Two-photon exchange: Experimental Overview

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

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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
$\varepsilon$-dependence of TPE effects: Cross section and polarization transfer
Rosenbluth extractions of $G_E$ and $G_M$

In the Born approximation:

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

\[ \tau = \frac{Q^2}{(2M)^2} \]

Initial Rosenbluth measurements consistent with form factor scaling

\[ G_M(Q^2) \equiv \mu_p G_E(Q^2) \]

For large $Q^2$ values, $\tau G_M^2$ dominates and $G_E^2$ becomes difficult to extract

Janssens et al., 1966

$Q^2 = 0.39 \text{ GeV}^2$

$\mu_p G_E / G_M = 1.061 \pm 0.058$
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

\[
R \equiv \frac{\sigma_{e^+}}{\sigma_{e^-}} = \frac{(A_{1\gamma} + A_{2\gamma})^2}{(A_{1\gamma} - A_{2\gamma})^2} \approx 1 + 4 \text{Re}(A_{2\gamma}/A_{1\gamma})
\]

- **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 \text{ 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

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

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

\[
P_N = 0
\]

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

\(G_E/G_M\) 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)

\(N. Dombey, Rev. Mod. Phys. 41, 236 (1969)\)
**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 factor of three at large \( Q^2 \)

Question about the form factors: as proton structure

Question about the form factors: as parameterization of \( \sigma_{ep} \) (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


Problem with polarization transfer technique? data?
Appears to be OK: systematics have been studied and will be checked in future independent measurements

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% $\varepsilon$-dependence, weakly dependent on $Q^2$, roughly linear in $\varepsilon$

$\tau G_M^2 (Q^2) + \varepsilon G_E^2 (Q^2)$

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

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: 
\[ \langle R \rangle_{e^+/e^-} = 1.003^{+0.005}_{-0.005} \]
\[ \langle R \rangle_{\mu^+/{\mu^-}} = 0.993^{+0.006}_{-0.006} \]

Problem: Data limited to low \( Q^2 \) or small \( \theta \) (\( \varepsilon > 0.7 \)) because of low luminosities

For \( Q^2 > 1.3 \), positron data only set limits for \( \varepsilon \approx 1 \)

Limited data at low \( \varepsilon \) shows evidence of \( \varepsilon \)-dependent TPE

NOTE: TPE effects appear to be largest at low \( \varepsilon \), so effect on \( G_M \) cannot be ignored
Impact of the discrepancy

Some cases need form factors to give cross section (including TPE)

*Experiment normalizations
*Cross sections as input to analysis, e.g. A(e,e’p)


Rosenbluth form factors $\rightarrow S_L \equiv S_T$

Polarization transfer form factors $\rightarrow S_L \sim 60\%$ 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: $\nu$-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 $\varepsilon$ values

**A. Afanasev, private communication**
- Axial-VMD model
- Provides $\varepsilon$-dependence (arbitrary magnitude)
- Out of date, included for completeness

My summary:
1) Calculations differ in magnitude and $\varepsilon$-dependence, but rapidly improving
2) **All show small effects at large $\varepsilon$**
   - All show decrease at low $\varepsilon$
   - All 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 $\alpha$.

Effects are generally small, but do have a significant $\epsilon$-dependence.

* Explains much (most?) of the low-$Q^2$ positron/electron ratio.
* Can explain up to 30-40% of the discrepancy for $Q^2 \approx 1$ GeV$^2$.
* Only explains a small part of the discrepancy above 3-4 GeV$^2$.

$\Delta G_M \approx 1\%$ (0.5-2.0 GeV$^2$)

Two-photon corrections: Model-independent analysis

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

$R_{\text{poltrans}} = \frac{\tilde{G}_E}{\tilde{G}_M} + \left(1 - \frac{2\varepsilon}{1+\varepsilon}\right)\frac{\tilde{G}_E}{\tilde{G}_M} Y_{2\gamma}$  

$R_{\text{Rosen}} = \left(\frac{\tilde{G}_E}{\tilde{G}_M}\right)^2 + 2 \left(\tau + \frac{\tilde{G}_E}{\tilde{G}_M}\right) Y_{2\gamma}$  

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

$\tilde{G}_E(\varepsilon,Q^2) = G_E(Q^2) + \Delta G_E(\varepsilon,Q^2)$  
$\tilde{G}_M(\varepsilon,Q^2) = G_M(Q^2) + \Delta G_M(\varepsilon,Q^2)$  
$Y_{2\gamma}(\varepsilon,Q^2) = 0 + Y_{2\gamma}(\varepsilon,Q^2)$

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

$R = \frac{G_E}{G_M}$ as extracted in one-photon formalism assuming $\varepsilon$-independent amplitudes  
(convenient, but not necessary)

\[ NE11: Q^2 = 2.5 \text{ GeV}^2 \]
Two-photon corrections: Model-independent analysis

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

\[ R_{\text{poltrans}} = \left( \frac{G_E}{G_M} \right) + \left( 1 - \frac{2\epsilon}{1+\epsilon} \right) \frac{G_E}{G_M} Y_{2\gamma} \]

\[ R_{\text{Rosen}} = \left( \frac{G_E}{G_M} \right)^2 + 2(\epsilon + \frac{G_E}{G_M}) Y_{2\gamma} \]

\[ R = G_E/G_M \text{ as extracted in one-photon formalism} \]

\[ \Delta G_E/G_M \text{ term is strongly suppressed} \]

\[ \Delta \sigma_{R}/G_M^2 \sim 2\pi \tilde{G}_M + 2\epsilon(\tau + G_E/G_M) Y_{2\gamma} \]

\[ \Delta \sigma_{R}/G_M^2 \sim 0.05-0.10 \text{ small effect} \]

\[ \Delta G_E/G_M \text{ from polarization} \]

NE11: \( Q^2 = 2.5 \text{ GeV}^2 \)


No significant uncertainty in \( G_M(e, Q^2) \) extraction (\( G_E \) has no effect on \( \sigma \) at low \( \epsilon \))

\( \Delta G_E/G_E \) is presumably also \( \sim 2-3\% \), well below the experimental uncertainties on \( G_E \) (4-10\%)

Don't need to know \( \Delta G_E/G_E \) to extract form factors, unless \( \Delta G_E/G_E, \Delta G_M/G_M, Y_{2\gamma} > > G_E/G_M \) from polarization

Two-photon corrections: Model-independent analysis
Two-photon corrections: Model-independent analysis

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

$R_{\text{poltrans}} = \left( \frac{G_E}{G_M} \right) + \left( 1 - \frac{2\epsilon}{1+\epsilon} \right) \frac{G_E}{G_M} Y_{2\gamma}$

$R_{\text{Rosen}} = \left( \frac{G_E}{G_M} \right)^2 + 2 \left( \tau + \frac{G_E}{G_M} \right) Y_{2\gamma}$

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

$\Delta G_E$ term is strongly suppressed

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

$R = \frac{G_E}{G_M}$ as extracted in one-photon formalism


Don't need to know $\Delta G_E$ to extract form factors, unless $\Delta G_E / G_E \approx \Delta G_M / G_M$, $Y_{2\gamma} > >$
Two-photon corrections: Model-independent analysis

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

$R_{\text{poltrans}} = \left( \frac{G_E}{G_M} \right) + \left( 1 - \frac{2\epsilon}{1+\epsilon} \right) \frac{G_E}{G_M} Y_{2\gamma}$

$R_{\text{Rosen}}^2 = \left( \frac{G_E}{G_M} \right)^2 + 2 \left( \tau \frac{G_E}{G_M} \right) Y_{2\gamma}$

$\frac{\Delta\sigma_R}{G_M^2} \approx 2\tau \frac{\Delta G_M}{G_M} \frac{G_E}{G_M} + 2\epsilon (\tau + \frac{G_E}{G_M}) Y_{2\gamma}$

Fixed by LT/PT discrepancy

$\Delta G_E$ term is strongly suppressed

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

e+/e− requires $\Delta\sigma_{2\gamma} \equiv 0$ at $\epsilon = 1$,

--> constrains $\Delta G_M/G_M$

Assuming knowledge of the $\epsilon$-dependence, we basically have two unknown amplitudes and two observables

$P.A.M.\text{Guichon and M. Vanderhaeghen, PRL 91, 142303 (2003)}$

$\Delta G_M$ from polarization

NE11: $Q^2 = 2.5$ GeV$^2$

$\sigma_R \approx 0.05$-0.10 small effect
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

\[ \frac{Δ G_M}{G_M} \approx -ε(1+ρ/τ) \]

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

$\Delta G_M$ determined by $e^+/e^-$ constraint:

$\Delta σ \equiv 0$ at large $ε$

$\Delta G_M/G_M \equiv -ε(1+ρ/τ) \ Y_{2\gamma}$  ($ρ=G_F/G_M$)

$Y_{2\gamma}$ extracted from the difference between $R_{LT}$ and $R_{Pol}$

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

\[ (\sigma_M/E^2) \]

JA, PRC 71, 015202 (2005)
Additional uncertainties from $\varepsilon$-dependence

Nonlinearity leads to uncertainty in extrapolation to $\varepsilon=0$, extraction of $G_M^{\text{TPE}}$

- $\delta G_M^{\text{TPE}} = 3.0\%$ (best SLAC limit)
- $\delta G_M^{\text{TPE}} = 1.1\%$ (best E01-001 limit)

Correction to polarization transfer ($G_E$) is extremely sensitive to $\varepsilon$-dependence

Even the sign depends on $\varepsilon$-dependence

**Emperical extractions:**
- $Y_{2\gamma}=A$, $\Delta G_M = B$
- $Y_{2\gamma}=A+B/\varepsilon$, $\Delta G_M = 0$
  (Both yield linear correction to $\sigma_R$)

**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 ($\sim 1-1.5\%$)
Additional uncertainty due to possible non-linearities at low $\varepsilon$ ($\sim 1\%$)

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

$G_E$: Main uncertainty in $\varepsilon$-dependence of TPE amplitudes

- Measure $\varepsilon$-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*)
  - Clean extraction of two-photon terms
  - Map out $Q^2$ and $\varepsilon$ dependence of $\Delta\sigma^{TPE}$
  - Can test TPE explanation
  - Map out TPE for $Q^2 < 1-2$ GeV$^2$

- **Precise e-p elastic cross sections** (*JLab*)
  - $\varepsilon$-dependence of cross section
  - Map out TPE for $Q^2 > 1-2$ GeV$^2$

- **Polarization transfer**: $P_1/P_t$ (*JLab*)
  - $\varepsilon$-dependence of polarization ratio

**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

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

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$^2$

World’s e+/e- data
Novosibirsk e+/e-

<table>
<thead>
<tr>
<th>$&lt;Q^2&gt;$</th>
<th>e+/e- slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 GeV$^2$</td>
<td>5.8 +/- 1.8%</td>
</tr>
<tr>
<td>1.6 GeV$^2$</td>
<td>10.4 +/- 2.2%</td>
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</table>

Projected slope based on TPE amplitudes from global extraction
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
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)


LT-PT comparisons provide $\Delta \sigma^{\text{TPE}}$ 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 $\Delta \sigma^{\text{TPE}}$

Reduce TPE uncertainties on $G_M$ by factor of 2-3 for all $Q^2$

*at or below the experimental uncertainties* (if $\varepsilon$-dependence known)

Final step: better knowledge of $\varepsilon$-dependence of amplitudes
E05-017: $\varepsilon$ dependence of $\Delta \sigma^{\text{TPE}}$

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**

$P_2 = 0.000 \pm 0.105$

$\delta \sigma (\varepsilon \rightarrow 0) = 3.0\%$

**JLab E01-001**

$P_2 = -0.008 \pm 0.069$

$\delta \sigma (\varepsilon \rightarrow 0) = 1.1\%$

**JLab E05-017**

$P_2 = \text{???} \pm 0.020$

$\delta \sigma (\varepsilon \rightarrow 0) = 0.4\%$

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 $\Delta \sigma^{\text{TPE}}$.

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, $G_E \longrightarrow 0$ and the ε-dependence is almost entirely from TPE.

*Extraction of TPE is almost as clean as in the e+/e- comparison.*
\[ \Delta G_M, \ Y_{2\gamma} \text{ both } \varepsilon\text{-independent yields linear effect on cross section} \]

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

These are \textit{indistinguishible} in the cross section, but yield different corrections to polarization transfer
E04-019 (Hall C): \( \varepsilon \) dependence of polarization transfer

\( \varepsilon \)-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 \textit{indistinguishible} in the cross section, but yield different corrections to polarization transfer.

E04-019: Measure \( \varepsilon \) dependence of \textit{polarization transfer} result

Very different sensitivity to \( \varepsilon \)-dependence of \( Y_{2\gamma}, \Delta G_M \)
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 $\epsilon$-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 $\rightarrow$ $\Delta$ 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 $\rightarrow$ TPE is $\sim 50\%$ of e-p $[(\mu_n/\mu_p)^2]$.

For $Q^2 \lesssim 1 \text{ GeV}^2$, $G_E^n$ 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% (**$\sim 10\%$ 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**

$K. \text{Aniol, et al., PRC69:065501 (2004)}$

Global analysis: $\Delta G_{E}^{2\gamma} = 7.5\%$ at $Q^2=0.5 \text{ GeV}^2$.

- **$1.2 \text{ ppm change in physics asymmetry}$** (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: $B(Q^2)$**

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

- 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 $^3\text{He}$ - can’t isolate $G_E$.

There are many reactions where TPE might be important (>1-2$\sigma$), 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 measurements can we make?
  DICS [see Bogdan’s talk]

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