How strange is the proton?

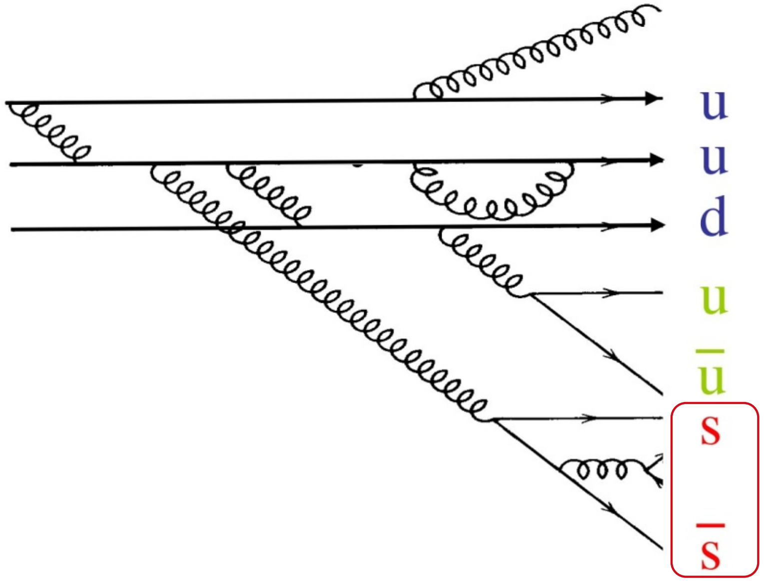
Chung-Wen Kao
Chung-Yuan Christian University,
Taiwan

In Collaboration with Hai-Qing Zhou(SouthEast U, China), Keitaro Nagata(CYCU, Taiwan), Yu-Chun Chen(AS, Taiwan), M, Vanderhaeghen(Mainz, Germany), Shin-Nan Yang (NTU,Taiwan)

22.5.2009 2009 National Cheng-Kung University, Tainan

The 8th Particle Physics Phenomenology (PPP8)

Strangeness in the nucleon



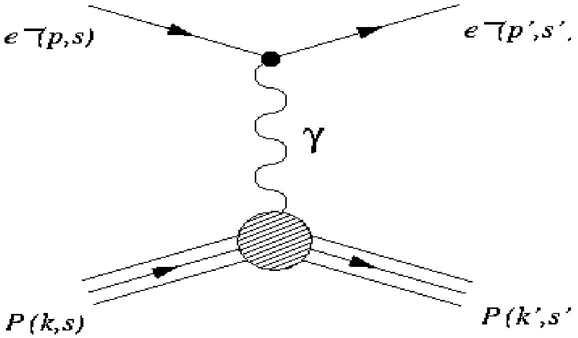
$$P = uud + \underbrace{u\bar{u} + d\bar{d} + s\bar{s} + g}_{\text{« sea »}} + ...$$

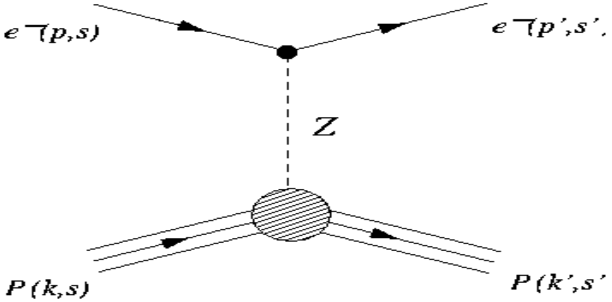
- s quark: cleanest candidate to study the sea quarks

Goal: Determine the contributions of the strange quark sea ($s\bar{s}$) to the charge and current/spin distributions in the nucleon :

"strange form factors" G^s_E and G^s_M

Parity Violating Electron Scattering





$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q_\ell \ell^\mu J^{EM}_\mu \qquad M^{NC}_{PV} = \frac{G_F}{2\sqrt{2}}\left[g_A \ell^{\mu 5} J^{NC}_\mu + g_V \ell^\mu J^{NC}_{\mu 5}\right]$$

Interference: $\sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2\mathrm{Re}(M^{EM*})M^{NC}$

Interference with EM amplitude makes Neutral Current (NC) amplitude accessible

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{\left|M^{NC}_{PV}\right|}{\left|M^{EM}\right|} \sim \frac{Q^2}{(M_Z)^2}$$

Tiny ($\sim 10^{-6}$) cross section asymmetry isolates weak interaction

Isolating the form factors: vary the kinematics or target

For a proton:

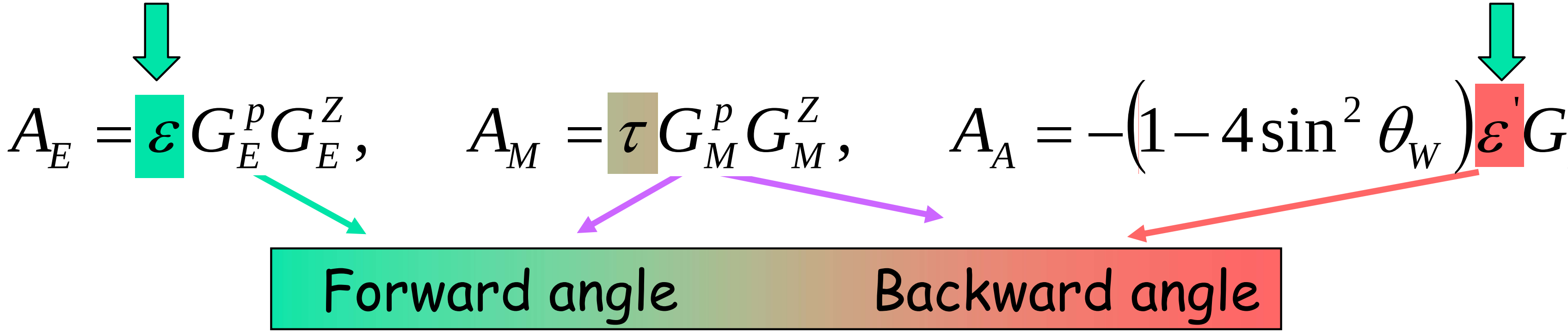
$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

~ few parts per million

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

$$1/\varepsilon \equiv 1 + 2(1+\tau)\tan^2\theta_{Lab}/2$$

$$\sqrt{\tau(1+\tau)(1-\epsilon^2)}$$



$$A_E = \varepsilon G_E^p G_E^Z, \qquad A_M = \tau G_M^p G_M^Z, \qquad A_A = -\left(1-4\sin^2\theta_W\right)\varepsilon' G_M^p G_A^e$$

Forward angle

Backward angle

Flavour decomposition

$$J_{\mu}^{EM} = \sum_{q} \mathrm{Q}_q \langle \overline{N} | \overline{u}_q \gamma_\mu u_q | N \rangle = \overline{N} \left[\gamma_\mu F_1^\gamma + \frac{i\sigma_{\mu\nu} q^\nu}{2M_N} F_2^\gamma \right] N$$

NC probes same hadronic flavour structure, with different couplings:

$$G_{E/M}^{\gamma} = \frac{2}{3} G_{E/M}^{u} - \frac{1}{3} G_{E/M}^{d} - \frac{1}{3} G_{E/M}^{s}$$

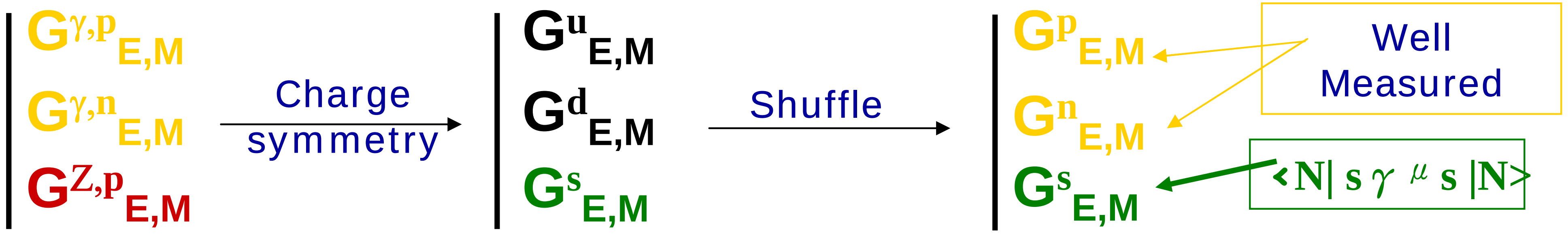
$$G_{E/M}^{Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right) G_{E/M}^{u} - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^{d} - \left(1 - \frac{4}{3}\sin^2\theta_W\right) G_{E/M}^{s}$$

$G^{Z}_{E/M}$ provides an important new benchmark for testing non-perturbative QCD structure of the nucleon

Apply Charge Symmetry

$$G^{p,u}_{E/M} = G^{n,d}_{E/M}, \qquad G^{p,d}_{E/M} = G^{n,u}_{E/M}, \qquad G^{p,s}_{E/M} = G^{n,s}_{E/M}$$

$$G^{\gamma,p}_{E/M} = \frac{2}{3}G^{u}_{E/M} - \frac{1}{3}G^{d}_{E/M} - \frac{1}{3}G^{s}_{E/M} \longrightarrow G^{\gamma,n}_{E/M} = \frac{2}{3}G^{d}_{E/M} - \frac{1}{3}G^{u}_{E/M} - \frac{1}{3}G^{s}_{E/M}$$



$G^{\gamma,p}_{E,M}$

$G^{\gamma,n}_{E,M}$

$G^{Z,p}_{E,M}$

Charge symmetry

$G^{u}_{E,M}$

$G^{d}_{E,M}$

$G^{s}_{E,M}$

Shuffle

$G^{p}_{E,M}$

$G^{n}_{E,M}$

$G^{s}_{E,M}$

Well Measured

$\langle N|\, s\, \gamma^{\mu}\, s\, |N\rangle$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{M_Z M_\gamma}{|M_\gamma|^2} = -\frac{G_F Q^2}{\sqrt{2}\pi\alpha}\mathrm{F}\left(G^{p}_{E/M}, G^{n}_{E/M}, G^{s}_{E/M}, G_A\right)$$

Extraction of strange form factors

$$A_{PV}^{1\gamma+Z} = A_1 + A_2 + A_3,$$

$$A_1 = -a\left[(1-4\sin^2\theta_W) - \frac{\epsilon G_E^{\gamma,p}G_E^{\gamma,n} + \tau G_M^{\gamma,p}G_M^{\gamma,n}}{\epsilon(G_E^{\gamma,p})^2 + \tau(G_M^{\gamma,p})^2}\right];$$

$$A_2 = a\frac{\epsilon G_E^{\gamma,p}G_E^{s} + \tau G_M^{\gamma,p}G_M^{s}}{\epsilon(G_E^{\gamma,p})^2 + \tau(G_M^{\gamma,p})^2},$$

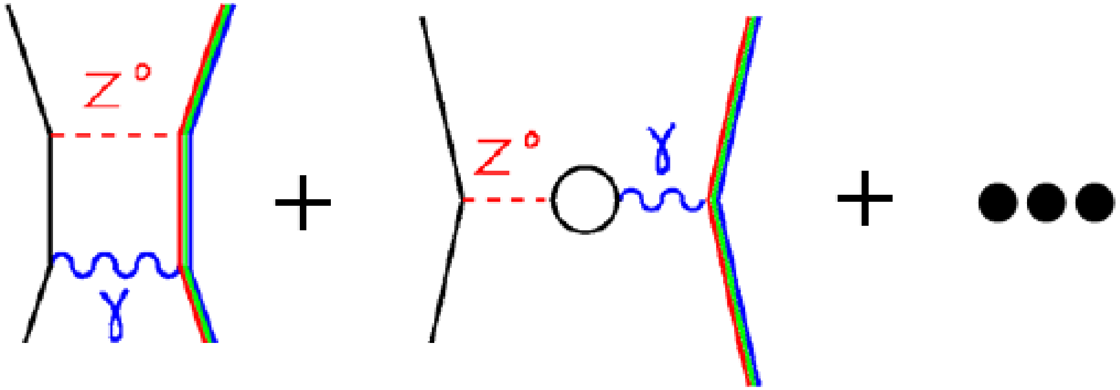
Strange form factors

$$A_3 = a(1-4\sin^2\theta_W)\frac{\epsilon' G_M^{\gamma,p}G_A^{Z}}{\epsilon(G_E^{\gamma,p})^2 + \tau(G_M^{\gamma,p})^2},$$

$$a = G_F Q^2/4\pi\alpha_{em}\sqrt{2}, \qquad \epsilon' = \sqrt{\tau(1+\tau)(1-\epsilon^2)},$$

A_2 / A_1 = only few percent

Electroweak radiative corrections



$$H_{PV}^{e-q} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d,s} [C_{1q}\bar{e}\gamma_\mu\gamma_5 e\bar{q}\gamma^\mu q + C_{2q}\bar{e}\gamma_\mu e\bar{q}\gamma^\mu\gamma_5 q].$$

Squeeze eq→eq amplitudes into 4-Fermion contact interactions

Electroweak radiative corrections

$$
\begin{aligned}
M^{(PV)} &\sim \frac{G_F}{\sqrt{2}} \sum_{q=u,d,s} [C_{1q}\overline{u}(p_1)\gamma_\mu\gamma_5 u(p_3)\overline{u}(p_2)\left(F_1^{q/p}\gamma^\mu + F_2^{q/p}\frac{i\sigma_{\mu\nu}}{2M}q^\mu\right)u(p_4) \\
&+ C_{2q}\overline{u}(p_1)\gamma_\mu u(p_3)\overline{u}_{p'}G_A^{q/p}\gamma^\mu\gamma_5 u(p)].
\end{aligned}
$$

$$\Downarrow$$

$$C_{1u} = \rho(-\frac{1}{2} + \frac{4}{3}\kappa\sin^2\theta_W),\ C_{1d} = \rho(\frac{1}{2} - \frac{2}{3}\kappa\sin^2\theta_W).$$

$$\Downarrow$$

$$\sum_q C_{1q}G_{E,M}^{q/p} = -\frac{1}{2}\rho\left((1-4\kappa\sin^2\theta_W)G_{E,M}^{\gamma/p} - G_{E,M}^{\gamma,n} - G_{E,M}^{s}\right).$$

Extraction of strange form factors

$$A_{PV}(\rho,\kappa) = A_1 + A_2 + A_3,$$

$$A_1 = -a\rho\left[(1-4\kappa\sin^2\theta_W) - \frac{\epsilon G_E^{\gamma,p} G_E^{\gamma,n} + \tau G_M^{\gamma,p} G_M^{\gamma,n}}{\epsilon(G_E^{\gamma,p})^2 + \tau(G_M^{\gamma,p})^2}\right]$$

$$A_2 = a\rho\frac{\epsilon G_E^{\gamma,p} G_E^{s} + \tau G_M^{\gamma,p} G_M^{s}}{\epsilon(G_E^{\gamma,p})^2 + \tau(G_M^{\gamma,p})^2}, \Leftarrow$$

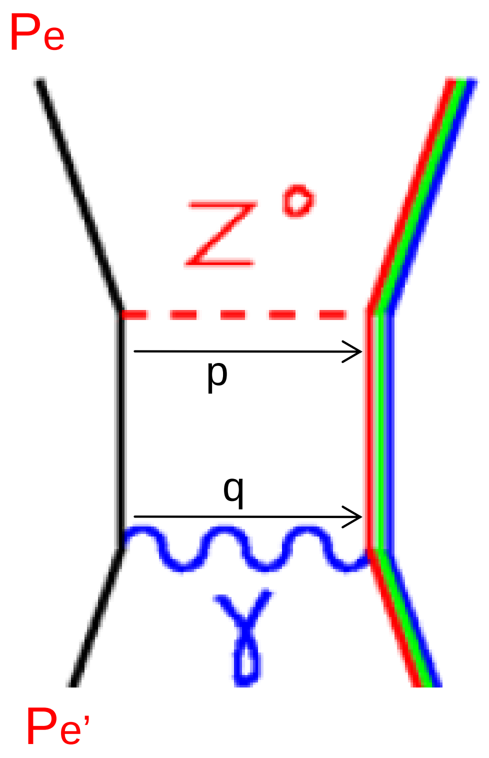
Strange form factors

$$A_3 = a(1-4\sin^2\theta_W)\frac{\epsilon' G_M^{\gamma,p} G_A^{Z}}{\epsilon(G_E^{\gamma,p})^2 + \tau(G_M^{\gamma,p})^2}.$$

ρ and κ are from electroweak radiative corrections

Zero Transfer Momentum Approximations for Box diagrams

$Q^2=(p-q)^2$



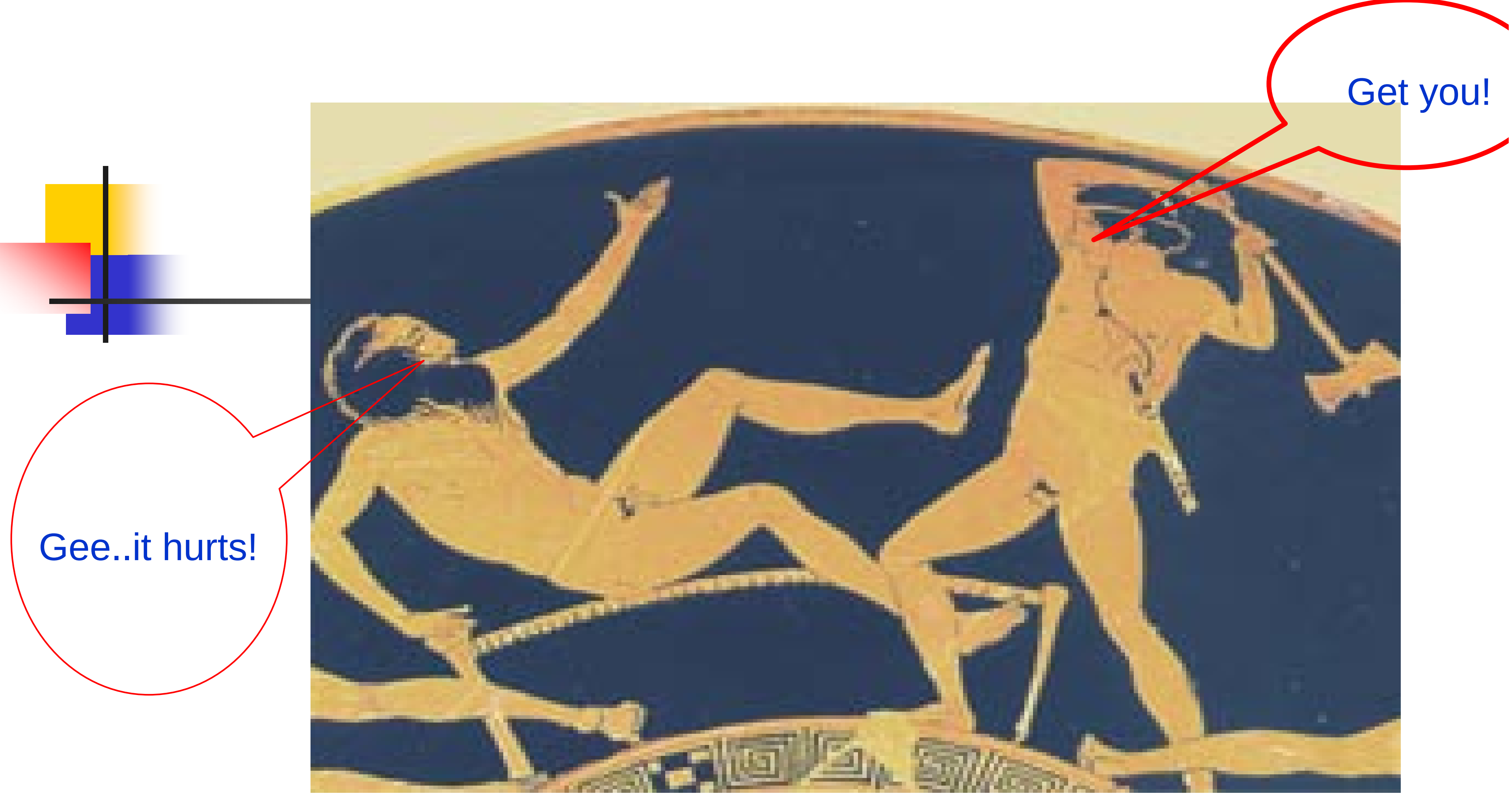
Approximation made in previous analysis:

$p=q=k$ $P_e=P_e'=0$

$$\Delta\rho = \frac{\alpha}{2\pi}4(1-4s^2)\left[\ln(\frac{m_z^2}{M^2})+\frac{3}{2}\right],$$

$$\Delta\kappa = \frac{\alpha}{2\pi s^2}(\frac{9}{4}-4s^2)(1-4s^2)\left[\ln(\frac{m_Z^2}{M^2})+\frac{3}{2}\right]$$

Marciano, Sirlin (1984)



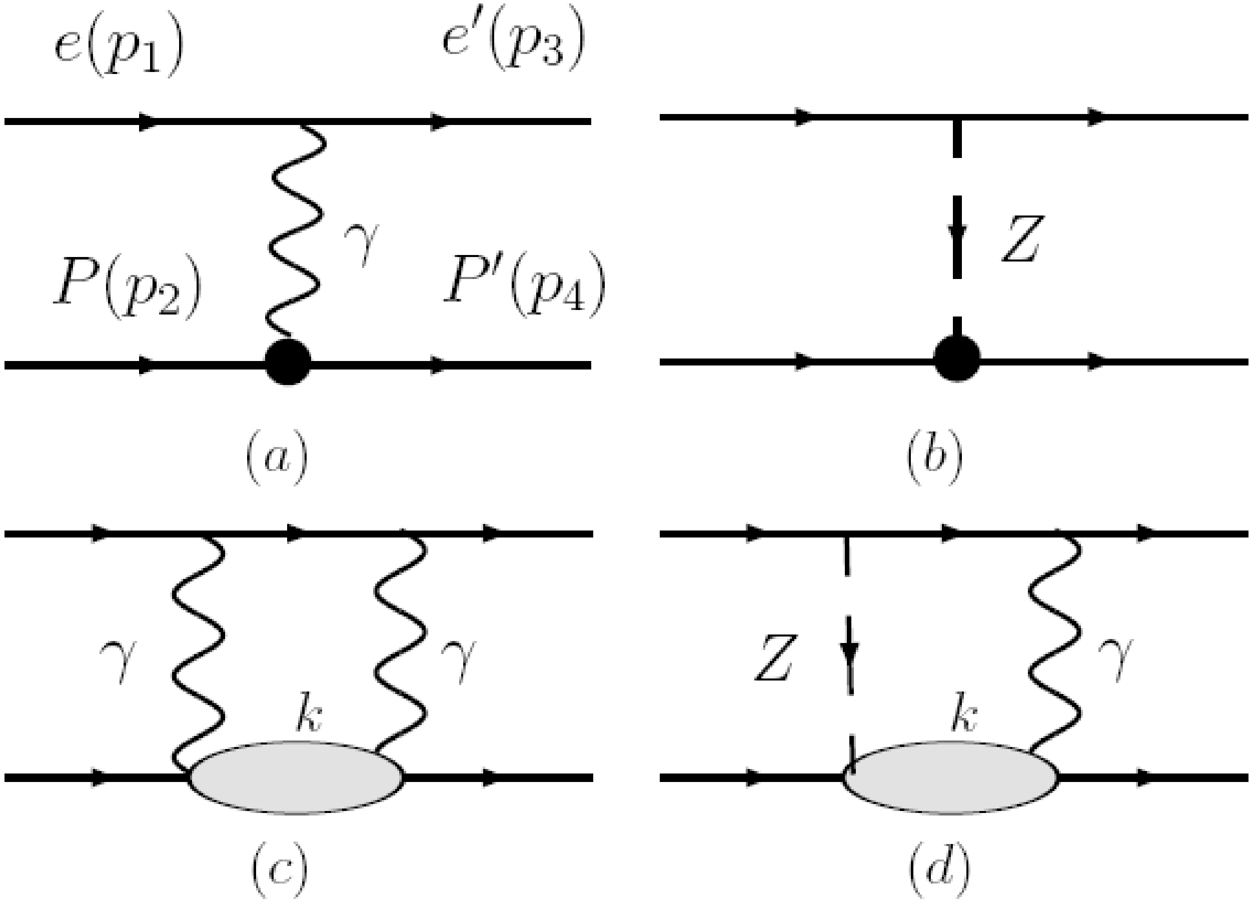
But this is nothing but a Procrustean bed!

Be aware of the Box!

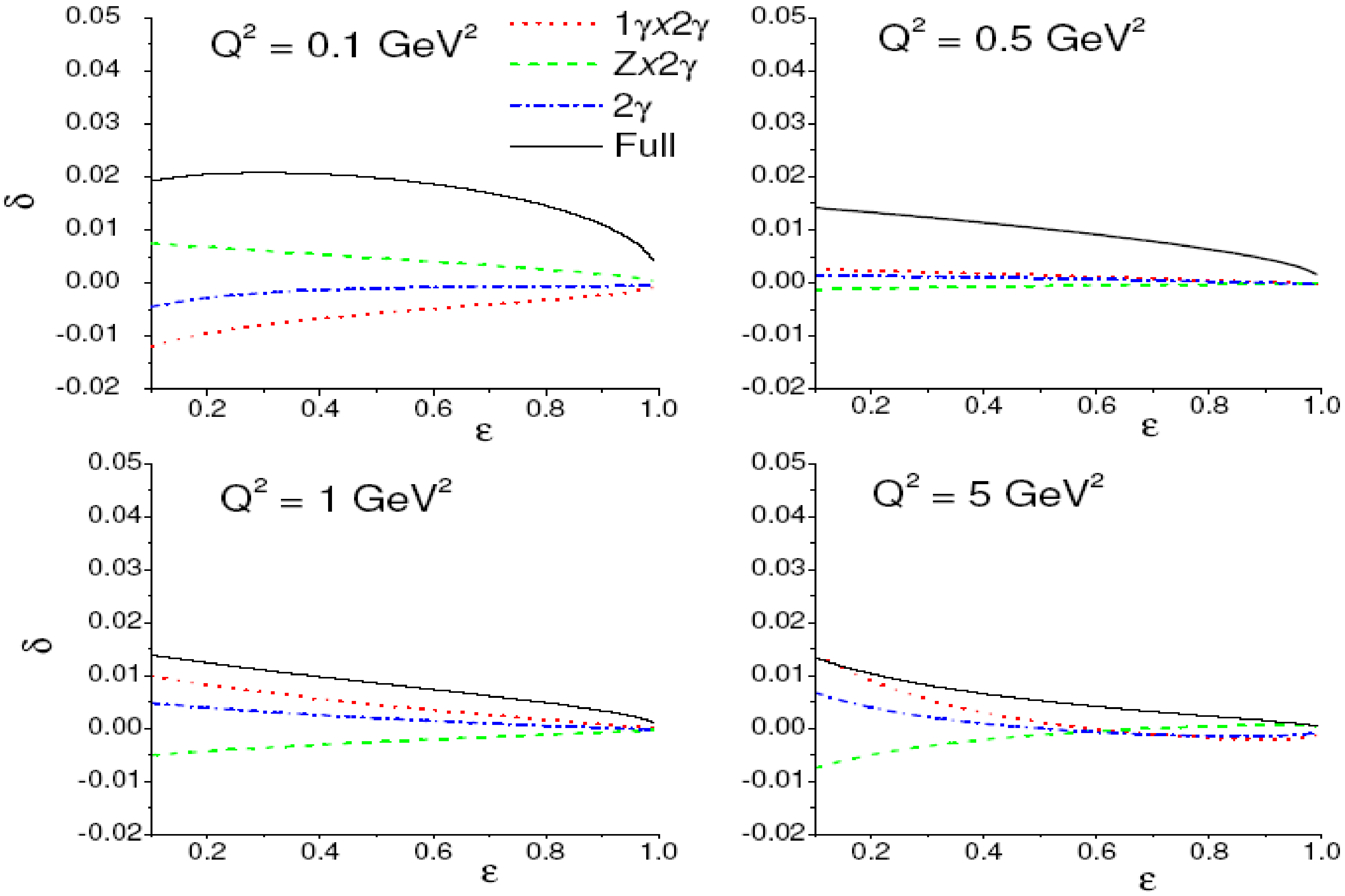

clipart.com

- Box diagram is intricate because it is related with the nucleon intermediate states.
- Box diagram is special because of its complicated Q^2 and ε dependence

One-loop box diagrams



HQ. Zhou, CWK and SN Yang, PRL, 99, 262001 (2007)



$$A_{PV}^{(1\gamma+Z+2\gamma+\gamma Z)} = A_{PV}^{(1\gamma+Z)}(1+\delta),$$

Impact of our results

$$\rho' = \rho - \Delta\rho \qquad \kappa' = \kappa - \Delta\kappa$$

Avoid double counting

$$\begin{aligned} A_{PV}^{(Exp)} &\equiv A_{PV}(1\gamma + Z + 2\gamma + \gamma Z), \\ &= A_{PV}(\rho', \kappa')(1+\delta). \end{aligned}$$

$$G_E^s + \beta G_M^s = \frac{\epsilon (G_E^{\gamma,p})^2 + \tau (G_M^{\gamma,p})^2}{a\rho\epsilon G_E^{\gamma,p}} [A_{PV}^{Exp} - A_1(\rho,\kappa) - A_3],$$

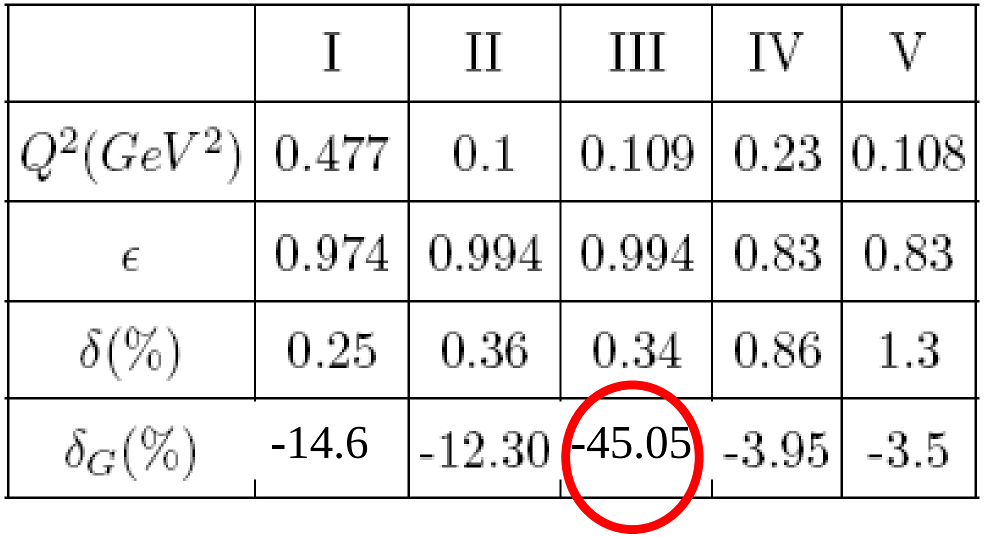
Old

$$\overline{G}_E^s + \beta \overline{G}_M^s = \frac{\epsilon (G_E^{\gamma,p})^2 + \tau (G_M^{\gamma,p})^2}{a\rho'\epsilon G_E^{\gamma,p}} \left[\frac{A_{PV}^{Exp}}{1+\delta} - A_1(\rho',\kappa') - A_3 \right]$$

New

$$\overline{G}_E^s + \beta \overline{G}_M^s = (G_E^s + \beta G_M^s)(1 + \delta_G),$$

Change of the results of Strange form factors



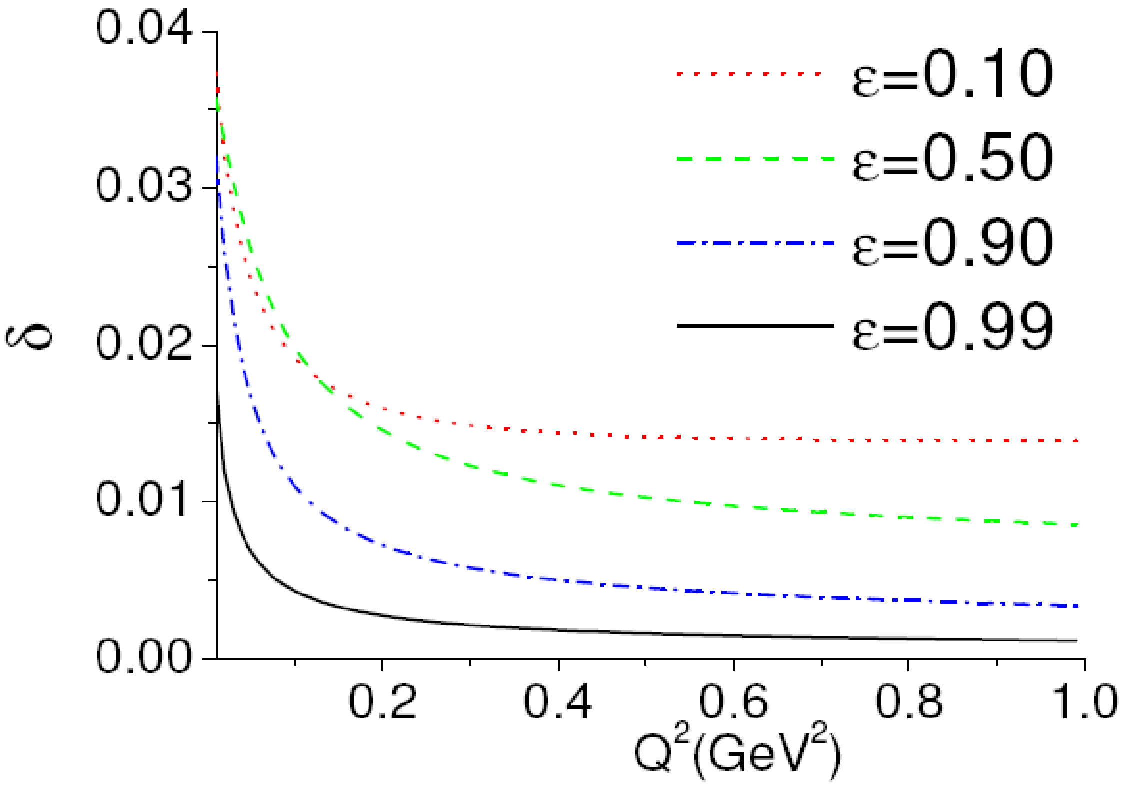
	I	II	III	IV	V
$Q^2(GeV^2)$	0.477	0.1	0.109	0.23	0.108
ϵ	0.974	0.994	0.994	0.83	0.83
$\delta(\%)$	0.25	0.36	0.34	0.86	1.3
$\delta_G(\%)$	-14.6	-12.30	-45.05	-3.95	-3.5

TABLE II: The corrections δ_G to $G_E^s+\beta G_M^s$ for HAPPEX and A4 experiments. I,II and III refer to HAPPEX data in 2004, 2006, and 2007 [6], and IV and V correspond to A4 data in 2004 and 2005, respectively [7].

Why such a big correction?

$$\delta_G = \frac{A_{PV}^{Exp}(\frac{\Delta\rho}{\rho} - \delta) + 4a\rho\sin^2\theta_W\Delta\kappa - A_3\frac{\Delta\rho}{\rho}}{A_{PV}^{Exp} - A_0}$$

$$A_0 = A_1 + A_3$$



Warning: It is sensitive to the choice of the input of the form factors.

Go data

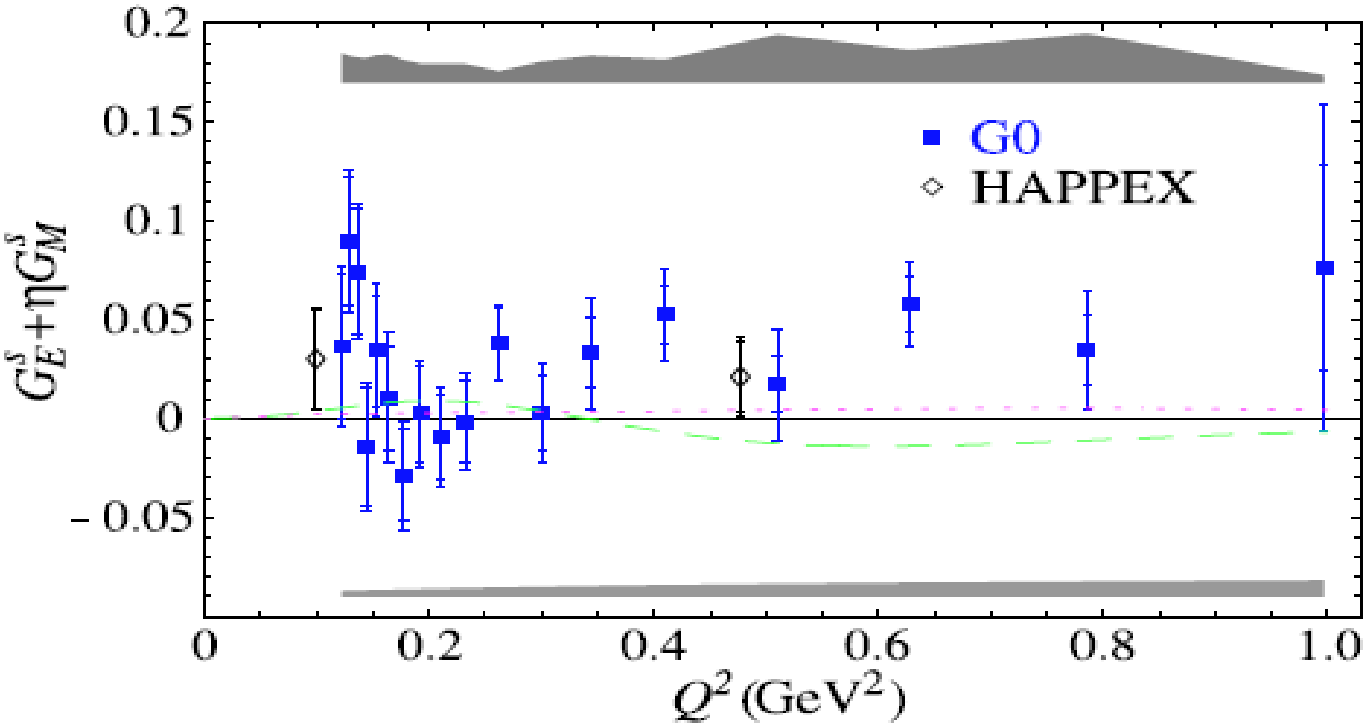
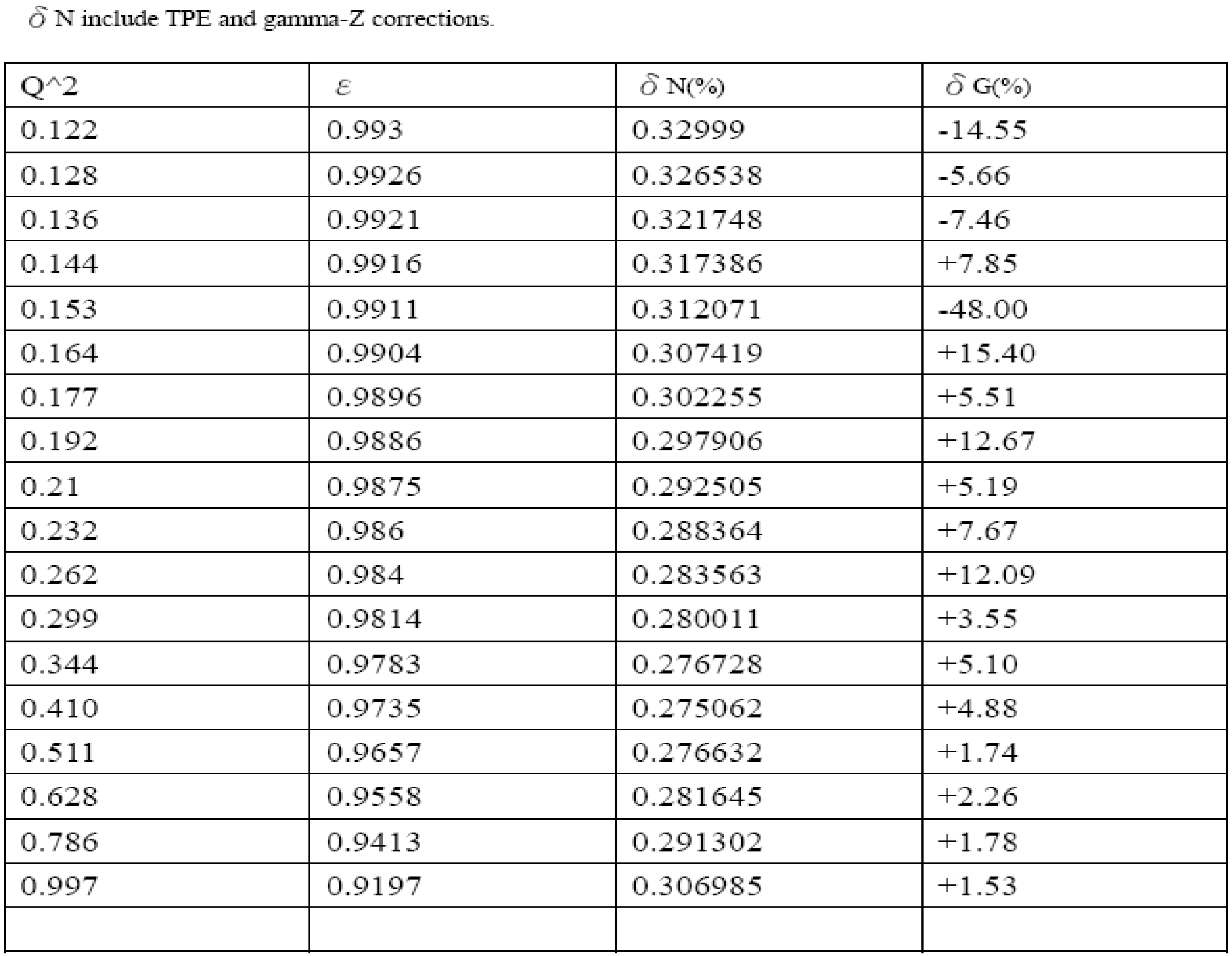


FIG. 2: The combination $G_E^s + \eta G_M^s$ for the present measurement. The gray bands indicate systematic uncertainties (to be added in quadrature); the lines correspond to different electromagnetic nucleon form factor models (see text).

Corrections to G0 data



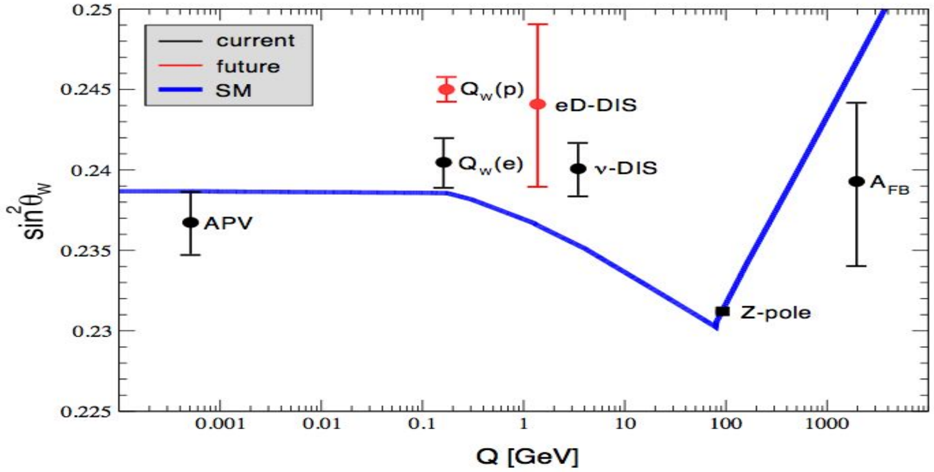
δ N include TPE and gamma-Z corrections.

Q^2	ε	δ N(%)	δ G(%)
0.122	0.993	0.32999	-14.55
0.128	0.9926	0.326538	-5.66
0.136	0.9921	0.321748	-7.46
0.144	0.9916	0.317386	+7.85
0.153	0.9911	0.312071	-48.00
0.164	0.9904	0.307419	+15.40
0.177	0.9896	0.302255	+5.51
0.192	0.9886	0.297906	+12.67
0.21	0.9875	0.292505	+5.19
0.232	0.986	0.288364	+7.67
0.262	0.984	0.283563	+12.09
0.299	0.9814	0.280011	+3.55
0.344	0.9783	0.276728	+5.10
0.410	0.9735	0.275062	+4.88
0.511	0.9657	0.276632	+1.74
0.628	0.9558	0.281645	+2.26
0.786	0.9413	0.291302	+1.78
0.997	0.9197	0.306985	+1.53

Qweak experiment

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -\frac{G_F Q^2}{4\sqrt{2}\alpha}[Q_W + Q^2 B(Q^2)]$$

Q_W=$1 - 4\sin^2\theta_W \sim 0.0721$ at tree level in the standard model.



The scattering angle at Q_{weak} is 8 degree and Q^2=$0.03GeV^2$ corresponding around $\epsilon = 0.99$

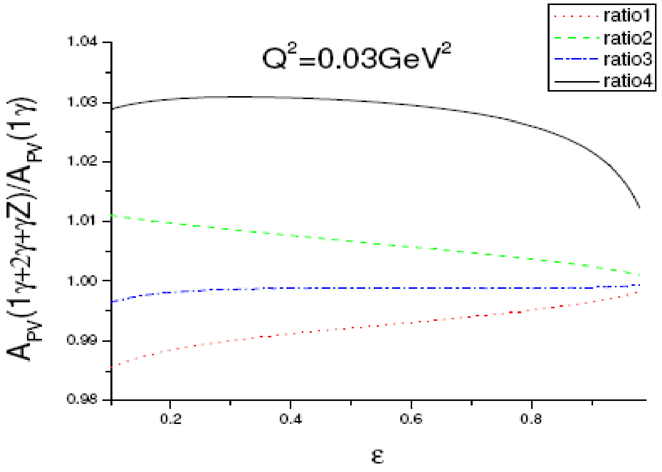
Effect of TBE in Qweak

$$A_{PV}(Q^2 \to 0, \epsilon \to 1) = \rho(1 - 4\kappa \sin^2\theta_W) \quad \Longrightarrow \quad Q_W^{old} = \frac{A_{PV}^{Exp}}{-a\rho};$$

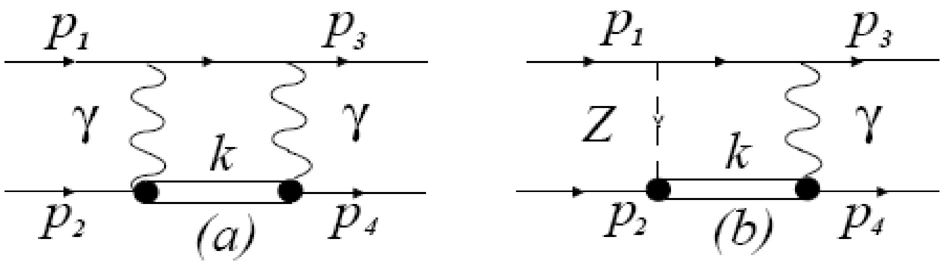
$$\begin{aligned} A_{PV}(Q^2 \sim 0, \epsilon \sim 1) &= -a(\rho - \Delta\rho)(1 - 4(\kappa - \Delta\kappa)\sin^2\theta_W)(1+\delta) \\ &= -a(\rho - \Delta\rho + \delta + 4\frac{\Delta\kappa \sin^2\theta_W}{1 - 4\sin^2\theta_W})(1 - 4\kappa\sin^2\theta_W) \end{aligned}$$

$$Q_W^{new} = \frac{A_{PV}^{Exp}}{-a(\rho - \Delta\rho + \delta + 4\frac{\Delta\kappa\sin^2\theta_W}{1-4\kappa\sin^2\theta_W})},$$

$$\delta_Q = \frac{Q_W^{old}}{Q_W^{new}} - 1 = \frac{1}{\rho}(\delta - \Delta\rho + 4\frac{\Delta\kappa\sin^2\theta_W}{1-4\kappa\sin^2\theta_W}) \sim -6.65\%.$$



Recent progress

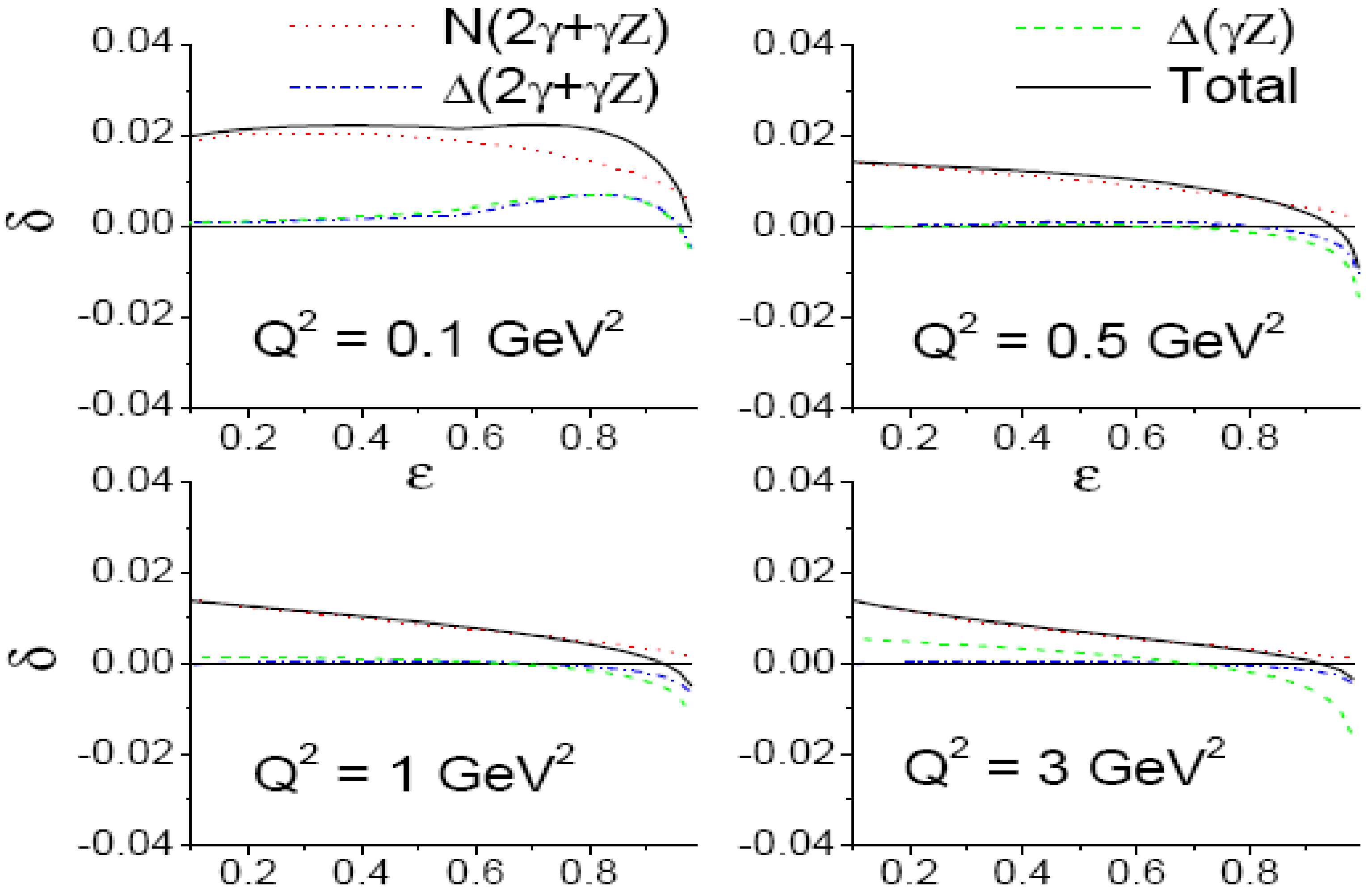


Keitaro Nagata, Hai Qing Zhou, CWK and Shin Nan Yang

arXiv:0811.3539 to be published in PRC

Δ(1232) plays an important role in the low energy regime due to its light mass and its strong coupling to π N systeam.

New Result (1)


N(2γ+γZ)
Δ(2γ+γZ)
Δ(γZ)
Total
δ
ε
0.04
0.02
0.00
-0.02
-0.04
0.2
0.4
0.6
0.8
Q² = 0.1 GeV²
Q² = 0.5 GeV²
Q² = 1 GeV²
Q² = 3 GeV²

New Result (2)

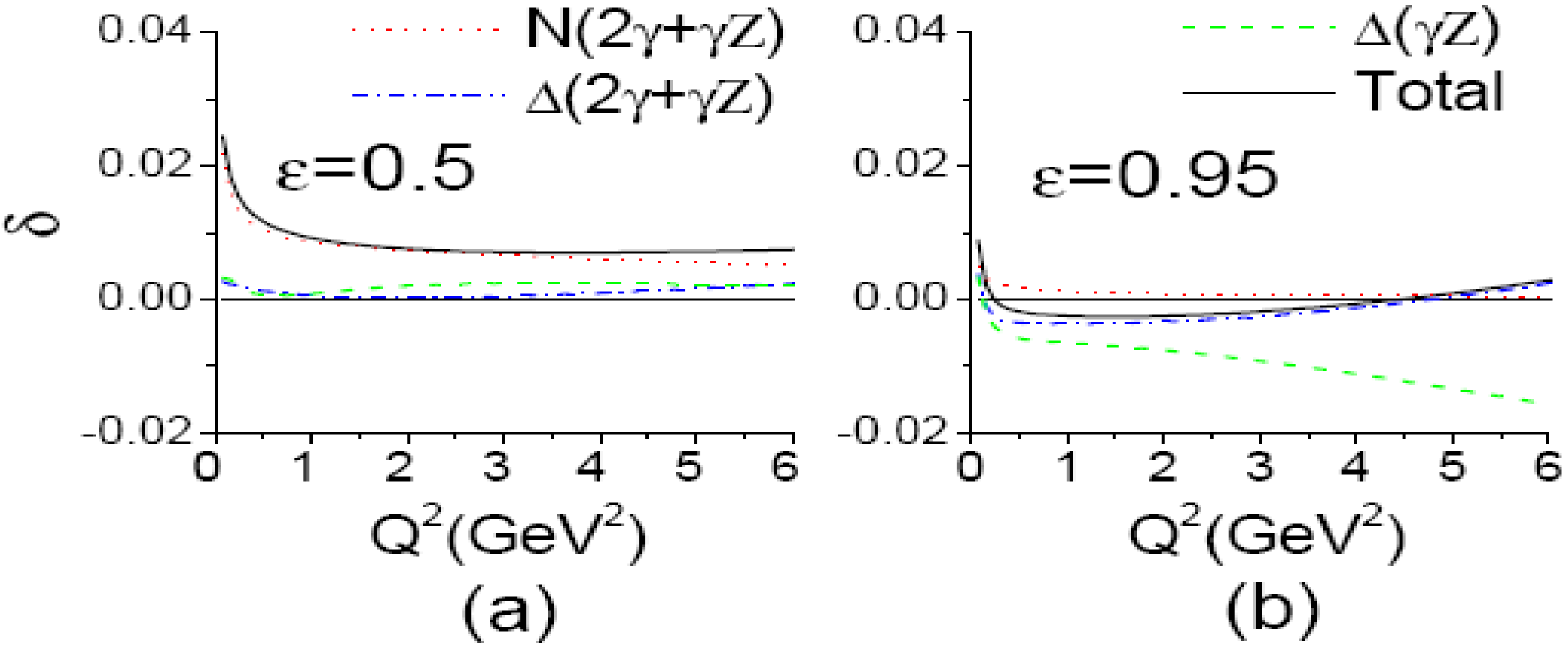
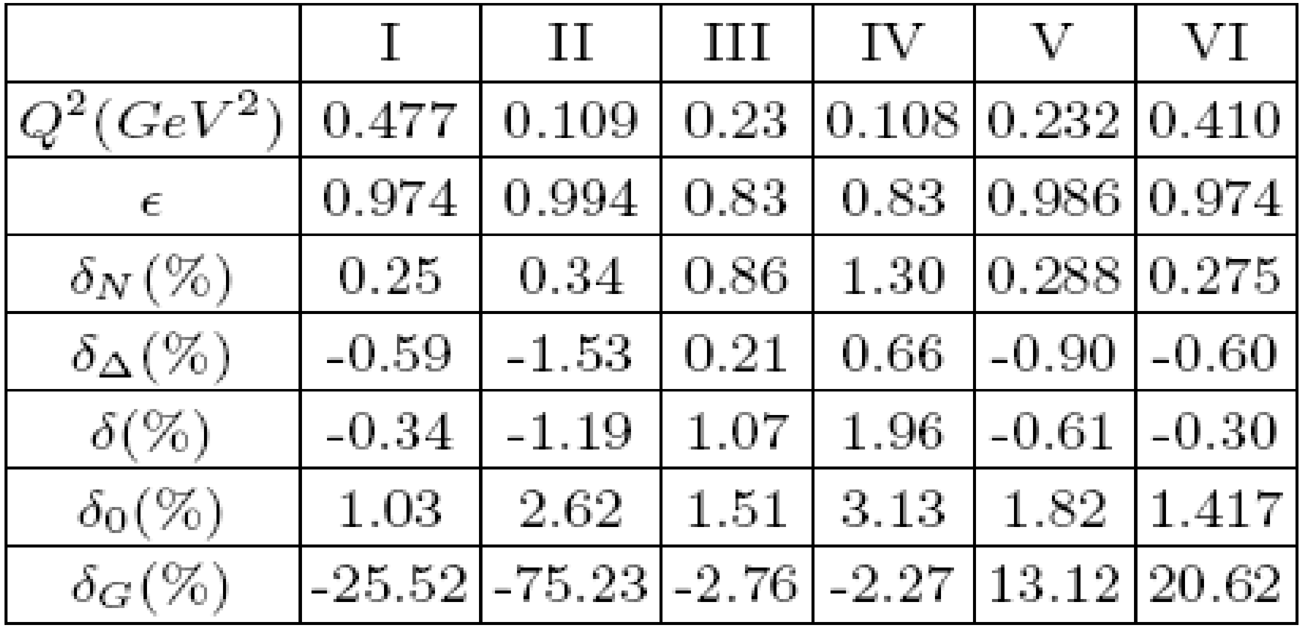


FIG. 4: TPE and γZ-exchange corrections with with nucleon and Δ intermediate states to parity-violating asymmetry as functions of Q^2 from 0.1 to 6 GeV^2 at $\epsilon = 0.5$ and 0.95.

New Result (3)

$\delta_G = 0$ if $\delta = \delta_0$.

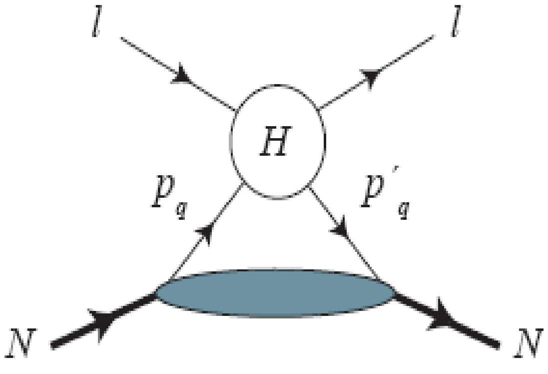


	I	II	III	IV	V	VI
$Q^2(GeV^2)$	0.477	0.109	0.23	0.108	0.232	0.410
ϵ	0.974	0.994	0.83	0.83	0.986	0.974
$\delta_N(\%)$	0.25	0.34	0.86	1.30	0.288	0.275
$\delta_\Delta(\%)$	-0.59	-1.53	0.21	0.66	-0.90	-0.60
$\delta(\%)$	-0.34	-1.19	1.07	1.96	-0.61	-0.30
$\delta_0(\%)$	1.03	2.62	1.51	3.13	1.82	1.417
$\delta_G(\%)$	-25.52	-75.23	-2.76	-2.27	13.12	20.62

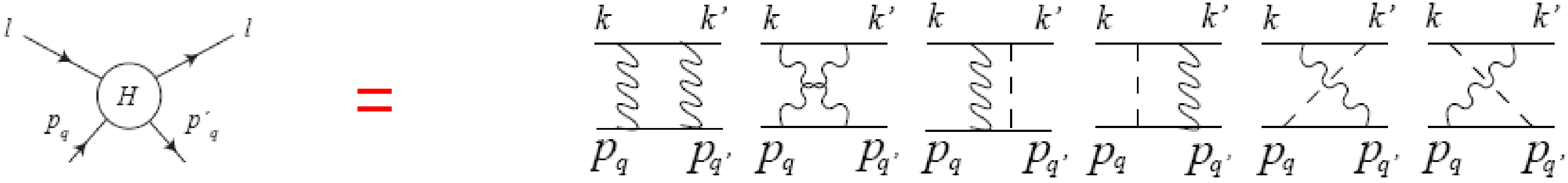
The corrections δ_G to $G_E^s + \beta G_M^s$ for HAPPEX, A4, and G0 experiments. (I, II), (III, IV), and (V, VI) refer to the HAPPEX, A4, and G0 data, respectively.

Partonic calculation of Box diagrams

Yu-Chun Chen, C-W K, M. Vanderhaeghen, arXiv 0903.1098

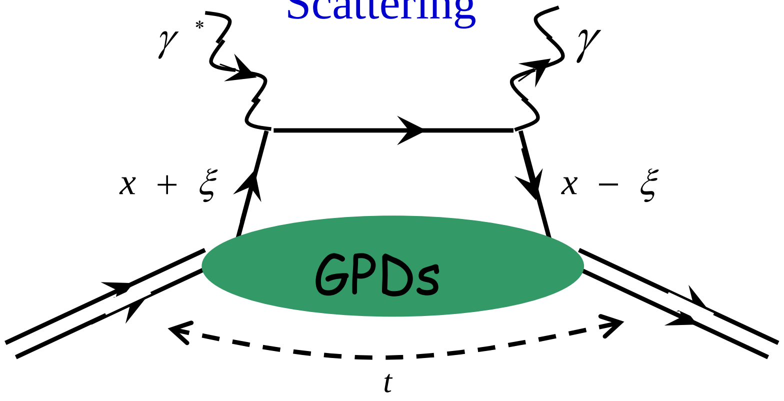


Handbag approximation for the elastic lepton-nucleon scattering. In the partonic process indicated by H, the lepton scatters from quarks within the nucleon, with momenta P_q and $P_{q'}$. The lower blob represents the GPD's of the nucleon.



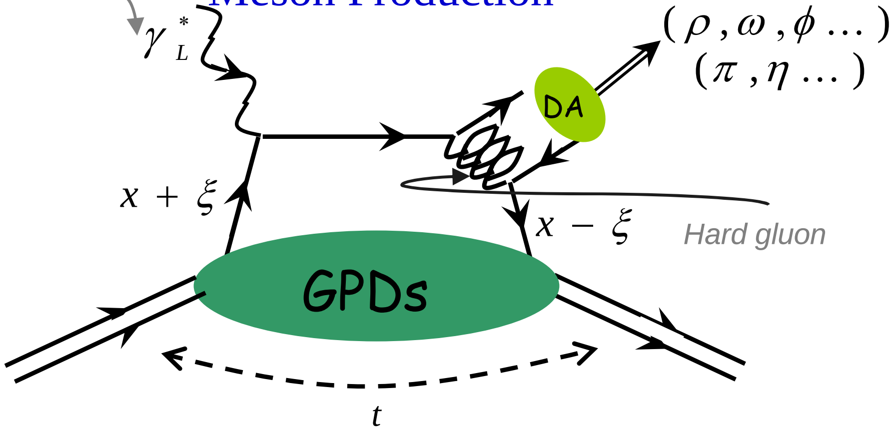
GPDs can be accessed via **exclusive reactions** in the **Bjorken** kinematic **regime**.

DVCS
Deeply Virtual Compton Scattering



DVMP
Deeply Virtual Meson Production

Longitudinal response ***only***

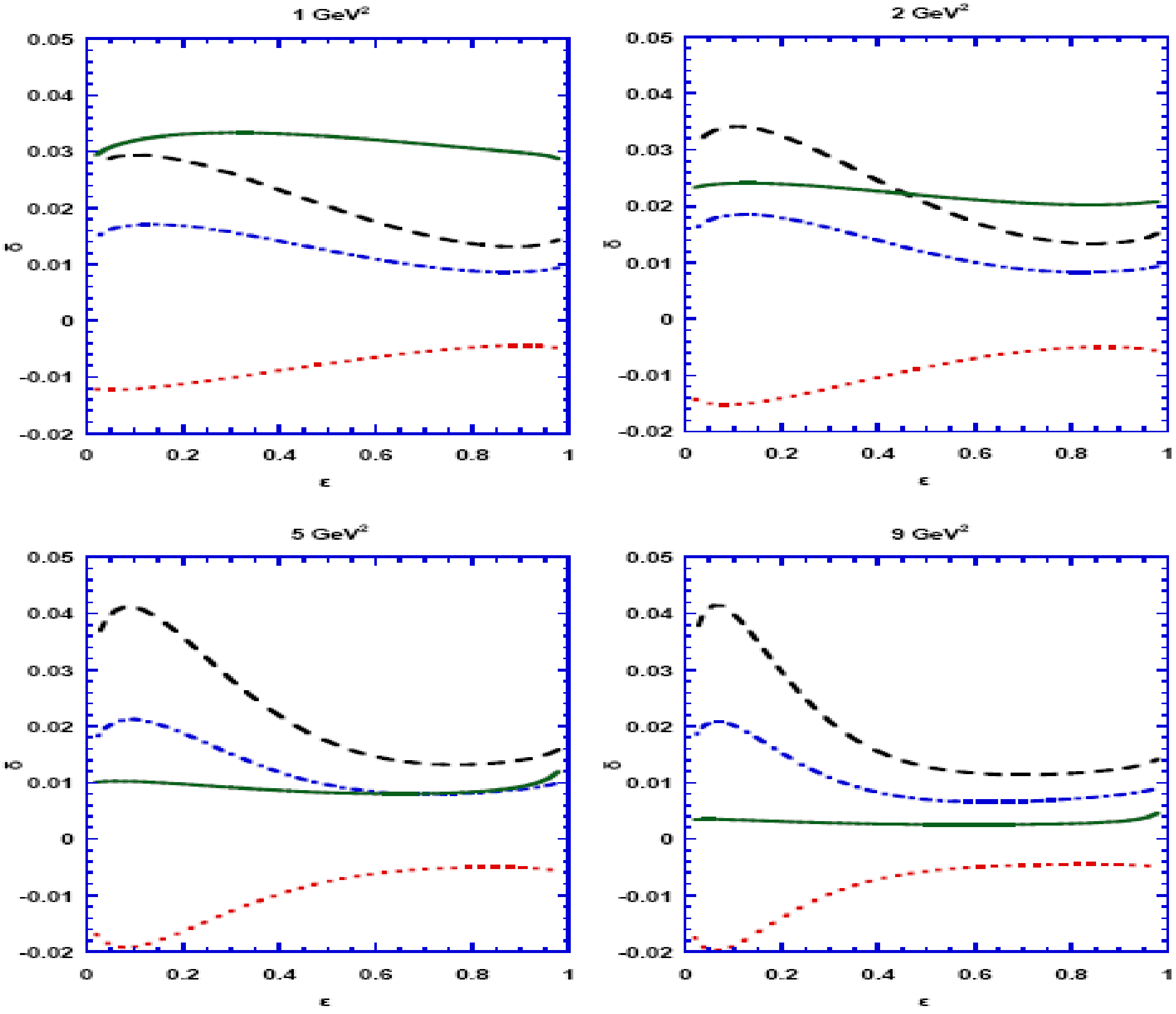


Hard gluon

❖ The DVCS process is identified via double (**eg**) or triple (**egN**) coincidences, allowing for **small scale detectors** and **large luminosities**.

Factorisation applies only to **longitudinally polarized virtual photons** whose contribution to the electroproduction cross section must **be isolated**.
.

Result of Partonic calculation



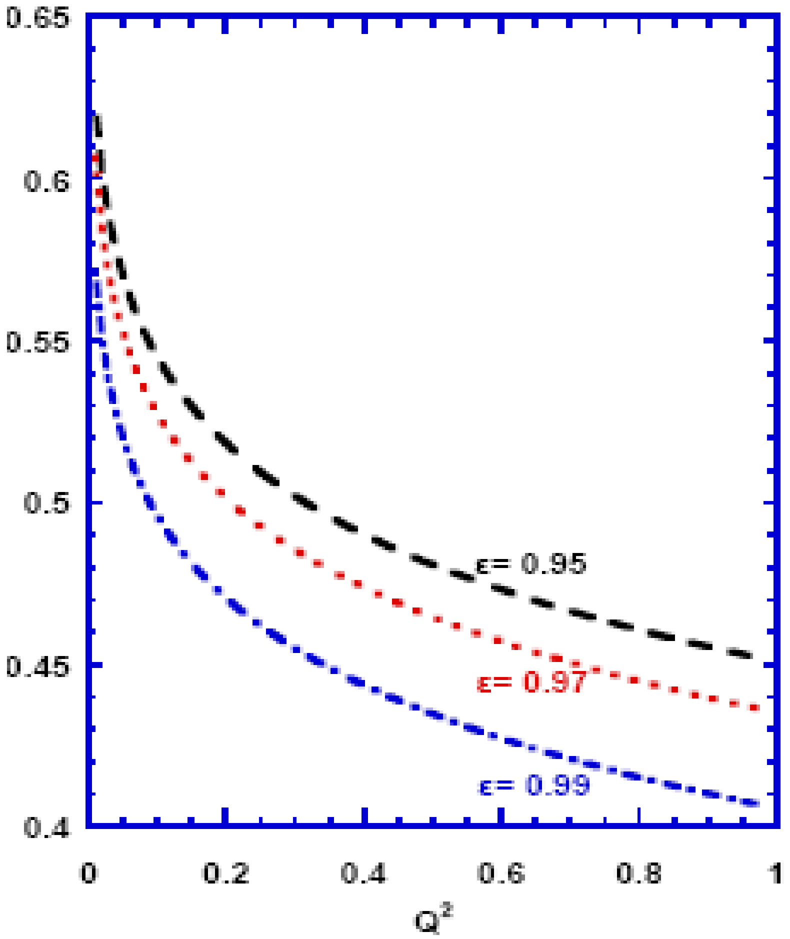
$\gamma(\gamma\gamma)$(dashed line)

$Z(\gamma\gamma)$(dotted lines)

TPE (dash-dotted lines)

$\delta_{\gamma Z}$ (solid lines)

Comparison with Marciano and Sirlin's approximation



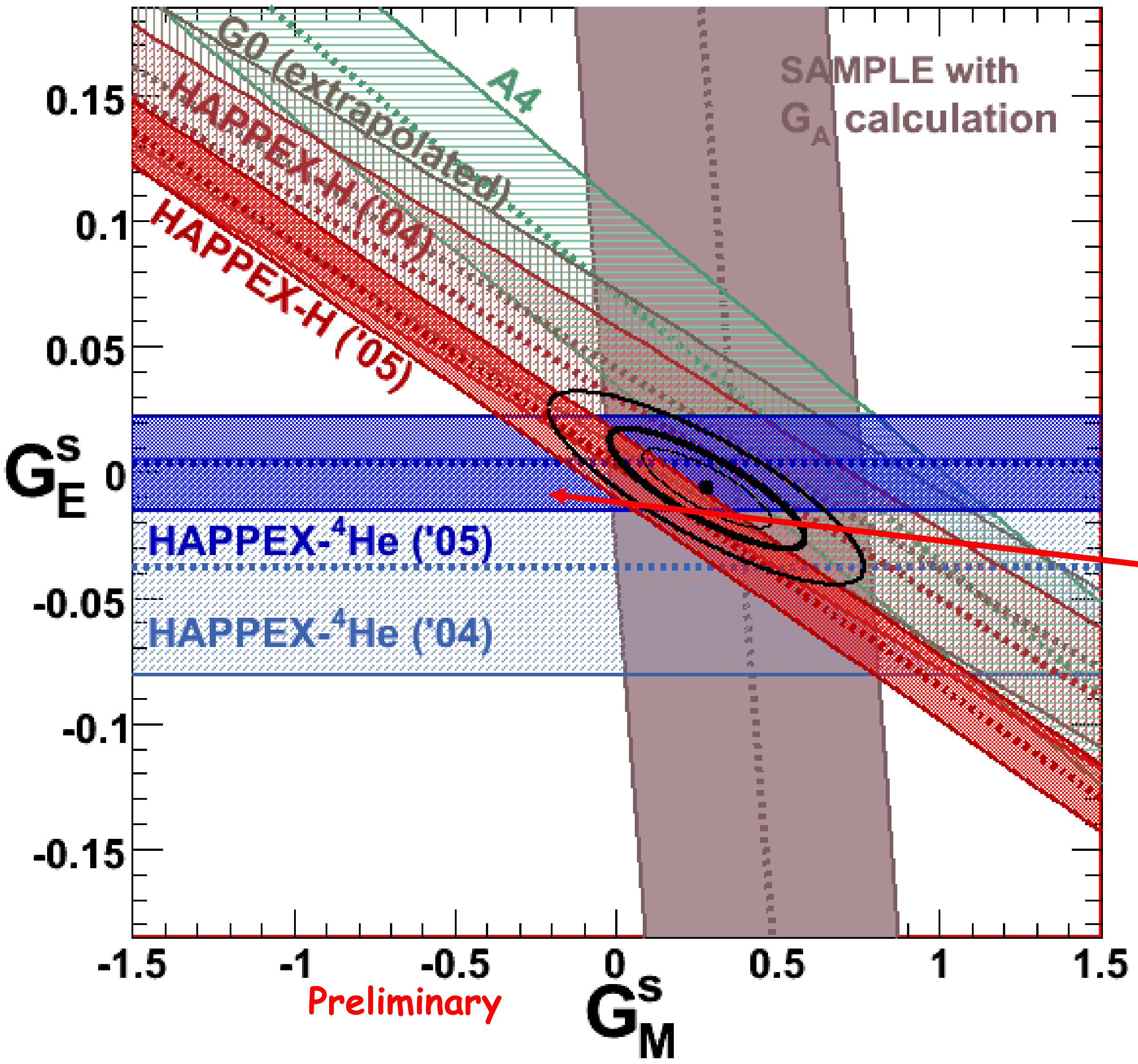
$$\Delta_{MS} = \frac{A_{PV}^{Parton}(\gamma Z)}{A_{PV}^{MS}(\gamma Z)}$$

$$= \frac{Re[\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{\gamma Z}^{PV,Parton}]}{Re[\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{\gamma Z}^{PV,MS}]}.$$

$\mathcal{M}_{\gamma Z,A}^{PV,MS}$

$$k = k' = 0$$

$$P_q \hat{=} P_{q'}$$



G_M^s = 0.28 +/- 0.20

G_E^s = -0.006 +/- 0.016

~3% +/- 2.3% of proton magnetic moment

~20% +/- 15% of isoscalar magnetic moment

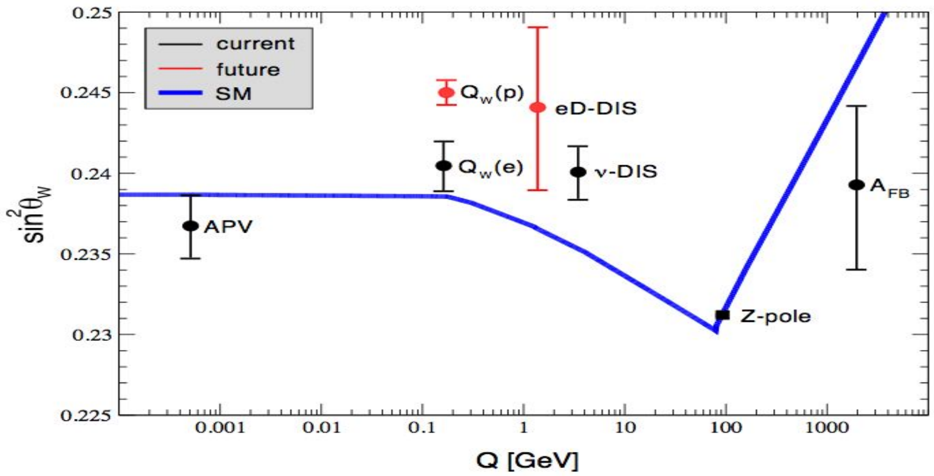
~0.2 +/- 0.5% of Electric distribution

One needs to be more sophisticated to extract the strangeness including box diagrams…..

Qweak experiment

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -\frac{G_F Q^2}{4\sqrt{2}\alpha}[Q_W + Q^2 B(Q^2)]$$

Q_W=1 $- 4\sin^2\theta_W \sim 0.0721$ at tree level in the standard model.



The scattering angle at Q_{weak} is 8 degree and Q^2=0.03GeV^2 corresponding around $\epsilon = 0.99$

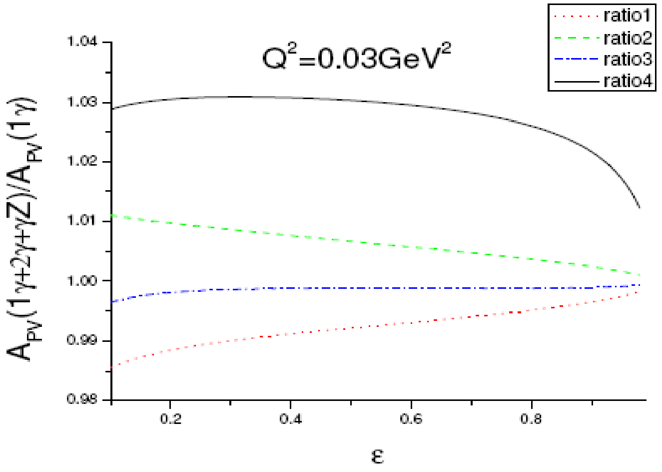
Effect of TBE in Qweak

$$A_{PV}(Q^2 \to 0, \epsilon \to 1)=\rho(1-4\kappa\sin^2\theta_W) \quad \Longrightarrow \quad Q_W^{old} = \frac{A_{PV}^{Exp}}{-a\rho};$$

$$\begin{aligned} A_{PV}(Q^2 \sim 0, \epsilon \sim 1) &= -a(\rho-\Delta\rho)(1-4(\kappa-\Delta\kappa)\sin^2\theta_W)(1+\delta) \\ &= -a(\rho-\Delta\rho+\delta+4\frac{\Delta\kappa\sin^2\theta_W}{1-4\sin^2\theta_W})(1-4\kappa\sin^2\theta_W) \end{aligned}$$

$$Q_W^{new} = \frac{A_{PV}^{Exp}}{-a(\rho-\Delta\rho+\delta+4\frac{\Delta\kappa\sin^2\theta_W}{1-4\kappa\sin^2\theta_W})},$$

$$\delta_Q = \frac{Q_W^{old}}{Q_W^{new}} - 1 = \frac{1}{\rho}(\delta-\Delta\rho+4\frac{\Delta\kappa\sin^2\theta_W}{1-4\kappa\sin^2\theta_W}) \sim -6.65\%.$$



Dispersion relation study

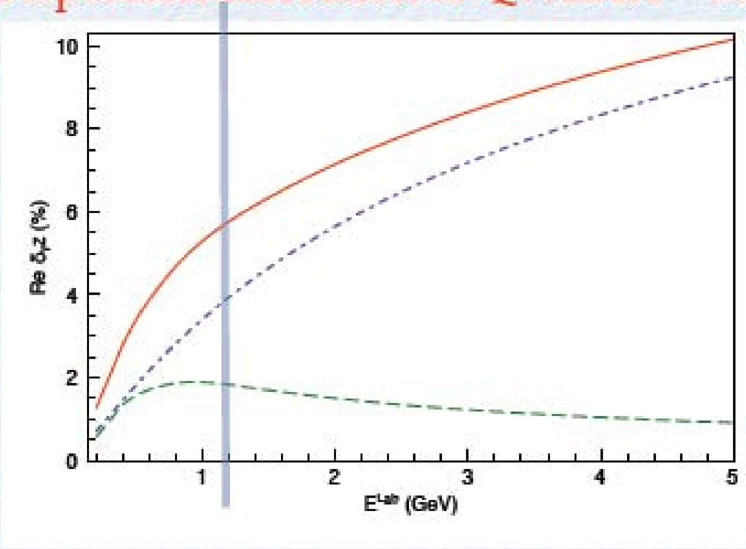
$$\mathrm{Re}\delta_{\gamma Z_A}(\nu) \quad = \quad \frac{2\nu}{\pi}\int_{\nu_\pi}^{\infty}\frac{d\nu'}{\nu'^2-\nu^2}\mathrm{Im}\delta_{\gamma Z_A}(\nu')$$

- in exact forward direction only

Parity violating asymmetry - to NLO

$$A^{PV} = \frac{G_F t}{4\pi\alpha\sqrt{2}} Q_W^p \left[1 + \mathrm{Re}\,\delta_{RC} + \mathrm{Re}\,\delta_{\gamma Z}(\nu)\right] + \mathcal{O}(t^2)$$

Dispersion correction to QWEAK ~ 5.5-6%



🟩 Resonance

🟦 Regge

🟥 Full

Mikhail Gorshteyn and Charles J. Horowitz
Nuclear Theory Center & Indiana University, Bloomington

arXiv:0811.0614 (hep-ph)

Current status of TBE physics

- Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.

Winston Churchill
After the second battle of
El Alamein, Nov 10,1942

Conclusion and Outlook

- Box diagrams are crucial for the extraction of the strangeness inside the nucleon!
- More delicate estimate of the TBE Box is needed badly! (including more resonances, consider quark-level contributions, QCD corrections…….)
- Neutrino-Proton scattering data should be included in the extraction of strangeness.
- Atomic parity-violation is also needed to be included.

Thank you for Listening!

How strange is the proton?

It depends on the size
of the Box!!!