Two-boson exchange corrections in PVES

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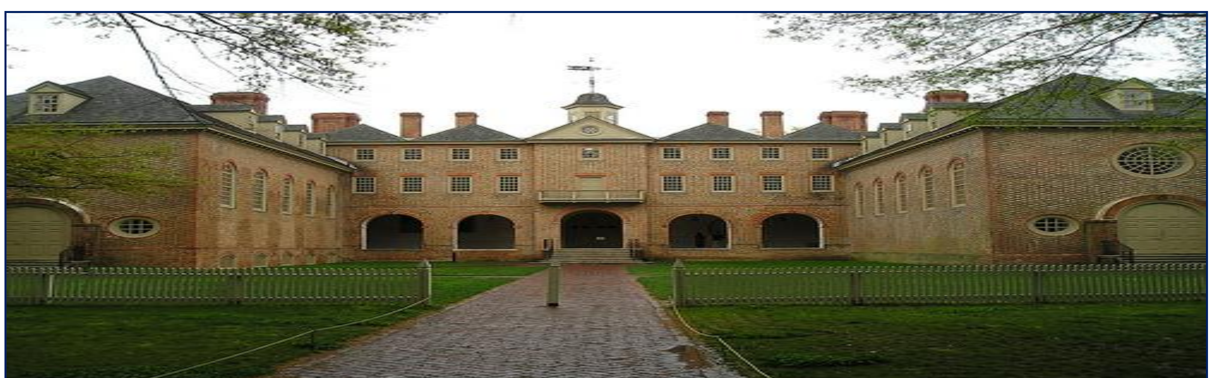


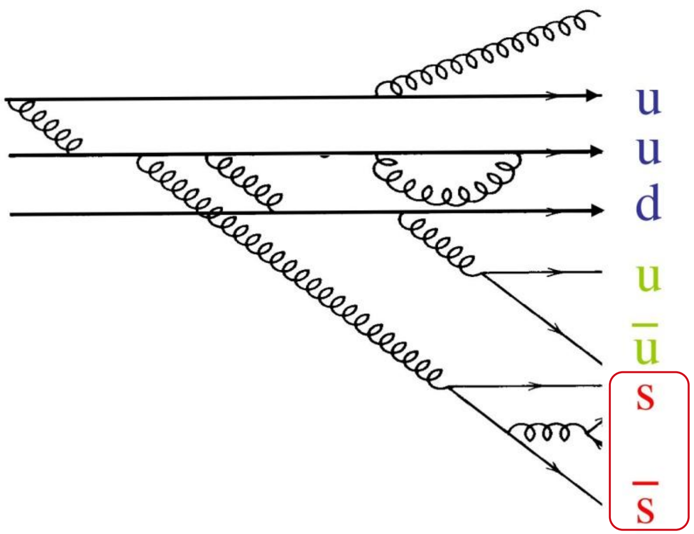
Collaboration and Reference

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

This talk is based on the following works:

(1) H-Q Zhou, CWK, S-N. Yang: Phys.Rev.Lett.99:262001,2007
(2) K. Nagata, H-Q Zhou, CWK, S-N. Yang: Phys.Rev.C79:062501,2009.
(3) H-Q Zhou, CWK, S-N Yang, K. Nagata: Phys.Rev.C81:035208,2010
(4) Y.C. Chen, CWK, M. Vanderhaeghen: arXiv: 0903.1098, submitted to PRD

Strangeness in the nucleon



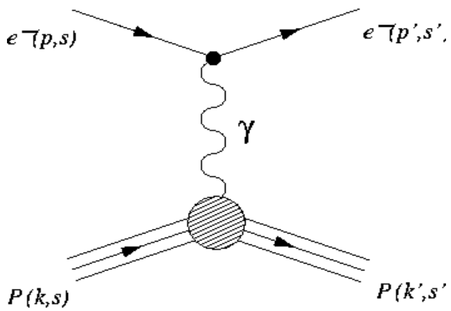
- $P = uud + u\bar{u} + d\bar{d} + s\bar{s} + g + ...$

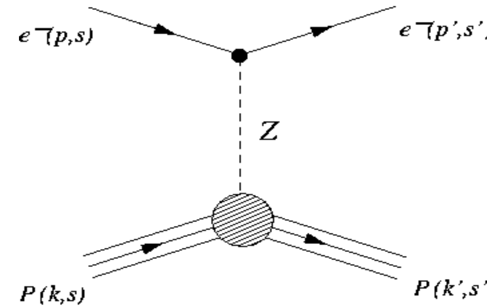
$\underbrace{u\bar{u} + d\bar{d} + s\bar{s} + g + ...}_{\text{« sea »}}$

- 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 ep Elastic Scattering





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

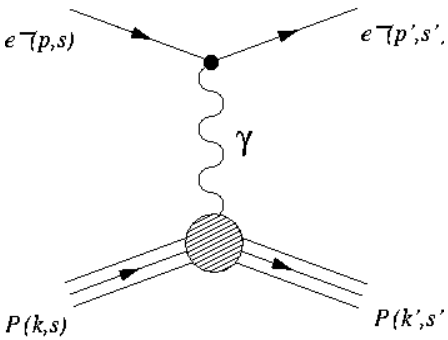
Interference: $\sigma \sim |M^{EM}|^2 + |M^{NC}|^2 + 2\mathrm{Re}(M^{EM*})M^{NC}$

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

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

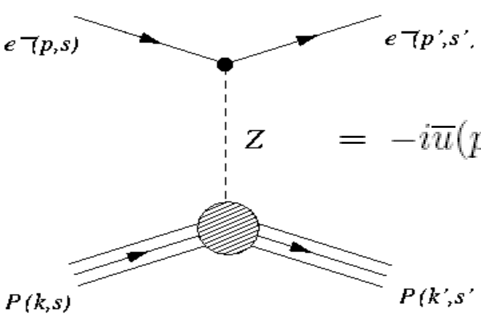
Tiny (~10^{-6}) cross section asymmetry isolates weak interaction

OPE vs OZE



$$-i\overline{u}(p_3)(-ie\gamma^\mu)u(p_1)\frac{-i}{q^2+i\varepsilon}\overline{u}(p_4)\Gamma^\gamma_\mu(p_4,p_2)u(p_2),$$

$$\begin{aligned}\langle p'|J^Z_\mu|p\rangle &= \overline{u}(p')\left[F_1^{Z,p}(q^2)\gamma_\mu + F_2^{Z,p}(q^2)\frac{i\sigma_{\mu\nu}}{2M_N}q^\nu + G_A^Z(q^2)\gamma_\mu\gamma_5\right]u(p),\\ \langle p'|J^{em}_\mu|p\rangle &= \overline{u}(p')\left[F_1^{\gamma,p}(q^2)\gamma_\mu + F_2^{\gamma,p}(q^2)\frac{i\sigma_{\mu\nu}}{2M_N}q^\nu\right]u(p),\end{aligned}$$



$$= -i\overline{u}(p_3)\left(\frac{ig\gamma^\mu}{4\cos\theta_W}\right)[(-1+4\sin^2\theta_W)+\gamma_5]u(p_1)\frac{-i}{q^2-M_Z^2+i\varepsilon}\ \overline{u}(p_4)\Gamma^Z_\mu(p_4,p_2)u(p_2),$$

Isolating the neutral weak form factors: vary the kinematics or the targets

For 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

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

NC probes same hadronic flavour structure, with different couplings:

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

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

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

Apply Charge Symmetry

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

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

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

$\xrightarrow{\text{Charge symmetry}}$

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

$\xrightarrow{\text{Shuffle}}$

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

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: Tree Level

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

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

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

Strange form factors

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

Axial form factors

$$a = G_F Q^2/4\pi\alpha_{em}\sqrt{2},$$

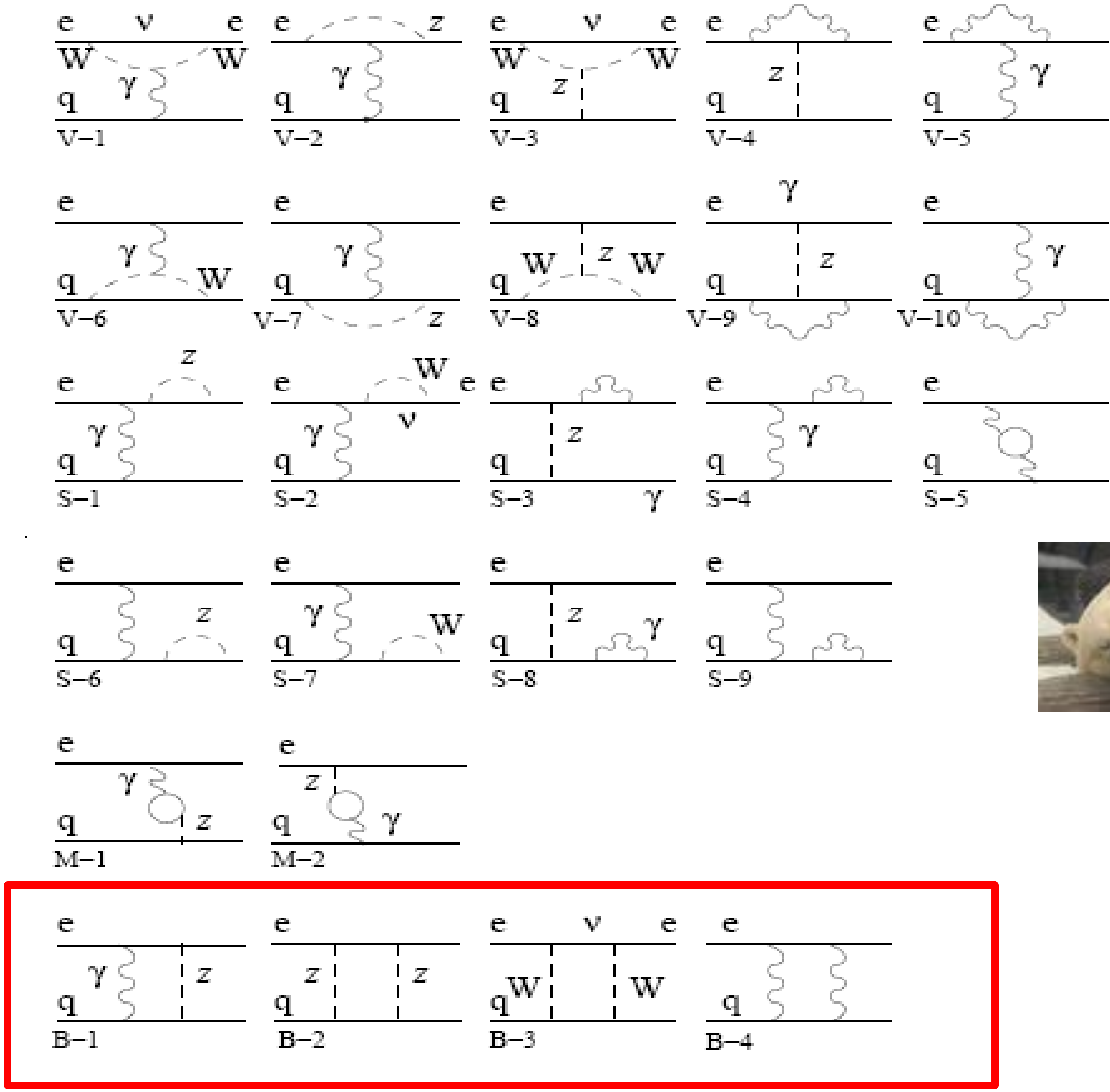
$$\epsilon' = \sqrt{\tau(1+\tau)(1-\epsilon^2)}$$

Parity-Violating Electron Scattering Program

Expt/Lab	Target/ Angle	Q^2 (GeV^2)	A_{phys} (ppm)	Sensitivity	Status
SAMPLE/Bates					
SAMPLE I	LH_2/145	0.1	-6	$\mu_s + 0.4G_A$	2000
SAMPLE II	LD_2/145	0.1	-8	$\mu_s + 2G_A$	2004
SAMPLE III	LD_2/145	0.04	-4	$\mu_s + 3G_A$	2004
HAPPEx/JLab					
HAPPEx	LH_2/12.5	0.47	-15	$G_E + 0.39G_M$	2001
HAPPEx II, III	LH_2/6	0.11	-1.6	$G_E + 0.1G_M$	2006, 2007
HAPPEx He	^4He/6	0.11	+6	G_E	2006, 2007
HAPPEx	LH_2/14	0.63	-24	$G_E + 0.5G_M$	(2009)
A4/Mainz					
	LH_2/35	0.23	-5	$G_E + 0.2G_M$	2004
	LH_2/35	0.11	-1.4	$G_E + 0.1G_M$	2005
	LH_2/145	0.23	-17	$G_E + \eta G_M + \eta' G_A$	2009
	LH_2/35	0.63	-28	$G_E + 0.64G_M$	(2009)
G0/JLab					
Forward	LH_2/35	0.1 to 1	-1 to -40	$G_E + \eta G_M$	2005
Backward	LH_2/LD_2/110	0.23, 0.63	-12 to -45	$G_E + \eta G_M + \eta' G_A$	2009

Tree Level is not enough!

- The strange form factors are found to be very small, just few percent.
- To make sure the extracted values are accurate, it is necessary to take the radiative corrections into consideration!
- So one has to draw many diagrams as follows…..



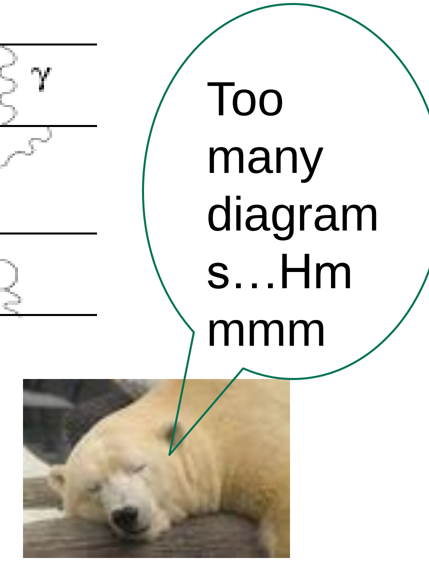
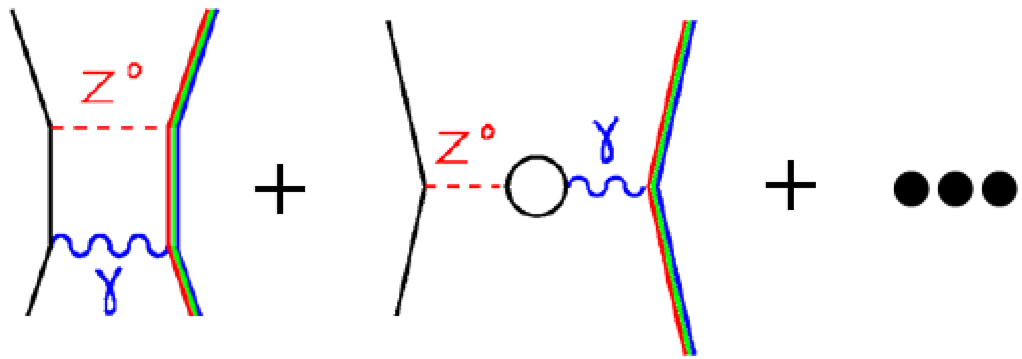


FIG. 2: The radiative corrections of the electron-quark scattering. (V-1) to (V-10) are the vertex corrections. (S-1) to (S-10) are the self energy insertion of the fermions and the photon. (M-1) to (M-2) are the γZ mixing diagrams. (B-1) to (B-4) are the box diagrams.

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

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

$$+ \; C_{2q}\overline{u}(p_1)\gamma_\mu u(p_3)\overline{u}_{p'}G_A^{q/p}\gamma^\mu\gamma_5 u(p)].$$

Define ρ and κ as follows:

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

$$\Downarrow$$

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

Extraction of strange form factors with radiative corrections

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

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

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

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 the constants derived from electroweak radiative corrections

$$\rho = 1 + \rho_{SE} + \rho_{Zqq} + \rho_{WW} + \rho_{\gamma Z} + \rho_{ZZ},$$

$$\kappa = 1 + \kappa_{SE} + \kappa_{Zqq} + \kappa_{WW} + \kappa_{\gamma Z} + +\kappa_{ZZ} + \kappa_{CR} + \kappa_{Mix};$$

$$\rho_{SE} = +\frac{\alpha_{em}}{4\pi}\left[\frac{3}{4s^4}\ln c^2 - \frac{7}{4s^2} + \frac{3}{4s^2}\frac{m_t^2}{M_W^2} + \frac{3}{4}\frac{\xi}{s^2}\left(\ln(\frac{c^2/\xi}{c^2-\xi}) + \frac{1}{c^2}\frac{\ln\xi}{1-\xi^2}\right)\right];$$

$$\kappa_{SE} = -\frac{\alpha_{em}}{2\pi s^2}\left[\frac{7}{9} - \frac{s^2}{3}\right].$$

, $s^2 = \sin^2\theta_W(Q^2 = M_W^2)$, $c^2 = 1 - s^2$, $\xi = M_\phi^2/M_Z^2$ here M_ϕ is Higgs

$$\rho_{Zqq} = -\frac{\alpha_{em}}{2\pi}, \kappa_{Zqq} = \frac{\alpha_{em}}{2\pi s^2}. \qquad \kappa_{CR} = \frac{\alpha_{em}}{2\pi s^2}\left[\frac{1-4s^2}{6}\left(\ln\frac{M_Z^2}{m_e^2} + \frac{1}{6}\right)\right];$$

$$\rho_{WW} = -\frac{\alpha_{em}}{2\pi s^2}, \kappa_{WW} = -\frac{\alpha_{em}}{2\pi s^2}\frac{9}{8s^2},$$

$$\kappa_{Mix} = -\frac{\alpha_{em}}{2\pi s^2}\frac{1}{6}\sum_f (C_{3f}Q_f - 4s^2 Q_f)\ln(m_f^2/M_W^2),$$

Q_f=fermion electric charge, C_{3f}=twice the weak isospin.

Be aware of the Box!

- Box diagram is intricate because it is related with nucleon intermediate states.
- Box diagram is special

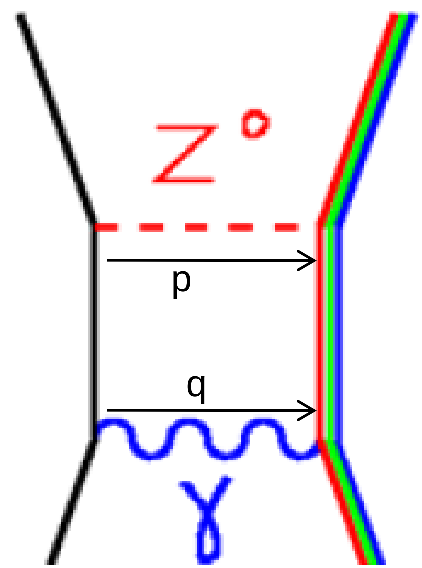
  because of its complicated Q^2 and ε dependence hence it is not trivial to squeeze it.

So how can one squeeze the box diagrams?

Zero Transfer Momentum Approximations

Approximation made in the previous analysis:

Pe



Pe'

$p=q=k \Rightarrow Q^2=t=(p-q)^2=0$

Pe=Pe'=0

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

Marciano, Sirlin (1983)

Refined evaluation of Box diagrams

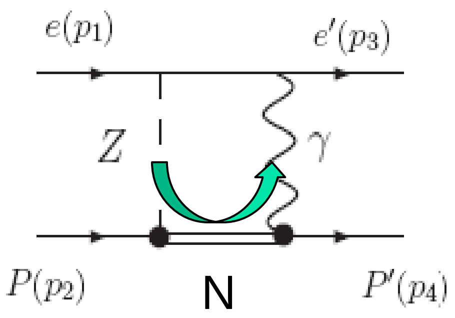
$$\rho_{\gamma Z} = -\frac{2\alpha_{em}}{\pi}(1-4\sin^2\theta_W)\left[K+\frac{4}{5}\xi_B\right],$$

$$\kappa_{\gamma Z} = -\frac{\alpha_{em}}{2\pi\sin^2\theta_W}\left(\frac{9}{4}-4\sin^2\theta_W\right)(1-4\sin^2\theta_W)\left[K+\frac{4}{5}\xi_B\right].$$

$K=8.58$, $4/5\xi_B=2.04$ Marciano, Sirlin (1984)

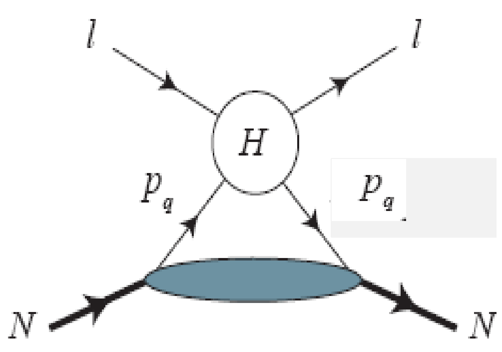
K is from the high loop momentum integrand containing QCD correction.
ξ is from the low loop momentum integrand.

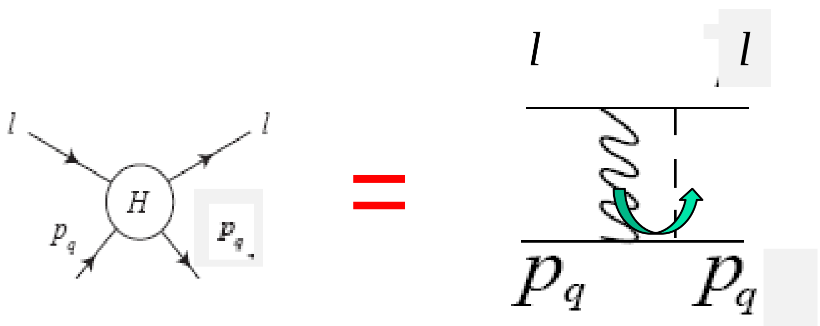
High and Low in MS scheme



Low Loop momentum Integration:
Only include N intermediate state.
Insert the on-shell form factors.

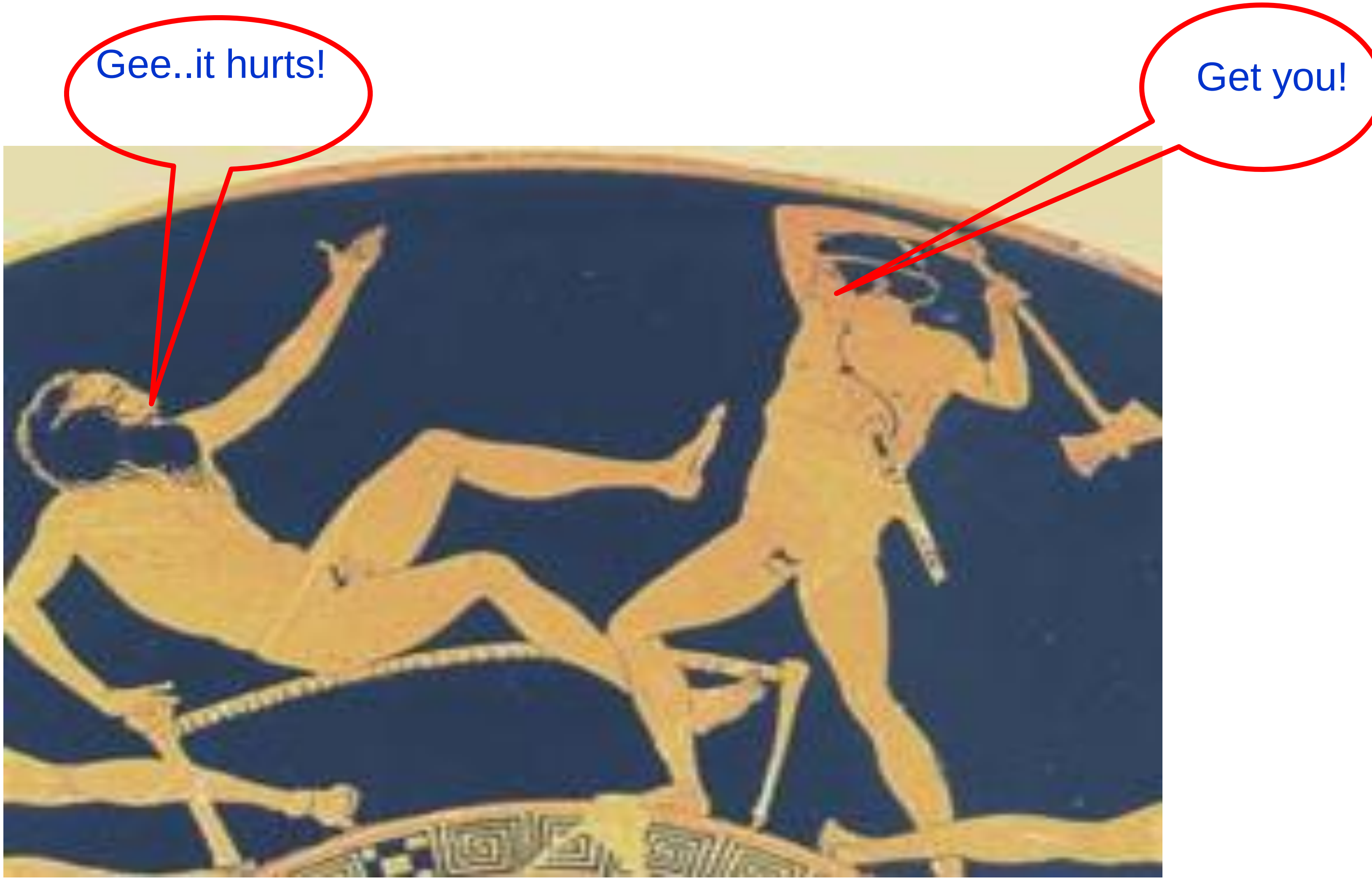
High Loop momentum Integration:
Lepton and a single quark exchange bosons.
Then one makes convoluation with PDF.





MS approximation

- Initially it is designed for atomic parity violation.
- Two exchanged boson carry same 4-momentum and lepton momenta are set to be zero. In other words MS approximation is a three-fold approximation:
- $Q^2=0$.
- $E_{lab}=0$.
- Coulomb force is taken away.



But this is nothing but a Procrustean bed!

Why is it Procrustean Bed?

- The best reason of making this approximation seemed to be only because it was the best way one could do in 1980s.
- On the other hand, since box diagrams are small, such an approximation has been supposed to be good enough and widely adopted.
- However if the Box diagram owns strong Q^2 and/or ε dependencies, its impact is not necessarily small! (Painful experience learned from TPE)

Indeed MS is not good enough !

Zhou et al, PRC81:035208 2010

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

MS value (Low-k)

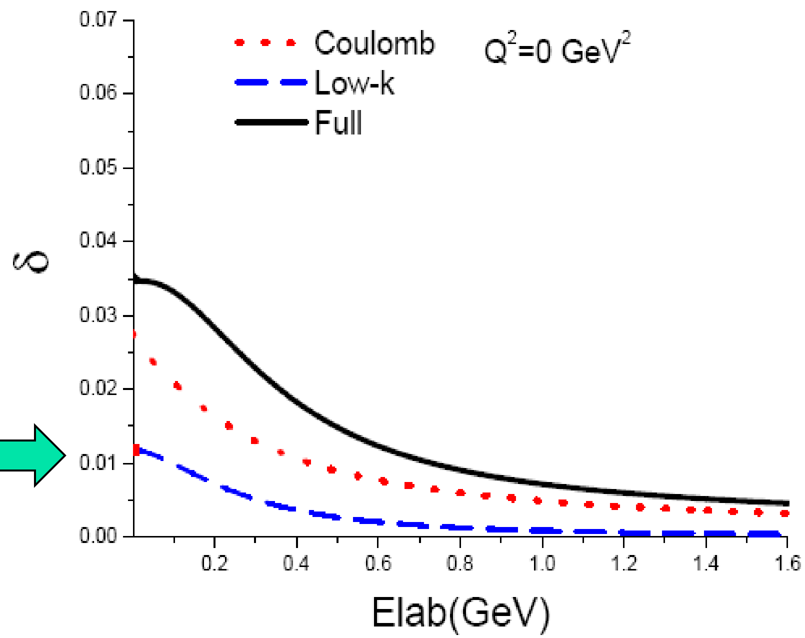
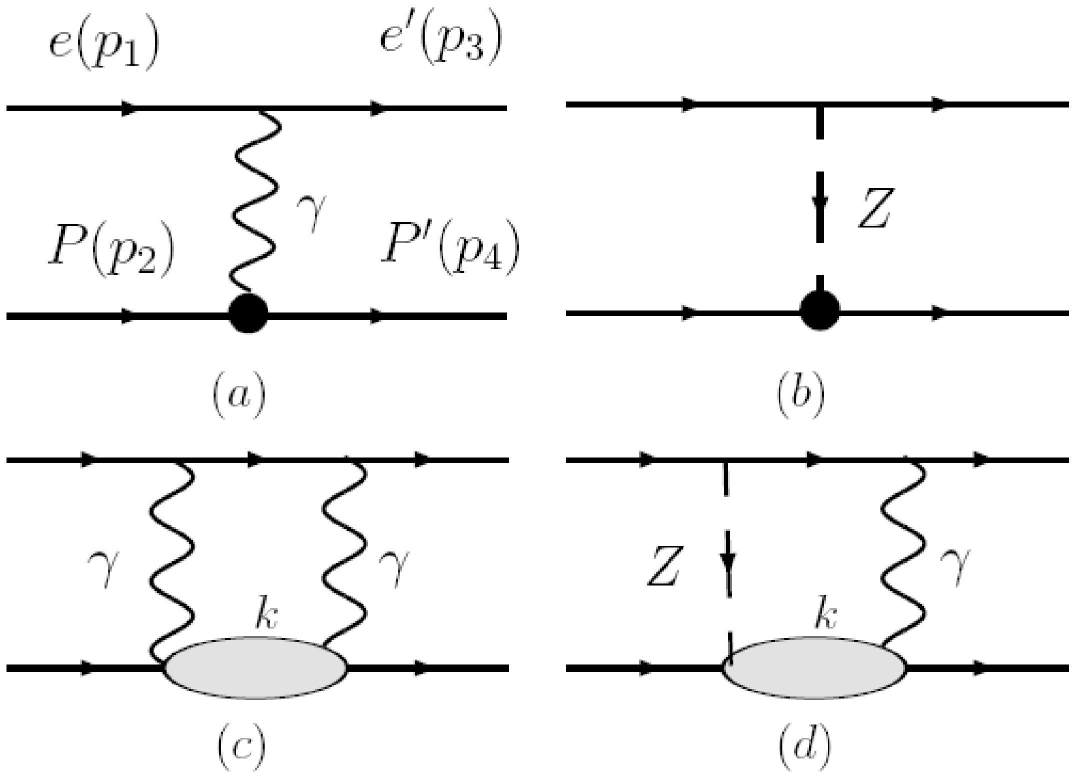


FIG. 9: Comparison between our result of δ at $Q^2 = 0$ with δ_{MS}. The dashed line denotes the contribution corresponding to the low-k part of the MS approximation with finite E_{lab}. The Coulomb part is represented by the dotted line and the total contribution is denoted as the solid line.

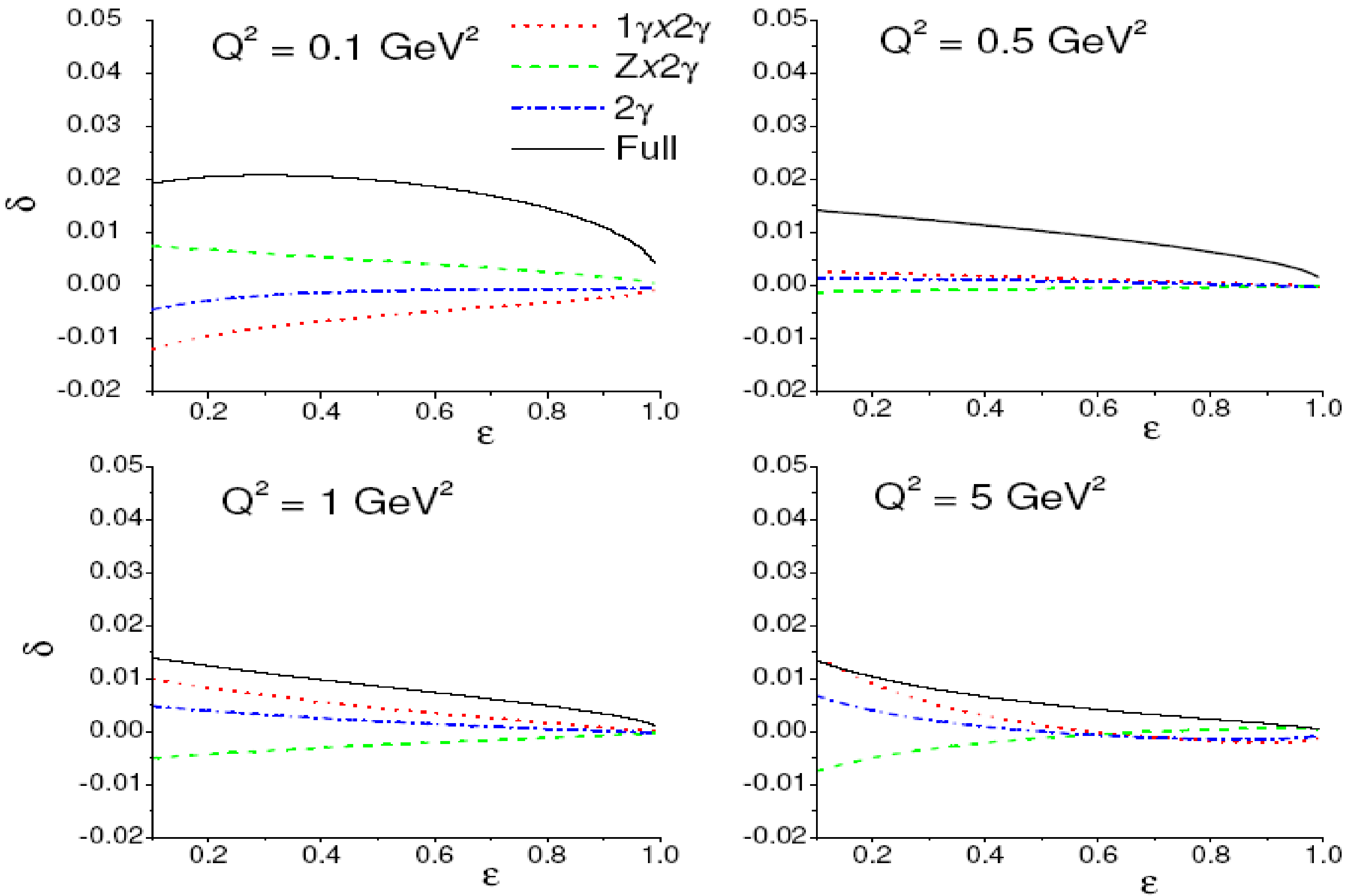
How about other box diagrams?

- MS approximation turns out to be good approximation for ZZ and WW box diagrams.
- On the other hand, 2γ diagrams are zero in MS limit due to the cancellation of box and cross-box diagrams.
- Hence one shall consider γZ **and** 2γ box diagrams beyond MS limit.

Two-Boson exchange diagrams

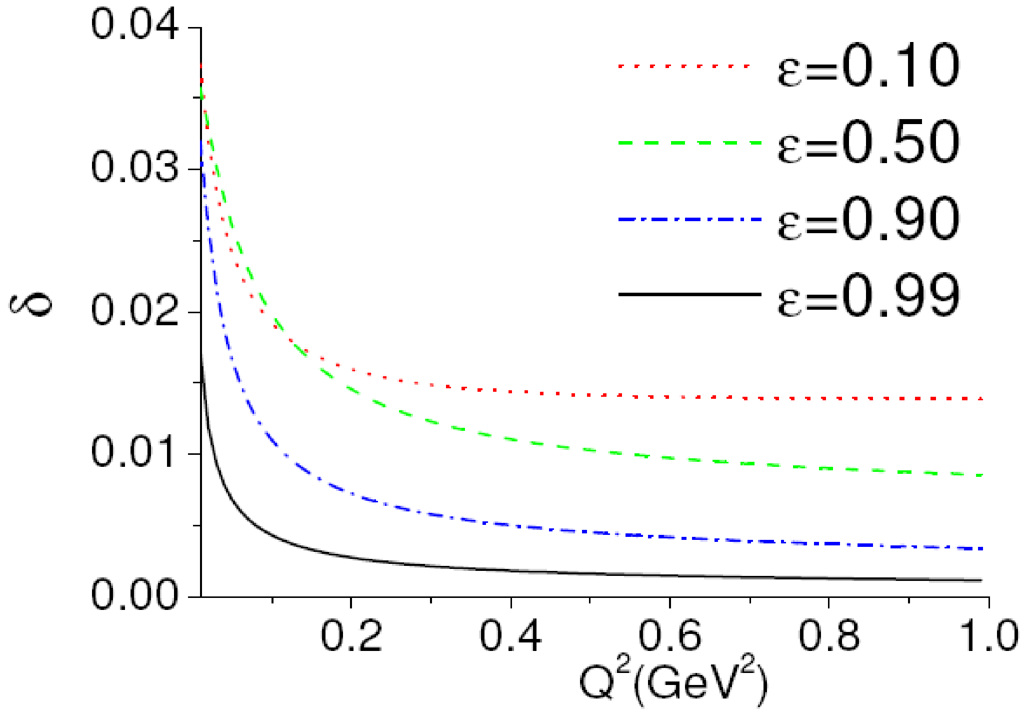


HQ. Zhou, CWK and SN Yang, PRL, 99, 262001 (2007)



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

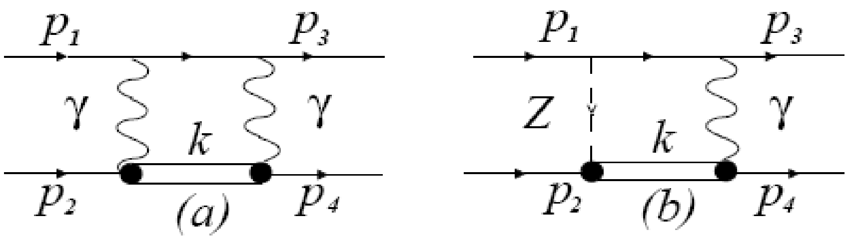
HQ. Zhou, CWK and SN Yang, PRL, 99, 262001 (2007)



Qualitative features of TBE effect

- $2\gamma E$ and γZE both vanish at forward limit. $2\gamma E$ is very small due to cancellation between $\gamma x 2\gamma$ and $Zx2\gamma$.
- γZE is dominant and decreases as scattering angle decreases.
- TBE decreases fast when Q^2 increases.

Adding resonances….

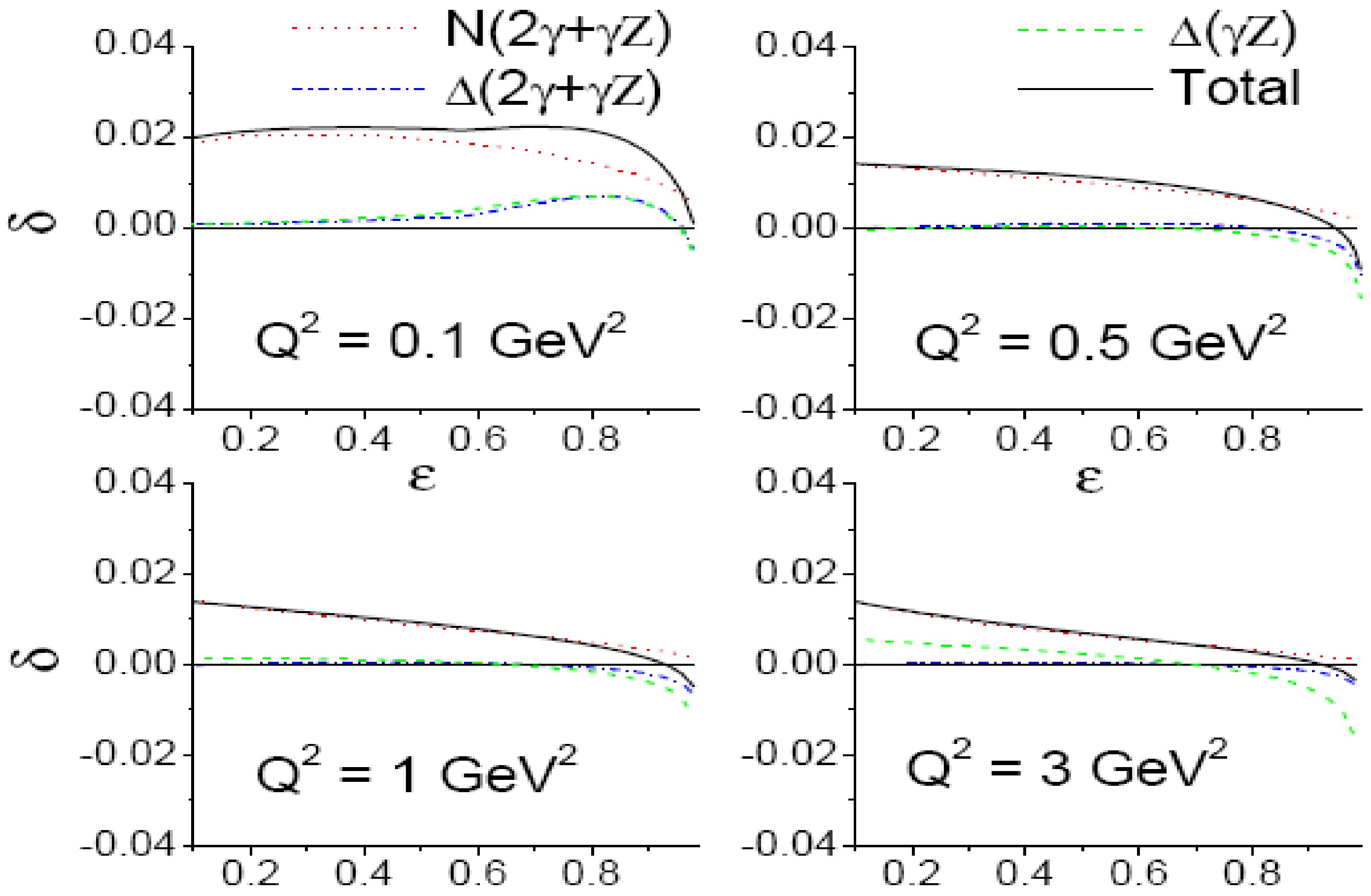


Keitaro Nagata, Hai Qing Zhou, CWK and SN Yang

arXiv:0811.3539 PRC79:062501 2009

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

Nagata et al, arXiv:0811.3539 PRC79:062501 2009



Nagata et al, arXiv:0811.3539 PRC79:062501 2009

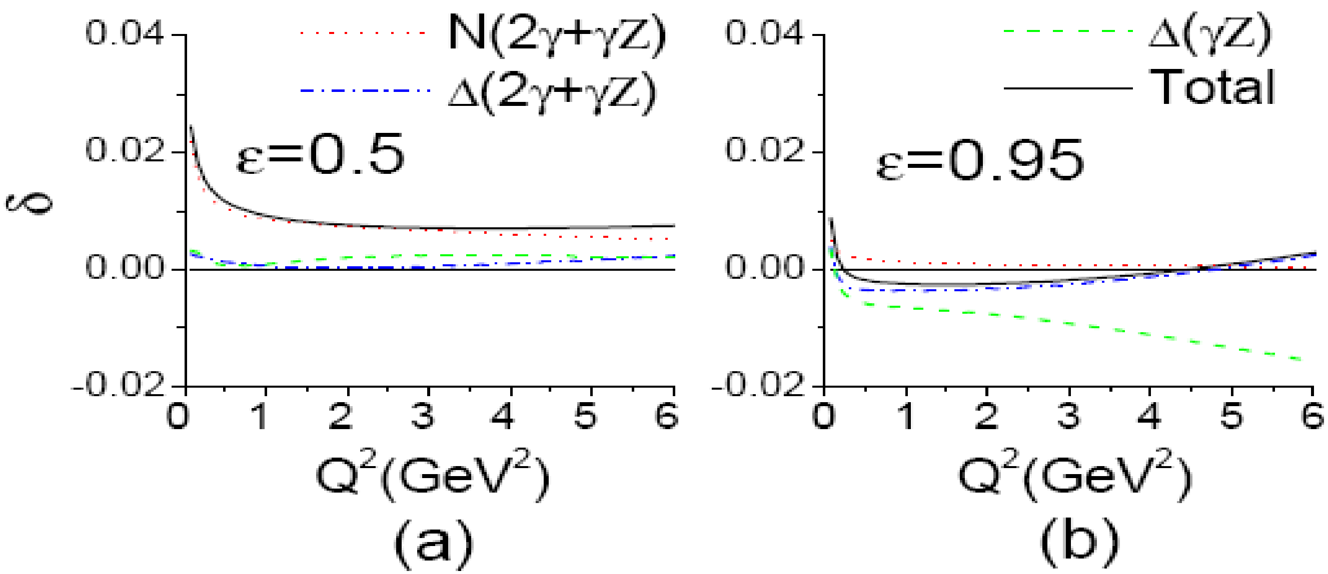
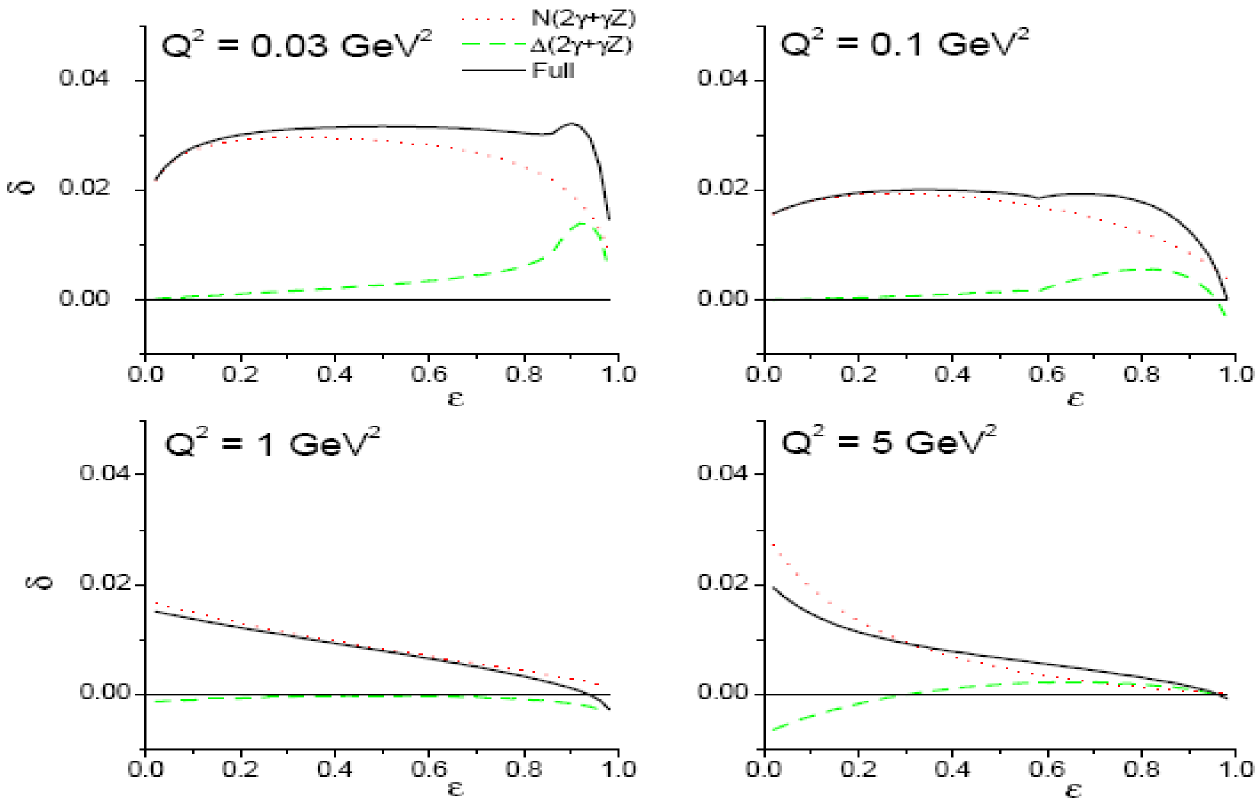


FIG. 4: TPE and γZ-exchange corrections with with nucleon and Δ intermediate states to parity-violating asymmetry as functions of Q^2 from 0.1 to 6 GeV^2 at $\epsilon = 0.5$ and 0.95.

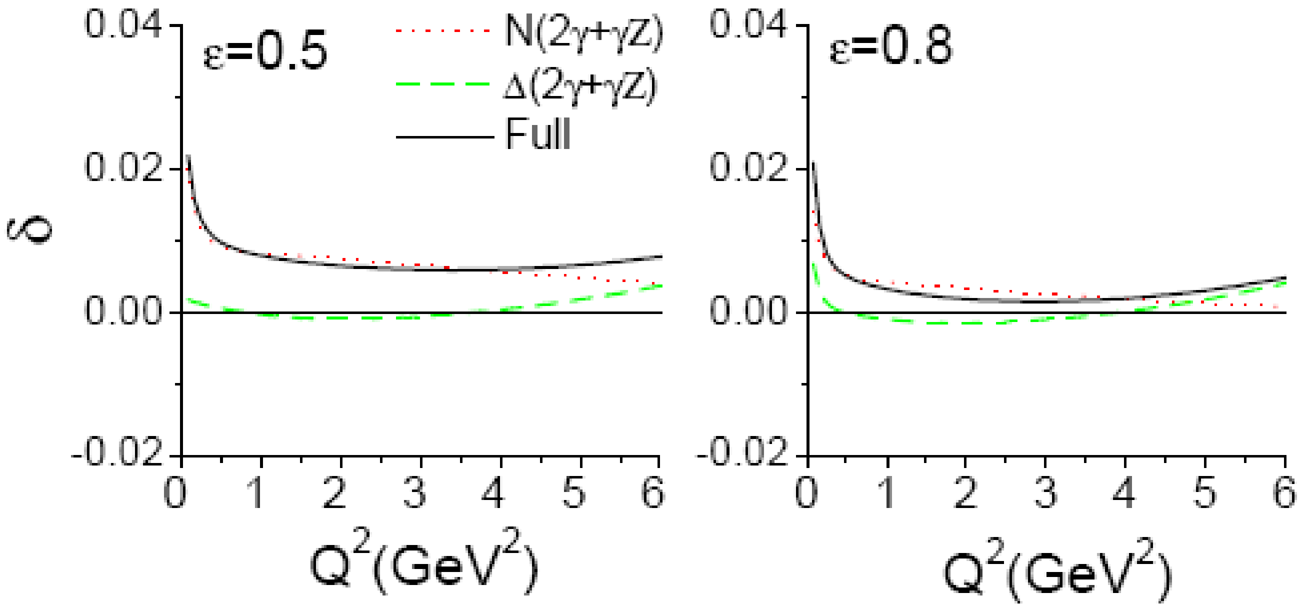
Updated results: Using physical Form factors

HQ Zhou, CWK, SN Yang, K Nagata **PRC 81 035208 2010**



Updated results: Using physical Form factors

HQ Zhou, CWK, SN Yang, K Nagata **PRC 81 035208 2010**



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

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

Exp	$Q^2(GeV^2)$	ϵ	$\delta_N(\%)$	$\delta_\Delta(\%)$	$\delta(\%)$	$\delta_0(\%)$	$\delta_G(\%)$	$G_s(10^{-2})$	$\Delta G_s(10^{-2})$
HAPPEX	0.477	0.974	0.18	-0.27	-0.09	0.20	-2.54	1.4	-0.04
HAPPEX	0.109	0.994	0.21	-0.80	-0.58	0.51	-20.63	0.7	-0.14
G0	0.122	0.9930	0.21	-0.72	-0.51	0.61	-3.63	3.9	-0.14
G0	0.128	0.9926	0.21	-0.70	-0.49	1.05	-1.28	9.2	-0.12
G0	0.136	0.9921	0.21	-0.67	-0.44	0.81	-1.60	7.7	-0.12
G0	0.144	0.9916	0.20	-0.64	-0.41	0.38	14.14	-1.1	-0.16
G0	0.153	0.9911	0.20	-0.61	-0.39	0.51	-3.50	3.8	-0.13
G0	0.164	0.9904	0.20	-0.58	-0.36	0.41	-9.18	1.5	-0.14
G0	0.177	0.9896	0.20	-0.55	-0.32	0.31	6.19	-2.3	-0.14
G0	0.192	0.9886	0.19	-0.52	-0.29	0.35	-16.05	0.8	-0.12
G0	0.210	0.9875	0.19	-0.48	-0.29	0.30	48.25	-0.3	-0.14
G0	0.232	0.9860	0.19	-0.44	-0.25	0.30	-20.25	0.6	-0.12
G0	0.262	0.9840	0.19	-0.40	-0.21	0.35	-2.26	4.6	-0.10
G0	0.299	0.9814	0.19	-0.36	-0.17	0.26	-8.68	1.2	-0.10
G0	0.344	0.9783	0.19	-0.32	-0.13	0.28	-1.99	4.4	-0.09
G0	0.411	0.9735	0.19	-0.27	-0.08	0.27	-1.18	6.4	-0.08
G0	0.511	0.9657	0.20	-0.23	-0.03	0.19	-2.10	2.8	-0.06
G0	0.628	0.9580	0.21	-0.20	0.01	0.20	-0.71	6.8	-0.05
G0	0.786	0.9413	0.22	-0.18	0.04	0.15	-0.81	3.9	-0.03
G0	0.997	0.9197	0.25	-0.18	0.07	0.15	-0.32	7.6	-0.02
A4	0.108	0.83	1.07	0.53	1.60	0.61	2.00	7.1	0.14
A4	0.23	0.83	0.66	0.14	0.80	0.29	2.85	3.9	0.11

HQ Zhou, CWK,
SN Yang, K Nagata
PRC 81, 035208,2010

$$\Delta G_s \equiv (\bar{G}_E^s + \beta \bar{G}_M^s) - (G_E^s + \beta G_M^s),$$

Here we only subtract the soft parts of **ρ and κ**

$$\Delta\rho = -\frac{2\alpha_{em}}{\pi}(1 - 4\sin^2\theta_W)\cdot\frac{4}{5}\xi_B$$

$$= -0.73 \times 10^{-3}$$

$$\Delta\kappa = -\frac{\alpha_{em}}{2\pi\sin^2\theta_W}\left(\frac{9}{4} - 4\sin^2\theta_W\right)$$

$$(1 - 4\sin^2\theta_W)\cdot\frac{4}{5}\xi_B$$

$$= -1.03 \times 10^{-3}.$$

Go data

4

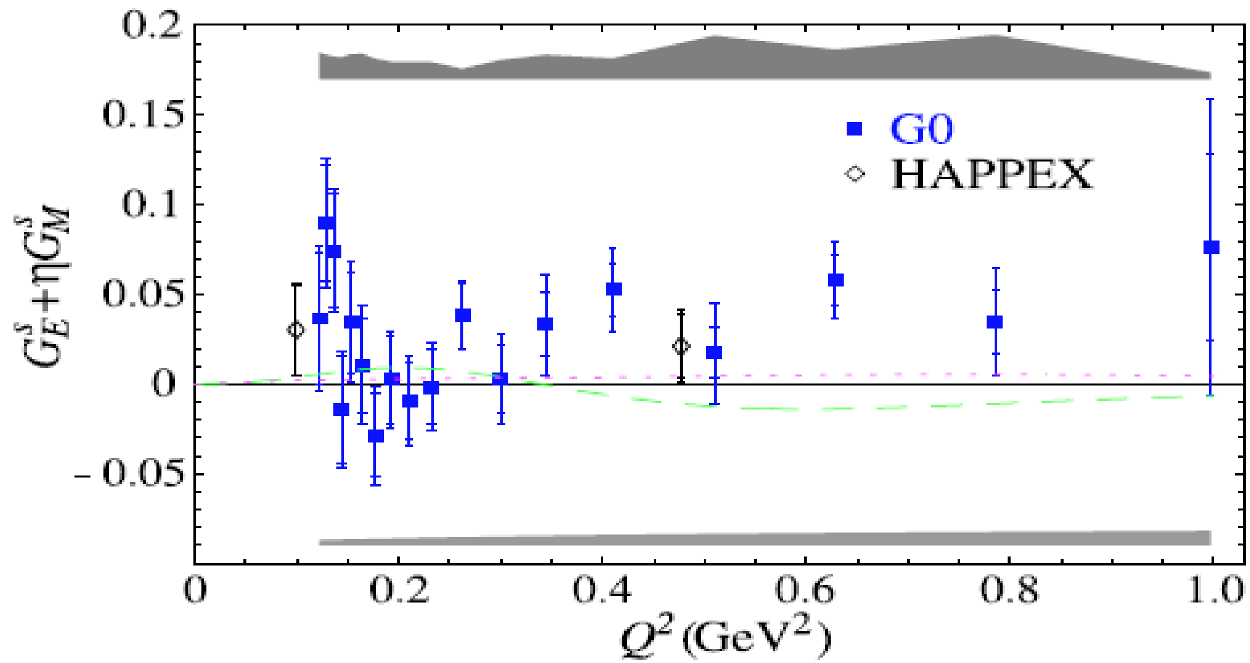
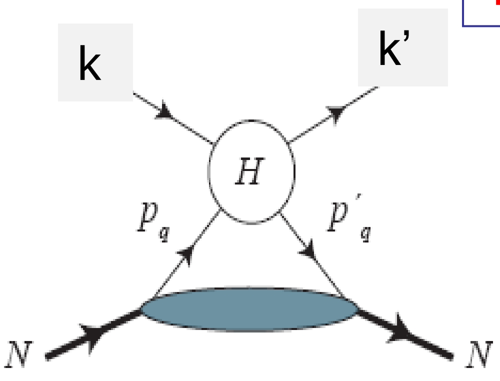


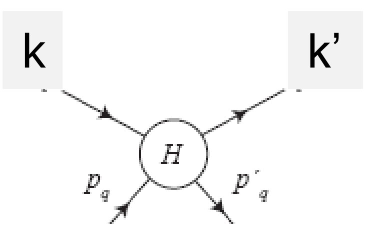
FIG. 2: The combination $G_E^s + \eta G_M^s$ for the present measurement. The gray bands indicate systematic uncertainties (to be added in quadrature); the lines correspond to different electromagnetic nucleon form factor models (see text).

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.



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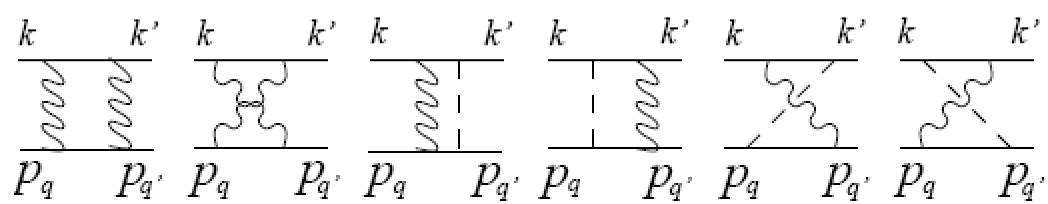
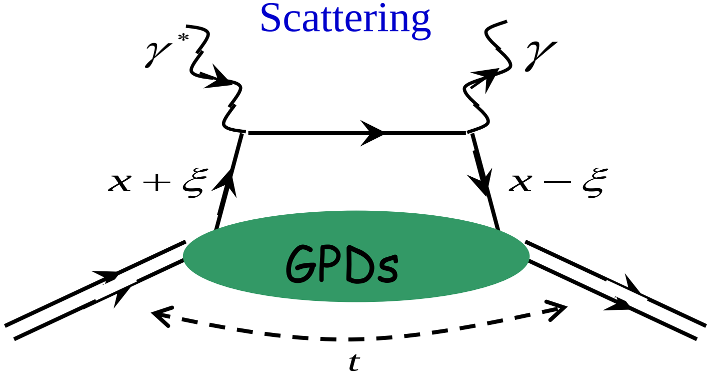


GPDs can be accessed via **exclusive reactions** in the **Bjorken** kinematic **regime**.

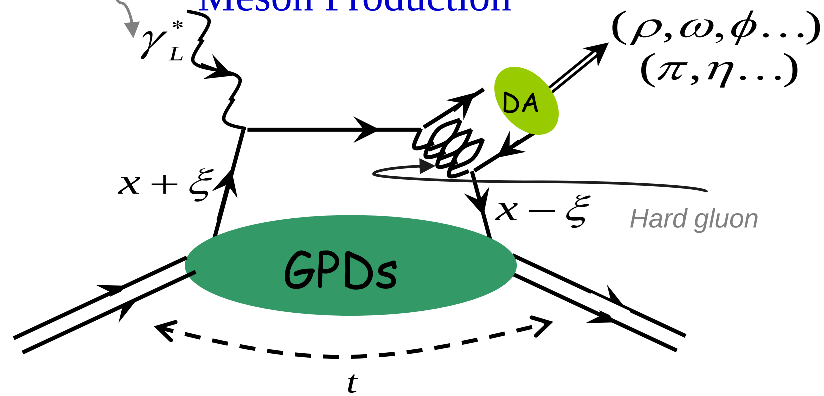
DVCS

Deeply Virtual Compton Scattering



DVMP

Deeply Virtual Meson Production



❖ 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**.

.

Partonic calculation of Box diagrams

$$\mathcal{M}^{PV}_{\gamma Z}(eq \to eq) = \frac{-iG_F}{2\sqrt{2}} \sum_{q=u,d} [t^1_q(\bar{u}_e\gamma_\mu\gamma_5 u_e)(\bar{q}\gamma^\mu q) + t^2_q(\bar{u}_e\gamma_\mu u_e)(\bar{q}\gamma^\mu\gamma_5 q)],$$

$$t^q_1 = Q_q[c_1 g^e_A g^q_V + c_2 g^q_A g^e_V] \qquad t^q_2 = Q_q[c_1 g^e_V g^q_A + c_2 g^q_V g^e_A]$$

removed because it is Soft contribution

$$c_1 = \frac{-e^2}{4\pi^2}\left[\ln\left(\frac{\lambda^2}{Q^2}\right) + \frac{\pi^2}{2}\right] + \frac{3e^2}{16\pi^2}\ln\left(\frac{\hat{u}}{\hat{s}}\right),$$

$$c_2 = \frac{e^2}{16\pi^2}\left[-7 + 3\ln\left(\frac{\hat{s}}{M_Z^2}\right) + 3\ln\left(\frac{\hat{u}}{M_Z^2}\right)\right]$$

$$\hat{s} = (P_q + k)^2, \hat{u} = (P_q - k')^2$$

In MS limit $c_1=0$ so that t^1_q is associated with g^e_V and t^2_q is associated with g^e_A.

Partonic calculation of Box diagrams

$$s=(p_1+p_3)^2,\ u=(p_2-p_3)^2$$

$$\mathcal{M}_{\gamma Z}^{PV,Parton} = -i\frac{G_F}{2\sqrt{2}}[\bar{u}_e\gamma_\mu u_e\bar{u}_N[\Gamma_1\gamma^\mu]\gamma_5 u_N + \bar{u}_e\gamma_\mu\gamma_5 u_e\bar{u}_N\left[\Gamma_2\gamma^\mu - \Gamma_3\frac{P^\mu}{M}\right]u_N]$$

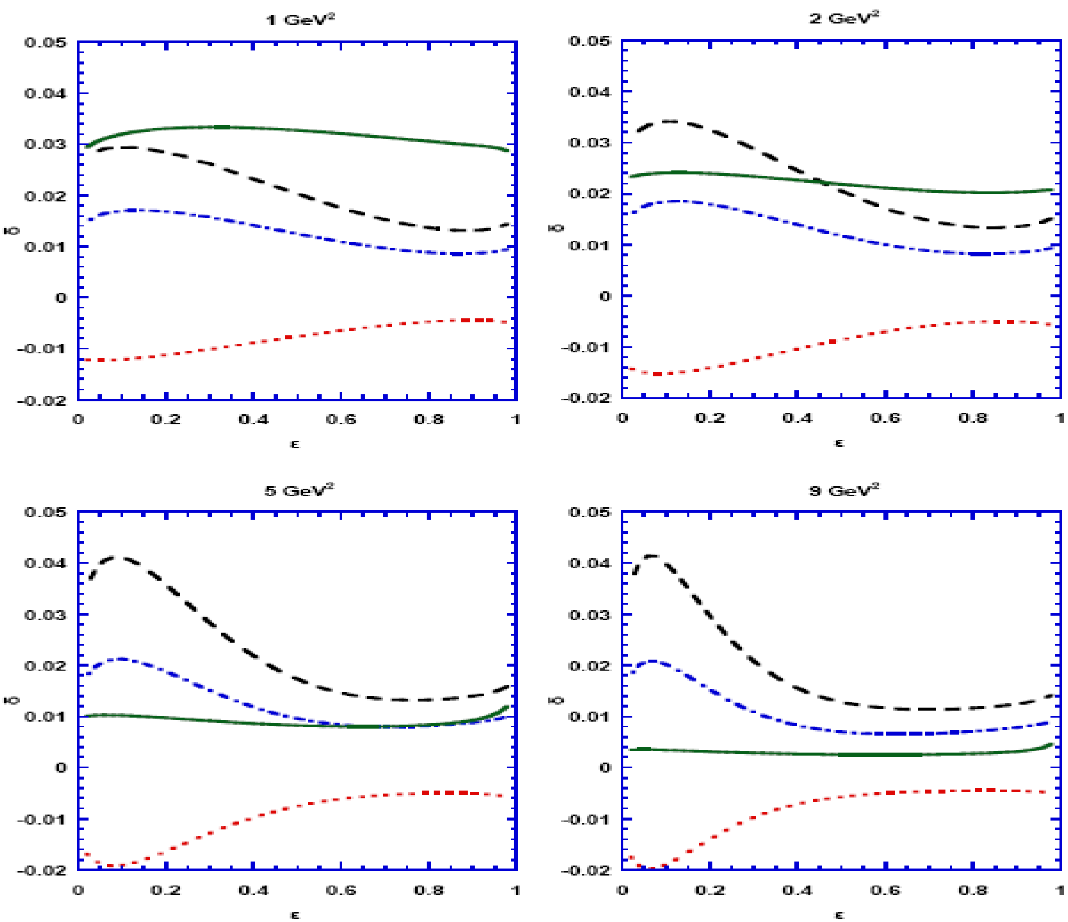
$$\Gamma_1 = \frac{1+\varepsilon}{2\varepsilon}F - \frac{1+\varepsilon}{2\varepsilon}\frac{Q^2}{s-u}D, \qquad D \equiv \int_{-1}^{1}\sum_{q=u,d}\frac{dx}{x}\frac{Q^2t_1^q+(\hat{s}-\hat{u})t_2^q}{s-u}(H^q+E^q),$$

$$\Gamma_2 = \frac{1+\varepsilon}{2\varepsilon}D - \frac{1+\varepsilon}{2\varepsilon}\frac{Q^2+4M^2}{s-u}F, \qquad E \equiv \int_{-1}^{1}\sum_{q=u,d}\frac{dx}{x}\frac{Q^2t_1^q+(\hat{s}-\hat{u})t_2^q}{s-u}(H^q-\tau E^q),$$

$$\Gamma_3 = \frac{1}{1+\tau}\left[\Gamma_2 - \sqrt{\frac{1+\varepsilon}{2\varepsilon}}E\right] \qquad F \equiv \int_{-1}^{1}\sum_{q=u,d}\frac{dx}{x}\frac{Q^2t_2^q+(\hat{s}-\hat{u})t_1^q}{s-u}sgm(x)\tilde{H}^q,$$

$$\frac{\nu}{M^2} = \frac{s-u}{4M^2}$$

Result of Partonic calculation



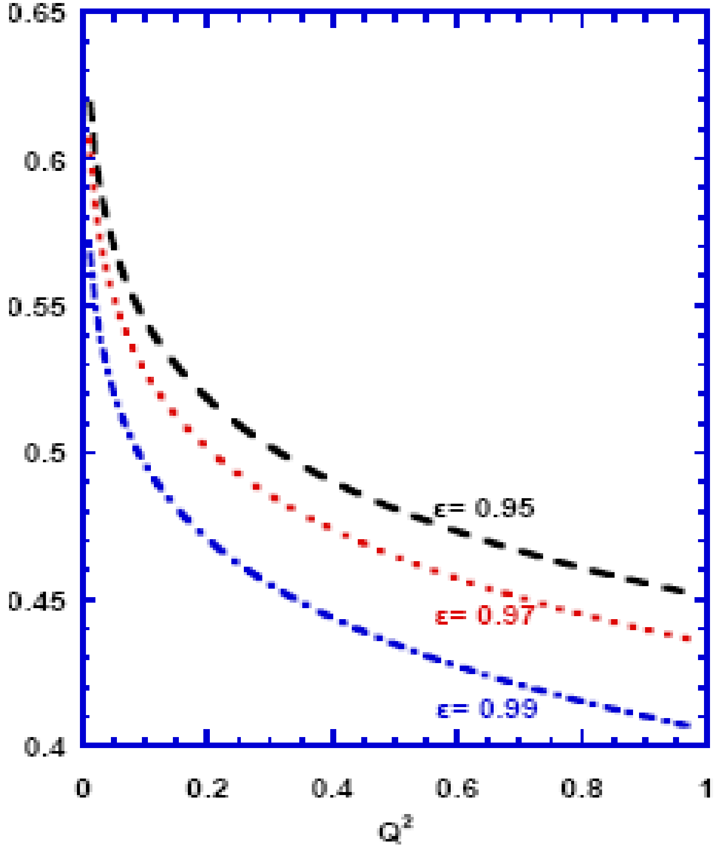
$\gamma(\gamma\gamma)$(dashed line)

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

TPE (dash-dotted lines)

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

Comparison with Marciano and Sirlin's approximation



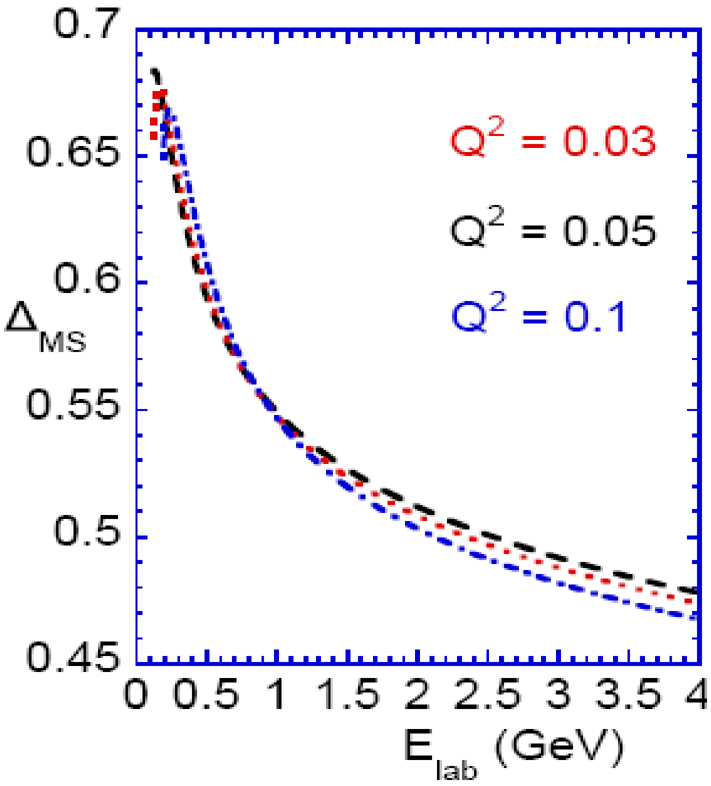
$$\Delta_{MS} = \frac{A_{PV}^{Parton}(\gamma Z)}{A_{PV}^{MS}(\gamma Z)}$$

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

$\mathcal{M}_{\gamma Z,A}^{PV,MS}$ $\qquad k = k' = 0$

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

Comparison with Marciano and Sirlin's approximation



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

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

$\mathcal{M}_{\gamma Z,A}^{PV,MS}$ $\quad k = k' = 0$

$$P_q \doteq P_{q'}$$

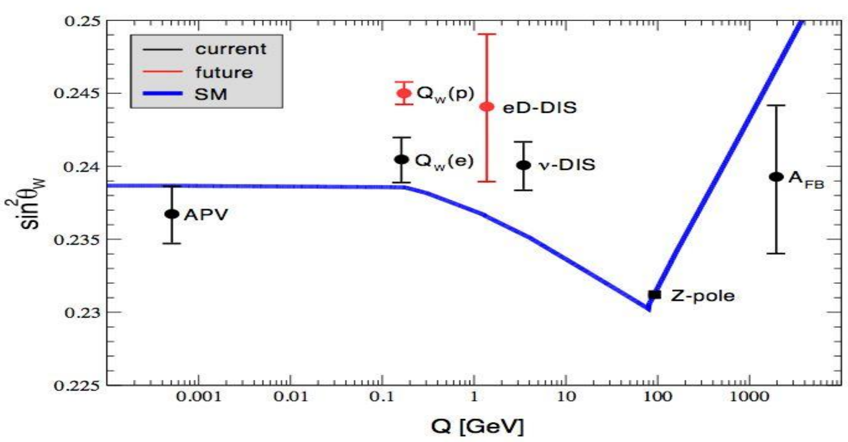
Hardon+GPD framework

- Hadron+GPD framework is a natural extension of MS approximation.
- It can be improved by adding more resonances (Hadron) and including QCD corrections (GPD)
- At MS limit we check that our result restores to MS original one.

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.



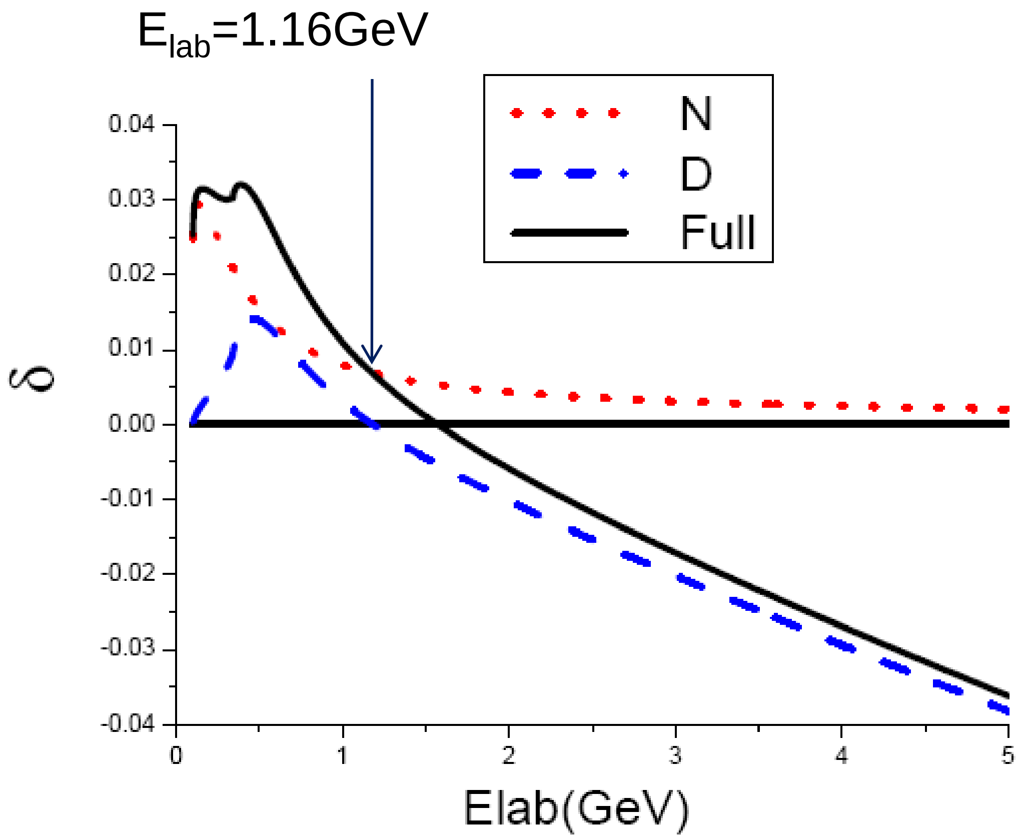
δQw / Qw = 4%

$\delta\sin^2\theta_W / \sin^2\theta_W$ = 0.3%

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

Our result @ Qweak Kinematics

δ_N=0.6%
δ_Δ=-0.1%



Dispersion relation study

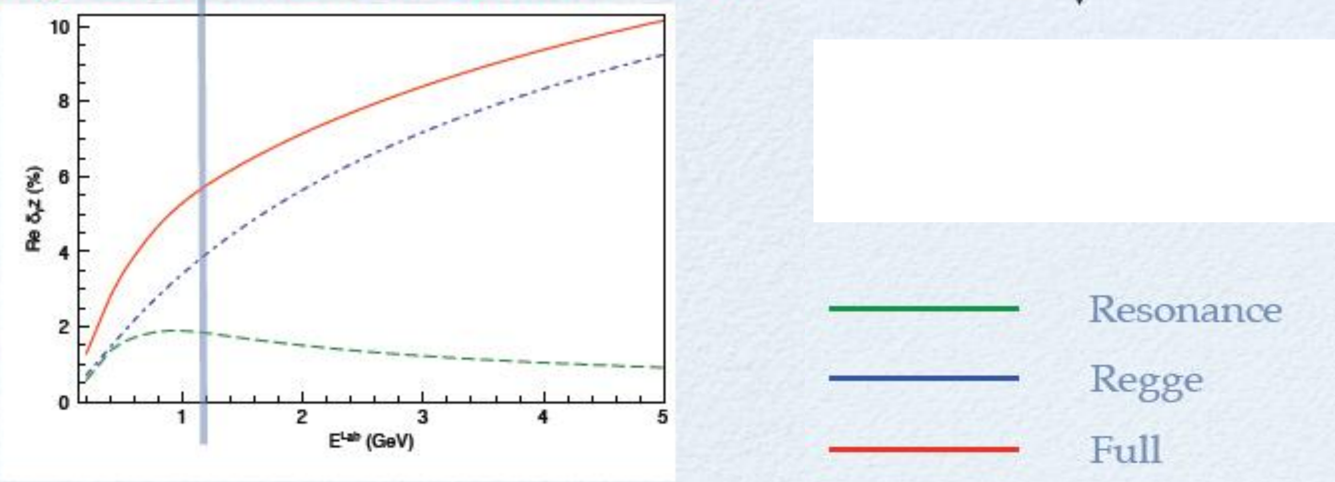
$$\mathrm{Re}\delta_{\gamma Z_A}(\nu) = \frac{2\nu}{\pi}\int_{\nu_\pi}^{\infty}\frac{d\nu'}{\nu'^2-\nu^2}\mathrm{Im}\delta_{\gamma Z_A}(\nu')$$

in exact forward direction only

Parity violating asymmetry - to NLO

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

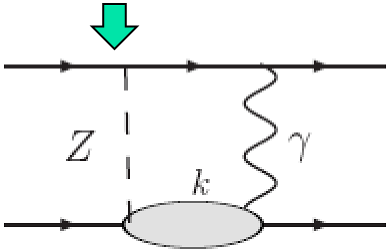
Dispersion correction to QWEAK ~ 5.5-6%



Mikhail Gorshteyn and Charles J. Horowitz
Nuclear Theory Center & Indiana University, Bloomington arXiv:0811.0614 (hep-ph)

Cut the Box into two pieces

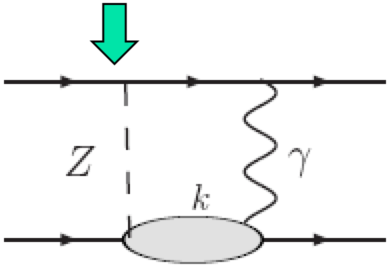
Zee axial coupling g_A^e



$$\delta_{\gamma ZA}$$

$$\delta_{\gamma ZA}(\nu=0)=0$$

Zee vector coupling g_V^e



$$\delta_{\gamma ZV}$$

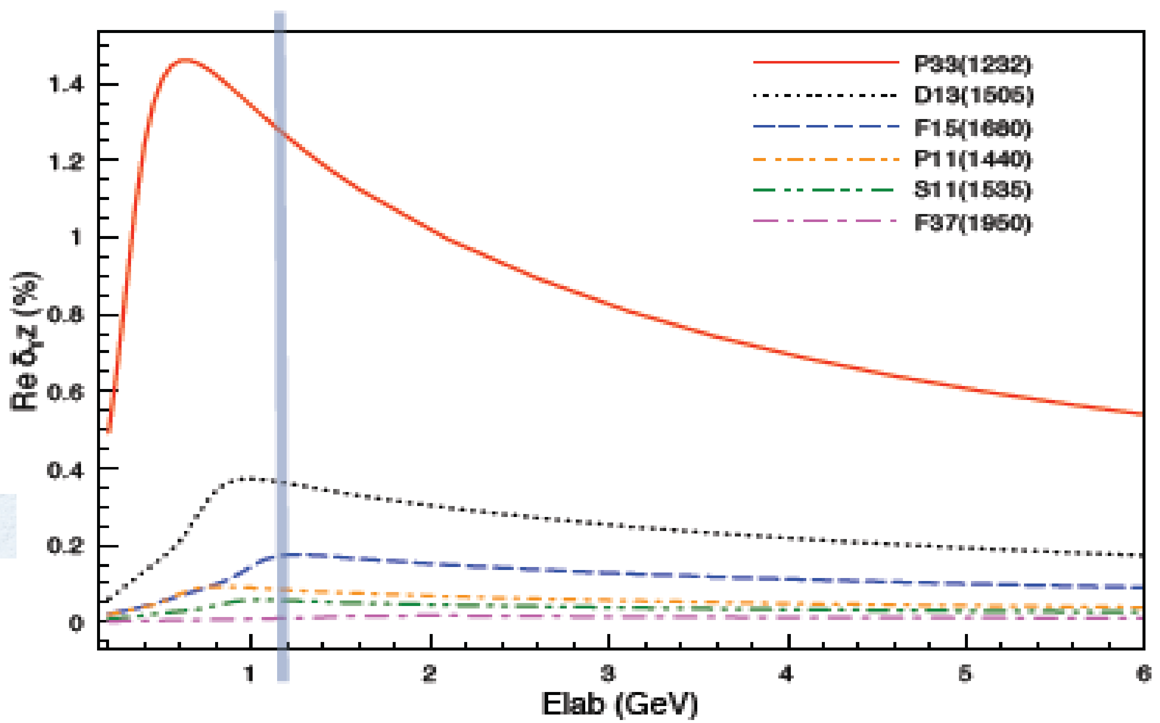
$$\delta_{\gamma ZV}(\nu=0)\neq 0$$

In dispersion calculation the N intermediate state is excluded.

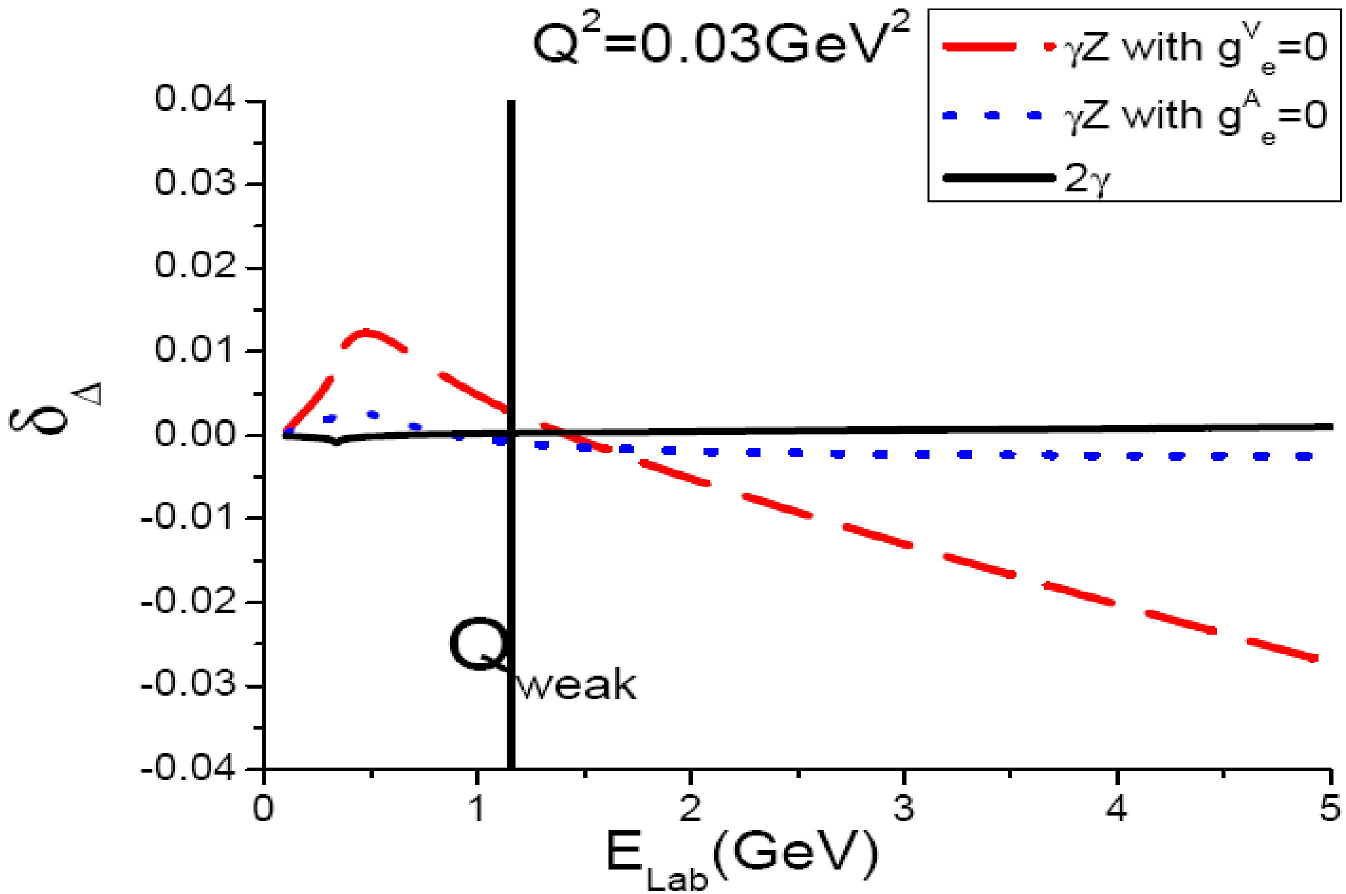
Δ(1232) contribution in dispersion approach

P33(1232)	1.3%
D13(1505)	0.4%
F15(1680)	0.16%
P11(1440)	0.1%
S11(1535)	<0.1%
F37(1950)	<0.1%

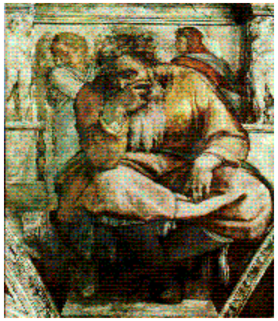
Full resonance contribution ~ 2%



Our result after separation



Conflict and confusion



- We check our result and indeed at $Q^2=0, E_{lab}=0$, $\delta\gamma zA$ does vanishes.
- We also check our result and indeed at MS limit we obtain the original MS values.
- However our result show that TBE effect decreases as E_{lab} increases at low Q^2 .
- But dispersion approach show $\delta\gamma zA$ increases as E_{lab} increases.

Possible resolution?

- Is it possible that $\delta\gamma Z_V$ decreases so fast and cancel the increase of $\delta\gamma Z_A$?
- Is it possible that the structures neglected in $Q^2=0$ produces large effect even at low Q^2?
- Or maybe Handbag approximation just does not work? (why?) or QCD correction is very large?
- Is it possible that PVDIS is very different with modified DIS data used in dispersion calculation?

Conclusion and Outlook

- TBE effect is sensitive to Q2 and scattering angle, hence its impact on strange form factors is not negligible.
- MS approximation is not good enough and it is necessary to go beyond it.
- Conflict with the result from dispersion relation requires more study.
- More investment is needed badly in this Box business……

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

Personal feeling…

Thank you for listening…..

Two bosons may be too many, but two cups of Italian ice cream are definitely not………