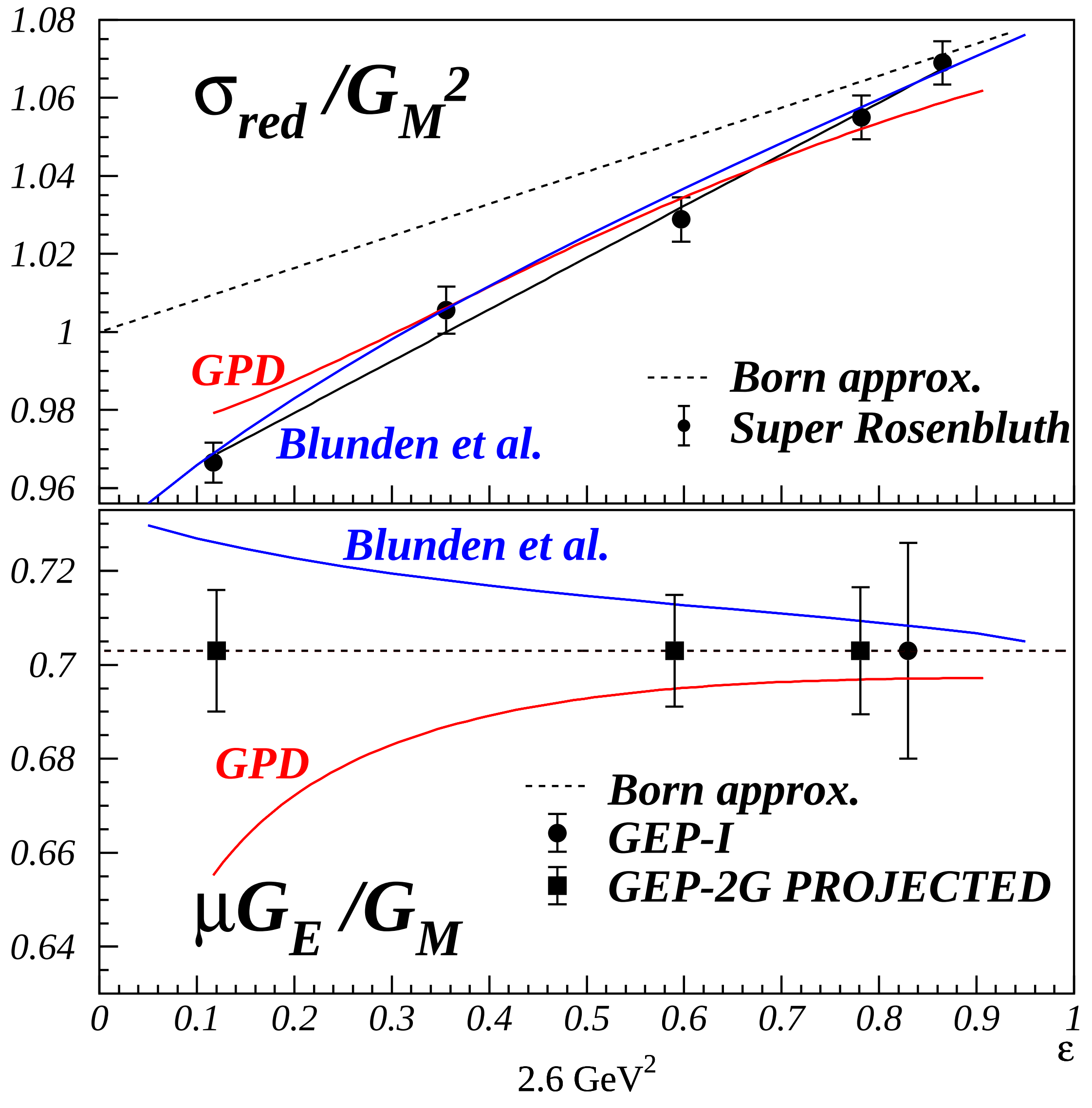
E04-019 (Hall C): ε dependence of polarization transfer

ε-independent TPE amplitudes yield linear effect on cross section,
but ΔG_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

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 twice 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

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!