Two-photon exchange in elastic e-p scattering: partonic picture

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Outline

Motivation

General scattering amplitude in elastic e-N scattering

Partonic calculation of two-photon exchange contribution at large Q^2

Result and other extensions

Summary

Motivation

Why we interested in two-photon physics

Starting from the electric and magnetic form factors (G_E & G_M)

which are defined by the electromagnetic current J^μ :

$$\langle N(p')|J^\mu(0)|N(p)\rangle = e\bar{u}(p')\left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}(p'-p)_\nu}{2M}\right]u(p),$$

$$G_M(Q^2) = F_1 + F_2$$

$$G_E(Q^2) = F_1 - \tau F_2 = G_M - (1+\tau)F_2$$

then the differential cross section for e-N scattering is given by:

$$\left(\frac{d\sigma}{d\Omega}\right)_{Born} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\frac{1}{1+\tau}\left[G_E^2(Q^2) + \frac{\tau}{\varepsilon}G_M^2(Q^2)\right],$$

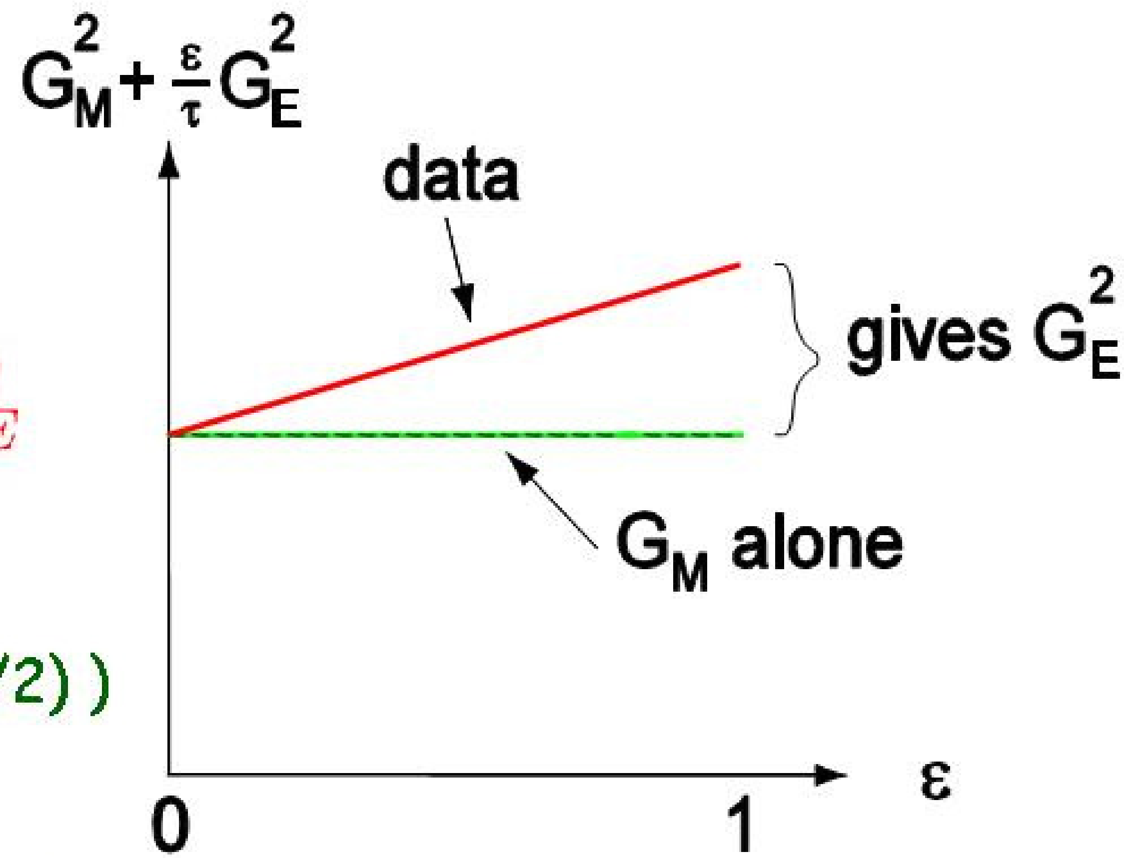
Rosenbluth separation method (LT)

reduced cross section:

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

at a fix Q^2, vary ε

$(1/\varepsilon = 1 + 2(1+\tau)\tan^2(\theta_{lab}/2))$



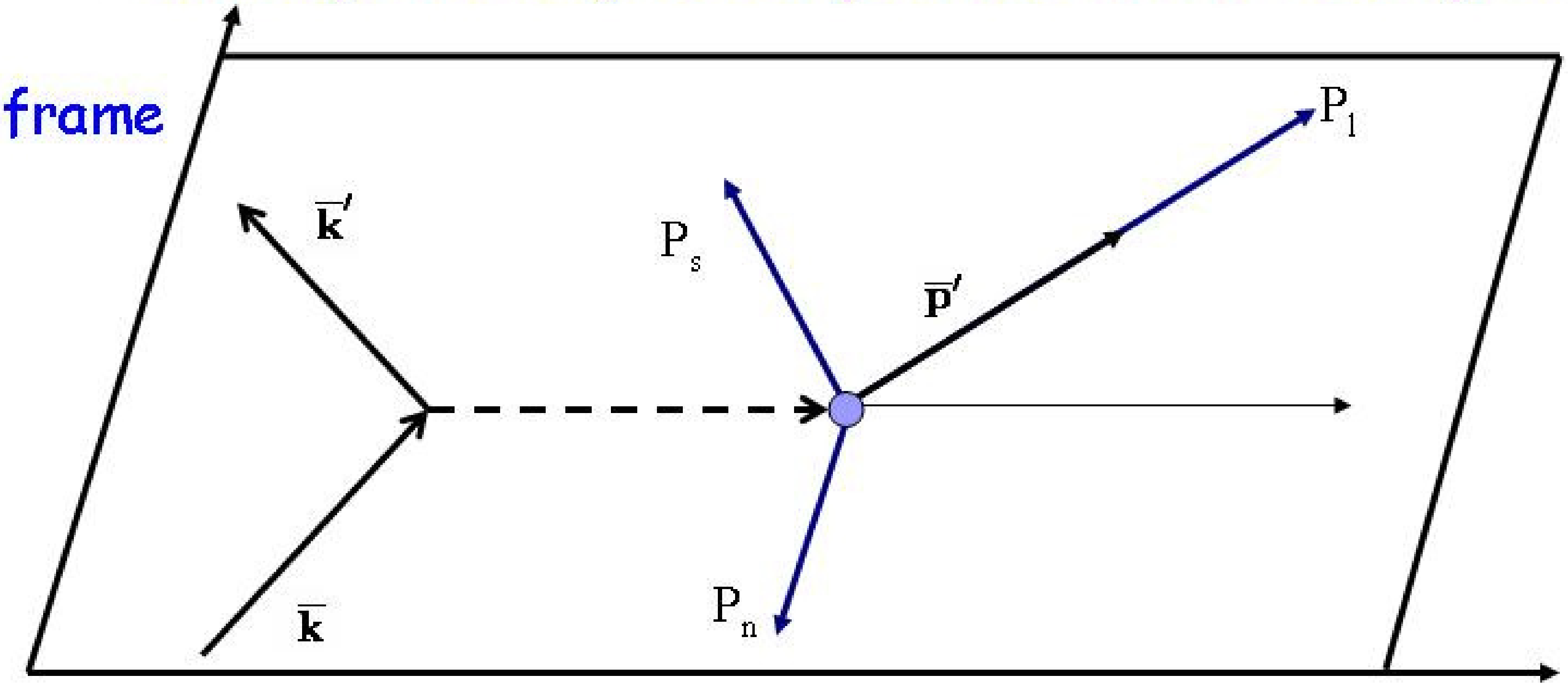
in the elastic e-p scattering, one gets:

$$G_M(Q^2)/\mu_p \cong G_E(Q^2) \cong \frac{1}{(1+Q^2/0.71GeV^2)^2} = G_D(Q^2)$$

Polarization transfer method

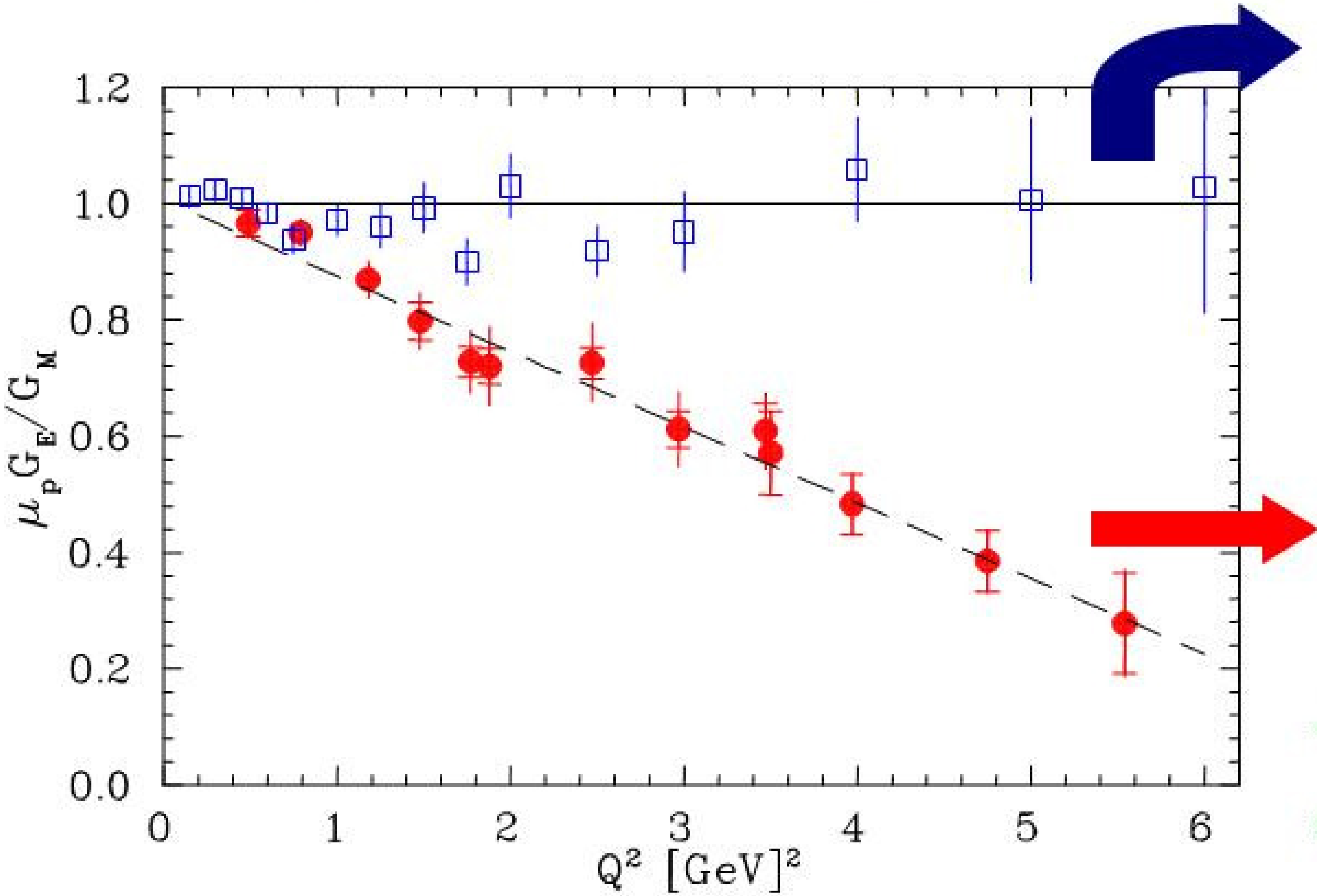
Polarized electron beam
→ sideways and longitudinal polarization for recoil proton

Lab frame



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

Two independent measurement of R(G_E/G_M)



SLAC

Rosenbluth data

Jlab/Hall A

Polarization data

Jones et al. (2000)

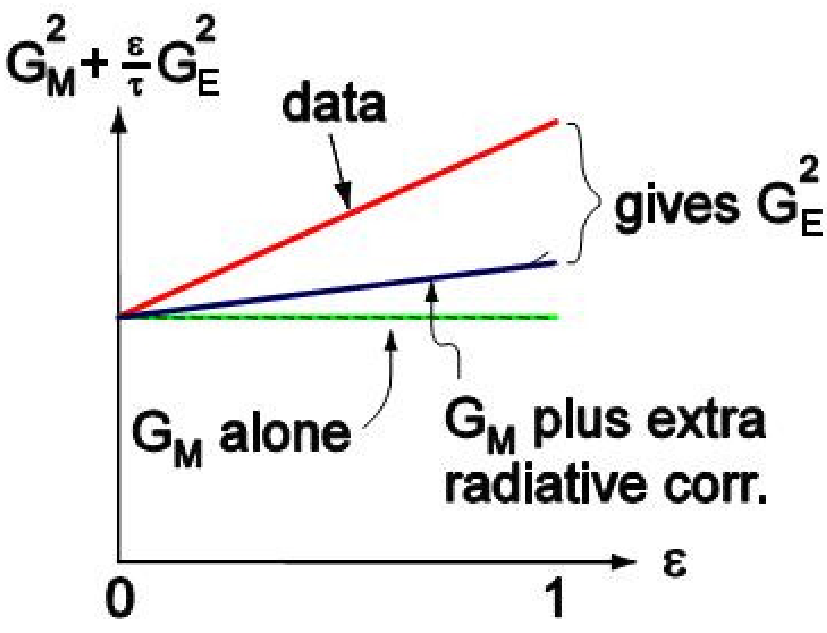
Gayou et al. (2002)

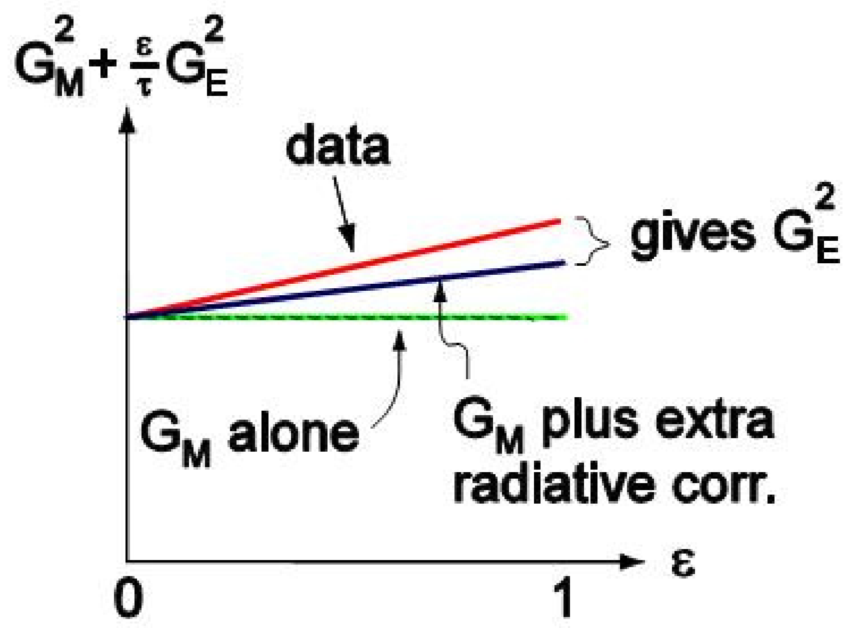
Two methods, two different results !

Speculation : missing radiative corrections

Speculation : there are radiative corrections to Rosenbluth experiments that are important and are not included

missing correction : linear in ε, not strongly Q^2 dependent



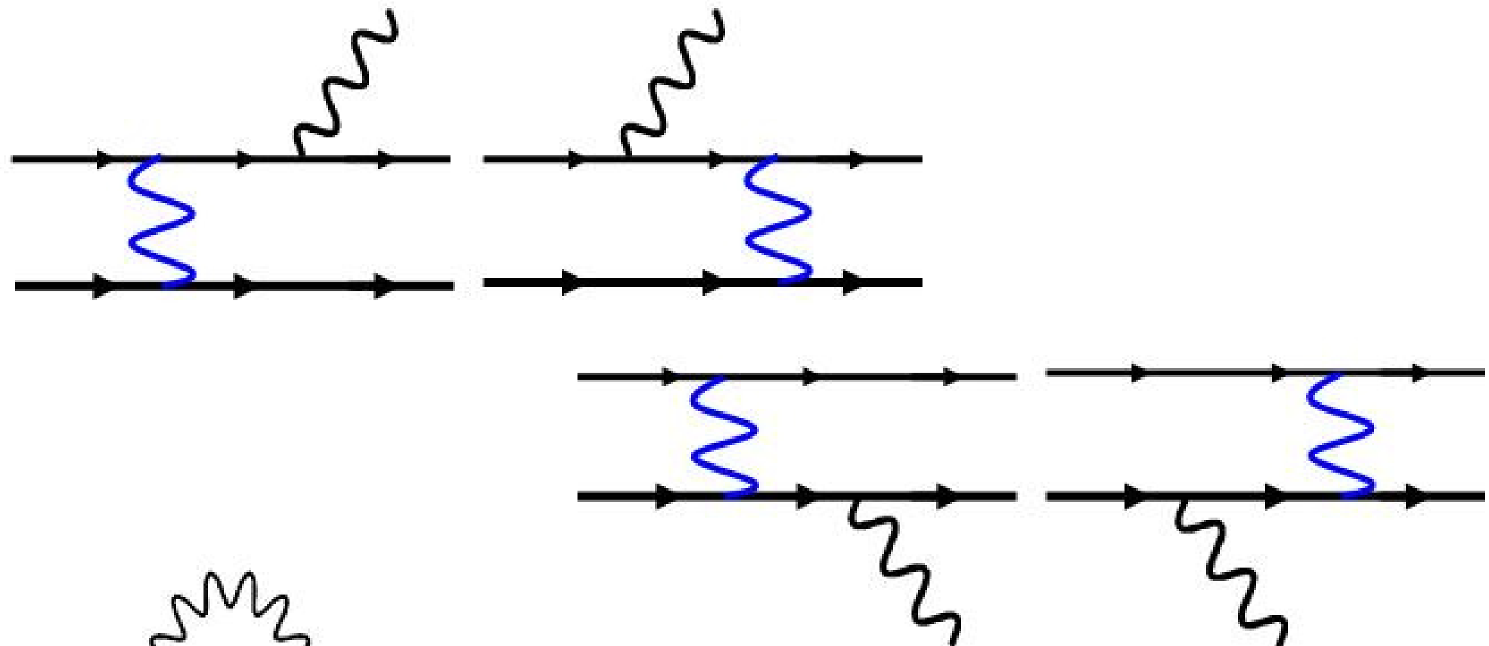


G_E term is proportionally smaller at large Q^2

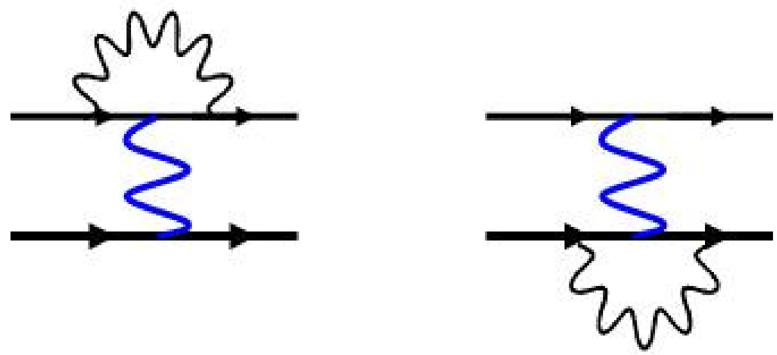
effect is more visible at large Q^2

Radiative correction diagrams

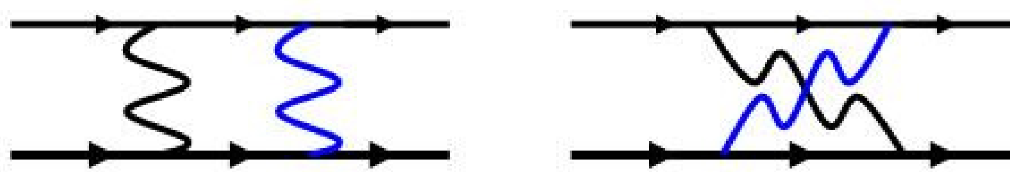
bremsstrahlung



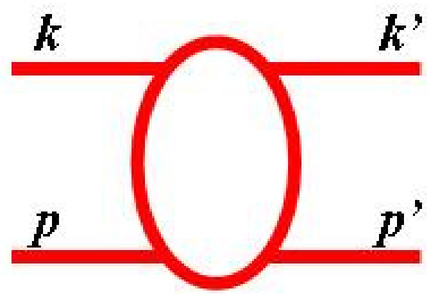
vertex corrections



2 photon exchange box diagrams



General scattering amplitude in elastic e-N scattering



$$l(k) + N(p) \rightarrow l(k') + N(p'),$$

$$P \equiv \frac{p+p'}{2}, K \equiv \frac{k+k'}{2}, s = (p+k)^2, u = (p-k)^2,$$

$$q = k - k' = p' - p, Q^2 = -q^2, \nu = (K \cdot P),$$

$$p^2 = p'^2 = M^2, k^2 = k'^2 = m_e^2 \ll M^2, s, u, Q^2.$$

For a theory respects Lorentz, parity and charge conjugation invariance, the elastic electron-nucleon scattering amplitude can be expanded in terms of six independent Lorentz structure, and one can separate the elastic electron-nucleon scattering amplitude into:

$$T = T^{non-flip} + T^{flip}$$

where

$$\begin{aligned} T^{non-flip}_{h'\lambda'_N, h\lambda_N} &= \frac{e^2}{Q^2}\,\bar{u}(k',h')\gamma_\mu u(k,h) \\ &\times \quad \bar{u}(p',\lambda'_N)\left(\tilde{G}_M\,\gamma^\mu - \tilde{F}_2\frac{P^\mu}{M} + \tilde{F}_3\frac{\gamma.K P^\mu}{M^2}\right)u(p,\lambda_N) \\ T^{flip}_{h'\lambda'_N, h\lambda_N} &= \frac{e^2}{Q^2}\frac{m_l}{M}\left[\bar{u}(k',h')u(k,h)\cdot\bar{u}(p',\lambda'_N)\left(\tilde{F}_4 + \tilde{F}_5\frac{\gamma.K}{M}\right)u(p,\lambda_N)\right. \\ &\quad \left. + \tilde{F}_6\,\bar{u}(k',h')\gamma_5 u(k,h)\cdot\bar{u}(p',\lambda'_N)\gamma_5 u(p,\lambda_N)\right] \end{aligned}$$

In one-photon-exchange approximation, the phases and all the F_{3-6} terms vanished, they must originate from process involving at least the change of two-photon. Similarly, define

$$\tilde{G}_E \equiv \tilde{G}_M - (1+\tau)\,\tilde{F}_2$$

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

$$\begin{aligned} \tilde{G}_M(\nu,Q^2) &= G_M(Q^2) + \delta\tilde{G}_M \\ \tilde{F}_2(\nu,Q^2) &= F_2(Q^2) + \delta\tilde{F}_2 \\ \tilde{F}_3(\nu,Q^2) &= 0 + \delta\tilde{F}_3 \end{aligned}$$

Observables including two-photon exchange

Real parts of two-photon amplitudes

$$\sigma_R = G_M^2 \left(1 + 2 \frac{\mathcal{R}\left(\delta \tilde{G}_M\right)}{G_M} \right) + \varepsilon \left\{ \frac{1}{\tau} G_E^2 \left(1 + 2 \frac{\mathcal{R}\left(\delta \tilde{G}_E\right)}{G_E} \right) + 2 G_M^2 \left(1 + \frac{1}{\tau} \frac{G_E}{G_M} \right) \underbrace{\frac{\nu}{M^2} \frac{\mathcal{R}\left(\tilde{F}_3\right)}{G_M}}_{Y_{2\gamma}} \right\} + \mathcal{O}(e^4)$$

$$\frac{P_s}{P_l} = -\sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}} \left\{ \frac{G_E}{G_M} \left(1 - \frac{\mathcal{R}\left(\delta \tilde{G}_M\right)}{G_M} \right) + \frac{\mathcal{R}\left(\delta \tilde{G}_E\right)}{G_M} + \left(1 - \frac{2\varepsilon}{1+\varepsilon} \frac{G_E}{G_M} \right) \underbrace{\frac{\nu}{M^2} \frac{\mathcal{R}\left(\tilde{F}_3\right)}{G_M}}_{Y_{2\gamma}} \right\} + \mathcal{O}(e^4)$$

Observables including two-photon exchange

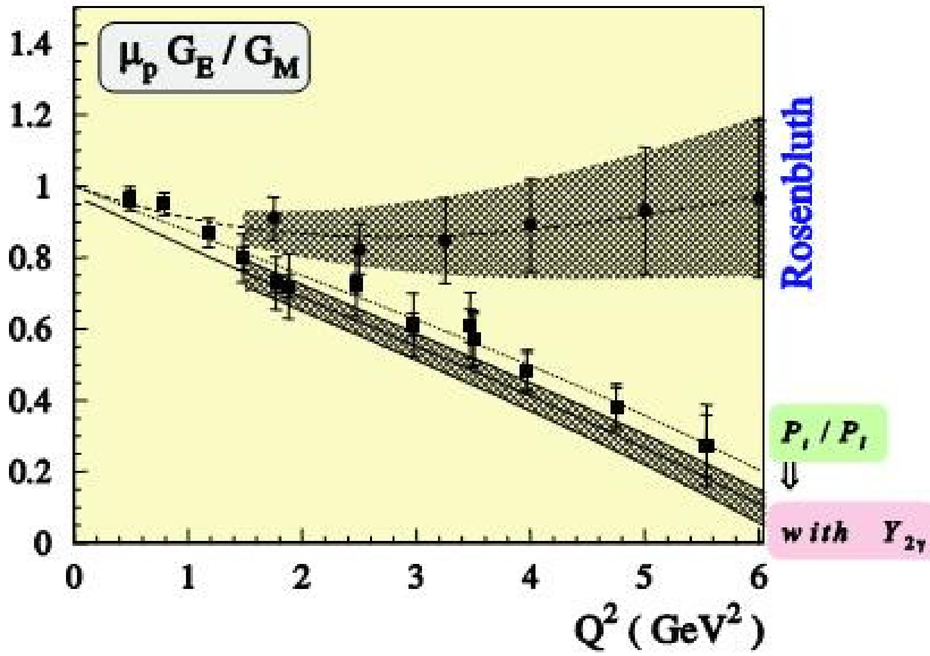
Real parts of two-photon amplitudes

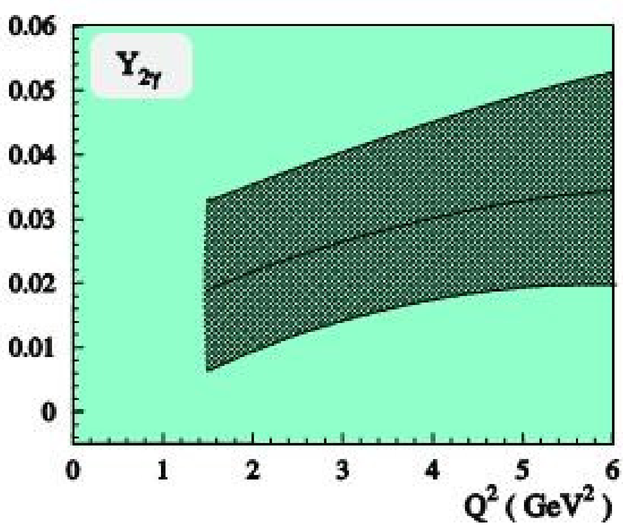
$$(R^{exp}_{Rosenbluth})^2 \simeq \frac{|\tilde{G}_E|^2}{|\tilde{G}_M|^2} + 2\left(\tau + \frac{|\tilde{G}_E|}{|\tilde{G}_M|}\right) Y_{2\gamma}$$

effect is more visible at large $Q^2(\tau)$

$$(R^{exp}_{Polarization}) \simeq \frac{|\tilde{G}_E|}{|\tilde{G}_M|} + \left(1 - \frac{2\varepsilon}{1+\varepsilon}\frac{|\tilde{G}_E|}{|\tilde{G}_M|}\right) Y_{2\gamma}$$

effect is small as $Y_{2\gamma}$ is small



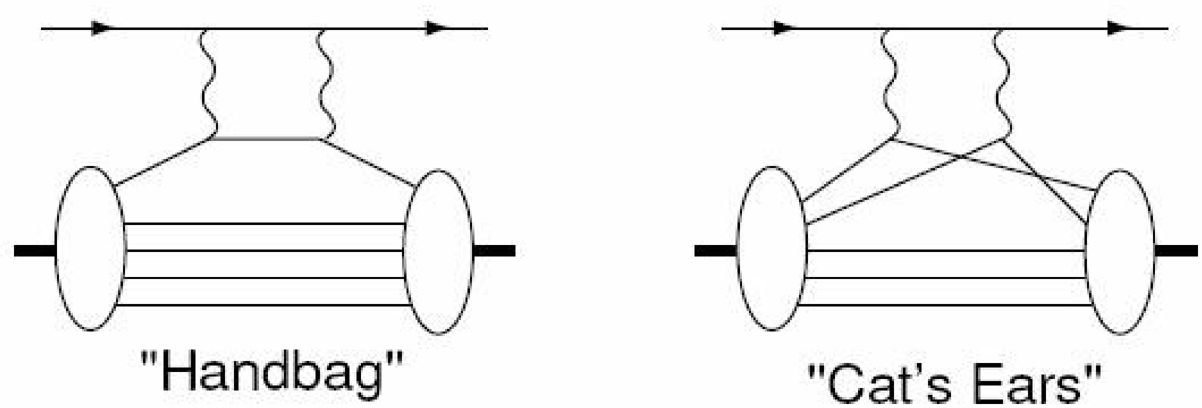


2-photon exchange is a candidate to explain the discrepancy between both experimental methods

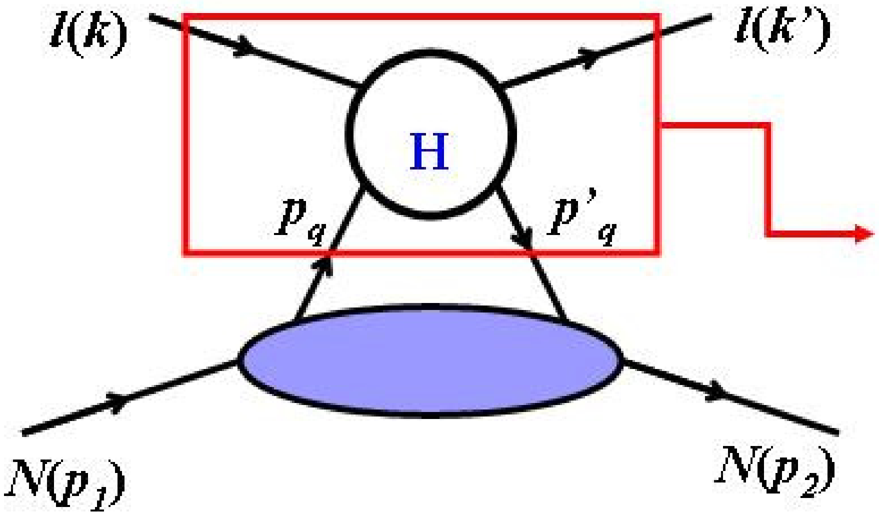
P. Guichon and M. Vanderhaeghen, (2003)

Partonic calculation of two-photon exchange contribution at large Q^2

To estimate δG_M, δF_2 ,and F_3 at large Q^2, we start from calculating the elastic e-q scattering with massless quarks.

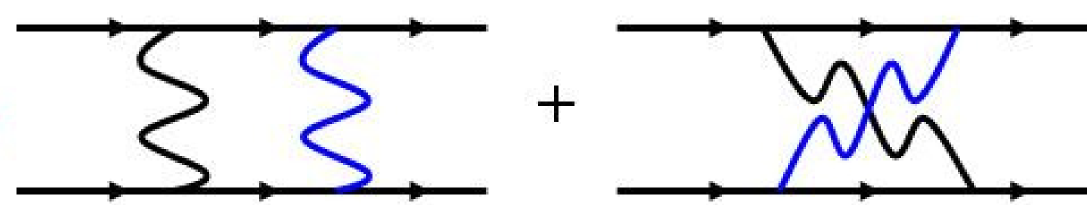


- Main contributions comes from "handbag diagrams" when both photons are hard at large Q^2.
- "Cat's ears" diagrams is important for getting over all IR divergence correct.



hard scattering amplitude

$l(k) + q(p_q) \rightarrow l(k') + q(p'_q)$



S_{Direct} and S_{Cross}

$$H_{h,\lambda} = \frac{(e\, e_q)^2}{Q^2}\, \bar{u}(k', h)\gamma_\mu u(k, h) \cdot \bar{u}(p'_q, \lambda)\left(\tilde{f}_1\, \gamma^\mu + \tilde{f}_3\, \gamma.K\, P_q^\mu \right) u(p_q, \lambda)$$

electron helicity

quark helicity

$$K \equiv (k + k')/2 \qquad P_q \equiv (p_q + p'_q)/2$$

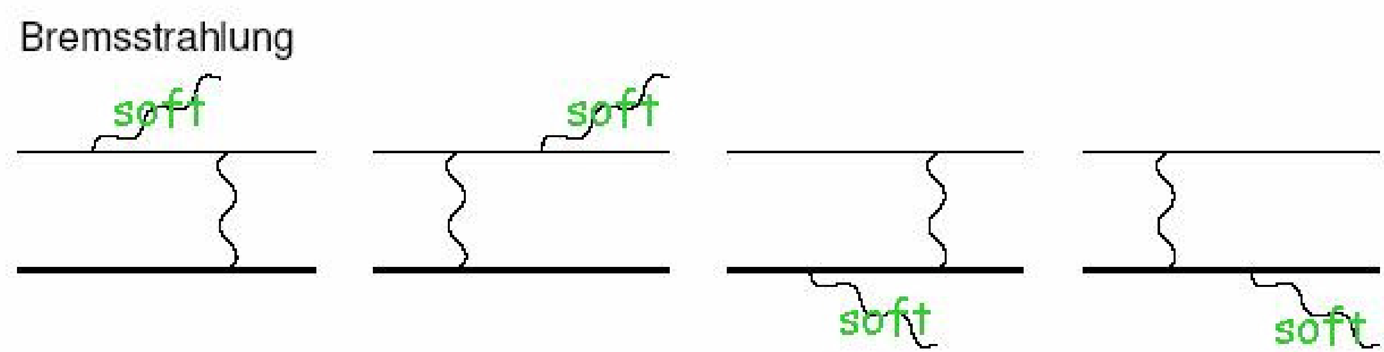
kinematics for partonic subprocess :

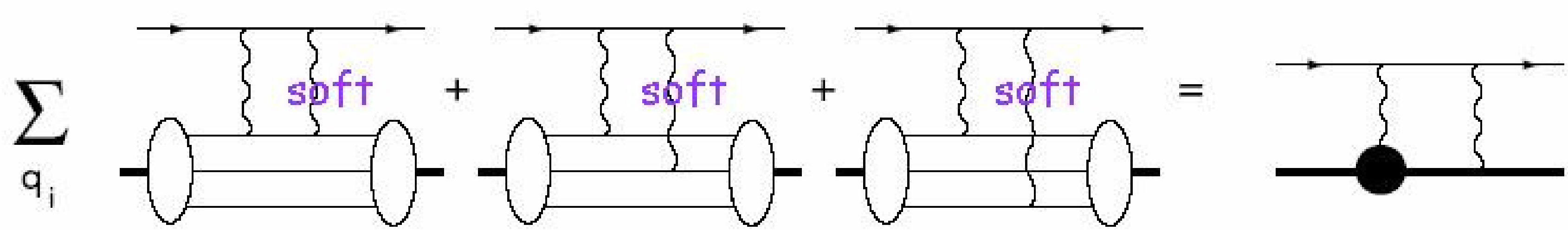
$$\hat{s} \equiv (k + p_q)^2, \quad \hat{u} \equiv (k - p'_q)^2, \quad \hat{s} + \hat{u} = Q^2$$

λ is infinitesimal photon mass

$$R\left(\tilde{f}_1\right) = \frac{e^2}{4\pi^2}\left\{\ln\left(\frac{\lambda^2}{\sqrt{-\widehat{s}\widehat{u}}}\right)\ln\left|\frac{\hat{s}}{\hat{u}}\right| + \frac{\pi^2}{2} + \frac{1}{2}\ln\left|\frac{\hat{s}}{\hat{u}}\right| + \frac{Q^2}{4}\left[\frac{1}{\widehat{u}}\ln^2\left|\frac{\hat{s}}{Q^2}\right| - \frac{1}{\hat{s}}\ln^2\left|\frac{\hat{u}}{Q^2}\right| - \frac{1}{\hat{s}}\pi^2\right]\right\}$$

$$R\left(\tilde{f}_3\right) = \frac{e^2}{4\pi^2}\left\{\hat{s}\ln\left|\frac{\hat{s}}{Q^2}\right| + \hat{u}\ln\left|\frac{\hat{u}}{Q^2}\right| + \frac{\hat{s}-\hat{u}}{2}\left[\frac{\hat{s}}{\hat{u}}\ln^2\left|\frac{\hat{s}}{Q^2}\right| - \frac{\hat{u}}{\hat{s}}\ln^2\left|\frac{\hat{u}}{Q^2}\right| - \frac{\hat{u}}{\hat{s}}\pi^2\right]\right\}$$





λ is infinitesimal photon mass

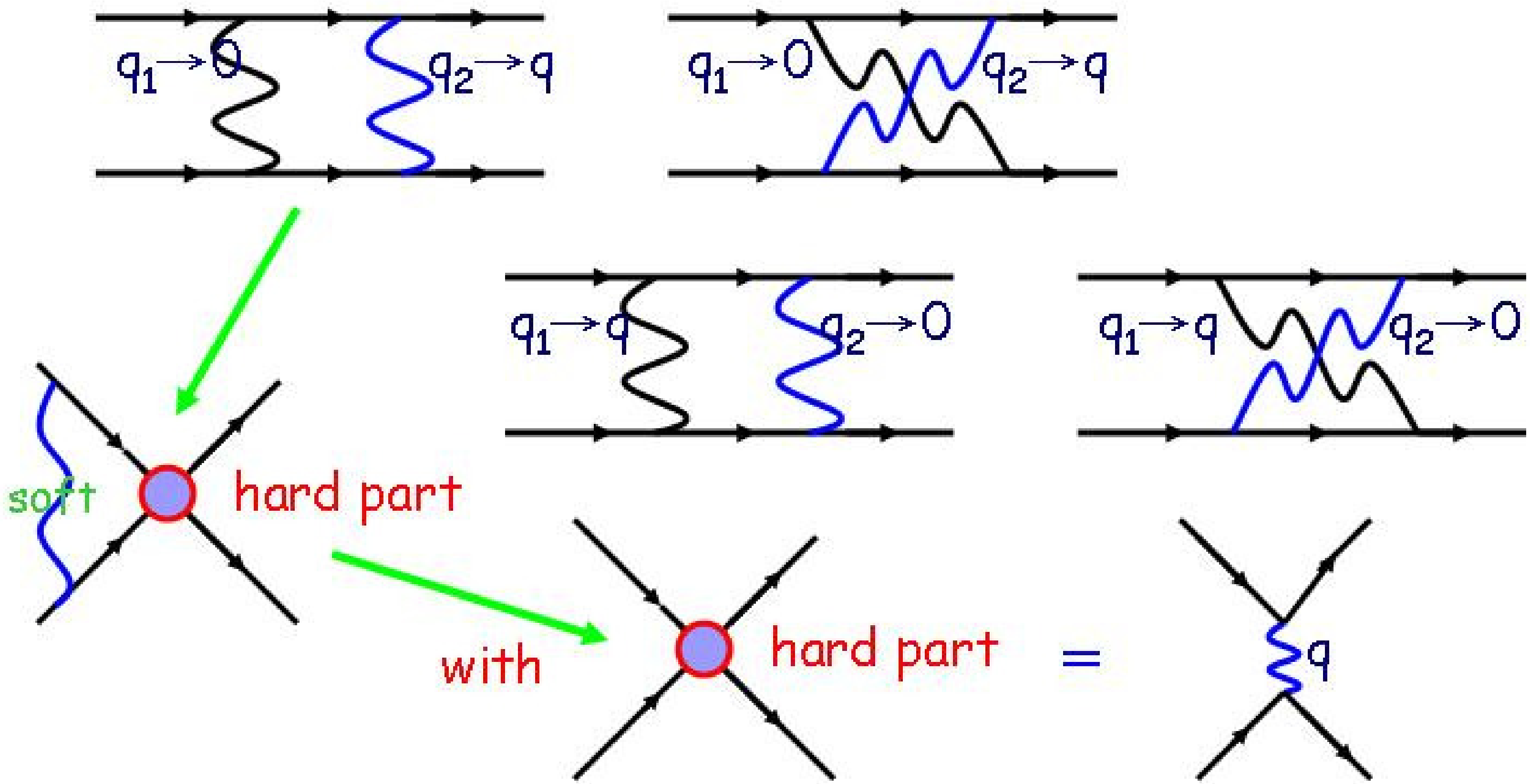
$$R\left(\tilde{f}_1\right) = \frac{e^2}{4\pi^2}\left\{\ln\left(\frac{\lambda^2}{\sqrt{-\widehat{su}}}\right)\ln\left|\frac{\hat{s}}{\hat{u}}\right| + \frac{\pi^2}{2}\right.$$

$$\left. + \frac{1}{2}\ln\left|\frac{\hat{s}}{\hat{u}}\right| + \frac{Q^2}{4}\left[\frac{1}{\hat{u}}\ln^2\left|\frac{\hat{s}}{Q^2}\right| - \frac{1}{\hat{s}}\ln^2\left|\frac{\hat{u}}{Q^2}\right| - \frac{1}{\hat{s}}\pi^2\right]\right\}$$

$$R\left(\tilde{f}_3\right) = \frac{e^2}{4\pi^2}\left\{\hat{s}\ln\left|\frac{\hat{s}}{Q^2}\right| + \hat{u}\ln\left|\frac{\hat{u}}{Q^2}\right| + \frac{\hat{s}-\hat{u}}{2}\left[\frac{\hat{s}}{\hat{u}}\ln^2\left|\frac{\hat{s}}{Q^2}\right| - \frac{\hat{u}}{\hat{s}}\ln^2\left|\frac{\hat{u}}{Q^2}\right| - \frac{\hat{u}}{\hat{s}}\pi^2\right]\right\}$$

$$\sigma_R^{lab} = \sigma_{1\gamma}^{lab}\left(1 + \underbrace{\delta_{2\gamma,\,soft} + \delta_{brems}^{ep}}_{\text{Should be IR finite}}\right)$$

Soft part of 2 γ box diagram (at nucleon level)



$$M_{(a)}^{IR} = e^4 \int \frac{d^4k_1}{(2\pi)^4} \frac{\bar{u}(k')\gamma^\mu(\gamma\cdot k_1 + m_e)\gamma^\nu u(k)\ \bar{N}(p)\gamma_\mu(\gamma\cdot(p+q_1)+M)\gamma_\nu N(p)}{[k_1^2 - m_e^2][(q_1)^2-\lambda^2][(q_2)^2-\lambda^2][(p+q_1)^2-M^2]}\Bigg|_{q_2\sim q, q_1 = k-k_1}$$

$$= \frac{e^4}{q^2}\int \frac{d^4k_1}{(2\pi)^4} \frac{\bar{u}(k')\gamma^\mu(\gamma\cdot(K+q/2)+m_e)\gamma^\nu u(k)\ \bar{N}(p)\gamma_\mu(\gamma\cdot(P-q/2)+M)\gamma_\nu N(p)}{[k_1^2-m_e^2][(k-k_1)^2-\lambda^2][(p+k-k_1)^2-M^2]}$$

soft part of electron-proton box

$$\delta_{2\gamma}^{soft} = \frac{e^2}{2\pi^2}\left\{\ln\left(\frac{\lambda^2}{\sqrt{(s-M^2)|u-M^2|}}\right)\ln\left|\frac{s-M^2}{u-M^2}\right| - L\left(\frac{s-M^2}{s}\right) - \frac{1}{2}\ln^2\left(\frac{s-M^2}{s}\right) + \mathcal{R}\left[L\left(\frac{u-M^2}{u}\right)\right] + \frac{1}{2}\ln^2\left(\frac{u-M^2}{u}\right) + \frac{\pi^2}{2}\right\}$$

where L(z) is the spence function defined by: $L(z) \equiv -\int_0^z dt \frac{\ln(1-t)}{t}$

The sum of the soft part of handbag and cat-ears diagrams in quark level give the whole soft contribution of box diagram in nucleon level.

Now, we can separate the soft part from handbag calculation result.

$$\mathcal{R}\left(\tilde{f}_1^{soft}\right) = \frac{e^2}{4\pi^2}\left\{\ln\left(\frac{\lambda^2}{\sqrt{-\hat{s}\hat{u}}}\right)\ln\left|\frac{\hat{s}}{\hat{u}}\right| + \frac{\pi^2}{2}\right\}$$

$$\mathcal{R}\left(\tilde{f}_1^{hard}\right) = \frac{e^2}{4\pi^2}\left\{\frac{1}{2}\ln\left|\frac{\hat{s}}{\hat{u}}\right| + \frac{Q^2}{4}\left[\frac{1}{\hat{u}}\ln^2\left|\frac{\hat{s}}{Q^2}\right| - \frac{1}{\hat{s}}\ln^2\left|\frac{\hat{u}}{Q^2}\right| - \frac{1}{\hat{s}}\pi^2\right]\right\}$$

Soft part in nucleon level

bremsstrahlung contribution : Maximon, Tjon (2000)

$$\delta^{ep}_{brems} = \frac{e^2}{2\pi^2}\left\{\ln\left(\frac{4(\Delta E)^2 E_e^2}{\lambda^2\, y\, E_e'^2}\right)\ln\left(\frac{E_e}{E_e'}\right) + L\left(1-\frac{1}{y}\frac{E_e}{E_e'}\right) - L\left(1-\frac{1}{y}\frac{E_e'}{E_e}\right)\right\}$$

where $y \equiv (\sqrt{\tau}+\sqrt{1+\tau})^2$ $\quad \Delta E = E_e'^{\,el} - E_e'$

$$\sigma_R^{lab} = \sigma_{1\gamma}^{lab}\,(1 + \underbrace{\delta_{2\gamma,\,soft} + \delta^{ep}_{brems}}_{\text{IR finite}})$$

The maximun energy of the soft emission photon (ΔE) dependence on the sensitivity of the detector. $\Delta E \approx 1\,\%\, E'_e$, so the above formula gives correction factor $(1 + \pi\,\alpha) +$ terms of size 0.001

Hard part in nucleon level (GPDs)

$$
\begin{aligned}
T^{hard}_{h,\lambda'_N\lambda_N} &= \int_{-1}^{1}\frac{dx}{x}\sum_q \frac{1}{2}\left[H^{hard}_{h,+\frac{1}{2}} + H^{hard}_{h,-\frac{1}{2}}\right] \\
&\times \left[H^q\left(x,0,q^2\right)\bar{u}(p',\lambda'_N)\,\gamma\cdot n\,u(p,\lambda_N) + E^q\left(x,0,q^2\right)\,\bar{u}(p',\lambda'_N)\,\frac{i\,\sigma^{\mu\nu}\,n_\mu q_\nu}{2M}\,u(p,\lambda_N)\right] \\
&+ \int_{-1}^{1}\frac{dx}{x}\sum_q \frac{1}{2}\left[H^{hard}_{h,+\frac{1}{2}} - H^{hard}_{h,-\frac{1}{2}}\right]\mathrm{sgn}(x)\,\tilde{H}^q\left(x,0,q^2\right)\bar{u}(p',\lambda'_N)\,\gamma\cdot n\,\gamma_5\,u(p,\lambda_N)
\end{aligned}
$$

result for e-q scattering amplitude

work in frame $q^+ = 0$, n^μ is a Sudakov vector ($n^2 = 0$, $n \cdot P = 1$)

handbag amplitude depends on GPD(x, $\xi = 0$, Q^2), $x = P_q^+/P^+$

$$\delta\tilde{G}_M^{hard} = C$$

$$\delta\tilde{G}_E^{hard} = -\left(\frac{1+\varepsilon}{2\varepsilon}\right)(A-C) + \sqrt{\frac{1+\varepsilon}{2\varepsilon}}\,B$$

$$\tilde{F}_3 = \frac{M^2}{\nu}\left(\frac{1+\varepsilon}{2\varepsilon}\right)(A-C)$$

A,B & C can be defined by GPD integrals

$$A \equiv \int_{-1}^{1}\frac{dx}{x}\frac{\left[(\hat{s}-\hat{u})\tilde{f}_1^{hard} - \hat{s}\hat{u}\tilde{f}_3\right]}{(s-u)}\sum_q e_q^2\,(H^q + E^q)$$ "magnetic" GPD

$$B \equiv \int_{-1}^{1}\frac{dx}{x}\frac{\left[(\hat{s}-\hat{u})\tilde{f}_1^{hard} - \hat{s}\hat{u}\tilde{f}_3\right]}{(s-u)}\sum_q e_q^2\,(H^q - \tau E^q)$$ "electric" GPD

$$C \equiv \int_{-1}^{1}\frac{dx}{x}\,\tilde{f}_1^{hard}\,\mathrm{sgn}(x)\sum_q e_q^2\,\tilde{H}^q$$ "axial" GPD

Final inputs for GPDs

use gaussian-valence model : Radyushkin (1998), Diehl et al. (1999)

$$
\begin{aligned}
H^q(x,0,q^2) &= q_v(x)\,\exp\left(-\frac{(1-x)\,Q^2}{4\,x\,\sigma}\right) \\
\tilde{H}^q(x,0,q^2) &= \Delta q_v(x)\,\exp\left(-\frac{(1-x)\,Q^2}{4\,x\,\sigma}\right) \\
E^q(x,0,q^2) &= \frac{\kappa^q}{N^q}(1-x)^2 q_v(x)\,\exp\left(-\frac{(1-x)Q^2}{4\,x\,\sigma}\right)
\end{aligned}
$$

$\sigma = 0.8$ GeV^2

Forward parton distributions at μ^2 = 1 GeV^2

MRST2002 NNLO

$$
\begin{aligned}
u_v &= 0.262\,x^{-0.69}(1-x)^{3.50}\,(1+3.83\,x^{0.5}+37.65\,x) \\
d_v &= 0.061\,x^{-0.65}(1-x)^{4.03}\,(1+49.05\,x^{0.5}+8.65\,x)
\end{aligned}
$$

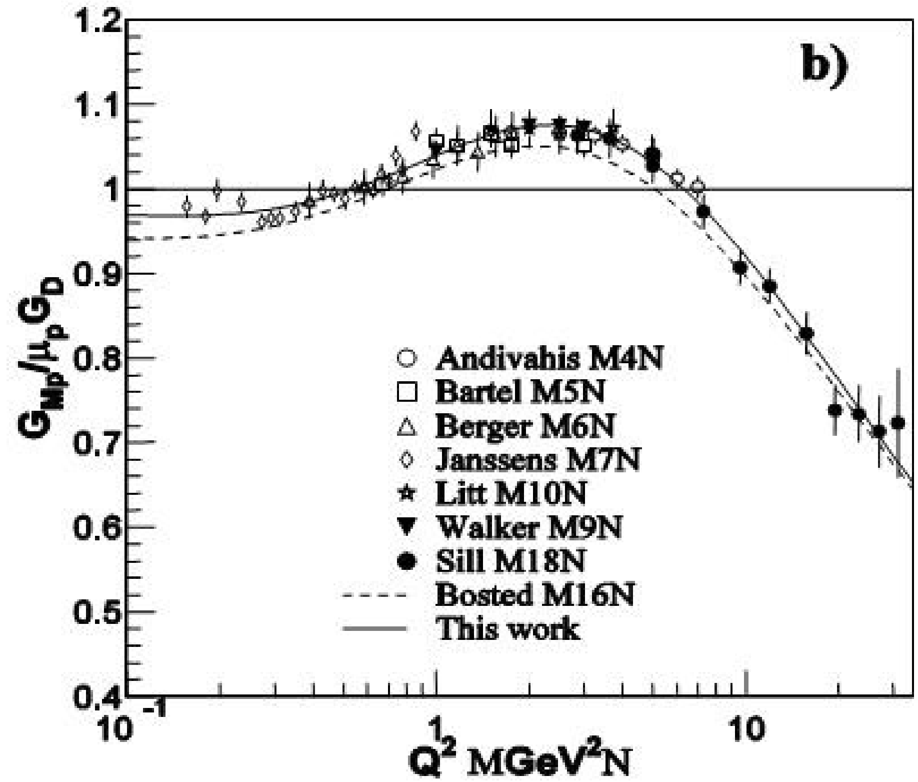
Leader, Sidorov, Stamenov (2002)

$$
\begin{aligned}
\Delta u_v &= 0.505x^{-0.33}(1-x)^{3.428}\,(1+2.179x^{0.5}+14.57x) \\
\Delta d_v &= -0.0185x^{-0.73}(1-x)^{3.864}\,(1+35.47x^{0.5}+28.97x)
\end{aligned}
$$

Fianl inputs for form factor G_M & $R(G_E/G_M)$

magnetic proton form factor

Brash et al. (2002)



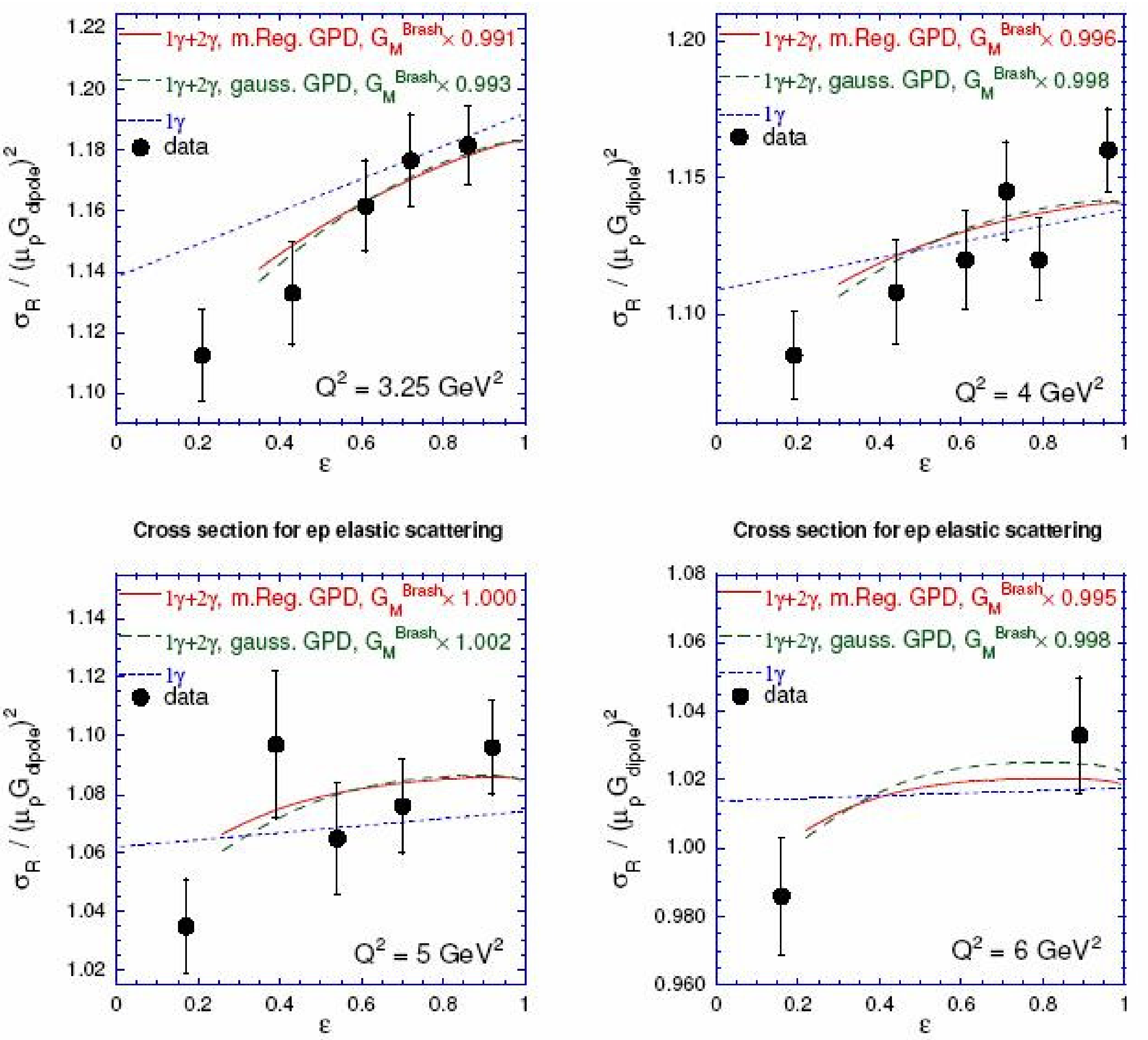
electric proton form factor :

G_E / G_M of proton fixed from polarization data Gayou et al. (2002)

$$G_{Ep} = \left(1 - 0.13(Q^2 - 0.04)\right) \frac{G_{Mp}}{\mu_p}$$

Result: cross section

with $G_D = 1/(1+Q^2/0.71)^2$

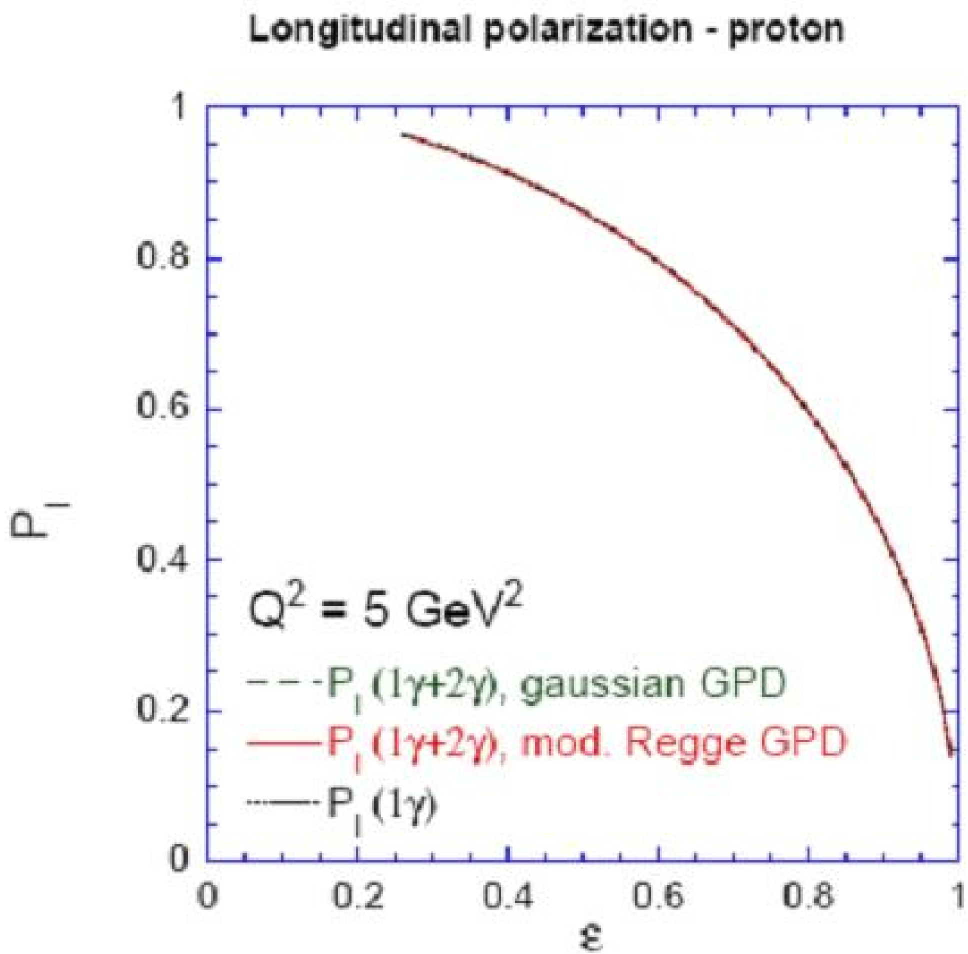


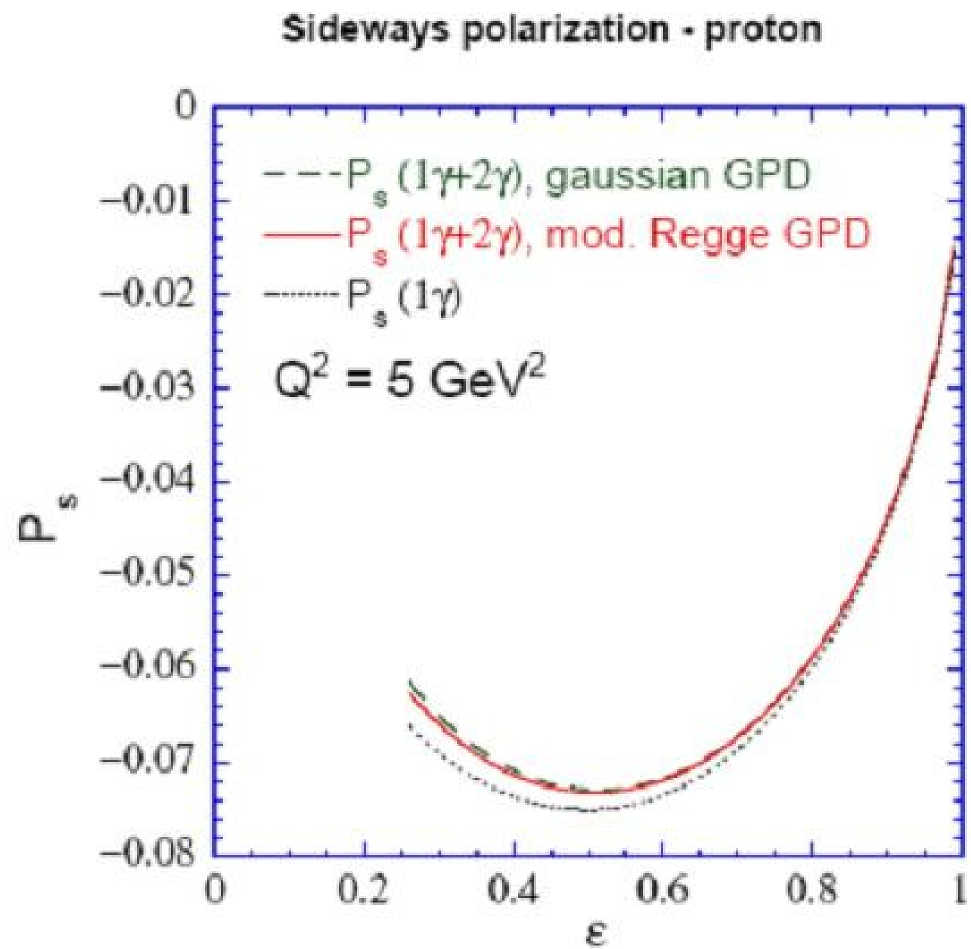
s, -u, $Q^2 > M^2$

Y.C. Chen et al.

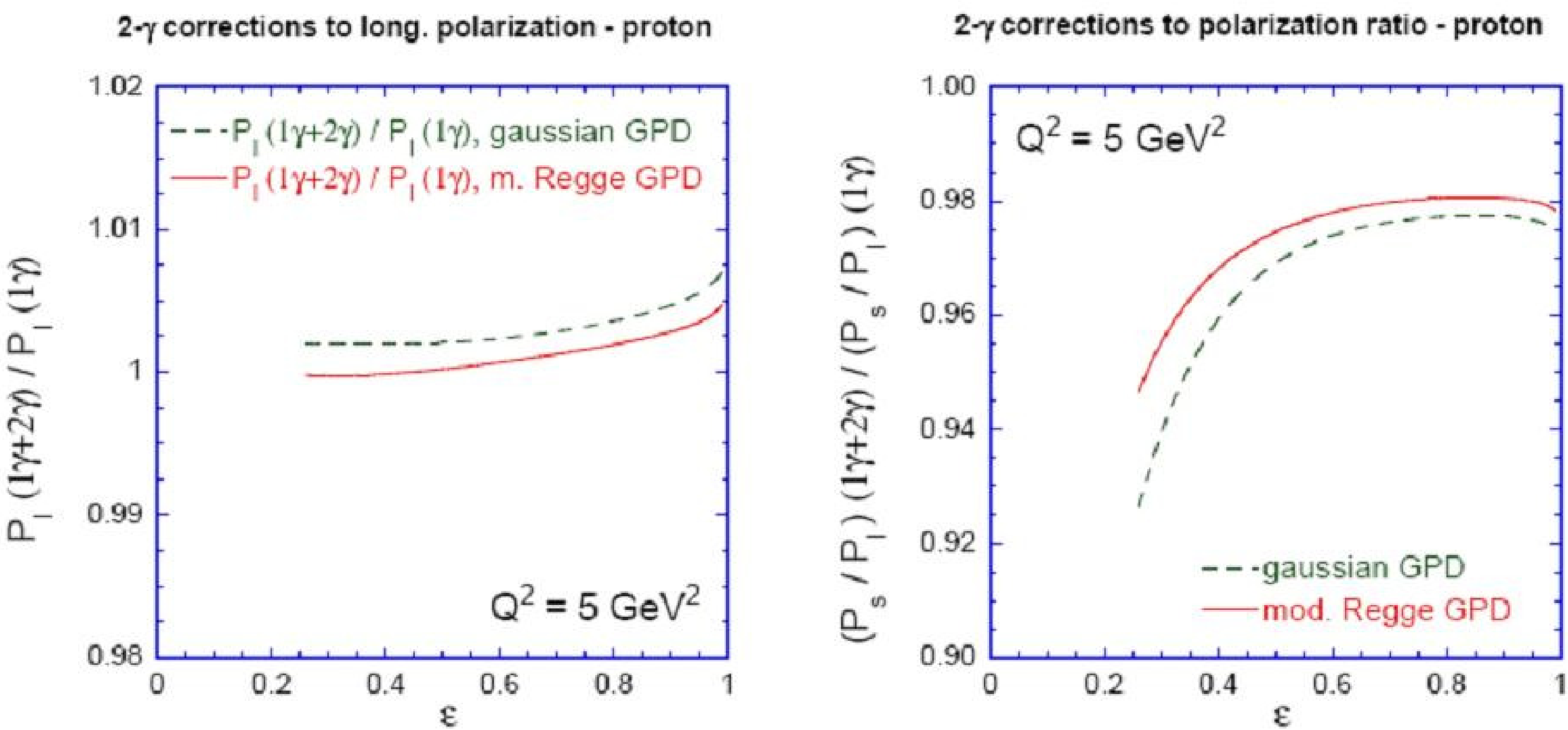
PRL(2004)

Result: polarization transfer observables

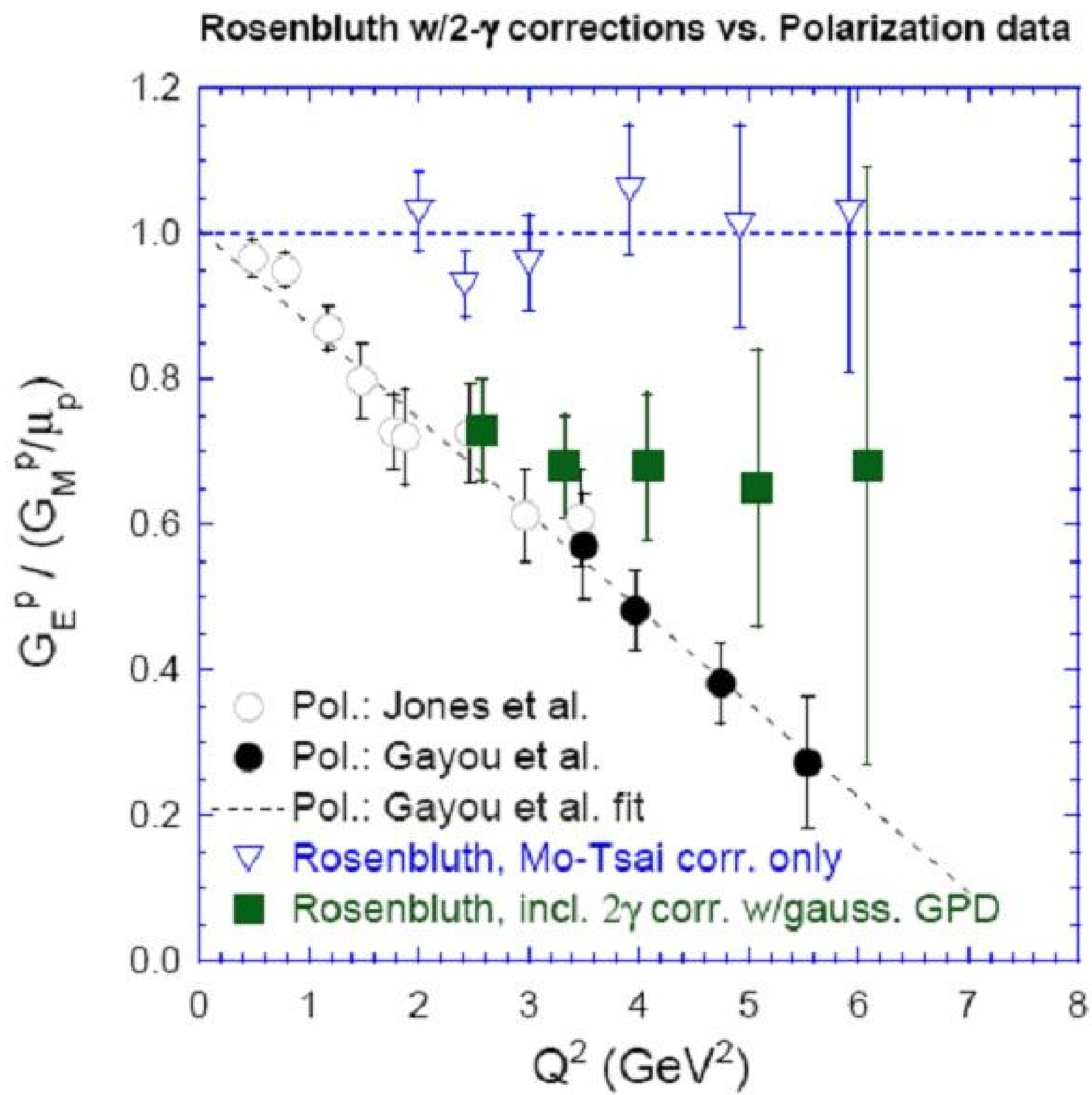




$s, -u, Q^2 > M^2$


2-γ corrections to long. polarization - proton
$P_l(1\gamma+2\gamma) / P_l(1\gamma)$
- - - $P_l(1\gamma+2\gamma) / P_l(1\gamma)$, gaussian GPD
—— $P_l(1\gamma+2\gamma) / P_l(1\gamma)$, m. Regge GPD
$Q^2 = 5\ GeV^2$
1.02
1.01
1
0.99
0.98
0
0.2
0.4
0.6
0.8
1
ε
2-γ corrections to polarization ratio - proton
$(P_s / P_l)(1\gamma+2\gamma) / (P_s / P_l)(1\gamma)$
$Q^2 = 5\ GeV^2$
- - - gaussian GPD
—— mod. Regge GPD
1.00
0.98
0.96
0.94
0.92
0.90
0
0.2
0.4
0.6
0.8
1
ε

$s, -u, Q^2 > M^2$



Rosenbluth w/2-γ corrections vs. Polarization data
$G_E^p / (G_M^p/\mu_p)$
Q^2 (GeV^2)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
Pol.: Jones et al.
Pol.: Gayou et al.
Pol.: Gayou et al. fit
Rosenbluth, Mo-Tsai corr. only
Rosenbluth, incl. 2γ corr. w/gauss. GPD

Other extension: Target normal spin asymmetry

- general formula, of order e^2

$$A_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_R} \left\{ -G_M\,\mathcal{I}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + G_E\,\mathcal{I}\left(\delta\tilde{G}_M + \left(\frac{2\varepsilon}{1+\varepsilon}\right)\frac{\nu}{M^2}\tilde{F}_3\right)\right\}$$

- involves the imaginary part of two-photon exchange amplitudes

Target normal spin asymmetry : partonic calculation

two-photon electron-quark amplitude

$$\begin{cases} \mathcal{I}\left(\tilde{f}_1^{soft}\right) = -\frac{e^2}{4\pi} \ln\left(\frac{\lambda^2}{\hat{s}}\right) \\ \mathcal{I}\left(\tilde{f}_1^{hard}\right) = -\frac{e^2}{4\pi} \left\{\frac{Q^2}{2\,\hat{u}} \ln\left(\frac{\hat{s}}{Q^2}\right) + \frac{1}{2}\right\} \\ \mathcal{I}\left(\tilde{f}_3\right) = -\frac{e^2}{4\pi} \frac{1}{\hat{u}} \left\{\frac{\hat{s}-\hat{u}}{\hat{u}} \ln\left(\frac{\hat{s}}{Q^2}\right) + 1\right\} \end{cases}$$

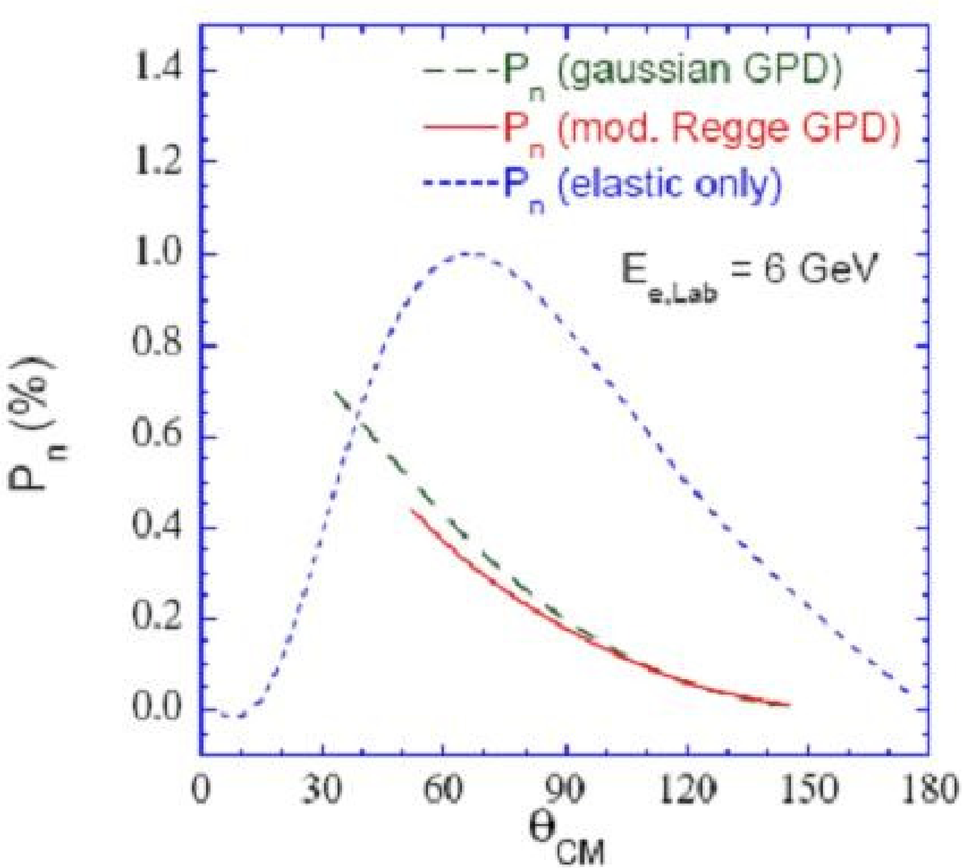
$$\Rightarrow \quad A_n = \sqrt{\frac{2\,\varepsilon\,(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_R}\left\{G_E\,\mathcal{I}(A) - \sqrt{\frac{1+\varepsilon}{2\varepsilon}}\,G_M\,\mathcal{I}(B)\right\}$$

$$A \equiv \int_{-1}^{1}\frac{dx}{x}\frac{\left[(\hat{s}-\hat{u})\tilde{f}_1^{hard} - \hat{s}\hat{u}\tilde{f}_3\right]}{(s-u)}\sum_q e_q^2\,\left(H^q + E^q\right)$$ "magnetic" GPD

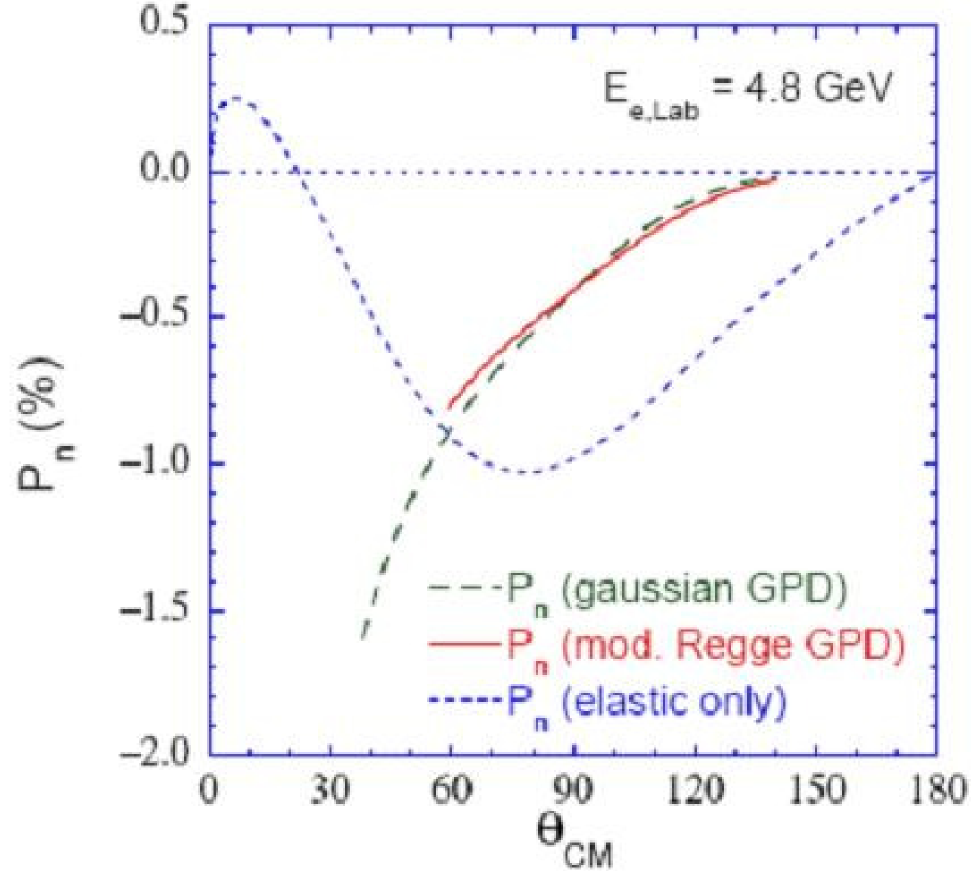
$$B \equiv \int_{-1}^{1}\frac{dx}{x}\frac{\left[(\hat{s}-\hat{u})\tilde{f}_1^{hard} - \hat{s}\hat{u}\tilde{f}_3\right]}{(s-u)}\sum_q e_q^2\,\left(H^q - \tau E^q\right)$$ "electric" GPD

Target normal spin asymmetry : results

Normal Polarization or Analyzing Power - Proton



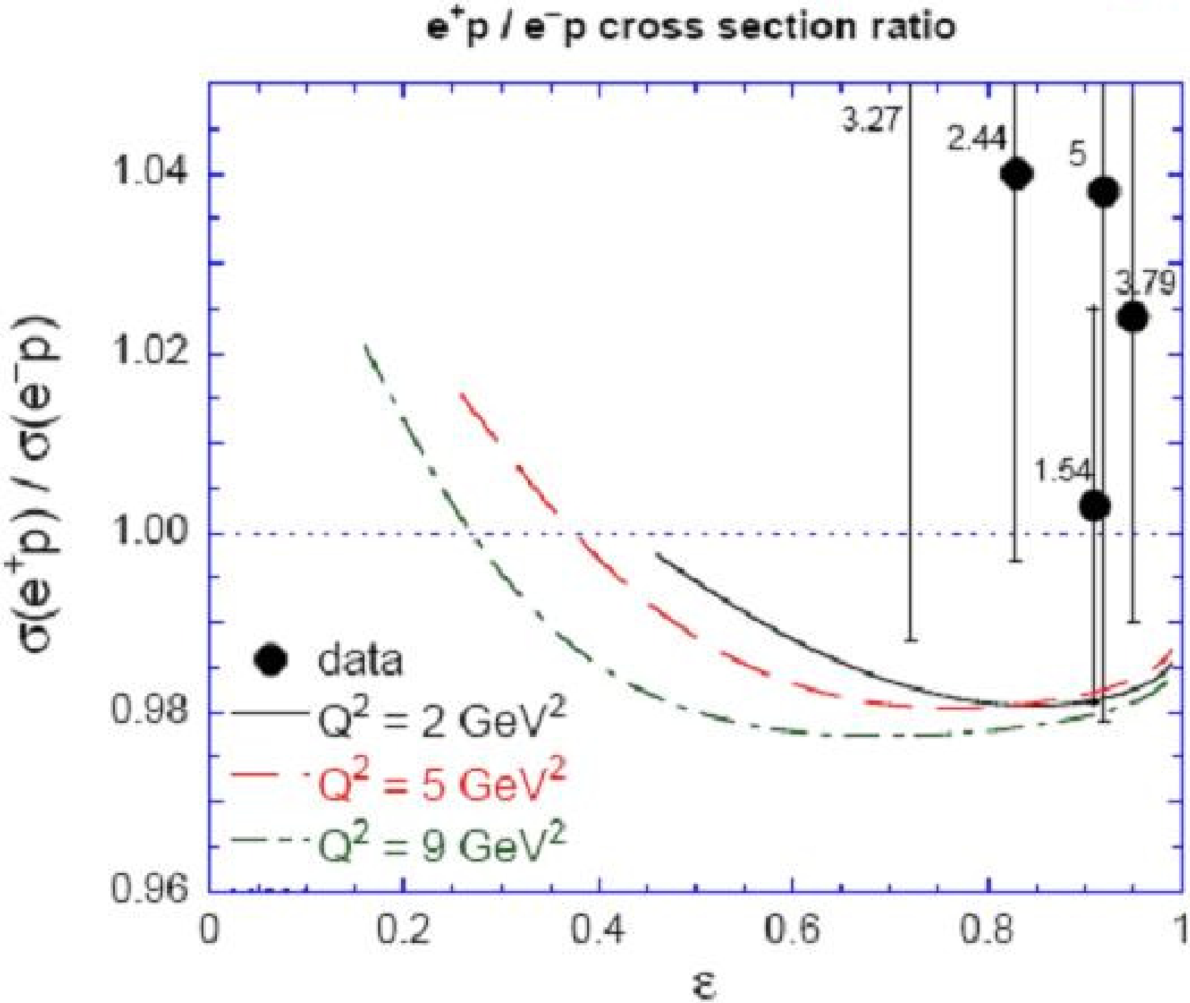
Normal Polarization or Analyzing Power - Neutron



$Q^2 > 1\ GeV$ $Q^2 > 2\ GeV$ $-u > M^2$

Other extension: $e^+ p / e^- p$ Ratio

Direct test of real part of 2γ amplitude



data figure from Arrington (2003)

Other extension: quark mass sensitivity

When quark mass does not set to zero:

$$\hat{s} \equiv \frac{(x+\eta)^2}{4x\eta}Q^2 + \frac{x+\eta}{x}m_q^2$$

$$\hat{u} \equiv -\frac{(x-\eta)^2}{4x\eta}Q^2 + \frac{x-\eta}{x}m_q^2$$

where

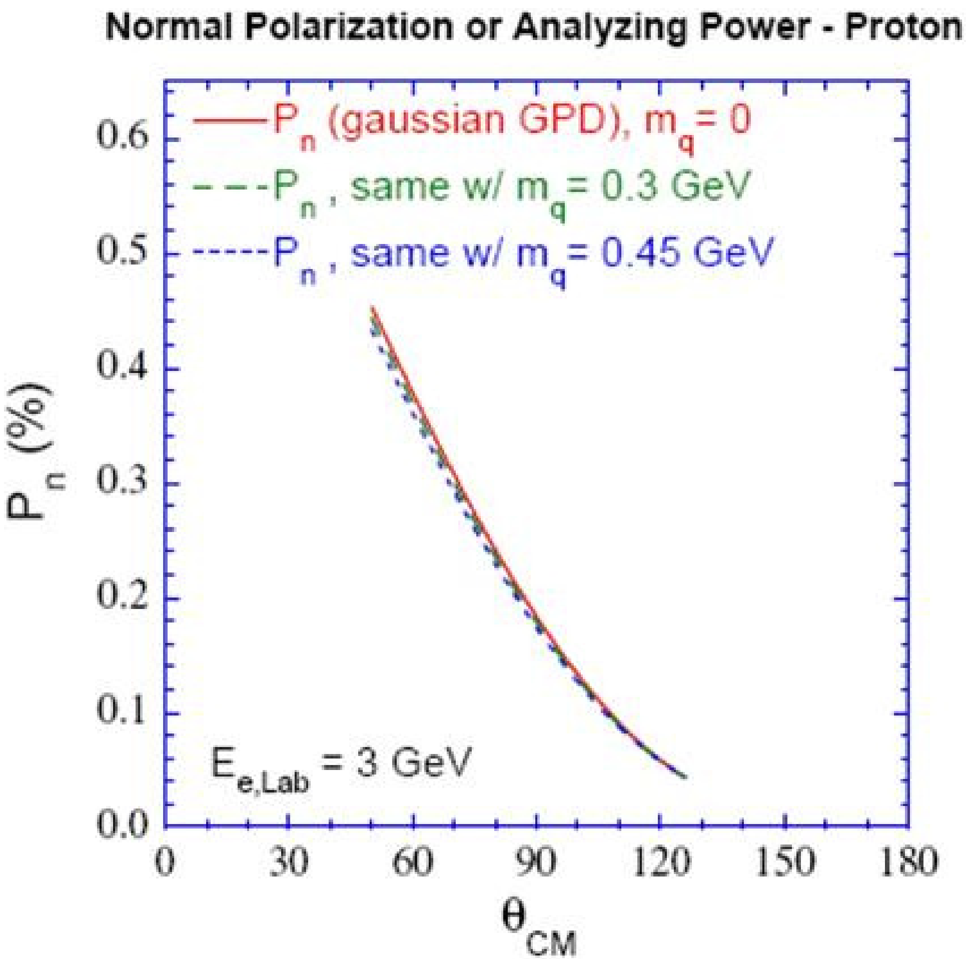
$$\eta \equiv \frac{k^+}{P^+} = \frac{k^0+k^3}{P^0+P^3} = \frac{s-u-2\sqrt{M^4-su}}{Q^2+4M^2}$$

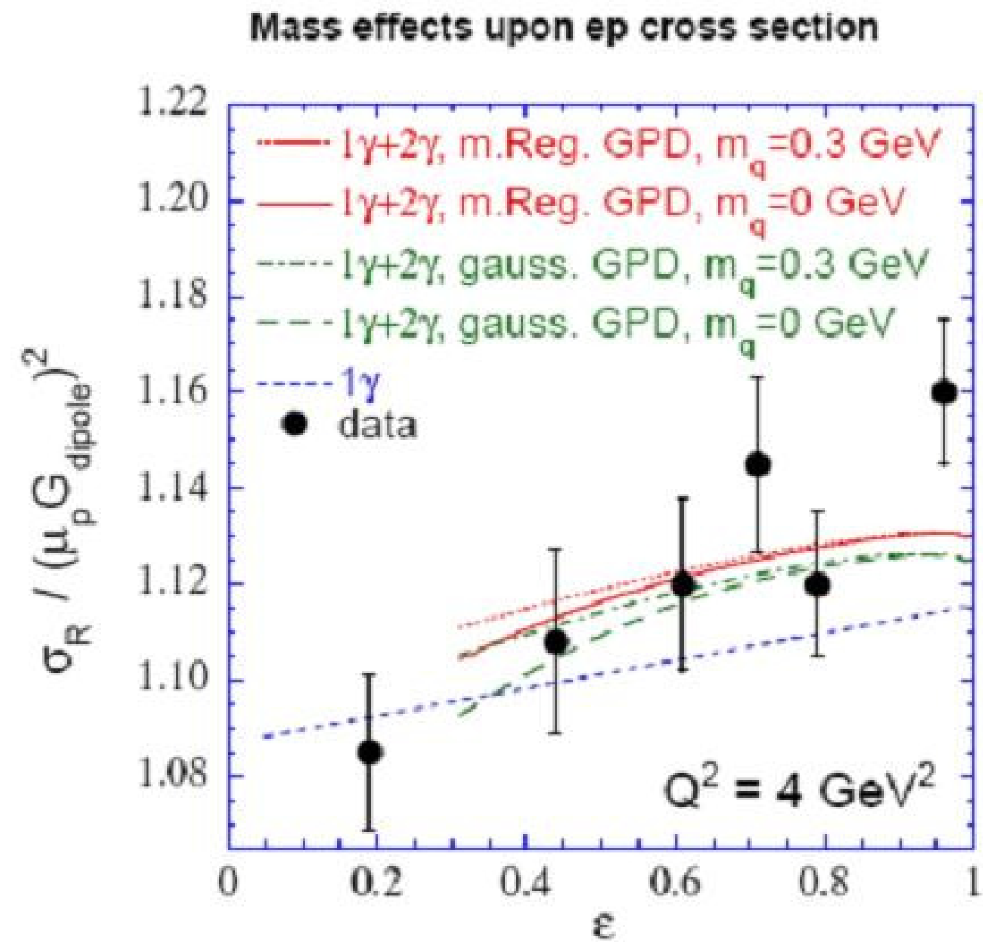
Change GPD's integral

and then

$$\frac{1}{2}\left[H^{hard}_{h,1/2} + H^{hard}_{h,-1/2}\right] \rightleftharpoons \overbrace{\frac{e^2}{Q^2}\left\{[\hat{s}-\hat{u}-\frac{2m_q^2}{\hat{s}-m_q^2}Q^2]\tilde{f}_1^{hard} + (m_q^4-\hat{s}\hat{u})\tilde{f}_3\right\}}$$

Quark mass sensitivity: result





Summary

- Develop the formalism to describe the elastic e-N scattering beyond one-photon exchange approximation.

- performed a partonic calculation of two-photon exchange contribtuon in GPDs.

- When taking the polarization transfer determinations of the form factors input, adding in the 2 photon correction, does reproduce the cross section data.

- The GPDs results also provide some useful cross-check such as recoil normal spin asymmetry (A_n) and e^+p/e^-p ratio.(see upcoming talks given by L. Weinstein & X. Jiang)

- Quark mass effect might be important at small values of ε, when u is close to zero.