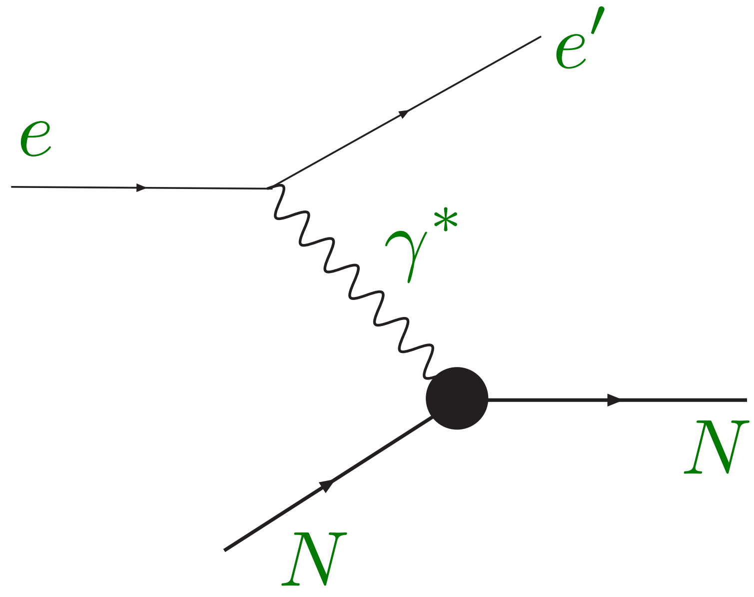
Outline

Lecture 3

- Elastic *ep* scattering
- Two-photon exchange
  - $\longrightarrow$ Rosenbluth separation *vs.* polarization transfer
- Global analysis of form factors
- Parity-violating electron scattering
  - $\longrightarrow$ strangeness in the proton
  - $\longrightarrow$ constraints on “new” physics

Elastic scattering

Elastic eN scattering



Elastic cross section

$$\frac{d\sigma}{d\Omega} = \sigma_{\text{Mott}} \; \frac{\tau}{\varepsilon \; (1+\tau)} \; \sigma_R$$

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

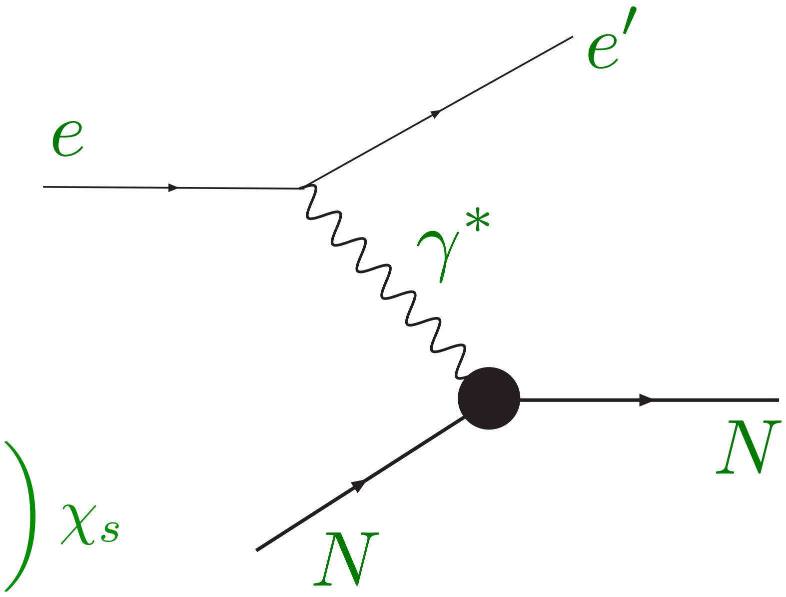
$$\varepsilon = \left(1 + 2(1+\tau)\tan^2(\theta/2)\right)^{-1}$$

$$\sigma_{\text{Mott}} = \frac{\alpha^2 E' \cos^2\frac{\theta}{2}}{4E^3 \sin^4\frac{\theta}{2}}$$ ← cross section for scattering from point particle

$$\sigma_R = G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$ ← reduced cross section

$G_E \;,\; G_M$ ← Sachs electric and magnetic form factors

Elastic eN scattering



In Breit frame

$$\nu = 0\ , \quad Q^2 = \vec{q}^{\,2}$$

electromagnetic current is

$$\bar{u}(p', s')\Gamma^\mu u(p, s) = \chi^\dagger_{s'} \left(G_E + \frac{i\vec{\sigma} \times \vec{q}}{2M} G_M \right) \chi_s$$

cf. classical (<u>N</u>on-<u>R</u>elativistic) current density

$$J^{\mathrm{NR}} = \left(e\ \rho_E^{\mathrm{NR}}\ ,\ \mu\ \vec{\sigma} \times \vec{\nabla} \rho_M^{\mathrm{NR}} \right)$$

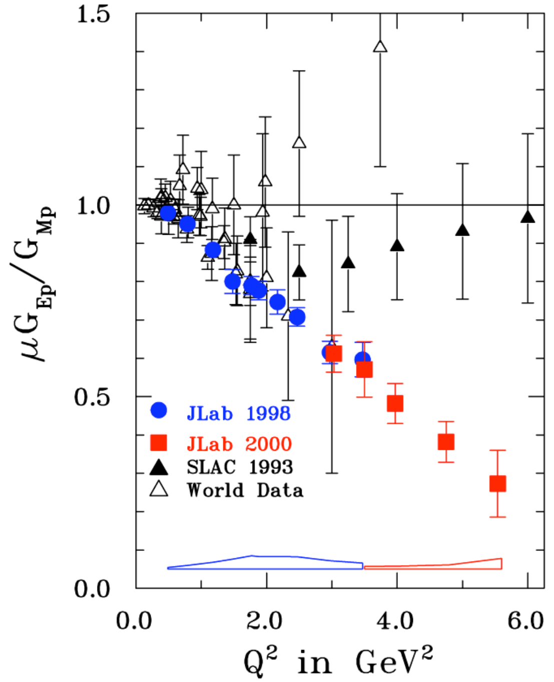
$$\rho_E^{\mathrm{NR}}(r) = \frac{2}{\pi} \int_0^\infty dq\ \vec{q}^{\,2}\ j_0(qr)\ G_E(\vec{q}^{\,2}) \longleftarrow \boxed{\textit{charge density}}$$

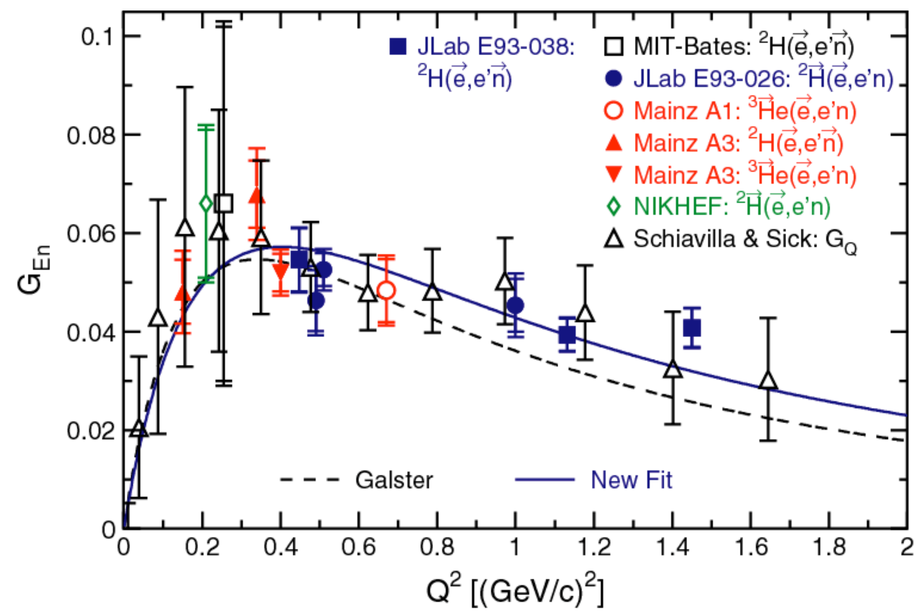
$$\mu\ \rho_M^{\mathrm{NR}}(r) = \frac{2}{\pi} \int_0^\infty dq\ \vec{q}^{\,2}\ j_0(qr)\ G_M(\vec{q}^{\,2}) \longleftarrow \boxed{\textit{magnetization density}}$$

proton

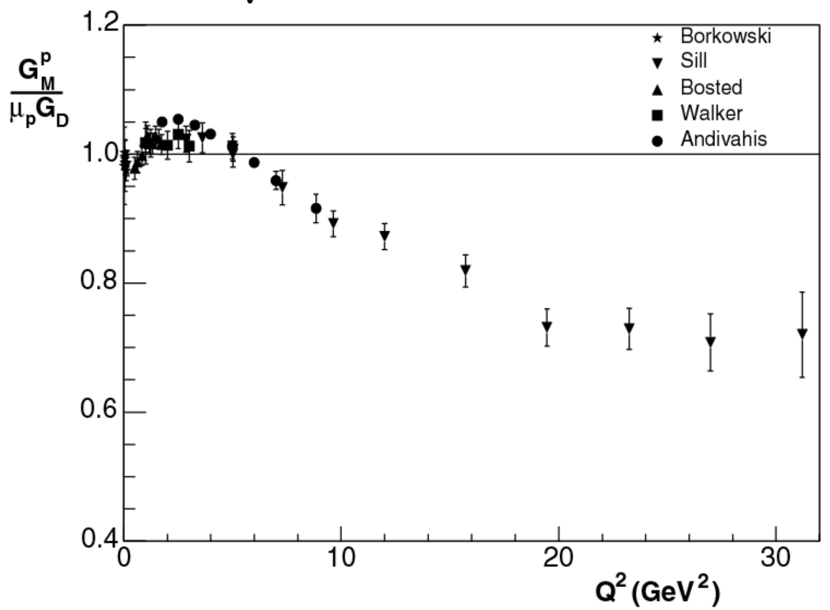
neutron

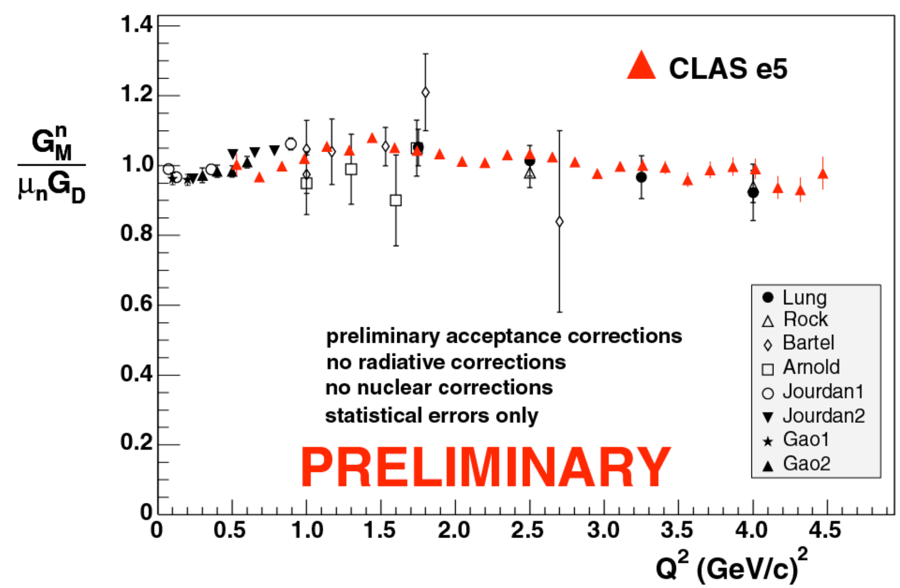
Electric



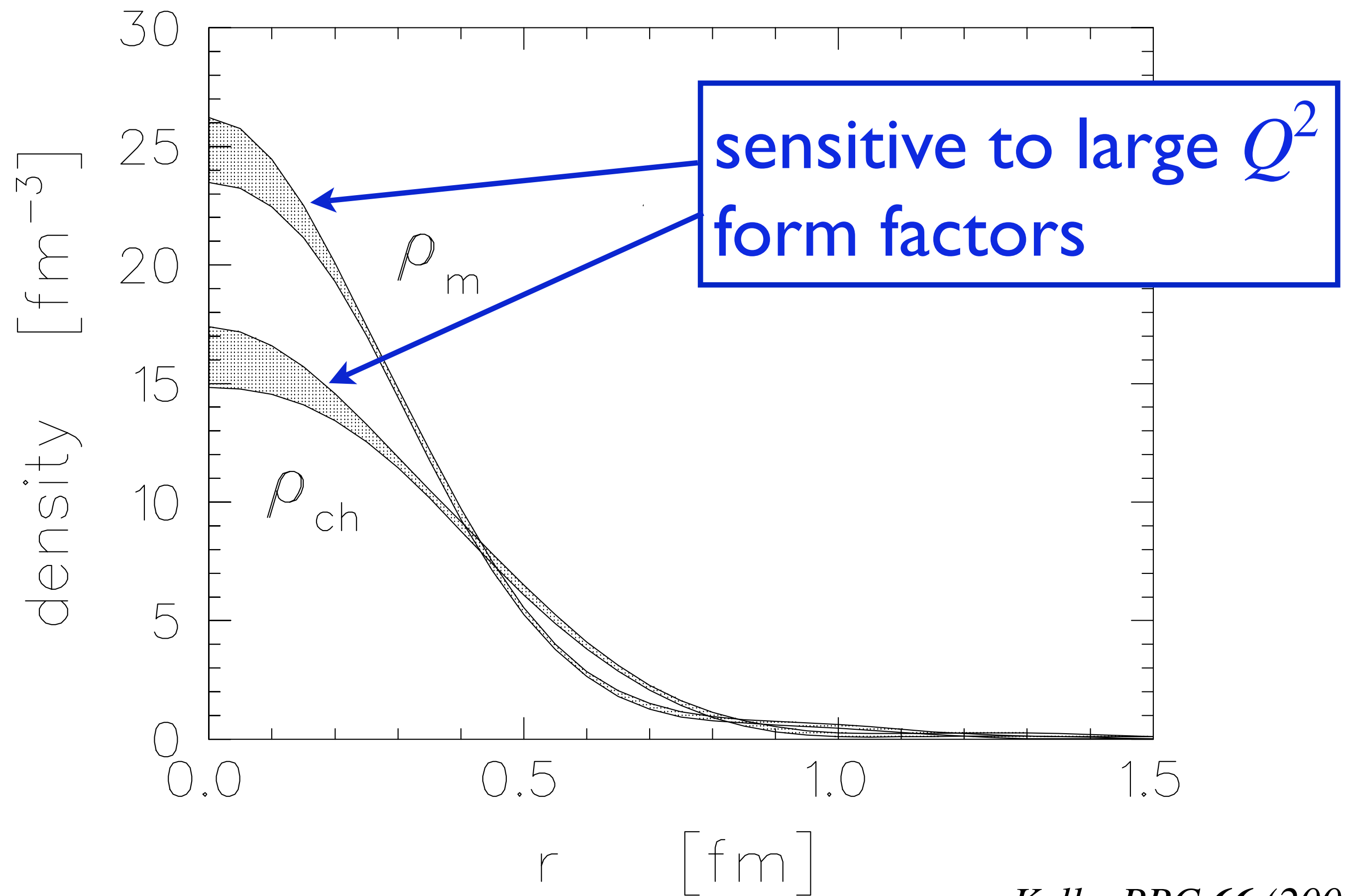


Magnetic



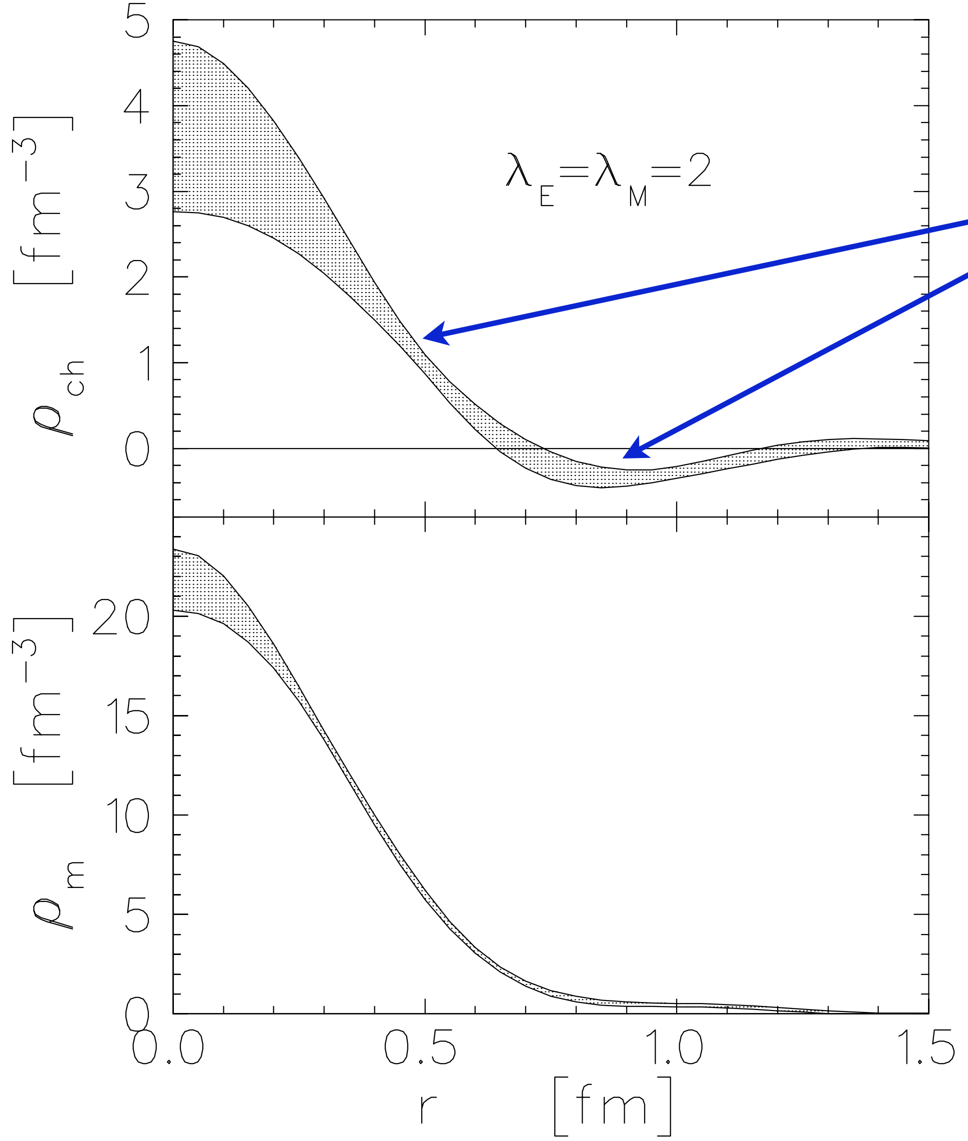


Proton densities



Kelly, PRC ***66*** *(2002) 065203*

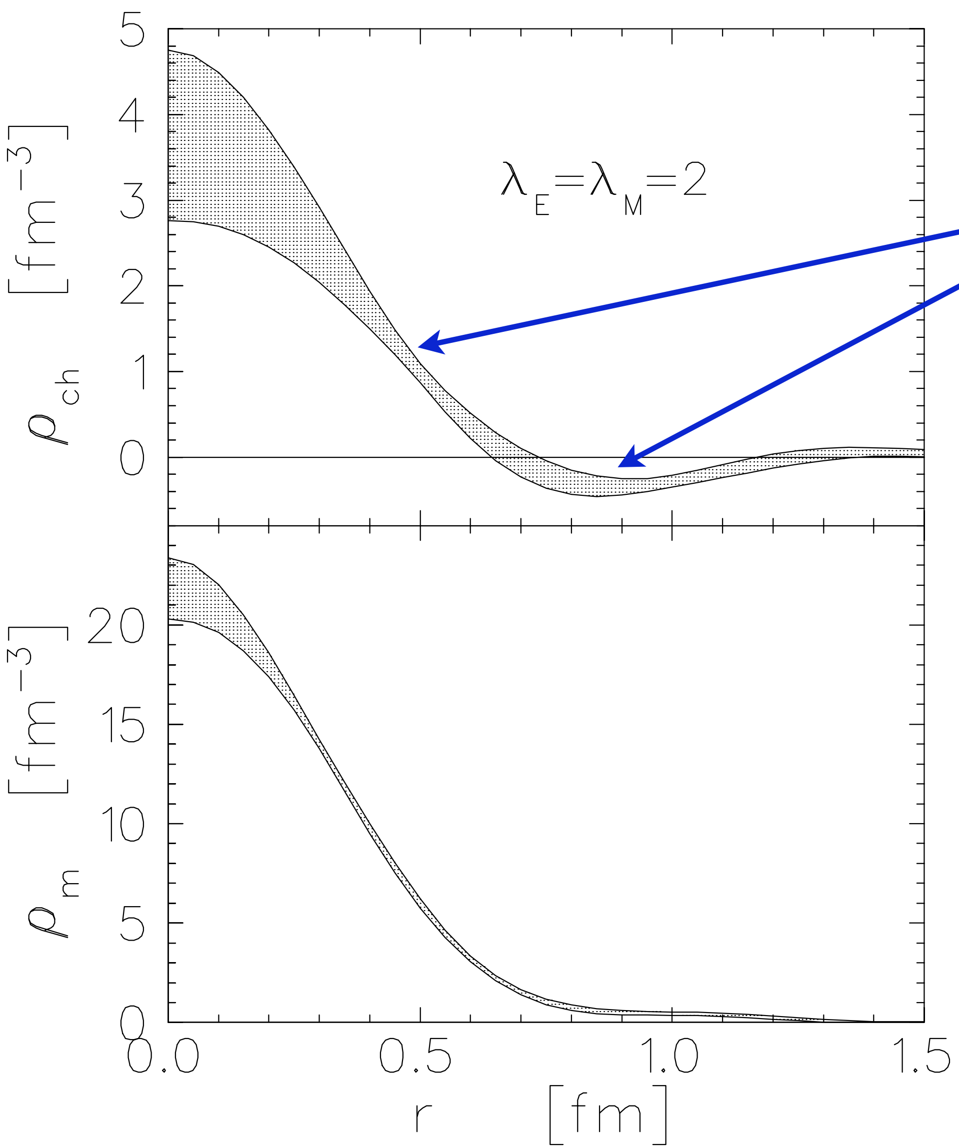
Neutron densities



neutron $\rho_E > 0$ at small r,
but < 0 at larger r

Kelly, PRC ***66*** *(2002) 065203*

Neutron densities

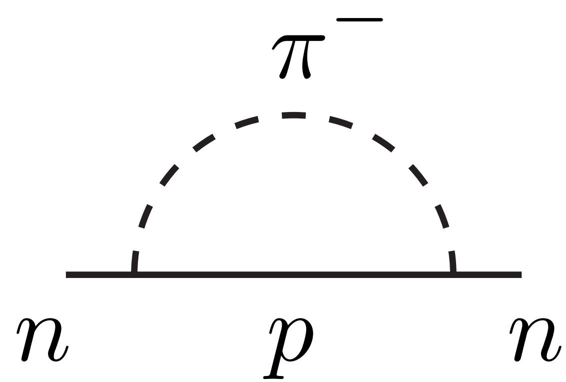


Kelly, PRC ***66*** *(2002) 065203*

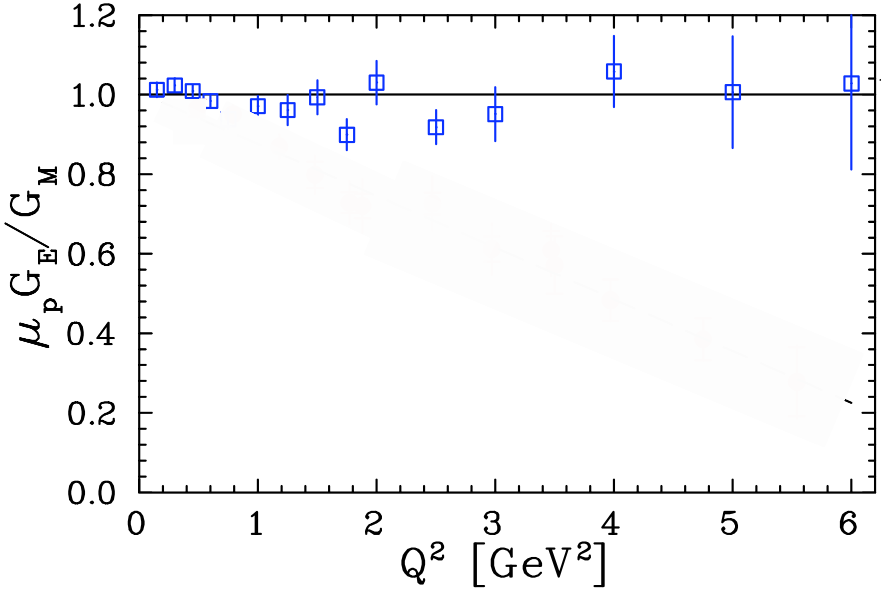
neutron $\rho_E > 0$ at small r,
but < 0 at larger r

same physics which gives $\bar{d} > \bar{u}$
also gives shape of neutron ρ_E

$\Longrightarrow$ pion cloud



Proton G_E/G_M Ratio



Rosenbluth (Longitudinal-Transverse) Separation

$$\boxed{\text{pQCD: } G_E^p/G_M^p \to \text{constant as } Q^2 \to \infty}$$

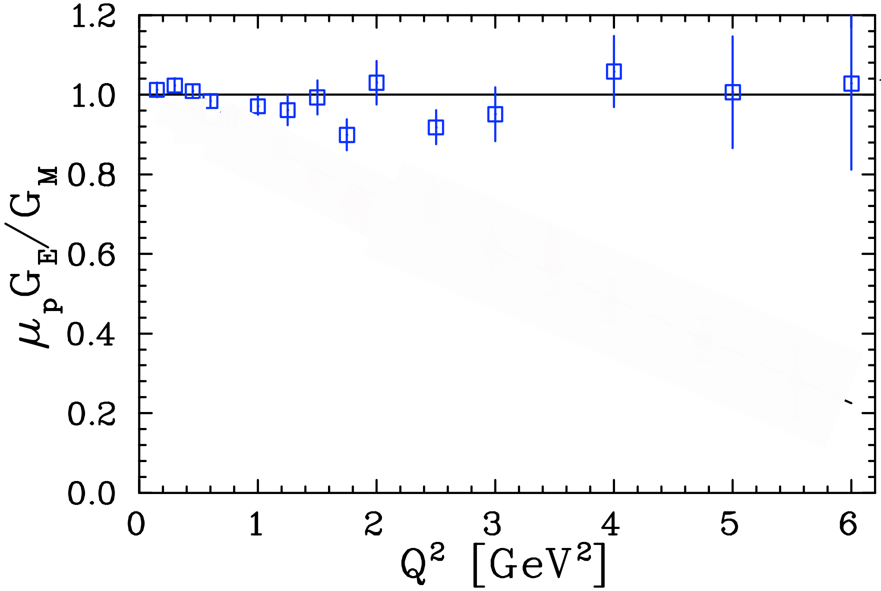
LT method

$$\sigma_R = G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$

$\longrightarrow$ G_E from slope in ε plot

$\longrightarrow$ suppressed at large Q^2

Proton G_E/G_M Ratio



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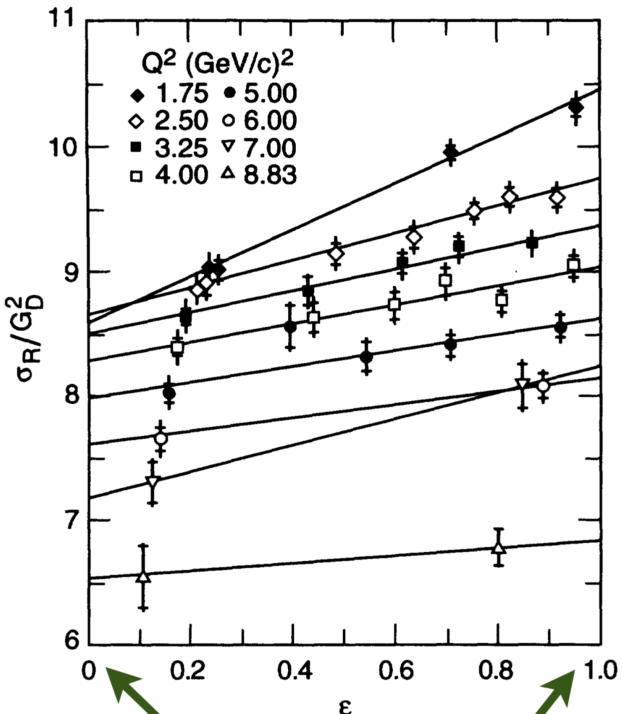
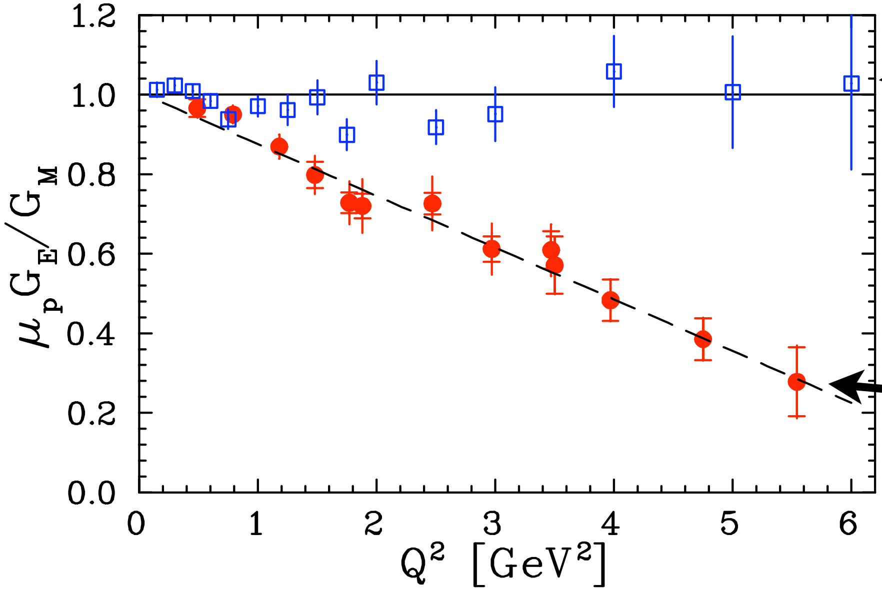


backward scattering forward

Proton G_E/G_M Ratio



Rosenbluth (Longitudinal-Transverse) Separation

Polarization Transfer

LT method

$$\sigma_R = G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$

→ G_E from slope in ε plot

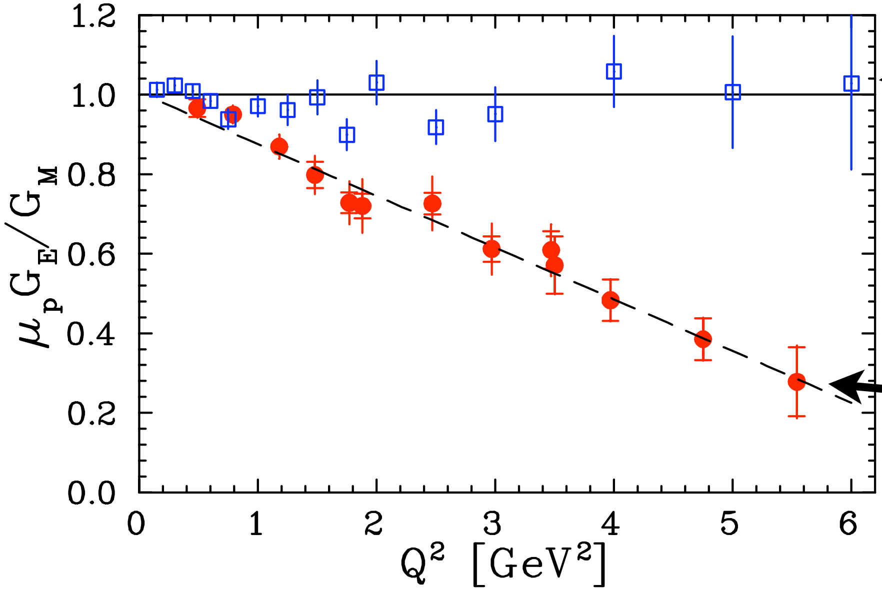
→ suppressed at large Q^2

PT method

$$\frac{G_E}{G_M} = -\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}} \frac{P_T}{P_L}$$

→ $P_{T,L}$ recoil proton polarization in $\vec{e}\, p \to e\, \vec{p}$

Proton G_E/G_M Ratio



Rosenbluth (Longitudinal-Transverse) Separation

Polarization Transfer

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PT method

$$\frac{G_E}{G_M} = -\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\frac{P_T}{P_L}$$

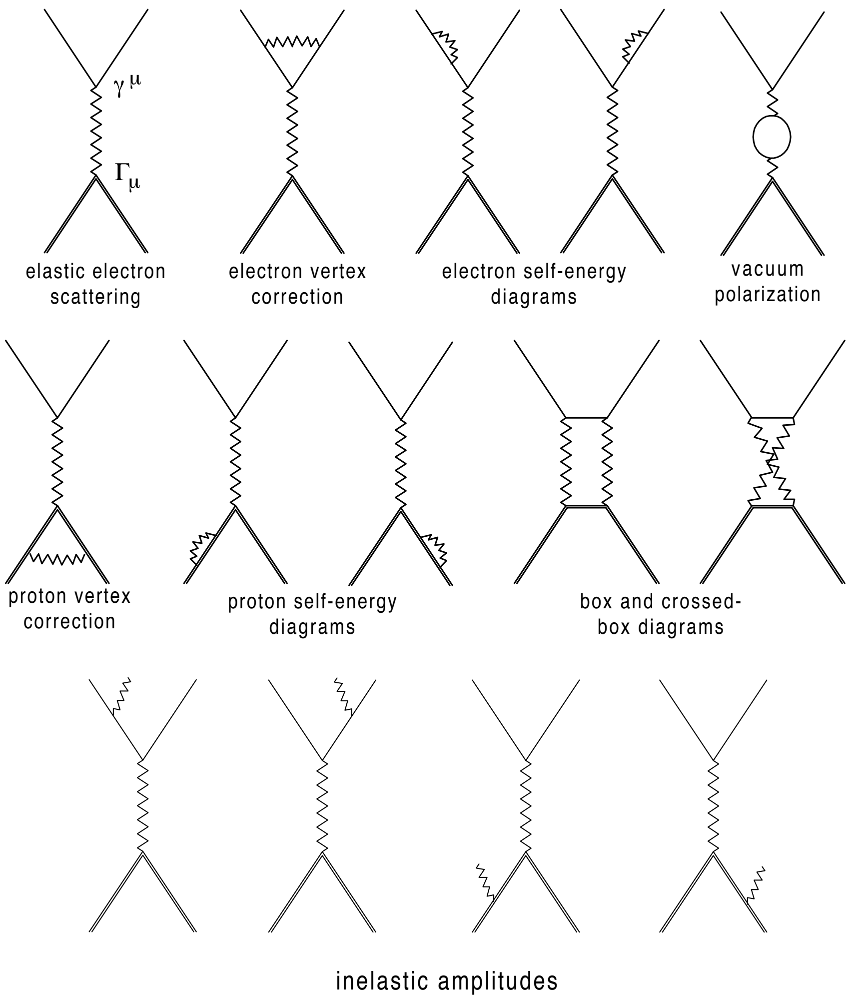
$\boxed{\text{Are the } G_E^p/G_M^p \text{ data consistent?}}$

Two-photon exchange

QED Radiative Corrections

- cross section modified by 1γ loop effects

$$d\sigma = d\sigma_0\,(1+\delta)$$



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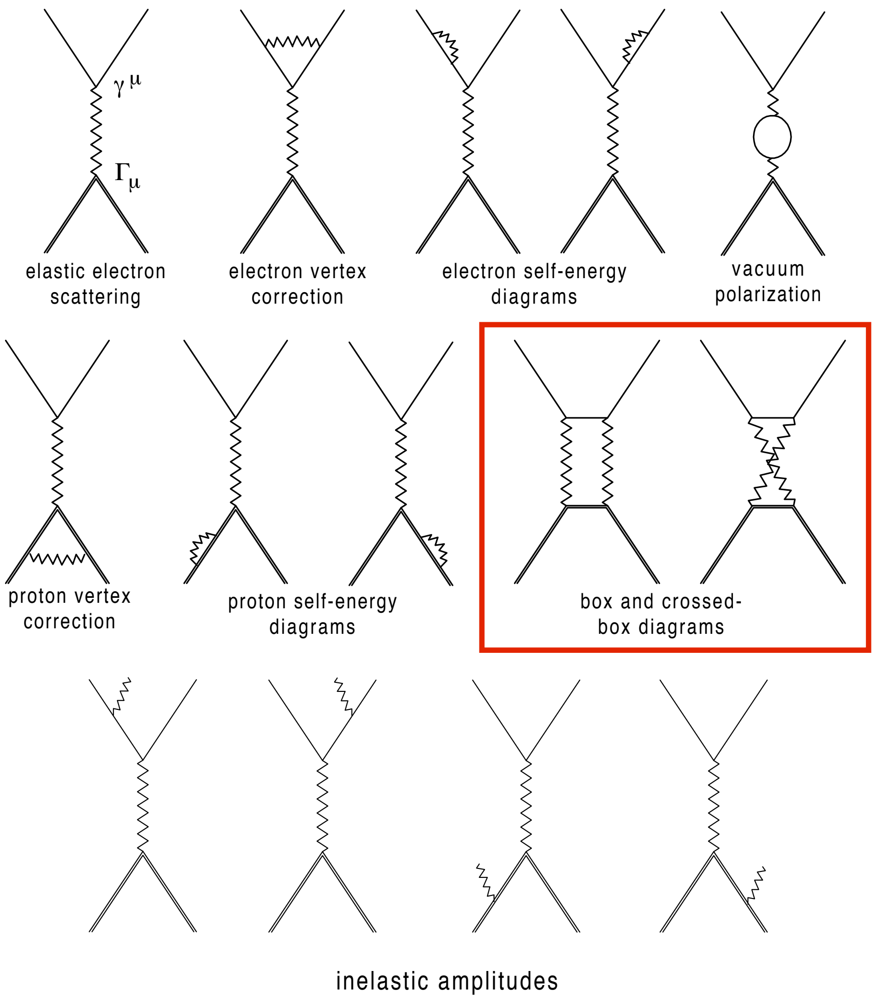

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δ contains additional ε dependence, mostly from box diagrams

(most difficult to calculate)

QED Radiative Corrections

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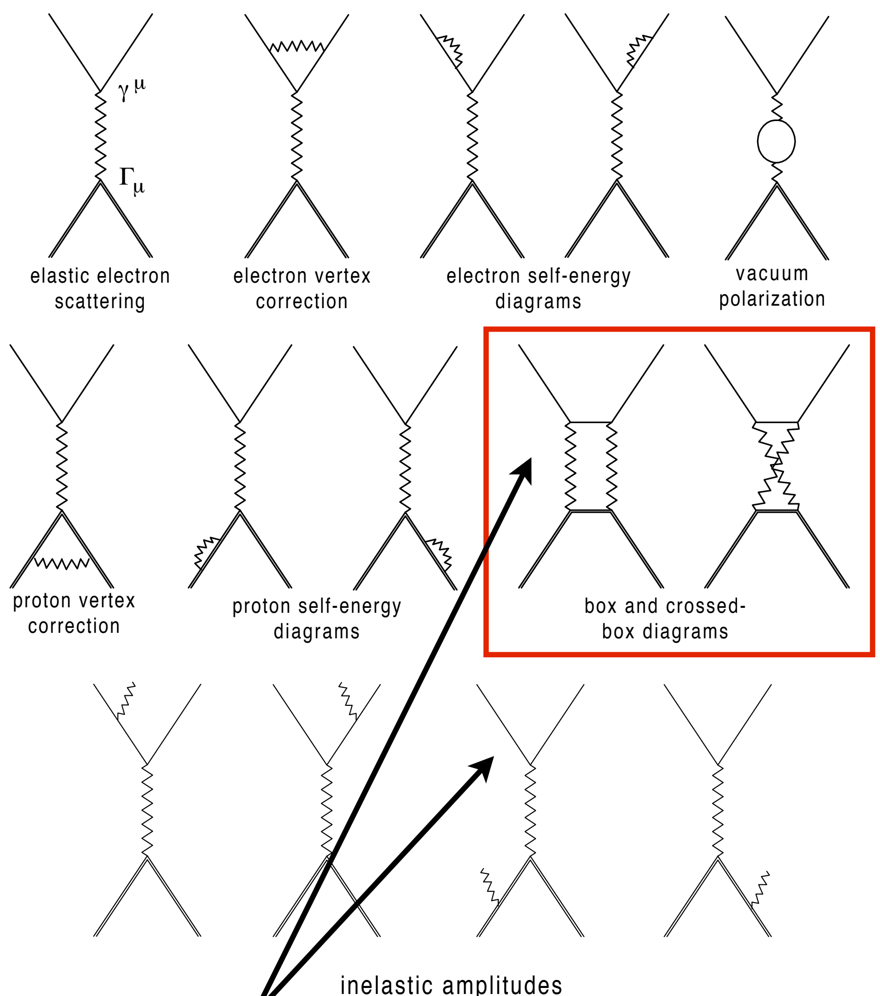


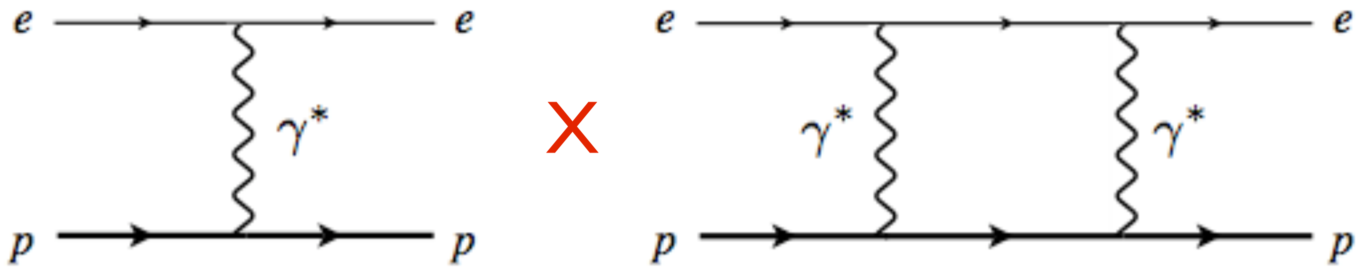
δ contains additional ε dependence, mostly from box diagrams

(most difficult to calculate)

infrared divergences cancel

Two-photon exchange

- interference between Born and two-photon exchange amplitudes



$\mathcal{M}_0$ $\qquad\qquad$ $\mathcal{M}_{\gamma\gamma}$

- contribution to cross section:

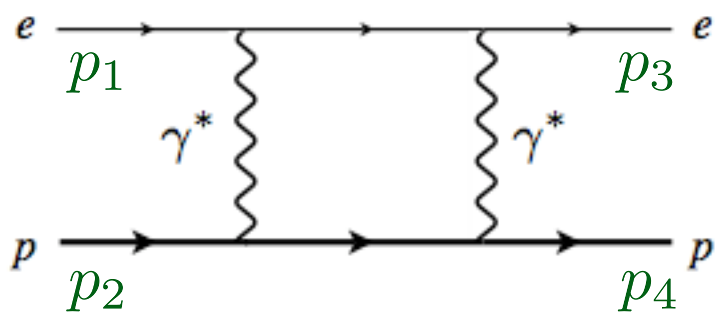
$$\delta^{(2\gamma)} = \frac{2\mathcal{R}e\left\{\mathcal{M}_0^\dagger\ \mathcal{M}_{\gamma\gamma}\right\}}{\left|\mathcal{M}_0\right|^2}$$

- standard "soft photon approximation" (used in most data analyses)

$\longrightarrow$ approximate integrand in $\mathcal{M}_{\gamma\gamma}$ by values at γ^* poles

$\longrightarrow$ neglect nucleon structure (no form factors) *Mo, Tsai (1969)*

Two-photon exchange



$$\mathcal{M}_{\gamma\gamma} = e^4 \int \frac{d^4k}{(2\pi)^4} \frac{N(k)}{D(k)}$$

where

$$N(k) = \bar{u}(p_3)\, \gamma_\mu (\not{p}_1 - \not{k} + m_e) \gamma_\nu\, u(p_1)$$
$$\times\ \bar{u}(p_4)\, \Gamma^\mu(q-k)\, (\not{p}_2 + \not{k} + M)\, \Gamma^\nu(k)\, u(p_2)$$

and

$$D(k) = (k^2 - \lambda^2)\, ((k-q)^2 - \lambda^2)$$
$$\times\ ((p_1 - k)^2 - m^2)\, ((p_2 + k)^2 - M^2)$$

with λ an IR regulator, and e.m. current is

$$\Gamma^\mu(q) = \gamma^\mu\, F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2M}\, F_2(q^2)$$

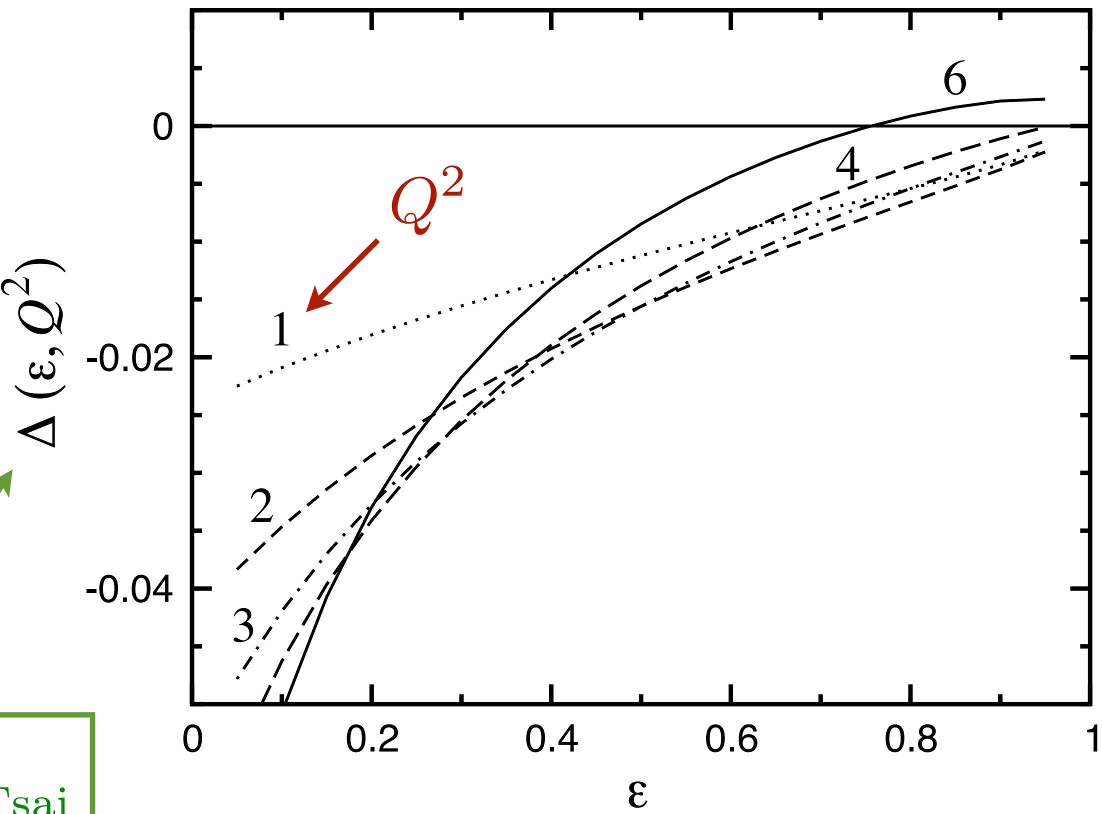
- Mo-Tsai: soft γ approximation
  $\longrightarrow$ integrand most singular when $k = 0$
  and $k = q$
  $\longrightarrow$ replace γ propagator which is
  not at pole by $1/q^2$
  $\longrightarrow$ approximate numerator $N(k) \approx N(0)$
  $\longrightarrow$ neglect all structure effects

- Maximon-Tjon: improved loop calculation
  $\longrightarrow$ exact treatment of propagators
  $\longrightarrow$ still evaluate $N(k)$ at $k = 0$
  $\longrightarrow$ first study of form factor effects
  $\longrightarrow$ additional ε dependence

- Blunden-WM-Tjon: exact loop calculation
  $\longrightarrow$ no approximation in $N(k)$ or $D(k)$
  $\longrightarrow$ include form factors

Two-photon exchange

- "exact" calculation of loop diagram (including $\gamma^* NN$ form factors)



$\delta^{(2\gamma)}_{\rm full} - \delta^{(2\gamma)}_{\rm Mo-Tsai}$

Blunden, WM, Tjon
*PRL **91** (2003) 142304;*
*PRC **72** (2005) 034612*

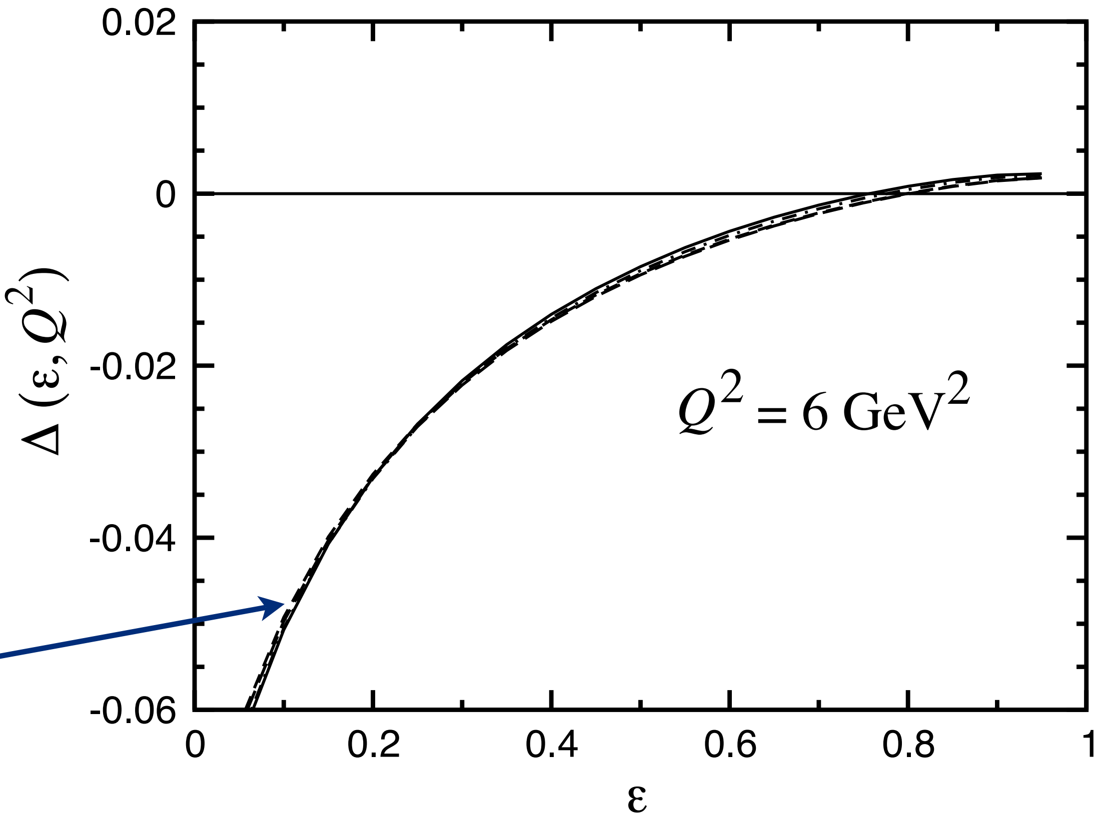
⇒ few % magnitude

⇒ <u>positive</u> slope

⇒ non-linearity in ε

Two-photon exchange

- “exact” calculation of loop diagram (including $\gamma^* NN$ form factors)

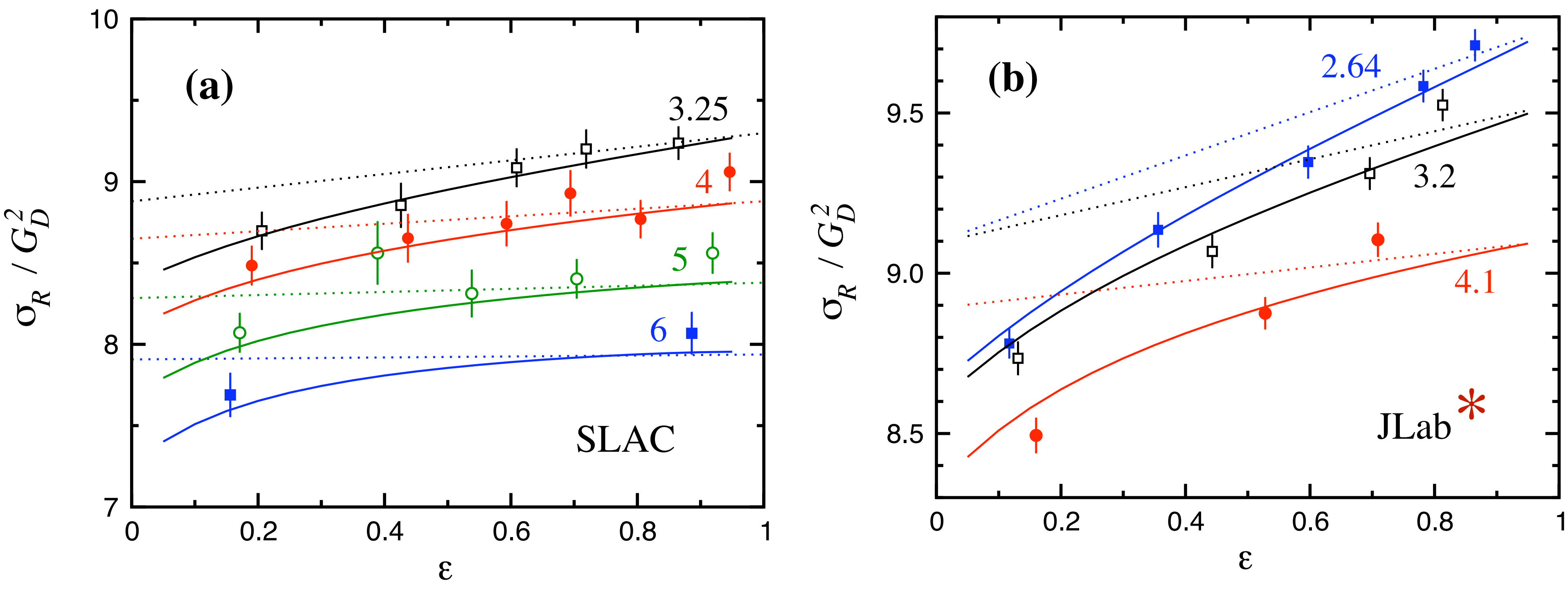


form factors:
Mergell et al. (1996)
Brash et al. (2002)
Arrington LT (2004)
Arrington PT (2004)

Blunden, WM, Tjon
*PRL **91** (2003) 142304;*
*PRC **72** (2005) 034612*

⟹ results essentially independent of form factor input

Effect on cross section



Born cross section with PT form factors

including TPE effects

* Super-Rosenbluth

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

Electric / magnetic ratio

- estimate effect of TPE on ε dependence
- approximate correction by linear function of ε

$$1 + \Delta \approx a + b\varepsilon$$

Electric / magnetic ratio

- estimate effect of TPE on ε dependence
- approximate correction by linear function of ε

$$1+\Delta \approx a+b\varepsilon$$

→ reduced cross section is then

$$\sigma_R \approx a\, G_M^2 \left[1+\frac{\varepsilon}{\mu^2\,\tau}\left(R^2(1+\varepsilon\, b/a)+\mu^2\,\tau\, b/a\right)\right]$$

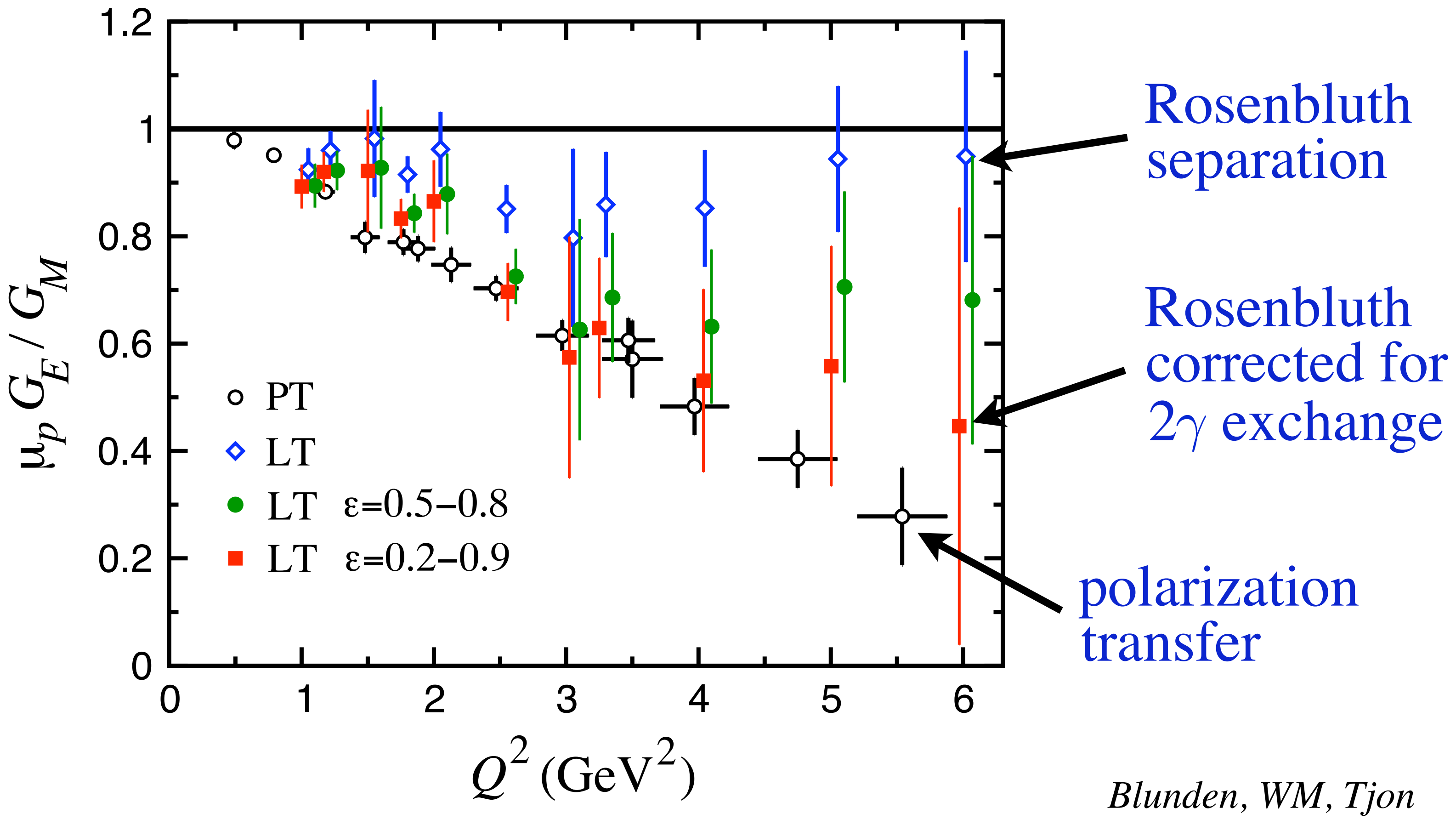
where "true" ratio is

$$R^2 = \frac{\widetilde{R}^2-\mu^2\,\tau\, b/a}{1+\bar{\varepsilon}\, b/a}$$

"effective" ratio
contaminated by TPE

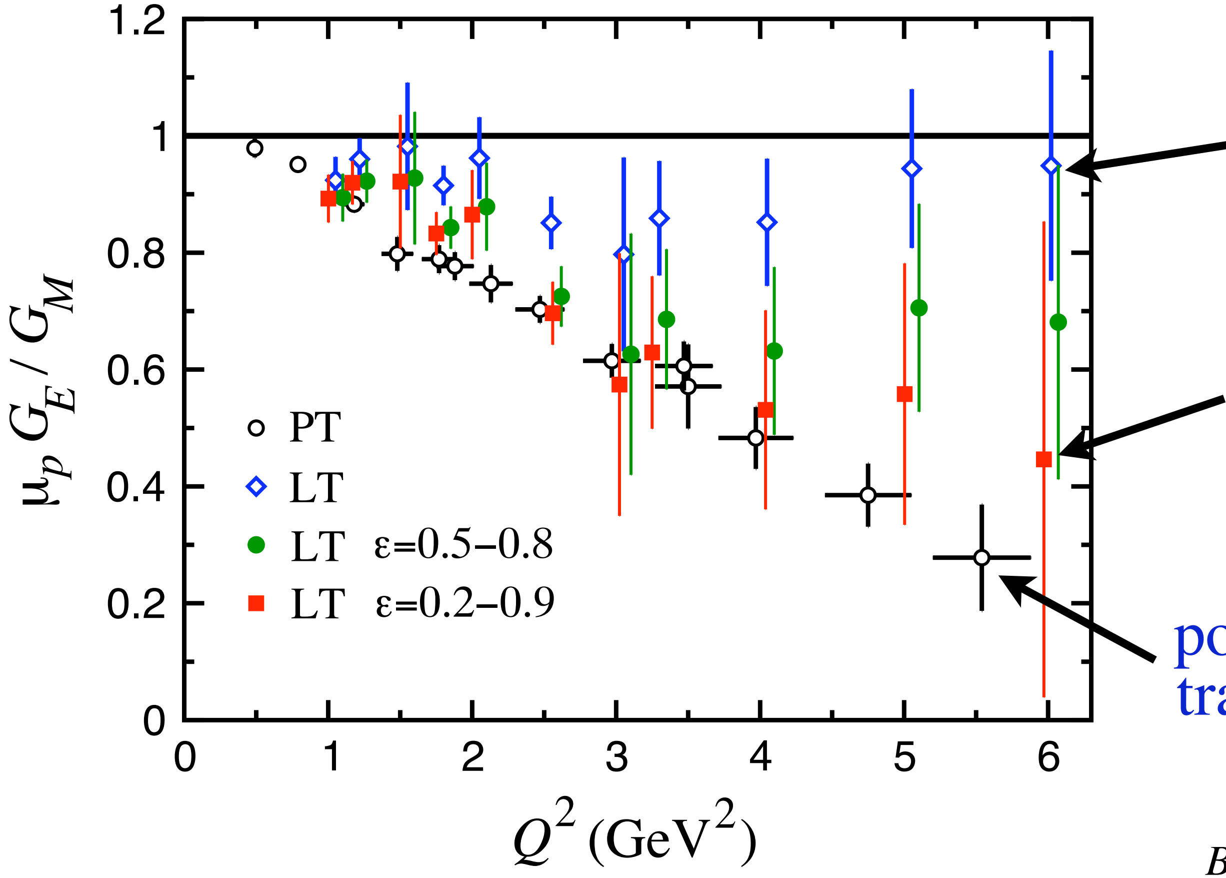
average value of ε
over range fitted

Electric / magnetic ratio



Blunden, WM, Tjon
*PRC **72** (2005) 034612*

Electric / magnetic ratio



Blunden, WM, Tjon
*PRC **72** (2005) 034612*

⇒ resolves much of the form factor discrepancy

Electric / magnetic ratio

- how does TPE affect polarization transfer ratio?

$\rightarrow$ $$\widetilde{R} = R\left(\frac{1+\Delta_T}{1+\Delta_L}\right)$$

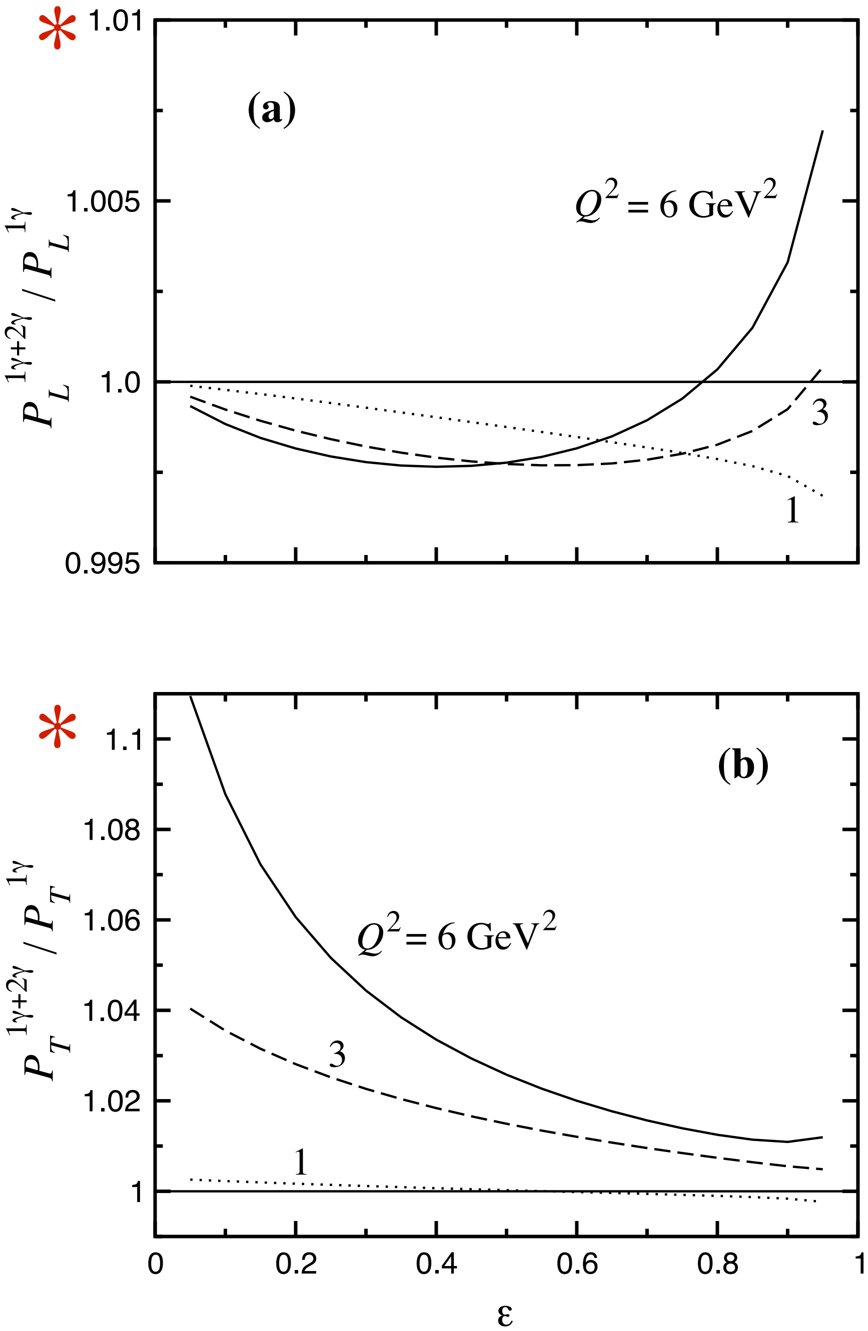
where $\Delta_{L,T} = \delta^{\text{full}}_{L,T} - \delta^{\text{Mo-Tsai}}_{\text{IR}}$ is finite part of 2γ contribution relative to IR part of Mo-Tsai

- experimentally measure ratio of polarized to unpolarized cross sections

$\rightarrow$ $$\frac{P^{1\gamma+2\gamma}_{L,T}}{P^{1\gamma}_{L,T}} = \frac{1+\Delta_{L,T}}{1+\Delta}$$

Electric / magnetic ratio

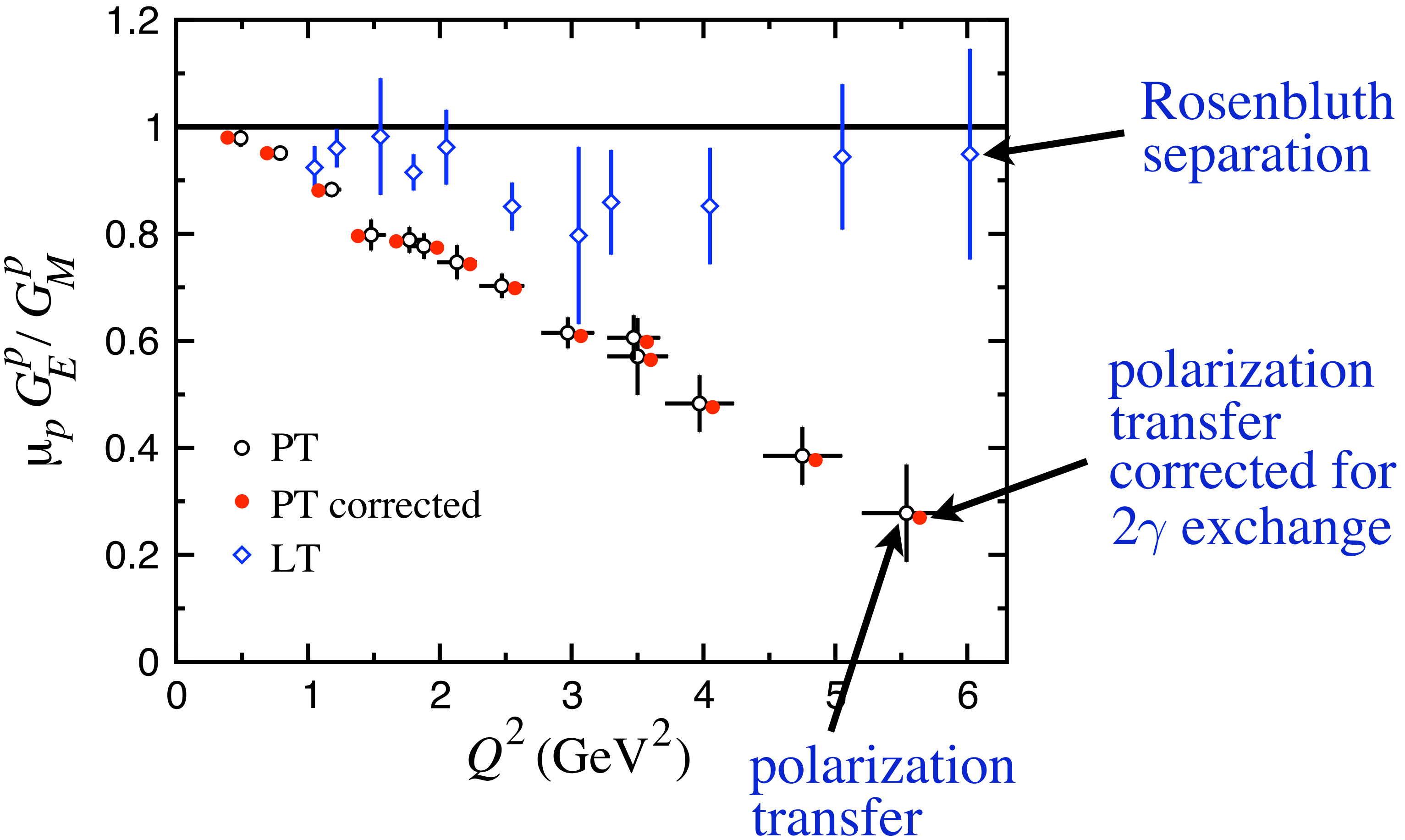
* Note scales!



→ small effect on P_L

→ large effect on P_T

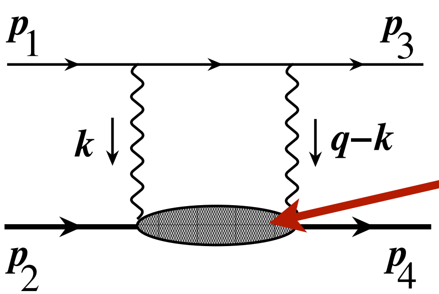
Electric / magnetic ratio



- large Q^2 data typically at large ε
- $< 3\%$ suppression at large Q^2

Excited intermediate states

What about higher-mass intermediate states?



$N,\ \Delta,\ P_{11},\ S_{11},\ S_{31},\dots$

- Lowest mass excitation is $P_{33}\ \Delta(1232)$ resonance

➡ relativistic $\gamma^* N\Delta$ vertex

form factor $\dfrac{\Lambda_\Delta^4}{(\Lambda_\Delta^2 - q^2)^2}$

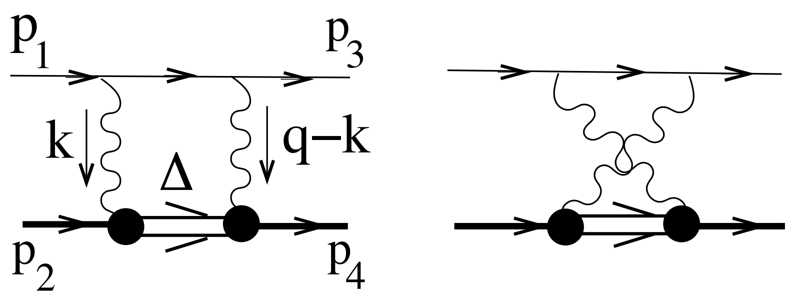
$$\Gamma^{\nu\alpha}_{\gamma\Delta\to N}(p,q) \equiv i V^{\nu\alpha}_{\Delta in}(p,q) = i\frac{eF_\Delta(q^2)}{2M_\Delta^2}\Big\{ g_1\left[\, g^{\nu\alpha}\not{p}\not{q} - p^\nu\gamma^\alpha\not{q} - \gamma^\nu\gamma^\alpha p\cdot q + \gamma^\nu\not{p} q^\alpha \,\right]$$

$$+ g_2\left[\, p^\nu q^\alpha - g^{\nu\alpha} p\cdot q \,\right] + (g_3/M_\Delta)\left[\, q^2(p^\nu\gamma^\alpha - g^{\nu\alpha}\not{p}) + q^\nu(q^\alpha\not{p} - \gamma^\alpha p\cdot q)\,\right]\Big\}\gamma_5\, T_3$$

➡ coupling constants

g_1	magnetic	➡	7
$g_2 - g_1$	electric	➡	9
g_3	Coulomb	➡	-2 ... 0

Two-photon exchange amplitude with Δ intermediate state



$$\mathcal{M}_{\Delta}^{\gamma\gamma} = -e^4 \int \frac{d^4k}{(2\pi)^4} \frac{N_{box}^{\Delta}(k)}{D_{box}^{\Delta}(k)} - e^4 \int \frac{d^4k}{(2\pi)^4} \frac{N_{x-box}^{\Delta}(k)}{D_{x-box}^{\Delta}(k)}$$

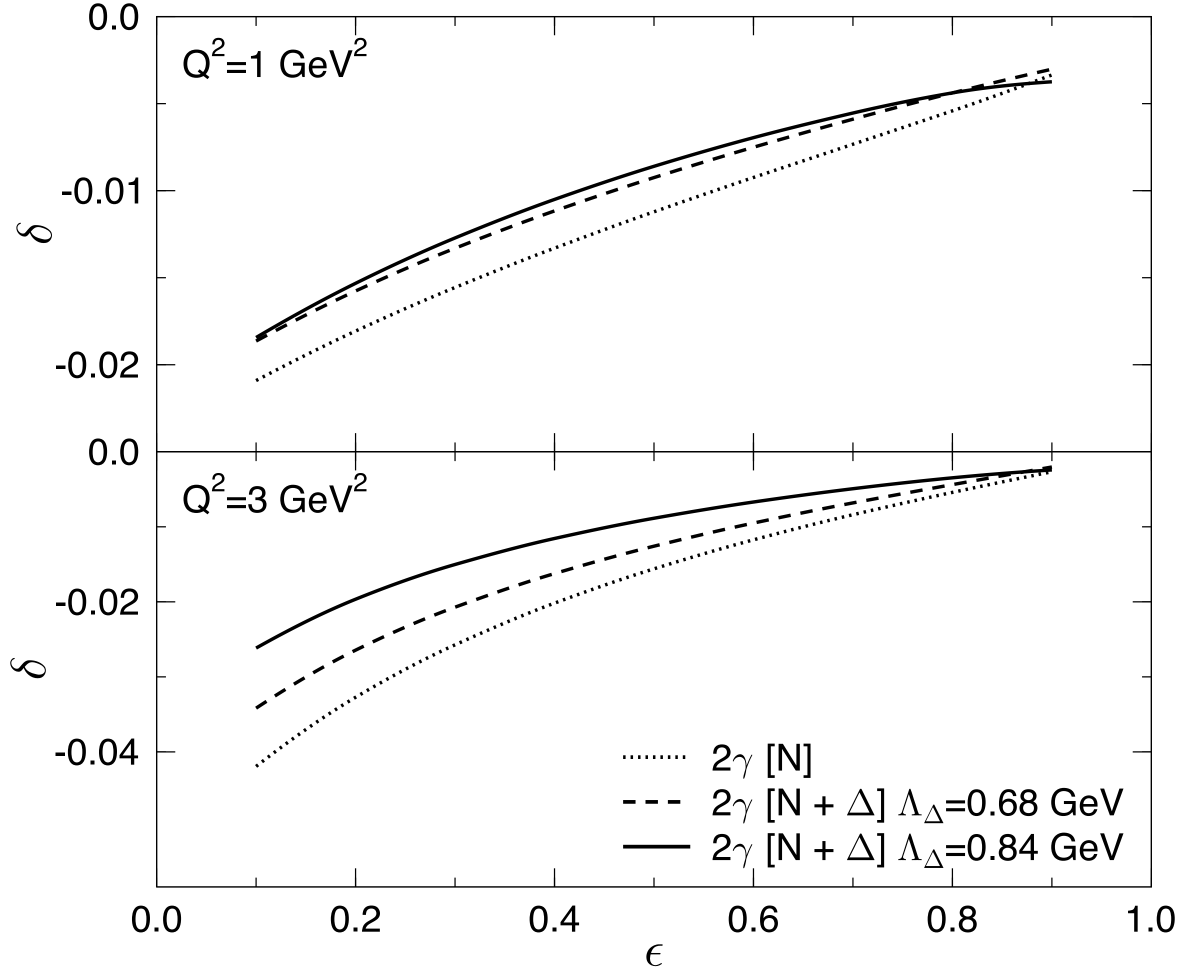
numerators

$$\begin{aligned} N_{box}^{\Delta}(k) &= \overline{U}(p_4) V_{\Delta in}^{\mu\alpha}(p_2+k, q-k) \left[\not p_2 + \not k + M_\Delta\right] \mathcal{P}_{\alpha\beta}^{3/2}(p_2+k) V_{\Delta out}^{\beta\nu}(p_2+k, k) U(p_2) \\ &\times \ \overline{u}(p_3)\gamma_\mu \left[\not p_1 - \not k + m_e\right] \gamma_\nu u(p_1) \end{aligned}$$

$$\begin{aligned} N_{x-box}^{\Delta}(k) &= \overline{U}(p_4) V_{\Delta in}^{\mu\alpha}(p_2+k, q-k) \left[\not p_2 + \not k + M_\Delta\right] \mathcal{P}_{\alpha\beta}^{3/2}(p_2+k) V_{\Delta out}^{\beta\nu}(p_2+k, k) U(p_2) \\ &\times \ \overline{u}(p_3)\gamma_\nu \left[\not p_3 + \not k + m_e\right] \gamma_\mu u(p_1) \end{aligned}$$

spin-3/2 projection operator

$$\mathcal{P}_{\alpha\beta}^{3/2}(p) = g_{\alpha\beta} - \frac{1}{3}\gamma_\alpha\gamma_\beta - \frac{1}{3p^2}\left(\not p \gamma_\alpha p_\beta + p_\alpha \gamma_\beta \not p\right)$$

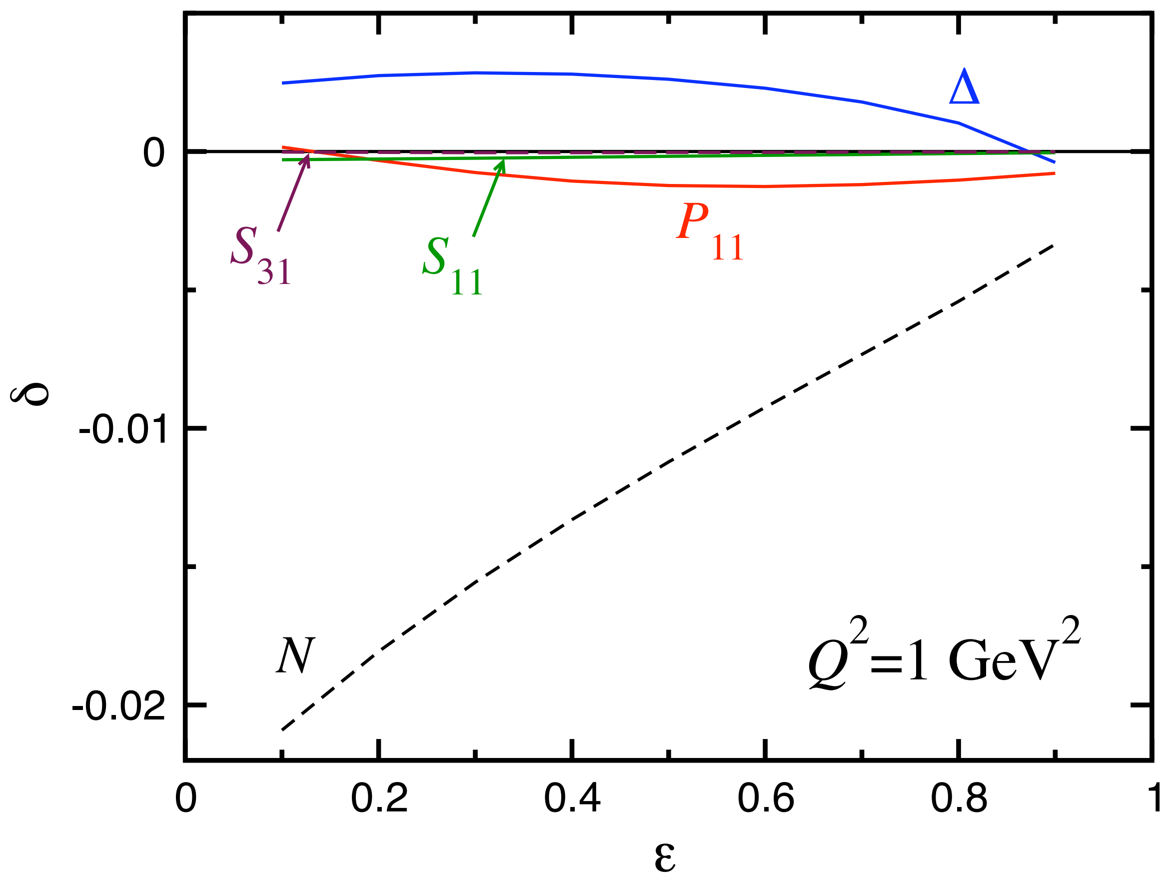


Kondratyuk, Blunden, WM, Tjon
*PRL **95** (2005) 172503*

- Δ has <u>opposite</u> slope to N
- cancels some of TPE correction from N

- Higher-mass intermediate states have also been calculated

  → more model dependent, since couplings & form factors not well known (especially at high Q^2)



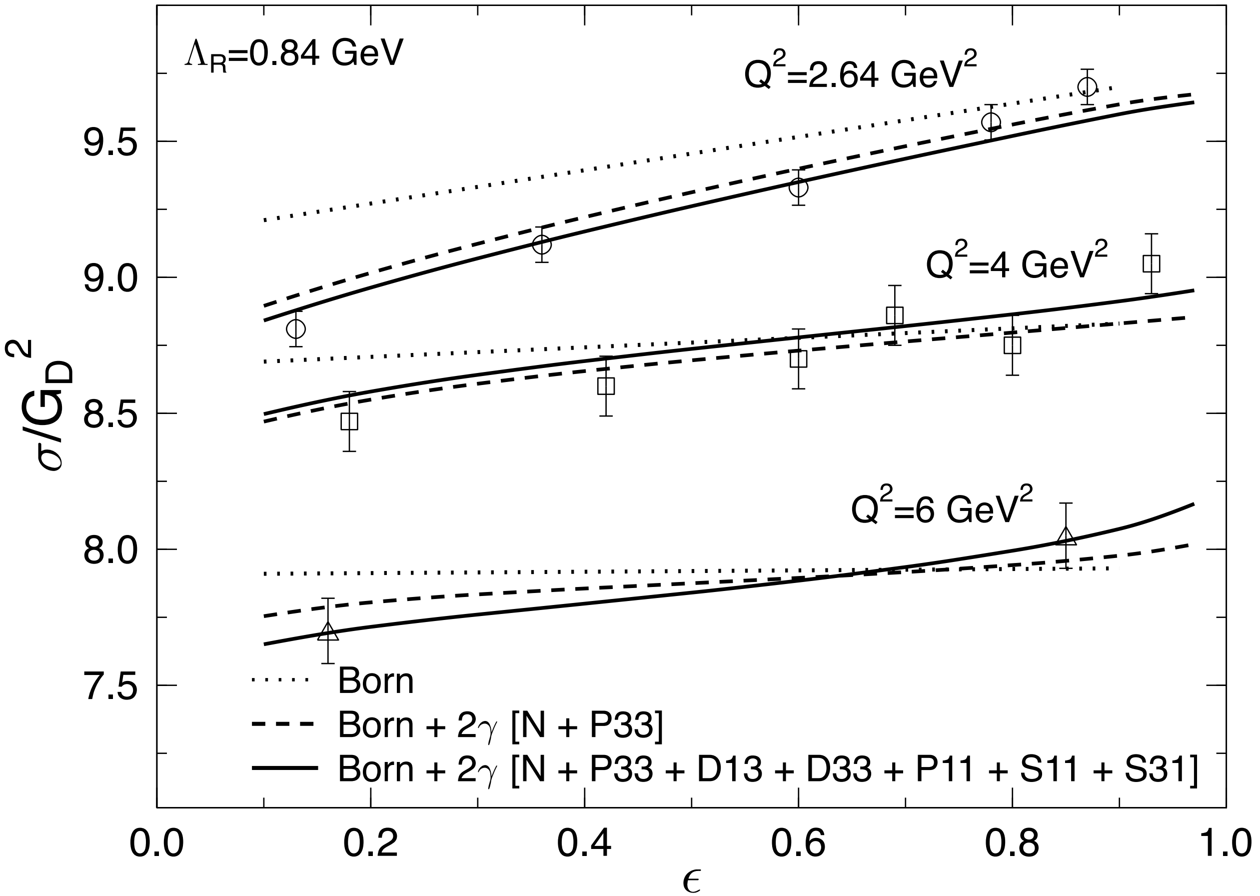
Kondratyuk, Blunden, WM, Tjon
PRL ***95*** *(2005) 172503*

Kondratyuk, Blunden
PRC ***75*** *(2007) 038201*

⇒ dominant contribution from N

⇒ Δ partially cancels N contribution

Higher-mass intermediate states have also been calculated



Kondratyuk, Blunden
PRC ***75*** *(2007) 038201*

- higher mass resonance contributions small
- much better fit to data including TPE

Global analysis

Global analysis

- reanalyze *all* elastic *ep* data (Rosenbluth, PT), including TPE corrections consistently from the beginning

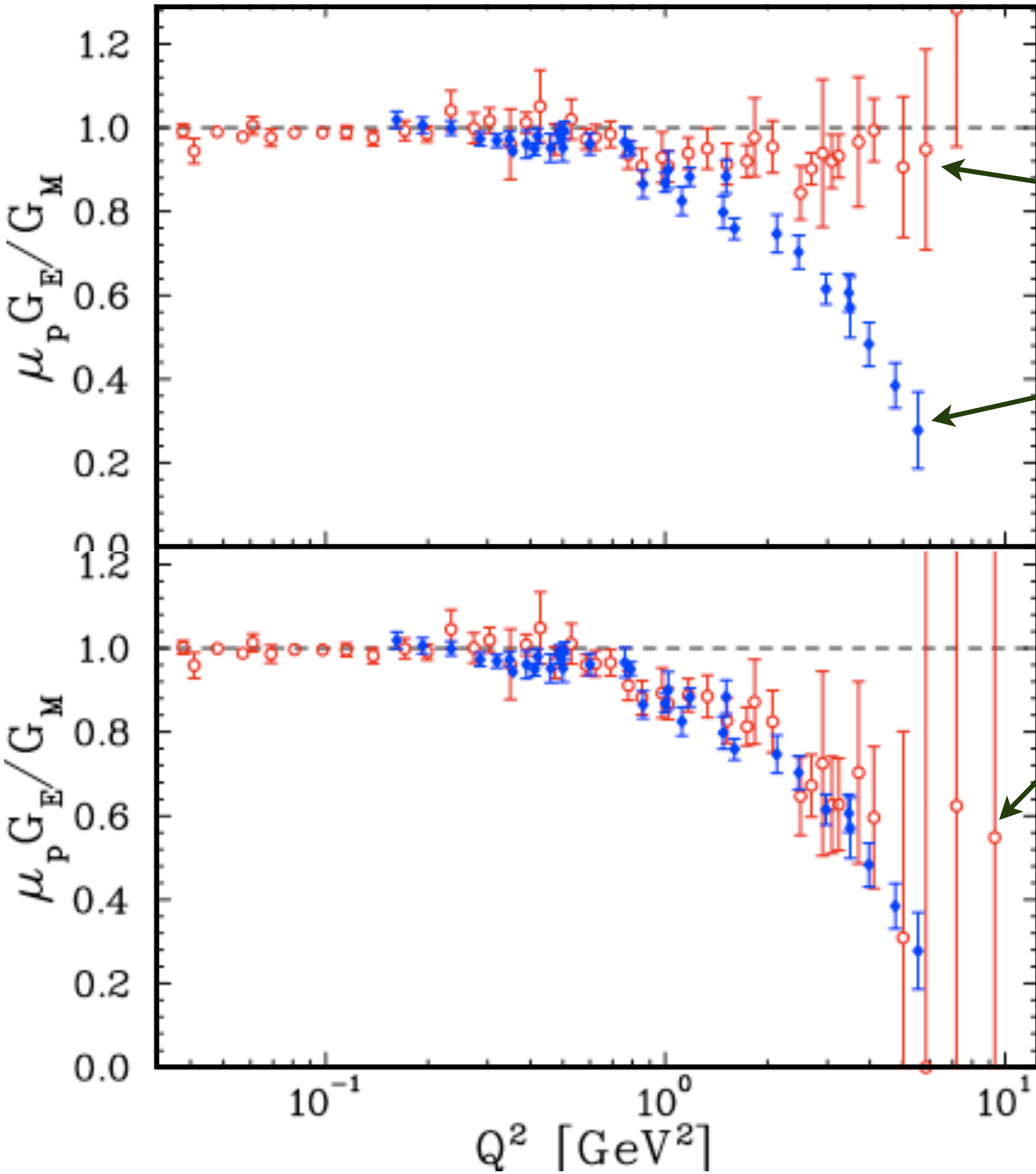
- use explicit calculation of N elastic contribution

- approximate higher mass contributions by phenomenological form, based on N^* calculations:

$$\delta^{(2\gamma)}_{\rm high\ \ mass} = -0.01\ (1-\varepsilon)\ \log Q^2 / \log 2.2$$

for $Q^2 > 1\ \mathrm{GeV}^2$, with $\pm 100\%$ uncertainty

→ decreases $\varepsilon = 0$ cross section by 1% (2%) at $Q^2 = 2.2\ (4.8)\ \mathrm{GeV}^2$



LT separation

polarization transfer

with TPE correction

➡ resolves discrepancy (within errors)

Arrington, WM, Tjon
*PRC **76** (2007) 035205*

Non-linearity in ε

- unique feature of TPE correction to cross section
- observation of non-linearity in ε would provide direct evidence of TPE in elastic scattering
- fit reduced cross section as:

$$\sigma_R = P_0 \left[1 + P_1 \, (\varepsilon - \frac{1}{2}) + P_2 \, (\varepsilon - \frac{1}{2})^2 \right]$$

- current data give average non-linearity parameter:

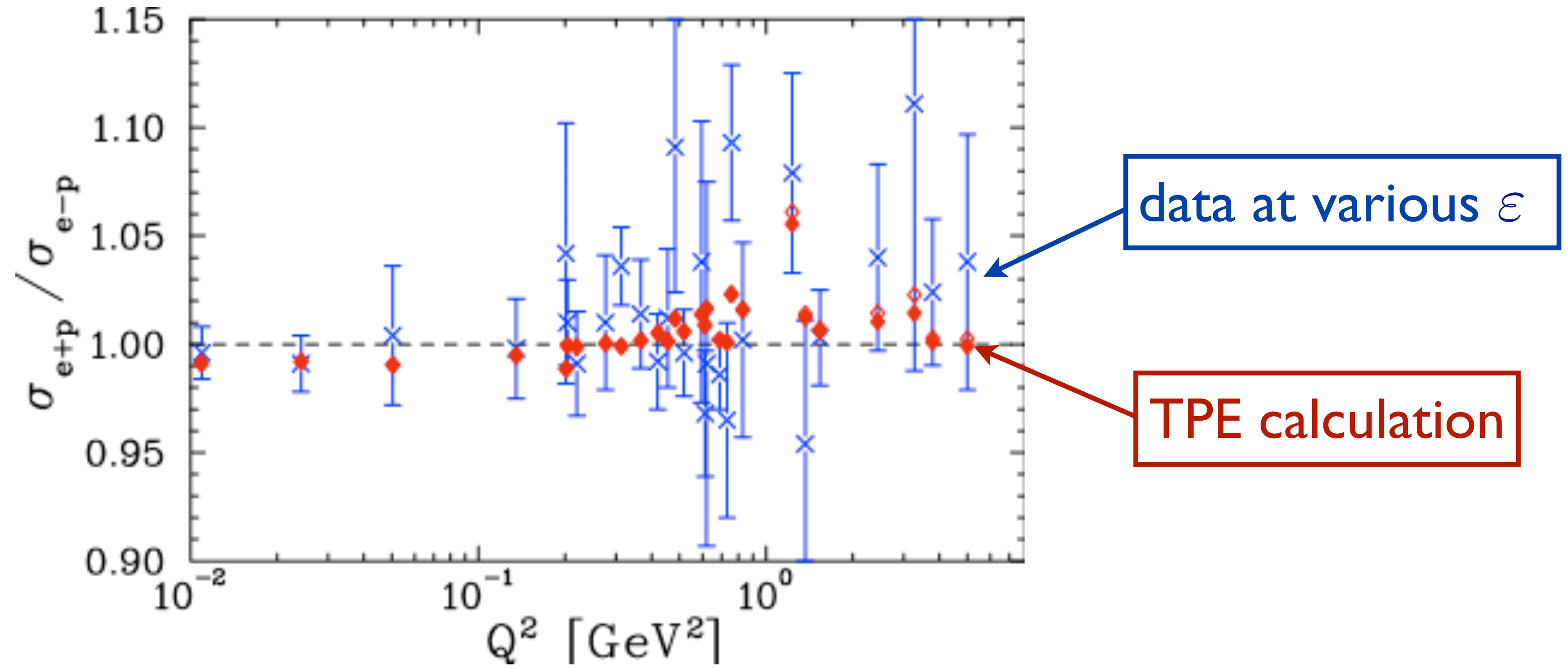
$$\langle P_2 \rangle = 4.3 \pm 2.8\%$$

- Hall C experiment E-05-017 will provide accurate measurement of ε dependence

e^+/e^- comparison

- 1γ (2γ) exchange changes sign (invariant) under $e^+ \leftrightarrow e^-$
- ratio of $e^+p\ /\ e^-p$ elastic cross sections sensitive to $\Delta(\varepsilon, Q^2)$:

$$\sigma_{e^+p}/\sigma_{e^-p} \approx 1 - 2\Delta$$



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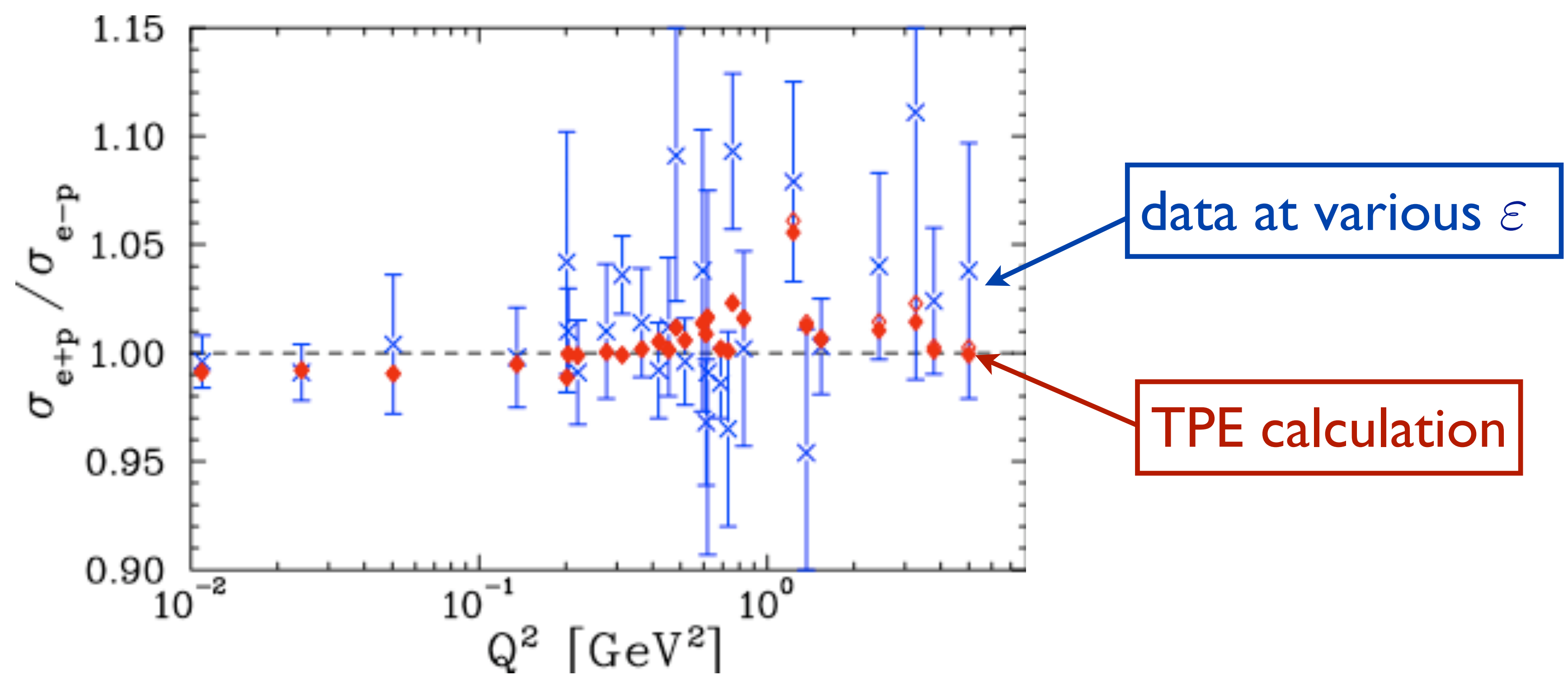
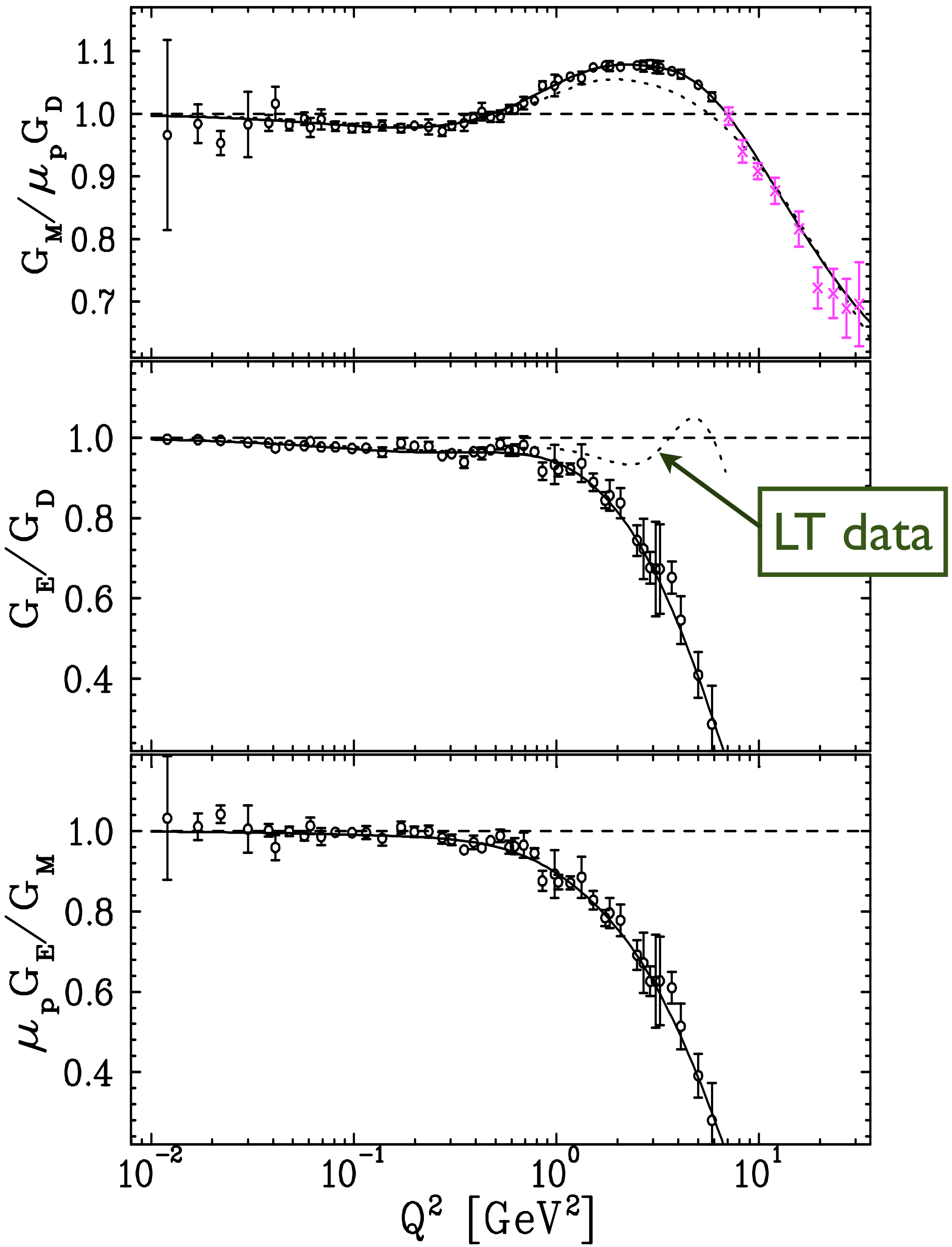
- ratio of $e^+p\,/\,e^-p$ elastic cross sections sensitive to $\Delta(\varepsilon, Q^2)$:

$$\sigma_{e^+p}/\sigma_{e^-p} \approx 1 - 2\Delta$$



→ simultaneous e^-p/e^+p measurement using tertiary e^+/e^- beam to Q^2 ~ 1-2 GeV^2 (Hall B expt. E-04-116)



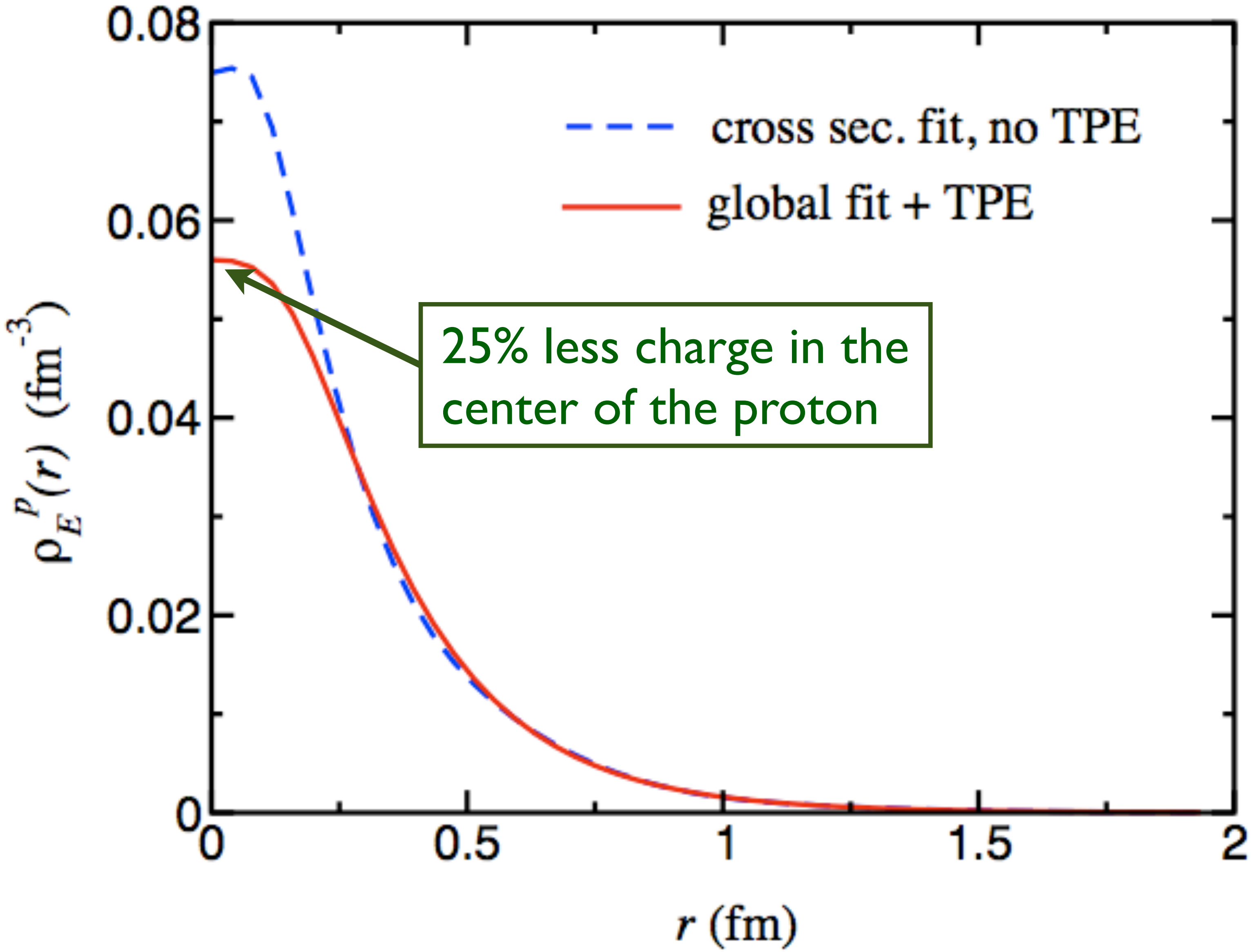
final form factor results from global analysis *including TPE corrections*

$$\left\{ G_E, \ \frac{G_M}{\mu_p} \right\} = \frac{1 + \sum_{i=1}^{n} a_i \tau^i}{1 + \sum_{i=1}^{n+2} b_i \tau^i}$$

Parameter	G_M/μ_p	G_E
a_1	−1.465	3.439
a_2	1.260	−1.602
a_3	0.262	0.068
b_1	9.627	15.055
b_2	0.000	48.061
b_3	0.000	99.304
b_4	11.179	0.012
b_5	13.245	8.650

Arrington, WM, Tjon
PRC ***76*** *(2007) 035205*

Charge density



Strange quarks in the nucleon

How strange is the proton?

- Suggestions for major role of strange quarks in the nucleon
  - $\longrightarrow$ nucleon "sigma"-term ($\sim$100 MeV contribution to N mass?)
  - $\longrightarrow$ proton "spin crisis" (s quarks carry large fraction of p spin)
  - $\longrightarrow$ how large is contribution to N magnetic moment?

- Proton and neutron electromagnetic form factors give two combinations of 3 unknowns:

$$G^p_{E,M} = \frac{2}{3} G^u_{E,M} - \frac{1}{3} G^d_{E,M} - \frac{1}{3} G^s_{E,M}$$

$$G^n_{E,M} = \frac{2}{3} G^d_{E,M} - \frac{1}{3} G^u_{E,M} - \frac{1}{3} G^s_{E,M}$$

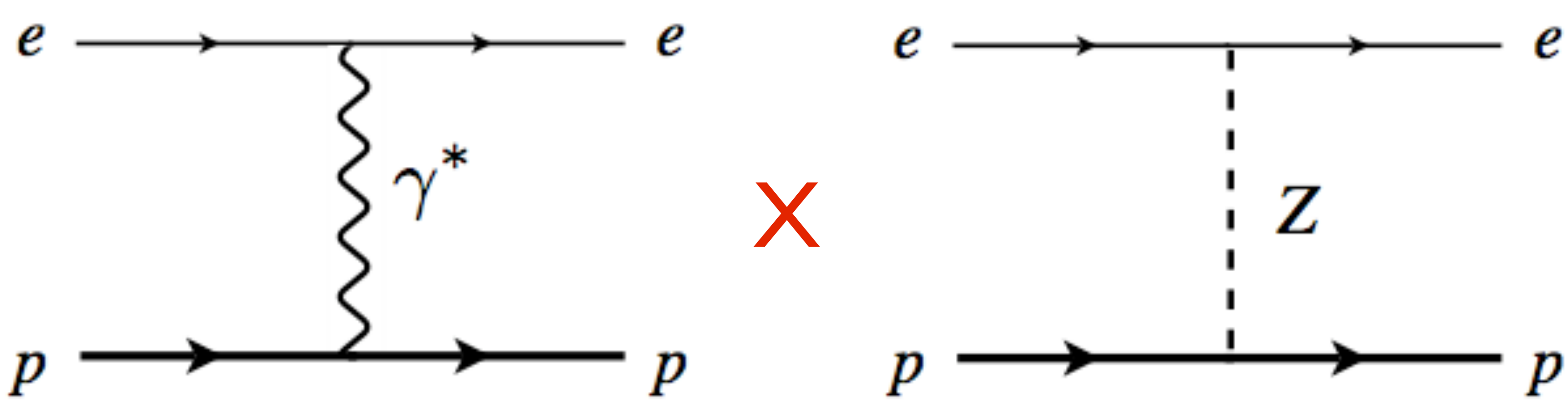
  - $\longrightarrow$ need third observable to extract $G^s_{E,M}$
  - $\longrightarrow$ parity-violating e scattering (interference of γ and Z^0 exchange)

Parity-violating e scattering

- Left-right polarization asymmetry in $\vec{e}\, p \to e\, p$ scattering

$$A_{\rm PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)(A_V + A_A + A_s)$$

$\rightarrow$ measure interference between e.m. and weak currents



Born (tree) level

Parity-violating e scattering

- Left-right polarization asymmetry in $\vec{e}\,p \to e\,p$ scattering

$$A_{\rm PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)(A_V + A_A + A_s)$$

$\longrightarrow$ measure interference between e.m. and weak currents

$$A_V = g_A^e \rho \left[(1 - 4\kappa \sin^2\theta_W) - (\varepsilon G_E^{\gamma p} G_E^{\gamma n} + \tau G_M^{\gamma p} G_M^{\gamma n})/\sigma^{\gamma p}\right]$$

using relations between weak and e.m. form factors

$$G_{E,M}^{Zp} = (1 - 4\sin^2\theta_W) G_{E,M}^{\gamma p} - G_{E,M}^{\gamma n} - G_{E,M}^{s}$$

Parity-violating e scattering

- Left-right polarization asymmetry in $\vec{e}\, p \rightarrow e\, p$ scattering

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+1

radiative corrections, including TBE

using relations between weak and e.m. form factors

$$G_{E,M}^{Zp} = (1 - 4\sin^2\theta_W) G_{E,M}^{\gamma p} - G_{E,M}^{\gamma n} - G_{E,M}^{s}$$

Parity-violating e scattering

- Left-right polarization asymmetry in $\vec{e}\,p \to e\,p$ scattering

$$A_{\rm PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)(A_V + A_A + A_s)$$

$\rightarrow$ measure interference between e.m. and weak currents

$$A_A = g_V^e \sqrt{\tau(1+\tau)(1-\varepsilon^2)}\; \widetilde{G}_A^{Zp} G_M^{\gamma p} / \sigma^{\gamma p}$$

$-1 + 4\sin^2\theta_W$

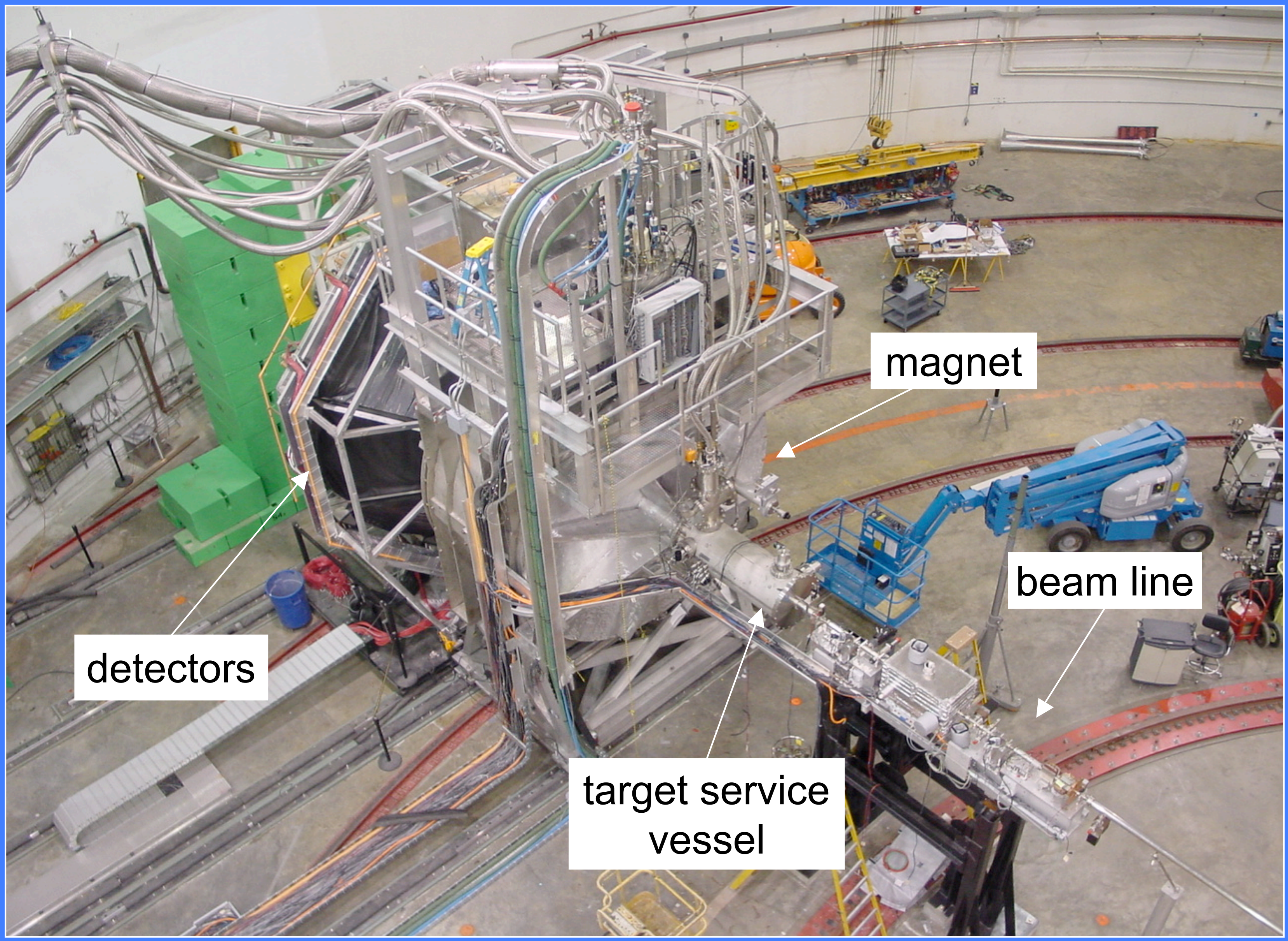
includes axial RCs

$$A_s = -g_A^e \rho \left(\varepsilon G_E^{\gamma p} G_E^s + \tau G_M^{\gamma p} G_M^s\right) / \sigma^{\gamma p}$$

strange electric &
magnetic form factors

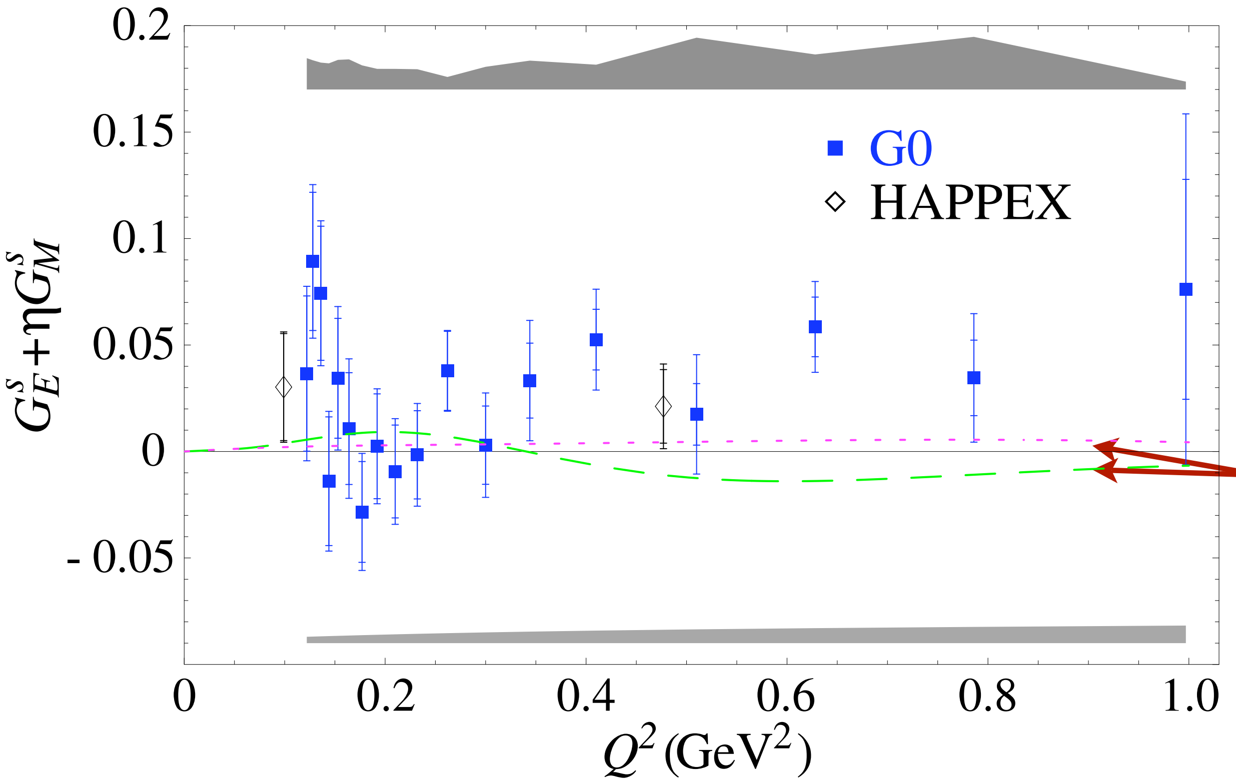
Parity-violating *e* scattering

G0 Experiment at Jefferson Lab



Parity-violating *e* scattering

Extracted strange form factors



$$\eta = \tau G_M / \varepsilon G_E$$

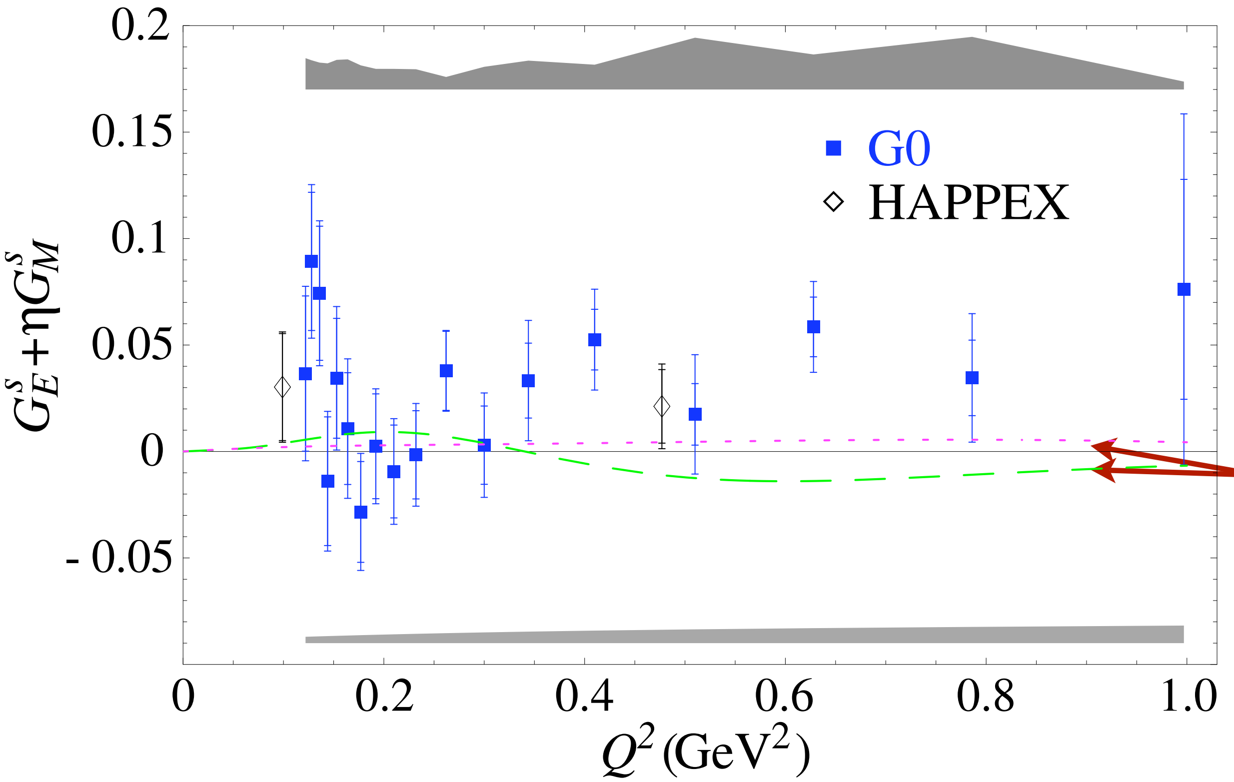
$$\sim \ 0.94\ Q^2$$

dependence of "zero-point" on e.m. form factors

Armstrong et al., PRL ***95*** *(2005) 092001*

Parity-violating e scattering

Extracted strange form factors



$$\eta = \tau G_M / \varepsilon G_E$$

$$\sim \; 0.94\, Q^2$$

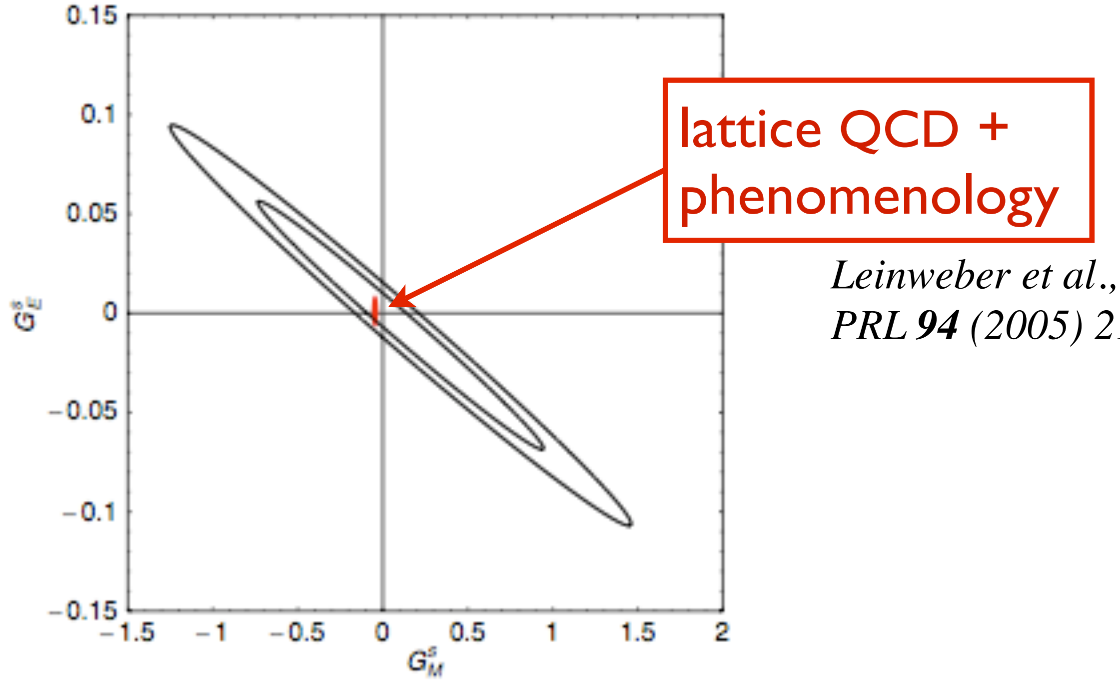
dependence of "zero-point" on e.m. form factors

Armstrong et al., *PRL* ***95*** *(2005) 092001*

- intriguing Q^2 dependence !
- trend to positive values at larger Q^2

Parity-violating e scattering

- global analysis of <u>all</u> PVES data at $Q^2 < 0.3\ \mathrm{GeV}^2$



Leinweber et al.,
*PRL **94** (2005) 212001*

$$G_E^s = 0.0025 \pm 0.0182$$

$$G_M^s = -0.011 \pm 0.254$$

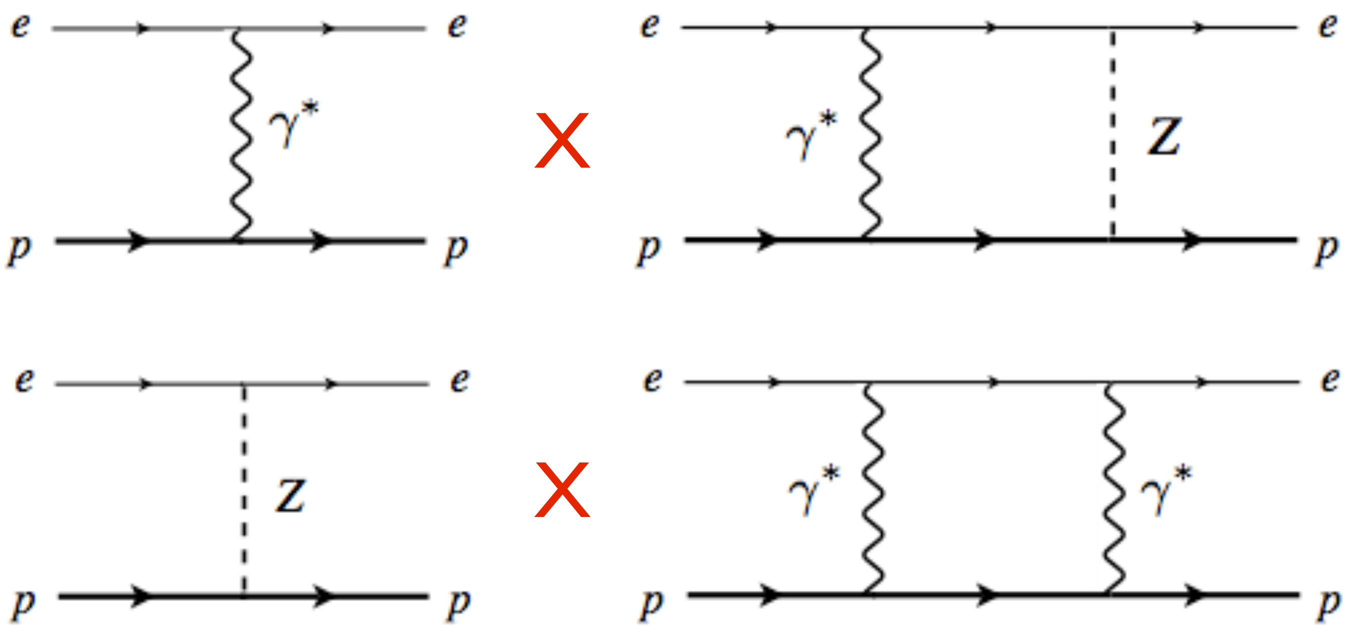
$$\text{at } Q^2 = 0.1\ \mathrm{GeV}^2$$

$\Longrightarrow$ very small!

*Young et al., PRL **97** (2006) 102002*

Two-boson exchange corrections

Two-boson exchange corrections



"$\gamma(Z\gamma)$"

"$Z(\gamma\gamma)$"

- current PDG estimates computed at $Q^2 = 0$

  Marciano, Sirlin (1980)
  Erler, Ramsey-Musolf (2003)

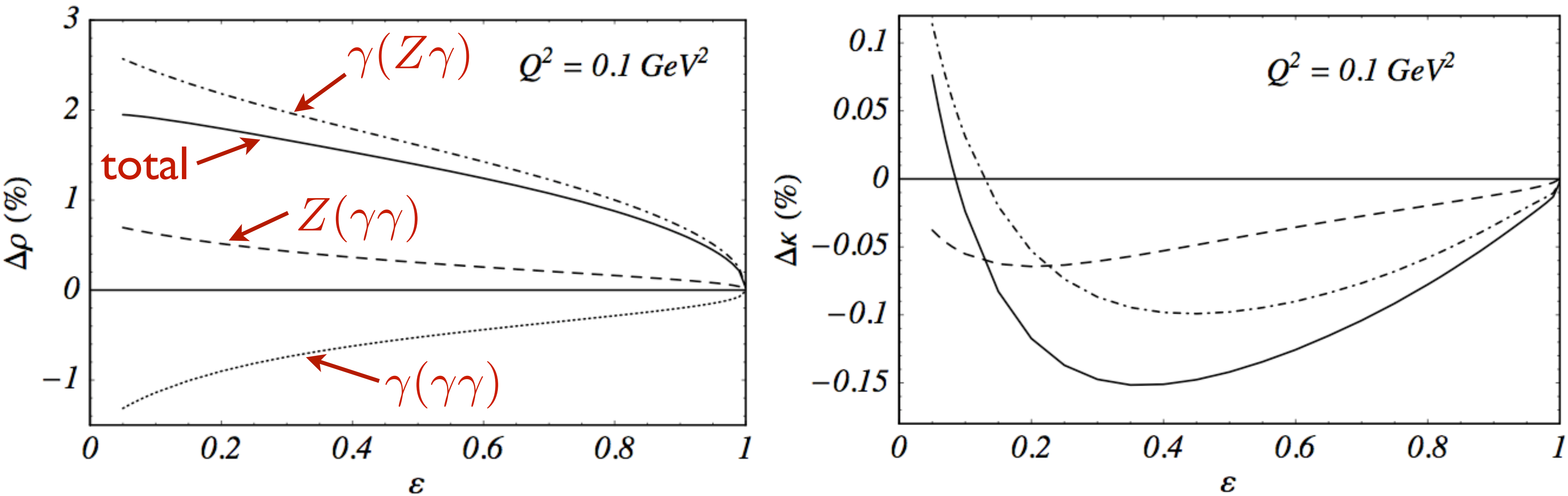
- do not include hadron structure effects
  (parameterized via ZNN form factors)

Including TBE corrections,

$$\rho = \rho_0 + \Delta\rho \;, \qquad \kappa = \kappa_0 + \Delta\kappa$$

standard RCs

Born-TBE interference

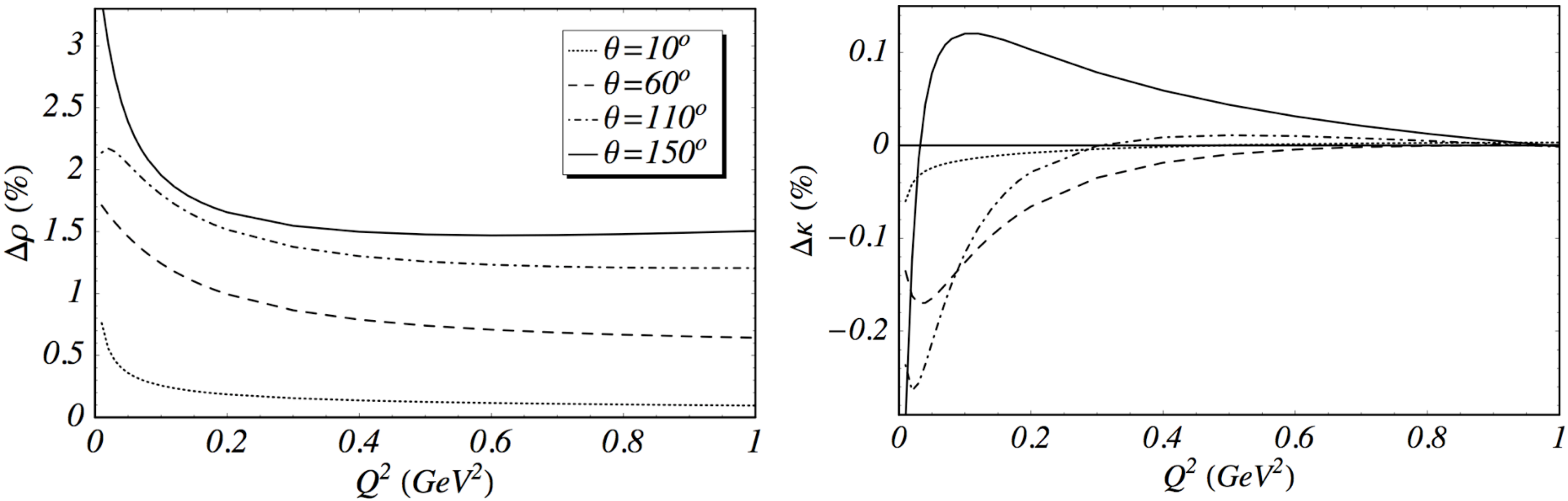


Tjon, WM, PRL ***100*** *(2008) 082003*

→ some cancellation between $Z(\gamma\gamma)$ and $\gamma(\gamma\gamma)$ corrections in $\Delta\rho$

→ effect driven by $\gamma(Z\gamma)$

Two-boson exchange corrections

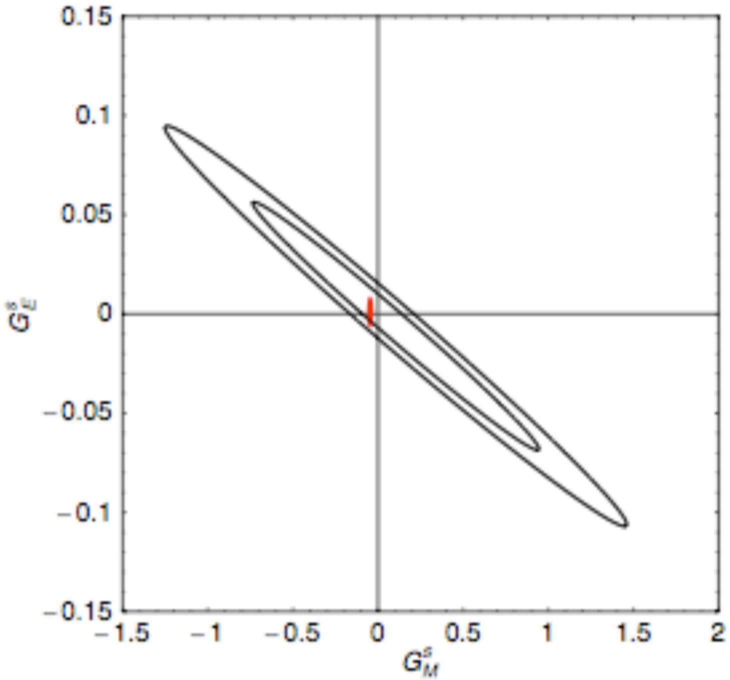


Tjon, WM, PRL ***100*** *(2008) 082003*

- 2–3% correction at $Q^2 < 0.1$ GeV^2
- strong Q^2 dependence at low Q^2

Effects on strange form factors

- global analysis of PVES data for $Q^2 < 0.3\ \mathrm{GeV}^2$



$$G_E^s = 0.0025 \pm 0.0182$$

$$G_M^s = -0.011 \pm 0.254$$

at $Q^2 = 0.1\ \mathrm{GeV}^2$

Young et al., PRL ***97*** *(2006) 102002*

- including TBE corrections:

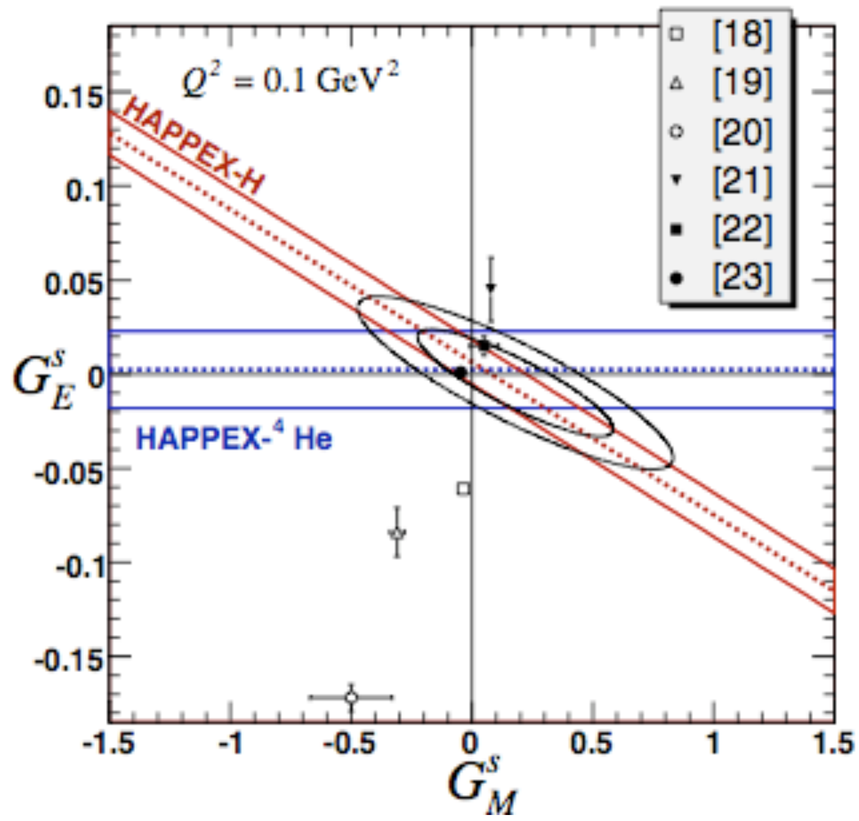
$$\boxed{\begin{aligned} G_E^s &= 0.0023 \pm 0.0182 \\ G_M^s &= -0.020 \pm 0.254 \end{aligned}}$$

at $Q^2 = 0.1\ \mathrm{GeV}^2$

$\Rightarrow$ qualitative result does not change

Effects on strange form factors

- even more recent data, from HAPPEX experiment at JLab (H and ^{4}He targets)



Acha et al., PRL ***98*** *(2007) 032301*

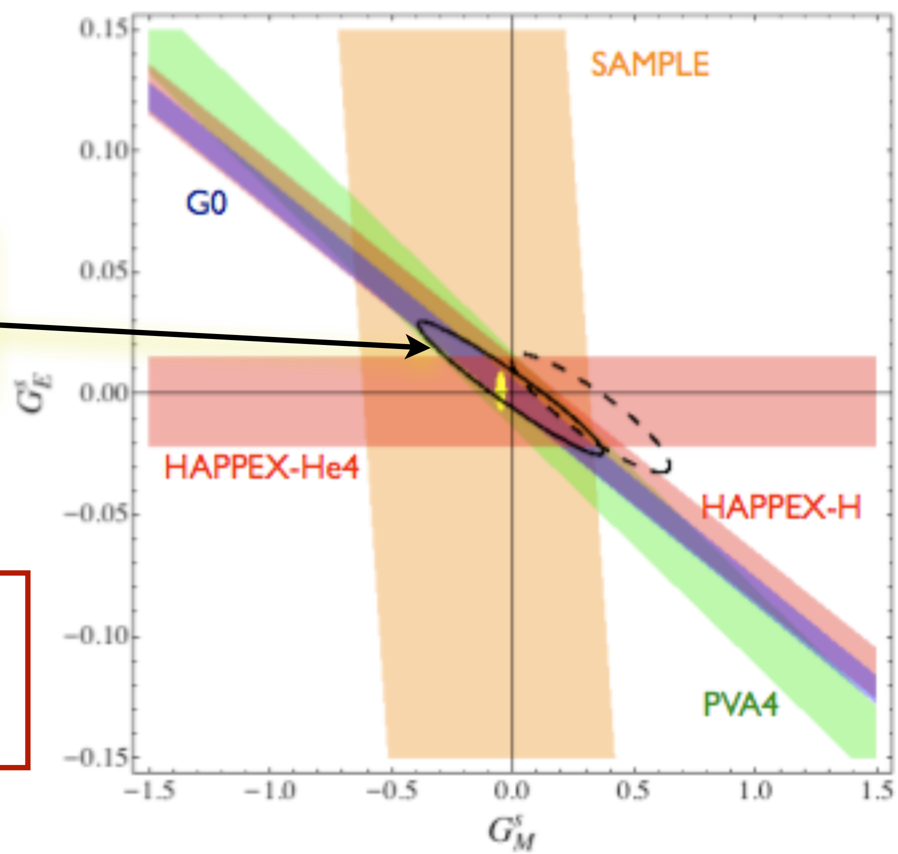
$$\boxed{\begin{aligned} G_E^s &= -0.005 \pm 0.019 \\ G_M^s &= -0.18 \pm 0.27 \end{aligned}}$$

from HAPPEX experiment

Effects on strange form factors

- combining new HAPPEX results with global data

constrained by data only



$$G_E^s = 0.002 \pm 0.018$$
$$G_M^s = -0.01 \pm 0.25$$

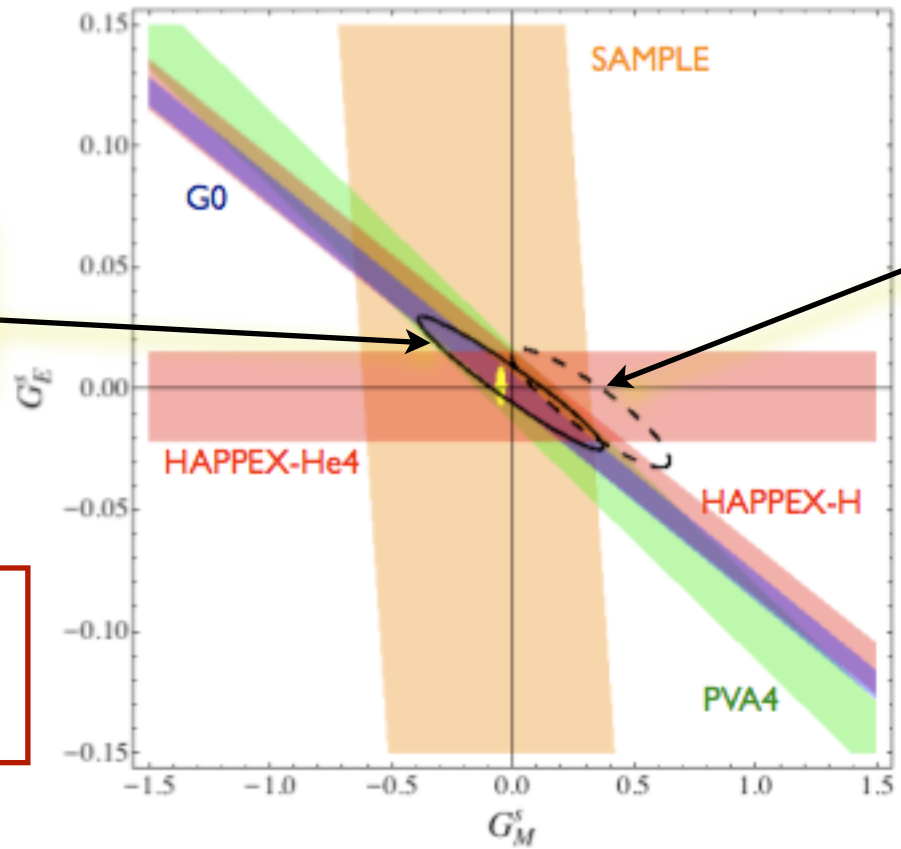
*Young et al., PRL **99** (2008) 122003*

Effects on strange form factors

- combining new HAPPEX results with global data

constrained by data only

includes theoretical prediction for G_A



*Young et al., PRL **99** (2008) 122003*

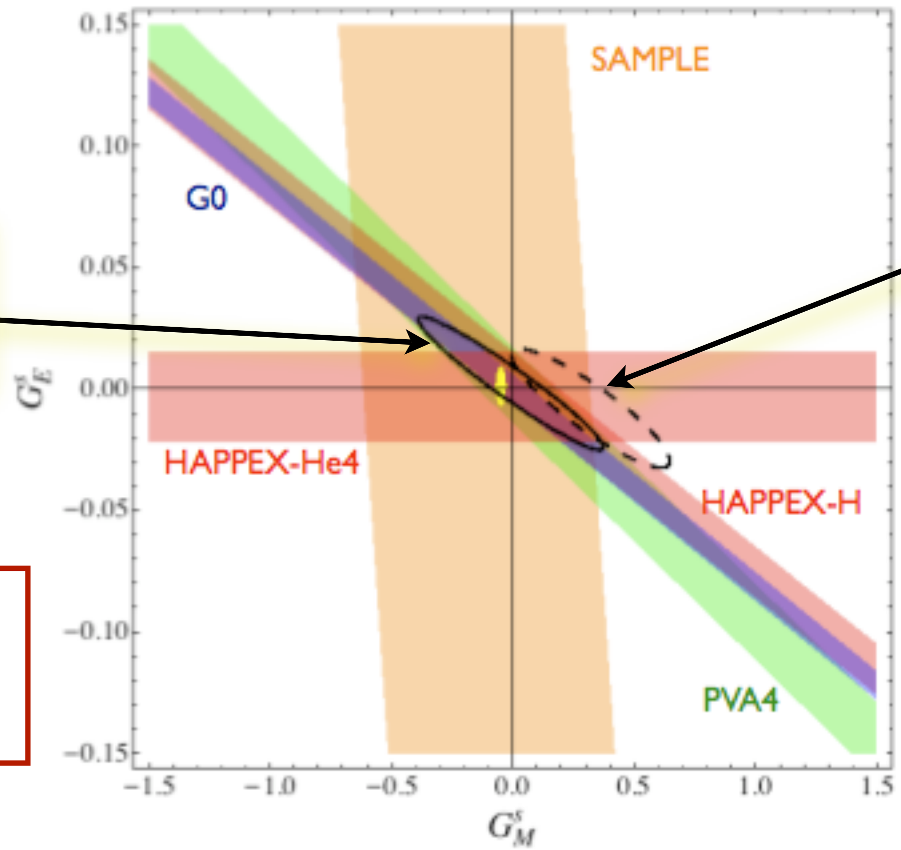
$$G_E^s = 0.002 \pm 0.018$$
$$G_M^s = -0.01 \pm 0.25$$

$$G_E^s = -0.011 \pm 0.016$$
$$G_M^s = 0.22 \pm 0.20$$

Effects on strange form factors

- combining new HAPPEX results with global data

constrained by data only



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$G_E^s = 0.002 \pm 0.018$
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$G_E^s = -0.011 \pm 0.016$
$G_M^s = 0.22 \pm 0.20$

Young et al., PRL ***99*** *(2008) 122003*

⇒ strangeness content of nucleon very small

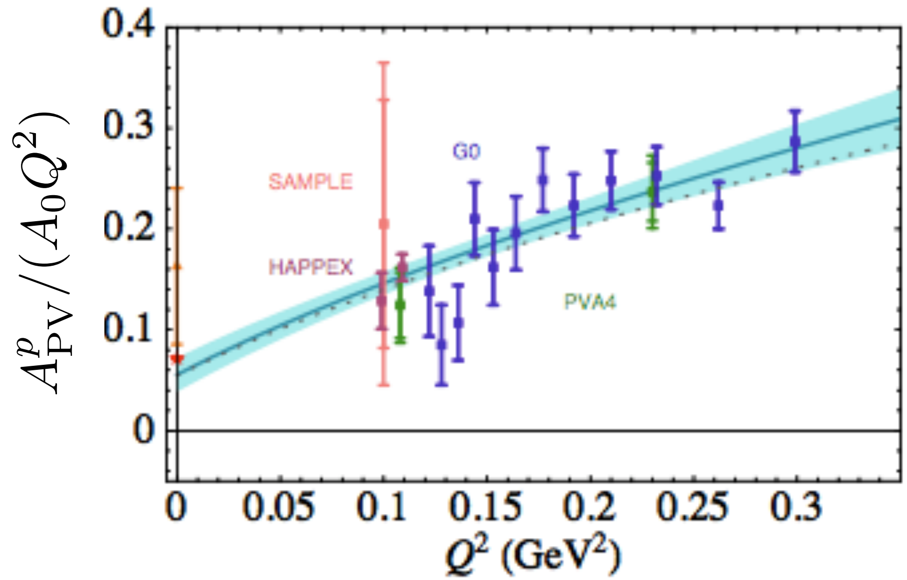
⇒ electromagnetic structure is valence quark dominated

Constraints on "new physics"

Constraints on "new physics"

- expand asymmetry in powers of Q^2 at low Q^2

$$A_{\mathrm{PV}}^p = A_0 \left(Q_{\mathrm{w}}^p Q^2 + B_4 Q^4 + \cdots \right)$$



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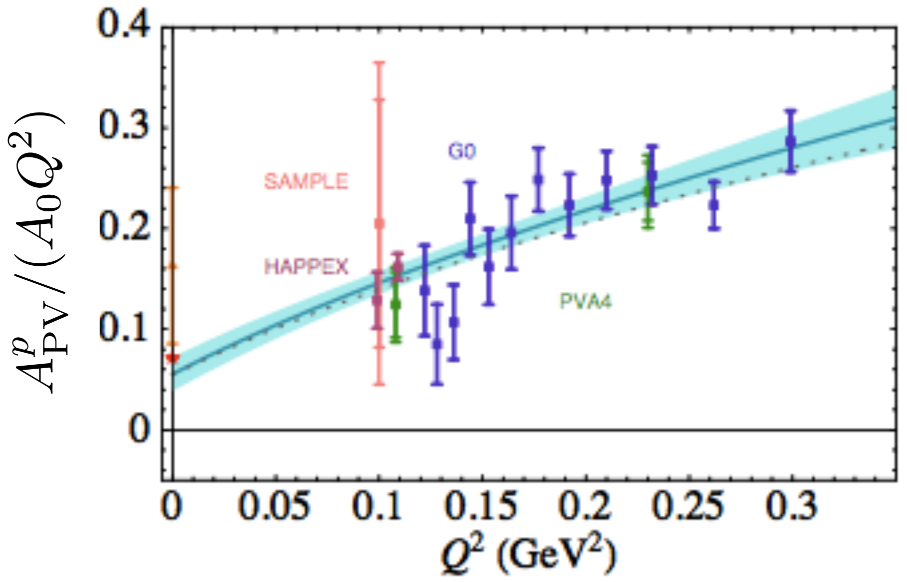
$$A_{\rm PV}^p = A_0 \left(Q_{\rm w}^p Q^2 + B_4 Q^4 + \cdots \right)$$

$-G_F/4\sqrt{2}\pi\alpha$

hadron structure dependent



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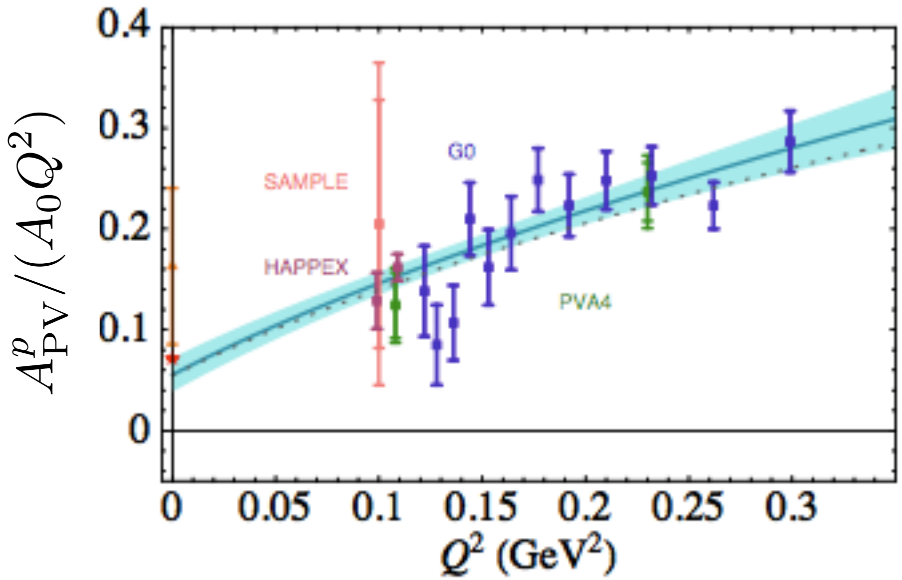

$\longrightarrow$ proton weak charge

$$\begin{aligned} Q^p_{\rm W} &= G_E^{Zp}(0) \\ &= -2\,(2C_{1u} + C_{1d}) \\ &= 1 - 4\sin^2\theta_W \end{aligned}$$

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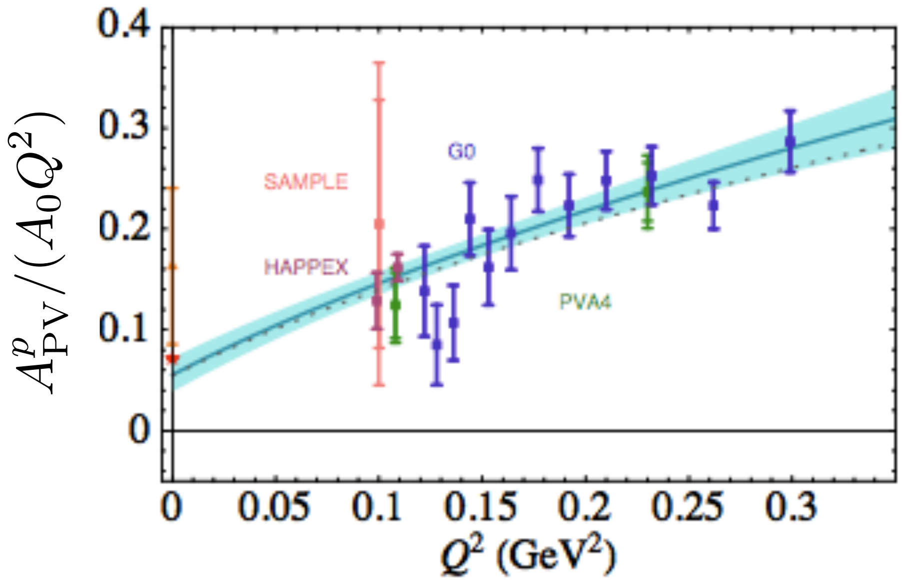

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PV eq effective interaction

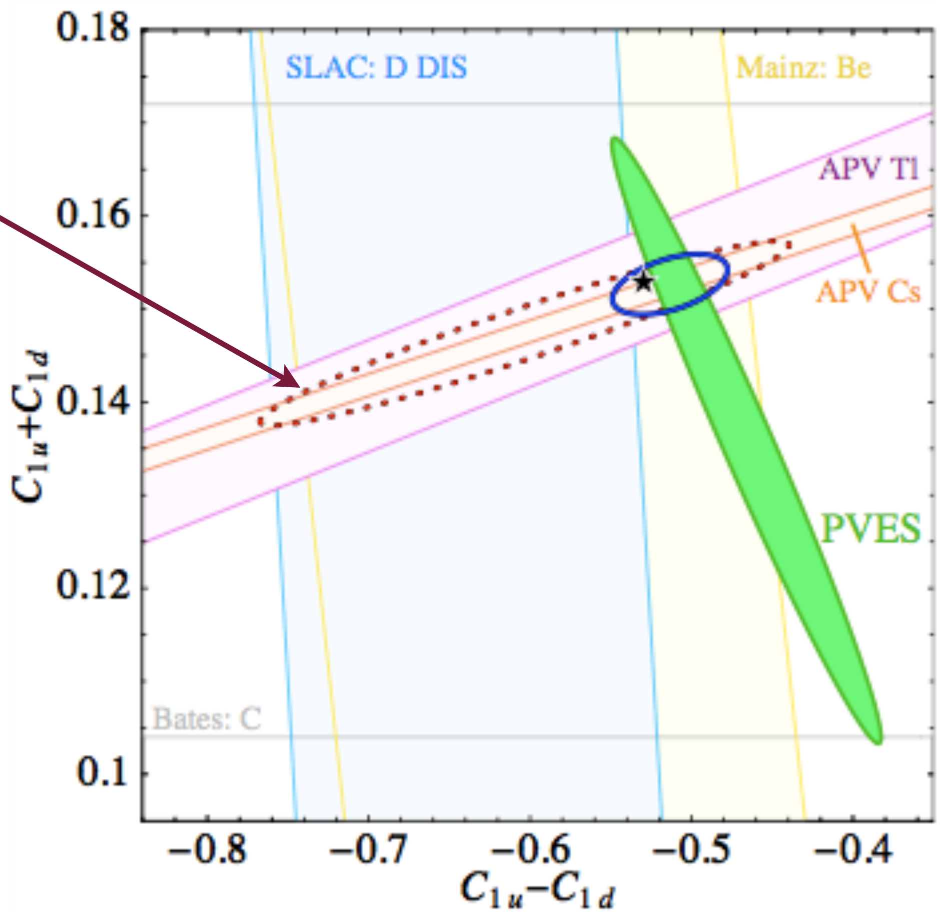
$$\mathcal{L}^{eq}_{\rm PV} = -\frac{G_F}{\sqrt{2}}\ \bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\ \bar{q}\gamma^\mu q$$

$$C_{1u} = g_A^e\ g_V^u = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W$$

$$C_{1d} = g_A^e\ g_V^d = +\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$$

Constraints on “new physics”

without PVES
(mostly Atomic
Parity Violation)



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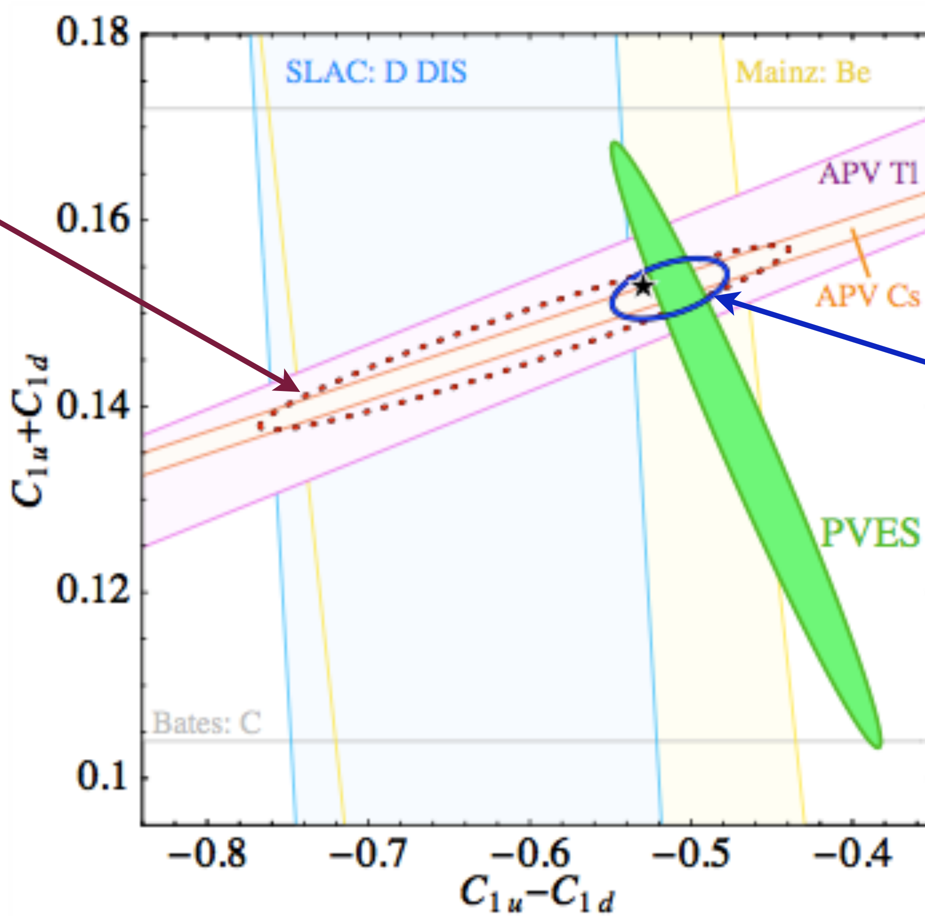
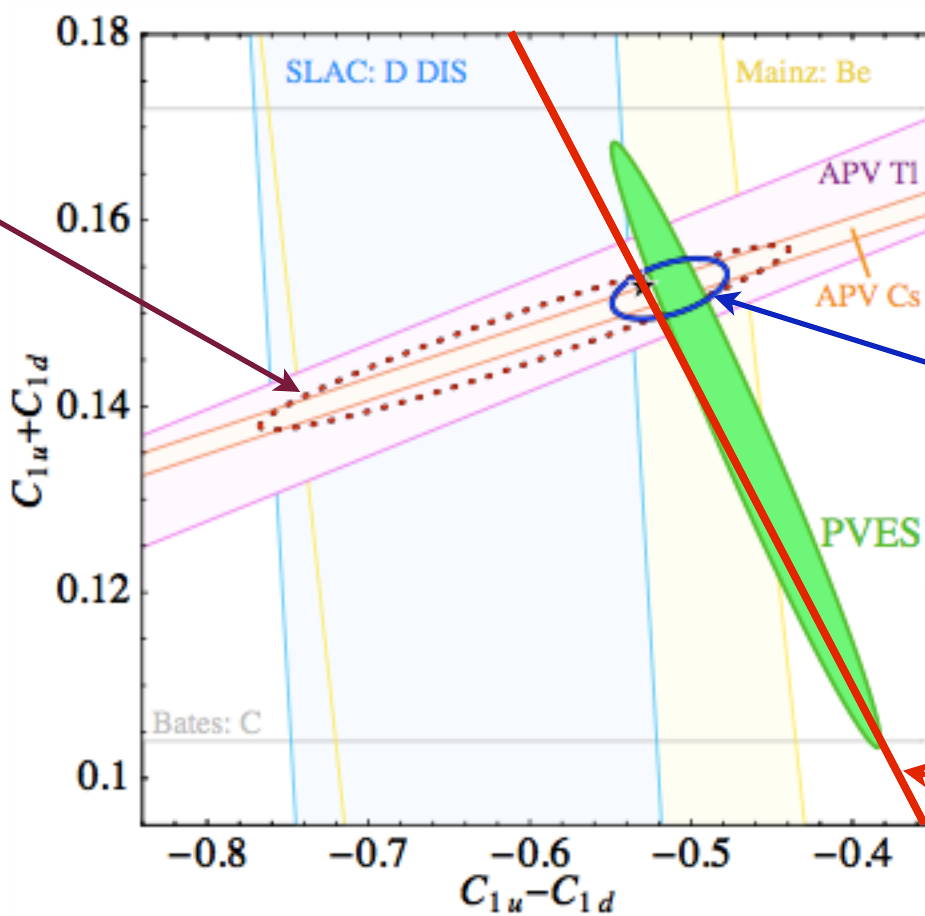


including PVES –
factor 5 reduction

Constraints on "new physics"

without PVES
(mostly Atomic
Parity Violation)

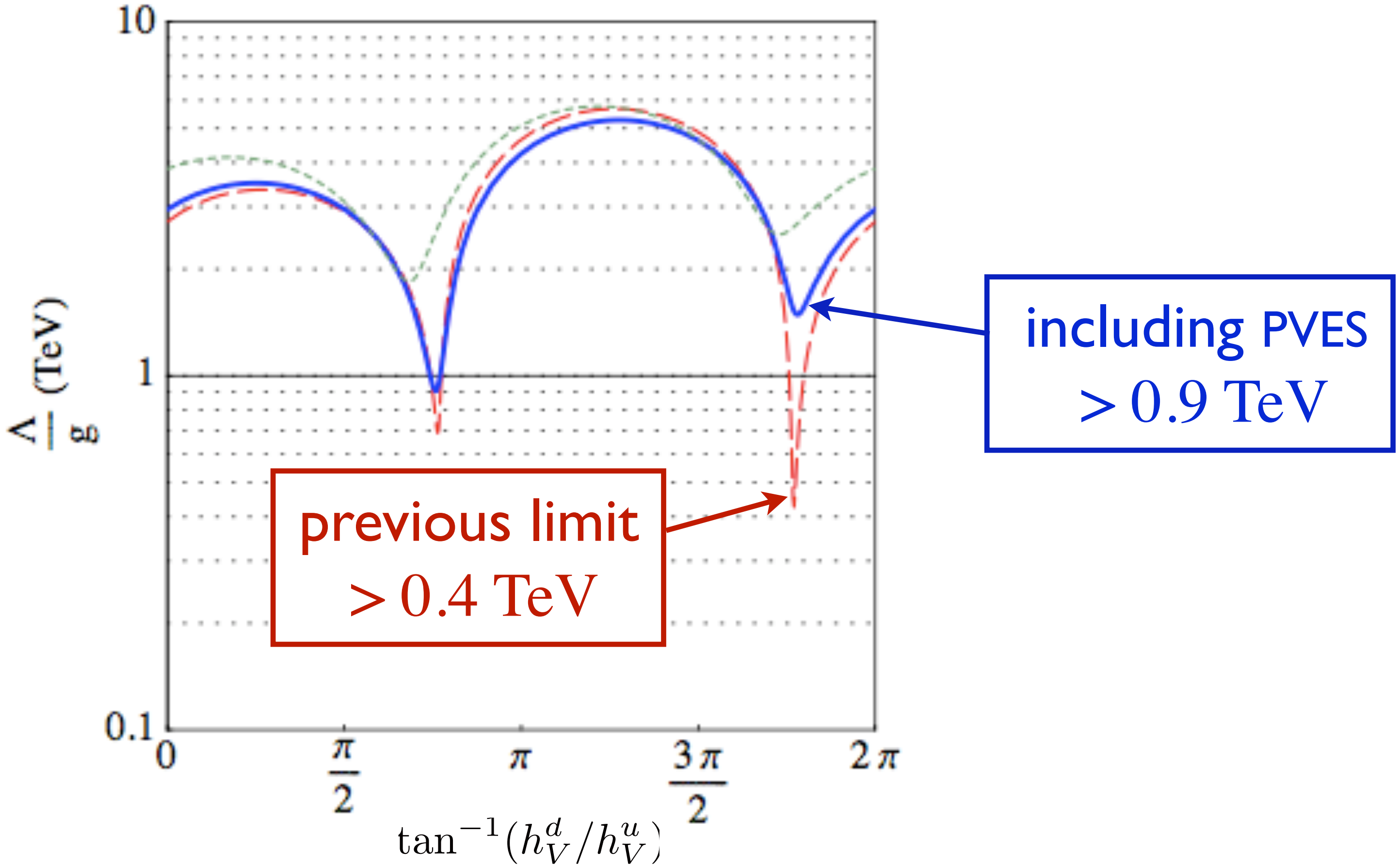


including PVES –
factor 5 reduction

"Q-weak" experiment
at 12 GeV JLab

Constraints on "new physics"

- new physics ($e.g.$ heavy Z' boson) expressed through effective contact interaction $$\mathcal{L}^{eq}_{\rm new} = \frac{g^2}{\Lambda^2}\ \bar{e}\gamma_\mu\gamma_5 e \sum_q h^q_V\ \bar{q}\gamma^\mu q$$



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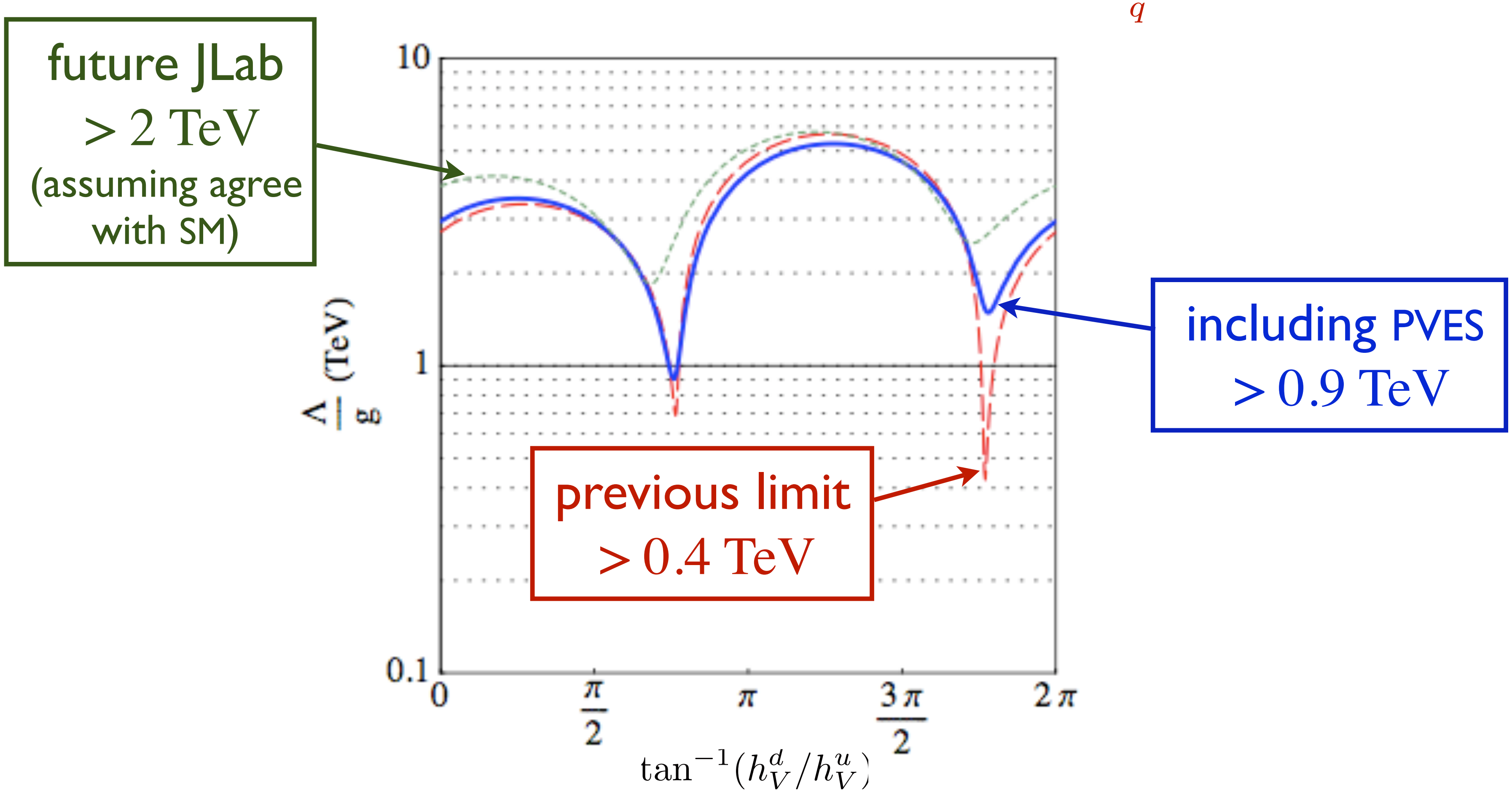

→ constraints complementary to LHC potential

Summary

- TPE corrections resolve most of Rosenbluth / PT G_E^p/G_M^p discrepancy

  $\longrightarrow$ excited state contributions $(\Delta, P_{11}(1440), S_{11}(1535), ...)$ small relative to nucleon

- Reanalysis of global data, including TPE from the outset

  $\longrightarrow$ first consistent form factor fit at order α^3

  $\longrightarrow$ "25% less charge" in the center of the proton

- Precise measurement of strange form factor

  $\longrightarrow$ very small (consistent with zero!)

  $\longrightarrow$ photon-Z exchange gives ~2% corrections

  $\longrightarrow$ constrains "new physics" to above ~ 1 TeV

The End

Research opportunities at JLab

www.jlab.org

- Ph. D. studies
  - → through nearby universities *(William & Mary, Old Dominion, etc.)*
  - → "sandwich" doctorate from Brazil (~ 1 year at JLab)

- Undergraduate summer* internships
  - → ~ 3 months research experience at JLab (June−August)

- HUGS (Hampton University Graduate Studies) summer* school
  - → annual 3 week school at JLab for graduate students

- Contact wmelnitc@jlab.org for more information

* northern summer

Obrigado!

Obrigado!

Boa sorte!